Accelerating Standards Readiness for Quantum Technology and other Critical and Emerging Technologies

Report and Recommendations

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Executive Summary

This report explores quantum technology – identified as a critical and emerging technology (CET) by the National Institute of Standards and Technology (NIST) – as it relates to the standardization process. As this is a nascent technology, much of the actual standardization work may take years to begin and complete. Subsequently, this report includes the following: a broad overview of standardization, with more focus given to the pre-standardization engagement process (PSEP); international and domestic work related to quantum technology; the significance of cost, capacity, and risk, and their impact on industry participation in standards; key themes gathered from stakeholder interviews; and recommendations focused on standards acceleration, addressing these areas of interest.

The background section highlights the standardization process, via the Standards Readiness Continuum (SRC), repurposed from a previous ANSI report, Enabling Standards Development Through Public-Private Partnerships (in that report, the Continuum was referred to as the "ANSI Notional Standards Readiness Phases"). The "Exploratory" phase is identified as the relevant standards readiness phase of the SRC, based on the current level of quantum technology maturity. Also introduced within this section is the potential role of the Advancing Standardization for Critical and Emerging Technologies Center of Excellence (ASCET CoE, formerly the NIST-funded Standardization Center of Excellence), and its PSEP. Both references are thus used to define the focus of the standardization process and place it within the context of developments in quantum technology and other CETs. This section also establishes ANSI's relevance and unique positioning within this domain.

Following this, international and domestic bodies of work are introduced, comprising various sectors. At the highest level is the Joint Technical Committee, IEC/ISO JTC3 - Quantum Technology; on the next level are measurement institutes, both International and National Measurement Institutes, whose work directly supports research and development work pertaining to quantum technology (and, of course, other CETs). A few efforts related to advancing quantum technology are detailed, including the Quantum Economic Development Consortium (QED-C), the Quantum STrategic industry Alliance for Revolution (Q-STAR), as well relevant work carried out by the International Bureau of Weights and Measures (BIPM).

Factors that may prohibit both technological advancement and standards participation, including potential supply chain concerns, are introduced and discussed, placing particular focus on rare earth elements (REEs) as this class of materials is finding increasing usage in the development of quantum computing and supporting computer architecture.

As prefaced, stakeholder interviews were conducted to gain an understanding of the organizational structures and perspectives of industry representatives, standards development organizations (SDOs), and NIST – with the objective of identifying the relationship between the public and private sectors needed to foster collaboration and accelerate technological and standards readiness. Key themes are presented based on the topics discussed.

The report concludes with four recommendations, informed by the stakeholder interviews and placed in the broader context of current domestic and international affairs – acknowledging the current status of the technology and the current phase of standards readiness. The recommendations address the need for education to foster public understanding and support of quantum and other CETs; the need to facilitate wider discussions relating to standardization of enabling technologies; the potential to expand existing public-private partnerships; and policy supporting quantum and other CETs. The goal of these recommendations is to place an emphasis on greater collaboration between the standards and technical domains, and, of course, to bolster standards acceleration efforts, in the interest of national and economic security.

Background

Standards development is an ongoing and important process, intended to drive innovation, promote safety, and maintain security, which are crucial aspects of ANSI's mission:

> To enhance both the global competitiveness of U.S. business and the U.S. quality of life by promoