Department for Business, Energy & Industrial Strategy

The Role of Standardisation in Support of Emerging Technologies in the UK

Final Report

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Contents

1. Introduction

Technopolis were commissioned by the UK Department for Business, Energy and Industrial Strategy (BEIS) to undertake a study exploring the role of standardisation in supporting the development and commercialisation of emerging technologies in the UK[1].

The intention was to inform the delivery of a joint Action Plan by BEIS and the National Quality Infrastructure (NQI) organisations; to help BEIS to determine what future role it should have in shaping the standards framework; and to inform the longer-term policy development of NQI members and BEIS.

The study included three main phases of work, with each resulting in separate chapters that are presented later in this document:

- A **literature review** on the role of standardisation and standards in supporting the development and commercialisation of emerging technologies (Section 3)
- A **landscape review** of the UK approach to standards development in support of emerging technology (Section 4)
- A **review of experiences** of standards and standardisation amongst innovators in four emerging technology areas (Section 5)

This document begins, however, with a **synthesis and recommendations** to the overall study (Section 2). This draws on the three main phases of research to identify opportunities to improve the functioning of the UK standardisation system, such that it better supports innovative firms in areas of emerging technology.

[1] It is not possible to consider all areas of emerging technology in detail within the study. However, the third phase looked in more depth at four areas (graphene, quantum computing, synthetic biology, hydrogen as a fuel).

2. Synthesis and recommendations

2.1. Introduction

This section provides a summary of conclusions and recommendations to the study. It draws on the three main phases of research (set out in Sections 3 to 5) to identify opportunities to improve the functioning on the UK standardisation system, such that it better supports innovative firms in areas of emerging technology.

The recommendations include:

1. Deepening and enhancing coordination across the NQI and with Innovate UK
2. Building standardisation into the design process of public innovation programmes
3. Leveraging existing structures to promote and raise awareness of standards
4. Ensuring relevant processes are in place to identify standardisation needs
5. Ensuring relevant processes are in place to develop standards in innovative areas
6. Increasing the dedicated resources available for standardisation activities

The conclusions and recommendations reached demonstrate the continued relevance of key actions already identified by government and the UK National Quality Infrastructure (NQI) partners in their recent (July 2021) joint Action Plan to unlock the value of standards for innovation, and show the importance of following through on the delivery of this plan.

2.2. Rationale and need

The literature review (see Section 3) summarised the well-established **beneficial impacts that standardisation has on innovation in emerging technologies**. This includes by:

- *Codifying knowledge* – where the information set out in standards can serve as an input for further innovation and also help to coordinate innovation activities both within and between organisations, and where standards can help to communicate information about product characteristics to potential users and consumers that then helps to foster sales
- *Reducing the variety of options* – which in emerging areas can enable economies of scale and critical mass, as well as cohesion in a sector as the basis for market growth, while also incentivising incremental innovation and investment in complementary infrastructure
- *Defining minimum levels of quality* – that can help to create trust among early adopters of emerging technologies and avoid incidents that undermine trust in new products, as well as avoid Gresham's Law (where low-quality products can drive out high quality goods in markets where there are high levels of information asymmetry)
- *Supporting interoperability* – with positive network externalities incentivising innovation

The literature review also highlighted evidence on the benefits gained from the standardisation process itself, where it can act as a platform for the production and exchange of knowledge around innovations. It highlighted that standards development can usefully help to collect ideas and perspectives on innovations from customers and competitors, while also helping to raise awareness of innovations amongst a wider group of investors and customers.

Whilst the review also highlighted several potential negative implications of standardisation for innovation (particularly the possible risks of market concentration or the lock-in of old or inferior technologies) the literature was also clear that these concerns are outweighed by the positives, at least when the standardisation process is open and transparent, and where the resulting standards do not include inaccessible intellectual property.

The landscape review (see Section 4) and the deep-dives into four emerging technologies (along with the collected experiences and views of innovators in these areas) (see Section 5) has then confirmed that there is a clear **rationale and need for public intervention in standards for emerging technologies**.

Stakeholders regularly highlighted that industry demand could not be relied upon to initiate and drive standardisation for emerging technologies. In established areas of technology, the standardisation "model" tends to work well and has stood the test of time, but there are various **reasons why this system may not be as well suited for emerging technologies**. In particular:

- Innovating SMEs are often narrowly focused on developing and commercialising their ideas, sometimes in isolation and / or with strong concerns about secrecy
- The emerging industries and communities (particularly where they involve new entrants) are often less well established, less integrated and less connected, either directly, or through representative or sectoral bodies
- There are often many newer, smaller innovative businesses (working alongside some more established and larger businesses) active in new technologies, who have less time and resources available to engage with the standardisation process
- Knowledge, experience or understanding of standardisation can be quite limited among SMEs/ new entrants in emerging sectors

There appears to be a general lack of awareness amongst companies developing emerging technologies (and some wider stakeholders in academia and policy) of the need for, or potential benefits of standards – and indeed it proved quite difficult during the study to engage innovative businesses on these topics in the four emerging technology areas selected. There also appears to be a lack of time, coordination or resources amongst businesses in emerging sectors to be able to easily engage with the standards process, even in those cases where a clear role and need for standards has already been established (e.g. through a strategy or roadmap).

As has been shown, standards can and do appear for emerging technologies – through formal or informal routes. However, without external intervention and support there is the risk that the process does not involve the full range of relevant stakeholders or consider the best timing for standards. There is also the risk that standards development is driven by stakeholders in other countries (with potentially little or no UK input) - with potential consequences for the scale and speed of UK innovation and commercial success. As such, for emerging technologies, there is a case for government intervention to support and encourage greater and earlier consideration of standardisation within the innovation process. Where innovation is still early stage and often supported through public funding anyway, it is not unreasonable that government should also look to assist in improving the framework conditions (including standards) within which the innovation process is operating.

As we have revealed during the study, **the UK standards and innovation support community (government, Innovate UK and NQI partners including BSI) have recognised this need and are already making efforts to better address and support the standards related needs of emerging technology**. For example, through:

- Encouraging large R&I programmes to consider standards (needs/funding) during initial programme design
- Supporting the development of standardisation roadmaps and strategies, which can usefully bring together a community to review the current standards landscape (existing standards, active committees, etc.) and identify gaps / needs for action
- The introduction and sponsorship of alternative fast-track BSI standards routes (PAS and FLEX), offering an alternative (or precursor) to 'traditional' standards
- An increased focus on emerging technology needs, within and across relevant support organisations, as well as closer working relationship between government, the NQI organisations and UKRI to ensure a more joined-up, systematic effort

However, more could be done, building on and extending these existing efforts, to support emerging technologies to a greater extent and more systematically, while not compromising the fundamental principles of standards and standardisation. Broadly, there are two areas or stages where such intervention would be beneficial: identifying needs and potential for standards; and processes for standards development. Across both areas there are a **series of challenges and needs to be further addressed**. In particular, ensuring that:

- Relevant stakeholders (SMEs, start-ups, academia and policy makers) are aware of the role that standards can play, and are involved in the identification of needs (what standards are needed and when) in relation to emerging technologies
- The appropriate processes are in place to make it easy for stakeholders to convene and to collaborate in the identification of needs for and development of standards
- The appropriate processes are in place for developing standards for emerging technologies, noting the different needs and challenges for emerging technologies
- Relevant resources are readily available for all of the above (to ensure that the right people are in the right place, with the right incentives to act, at the right time)

2.3. Recommendations

Based on these conclusions, we set out below a series of recommendations to improve the functioning of the UK standardisation system, such that it better supports innovative firms in areas of emerging technology.

1. Deepening and enhancing coordination across the NQI and with Innovate UK

Firstly, we see benefits to further deepening the links between BSI (and the NQI more widely), and Innovate UK. This is already underway but should continue and be further strengthened. In the past 1-2 years the concept of a UK NQI has developed into a more tangible 'entity', coordinated by BEIS (through BRE) and meeting on a monthly basis to share information and knowledge. NQI stakeholders consulted were positive and enthusiastic about this closer working relationship, as well as the potential benefits of further joined-up working. The important role of BEIS BRE in harnessing and encouraging this joint effort was also highlighted.

The NQI organisations have also worked with BEIS BRE and OPSS to develop an Action Plan (July 2021) to 'unlock the value of standards for innovation', which identifies six key areas for action going forward. We believe it is important that this group engages also with wider government and with Innovate UK in the deployment of this action plan, and so it is encouraging to see the recent establishment of a strategic coordination group on future standards, which will bring together expertise from across several government departments, the NQI partners and Innovate UK. This group is intended to identify potential opportunities and priority areas where the development (or review) of standards and the wider NQI infrastructure can support innovation and deployment of emerging technologies, with the aim of fostering greater coherence and synergy between policy and standardisation in areas of innovation.

BEIS has recently published its response to a consultation on its future approach to regulation. This included a question on whether consideration of standardisation (as an alternative or complement to regulation) should be formally embedded in the early appraisal options for new regulations. The response highlights that regulation should only be pursued where absolutely necessary and that best use should be made of alternatives. It sets out plans to introduce independent scrutiny earlier in the process of developing new regulation, asking government departments to provide a clear justification of their decision to pursue regulatory options, having engaged with the Better Regulation Executive to fully consider alternatives. These plans will further enhance earlier and wider consideration of the potential of standards in areas of emerging technology, amongst others.

2. Building standardisation into the design process of public innovation programmes

We would also suggest that there should be a further push to ensure consideration of standards in all public interventions in innovation - at the design / business case stage – which would enable the appropriate actors, processes and funding to take this forward to be put in place from an early stage and then embedded within the activities of the programme.

The stakeholders consulted suggested that there is no optimal time to introduce or create standards for emerging technologies, given that each technology, sector or context is different. Timing can also reflect the different roles that standards play in different application areas or user sectors (e.g. providing information, variety reduction, minimum quality / safety, compatibility / interface). These factors mean that engagement and discussion are key to understanding needs and supporting relevant standardisation activity at the appropriate time.

Innovate UK reported that it has recently pushed for consideration of standardisation as part of the development of the Industrial Strategy Challenge Funds (ISCFs) and other significant programmes, while BSI reported having engaged with all ISCF Directors to explore the potential role of standards in their challenge domain. There were some notable successes, in terms of this leading to standardisation activity, e.g. Connected and Autonomous Vehicles, Faraday Battery and the Medicines Manufacturing ISCFs, demonstrating that the approach works.

Stakeholders highlighted that having thinking and discussion of standardisation built into these kinds of multi-year programmes is likely to help with the identification of needs for standards at the right time and provides an opportunity for ongoing engagement among the relevant actors. The approach should therefore be rolled out systematically across all significant innovation interventions, with stronger requirements to consider standards as part of programme design.

3. Leveraging existing structures to promote and raise awareness of standards

More broadly, existing convening structures (such as the ISCFs and Knowledge Transfer Networks) should be used to a greater extent to engage relevant communities on standardisation. In most areas of emerging technology, one sees different fora and groupings emerge for meeting and the sharing of ideas. However, this process can take time, and multiple different structures and groupings may emerge in parallel without a clear single focal point. The ISCFs have shown that big programmes and missions can provide a good central point for convening actors in relation to (some) emerging technologies and therefore for engagement on standardisation (for consideration of needs and for the development of strategies and roadmaps). However, there is a question mark over what happens beyond the ISCFs (i.e. when they come to an end) and also what other pre-existing structures could usefully be targeted for engagement (particularly in areas of emerging technology not currently covered by these large-scale multi-annual innovation programmes).

There is also a need to bring in other actors into these groups, such as standards experts from BSI or Innovate UK (or indeed experts from the wider NQI to discuss e.g. metrology or accreditation), in order to stimulate consideration of needs for standards and to coordinate and facilitate the process. BSI has invested in additional staff resource and established sector leads within its standards development team who are responsible for outward-facing engagement, including in areas of emerging technology. They should work closely with IUK to identify opportunities to participate in and engage with relevant programme opportunities.

4. Ensuring relevant processes are in place to identify standardisation needs

Roadmaps or strategies have been a common starting point in recent years for thinking about the role of standardisation to support emerging technologies, and there are several examples already where these have led to standardisation. We would therefore encourage further use of the approaches, with additional support and encouragement (by government, Innovate UK and/or BSI) targeted at the convening of relevant stakeholders to develop standardisation roadmaps and strategies for emerging technologies.

5. Ensuring relevant processes are in place to develop standards in innovative areas

For the standardisation process itself, it appears that the BSI PAS and FLEX options are well regarded and have successfully enabled many emerging technology areas to take first steps into standardisation using an approach that is more suited to needs. BSI will need to keep these processes under review (and in particular FLEX, which is less well tried and tested at this stage) – but we have seen no reason to suggest that these need to change. There may, however, be a need to further promote consideration and understanding of the PAS and FLEX routes as an option, and to enable easy access to sponsorship funding, where a need is identified.

6. Increasing the dedicated resources available for standardisation activities

There is also a need for additional dedicated sources of funding to support the development of roadmaps / strategies and standards (particularly PAS and FLEX) for emerging technologies.

Stakeholders reported that standards strategies and roadmaps, as well as subsequent PAS / FLEX development, rarely happen in relation to emerging technologies without a specific source of external (public) funding. In recent years this has mainly come through Innovate UK or individual government departments, but there is no central funding (or prioritisation or selection) mechanism or policy in place for such activities, so there is a reliance on the interests of individual people within these organisations and their knowledge and understanding of the potential benefits of standardisation to drive this forward. The sums involved are relatively small (e.g. £80k-£100k for sponsorship of a PAS), but nevertheless can be hard to secure. Dedicated funding – be that within innovation programmes, within BEIS, or through the public grant to BSI – may therefore help to increase the scale of activity and make it less reliant on the knowledge, understanding, interest or drive of particular individuals or organisations.

Where standardisation roadmaps and strategies are developed, there is a risk that these are not taken forward if there is insufficient funding, commitment or leadership in place. The example put forward during the study was of the industrial biotechnology standards roadmap, which was driven by the Industrial Biotechnology Leadership Forum (IBLF) with Innovate UK funding (and which aligned with wider government priorities and funding), but where there was reportedly no follow-up activity and the next steps for taking the roadmap forward were unclear. It is therefore important that these activities do not take place in isolation but are instead part of a sustainable and longer term coordinated programme of effort.

Suggestion for further research

Finally, this study has sought to take a technology agnostic approach to understanding the role of standards and key features of the UK framework. This means that (for example) we have not sought to map out the complex digital standards landscape (where much standardisation work takes place outside of the NQI, often internationally and through direct industry participation), where the government's work is led by the Department for Digital, Culture, Media and Sport (DCMS). There may be useful lessons that can be learnt from the digital standards world, as well as potential benefits to be gained from a more joined-up approach across government and stakeholder organisations. However, this would need to be explored further through a specific piece of research and / or further discussion between the parties involved.

3. Literature Review

3.1. Introduction

This section presents the findings from the first phase of research; a comprehensive literature review. The objective of this exercise was to draw on domestic and international examples, literature and documents in order to review the role of standardisation and standards in supporting the development and commercialisation of emerging technologies. The review builds on and updates previous research, in particular the Institute for Manufacturing study of the Role of Standardisation in support of Emerging Technologies (O'Sullivan and Brévignon-Dodin 2012) and Blind (2016). It is intended to inform our understanding of what works in terms of supporting the development and implementation of standards for emerging technologies, as well as inform the development of the conceptual framework for the remainder of the study.

The section provides a systematic review of recent and relevant literature, identified through searches for publications addressing innovation and standardisation listed in Web of Science and Scopus, but also Google Scholar. The search strategy was based on key word searches, but also focused on the few well-known authors in the field, some of whom were contacted directly, and citations of their work.

The search was also expanded to capture the role of standards within the wider National Quality Infrastructure (NQI) to support innovation and emerging technologies. However, as expected, the literature here turned out to be rather limited, with the few publications available focused on emerging economies. The search did not identify any relevant grey literature and studies published recently by standard developing organisations (SDOs) (e.g. such as BSI, CEN and ISO), public agencies and institutes (e.g. NIST), or government departments and intergovernmental organisations (e.g. World Bank, OECD, European Commission).

Following this brief introduction, the literature review is set out as follows:

- Approaches to conceptualising the functions of standards and their impacts on innovation
- Impacts of the standardisation process on innovation
- Functions of standards and standardisation in innovation systems
- Standardisation road-mapping
- Concluding remarks on the main lessons considered in this review

A list of references for the literature review can be found in Appendix A.

3.2. The economic functions of standards

From the seminal contribution by Schumpeter (1911) on the economics of innovation, which stresses the creative destruction of existing technologies and industries by innovation, we can derive implications for existing standards. In particular, innovative technologies require the development of new standards, which in general challenge existing standards (that are often supported by the incumbents of the established markets). The new standards and technologies become dominant, as introduced by Nelson and Winter (1982) in their model of evolutionary economics (Blind 2021), before they are challenged by the next wave of creative destruction.

Alongside the implications for standards derived by the entrepreneurial driven Schumpeterian approach, the 'Porter Hypothesis' (Porter and van der Linde 1995) must also be mentioned. This claims that demanding product market regulations and standards can force or encourage innovation. For example, new environmental or sustainability standards are currently major drivers for innovation (e.g. Lim and Prakash 2014).

There is a significant body of literature that deals with the different functions of standards. In the first overview provided by Swann (2000), he distinguishes four major economic functions, following David (1987):

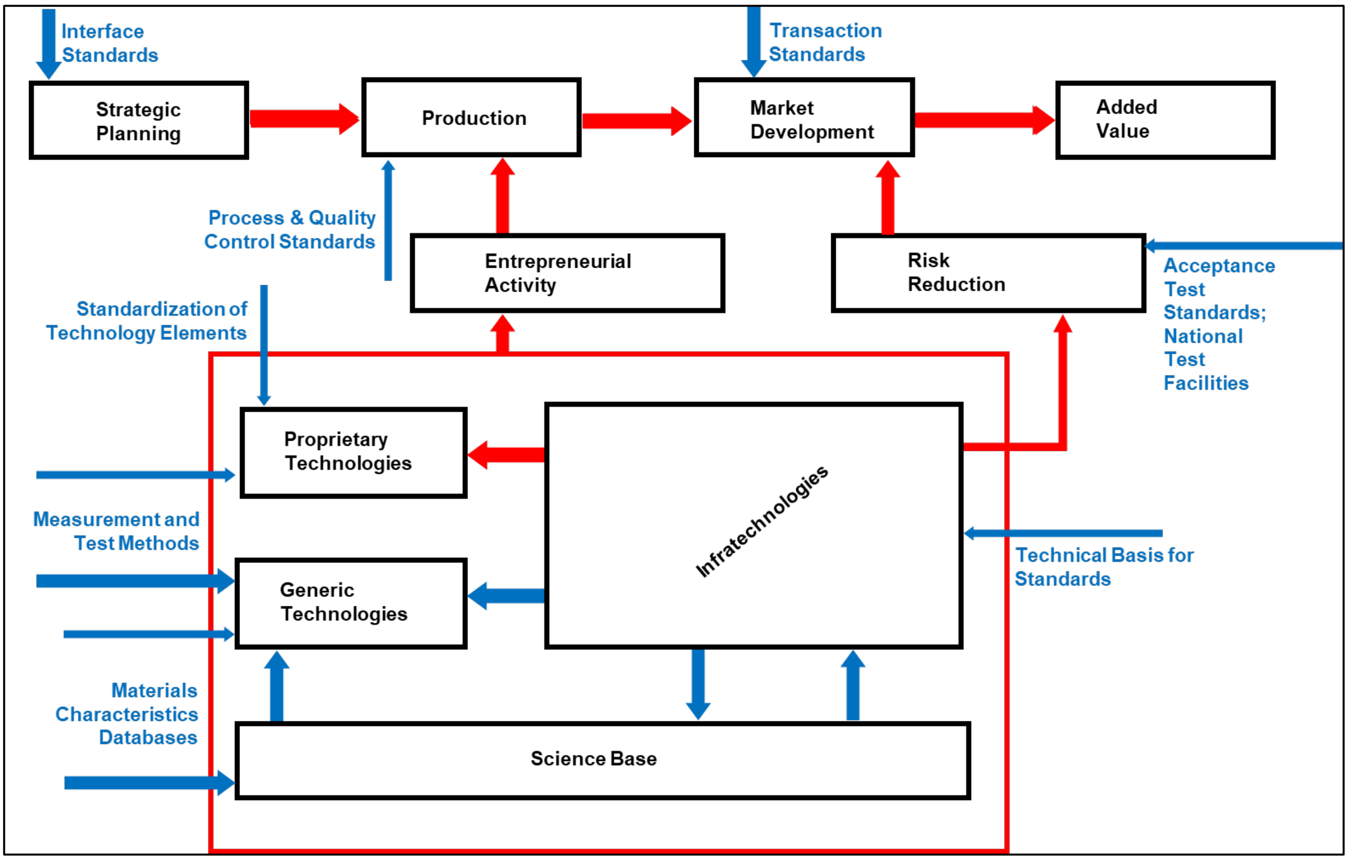
- At first, standards codify knowledge, in much the same way publications or patents do. This reduces transaction costs, which accrue between actors within organisations, but mainly between different organisations. In addition to this generic function, relevant for all standards, Swann (2000) distinguishes a further three economic functions.
- Standards reduce the variety of options of technologies, products and processes. This characteristic is also applicable to most standards, although to differing degrees, depending on the level of detail of the specifications.
- Standards can help to define a minimum level of quality, including the intention to protect health and safety and to limit the environmental impact of products and processes.
- Due to the increasing relevance of ICT, the definition and implementation of relevant standards ensures compatibility and interoperability of components by different suppliers (see already David and Greenstein 1990 or David and Steinmueller 1994). The value of final network products, such as mobile phones or social media, depends on both their characteristics and on the positive network externalities afforded many users, which can only be achieved through common communication standards.

In parallel to Swann (2000), Tassey (2000) identifies various functions of standards in technology-based activities, recently updated by Tassey (2017a, b). He also differentiates by economic functions, but specifies standards further and embeds them in a heuristic model of technology-based activities (see Figure 1).

Finally, Sherif (2001) publishes independent both from Swann (2000) and Tassey (2000) a layered architecture for technical standards. This has reference standards for units, references, and definitions as a first layer, followed by similarity standards for variation reduction, compatibility standards for interactions and eventually flexibility standards for evolution as a last layer. Standards for performance and quality can be found at all four layers.

Since neither the taxonomy of Tassey (2000) nor the one presented by Sherif (2001) support an immediate application to innovation, the following sections apply the basic economic functions introduced by Swann (2000) to innovation and emerging technologies.

Figure 1 Various functions of standards in technology-based activities



Source: Tassey 2000, p. 588

3.3. The impact of standards on innovation

Based on the generic economic functions of standards, Blind (2016, 2017 and 2021) derived their implications for innovation.

The pure codification of knowledge in standard documents, like scientific publications and patents, generates knowledge spill overs which can be used by firms and other organisations as an input into their innovation activities. Among the list of information sources for innovation used in a recent German edition of the Community Innovation Survey, more than 10% of the innovative firms relied on standards (Rammer 2020), where the share was only around 5% two years before (although based on a slightly different wording of the question) (Rammer 2018).

Wiegmann (2018) even highlights the coordinating role of standards (based on the information they contain) in collaborative innovation activities between companies. Complementary to this, Lorenz et al. (2019) elaborate the role of standards to coordinate between process and product innovation within companies. Finally, Blind and Gauch (2009) stress the role of standards between the different phases of research and innovation (see below in detail).

However, having too many standards relevant for the development of new products and processes requires companies to screen and analyse all these standard documents (which are often released by different standard setting organisations). This requires effort and time that is not available for innovation activities. In addition, if standards and their requirements are too detailed, they might also disclose too much relevant knowledge to a company's competitors, increasing the level of competition and disincentivising innovation (see Aghion et al. 2005).

Since standards reduce the variety of technologies, products and processes, the available choices for the demand side are also reduced. However, standards can help to achieve a critical mass on the supply side, enabling economies of scale and allowing for decreased prices and increased demand. In addition, incentives to invest in complementary infrastructure increases, as in the case of plugs for electric cars (Wiegmann et al. 2017). However, in the long run this concentration of companies at the supply side might reduce the pressure of competition and investments in alternatives to those technologies specified in standards (Cabral and Salant 2014). If the pressure to decide for a specific technology and against alternatives leads to premature standard setting, then the risk of choosing inferior or less innovative technologies increases (David 1985; Uotila et al. 2017).

Technological irreversibility after the successful implementation of a standard can restrict subsequent innovation activities (Ho and O'Sullivan 2017, Wiegmann 2018). If we assume that dominant designs are based on standards, then already existing dominant designs (i.e. established standards) have positive impacts on incremental innovations but negative impacts on radical product innovations (Brem et al. 2016, see also the various references in Narayanana and Chen 2012). This finding is in line with Foucart and Li (2021), who assume that standards can be used by firms as an "insurance", hedging against the risky process of developing new products. Their empirical investigation reveals that this incentive mechanism fosters incremental innovation, especially for those firms positioned further away from the technological frontier, but reduces the incentives for radical innovation. These results are in line with previous conceptual research, showing that well-established standards challenge the success of radical innovations (e.g. Arthur 1989; Katz and Shapiro 1992), whereas incremental innovations are either not influenced or are even promoted, as revealed by Anderson and Tushman (1986).

Standards, implemented properly, can increase trust among users and consumers by defining a minimum quality of products and processes, including specifications restricting negative safety, environmental and health impacts. Related to new products, which might be accompanied by a higher level of risk due to limited experience of usage, standards are able to promote the level of trust by pioneering users, who are crucial for the successful launch of new products. However, if the adequate implementation of quality standards proves challenging (and costly) for suppliers in a specific market, it might lead in the long run to a monopolisation of the market and eventually a reduction in the incentives to innovate. Consequently, the review of the literature by Manders et al. (2016) on the impacts of the international quality management system standard series ISO 9001 on product innovation shows more studies revealing negative instead of positive impacts. This finding can be explained by significant implementation costs (with resources then not available for research and innovation) and possible restrictions on implementing new processes.

Finally, in network industries based on ICT, the success of new products requires common standards as the basis for positive network externalities (see David and Greenstein 1990 on compatibility standards). For example, the various generations of mobile communication standards allow the frictionless communication of billions of users, which increase the incentives for investments in future generations of standards (Baron et al. 2016), but also complementary products. Compatibility standards also allow the combination of components of complex technologies provided by different suppliers, which enables both a broader diversity of products and dynamic innovation because of the option to substitute single components by more innovative ones without changing the whole complex product or system.

If a generation of a standardised technology is substituted by a more innovative one, standards assuring their compatibility reduce the likelihood of lock-ins to old technologies due to the stronger incentives to invest into new generations, e.g. by allowing the communication between 4G and 5G mobile phones. If these compatibility standards are proprietary in nature, they can generate monopolistic, or even uncontestable market structures due to strong network effects. They can then become technological bottlenecks (Ho and O'Sullivan 2017). Proprietary standards generate higher profits for their owners, incentivising and allowing higher investment in R&D. However, the innovation dynamics of the whole market are reduced due to the lower incentives on incumbents who can exploit their market power based on proprietary standards. Even compatibility standards without proprietary rights can promote lock-in. The design of QWERTY keyboards is such an example, characterised by strong network externalities without compatibility to follow-up technologies (David 1985; Arthur, 1989; Katz and Shapiro, 1992).

In Table 1, we summarise the various impacts and agree with Allen and Sriram (2000), as well as Swann (2005), that the positive impacts of the different types of standards on innovation outweigh the negative ones. However, necessary requirements are the openness and transparency of the standardisation processes and that the standards (or some of their parts) are not covered by inaccessible proprietary property rights, like patents.

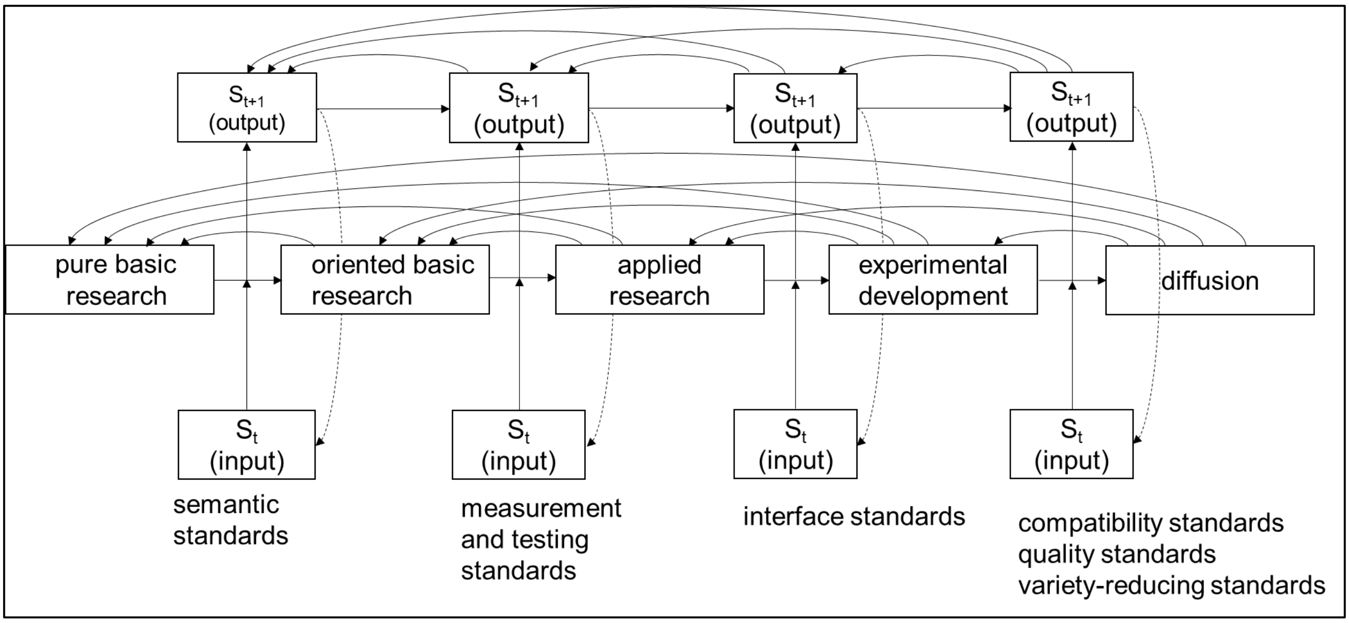
Functions of standards	Positive impacts on innovation	Negative impacts on innovation
Information	Providing codified knowledge relevant for innovation Coordinating collaborative innovation activities	Unintended knowledge spillovers to competitors
Variety reduction	Economies of scale Critical mass in emerging technologies and industries Incentives for incremental innovation Incentives for process innovation	Reducing choice Market concentration Premature selection of technologies Less incentives for radical innovation
Minimum quality	Creating trust	Market concentration
Compatibility	Positive network externalities Avoiding lock-in old technologies Increasing variety of system products	Monopoly power Lock in old technologies in case of strong network externalities

Source: based on Blind (2004, 2016, 2017) and Swann (2000)

In addition to the impacts of standards on innovation (elaborated above), standards can also provide enabling framework conditions for research (see Blind and Gauch 2009). This is especially the case for terminology standards in relation to basic research, which can facilitate the communication amongst researchers. Metrology, measurement and testing standards are also increasingly relevant in the subsequent stages of applied research. However, Swann (2009) stresses the importance of pre-normative research, e.g. related to metrology for test and analysis methods as a prerequisite for effective and efficient standards and even certification systems. Consequently, research, metrology, standardisation and eventually innovation follow a virtuous cycle (as illustrated by the feedback loops in Figure 2). As already elaborated above, quality, but also health, environmental and safety standards are necessary requirements for the last stage of successful market introduction of innovations by restricting the possible risks of new technologies and products. Finally, compatibility standards can promote the diffusion of information and communication technologies and related products and systems. In order to exploit these various functions of standards as enablers for research and innovation, their development has to be initiated in a timely manner, which requires systematic standardisation foresight (Goluchowicz and Blind 2011) or technology roadmapping (Featherston et al. 2016, Ho and O'Sullivan 2017, Ho and O'Sullivan 2017).

Figure 2 displays the various functions of standards along the different phases of the research and development process, but also incorporates the conceptual open innovation inspired approach by Grossmann et al. (2015). They consider standards as both inputs to the research and development process, and as outputs of the innovation process, which are expanding or updating the current stock of standards.

Figure 2 Various roles of different types of standards in the innovation process



Source: Blind 2017, p. 51

In parallel to Swann (2000), Sherif (2001) introduces anticipatory, participatory and responsive standards in the context of product or service life cycles:

- Anticipatory standards are essential for the acceptance of technologies, products and services and are released before (or at the very beginning of) their introduction to the market, including a minimum set of features.
- Participatory standards are used to test the implementation of technologies before they are eventually adopted.
- Responsive standards codify the characteristics of products and services that have already been successfully commercialised, as well as their quality or performance levels.

Within the framework of information technology, Rachuri et al. (2008) present a slightly different taxonomy of standards along the product life cycle consisting of product development, production, use and identification standards linked to product life cycle traceability.

Since the taxonomies by Sherif (2001) and Rachuri et al. (2008) are derived from examples of information and communication technologies, we still stick to the more basic taxonomy by Swann (2000), when we differentiate between different types of standards.

3.4. The impact of standardisation processes on innovation

The standardisation process can promote innovation, providing a platform for knowledge exchange and production (Blind 2006) or a form of open innovation (Grøtnes 2009). However, the mechanisms in detail and their impacts on innovation have only recently been investigated.

Abdelkafi and Makhotin (2014) develop a process model for leveraging standards and standardisation for innovation. In particular, they distinguish between support to invention and exploitation, and also between the role of standards and the standardisation process, revealing six types of opportunities (as set out in Figure 3). Based on several case studies, they conclude that standardisation processes can support the invention stage by collecting ideas from customers, competitors and other stakeholders involved. For exploitation, it can help to both communicate and raise awareness of innovations, and to absorb innovations generated by others within the standardisation process.

Based on conceptual considerations and a case study, Xie et al. (2016) derive four different knowledge search processes (depending on the complexity and the codifiability of knowledge). These processes range from decentralised and passive to active and integrative knowledge search in standardisation, connecting them with incremental and architectural on the one hand and modular and radical innovation on the other.

Figure 3 Opportunities for the support of innovation through standards and standardisation

	Invention-Support…	**Exploitation-Support…**
… through Standards	• Exceeding the requirements of standards • Efficient and target-oriented innovation • Stimulating innovation through updates of standards and new standards	• Business model innovation (e.g. laboratories)
… through the Standardisation process	• Stimulating innovation from participation in standardization process (ideas/insights from customers, competitors and other stakeholders)	• Innovation communication • Absorption of innovation during standardization process

Source: Abdelkafi and Makhotin 2014, p. 46

There are only a few empirical studies on the role of the standardisation process for companies' innovation performance. Blind et al. (2021) and Wakke et al. (2015) do show that the more R&D intensive companies in Germany and the Netherlands enter standardisation processes, but do not explore the impact of participating on innovation performance.

Knowledge seeking is an important motive to participate in standardisation, in particular for small companies (Blind and Mangelsdorf 2016). Those technical committees (within standardisation bodies) that are crucial to a company's existing product portfolio contribute to its competence in enhancing existing innovations, i.e. rather incremental innovations. In contrast, participation in peripheral technical committees contribute to a company's competence in generating new innovations (Nambisan 2013). Participation in research consortia enhances productivity of invention and increases the incentives to invest in R&D by internalising potential externalities (Delcamp and Leiponen 2014). Joining standardisation consortia, which ensure the free access to other contributors' R&D results, can increase a company's innovative performance measured by patents. This is not the case where there are a high number of costly standard-essential patents (Baron et al. 2014). Recently, Zhang et al. (2020) revealed an innovation promoting effect of standardisation participation for Chinese firms mainly through improving their R&D efficiency, reducing financial constraints, and inducing collaborative innovation.

Finally, Wen et al. (2020) find that taking a central position in standardisation alliance networks is negatively related to firms' speed in bringing new products to the market, but positively correlated to their share of new products successfully introduced in the market. The strong role of incumbents in standardisation committees can also be a barrier to innovation. For example, Ranganathan and Rosenkopf (2014) reveal that proposals for standards suggested by newcomers are likely to be opposed by incumbents.

Gauch and Blind (2015) stress the potential of standardisation processes to push the convergence of different technologies, which is confirmed by Kim et al. (2017) in their analysis of standards in the area of the Internet of Things.

In summary, standardisation processes allow the exchange of existing knowledge and generate new knowledge, in particular by the involvement of stakeholders with different backgrounds. Consequently, companies benefit from their participation in the form of increased innovation performance, although the empirical evidence is still limited.

3.5. The functions of standards and standardisation in innovation systems

The analysis of the impact of standards on innovation according to their different economic functions has been extended to the function of the whole standardisation process (including the produced standards) within the innovation system approach. For example, O'Sullivan and Brévignon-Dodin (2012) focus on the standardisation landscape within the national innovation system of Germany and the United States, but also on technological innovation systems of additive manufacturing technologies, regenerative medicine-based tissue engineering, smart grid technologies and synthetic biology.

Swann (2010) analyses the role of various specific policy initiatives related to standardisation to address failures of innovation systems related to infrastructure, institutions, interactions, transitions and learning. In parallel, Blind (2010) puts the regulatory framework, including the standardisation system, into the context of the innovation system approach by considering the various functions of innovation systems according to Hekkert et al. (2007). Recently, Markard (2020) presents a life cycle model of innovation systems in contrast to industry and technology life cycles and characterises standards, like regulations, as institutions. In contrast, Bergek et al. (2008) perceive standardisation organisations as actors and the involved stakeholders as networks within innovation systems. By differentiating between formation, growth, mature and decline phases, Markard (2020) perceives intermediary actors, such as standardisation committees, to appear only in the growth phase, and being in competition about which standards are to be developed and implemented. However, this conceptual model is based on case studies, e.g. in the area of mobile communication, which is characterised by strong competition between different technological alternatives at the early stage of this new emerging technology. This phase is characterised by increasing development of standards, but also regulations.

Relying closely on Ho and O'Sullivan (2017) — who use the functions of innovation system to structure their review of the roles of standards and standardisation for innovation — Blind (2017) presents the following insights, which are completed by findings derived from a more comprehensive review of the literature.

Based on a comprehensive review, Ho and O'Sullivan (2017) conclude that standards are in particular linked to the legitimation function, but are also effective in influencing the direction of knowledge search, promoting positive externalities, knowledge development and diffusion within the set of functions listed by Bergek et al. (2008). Blind (2017) also includes the market formation function to this list, supported by evidence from Musiolik and Markard (2011), who set out the role of standards for the market development of stationary fuel cells.

For the establishment of emerging technologies and related innovations within an innovation system, legitimacy is also a prerequisite to provide them with appropriateness and desirability, facilitating the mobilisation of resources, but also promoting demand (Bergek et al. 2008). This required legitimacy can be realised in two ways according to Botzem and Dobusch (2012). First, standards reduce uncertainty and promote interactive learning amongst the stakeholders in an innovation system by their information function. Consequently, they generate incentives to invest in innovation, but also promote acceptance and trust in new technologies and related innovations. Eventually, market volumes might grow. Second, consensual standardisation processes that solve conflicts of interest between stakeholders foster the acceptance of the developed standards and the related technologies (Botzem and Dobusch 2012; Simcoe 2012).

The direction of search and learning activities of the actors within an innovation system is guided by standards and the information they contain, but also by the experiences collected through their implementation, e.g. related to quality (Manders et al. 2016) or environmental management (Lim and Prakash 2014). For clean-tech innovations, standards (and related certifications) can provide guidance even for transnational innovation systems, as shown by Gosens et al. (2015). By defining performance levels, standards also provide targets and guidance on how to achieve them, e.g. standards for stationary fuel cells analysed by Musiolik and Markard (2011).

If the demand side is actively involved in the development of standards, its preferences are easily accessible even to producers that are not directly involved in standardisation processes, to guide their product development processes.

Finally, dominant designs based on a set of standards can promote the mobilisation of resources, i.e. the investment in complementary assets (Suarez 2004). Overall, standards can effectively and efficiently guide the direction of search and learning within innovation systems, but also attract investments into new technologies and innovative products.

Since standardisation processes not only promote the exchange of existing knowledge, but also the production of new knowledge, which is eventually codified in standards, both contribute to the creation and transfer of knowledge within innovation systems. In particular by involving stakeholders with heterogeneous backgrounds (Blind 2006), the combination of technology, market-driven and user-oriented insights generate new knowledge, which attracts companies especially interested in the exchanged knowledge (Blind and Mangelsdorf 2016). In particular, the simultaneous involvement of researchers from public research organisations (e.g. Zi and Blind 2015, Blind et al. 2018a) and companies, standardisation processes and the implementation of the developed standards are channels of knowledge and technology transfer (as already argued by Blind and Gauch 2009).

As elaborated in the overview of the economic functions of standards for innovation, compatibility standards in particular can foster positive network externalities, i.e. additional users of a standardised technology increase their attractiveness for further users. If a threshold or critical mass of users is achieved, these network effects promote a faster and broader diffusion of innovations. Consequently, actors in the innovation system have strong incentives to invest in the formation of markets to exploit both economies of scale at the supply side, direct and indirect network externalities at the demand side and even the opportunities of multi-sided markets or even platforms combining both supply and demand side externalities.

In contrast to Ho and O'Sullivan (2017), Blind (2017) addresses the market formation role of standards as already explicitly highlighted by Bergek et al. (2008) and exemplified by Musiolik and Markard (2011), because institutional support or even change via the formation of standards is often a prerequisite for emerging markets to evolve. Bergek et al. (2008) even claim that market formation is blocked by an absence of standards causing fragmented markets and eventually the failure of markets.

In summary, Blind (2017) derives the main role of the economic functions of standards within their functions in innovation systems (as shown in Table 3). For comparison, Swann and Lambert (2017) take a slightly different approach of combining the one-step mechanisms of standards on innovation based on their economic functions with two-step mechanisms. This involves a first step from standards to the innovation infrastructure and a second step from this system or infrastructure to innovation. However, Swann and Lambert (2017) do not define innovation infrastructure or systems, while their understanding is also not aligned to the mainstream understanding of the innovation system. In addition, some aspects of the second step of the mechanism, like the reduction of transaction costs, is already included in the first step.

However, as elaborated above, the economic function of standards and the standardisation process are overall drivers for innovation. Consequently, a lack of standards might be a barrier for innovation, in particular for the creation of markets. Standardisation processes can help to promote the legitimacy of new technologies by involving all relevant stakeholders and the variety of their interests, but also relying on their knowledge for specifying standards. The overall positive assessment of standards and standardisation related to innovation relies on the general focus of the innovation system approach on emerging new technologies and the formation of new markets. Only recently, Markard (2020) introduces a life cycle model of innovation systems. As already elaborated by Swann (2000), the economic functions of standards play different roles in emerging, growing or maturing product market phases. In particular, in the emerging and growing phases of new technologies, innovative products and markets, standards can generate positive network externalities at the demand side, but also economies of scales at the supply side and trust between the different actors in innovation systems.

Only after the recent introduction of the life cycle approach related to innovation systems, the focus is expanded both to mature and even declining markets. However, in mature markets strong incumbents make use of standards and their influence on the standardisation process by restricting competition, establishing monopoly power (in combination with proprietary assets, like patents) and raising rivals’ costs to protect their established technologies and products against newcomers trying to introduce innovative solutions. As a consequence, entrants into their markets and new technologies as drivers for innovations are hindered, as shown by the analysis of the voting behaviour of participants in standardisation committees by Ranganathan and Rosenkopf (2014). Complementarily, Ranganathan et al. (2018) find that firms who share many common technology preferences with others support new standards more strongly when they are in more competitive product markets. Blind et al. (2017) reveal the innovation inhibiting impacts of standards in comparison to regulations (see the impacts differentiated by type of regulation in Blind 2012) in mature markets, because they are more prone to regulatory capture. However, in the case of high market uncertainty (in relation to emerging technologies), regulations impose higher compliance and consequently innovation costs as they suffer from a higher amount of information asymmetry for the regulators compared to the stakeholders involved in standard setting. To avoid these negative impacts on innovation, standardisation processes have to be open and transparent for those interested in proposing new ideas. In addition, the implementation of standards should be not hindered by intellectual property rights.

Table 3 Main economic functions of standards within their functions in innovation systems

Economic Functions of Standards	Legitimation	Influence on the direction of search	Knowledge development and diffusion	Development of positive externalities	Market formation
Compatibility / Interoperability		X		X	X
Minimum Quality/ Safety	X	X			X
Variety Reduction		X		X	X
Information			X		
Standardisation Process	X		X		

Source: based on Blind 2017, p. 46

In addition to positioning standardisation and standards into the context of innovation systems, several studies expand this narrow focus to the whole national quality infrastructure. Frenz and Lambert (2012) try to show how the role of the infrastructure defined by standards, measurement, accreditation, design and intellectual property can be integrated into a quantitative model of the innovation system. In a second step, they then try to reveal the impact of this infrastructure on labour productivity, as well as on growth in turnover and employment. However, only the number of ISO 9001 certificates issued by certification bodies accredited by the UK Accreditation Services (UKAS) (which are therefore an indicator for accreditation, but not certification) has a significant impact. Furthermore, Frenz and Lambert (2012) do not disentangle the impacts of certification and accreditation, but Blind et al. (2018b) reveal different impacts of certifications on trade depending on whether they are issued by an accredited body.

In parallel, Harmes-Liedtke (2010) presents a conceptual model on the role of quality infrastructure in promoting innovation systems in developing countries, which doesn't take into account the above referenced literature on innovation systems. In a further step Gonçalves and Peuckert (2011) theorise the general contribution of quality infrastructure on innovation systems (see Table 4), before exploring specific impacts of different elements of quality infrastructure services (see Table 5). Finally, Gonçalves and Peuckert (2012) argue that the development of national quality infrastructures is a strategic policy option to address typical weaknesses of emerging innovation systems. Consequently, they conclude that the building up of an innovation-supporting quality infrastructure is an especially important policy instrument for developing countries.

Table 4 Contributions of quality infrastructures to innovation systems

Rising concerns	Importance of innovation system	Contributions of quality infrastructure
Reaching global markets	• Capacity to constantly adapt to foreign requirements • Ensure compliance • Guarantee competitiveness • Production of goods with higher value	• Traceability of measurement units and procedures, resulting in the comparability of the results • Development and calibration of measurement instruments • Cost-effective adaptation processes • Making innovations visible to consumers
Integrating global value chains	• Integration in more complex production systems • New forms of integrating different productive sectors • Increase number of partnerships • Integration in global innovation Systems	• Harmonisation of processes, materials, measurement units and instruments • Comparability allows writing of contracts • Decrease of uncertainty and leverage trust between worldwide productive agents • Harmonising tools and methods for R&D
Protection of consumers and environment	• Ability to measure certain properties • Guarantee quality of product • Discovering cost-effective procedures • Protect SMEs	• Development of tools to measure such properties • Setting technical regulations and guaranteeing conformity • Avoidance of regional imbalances • Minimisation of market power creation

Source: Gonçalves and Peuckert (2011), p. 9

Table 5 Impact expected from quality infrastructure services

NQI	Activity	Main functions	Main beneficiaries	Main impacts
Standardisation	Formulation of standards (optional compliance) and technical regulations (compulsory compliance)	• Knowledge exchange • Coordination • Harmonisation of products and procedures	• Firms • Consumers	• Economies of scale • Economies of learning • Innovation • Diffusion of technology • Competition • Lower market prices • Consumers and environment protection
Metrology	Establish measurement procedures and ensure calibration of measurement instruments	• Traceability • Comparability • Uncertainty reduction	• Firms • Industry • Government • Consumers	• Efficiency of R&D • Access to foreign markets • Integration in global value chains • Stability of government revenues • Consumer protection against fraud

NQI	Activity	Main functions	Main beneficiaries	Main impacts
Conformity Assessment	Check whether management procedures, products or services conform with established standard	• Conformity • Confidence • Reliability	• Firms • Consumers	• Reduction of information asymmetry • Innovation premium
Accreditation	Formal recognition that an organisation or person is competent to carry out specific tasks	• Competence • Traceability • Transparency • Political independence	• Quality infrastructure as a whole	• Economic integration in international markets and value chains • Provide information to quality services about better practices

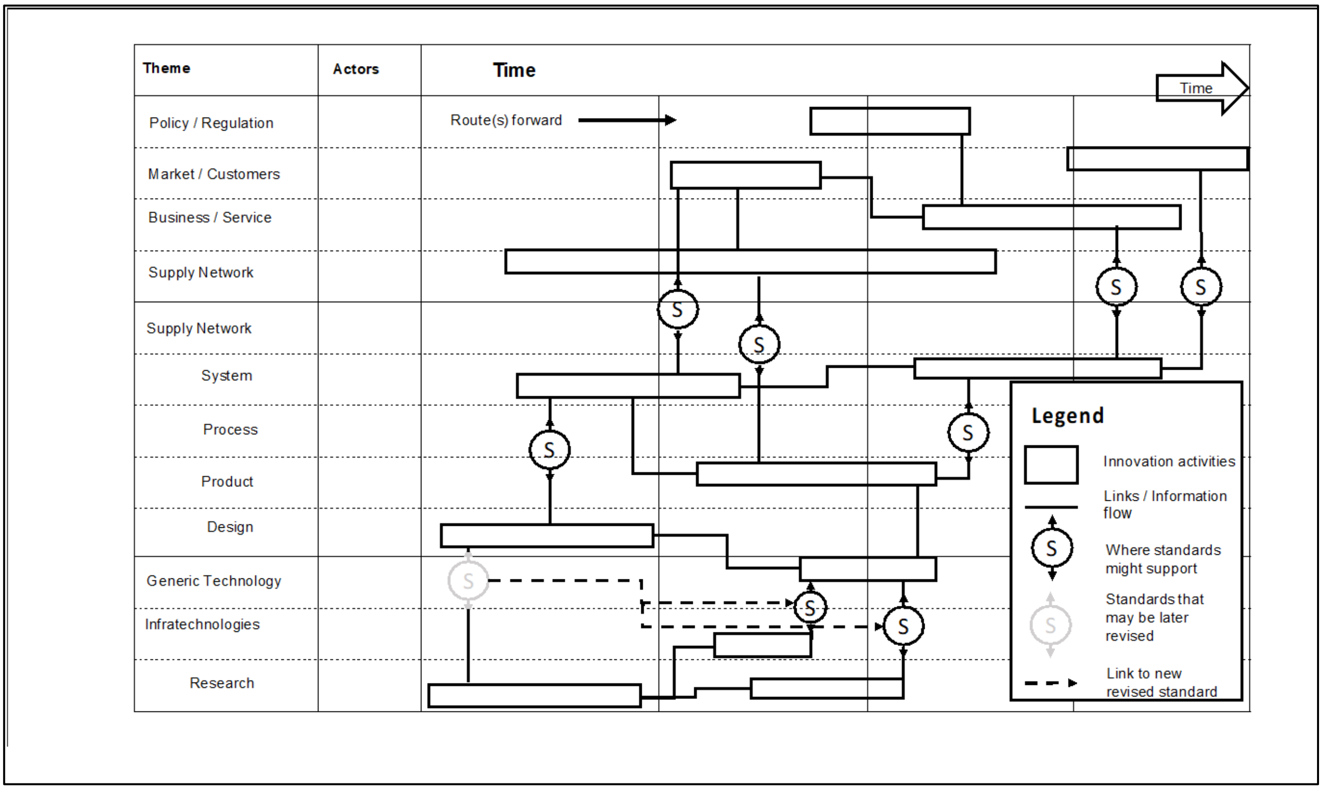
Source: Gonçalves and Peuckert (2011), p. 21

3.6. Standardisation roadmapping

Starting from the various studies on the role of standards and standardisation processes in the context of innovation systems, and even their life cycles (Markard 2020), Featherston et al. (2016) go one step further and incorporate foresight approaches. They present a technology roadmapping-based framework to anticipate standards needs for emerging technologies and their related innovation systems which takes into account different types of standards and their sequencing, plus the roles of involved stakeholders (see Figure 4).

The framework is successfully applied in case studies in synthetic biology, additive manufacturing and smart grids, revealing how standards codify and diffuse knowledge to support innovation. Overall, they claim that the framework is able to reveal not only where standards might support innovation, but also which types of standards are needed and which stakeholders should be involved, taking into account requirements for alignment, coordination and sequencing of standardisation activities.

Figure 4 Standards mapping framework, highlighting important categories of innovation activities

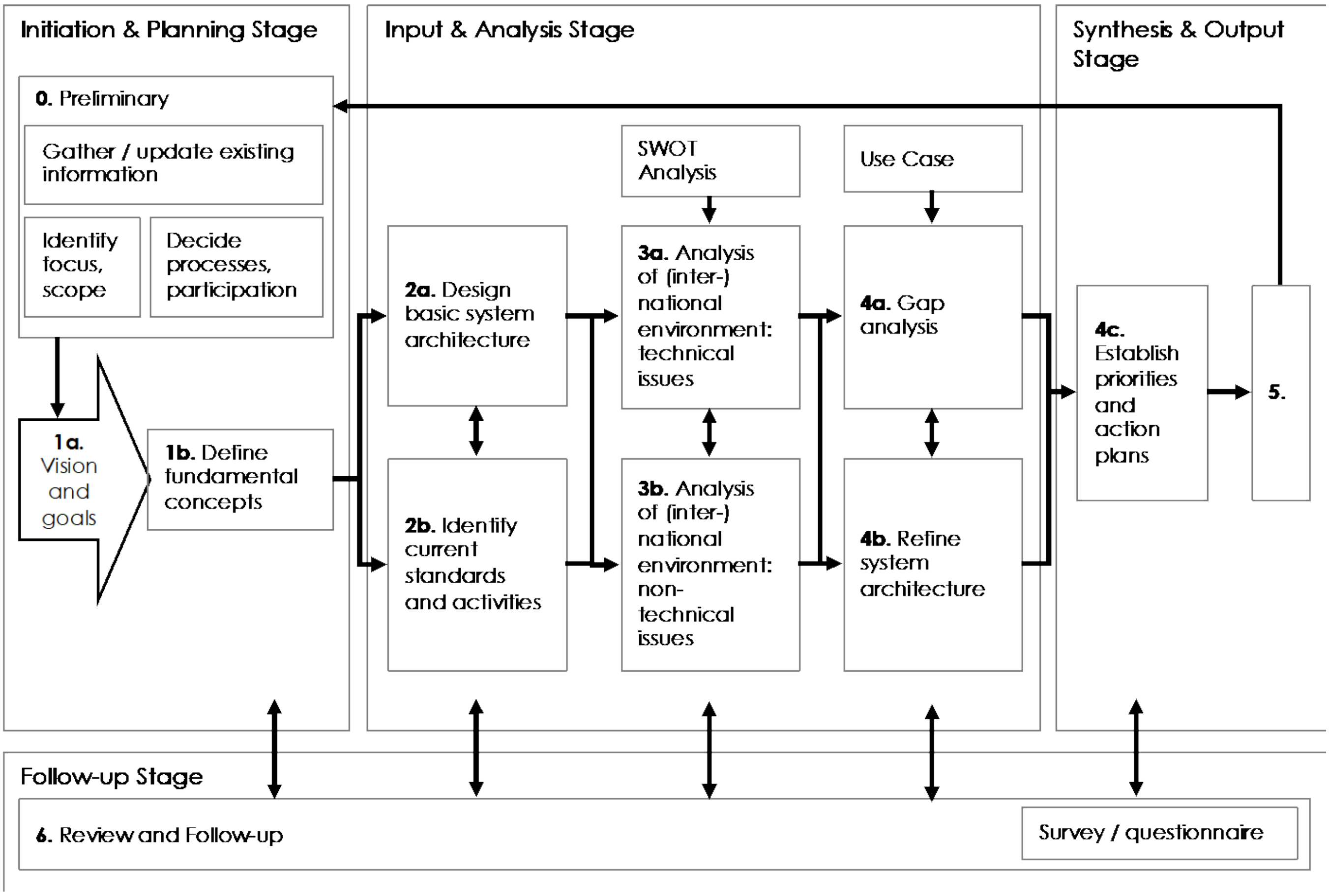


Source: Featherston et al. 2016, p. 30

Based on the standards mapping framework developed by Featherston et al. (2016), Ho and O'Sullivan (2017) apply the roadmapping approach to ICT-based "smart systems" as a specific complex area based on a set of already available roadmapping exercises. They present a systematic process, including new standardisation-related steps for conducting roadmapping exercises to tackle the increased challenges related to standardisation, with particular application in complex areas requiring multiple stakeholders and multiple disciplines.

The insights from Featherston et al. (2016) provide the conceptual background for the proposed standardisation roadmapping process elaborated in Ho and O'Sullivan (2017) (see Figure 5).

Figure 5 Proposed process model for managing standardisation roadmapping exercises of smart systems



Source: Ho and O'Sullivan 2017, p. 309

Ho and O'Sullivan (2018) expand the standardisation roadmapping approach by Ho and O'Sullivan (2017) and develop a mapping framework for systematic and comprehensive analyses of how standardisation can support innovation. They integrate the key dimensions of standardisation elaborated in already existing conceptual models, e.g. by Tassey (2000), Sherif (2001) and Blind and Gauch (2009). Based on a longitudinal case study of photovoltaic technology covering multiple technological life cycles, they then illustrate the evolving dynamics of these key dimensions. Eventually, Ho and O'Sullivan (2020) present an integrated innovation roadmapping, which considers standardisation as one important dimension.

Based on the literature of standards and standardisation within the context of innovation systems, Ho and O'Sullivan (2019) present a framework based on the innovation system approach to analyse standard-related challenges for innovation, possible roles for governments to play and the instruments that should be used to fix the problems.

- Firstly, they identify the challenges attributed to structural elements of innovation systems (e.g. actors or institutions) related to standardisation.

- Secondly, they present policy instruments and their implementation to address various challenges related to standardisation.

The study presents this framework in the context of the policies adopted in the USA to promote standardisation of photovoltaic technology. The challenges for the various components of the innovation system are identified, as well as the different roles that governments can play to solve them, like being a convener for different stakeholders, a coordinator of standardisation activities, an educator for users or just an observer of emerging standardisation needs.

Furthermore, policy instruments to address systemic problems associated with standardisation, such as regulation, financial support or soft laws, are presented, differentiated by the dimensions of standardisation and eventually divided into supply-side, demand-side and systemic instruments.

3.7. Concluding remarks

Based on a comprehensive review of the literature on standardisation and innovation, including emerging technologies and markets, the most relevant publications have been structured, starting with the different conceptual approaches addressing the functions of standards and their impact on innovation.

While the impact of standards on innovation has attracted significant research and generated several studies, the impact of standardisation processes on innovation has only been analysed to a limited degree due to the limited access to data about the rather complex standardisation processes. However, standardisation processes themselves play a particularly important role in emerging technologies. This has been shown mainly by the increasing number of technology-specific case studies in the context of the investigations of the functions of standards and standardisation process within the conceptual framework of innovation systems.

The very few studies on the role of the whole quality infrastructure on innovation have been conducted within the framework of the innovation system approach.

Finally, the methodology of standardisation roadmapping to structure future needs related to standardisation in complex technologies and markets has been developed and implemented in specific cases of emerging technologies.

4. Landscape Review

4.1. Introduction

This section presents findings from the second phase of research; a **review of the UK approach to standards development in support of emerging technology**.

The aim was to review the standards landscape in the UK (operating through the NQI) to understand how this supports the development and commercialisation of emerging technology, paying special attention to the roles, practices, support programmes and engagement models currently in place.

The review has deliberately not focused in detail on digital and telecommunications standards, where the government's work is led by the Department for Digital, Culture, Media and Sport (DCMS) and where much standardisation work takes place outside of the NQI (as briefly introduced later).

Key areas to explore and questions to address for this review included:

- **Who are the relevant actors and stakeholders** involved in standards for emerging technologies in the UK? What are their roles and how do they interact?
- **How do these actors engage** with standards for emerging technologies in the UK? What approaches and processes exist to convene actors and develop standards? How well does the use of standards support emerging technologies in the UK?
- **What factors influence why, when and how** standards are developed and used for emerging technologies in the UK?

The intention was to provide a technology-agnostic review and description of how the system currently functions. Key technology and sector differences in approach were explored further (for four selected emerging technology areas) as part of the next stage of the study.

This review was developed based on desk research, plus views and insights gathered through interviews with 11 key stakeholders (representatives from BSI, NPL, UKAS, Innovate UK, IPO, BEIS, DCMS and FCDO).

4.2. Relevant actors and stakeholders

The **national innovation system** consists of "a set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which government forms and implements policies to influence the innovation process"[2]. **Standards and standardisation**[3] form part of the infrastructure for this system, helping to provide the framework conditions necessary for innovation. They are closely linked to political, research and industrial systems and actors (as shown in Figure 6 below).

Note that the UK standards landscape is also closely integrated with European and international systems (as well as with direct access, industry-led standardisation activities that are the main model for digital standards, among others). For example, there is UK representation and involvement in international standards development activities, while many standards that have been developed internationally are subsequently transposed into national standards.

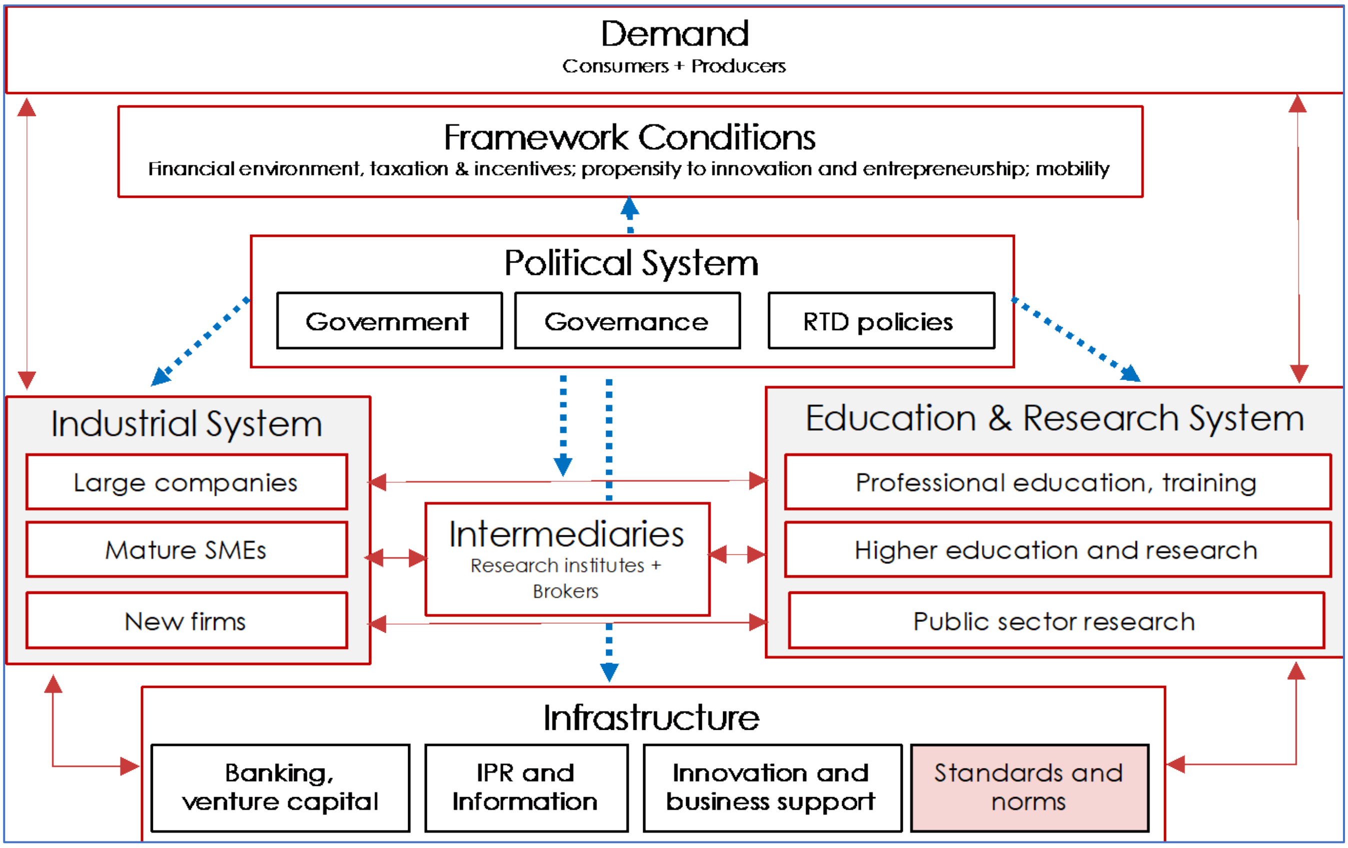
[2] Metcalfe, J. S. (1995) Technology systems and technology policy in an evolutionary framework. Cambridge journal of economics, 19 (1): 25–46.

[3] Defined as follows:

Standard: a document, established by consensus and approved by a recognised body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context.

Standardisation: the activity of establishing, with regard to actual or potential problems, provisions for common and repeated use, aimed at the achievement of the optimum degree of order in a given context. [ISO/IEC Guide 2:2004]

Figure 6 Standards within the national innovation system



Source: Adapted from Arnold and Kuhlmann, 2001

The British Standards Institute (BSI) is the central actor in the UK standards landscape and is appointed by the UK government as the national standards body for the UK. It is a private company, incorporated by Royal Charter, but receives some public funding (a ~£3m/year grant currently) in recognition of work undertaken that is of strategic interest to government.

BSI's role is to help improve the quality and safety of products, services and systems by enabling the creation of standards and encouraging their use. It publishes 3,000+ national, European and international standards annually, each reflecting current good practice, with a 'stock' of over 30,000 standards now available. These standards are primarily industry-led (i.e. proposed and developed by businesses and their representatives), but are underpinned by a collaborative approach that engages with a variety of expertise, not only from businesses of all sizes, but also with government bodies, trade associations and consumer representatives, among others.

BSI is also a member and represents UK interests at the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the European Standards Organisations (CEN, CENELEC and ETSI). ISO and CEN are generalist in their approach and work across multiple sectors (not elsewhere covered), including construction, management systems, environmental issues and manufacturing. IEC and CENELEC promote electrotechnical standardisation, such as wiring and white goods. ETSI's focus is on telecommunications[4]. ISO and IEC draw their membership from national standards bodies around the globe, with one member per country. CEN and CENELEC consist of 34 national members each, centred on Europe. All are independent, and BSI is the UK's member in each case, seeking to ensure that UK expert voices are represented in their technical committees.

These organisations form part of a broader international ecosystem of standard developing organisations that includes:

- **Formal / de jure standardisation**: Bodies that are officially recognised by government and operate in line with World Trade Organisation (WTO) standardisation principles of transparency, openness, impartiality, consensus, effectiveness, relevance and coherence. Their (voluntary) standards can be used as evidence in supporting certain regulatory requirements. This group of formal standardisation bodies includes those mentioned above — BSI (and equivalent national standardisation organisations in other countries), plus CEN-CENELEC, ISO, IEC and (in some areas) ETSI — but also the International Telecommunication Union (ITU), which is a government-led UN agency that coordinates standards ("Recommendations") for telecommunications and information communication technology[5]. Another relevant example is the Codex Alimentarius, which is a collection of internationally recognised food standards published by the UN Food and Agriculture Organisation.
- **Informal / de facto standardisation**: Bodies that are industry-led, but adhere to WTO standardisation principles, and have established leadership in their respective fields. The most relevant include ETSI (in relation to its international work not tied to EU regulations), as well as organisations such as the Institute of Electrical and Electronics Engineers Standards Association (IEEE SA), the Internet Engineering Task Force (IETF) and the World Wide Web Consortium (W3C).

In addition, there are other informal standardisation bodies that don't follow WTO standardisation principles (and therefore don't quite meet our definition for a standard, as a document established by consensus and approved by a recognised body), and tend to be focused on a particular sector[6]. These numerous organisations tend to arise through industry / professional bodies and associations and their standardisation work is driven by industry. They produce specifications that can become widely recognised and considered as de facto standards (i.e. they become accepted as the best standard for their purpose because of wide support or market forces, rather than because they have been developed by a formally approved authority). Linked to this group are those involved in the development of software

[4] In 1988 the UK government, along with other Governments across Europe, took electronic communications out of the formal national standards system to create a pan European approach. This sat alongside the already existing ITU international system. ETSI was created and took over existing electronic communications work from CENELEC, national standards bodies and national telecommunications operators. In particular it focused on mobile telecommunications. ETSI has a direct industry access model with a nationally oriented structure for constitutional decisions.

[5] The UK is represented in ITU by the Department for Digital, Culture, Media and Sport (DCMS).

[6] Examples of such organisations that produce 'standards' include the Digital Video Broadcasting (DVB) project, the European Computer Manufacturers Association, the JEDEC Solid State Technology Association or the VMEbus International Trade Association.

(and in particular open source software), which is increasingly being used as an alternative to standards.

Standardisation is one of the key components of the UK's National Quality Infrastructure (NQI), which comprises five core components:

- **Standardisation** – creates the national and international standards that describe good practice in how things are made and done.
- **Accreditation** – ensures that those who carry out conformity assessment, testing, certification and inspection are competent to do so.
- **Measurement** – implements specifications and standards (relating to measurement and good practice) to ensure accuracy, validity and consistency.
- **Conformity assessment** – ensures the quality, performance, reliability or safety of products meet specifications and standards before they enter the market.
- **Market surveillance** – checks whether products meet the applicable safety requirements, taking the necessary steps to ensure requirements are met, or imposing penalties.

These components are largely delivered by four long-established and internationally respected UK institutions. In addition to BSI (already discussed above), which is responsible for producing national and international standards, the other key institutions in the UK NQI are:

- **The National Physical Laboratory (NPL)**, which is the UK's National Metrology Institute[7]. A Public Corporation owned by BEIS, NPL is responsible for developing and maintaining the UK's primary measurement standards (the so-called "etalon"). These ensure the accuracy and consistency of measurement and so provide confidence in measurement results and data. NPL is actively involved in early stage standardisation work (e.g. defining the properties of a new material) and also produces its own good practice guides (of which there are currently ~100). These are designed to support agreement on measurement issues; what to measure, how to measure and how to understand the results.
- **The UK Accreditation Service (UKAS)** is the National Accreditation Body and is appointed by government to assess and accredit conformity assessment organisations that provide services including certification, testing, inspection and calibration (usually against national or international standards, but also other normative documents). It is licensed by BEIS to confer national accreditation symbols, which provide assurance of the competence, impartiality and integrity of conformity assessment bodies. UKAS is a non-profit-distributing private company and self-financing (charging fees to conformity assessment bodies). However, it does receive some funding from BEIS to undertake activities of strategic interest to government, including representing the UK in the global accreditation system. Historically, UKAS has had a limited role in the development (rather than use) of standards, particularly in new and emerging areas of technology. However, in recent years it has become more active in early standardisation activities

[7] Metrology is the science of measurement.

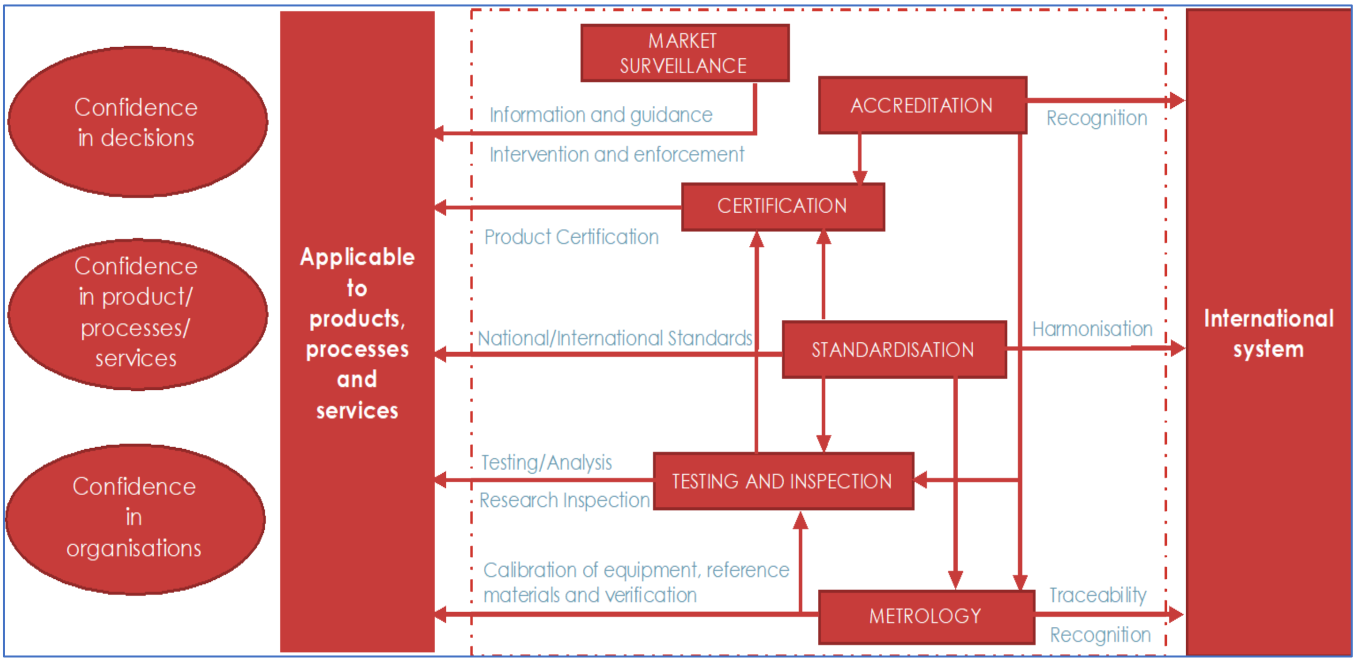
and is now regularly approached by government departments and BSI to be part of discussions, to ensure that subsequent standards are fit for purpose.

- **BEIS Office for Product Safety and Standards (OPSS)**, which provides the regulatory and market surveillance infrastructure to ensure only safe products are put onto the market and enabling businesses to export goods globally.

As a system (visualised in Figure 7), the NQI guarantees the definition and control of quality criteria, giving confidence in products, services, processes and organisations. Coordination and mutual recognition of the NQI at an international level also underpins international trade, agreements and cooperation.

The concept of a UK NQI has existed for many years, but in the past 1-2 years it has developed into a more tangible effort, coordinated by BEIS (through BRE) and meeting on a monthly basis to share information and knowledge, as well as to coordinate efforts. Stakeholders consulted for this study were positive and enthusiastic about this closer working relationship between the NQI actors, reporting higher levels of understanding and exchange between the organisations as a result. BEIS (BRE) patronage was regarded as very important in harnessing and encouraging this joint effort, which is unlikely to occur to the same degree otherwise. However, each of the NQI partners also indicated a strong willingness to be working closely together. They believe that the combined and coordinated power of the NQI is already a UK strength, many years ahead of most countries in terms of coordination and interaction between the different parts, but that there is also greater potential for benefits through further joined-up working.

Figure 7 National Quality Infrastructure (NQI) concept



Source: Adapted by Technopolis based on: Harmes-Liedtke (2020) and on: The answer to the global quality challenge: A national quality infrastructure, Clemens Sanetra. Rocio M Maraban

In June 2019, the government published its Regulation for the Fourth Industrial Revolution White Paper, which emphasises that standards can play an important role in enabling and stimulating innovation. However, it also notes that standards — while often more agile than regulation — can still face challenges in keeping pace with technological innovation, and need to be developed and reviewed in a timely and inclusive way. The accompanying action plan sets out intentions to support businesses, policymakers and regulators to make effective use of standards where appropriate, as well as to invite the NQI to set out their vision for how the development and review of standards should evolve as we enter the Fourth Industrial Revolution.

In September 2019, the NQI organisations jointly responded, setting out their vision on how standardisation needs to evolve (and is already evolving) to support the commercialisation of innovation and complement outcome-focused regulation, as well as views on the role that government can play to support this.

Following on from this, the NQI organisations have been working with BEIS BRE and OPSS to develop an Action Plan (July 2021) to ‘unlock the value of standards for innovation’, which identifies six key areas for action:

- Deploying an **agile approach** to develop and review standards in priority areas to respond to the challenges of fast-paced technological change
- Accelerating the **digitisation of standards** to foster greater efficiency and flexibility for industries of the future
- Upscaling **engagement with stakeholders**, in particular innovators, small businesses and consumer representatives, to boost their participation in standardisation
- Strengthening the **strategic coordination** between government, the NQI partners and UK Research and Innovation (UKRI) on future priorities for standardisation and the wider NQI to support innovation
- Raising **awareness** of how standards and the wider NQI can help inform and support the delivery of government policies, in particular to enable innovation and the deployment of emerging technologies
- Embedding consideration of standards in the **policy-making** process to unlock their value in fostering growth and innovation

A Project Board and joint working group have then been set up, with representation from each partner organisation (BRE, OPSS, BSI, NPL, UKAS and Innovate UK) to guide and monitor the implementation of the Action Plan going forward.

Other key actors in the UK standards landscape include:

- **The National Measurement System (NMS)**, which provides the UK with an infrastructure of laboratories that deliver world-class measurement science and technology and that provide traceable and accurate standards of measurement. The NMS is delivered by BEIS, with science programmes delivered by the UK's measurement institutes.[8]
- **Innovate UK (IUK)**, the UK's innovation agency, which seeks to drive productivity and economic growth by supporting businesses to develop and realise the potential of new ideas. IUK reported that it is increasingly encouraging consideration of standards within its own programmes (from the programme design stage). It also has a strong relationship with the UK NQI, including with BSI – both at a corporate and technical level – and has provided funding for the development of standards strategies / roadmaps and Publicly Available Specifications (PAS). Its recent action plan for business innovation 2021-2025 includes numerous references to the role that standards can play in stimulating innovation and makes various commitments to support this, including by:
    - Embedding standards into programme development
    - Helping businesses to gain the skills to apply standards
    - Playing an active role in global innovation groupings and associations to ensure that the UK is at the forefront of standards
    - Consulting and involving innovative businesses in developing standards
    - Increasing representation of UK perspectives in the development of international standards (through BSI and its quality infrastructure partners)
- **The Intellectual Property Office (IPO)**, the official UK government body responsible for intellectual property rights including patents, designs, trademarks, and copyright. The IPO aims to ensure it maintains a world-leading IP framework that promotes innovation and creativity both now and, in the future, while supporting the government's ambitions set out in the Innovation Strategy. In December 2021 the IPO published its call for views on Standard Essential Patents (SEPs) and Innovation, which closed in March 2022 (a patent that is essential to implementing a standard is called a standard essential patent). The purpose of the call for views was to better understand whether the frameworks around SEPs are functioning efficiently or whether those frameworks may be hindering innovation. The call for views included questions on various topics including market functioning; transparency; and the efficiency and effectiveness of the legal and regulatory frameworks applicable to SEPs. The IPO is currently analysing the responses from the call for views and is due to publish a government summary of responses during summer 2022.

[8] The National Physical Laboratory (NPL), the National Measurement Laboratory (NML) at LGC, the National Engineering Laboratory (TUV-NEL), the Office for Product Safety and Standards (OPSS), the National Gear Metrology Laboratory (NGML) and the National Institute for Biological Standards and Control (NIBSC).

- **Government departments**. OPSS, as part of BEIS, leads standards and accreditation policy across government, as well as the relationship between government and both UKAS and BSI (the latter alongside the BEIS Better Regulation Executive). OPSS also manages the government grant funding to BSI and provides ad-hoc funding for the development of particular standards (e.g. commissioned Publicly Available Specifications, such as the recent PAS 7055:2021 on button batteries) or to enable particular standards.

  The Better Regulation Executive (BRE), within BEIS, leads the regulatory reform agenda across government, including in relation to innovation. As part of its policy responsibility to evolve the UK's regulatory system to best support innovation, BRE takes an interest in the role that standards can play as a complement and alternative to statutory regulation and unlocking their value to support innovation.

  In addition, other departments across government take an interest in and lead on standardisation in their specific policy areas. For instance, the Department for Digital, Culture, Media and Sport (DCMS) leads the government's work on digital and telecommunications standards. It represents the UK within the International Telecommunications Union (ITU) and UK views within ETSI (which is a direct access standards organisation and does not work with national representation for standard setting). It is also engaged within a number of other relevant international standardisation bodies (e.g. IETF and W3C) seeking to bring greater societal and political perspectives and considerations (e.g. relating to accessibility, resilience, security and the environment) to what are largely industry-driven processes, thereby helping to improve the resulting standards (and possibly reducing the need to legislate / regulate).

  Other government departments and agencies are also active in relation to standardisation within specific areas, e.g. NCSC/GCHQ (electronic / cyber security standards), MoD (defence equipment and services), Home Office (emergency services vehicles and equipment), DHSC/MHRA (medical equipment and services), BEIS (energy), DIT (trade).

  Also, the Foreign, Commonwealth and Development Office (FCDO) leads the UK Regulatory Diplomacy Network (along with BEIS and the Department for International Trade), which seeks to better monitor and influence international standards in all areas of UK policy interest (trade, market access, security, etc.).

4.3. Approaches and processes

4.3.1. Identifying standardisation needs for emerging technologies

Anyone can propose a new British, European or international standard (or the revision of an existing one) to **BSI** (or can do so directly for ITU and ETSI standards), but those making such a proposal are expected to be able to demonstrate a broadly-based need and likely active support from a wide range of relevant interests. BSI will then assess whether there are enough resources to complete the project within a reasonable timescale and whether any conflict would exist with other developed / developing standards. Further consultation and consideration of market demand and available resources is then required for the initiation of standardisation work at a European or international level.

BSI report that while in established fields this model functions well, there can be greater barriers to initiating standardisation activities around emerging technologies. These barriers can include lower awareness, understanding and experience of standards / standardisation, less well organised and connected (and smaller) communities of relevant actors (often consisting mainly of small organisations and individuals with limited resources), and greater uncertainties about the technologies or their application (or about the wider market, regulation or policy). Further discussion of the issues and challenges are presented later.

BSI report that its own approach to supporting and encouraging standardisation for new and emerging technologies has evolved over time and become increasingly proactive. Looking back 20 years, the organisation directed its activities based on what government saw as a priority (and where it was targeting R&D funding), for example nanotechnologies at the time. However, it was reported that trying to force a very formal top-down process onto a fast moving technology domain tended not to work too well. Over the past decade it has therefore increasingly taken a more strategic, holistic and consultative approach, engaging more closely with relevant actors and intermediaries (such as through the Industrial Strategy Challenge Funds) to reach a better collective understanding as to if and how standardisation could aid areas of innovation.

BSI has also now invested in additional staff resource and established sector leads within its standards development team. These individuals are responsible for outward engagement and landscape scanning (plus some horizon scanning), including in areas of emerging technology. Recently, these sector leads have also been freed up from other commitments (e.g. supporting BSI committees), so that they can focus even more effort on these outward-facing activities.

Innovate UK has similarly reported an increasingly proactive approach to supporting the discussion and identification of standardisation needs in areas of new and emerging technologies, with the organisation now seeing itself as a catalyst for subsequent standards development. For instance, when designing new Innovate UK programmes, technical leads are explicitly asked (as part of the business case development process) to consider existing standards and the need for new or modified standards (as well as the resource requirements necessary for supporting this). This has resulted in some notable successes, for instance within the Faraday Battery ISCF, where needs were identified for standards relating to the recharging and disposal of batteries, which has led to subsequent standardisation work with BSI.

Innovate UK have also sponsored the development of BSI standards roadmaps and strategies for emerging technologies (e.g. the Industrial biotechnology strategic roadmap for standards and regulations, March 2021, or the battery manufacturing and technology standards roadmap, July 2021, both sponsored by Innovate UK) or otherwise contributed to these (e.g. the connected and autonomous vehicles standards roadmap, August 2020, which was prepared by BSI with the Innovate UK Connected Places Catapult).

Beyond the activities of BSI and Innovate UK, the consulted stakeholders also mentioned **other means** by which standards needs were identified in relation to emerging technologies, including:

- **Specific events** – which grab attention, focus minds and drive a call for standardisation, often to address health and safety concerns. For example, the Gatwick drone incident led the Department for Transport to approach the NQI to discuss standardisation, resulting in a review of drone/UAS standards landscape (August 2021). Similarly, but not relating to emerging technologies, the Grenfell fire led to the BSI FLEX 8670 standard, on building safety, while the COVID-19 pandemic led to BSI FLEX 5555 standard on face coverings (an initiative instigated and led by BSI itself).
- **International activity** – where the emergence of standardisation work elsewhere may prompt the establishment of groups or the launch of activities in the UK to follow or influence this process. Over 90% of British standards have their origins in international work, where UK experts (nominated via BSI's technical committees) discuss and agree the content of standards in their sectors with international peers. BSI maintains technical committees ("mirror committees") that reflect many areas of European and international activity within CEN-CENELEC, ETSI, ISO and IEC, but not all (as determined by need and resources), as well as some other standardisation bodies (though to a lesser extent).

  The UK Regulatory Diplomacy Network (mentioned above) is attempting to further strengthen this, by seeking to identify international standardisation activity of relevance to the UK, but where there is insufficient UK involvement. It is early days for this network, but it already offers an example of how this can spur UK standardisation activity, with the setting up of a BSI mirror committee for rare earth minerals in response to the identification of a new ISO committee without UK representation.

  The various BSI standards roadmaps and strategies similarly look to current and potential international activity, as part of their landscaping efforts.

Finally, as one of the commitments from their joint Action Plan, government and the NQI partners have recently established a strategic coordination group on future standards. The purpose is to bring together expertise from across government, the NQI partners and Innovate UK to identify potential opportunities and priority areas where the development (or review) of standards and the wider NQI can support innovation and deployment of emerging technologies. The aim is to facilitate join-up and foster greater coherence and synergy between government policy and standardisation in areas of innovation and emerging technologies in a systematic way.

4.3.2. Developing standards for emerging technologies

The development time for a full British Standard ranges between one and four years, depending on the complexity of the subject and the range of stakeholders involved, with international standards often taking even longer. These timescales (and the necessary investment of time and resources for their development) mean such standard processes are often not well aligned with the needs of fast-developing emerging technology areas.

As such, BSI also offers faster alternatives; the BSI Publicly Available Specification (PAS) process, and more recently introduced BSI FLEX standards (both of which are described in more detail below). BSI advertise that PAS is best suited to “areas where new concepts are becoming widely accepted and minimal change is expected”, while BSI Flex is designed for “emerging areas where there is a low level of certainty about what good looks like and good practice needs to evolve through a series of iterations”.

BSI Publicly Available Specification (PAS)

The BSI PAS is a fast-track standardisation document, that is developed by a steering group of stakeholders from relevant fields, with considerable support and facilitation by BSI, and usually published within 9-12 months. There are now over 300 BSI PAS available, across a range of different sectors. ISO and IEC also develop PAS, having adopted the approach from BSI.

PAS development is usually sponsored (i.e. commissioned and paid for by an external body) to define a particular solution – although BSI then ensures an independent process is followed (e.g. involving a range of representation in the steering group). BSI report that around half of the PAS developed are sponsored by the public sector (the rest by industry, trade associations and professional bodies), but that this figure is much higher for PAS that relate to new and emerging technologies, where they are usually sponsored by government departments and agencies, or Innovate UK. Sponsoring a PAS usually costs £80-100k, or closer to £150k if the commissioning body wants to include a roadmap and have the resulting PAS freely available to download. This might be considered a relatively small amount for the kinds of organisations that tend to sponsor PAS work, but BSI report that it can still be difficult to secure the necessary financing, due to the lack of an established standardisation funding system or mechanism.

Stakeholders highlighted that a PAS often represents a first attempt at standardisation in an area (usually focusing first on vocabulary or definitions) and therefore highly relevant for emerging technologies. It can help to bring parties together, with minimal commitment or resource requirements, and to quickly develop a ‘good starting point’ that might not come about otherwise. The availability of funding for PAS development can therefore act as an important catalyst and enabler for standardisation in an emerging technology area. The box below provides an example of a series of PAS relating to the adoption of digital technologies in UK manufacturing.

High Value Manufacturing PAS

The High Value Manufacturing Catapult asked BSI to establish how standards could help overcome barriers to the adoption of new digital technologies in UK manufacturing. BSI and the Institute for Manufacturing (IfM) identified five priority opportunities for standards development and then proposed a plan for standards adoption and development to address these areas, speed up innovation and help UK manufacturing remain globally competitive.

A group of stakeholders, including the Ministry of Defence, the Aerospace Technology Institute and companies were convened to then develop a series of PAS, which included:

- PAS 280:2018 Through-life engineering. Adding business value through a common framework.
- PAS 1085:2018 Manufacturing. Establishing and implementing a security-minded approach.
- PAS 1040:2019 Digital readiness. Adopting digital technologies in manufacturing.
- PAS 7040:2019 Digital manufacturing. Trustworthiness and precision of networked sensors.

In some cases, a PAS will be enough, in terms of being sufficient for the needs of a community (perhaps just needing an update after a few years). In other cases, the PAS can serve as a useful starting point and route for the subsequent development of a full British or International standard, building on the early thinking and experience gained, and the community developed, through the PAS development and implementation process.

BSI FLEX

The FLEX is a newer, more flexible fast-track standard. As with PAS, it is sponsored and developed by a steering group of representatives from relevant fields, led by BSI. However, it is developed in shorter intensive sprints, seeking to encapsulate best practice at that point in time, but then allowing for further iterations, according to market need, over an extended period of time. Each iteration can be done within an online working space and achieved in weeks, rather than months, and then repeated as necessary. The process was likened by stakeholders to a software development release, available online and updated according to need, with past versions and comments trackable. BSI also suggested that because of the quick and straightforward approach, stakeholders are more willing to ‘give FLEX a go’, to see if it works and helps. It therefore provides a promising addition to the approaches available through BSI.

The first BSI FLEX standard was for vocabulary for connected autonomous vehicles, which was made available through an interactive website. Three versions, or iterations, of the vocabulary were created within less than a year, with new terms emerging and existing ones amended, or sometimes dropped based on stakeholder feedback. The process is also soon to be employed with the Manufacturing Made Smarter ISCF, where there is a need for a first attempt to define good interoperability practice, which can then be tested through ISCF testbeds, before another improved version is developed.

However, FLEX standards are not just for emerging technologies. They have also been developed for safe working environments during the pandemic (which was self-sponsored by BSI and has since been taken up internationally) and for building safety (which is currently on its third iteration and will transition to being a British Standard next year).

The **PAS and FLEX** mechanisms embody the recognised need for 'agility in standards development', as was discussed in the BSI Agile Standards white paper (2021)[9]. This document provides a useful summary (Table 6) of the features that agile standards may have in common with more established routes, as well as where agile approaches may build on these features.

Table 6 Key features of 'established' and 'agile' approaches to standards development

In common with established approaches to standards development	Enhancement to / divergence from established approaches to standards development
Consensus: agreement on the scope and technical content of a standard Participation: an opportunity for all interested parties to contribute and have their say Governance principles: to ensure that participation is balanced, decision making is robust and the output is credible Functional structure of the content: designed to work as a standard and is developed with a specific outcome in mind Fits within a wider standards landscape: complements and supports the purpose of other standards	Iteration: smaller milestones delivering value earlier and more frequently Consensus: option to "park" components that are not ready for a decision and review in the next iteration; potential for modular updating Flexible timescales: alignment with external milestones and events, e.g. pilots Flexible process with governing principles: different options for taking work forward depending on industry needs and maturity of the knowledge Dynamic group of users and makers: changing composition over time Enhanced communications: clarity around current status, what will be happening next, what may change, version history Working environment: Tools and approaches to support collaborative content development

Source: Agile Standards white paper (BSI, 2021)

Related to this, the NQI Action Plan 'Standards for the Fourth Industrial Revolution' highlights that BSI is continuing to develop its capabilities to deliver **machine-readable** digital standards (i.e. standards as code, models or databases, rather than prose). These are intended to be better suited and responsive to the needs of industries of the future, saving time and money, increasing quality and providing faster routes to innovation. In recent years, BSI participated in two CEN and CENELEC pilot projects aimed at defining how future standards could be drafted to make them easier to use by people and machines. This included elaborating a model for

[9] BSI Agile Standards white paper (2021), www.bsigroup.com/globalassets/localfiles/en-th/developing-standards/agile-standards_ks.pdf

standards that are machine applicable, readable and transferable. This work has subsequently been taken up and continued in the UK by the BSI Innovation team.

4.3.3. Funding standards development for emerging technologies

As already introduced, BSI is a private company. It relies on the sale of standards, alongside other products and services, plus a relatively modest government grant (as well as in-kind contributions in terms of time and effort) to resource its standards development activities. As such, proposals for new or revised British standards are expected to be able to demonstrate a broadly-based need and likely active support from a wide range of relevant interests. Even so, the development of standards is then often cross-subsidised by BSI from other activities and income streams.

For the development of standards strategies or roadmaps, or for the development of PAS or FLEX standards, external sponsorship (funding) is usually required. In emerging technology areas, where innovation is still early stage and often publicly funded, the source of such funding for standardisation work is mainly government departments, agencies and bodies. However, there is no central funding mechanism or policy in place to support these activities and each case of sponsorship is separately identified and arranged by BSI and the relevant funder.

Innovate UK have funded several PAS in recent years. This is not a centrally coordinated activity and there is no central record of all commissioned work that has taken place. However, the stakeholders consulted noted the following examples of Innovate UK-sponsored PAS:

- PAS 1040 (digital readiness level - adopting digital technologies in manufacturing)
- PAS 7040 (networked sensors in digital manufacturing – guide)
- PAS 440 (responsible innovation – guide)

Individual government departments also sponsor BSI PAS development (in addition to the core grant from BEIS) and BSI provide BEIS with an annual report of these activities. Recent examples mentioned by the stakeholders include: DEFRA's sponsorship of a PAS on low cost sensors (which NPL are authoring) and OPSS' sponsorship of a PAS on battery packaging.

The 2019/20 Annual Report from BSI to BEIS lists ~20 ongoing projects of PAS development or revision sponsored by government departments or Innovate UK.

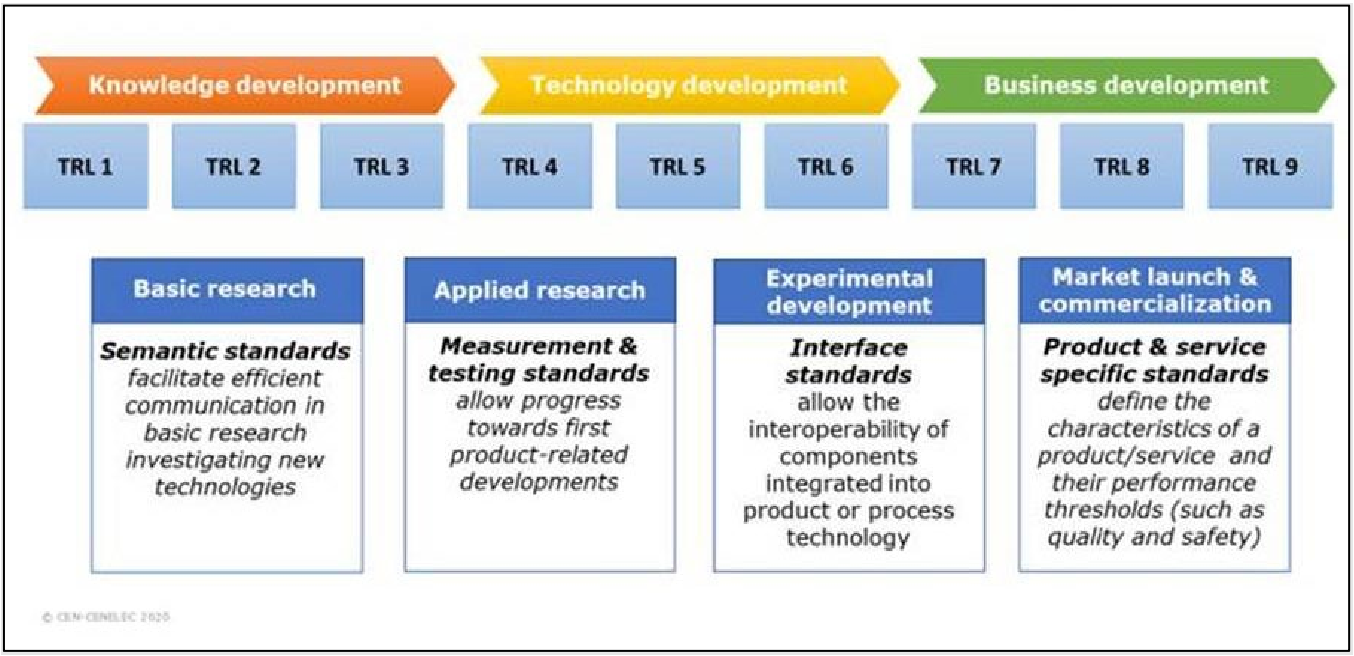
4.4. Influencing factors

A 2012 study on the role of standardisation in support of emerging technologies[10] highlighted that there are a range of factors that influence the different trajectories of new technology emergence and associated evolving standards development needs. These factors include: multiplicity of stakeholders, societal infrastructure, degree of regulation, system complexity of application, multiplicity of competing technological approaches, multiplicity of application domains, and levels of interest and investment from government. According to the study, "these factors can have a significant influence on which organisations are most appropriate to lead, fund and convene standards development activities at different phases in the life-cycle of an emerging technology."

The report goes on to explain that standards are associated with the level of technology maturity and that "there are evolving levels of emphasis on different types of standards depending on the phase of the technology's lifecycle. Different types of standards will therefore be appropriate at different phases in the emergence of a new technology and this evolving character of standardisation raises issues in terms of timing and standardisation readiness level."

The following figure, produced by CEN-CENELEC, provides a useful summary of the types of standards that tend to be needed and developed at different Technology Readiness Levels (TRLs) of new and emerging technology.

Figure 8 Types of standards and TRLs



Source: CEN-CENELEC 2020

The stakeholders consulted for the current study suggested that there is no optimal time to introduce or create standards, given that each technology, sector, or context is different.

[10] O'Sullivan, E. & L. Brévignon-Dodin (2012): Role of Standardisation in support of Emerging Technologies A Study for the Department for Business, Innovation & Skills (BIS) and the British Standards Institution (BSI)

Timing can also reflect the different roles that standards play in different application areas or user sectors (information, variety reduction, minimum quality / safety, compatibility / interface). These factors mean that engagement and discussion are key to understanding needs and supporting standardisation activity at the appropriate time.

Through the stakeholder discussions, a number of common themes also emerged concerning **enablers or barriers to standardisation** for emerging technology in the UK. These included:

- **A lack of awareness, time or interest amongst the UK's emerging technology companies, which can delay or prevent standards emergin**g.

  Standards tend to originate where you have a group of people with a common need. However, for emerging technologies, this 'group' can be smaller, less well established and less integrated. The individual companies (or academics) involved can also be very much focused on developing and commercialising their product or idea, often working in secrecy or isolation in a 'race to the market'. Standardisation may not be on their radar, or not a sufficiently high priority. It can also be perceived as prohibitively costly, in terms of the resources required to develop standards, or even the cost of purchasing these.

  As such, stakeholders suggested that industry demand could not be relied upon to initiate and drive standardisation for emerging technologies[11] – and yet the UK standardisation system is currently based around responding to industry needs. Instead, there was felt to be a need for outside (probably government) intervention to support and encourage consideration of standardisation as an integral part of the innovation process, supporting both innovation goals, as well as wider policy objectives (e.g. safety or security).

- **Appropriate convening 'places and spaces' can be important for initiating discussion and activities around standardisation for emerging technologies in the UK**.

  In established fields, you have well established organisations and individuals involved in standardisation, and the model functions well. For emerging technologies, the community can be quite small – and may not even recognise itself as a community.

  The UK's Industrial Strategy Challenge Funds (ISCF) have recently provided a good focal point for convening actors in relation to (some) emerging technologies and therefore for engagement on standardisation (for consideration of standardisation needs and for the development of strategies and roadmaps). Innovate UK reported that it has pushed for consideration of standardisation as part of the development of the ISCFs and other significant programmes, while BSI reported having engaged with all ISCF Directors to explore the potential role of standards in their technology domain. There have been some notable successes, in terms of this leading to standardisation activity, e.g. Connected and Autonomous Vehicles, Faraday Battery and the Medicines Manufacturing ISCFs.

[11] It was also mentioned that academics could often be useful and active as participants in standards development for emerging technology (and more widely), but that they also tended not to initiate or drive this standardisation work.

Stakeholders highlighted that having thinking and discussion of standardisation built into these kinds of multi-year programmes is likely to help with the identification of needs for standards at the right time, and provides an opportunity for ongoing engagement among the relevant actors. Staying connected, networked and aware across the innovation system (as well as internationally) was a common theme in discussions, and therefore making use of established networks and already convened groups was a good way of introducing and maintaining standardisation thinking and action.

- **Standards roadmaps or strategies are a common starting point for UK standardisation in emerging technologies (often building on many years of active research and innovation)**.

  There are several good examples (e.g. CAV, Faraday Battery ISCFs), where such documents have then led to further standardisation progress. However, there is also a risk that the documents are not taken forward, if there is insufficient funding, commitment or leadership to drive the implementation of next steps. The example given was of the industrial biotechnology standards roadmap, which was driven by the Industrial Biotechnology Leadership Forum (IBLF) with Innovate UK funding (and which aligned with wider government priorities and funding), but where there had been no follow-up activity and the next steps for the taking the roadmap forward were unclear.

- **Early standardisation work in the UK for emerging technologies (the identification of needs and the development of preliminary standards) often requires public funding, but current arrangements are ad-hoc due to the lack of an established funding mechanism**.

  Stakeholders reported that standards strategies and roadmaps (and subsequent PAS / FLEX development) rarely happen, particularly in relation to emerging technologies, without a specific source of external (public) funding. In recent years this has mainly come through Innovate UK or individual government departments, but there is no central funding mechanism or policy in place for such activities, so there is a reliance on the interests of individual people within these organisations and their knowledge and understanding of the potential benefits of standardisation to drive this forward.

- **Awareness of the option (and benefits) of standardisation is limited across government**.

  Stakeholders were clear that government (its departments and agencies) had some role to play in encouraging and supporting standardisation in emerging technology areas – both to support innovation and economic growth, as well as other public policy goals (e.g. safety or security). However, most stakeholders also mentioned that staff turnover and movement within the Civil Service was an issue in terms of being able to develop and maintain awareness, interest and drive (and therefore also funding) for emerging technology standardisation. The FCDO also highlighted that policy representation on BSI mirror committees was sub-optimal and that it had generally proved difficult to establish strong policy interest or involvement in ongoing standardisation activities.

- **The regulatory framework can act as an enabler or barrier to standardisation**.

  The NQI Action Plan sets out several ways in which standards can support policy making:

  - Insights and best practice generated through early-stage standardisation in areas of innovation or emerging technology can help inform regulatory approaches and make sure they are rooted in the emerging consensus within industry.
  - Standardisation can act as a form of self-regulation, potentially reducing the need for direct government or regulator intervention.
  - Standards can complement outcome-focused regulation, by providing an accepted means to demonstrate compliance with essential regulatory requirements.

  Interviewed stakeholders also highlighted that the UK's departure from the EU may also offer opportunities (e.g. greater scope to explore mechanisms such as regulatory sandboxes and innovation testbeds, where standardisation can also play a role). The Taskforce on Innovation, Growth and Regulatory Reform (TIGRR) report (June 2021) proposed that the UK can reshape its approach to regulation and seize opportunities with its new regulatory freedom. Its recommendations were then reflected in the UK government's consultation on the Better Regulation Framework, which asked whether consideration of standards (as an alternative or complement to regulation) should be formally embedded in the early appraisal of options for new regulations. The government's response to this consultation[12] highlighted that regulation should only be pursued where absolutely necessary and that best use should be made of alternatives. The document also sets out plans to introduce independent scrutiny earlier in the process of developing new regulation, asking government departments to provide a clear justification of their decision to pursue regulatory options, having engaged with the Better Regulation Executive to fully consider alternatives. The DCMS Plan for Digital Regulation[13] similarly highlights the potential of industry-led standards as alternatives or complements to traditional regulation.

  It should be noted that examples were also given by stakeholders of where certain regulations can instead lock-in technologies or discourage rapid innovation and associated standardisation. For example, in the aerospace sector, designs are approved by the regulator and put into service for 30 years, during which time the specification can't be changed (e.g. to make it safer or reduce emissions).

[12] The Benefits of Brexit: How the UK is taking advantage of leaving the EU, January 2022
[13] Digital Regulation: Driving growth and unlocking innovation, July 2021

4.5. Concluding remarks

This brief review has sought to provide an overview of the standardisation landscape in the UK specifically in relation to standards development for emerging technology. It has discussed the main actors involved and the main approaches and mechanisms deployed for identifying needs and developing standards. It has also highlighted key factors that tend to enable or act as barriers to the development of standards for emerging technology.

The review has shown that there are standardisation systems and processes in place in the UK that are appropriate for the development of standards for emerging technologies (the BSI PAS and FLEX standards approaches), but that a critical issue is getting the right stakeholders together to identify and discuss what standards might be needed and when, as well as to encourage the necessary resource to support standards development, testing and iteration.

This process (of convening, collective road mapping and drafting) will tend to happen less easily or quickly in relation to emerging technologies, compared with more established sectors and communities. As such, encouragement and (financial) support from government is important to catalyse activity. This includes encouraging consideration of standards, understanding and explaining the potential benefits of standards (to relevant actors across industry, policy and regulation), helping to convene actors and encourage interaction across the innovation system, and providing the financial resources necessary to support the development of standards.

5. Experiences of Innovators

5.1. Introduction

This section presents a summary of findings from the third phase of research. It results from an exercise to understand the experiences of innovative firms in terms of their interactions with standards and standardisation.

The section focuses on four emerging technologies that were selected by BEIS and that cover a range of technology / commercial readiness levels. These are:

- Hydrogen as a fuel
- Graphene
- Synthetic biology
- Quantum computing

The exercise involved semi-structured interviews with 41 innovators and stakeholders across the four emerging technology areas, complemented by additional desk research. The consultees were identified through discussion with Innovate UK and BSI sector leads, alongside desk research and recommendations from early interviewees.

The majority of the experts interviewed worked at innovative firms (start-ups as well as more established businesses), while a small number of interviews were also undertaken with applied researchers working at the frontier of innovation and a selection of other key stakeholders (e.g. the relevant sector lead at BSI). Interviews were semi-structured, based around a topic guide, but adapted to the specific situation and experience of the interviewee.

This section begins with a summary of findings, before taking a more detailed look at each of the four technology areas in turn.

5.2. Summary of findings

5.2.1. Hydrogen as a fuel

Hydrogen is a clean fuel and an energy carrier that can be used in internal combustion engines or fuel cells, producing virtually no greenhouse gas emissions. With the global push towards decarbonisation, it has enjoyed unprecedented political and business momentum in recent years, including in the UK where it has been recognised as critical to achieving net zero targets.

Many regulations, guidelines and standards have already been established and written for hydrogen at both international and national level as it has been used for many years in industrial applications. However, its wider adoption and commercialisation is anticipated in sectors where it has not been used previously, including domestic and commercial settings. Therefore, new or adapted standards will still be needed for hydrogen fuel technologies.

At the international level, ISO and IEC have been active - recently developing hydrogen fuel standards, including around definitions and terminology, safety considerations, fuel quality and performance. On the national level, the UK government and key standardisation bodies, such as BSI and the Institute of Gas Engineers and managers (IGEM) are also now working with an increasingly strong and diverse community to develop hydrogen codes, regulations, and standards (including a recent BSI PAS on hydrogen fired gas appliances). The UK government has also initiated several important R&D programmes that have been actively contributing to the development of codes, regulations and standards for hydrogen fuel.

An official UK “low-carbon hydrogen” standard is expected in 2022, while BSI is also currently developing three additional fast-track hydrogen end user standards that will support UK hydrogen trials and will be focused on hydrogen metering and ancillary devices.

Hydrogen related standards and regulations are therefore now evolving rapidly as the role of hydrogen as an energy vector is growing. Interviewees mentioned that they have used various different standards already, and are also increasingly looking at informal standards (or best practice guides) to meet their needs. Generally they report using standards mainly during the demonstration and commercialisation stage (TRL 5-9), which is one of the reasons why the historic lack of standards specific to hydrogen as a fuel has not slowed down innovation.

Now there is a more pressing need. Although there are some existing standards (especially standards that apply to gas more generally) that can be used for hydrogen fuel, there are areas in which more work is needed. Priorities include safety standards, standards for the installation of hydrogen appliances, hydrogen blending standards, and standards for retrofit.

At the same time, the hydrogen landscape is becoming very complex, with different technologies being developed at the same time in multiple sectors. Several standards and best practices are emerging across different sectors/industries and it is becoming hard for business to navigate the landscape. In response, initiatives are starting to appear that aim to provide more central coordination in the hydrogen landscape, including around standards.

5.2.2. Graphene

Graphene was discovered in 2004 at The University of Manchester. It is the thinnest and strongest known compound, the lightest material, the best conductor of heat at room temperature and the best conductor of electricity. It has therefore been referred to as a “wonder” material. Nevertheless, despite its potential to revolutionise a significant number of sectors (biomedical, electronics, energy, coatings, membranes, etc.) the difficulty of scaling up production, a lack of understanding and trust in the material and existing regulations in certain fields, have all been highlighted as limiting its wider adoption.

After an initial period where academia and researchers were leading the discussion and driving the development of standards to characterise graphene, it seems that innovators are also now increasingly pushing for new standards. This suggests that graphene has entered the commercialisation phase and companies are now trying to optimise and scale-up the production process. In this regard, the UK, through BSI and NPL, has been leading the development of international graphene standards, having an important role within the relevant Technical Committees at both ISO and IEC. BSI have also published a PAS on the properties of graphene flakes, developed a UK Graphene Standards Strategy, and established a joint working group with China to promote cooperation on graphene standardisation.

While most innovators were aware of the available standards for graphene, they mentioned it would be important to get more information on new developments and initiatives, as they would like to have the chance to contribute to the discussion as early as possible. Companies who already have experience of standardisation were also clear on the value of participating in the elaboration and development of standards, as a way to shape the market and potentially gain some competitive advantage.

The “first stage” of standardisation seems to be completed, with graphene standards now in place to define the material and explain its properties and limitations. Companies and innovators can follow these standards to determine whether a specific material can be defined as graphene, which helps avoiding potential misinterpretations, as there are several “intermediate” materials between graphene and graphite. However, there is still scope for standards and standardisation to help improve the adoption of graphene, in particular:

- Standards on testing large batches to reduce costs and scale-up production
- Revising standards related to application areas to allow for the use of graphene as a substitute for other (already approved) materials
- Developing standards for intermediate materials between graphene and graphite

Developing these standards could help unlock the potential of graphene and boost its mass production, making graphene more readily available to be used in a variety of applications.

5.2.3. Synthetic Biology

The specific scope of synthetic biology remains somewhat undefined. However, broadly it concerns the convergence of multiple fields with the aim to design, redesign and/or build biological devices or systems, particularly those that do not exist in the natural world. It has been a strategic priority for the UK since the publication of the national Synthetic Biology Roadmap in 2012, with its potential further highlighted in other more recent strategies from government and the Industrial Biotechnology Leadership Forum.

There are currently few formal standards in place that relate specifically to this area of emerging technology, although a number of broader international biotechnology standards cover processes and issues of relevance. In the UK, BSI (along with NPL and SynbiCite) have published a PAS on digital biological information, while a Centre for Engineering Biology and Metrology Standards was also established in 2018 to establish standards for the sector. Several informal standards for synthetic biology have also emerged, relating to computational language, but these are at an early stage and have not been widely adopted.

Interviews suggest that there is a lack of awareness across the industry of active work to create further standards. Also, while policy documents appear to suggest an imminent need and role for standards, this viewpoint was not shared amongst the innovators spoken to. However, interviewees did report that there were a diffuse set of practices within the sector, with difficulties experienced in collaboration, interoperability, and reproducibility between labs – all of which would support the rationale for further standardisation work.

Where standardisation does take place within synthetic biology there is a need to actively involve a wide variety of stakeholders, targeting different end uses throughout the process, with consideration for reducing barriers and enhancing support for innovative SMEs to engage.

There are potential roles for standards in supporting both the platform technology and the end-use applications. However, it is likely to be too early for most technologies to consider standards that are focused on end-use applications. There was more widespread agreement that immediate action on setting standards for experimental procedures would be highly useful.

5.2.4. Quantum Computing

Quantum computing is an emerging type of computation that harnesses the properties of quantum physics to perform calculations. This provides new and powerful methods of solving problems or tackling large scale challenges that would be difficult for conventional computers.

As quantum computing is still in its infancy, there is a need to maintain the freedom to innovate. At this stage, determining formal standards that define performance or product specifications is largely not appropriate, as different emerging quantum computing hardware technologies work in such different ways and no single benchmark would effectively capture their relative merits or mechanisms. There is however a need for definitions around terminology in quantum computing, an activity already underway. Similarly, there is potential benefit in further exploring where standards could and should be applied to the “classical” components of quantum systems to enable interoperability between sub-systems and suppliers. In future, the adoption of quantum computing will require alignment with existing ICT standards (e.g. for platform as a service and cloud), as well as standards for interoperability with conventional computing.

Prominence of the UK in quantum technologies more generally offers an opportunity for it to be at the forefront of standard setting dialogue and processes. However, the UK needs to look outwards internationally and keep fully abreast of international standards, both to ensure its voice is heard and to inform its own standardisation activities. Though the UK does have involvement in international standards activities, there is a need to identify ways to enable SMEs to also influence or have a voice in these processes as these emerge and evolve.

There is also a need to support the convening of the quantum computing sector and to support the engagement of small firms, particularly start-ups. In many ways the formation of the BSI Panel could address this need, but as this panel currently spans across quantum technologies as a whole, the representation of quantum computing companies specifically is limited.

As many relevant SMEs, particularly those arising from the research base, are unfamiliar with the standards development process, there is a need for some education, communication and central coordination of the sector. This also extends to raising awareness of existing standards with relevance to any form of product development and commercialisation. As it stands, the ISCF Commercialising Quantum Technologies may facilitate convening in the short-term. In the longer-term, the quantum industry group (in the process of being established) could also do so, as could the National Quantum Computing Centre, both of which are likely to be sustained.

In order to lower the barriers to SME engagement in the quantum technologies standards development process, there is a need to provide some form of incentive or support to compensate small companies for their contributions to the standards development process.

5.3. Hydrogen as a fuel

Technology / Commercial Readiness	• Technology is still being developed / adapted for the use of hydrogen in transport, heat and power, with significant increases in public (and private) investment in innovation • Some technology is at demonstration / commercialisation stage when standards are deemed to be more relevant • Emerging sub-sectors are comprised of start-ups and well-established firms • Significant policy interest and evolving legislative / regulatory framework
Current standards landscape	• Long history of industry-driven gas standards (that include / can be applied to Hydrogen) • Recent increase in standardisation specifically around Hydrogen as a fuel, particularly at international level (ISO/IEC), but also nationally (BSI PAS plus various best practice guides) • UK government commitment to development of hydrogen standards • Publicly funded R&I programmes (e.g., Hy4Heat) now active in standardisation activities

Functions	Activities to date	Activities required
Codifying knowledge	• Several international standards developed around definitions and terminology	• Informal standards / guidance has become common, and may benefit from formal process • Desire for faster / iterative (pre-) standards process • Need to organise standards portfolio to structure increasing complexity and help identify gaps
Reducing variety of options	• None yet – significant infrastructure decisions to be made	• Updated standards to allow higher hydrogen blends in the network
Defining minimum quality levels	• ISO: Safety considerations, Fuel quality, Fuel tanks. IEC: Performance indicators • BSI PAS: Hydrogen fired appliances	• Additional safety standards for hydrogen in new settings (storage, transport, heating, network) • Additional standards for installation / training
Supporting interoperability	• ISO: Refueling connection devices • Liaison between ISO TC Hydrogen and other ISO/IEC TCs (boilers, road vehicles, fuel cells)	• Standards for retrofitting (e.g., vehicles) • Need for communication / collaboration between standards making bodies / committees (e.g., new CEN/CLC joint task force and proposed BSI hydrogen standard coordination committee)

5.3.1. Introduction to the emerging technology

Hydrogen is a clean fuel and an energy carrier that can be used in internal combustion engines or fuel cells, producing virtually no greenhouse gas emissions when combusted with oxygen. Over the past decade, with the global push towards decarbonisation, hydrogen fuel (especially low-carbon hydrogen[14]) has enjoyed unprecedented political and business momentum. It has been named among the top 10 emerging technologies of 2021 and one of the four technologies necessary for meeting the Paris Agreement goals[15].

There are three key areas where hydrogen fuel innovation is likely to play a major role:

- **Transport** - Mainly through the deployment of hydrogen-powered fuel cell vehicles which offer high efficiency and low emissions and can reduce emissions from long-haul trucks, buses, non-road machines, trains, ships, and planes
- **Heat/Buildings** - Hydrogen could be blended into existing natural gas networks with the highest potential in commercial and multifamily buildings. Long-term prospects also include the direct use of hydrogen in hydrogen boilers or fuel cells
- **Power** - Hydrogen is one of the leading options for storing renewable energy. Hydrogen and ammonia can also be used in gas turbines to increase power systems flexibility

More widely, multiple governments and experts are contemplating a hydrogen economy/ society as a complete and sustainable alternative to the current fossil-fuel based economies. Several strategies and road maps have been published, including the globally known report from the IEA "The Future of Hydrogen"[16], a landmark report which analyses the current state of play for hydrogen and offers guidance on its future development. The European Union has also recently published its "Hydrogen Strategy for a Climate-neutral Europe"[17] which sets the path for how hydrogen can bridge the gap between electricity production from renewable energy and the goal of decarbonising a large share of the EU's energy consumption by 2050.

In the UK, hydrogen fuel has been recognised as critical to achieving the UK's net zero targets. As part of the Ten Point Plan for a Green Industrial Revolution[18], in November 2020 the Prime Minister announced the UK's ambition to deploy 5GW of low carbon hydrogen production capacity by 2030. Additionally, in August 2021, the government published a National Hydrogen Strategy[19] which sets out how the UK government will support innovation and stimulate investment in the 2020s to scale up the low carbon hydrogen economy by 2030.

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[14] Which includes green hydrogen (hydrogen from renewable electricity), blue hydrogen (hydrogen from fossil fuels with CO2 emissions reduced using Carbon Capture Use and Storage) and aqua hydrogen (hydrogen from fossil fuels via the new technology). www.sciencedirect.com/science/article/pii/S0360319921012684
[15] World Economic Forum (2021) Top 10 Emerging technologies, www3.weforum.org/docs/WEF_Top_10_Emerging_Technologies_of_2021.pdf
[16] IEA (2019) The Future of Hydrogen, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf
[17] European Union (2020) Hydrogen Strategy, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
[18] HM Government (2020) The ten points plan for a green industrial revolution www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution
[19] HM Government (2021) UK Hydrogen strategy, www.gov.uk/government/publications/uk-hydrogen-strategy

The strategy refers several times to the role that standards will play. It includes commitments to: "finalise design of a UK standard for low carbon hydrogen by early 2022" and update and develop "wider standards (e.g. safety, installation, equipment and purity)" by mid 2020s.

5.3.2. Standards and the standardisation landscape

Many regulations, guidelines and standards have already been established and written for hydrogen fuel at both international and national level as it has been used for many years in industrial applications. However, its wider adoption and commercialisation is anticipated in sectors where it has not been used previously, including domestic and commercial settings. Therefore, new regulations and standards may still be needed for hydrogen fuel technologies.

International

International standardisation committees have been created to facilitate the world-wide industrialisation and commercialisation of hydrogen systems and fuel cells.

At ISO the technical committee ISO TC 197 Hydrogen technologies[20] was created in 1990. Its scope is the development and discussion of standards in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. The committee has 28 participating members (including the UK, represented by BSI) and 12 observing members. Eighteen standards have been published and a further 17 are under development.

Some of those developed through ISO TC 197 so far include:

- ISO/TR 15916:2015 - Basic considerations for the safety of hydrogen systems
- ISO 17268:2020 - Gaseous hydrogen land vehicle refuelling connection devices
- ISO 14687:2019 - Hydrogen fuel quality — Product specification
- ISO 13985:2006 - Liquid hydrogen. Land vehicle fuel tanks
- ISO 26142:2010 - Hydrogen detection apparatus — Stationary applications

Standards under development cover areas such as hydrogen fuel quality, fuelling stations, land vehicle specifications, fuelling protocols and safety requirements for the use of hydrogen in commercial and residential applications.

[20] www.iso.org/committee/54560.html

ISO TC 197 also liaises and closely collaborates with other committees. The most important are:

- ISO/TC 11 Boilers and pressure vessels
- ISO/TC 22 Road vehicles (ISO 12619 Road vehicles – Compressed gaseous hydrogen and hydrogen/methane blends fuel components)
- ISO/TC 58/SC 3 Gas cylinder design (ISO 11114 Gas cylinders – Compatibility of cylinder and valve materials with gas contents)
- ISO/TC 220 Cryogenic vessels
- ISO/TC 158 – Analysis of Gases (ISO 21087 Gas analysis- Analytical methods for hydrogen fuel - PEM fuel cell applications for road vehicles)

ISO TC 197 also works with IEC/TC 105 Fuel cell technologies[21]. This Technical Committee was created in 1996 and is dedicated to fuel cell systems with the purpose of preparing international standards regarding fuel cell technologies for all applications. IEC TC 105 has developed a standard that establishes performance indicators and test procedures of power-to-power energy storage systems using hydrogen IEC 62282-8-201[22] (adopted in the UK as BS EN 62282-8-201) and is in the process of developing a hydrogen safety standard.

Another international organisation actively involved in the development of hydrogen standards is the American Society for Testing and Standards (ASTM). The organisation has approved nine methods to support the commercialisation of hydrogen vehicles and the ATSM subcommittee D03.14 Hydrogen and Fuel Cells (alongside SAE international and ISO) has developed the last two of a series of standards designed to support quality standards for hydrogen fuel cell vehicles[23].

For hydrogen fuel vehicles, additional relevant requirements include:

- The Regulation (EC) No 79/2009 European regulation of hydrogen-powered motor vehicles[24] developed by the European Environmental Agency, Technical Committee Motor Vehicles (TCMV) which stipulates that Manufacturers shall demonstrate that all new hydrogen-powered vehicles are type-approved in accordance with this Regulation and its implementing measures.
- The Global Technical Regulations G13 Global technical regulation on hydrogen and fuel cell vehicles[25] developed by the Inland Transport Committee (ITC) of the United Nations Economic Commission for Europe UNECE.

[21] www.iec.ch/dyn/www/f?p=103:7:504768534243471::::FSP_ORG_ID,FSP_LANG_ID:1309,25
[22] https://standards.iteh.ai/catalog/standards/clc/fc0d91e5-c247-4f2b-96ac-4decf42bcaac/en-iec-62282-8-201-2020
[23] ASTM (2011) https://sn.astm.org/?q=update/hydrogen-fuel-nd11.html
[24] www.eea.europa.eu/policy-documents/regulation-ec-no-79-2009
[25] https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs

- The International Organization of Legal Metrology OIML R 139-1 is also a recognised recommendation (which could become a standard) for compressed gaseous fuel measuring systems for vehicles.

As hydrogen usage in the maritime sector is relatively new, few standards have yet been developed, but the IGF – International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels: Part E developed by the International Maritime Organization (IMO) focuses on Development of safety provisions for ships using fuel cells contains information that can be used for hydrogen. Additionally, IMO Sub-Committee on Carriage of Cargoes and Containers have draft interim guidelines intended to ensure the safe and reliable delivery of electrical and/or thermal energy through the use of fuel cell technology (including hydrogen fuel cells)[26].

On the European level, apart from the EEA and UNECE standards mentioned above, CEN and CENELEC have a joint Technical Committee (JTC 6) Hydrogen in Energy Systems[27] which deals with standardisation in the field of systems, devices and connections for the production, storage, transport, and distribution of hydrogen. The scope includes cross cutting items such as: terminology, Guarantee of Origin, interfaces, operational management, relevant hydrogen safety issues, training, and education. Moreover, the CEN-CENELEC Sector Forum Energy Management Working Group 'Hydrogen', the CEN Sector Forum Gas Infrastructure and the Sector Forum Gas Utilization have formed a Joint Task Force in hydrogen in natural gas systems to provide advice in the different CEN and CENELEC Technical Committees, which will "allow a safe and reliable use of hydrogen in a decarbonizing energy systems".[28]

National

On the national level, the UK government and key standardisation bodies, such as BSI and the Institute of Gas Engineers and managers (IGEM) are working with an increasingly strong and diverse stakeholder community to develop hydrogen codes, regulations, and standards and to identify standards gaps and areas that would benefit from standards harmonisation.

BSI has several committees which develop British standards and provide input to ISO and European hydrogen-related committees. One of the most important is PVE/3/8 – Gas containers – Hydrogen technologies[29] which is responsible for the UK input into ISO/TC 197 and CEN-CLC/JTC 6 for standards related to systems and devices for the production, storage, transport, measurement and use of hydrogen. The committee has published 21 standards and 3 are in progress. BSI GSE/30 Gas installations committee[30] is also providing guidance and developing standards to ensure that gas meters, pipework and appliances on a hydrogen network are correctly commissioned, installed and maintained. Currently, BSI is in the process of creating a formal hydrogen standard coordination committee. The members are expected to come mostly from the existing BSI science and technical committees such as PVE/3/8.

[26] www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-7th-session.aspx
[27] www.cencenelec.eu/areas-of-work/cen-sectors/energy-and-utilities-cen/hydrogen/
[28] https://publications.jrc.ec.europa.eu/repository/handle/JRC117765
[29] https://standardsdevelopment.bsigroup.com/committees/50184404#:~:text=Overview%3A%20Under%20the%20direction%20of,excludes%20cryogenic%20vessels%20and%20aerosols.
[30] https://standardsdevelopment.bsigroup.com/committees/50000784

In recent years the UK government has also initiated a number of important R&D projects and programmes of relevance, including HyNet[31], H21[32] and Hy4Heat. Some of these projects have contributed to the development of codes, regulations and standards for hydrogen.

One example is Hy4Heat[33], which sought to establish if it is technically possible, safe and convenient to use hydrogen in residential and commercial buildings and gas appliances. To support this, BSI was actively involved in the delivery of WP3 and co-developed PAS 4444 Hydrogen fired gas appliances[34] guide which provides principles and guidance for appliance manufacturers on the functionality, safety, installation, operating, and servicing requirements of hydrogen-fuelled and hydrogen/natural gas dual-fuelled or converted appliances. Additionally, also as part of Hy4heat, IGEM created IGEM/H/1 Reference Standard for low pressure hydrogen utilisation[35] which aims to identify and discuss the principles required for the safety and integrity of Hydrogen installation and utilisation in premises.

The Institute of Gas Engineers and Managers (IGEM) is also leading a Hydrogen committee[36]. This discusses and considers all the technical and safety matters relating to Hydrogen, including the environmental impact of the construction and use of Hydrogen installations, transmission, distribution, measurement, and utilisation. Members of the committee include organisations such as the Health and Safety Executive (HSE), BEIS and the Gas Distribution Networks.

Other organisations are also playing an important role in the development of hydrogen standards or gas standards that can be used for hydrogen. For instance:

- The Energy Institute – In 2017 the Institute published a supplement[37] of the Blue Book[38] which provides guidance for companies that provide hydrogen for the refuelling of motor vehicles and for authorities responsible for granting permits and supervising these companies when co-location with petrol filling stations (PFSs) is proposed
- British Compressed Gases Association – Control several of the safety standards for the use of compressed gases including hydrogen (E.g. COP CP 33 Bulk storage of gaseous hydrogen at user's premises published in 2005)
- The Institute of Mechanical Engineers – The IMechE represent engineers in the UK and across the world and has established a Hydrogen Technical Advisory Committee

[31] HyNet is a project led by Cadent and Progressive Energy, based on the production of hydrogen from natural gas. It includes the development of a new hydrogen pipeline; and the creation of the UK's first CCUS infrastructure
[32] Led by Northern Gas Networks, H21 is a suite of gas industry projects, designed to support conversion of the UK gas networks to carry 100% hydrogen.H21 has already proved conversion of the existing gas grid to carry 100% hydrogen is technically possible and economically viable, through the 2016 H21 Leeds City Gate report.
[33] www.hy4heat.info/
[34] https://shop.bsigroup.com/products/hydrogen-fired-gas-appliances-guide/standard
[35] www.igem.org.uk/_resources/assets/attachment/full/0/65321.pdf
[36] www.igem.org.uk/technical-services/hydrogen-committee/
[37] Energy institute (2017) Guidance on hydrogen delivery systems for refuelling of motor vehicles, co-located with petrol fuelling stations (Supplement to the Blue Book)
[38] The Blue Book is the established technical guidance on providing information about storage and dispensing of petroleum products used as fuels for motor vehicles (including petrol, diesel and autogas (also known as LPG).

- The Health and Safety Executive (HSE) –HSE focuses on ensuring hydrogen can be used safely in its multiple applications such as a transport fuel, in pipeline distribution and in gas turbines. HSE plays a key role in a number of national and international initiatives including HyIndoor[39] and Hydrogen Power[40]. It has also adapted international standards and regulations, so they are suitable for the UK context. For example, the Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version[41].

Other organisations such as the Energy Systems Catapult (ESC) and the Scottish Hydrogen and Fuel Cells Association (SHFCA) have also helped to coordinate and provide guidance to the government and private sector about the future of hydrogen in the country. ESC has initiated a scoping of the UK's Hydrogen Landscape[42] and has produced a roadmap setting steps to support the UK transition to a hydrogen society "Accelerating a UK Hydrogen Economy"[43].

The UK government, alongside the National Hydrogen Strategy, launched a consultation process for a low carbon hydrogen standard.[44] During the consultation views were provided on design options for a UK standard that defines 'low carbon' hydrogen, to underpin the support provided by government for hydrogen production. The consultation process has closed, and it is expected that the official UK "low-carbon hydrogen" standard will be published in 2022. Following the success of PAS4444, BSI is also currently developing three additional fast-track (PAS) hydrogen end user standards. These standards will support UK hydrogen trials and will be focused on hydrogen metering and ancillary devices.

5.3.3. Experiences of innovators

The conclusions presented below are drawn from interviews with 11 representatives working on the hydrogen fuel area in the UK and internationally. This includes companies and organisations working with hydrogen in diverse sectors including transport, building/heating and maritime across the whole value chain. For more than half of the companies hydrogen was the sole area of business. For the rest, although hydrogen plays a large role in their daily activities, they also work in other fields and with other technologies. Additionally, the companies and organisations interviewed were equally divided between SMEs, large companies and consultancy firms (who provide support and guidance to firms and government).

Use of standards

The stakeholders interviewed use various standards in their daily activities. The decision to use national, European, or international standards is determined by the nature of the project and the client. If the project is focused exclusively on the UK, generally companies use national

[39] Focuses on making sure hydrogen can be used safely in rooms and enclosures.
[40] The work focuses on how waste gases, particularly Bio and SynGas, which have differing performance as a fuel.
[41] HSE (2009) www.hse.gov.uk/research/rrpdf/rr715.pdf
[42] https://esc-non-prod.s3-accelerate.amazonaws.com/2021/06/ESC-Hydrogen-Landscape-cons-lr.pdf
[43] https://catapult.org.uk/wp-content/uploads/2021/04/9384_Accelerating-a-UK-Hydrogen-Economy-1.pdf
[44] www.gov.uk/government/consultations/designing-a-uk-low-carbon-hydrogen-standard#documents

standards (when available) and best practice guidelines. National standards are especially important for projects related to energy systems. On the contrary, if the project is for an international client or the aim is the commercialisation of a product internationally, companies use international standards developed by organisations such as ISO, CEN, CENELEC or ETSI, as these reflect wider consensus, and are therefore accepted by the international community as allowing for greater interoperability, comparability and removal of trade barriers.

This approach has also been followed for hydrogen fuel. Hydrogen related standards and regulations are evolving rapidly as the role of hydrogen as an energy vector is growing. Interviewees mentioned that they have used different standards (described in the above section). Likewise, interviewees have stated that in the hydrogen fuel area they are also increasingly looking at informal standards (also known as best practice guidelines) which are developed almost as a self-organising process, with stakeholders and industry developing and agreeing guidelines that are organically adopted by the relevant communities. It is important to note that these best practice codes or guidelines may, in time, become de-facto standards.

A general view amongst interviewees was that to date there are more international than national hydrogen fuel standards. It was recognised that international standards are more well-developed, even though the UK is ahead in the hydrogen innovation sphere. Interviewees mentioned that an ideal scenario in terms of standards development and adoption would be for national (UK) standards to be adopted by the European or international community. Having said this, there have been discussions between UK and European standards organisations around the possibility of adopting PAS4444 as a European standard.

In terms of the point at which standards are adopted or used, interviewees mentioned that generally they use standards during the demonstration and commercialisation stage when the Technology Readiness Level of technologies is between 5-9. Interviewees highlighted that even though there have been instances in the past, standards should not be developed or implemented before innovation occurs. This is one of the reasons interviewees provided for why the current lack of standards has not affected or slowed down hydrogen innovation so far. It was also mentioned that industry and government need to continue conducting more R&D on hydrogen technologies before developing additional standards.

Involvement in the standardisation process

Interviewees noted that the development of hydrogen standards has historically been initiated by industry. However, they had noticed a shift in recent years, with government increasingly initiating the process, principally via public funded programmes such as Hy4Heat and H21.

Most of the innovators and sector stakeholders interviewed indicated having been involved in the development of gas related standards (including hydrogen) at both national and international level. Some had been/are members of multiple standards committees, while for others their participation has been limited to the consultation stage. Large well-established companies are the most actively involved, as they have more resources, and are the industrial stakeholders most frequently invited to be part of standards committees and steering groups.

Overall, interviewees agreed that the current process for the development of hydrogen standards, similar to other areas, is extremely inefficient, especially because it is a very long process. Some consultees have suggested to substitute the current standardisation process (standard is developed > reviewed > modified > imposed) by a sandbox type co-development/ beta testing[45] process (develop > test > monitor > review > reform > implement) in which more time is used to test a “pre-standard” before having a final/formal standard.

The BSI PAS model follows some of the principles of the beta testing suggested. It is a more iterative process which allows an initial standard to be made available to the market relatively quickly (9-12 months). It can be tested and used in implementation and reviewed again (within two years of publication) and, where a decision is made for the PAS to be updated as a PAS[46], it is opened again to consultation so the users can come and share their implementation experiences. Most of the interviewees recognised that the PAS model has been very successful in the hydrogen sector. Some interviewees were part of the development of PAS4444 and mentioned that the standard has not only been very well received by the national and international community but also the process for its development worked particularly well.

PAS4444 was funded by Hy4Heat programme as a result of a gap in available standards identified during the programme. Throughout the PAS process, appliance manufactures worked closely with BSI and Arup to develop the standard. Interviewees mentioned that the key factors for success were: identifying the best process/model to develop the standard since the beginning, identifying the appropriate person or organisation to coordinate the process and finally, developing the standard almost in parallel with the development of innovation.

Interviewees also stated for hydrogen, the development of best practice guidelines instead of standards is becoming common practice. These guidelines are quicker to develop than standards and can help to improve integration between elements across the energy sector which can increase confidence in the system to improve user satisfaction, boost uptake and de-risk investment in the market. However, interviewees also recognise that these best practice guides[47] are not always appropriate or sufficient to substitute the function of a formal standard.

Organisations spoken to that have not contributed or played an active role in the development of standards (mostly small innovative companies) expressed that some elements of the process are unclear, including how the process is initiated, which organisations are leading it and what the key steps of the process are. Interviewees also suggested that it was confusing that each organisation has their own process to develop standards. BSI has a very well-

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[45] Beta testing is used mostly during the development of software. It is a type of user acceptance testing where the product team (in this case the standard committee or organisation) gives a nearly finished product (standards) to a group of target users to evaluate product (standard) performance in the real world.

[46] When a PAS is reviewed a decision can be made to keep it as is; to update it with the latest market and technological developments; or to put the PAS forward to be developed as an international or European standard.

[47] Best practice guidelines are often developed by innovators or sector stakeholders as part of their internal R&D processes or while working for an external client. Once the projects have concluded the best practice guidelines or codes are published in a report format. Some interviewees have also stated that on a few occasions they have been directly commissioned by clients (mainly Government) to develop these best practice guidelines/codes.

defined process for developing standards BS0: A standard for standards[48] which matches the process to develop standards at the European and international levels. Nevertheless, interviewees feel that it is unclear if other organisation (IGEM, HSE, etc.) follow the same process.

5.3.4. Needs, issues and barriers

Overall, interviewees agreed that although there are some existing standards (especially standards that apply to gas more generally) that can be used for hydrogen fuel, there are areas in which more work is needed. Nevertheless, it was also recognised that many standards development organisations and key stakeholders are already working in the development of these codes and standards. In addition, interviewees mentioned that since hydrogen has been used for many years in different industries (such as nuclear and aerospace) existing standards and regulations might be adopted and adapted from other industries to fill gaps.

Priority areas where standards are needed according to innovators and stakeholders include:

- **Safety standards** – There is a need to provide a framework to enable safety and standardise technology for the various possible hydrogen markets of the future. There are already some safety standards and best practice guidelines such as the Hy4Heat safety annex. However, interviewees noted that more standards are needed to prevent accidents from the use of hydrogen in new settings. The Health and Safety Executive, UK government and industry are working closely together to understand the safety impacts of the use of hydrogen and develop new safety standards in different areas (e.g. for hydrogen storage options, injected hydrogen in the network, transport hydrogen, or hydrogen for heating)
- **Hydrogen appliances installation/Training** – Standards/guidelines to instruct and train engineers to install hydrogen appliances and to understand hydrogen standards was identified as a priority. A general view amongst interviewees was that there is sometimes a disconnect between standards and people who are working in the field (engineers). Therefore, more trained people prepared to "face the challenges of complying and applying hydrogen standards in the real world" are required.
- **Hydrogen blending standards** – The injection of minor shares of hydrogen into the gas network does not create particular technical problems in the transportation and usage of the resulting mix. However, some sector stakeholders consulted noted that the current Gas Safety Regulations (1996[49]) only allow to blend 0.1% of hydrogen with natural gas. Currently, in the UK this is being tested to increase the hydrogen blend up to 20%. If successful, the regulations and standards will need to be amended to allow for this higher blend.

[48] www.bsigroup.com/globalassets/localfiles/en-gb/standards/bs-0-2021---a-standard-for-standards.-principles-of-standardization.pdf
[49] www.hse.gov.uk/pubns/books/l80.htm

- **Retrofit** – A few innovators identified a gap in the UK and Europe in retrofit policy. This means, that there are not standards yet to certify when a vehicle has been converted to run with hydrogen fuel. Particularly existing standards and certifications are not sufficient to show investors and clients how clean hydrogen vehicles are (how much CO_2 emissions are being reduced from using hydrogen instead of petrol).

Interviewees also mentioned that hydrogen applications for the maritime world and for non-road machinery are less mature than on-road applications and require additional development efforts in order to become more competitive with incumbent technologies. Hydrogen standards in these sectors are currently non-existent or very limited, as such it was recognised that more R&D as well as new standards and regulation in these areas are needed.

In addition, it was considered that in some situations only one standard is needed across sectors. For example, for purity and quality of hydrogen in all its applications only one standard would be the most effective alternative, as there is a risk that the industry ends up with many different purities for different applications adding complexity and requiring greater volume of regulation and standards. This is only one of the examples provided, but to avoid ending up with too many prescriptive standards that stifle hydrogen fuel innovation it was suggested to adopt a unique standard framework approach.

According to interviewees, a standard framework would be more flexible, allowing for more experimentation and testing than a specific formal standard. A hydrogen fuel standard framework would need to be built using a horizontal approach, meaning that as technologies are designed, developed, and accelerated across different sectors, it is important to see what has been done in other areas and have conversations across industries. Therefore, a unique hydrogen standard framework would work in a pyramidal structure in which at the top there would be a flexible and general standard and/or regulations across sectors. Then a standard block can start to be built within a sector or for a specific use considering how that technology is deployed within the sector and what the specific requirements are in terms of its application.

Several consultees (innovators) mentioned that there is a lot of “frustration” around hydrogen standards because experts in the area (primarily innovators) are not consulted during their development, and consequently the standards end up being overly prescriptive and unrepresentative of reality (which can then create a barrier for innovation). In contrast, most of the wider stakeholders interviewed suggested that there was more of an issue with there not being many experts in the UK who know enough about hydrogen across sectors. Therefore, with only a small pool of experts (who work voluntarily) and all the standards development organisations trying to tap into the same experts, processes become inefficient and slower.

Innovators also mentioned that as there is very little expertise in the UK to develop hydrogen standards the best short-term option is to keep using European standards and working closely with European standards organisations to ensure that new regulations and standards can also be applied at the national level.

It was highlighted that communication between organisations developing standards at the national, European and international level needs to be improved, especially to enable the interoperability of standards. The challenge is that everyone is developing things at the same time in parallel and (apart from BSI mirror committees[50]) there is not enough communication at different levels. Knowledge sharing and information exchange mechanisms that enable co-creation across different territories need to be improved in the coming years.

Finally, the principal barrier identified by all interviewees is that the hydrogen landscape is becoming very complex, with different technologies being developed at the same time in multiple sectors. Several standards and best practices are emerging across different sectors/industries and it is becoming hard for business to navigate the landscape. A general concern is that the industry ends up with standards and regulations that no one needs. Interesting initiatives are starting to appear aiming to provide more central coordination in the hydrogen landscape and realise the UK's potential as a global leader in the development and commercialisation of hydrogen fuel technologies.

The Hydrogen Innovation Initiative[51] is an example of the efforts being made "to connect all the dots across different sectors/areas while supporting knowledge sharing". The initiative is being developed and lead by the Catapult Network. Through this initiative the Network is working alongside its partners to create a platform or vehicle that companies and organisation can use to know what is happening in the UK, who is the best person or organisation to ask for help, and where the relevant activities on standards and regulation are taking place in the country. The initiative will support the creation of new linkages between sectors to drive efficient, complimentary development and maximise technology exploitation. It has been recognised that the platform has a high potential to play an important role in the development of hydrogen in the UK and supporting the UK to benefit from innovation in this area.

Additionally, the Energy Systems Catapult has created a Hydrogen landscape and an energy systems-of-system map which sets out the relevant hydrogen policy, regulations and associated stakeholders to enable exploration of the integration and interrelationship of different hydrogen policy and regulations as part of the wider whole energy system. This also helps understand where standards and legislation might need to be developed or changed. Consultees expressed that more similar initiatives, coordinated and supported financially by government, are needed to accelerate the UK hydrogen economy.

[50] The role of mirror committees is to form positions at the national level on the issues debated in the corresponding European or international (ISO) Technical Committees.
[51] https://es.catapult.org.uk/report/accelerating-a-uk-hydrogen-economy/

5.4. Graphene

Technology / Commercial Readiness	• A well-established technology (material) with strong credentials (in terms of weight, strength, conductivity, flexibility, etc.) with a wide range of potential applications • Thousands of graphene-related patents and large numbers of 'graphene' suppliers • Uptake / application is still quite limited, due to production cost, lack of understanding/trust and existing standards/regulations acting as a barrier in certain application areas
Current standards landscape	• UK (BSI & NPL) has been leading international (ISO/IEC) standardisation • Several important ISO & IEC standards (+ BSI PAS) published in recent years • Initial work driven by academia – but increasingly innovators / start-ups are engaged

Functions	Activities to date	Activities required
Codifying knowledge	• UK-China Joint Working Group on graphene standardisation • ISO/ IEC activity in definitions & measurement	• Nothing further identified
Reducing variety of options	• ISO / BSI PAS: Key properties, Measurement techniques, Standardised product descriptions*	• Current standards are sufficient to characterise whether a material is graphene • Need to define / characterise non-graphene (but similar) material
Defining minimum quality levels	• As above	• Testing of large batches (to support scaling of production) • Standards to enable demonstration of performance
Supporting interoperability	• ISO: Nomenclature, Definitions	• Existing standards (e.g., in construction) limiting wider adoption by not allowing use of different materials • Links to regulation may prove additional barrier

* Important as it is possible to obtain very different structural & chemical properties for materials that are labelled as "graphene" – and the resulting uncertainty had slowed the pace of investment / use.

5.4.1. Introduction to the emerging technology

"Graphene is a two-dimensional carbon-based material with a molecular structure that results in a combination of unique properties such as high strength, thermal and electrical conductivity, flexibility and high surface area. Its superior performance against other existing advanced materials makes it attractive for a wide range of applications ranging from lightweight composites, functional coatings to energy harvesting and storage."[52]

Graphene, defined as a single layer (monolayer) of carbon atoms[53], tightly bound in a hexagonal honeycomb lattice, was discovered in 2004 at The University of Manchester. It is the thinnest compound currently known at one atom thick, the lightest material, the strongest compound, the best conductor of heat at room temperature and also the best conductor of electricity.[54] Due to these characteristics, Graphene is also known as a "wonder" material.

There are generally two ways to categorise the production of graphene: "bottom-up" and "top-down" techniques. The former involves using chemical reactions to produce 2D graphene from hydrocarbon precursors, while the latter uses graphite as a precursor, deconstructed into sheets of graphene.[55] The material properties are sensitive to the approach used.

Despite its potential to revolutionise a significant number of sectors, the difficulty of scaling up production, particularly from a cost point of view, has been limiting its wider adoption. Additionally, the quality of graphene also depends on the approach used, which also complicates the production process. According to Stafford et. al. (2018, pp. 3250-1)[56]:

- Bottom-up approaches typically produce monolayer graphene and multilayer graphene (MLG, 2 < Nl < 10), with highly-controlled layer numbers (Nl). Top-down approaches utilise graphite (Nl > 10) and exfoliate this precursor into monolayer and multilayer graphene with a broad distribution in layer number.
- Graphene of high quality can be produced through bottom-up approaches, which is suited for use in electronic devices. These techniques, however, have generally suffered from very low production rates. In contrast, top-down processes, which most commonly use liquid-phase exfoliation, produce graphene at much higher production rates but often result in noticeably lower quality… The resulting graphene has been typically reserved for composites, conductive inks, coatings and flexible electronics applications.

Notwithstanding this, over the past few years there have been some major improvements in scaling-up production, as well as an increase in the number of graphene-related patents. For

[52] BSI (2018): Developing a UK Standards Strategy for Graphene.
[53] A single layer is the strictest definition, but there are ongoing discussions over the definition of graphene.
[54] www.graphenea.com/pages/graphene#.Ya4woy2l2fU
[55] For a detailed description of methods to characterize, Mansfield, Kaiser, Fujita and de Voorde (Eds., 2017), Graphene, see Metrology and Standardization for Nanotechnology: Protocols and Industrial Innovations.
[56] Stafford, J., Patapas, A., Uzo, N., Matar, O. K., and C. Petit (2018): "Towards scale-up of graphene production via nonoxidizing liquid exfoliation methods"; AIChE Journal, 64(9), pp. 3246-3276.

example, between 2005 and 2014, more than 25,000 Graphene patents were published, corresponding to over 13,000 patent families.[57]

Currently, the National Graphene Institute identifies six main application areas where Graphene is already being used: Biomedical, Composites and coatings, Electronics, Energy, Membranes and Sensors.[58] In particular, Graphene can play a major role in achieving Net Zero by improving energy storage in devices such as (car) batteries and supercapacitors.

5.4.2. Standards and the standardisation landscape

There are many forms of the material that can be labelled as “graphene” because, depending on the production process, it is possible to obtain very different structural and chemical properties. Acknowledging this fact, the international community highlights the importance of defining terminology and having a clear way to compare the different materials already available in the market. Furthermore, these issues are exacerbated because of the large number of suppliers already available in the market, each providing different grades of material and listing different measurands on technical data sheets. In other words, relying solely on product information, a comparison of materials becomes extremely difficult.

International

The ISO Technical Committee (TC) 229: Nanotechnologies was established in 2005, and is led by the British Standards Institute (BSI). It aims to develop standards to support control, processes and properties of nanoscale materials and ultimately lead to materials, devices and systems with better performance. Due to its intentionally broad scope (no application or material specified), the committee is able to include current and future methods and products that may fit under this general science remit instead of an application or sector-specific activity.

In early 2007, the International Electrotechnical Commission (IEC) also established Technical Committee 113 to develop standards for “technologies relevant to electronic products and systems in the field of nanotechnology.”[59]

Recognising the overlap in scope and work in developing (i) standards for terminology and nomenclature, and (ii) standards for measurement and characterisation, ISO TC229 and IEC TC113 established two joint working groups (JWG 1 and JWG2) for standardisation in these two areas. From this collaboration, three important standards have been developed:

- ISO/TS 80004-13:2017: led by National Physical Laboratory (NPL) and the first standard to discuss definitions for graphene and other 2D materials and terms for naming production methods, properties and characterisation.[60]
- ISO/NP TR 19733:2019 provides a matrix which links key properties of graphene and related two-dimensional (2D) materials to commercially available measurement

[57] A patent family is a collection of patent applications covering the same or similar technical content. www.gov.uk/government/publications/graphene-the-worldwide-patent-landscape-in-2015
[58] www.graphene.manchester.ac.uk/learn/applications/
[59] www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1315,25
[60] For example, this standard defined, for the first time, the difference between ‘graphene’ (one single layer of sp2 hybridised carbon) and ‘few-layer graphene’ (three to ten layers).

techniques. The matrix includes measurement techniques to characterise chemical, physical, electrical, optical, thermal and mechanical properties of graphene and related 2D materials.[61]

- ISO/TS 21356-1:2021: facilitates determination of whether a material contains graphene. It describes the decision-making process and measurements required for understanding the structural properties of graphene particles in a powder form or in liquid dispersions.

There is also another ISO/IEC standard under development:

- IEC/CDV 62565-03-01: describes "the measurands that should be included in technical data sheets for graphene and related 2D materials, to provide a consistent set of descriptors to compare between products" (Clifford et al., 221, p. 233).

In 2015, the IEC/TC 113 also created "Working Group 8: Graphene related materials and carbon nanotube materials" to develop and discuss standardisation projects.[62] These standards are intended to "facilitate the assurance of quality and reliability of materials and intermediates, subject to the general concepts of blank detail specifications (BDS) and key control characteristics" (Mansfield, Kaiser, Fujita and de Voorde, 2017).

In 2013, the European Commission (EC) launched the Graphene Flagship[63], aimed at bringing graphene innovation out of the lab and research institutes and into commercial applications. The initiative gathers 170 academic and industrial partners from 22 countries, all exploring, studying and applying different aspects of graphene. More recently, the EC has also funded an experimental pilot for graphene-based electronics, optoelectronics and sensors. Within the Graphene Flagship, the Standardisation Committee (GFSC) is working on the development of new standards to enable the widespread use of graphene. The GFSC connects the Graphene Flagship with international standardisation at both ISO and IEC.

The Versailles Project on Advanced Materials and Standards (VAMAS)[64] has also launched the Technical Working Area (TWA) 41 Graphene and Related 2D Materials, aimed at validating measurement, sample preparation and data analysis methodologies on graphene. Through this initiative, it is possible to compare the measuring systems used by different laboratories, understand the measurement uncertainty and ensure repeatability of results.

National

The UK, through BSI and NPL, has been leading the international development of Graphene and graphene product-related standards. NTI/1 is the BSI technical committee responsible for formal standards development in nanotechnologies. It also mirrors and participates in all of ISO/TC 229 and IEC/TC 113 work. Within this committee, BSI aims to have a balanced mix of stakeholders to represent the UK and anyone can apply to join.

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[61] www.iso.org/standard/66188.html
[62] www.iec.ch/dyn/www/f?p=103:14:0::::FSP_ORG_ID,FSP_LANG_ID:12359,25
[63] https://graphene-flagship.eu
[64] VAMAS develops best practices in measurement methods of advanced materials, through collaboration on pre-standards measurement research, laboratory intercomparison and agreement on standards priorities.

In 2017 BSI (supported by BEIS), started a programme to conduct research into how standards can help support UK innovators accelerate the rate of commercialisation of graphene applications. From this programme it established a partnership with the Standardisation Administration of China (SAC) on graphene standardisation. BSI and SAC have set up the UK-China Joint Working Group, aiming to promote cooperation between the two countries on graphene standardisation, through pre-standardisation work and standards proposals related to graphene information, handling, transportation, storage and testing. It has also developed a UK Graphene Standards Strategy, which encourages the use of common graphene standards by other international standards bodies in all relevant countries.[65]

In 2018, BSI published a Publicly Available Specification (PAS), sponsored by Innovate UK, entitled "Properties of Graphene Flakes – guide" (PAS 1201) to explain the physical and chemical properties of graphene flakes, as well as provide guidance on the information to be given so that prospective users of graphene flakes can have comparative information.

Innovate UK has sponsored the Graphene Engineering Innovation Centre (GEIC), which is specialised in rapid development and scale-up of graphene and 2D materials applications, while NPL has been heavily involved with ISO TC 229 and IEC TC 113 in developing the standards required for a global graphene industry. In particular, NPL led the first graphene ISO standard defining the terminology of graphene and related 2D materials (ISO/TS 80004-13:2017).

5.4.3. Experiences of innovators

Use of standards

Innovative firms were aware of most of the formal standards with relevance for their work, both in producing graphene and in using it to develop other products.

It was also acknowledged that prior to the existing standards (i.e. before 2018) the industry was developing at a rather slow pace in part because companies would use the label "graphene" loosely (meaning potential clients did not have enough trust to use and invest in graphene products). In this regard, graphene standards were important to define the material and explain its properties and limitations, validating graphene as a trustworthy component. Additionally, standards helped in ensuring that data is comparable amongst companies, in boosting sector regulation and in developing the necessary procedures to test the material. However, interviewees highlighted that the current standards are probably now sufficient to characterise graphene and check if a new material can be characterised as graphene.

Overall, most companies consulted in the graphene area recognised that standards were not a barrier to innovation because they enable new product developments while ensuring that all innovators can demonstrate whether and how their products meet (or exceed) the quality requirements. This is particularly relevant if standards can be defined and implemented at a steady pace, which is not always the case. For situations where standards are expected to

[65] BSI (2018): Developing a UK Standards Strategy for Graphene.

take several years to be developed, it was felt that a PAS can be more effective, as it combines speed with rigorous technical guidance.

Despite the positive impact on innovation, however, it seems that most clients are not particularly interested in buying graphene per se, but focus rather on the desirable properties of the material. Depending on their needs, clients are willing to buy materials "similar" to graphene at lower cost.

One company highlighted some of the risks of sectors not making use of relevant standards, however. For example, in Canada, a Chinese company was claiming to sell face masks with graphene to prevent the spread of Covid-19. After several reports of breathing problems and headaches, Health Canada prohibited the use of face masks with graphene.[66] A few months later, it was discovered that this company was not using graphene but rather a "similar" material and the Canadian Government authorised again the use of a specific type of face masks with graphene.[67] In other words, not following the existing standards can put people at risk and slow down the adoption rate of graphene in other areas.

Involvement in the standardisation process

The majority of companies interviewed were aware of the existing standards, standards organisations and standards setting processes. A few had been actively participating in standardisation activities, such as the UK-China Joint Working Group and GEIC initiatives, sharing their experiences and their internal procedures with the committee. These companies acknowledged the advantages of participating in discussions, such as the ability to influence and contribute to the elaboration of a standard which, in itself, can shape or even create a new market, and / or give them some advantages when compared to other companies.

While none of the companies mentioned any particular need for change in the standardisation process, some companies highlighted that these discussions take too much time and effort, and they would like to see the process moving faster. One particular company stated that a timeline should be formally established to fully develop a standard. This would mean that, from the moment a need for a standard was identified, the competent authorities and stakeholders would have a specific amount of time to develop and publish. This would help innovators planning their activity and increase their engagement with the process.

Some companies also mentioned that it was not feasible to attend standardisation meetings due to a lack of financial and human resources. Additionally, while companies and innovators are familiar with the current standards, they would like to get more information on new developments. In particular, it was mentioned that very often companies are not aware of what is being developed until the standard is published. As such, interviewees highlighted a need for joint initiatives with innovators to anticipate and discuss future standards needs.

[66] https://montreal.ctvnews.ca/after-recalling-graphene-coated-masks-out-of-safety-concerns-health-canada-says-some-models-can-come-back-on-the-market-1.5509111
[67] https://recalls-rappels.canada.ca/en/alert-recall/graphene-face-masks

5.4.4. Needs, issues and barriers

Interviewees identified three potential barriers hindering the overall widespread adoption of graphene and where standardisation could have an important role:

- The high costs of producing graphene: while graphene is associated with higher levels of efficiency (e.g. in electronics) and durability (e.g. in construction), it is still very costly to produce. One way to reduce costs would be to develop standards on testing large batches, which could help in scaling up production (and thereby in reducing overall costs). Several companies highlighted that the current standards focus on analysing and testing very small areas of graphene, in part because these standards come from academia, which does not work with large areas. However, in order to scale-up production in a consistent manner and avoid batch-to-batch variation, it would be important to have a clear standard on how to test large batches, detailing the methods to be followed. One company in particular stated that some companies might be already using different methods to avoid testing graphene on a “millilitre by millilitre” basis, such as thermogravimetric analysis. However, while this method might be useful to test large batches, without a standard on this it might not be possible to provide consistent results.
- Standards (or regulations) in some application areas of graphene (e.g. building construction): since these do not allow the use of different / new materials apart from the ones already defined, companies are not able to take full advantage of graphene. For example, in the construction sector, an innovator stated that it is not possible to reduce the amount of cement composition below a specific threshold. This is particularly important because the cement industry is one of the main producers of carbon dioxide and, therefore, replacing it with graphene could help in protecting the environment and achieving net zero. One of the ways to increase widespread use would be to change or revise these standards to ensure that graphene could be used. However, changing standards, particularly those associated with regulation, could be a difficult task.
- The lack of standards for materials between graphene and graphite: The current standard framework seems to be sufficient for the companies consulted to operate within the market and conduct their own research and develop their products. However, the focus of clients on the characteristic of the materials (both graphene and products using graphene) means that currently some do not follow graphene standards, but prefer to rely more on testing procedures. This approach means that some companies are using the term “graphene” loosely to refer to materials that are between graphene and graphite. These materials have interesting proprieties and are much cheaper and easier to scale-up production, but they are not graphene. It would be important to acknowledge their properties through the development of standards, which in turn would make it easier to distinguish them from graphene and, at the same time, increase their trustworthiness.

5.5. Synthetic biology

Technology / Commercial Readiness	• Emerging technology across multiple sectors • The term 'synthetic biology' is not well recognised / defined • Nevertheless, it was a key part of the government's 2030 bioeconomy strategy
Current standards landscape	• Very limited standardisation to date, despite increasing calls for action • Limited knowledge of existing standards / standardisation amongst innovators • Health / biopharma likely to have different needs to industrial synthetic biology • NIST (US) increasingly active in developing standards for this area

Functions	Activities to date	Activities required
Codifying knowledge	• None yet	• Defining the sector • Could consider means of supporting standardisation through UKRI grants
Reducing variety of options	• None yet	• None yet
Defining minimum quality levels	• None yet	• Need to reassure the market and / or provide public confidence • Supporting the development of a regulatory framework for the sector (noting that health/biopharma and industrial synbio face different regulatory structures)
Supporting interoperability	• ISO and BSI PAS on use / sharing of biological data • Open-source computational language for SynBio (not widely adopted)	• Overcoming fragmented and diffuse practices that are hampering collaboration, interoperability and reproducibility

5.5.1. Introduction to the emerging technology

The specific scope of synthetic biology (also sometimes referred to as engineering biology) remains somewhat undefined. However, broadly it is the convergence of multiple fields with the aim to design, redesign and/or build biological devices or systems, particularly those that do not exist in the natural world.[68] These efforts are underpinned by applying engineering principles to biological systems, in particular the design, build, test and learn cycle.

The recent draft of the National Security and Investment Act 2021[69] defines synthetic biology as including:

- The design and engineering of biological-based parts of enzymes, genetic circuits and cells, or novel devices and systems
- Redesigning existing natural biological systems
- Using microbes to template materials
- Cell-free systems
- Gene editing and gene therapy
- The use of DNA for data storage, encryption, and bio-enabled computing

Synthetic biology has been a strategic priority for the UK since the publication of the national Synthetic Biology Roadmap in 2012[70]. The size and strength of the UK sector has grown since and synthetic biology has also been included in several further strategic documents. For instance, the (now withdrawn) UK government 2030 Bioeconomy Strategy[71] highlighted three sectors of research priority for synthetic biology: agri-food, manufacture (chemicals and materials) and healthcare. These were also mentioned by the Industrial Biotechnology Leadership Forum in its bioeconomy strategy,[72] where synthetic biology featured in many case studies, and was considered to have high potential for the manufacture of medicines, chemicals and green fuels, as well as having a key role in enabling industrial biotechnology.

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[68] Nature, Synthetic Biology. www.nature.com/subjects/synthetic-biology

[69] Draft Regulations laid before Parliament under section 63(5) of the National Security and Investment Act 2021, www.gov.uk/government/publications/national-security-and-investment-act-draft-notifiable-acquisition-statutory-instrument

[70] Synthetic Biology Roadmap Coordination Group, A Synthetic Biology Roadmap for the UK www.ifm.eng.cam.ac.uk/uploads/Roadmapping/Synthetic_Biology_Roadmap_-_TSB.pdf

[71] BEIS, Growing the Bioeconomy, www.gov.uk/government/publications/bioeconomy-strategy-2018-to-2030

[72] Industrial Biotechnology Leadership Forum Growing the UK Industrial Biotechnology Base: Enabling Technologies for a Sustainable Circular Bioeconomy: A National Industrial Biotechnology Strategy to 2030 www.bioindustry.org/uploads/assets/uploaded/d390c237-04b3-4f2d-be5e776124b3640e.pdf

5.5.2. Standards and the standardisation

This section discusses recent standardisation activity in synthetic biology. It highlights standards that are already in place (summarised in the table below), focusing on three in particular: ISO/TR 3985:2021, PAS 246:2015, and the Synthetic Biology Open Language.

Table 7 Key standards within synthetic biology

Type	Standard	Brief description of areas covered
International	ISO/TR 3985:2021	Initial outlines of how to handle data within biotechnology, generally including synthetic biology applications.
	ISO 5058-1:2021	Vocabulary and taxonomy around genome editing, including those relevant for synthetic biology applications.
	ISO 20395:2019	Focus on evaluating the performance of Polymerase Chain Reaction (PCR) technologies for quantifying biological targets.
	ISO 20397-2:2021	Covers the evaluation of data from massively parallel sequencing (MPS), a large-scale process for investigating genomes, transcriptomes and specific nucleic targets.
National	PAS 246:2015	Covers the use of data within synthetic biology.
Informal	Synthetic Biology Open Language (SBOL)	A computational language used within the synthetic biology sector.

International

There are currently no international standards that relate specifically to synthetic biology. However, synthetic biology is impacted by several existing biotechnology standards, such as ISO/TR 3985:2021, ISO 5058-1:2021, ISO20395:2019 and ISO20397. All of these cover processes and issues of relevance to synthetic biology, but not specific to it, such as processes used to investigate genetic sequences (e.g. PCR and MPS techniques) and data usage guidelines.

As an example, ISO/TR 3985:2021 'Biotechnology Data publication: Preliminary considerations and concepts'[73] focuses on the use of data across the life sciences, including synthetic biology. It seeks to set out a basic framework of concepts, to ensure data is searchable and understood by researchers across different institutions and organisations. It includes guidance around how particular types of data should be described and considerations for organisations to make appropriate data-sharing plans. As its name suggests (preliminary considerations…), the standard is not overly specific or prescriptive.

[73] ISO, ISO/TR 3985:2021, www.iso.org/standard/79690.html

At the international level, it is also worth noting the Horizon 2020 project 'BioRoboost', which sought to facilitate standards development in synthetic biology. No formal documentary standards[74] have been produced by the project (as of yet), but it has resulted in 'Standardisation in Synthetic Biology: a white book', which provides recommendations for policymakers[75] around how standards development in synthetic biology should take place.

National

In 2014 Innovate UK and BSI published 'The ascent of digital biomanufacturing – creating a new manufacturing industry through the development of synthetic biology standards'. This white paper highlighted that no existing standards were in place, and that a drive towards standardisation was a priority for the industry. It recommended that standards be developed for how digital biological information should be handled and transferred between machines[76].

Since then SynbiCite has been a key actor involved in standards making in the UK. SynBiCite is Innovate UK's Innovation and Knowledge Centre for Synthetic Biology, based at Imperial College London, and seeks to accelerate the commercialisation of emerging technologies in the field[77]. It is well respected across the industry and has worked closely with NPL and BSI. This collaboration has had two components:

- The first was BSI's publication of PAS 246:2015, 'Use of standards for digital biological information in the design, construction and description of a synthetic, biological system guide'[78]. This was BSI's first standard covering synthetic biology specifically, and provides standards for digital biological data, including how data in the industry should be laid out across different components of the synthetic biology industry.
- The second, in 2018, was the establishment of the UK Centre for Engineering Biology and Metrology Standards. This is a virtual laboratory that involves a collaboration between NPL, SynBiCite, National Measurement Laboratory (NML) at LGC[79] and the National Institute for Biological Standards and Control (NIBSC). The centre aims to establish standards for measurement and standardised reference material for the synthetic biology sector.

Beyond PAS 246, no other formal standards for synthetic biology have been published in the UK. However, several informal standards have emerged[80], including the Synthetic Biology Open Language (SBOL)[81], the Standard European Vector Architecture (SEVA)[82] and

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[74] Standards that have been codified within published documents (such as ISO and PAS Standards)
[75] Bioroboost, Standardisation in Synthetic Biology: A White Book, https://standardsinsynbio.eu/wp-content/uploads/2021/09/Standardisation-in-Synthetic-ebook.pdf
[76] BSI, The ascent of digital biomanufacturing, www.bsigroup.com/LocalFiles/en-GB/standards/BSI-The-ascent-of-digital-biomanufacturing-UK-EN.pdf
[77] Synbicite, www.synbicite.com/about-us/
[78] BSI, PAS 246:2015, https://shop.bsigroup.com/products/use-of-standards-for-digital-biological-information-in-the-design-construction-and-description-of-a-synthetic-biological-system-guide
[79] LGC, formerly known as the Laboratory of Government Chemist, but renamed LGC after privatisation in 1996 (www.lgcgroup.com/about-us/our-history/)
[80] Beal et al, The long journey towards standards for engineering biosystems, www.embopress.org/doi/full/10.15252/embr.202050521
[81] an open-source language that allows communication of synthetic biology designs
[82] that is a format that allows genetic constructs to be shared.

DICOM-SB[83]. We understand that these remain in 'early adopter' phase, however, (i.e. used by a small proportion of the UK (or international) firms involved in developing, selling, or exporting new technology) and are yet to be more widely adopted.

Nevertheless, as the understanding of the potential for synthetic biology has grown, so has interest in the potential role of standards and standardisation in the sector. For instance, the Royal Academy of Engineering's 2020 'Engineering Biology as a Growth Priority'[84] notes that in the synthetic biology sector there is a high degree of fragmentation with good practice occurring in silos. To realise the potential of the industry, it suggests, there is a need to bring different components together. This is further elaborated by the Engineering Biology Leadership Council who called in 2021 for a "governance system to set standards and reassure the market"[85], highlighting a need for standards to support public confidence and collaboration within the industry.

In 2017, BSI also commissioned 'developing standards to support the synthetic biology value chain'[86], in which the Rand Cooperation outlined four scenarios, ranging from a catastrophic event within the sector leading to heavy regulation and a sector dominated by large longstanding companies, to a sharing economy model, with few standards and an open-access model across processes, in which SMEs dominated. While these scenarios are by their nature reductive, the UK synthetic biology sector currently appears to be developing along the lines set out in the second scenario, with a sector supported by public funding, with a mixture of SMEs and large incumbents, and low regulation. This scenario does however suggest high levels of metrology, technical, scientific, containment and environmental standards are in place, which is not the case. The report notes that "the UK has been developing nascent standards and has been placing rhetoric in this direction, though they are still early in nature, making continued progress in this area uncertain".

Across the various strategies published in relation to synthetic biology, it is suggested that the next steps for standards in this area would be standardised metrics for fundamental units and references for gene expression, computational languages, and mapping potential synthetic biology chassis and setting related standards for each.

[83] DICOM-B is a computational standard based on the Digital Imaging and Communications in Medicine (DICOM) standard, that has been adapted to specifically suit the needs of Synthetic biological. IT has recently undergone testing at Imperial College London and Nanyang Technological University. https://spiral.imperial.ac.uk/handle/10044/1/33576

[84] Royal Academy of engineering. Engineering Biology as a priority for growth, /www.raeng.org.uk/publications/reports/engineering-biology-a-priority-for-growth

[85] EBLC, Building back better with Engineering Biology, https://ktn-uk.org/wp-content/uploads/2021/07/EBLC-Building-back-better-with-Engineering-Biology_upload.pdf

[86] RAND &BSI, developing standards to support the synthetic biology value chain, www.rand.org/pubs/research_reports/RR1527.html

5.5.3. Experiences of innovators

This section presents the findings from interviews with a selection of innovators and stakeholders in the area of synthetic biology. This included a mixture of stakeholders from the National Quality Infrastructure, members of the engineering biology leadership council, prominent academics and representatives of innovative SMEs.

Use of standards

Interviews with both stakeholders and innovative firms in the UK synthetic biology sector suggest that few in the industry (or within academia) are currently aware of synthetic biology specific standards. The work on informal standards was also reported as being still at an early stage. While several stakeholders pointed to SBOL and the 'bio blocks' initiative, the first is only used by a set of early adopters and the second was considered not at an operational stage yet.

Despite this, interviewees did suggest there was a potential role for standards, in that they commonly reported that there were a diffuse set of practices within the sector, with difficulties experienced in collaboration, interoperability, and reproducibility between labs.

Involvement in the standardisation process

Interviewees highlighted that there had been many calls for standards for synthetic biology, including in government policy documents, and yet there had been very little action so far.

There was very little awareness amongst those consulted of any ongoing standardisation activity, either internationally or in the UK. There was some limited awareness of the ongoing work of the NPL virtual laboratory for Engineering biology and Metrology standards. However, one interviewee raised concern that finance for the centre may come to an end shortly (with the end of the Industrial Strategy Challenge Fund) and that this may slow progress further.

None of the innovative companies spoken to reported having been involved in standards making, while the academic and NQI stakeholders had. The latter reported that larger companies or those with larger market shares tended to dominate the standards making, creating a risk that the resulting standards are not always suitable for SMEs.

The barriers to the involvement of synthetic biology innovators (and particularly SMEs) in standardisation that were suggested by interviewees included:

- Funding: BBSRC is the largest funder of synthetic biology in the UK, while Innovate UK is another major source of grants for the emerging sector. Interviewees noted that the terms and conditions on their grants should be reviewed to ensure that they allowed for (or even encouraged) involvement in standardisation. Specific funding support for SMEs to engage in standards-making might also be considered.
- Location: Different subsectors of the synthetic biology sector are clustered in different locations, such as London, Cambridge, Manchester, Norwich and Edinburgh. In particular, while companies exploring healthcare applications are predominantly located in the southeast, those exploring industrial synthetic biology tend to be based

elsewhere. Given the limitation on time and capacity of SMEs, it may be important that the concentration of subsectors in different parts of the country are considered when any in-person standards making sessions are planned and organised.

- Outreach: When reaching out to the synthetic biology sector in the UK, interviewees suggested it would be important to engage through multiple channels, to avoid creating processes that are dominated by a certain subsector. For instance, it was noted that the majority of members of the BioIndustry Association (BIA) related to pharmaceutical and healthcare applications, rather than industrial synthetic biology.
- Education: Several stakeholders suggested more needed to be done to educate innovators in the sector on the benefits of standards and standardisation, as well as how to engage with potential standardisation processes.

Finally, many stakeholders highlighted that the synthetic biology industries of the United States, South Korea and China have seen significant investment, with each country spending several hundreds of millions of dollars on major synthetic biology projects in recent years. They feared that as a result the UK industry may be falling behind and suggested that government should renew its commitment to synthetic biology by providing significantly more funding to the industry through UKRI. It was also noted that the National Institute of Standards and Technology (NIST) in the US had been increasingly active in recent years, working with US companies to begin to develop standards for synthetic biology. As a result, many of the stakeholders suggested that to be successful in developing standards, the NQI in the UK will need to work collaboratively with international equivalents, with NIST in particular.

5.5.4. Needs, issues and barriers

Most interviewees suggested that calls for synthetic biology standardisation were coming mainly from academia, and that generally there was not currently an urgent need felt within the business community. Several innovators clarified that further progress on commercialisation was felt to be needed before standardisation would become more relevant for them.

Nevertheless, across the different stakeholders consulted, three areas of standardisation were identified that could support the growth of the synthetic biology sector in the UK. These were:

- Application standards for different synthetic biology use-cases (suggested by industry)
- Technical standards for biological components (suggested by academics)
- Standards for experimental procedures (suggested by various stakeholders)

While the industry stakeholders did not regard standards as a particular priority, some thought that application standards would be needed as technologies progressed further towards commercialisation. The relevant interviewees felt that such standards might help to build consumer trust in the new technology and could also help to progress through regulatory barriers. Industry stakeholders also highlighted, however, that the standards needed to be specific to the use case, such that standards in one area didn't hamper solutions in another.

This links to a broader consideration raised by interviewees that there are common but different standards needs within synthetic biology. For instance, it was suggested that you might have a need for a standard in a specific area across different use-cases that are using a similar platform technology. However, these different use cases will require different features within the standard depending on the environments they are operating in and what they need from the standard.

Other stakeholders interviewed (predominately academics) were more concerned with universal technical standards that could support the platform technology of synthetic biology. The areas mentioned focused on defined computational languages, production processes and definitions and engineered biological components, such as chassis. They also highlighted the need for a clearer definition of agreed terminology, as well as a need for metrology standards.

Several stakeholders took this further, suggesting that technical standards should eventually lead to the development of a synthetic biology 'toolkit': a set of well understood and highly studied biological components. This would require first supporting basic research to create an open-source set of biological components that are very well understood and could form the basis for further basic and applied research. Also, interviewees felt that such a toolkit would not be developed, unless it was championed (and financially supported) by government.

There was also widespread agreement that there is considerable frustration around collaboration, interoperability, and replicability between laboratories. Many suggested a more defined set of standards around experimental protocols could help to promote cooperation and partnership and reduce this frustration.

To provide an overview of the key considerations across the different types of standards discussed in this section, a summary is highlighted in the table below.

Table 8: Considerations for standards making, by key area of standards need

Standard areas	Summary of key considerations for standards needs
All standards	• There is still dispute over the extent to which synthetic biology as a sector is ready to begin developing widespread standards. • Understanding of common but differentiated needs of different applications.
Application standards	• NQI should support the industry in engaging with existing standards and regulations. • These standards should help to build consumer confidence and trust in synthetic biology.
Technical standards for biological components	• This type of standardisation requires a considerable programme of funding across basic research as well as a regular standard making process of building consensus amongst stakeholders.
Standards for experimental procedure	• The development of standards should focus most on areas that assist in reproducibility, interoperability between labs.

5.6. Quantum computing

Technology / Commercial Readiness	• Technology still being developed (5-10 years to widespread use) and dominant variety remains open • Emerging sector comprised of start-ups (including university spinouts) and multi-nationals worldwide • A few early adopters among end-users • Significant investor interest
Current standards landscape	• Currently USA and China are active in developing national standards, but UK prominence in QC offers opportunity to be at the forefront of standard setting internationally • NPL experts represent UK on ISO/IEC joint WG on QC • Very limited involvement of UK SMEs

Functions	Activities to date	Activities required
Codifying knowledge	• Some work underway at international level to define terminology & vocabulary – to aid collaboration within the industry and for clearer communication with investors	• Nothing additional – but could consider ways to facilitate UK SME role in international activities
Reducing variety of options	• None yet – and too soon as the most appropriate / effective QC technology is still open	• None yet
Defining minimum quality levels	• None yet - and some resistance to this among innovators at this early-stage of development	• None yet, though benchmarking standards are in development at ISO & IEEE
Supporting interoperability	• None yet	• Required for interoperability for QC components (near-term need), QC-QC interoperability (less immediate need) and possibly eventually, interoperability of QC to current ICT technologies

5.6.1. Introduction to the emerging technology

Quantum computing is an emerging type of computation that harnesses the properties of quantum physics to perform calculations. This provides new and powerful methods of solving problems or tackling large scale challenges that would be difficult for conventional computers. Eventually, quantum computers are expected to lead a disruptive transformation of society, intensified when combined with other technologies such as artificial intelligence. Quantum computers may be able to solve certain problems that no conventional computing could solve in any feasible amount of time, which is the “quantum supremacy” but is more commonly known now as demonstrating “quantum advantage”.

There are several types of quantum computers that utilise different technologies and systems[87] to create and manipulate the quantum bit (or qubit) – somewhat analogous to the bit in conventional computing. As it stands, it is not clear which of these technologies or systems will emerge as the dominant design. One of the great technological challenges will be the development of robust (error-corrected) logical qubits and scalable quantum computers, algorithms and practical programmes.

A quantum computing system is comprised of a huge number of different components, including a core “quantum” component (e.g. a microfabricated chip) embedded within a full system of read-out and control electronics, vacuum chambers, cryogenics, packaging etc. As a result, the development and application of standards for quantum computing in practicality is not straightforward.

Whilst significant strides have been made in the development of quantum computers in recent years, the technologies are still at various early stages of maturity. Today’s quantum computers are mainly technology demonstrators and will still be 5-10+ years before the first quantum computers are suitable for widespread commercial exploitation.[88]

Though quantum computing is still relatively immature, there are other areas of quantum enabled technologies which are more near term, from which capabilities and lessons can be drawn. For example, linked to quantum computing is quantum communications which includes Quantum Key Distribution (QKD), which already has established standards with a strong UK input from NPL, Toshiba and academic researchers. For this reason, some aspects of this case relate to quantum technologies as a whole or other parallel quantum enabled technologies, where appropriate to innovation and standardisation in quantum computing.

Despite the relative infancy of the technology, quantum computing, and quantum technologies more broadly, are a key priority for government investment – best demonstrated by its prominence in the 2021 Innovation Strategy which highlighted quantum technologies as an area of strength and future investment for the UK.[89] Recent demonstrations of “quantum advantage”, although not addressing a high value problem as yet, have increased credibility and stimulated the development of the emerging ecosystem. The quantum technologies sector

[87] Such as superconducting loops, optical qubits, neutral atom qubits, ion traps, silicon spin qubit, diamond vacancies, topological qubits
[88] https://epsrc.ukri.org/newsevents/pubs/quantumtechroadmap/
[89] www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it

in the UK is still small at the moment, currently the emerging sector in the UK is estimated to consist of only ~300 business (excluding end-users).[90] This consists of a large number of SMEs as well as an emerging specialised supply chain. In the case of quantum computing, we also see large enterprises such as Google, IBM, Amazon, Microsoft, and Huawei etc also investing heavily and seeing quantum computing as an integral part of their technology roadmaps.

5.6.2. Standards and the standardisation landscape

Interest in and conversations around the needs for standards in quantum computing are relatively recent. However, some key developments in multinational companies and increasing competition between companies and nations, in addition to the media attention around quantum, has now catalysed conversations in a range of standards developing organisations to begin exploring needs.

International

All major international standards developing organisations (SDO) have established study or advisory groups to better understand their role in the future of quantum computing, some of which have resulted in further work towards formal standards. Though there is currently a degree of overlap between some strands of activity, interviewees expected the outputs to be largely complementary. Furthermore, these overlaps are not unexpected whilst the committees get established and before the foundational components are finalised. Whilst there is potentially a risk for SDOs to work in silos, many have successfully worked in collaboration and harmony and are aware of wider developments such to avoid duplication of work.

The International Electrotechnical Commission (IEC) and ISO established a joint working group for quantum computing in June 2020 (ISO/IEC JTC1/WG14).[91] The current key areas of work include:

- Developing the ISO/IEC AWI 4879[92] Quantum computing – Terminology and vocabulary, specification of the terms and vocabularies commonly used in quantum computing, is expected to be published in May 2022.
- A new Technical Report project, launched in September 2021 to provide an introduction to Quantum Computing and related technologies, applications, industrial chain and standardisation activities'.

[90] Technopolis (2021) ISCF Commercialising Quantum Technologies Evaluation Baseline Report
[91] https://jtc1info.org/technology/working-groups/quantum-computing/
[92] www.iso.org/standard/80432.html

There are also two other IEC standards in development that are linked to quantum communications:

- ISO/IEC CD 23837-1.2 ‘Information technology security techniques — Security requirements, test and evaluation methods for quantum key distribution — Part 1: Requirements‘
- ISO/IEC CD 23837-2.2 ‘Information technology security techniques — Security requirements, test and evaluation methods for quantum key distribution — Part 2: Evaluation and testing methods’

The Institute of Electrical and Electronics Engineers (IEEE) currently has four standards development efforts in place in relation to quantum computing. This work is led by the Quantum Computing Benchmarking Working Group (QCB-WG) and the

Quantum Algorithm Design and Development Working Group (QuADD/WG). This work is largely driven by the US quantum computing industry and is therefore more focussed on computing based on quantum annealing than in other international efforts:

- P1913-Software-Defined Quantum Communications
- P7130-Standard for Quantum Technologies Definitions
- P7131-Standard for Quantum Computing Performance Metrics and Performance Benchmarking
- P2995- Trial-Use Standard for a Quantum Algorithm Design and Development

The International Telecommunication Union (ITU) has touched on QKD as part of study groups 13 (Future Networks) and 17 (Security), and the ITU-T Focus Group on Quantum Information Technology for Networks’ (FG-QIT4N). This focus group which came to a close in 2021, conducted exploratory ‘pre-standardisation’ studies to identify emerging standardisation demands and anticipate demands in view of their foreseen applications in ICT networks. To continue on from the work of the focus group, the ITU-T, in collaboration with the IEC, IEEE UK and Ireland Photonics Chapter, organised a Joint Symposium on Standards for Quantum Technologies (March 2021).[93] The workshop aimed to establish an opinion on the appropriate shape of a ‘standardization roadmap’ for quantum information technologies.

In April 2020, CEN/CENELEC set up a Focus Group on Quantum Technologies (DIN secretariat) and includes three representatives from the UK (NPL). The aim of the group is to develop a roadmap for standardisation and will ensure interaction between stakeholders interested in identifying standardisation needs in the field of Quantum Technologies and recommend further actions to ensure that standards support the deployment of such technologies in industry.[94] The focus group will not develop standardisation deliverables. The Focus Group mirrors the €1bn EU Quantum Technology Flagship, launched in 2018 to support research and innovation projects.

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93 www.itu.int/en/ITU-T/Workshops-and-Seminars/2021/0323/Pages/default.aspx
94 www.cencenelec.eu/news/articles/Pages/AR-2020-015.aspx

Under EURAMET, a group of European National Metrology Institutes (NMIs) and Designated Institutes (DIs) have recently created a European Metrology Network for Quantum Technologies (EMN-Q). The objective of EMN-Q is to coordinate activities of the European NMIs and DIs, develop new measurement capabilities and dedicated services to serve the needs of industry and research institutions in quantum technologies in synergy with the EC Quantum Flagship and national quantum technologies programmes.

The European Telecommunications Standards Institute (ETSI) is working on quantum through the Quantum Safe Cryptography Working Group and the Quantum Key Distribution (QKD) Industry Specification Group (ETSI ISG in QKD). The ISG in QKD, which includes NPL representatives, is working on various specifications relating to the architecture, interfaces, characterisation and protection of QKD to enable interoperability of quantum communication networks and thus far has published 10 standards.

The European Quantum Industry Consortium (QuIC), founded in 2021, has more than 135 members from across Europe (including the UK) spanning quantum technologies. The association has an objective to be involved in the standardisation process, defining QuIC member needs and collaborating with standardisation bodies and policy makers.

China and the USA are also very active in developing standards, each of which have a number of national development activities and groups, reflecting their leadership in development of quantum technologies.

The USA is probably most advanced in terms of considering / developing standards for quantum, with groups convening to discuss – but this is still early stage. NIST are very active, with a particular focus on quantum-safe cryptography (QSC) and existing standards in cryptography. In 2018, NIST launched the Quantum Economic Development Consortium (QED-C), a consortium of stakeholders that aims to enable and grow the U.S. quantum industry in computing, communications and sensing.[95] QED-C has a Technical Advisory Committee focused for Standards and Performance Metrics Technical Advisory Committee and has been contributing to the development of performance benchmark programs.

In November 2021, the UK and the USA signed a new joint statement of intent to strengthen collaboration in the area of quantum science and technologies.[96] The agreement also seeks to grow the long-standing partnership between the National Physical Laboratory and the National Institute of Standards and Technology through alignment of projects and the exchange of staff and students in key areas, including quantum metrology, computing, clocks and future technical standards.

China is another country with many standards development activities in relation to quantum technologies and quantum computing, primarily led by the China Electronics Standardisation Institute (CESI).[97]

95 https://quantumconsortium.org/
96 www.gov.uk/government/news/new-joint-statement-between-uk-and-us-to-strengthen-quantum-collaboration
97 CESI also has convenorship over WG 14 of ISO/IEC JTC1.

The National Quantum Computing and Measurement Standardisation Technical Committee (SAC/578), established in January 2019, are working on developing their own national standard for "Quantum Computing Terms and Definitions".[98] Launched in March 2021, this activity aims to establish a conceptual system for the core terms and frequently-used terms in the field of quantum computing, clarify term definitions, and fill the gaps in standards in this field.

National

The prominence of the UK in quantum technologies in general presents an opportunity for the UK to be at the forefront of standard setting dialogue and process. To date, the national activities in standardisation for quantum computing has been early discussions and coordination with some specific projects. Notably though, these discussions and groups often extend beyond quantum computing to include a range of quantum technologies.

Many of these activities fall under the umbrella of the UK National Quantum Technology Programme (NQTP)[99]. Launched in 2013, the programme has been supported by over £500m of government investment to aid the development and commercialisation of quantum technologies.[100] The new strategy for Phase 2 of NQTP (2020) recognises the need for standards and sets an objective to “Strengthen engagement in international standards and benchmarking; develop testing and evaluation capabilities to support market growth”.[101]

Within the strategy, this primarily refers to the activities of NPL’s Quantum Metrology Institute (QMI) to provide expertise and facilities to test, validate and ultimately commercialise new quantum research and technologies. More widely, NPL have been heavily involved in international standards development activities around quantum technologies through engagement with ISO, IEC, ITU, ETSI, and cross technology groups such as CEN/CENELEC, as well as the international metrology community in groups such as the European Metrology Network for Quantum Technologies.

The Industrial Strategy Challenge Fund for Commercialising Quantum Technologies also supports a couple of projects that are exploring standards (e.g., NISQ.OS and ORNG). NPL has been a key partner for these ISCF projects.

The new National Quantum Computing Centre (NQCC) has developed a technology roadmap to deliver an early-stage quantum computer (a Noisy Intermediate Scale Quantum, NISQ machine) by 2025. The technology roadmap to achieve this goal includes determining technical performance specifications, for both hardware and software, related to emerging quantum processors. This work involved appraising existing and new metrics for measuring performance of quantum processors.

[98] https://en.tc578.org/portal/article/index/cid/1/id/113.html
[99] https://uknqt.ukri.org/
[100] The first phase of NQTP was allocated £270m for 2013-2017 and the second phase was allocated £235bn 2019-2024.
[101] https://uknqt.ukri.org/files/strategicintent2020/

In 2021 BSI (with support from NPL) launched a new panel to bring together interested parties from across the UK quantum technology landscape, to review and feed into current international standards activity, and to begin to identify UK priorities for new standards work (ICT/1/1/2).[102] The intention is to start this panel with a single group across the whole of the quantum technology landscape (sensors, timing, imaging, communications, computing) – but as the work develops, subgroups may be formed. To date, most panel members are from SMEs and research bodies. This panel will provide feedback on draft documents being considered by various international standards organisations, coordinate a UK approach to feed into international standards development programmes and guide priority setting for standards for the UK. BSI have actively engaged Innovate UK in the area of quantum technologies and will benefit from their support in identifying relevant innovative organisations and convening support for this panel.

BSI will run workshops in collaboration with NPL in the coming year with key actors from the quantum technologies landscape to identify UK needs and interests in relation to standards, starting with engaging with the EPSRC Quantum Technology Hubs.

The emergence of quantum computing is still technology driven and therefore many of these activities are supported by BEIS funding. Though DCMS have referred to quantum computing in their Top 10 Tech Priorities[103], quantum computing is still some way off a level of maturity at which it will be incorporated into the wider ICT infrastructure.

5.6.3. Experiences of innovators

The conclusions presented below are drawn from interviews with 10 representatives working in the area of quantum computing in the UK. This includes companies working to develop hardware, software or both for quantum computing. For most companies, quantum computing was the sole area of business, though some were also working in other quantum technology enabled fields. Most companies were SMEs, with some exceptions, and most had not yet commercialised their quantum computing technologies.

Use of standards

Overall, the majority of small innovative companies focussed on quantum computing interviewed were not aware of the existing standards, standards organisations or standards development processes. The exception being those large organisations with existing positions on relevant working groups or focus groups (e.g. Microsoft or IBM).

Notably, interviewees did not refer to other existing standards with implications for product development (even when asked directly), such as ISO 9001, CE Marking or EMC Compliance. As a couple of interviews with wider stakeholders noted, the majority of SMEs working in the field of quantum computing have emerged directly from either academia and/or experimental physics. As a result, knowledge and awareness of critical standards relating to product engineering and how they can and should be applied was limited.

[102] www.bsigroup.com/en-GB/industries-and-sectors/quantum-technology/
[103] https://dcms.shorthandstories.com/Our-Ten-Tech-Priorities/index.html

Involvement in the standardisation process

Industry involvement in the standards development processes seems to largely remain the remit of large multinational companies who are leading the commercial investment and development of quantum computers, and have sufficient experience and resources to lead and contribute to these standards development activities.

Interviewees did note however that there are exceptions to this, with a couple of key UK companies heavily involved in the standards development process (namely Riverlane and ORCA Computing[104]). Organisations are also participating in informal standards development processes through participation in wider discussions and research collaborations, e.g., through participation in Innovate UK projects or collaboration with UK Quantum Technology Hub in Computing and Simulation, NPL or Fraunhofer.

Interviewees agreed that the needs for standards in quantum computing would emerge from industry. To support this, BSI have established the panel for quantum technologies. For BSI, the majority of participants on the new quantum technologies panel are new to the standards development process, so there has also been a process of improving understanding and awareness in general. To support this, BSI have brought in experts from parallel technology areas who do have experience of standards development.

Overall, most interviewees were still interested in being part of the conversations around standards development, however they were often not aware of which organisations or individuals would be appropriate to get further information from. A couple of interviewees felt their companies were too small to be involved in the standards development process and didn’t have the resources (time) to commit to the process.

5.6.4. Needs, issues and barriers

Overall, the view of interviewees was that quantum computing is still in its infancy in many ways and therefore it was too early to think about standards meaningfully. As the systems and technologies are still under development and new systems are still emerging, there is a strong aversion to implementing standards pre-emptively. Similarly, programming language and software platforms are largely expected to be developed and provided on an open-source basis until such a time when then hardware becomes firmer.

It might be that a standard could define the capability of quantum computers through its characteristics (e.g., number of qubits, gate fidelity, connectivity/coupling, speed, etc.), however independently, each of these characteristics are meaningless and are not indicators of the success of the system. Therefore, there is limited use in defining separate standards. Instead, all of these parameters need to be taken collectively and combined with the contextual factors (e.g., application, integration, manufacturability, software) before one is in a position to understand (let alone quantify) the value of a system or product to end-users. Some measures such as quantum volume do combine different parameters into a single measure, however this was still thought by interviewees to be flawed and not provide an accurate view of which

[104] Both companies were approached for interview but were unavailable

platforms were leading or useful. These challenges and questions are the primary drivers of the NQCC commissioned project to appraise existing and new metrics for measuring performance of quantum processors.

However, there are some areas where innovators would benefit from standards. Many interviewees expressed a need and interest in shared definitions for quantum computing and its requisite components. These definitions would support further collaboration within the industry as well as supporting clearer communications with investors. however, there was also the view that these definitions should still maintain a degree of flexibility and openness, so as not to limit any emergent innovations.

A couple of interviewees noted that in the initial stages of adoption, quantum computing will likely be embedded within or used in partnership/parallel with conventional supercomputing. As a result, standards around interoperability will also be necessary at the point when this is adopted.

Where the hardware for quantum computers depends on very specific environmental characteristics, innovators also expressed interest in standards and measurements relating to the performance benchmarks for the equipment and infrastructure that support quantum computing (e.g., vibration, vacuum, cryogenics, electromagnetic interference, which materials are appropriate for use in these environments). Therefore, there is perhaps a need for more clarity and discussion around where standards need to be applied to “classical” components and software to enable interoperability between sub-systems from many different suppliers.

Though innovators interviewed did not specifically highlight any technical standards needed, there may be a need within the (academic) research community. As the scale of quantum research within universities grows, so too does the need for standards for quantum specific lab equipment and subsystems to the benefit of both researchers and suppliers. According to the IEEE, this would include standards for products such as cryogenic refrigerators, “chandeliers,” microwave amplifiers, and software, to ensure combability.[105]

As the technology for quantum computing is still open and in many ways exploratory, there is a risk that where technology areas develop in silos, the standardisation process struggles to engage with sufficient breadth of subject matter experts. Therefore, there is a need to bring together a large team of experts to provide a broader picture of the technology landscape (and therefore standards needs). The current processes (employed by BSI/NPL and ISO) were viewed as sufficient for identifying and addressing these gaps.

In the longer-term however, there is no single organisation or contact point that brings together companies working in the field of quantum computing (or quantum technologies more widely). The NQTP provides a valuable overarching umbrella to support coordination between the various research and industry efforts, as well as the work around metrology under the Quantum Metrology Institute (QMI). NPL provides regular updates to the programme board on standards related activity, however it is not immediately clear how the programme is bringing together these various activities and providing a single touchpoint/ access point for

[105] https://quantum.ieee.org/images/files/pdf/ieee-support-for-standards.pdf

coordination with the standards development process. In the interim, BSI are coordinating with NPL and the EPSRC Hubs. A new industry group, UK Quantum[106], is currently being established and has a mission to represent and champion the UK quantum industry nationally and internationally. As of December 2021, the group has an executive committee of 11 members (three of whom are quantum computing companies) and will be opening up to wider membership. The intention is for NPL to report the work of the BSI committee, and for BSI to work collaboratively and actively liaise with the group, to ensure that industry is engaged.

The 2016 Blackett review set out that core components to supporting the emergence and commercialisation of quantum technologies are i) commissioning pilot projects to deploy emerging technologies, ii) funding applied research to address standardisation problems and iii) considering funding participation in standardisation bodies.[107] The various programmes and activities under the NQTP address the first two recommendations, however the final recommendation appears not currently to be addressed for industry participation, although NPL is representing the UK in many standards organisations.

[106] www.ukquantum.org/
[107] www.gov.uk/government/publications/quantum-technologies-blackett-review

Appendix A: Literature Review References

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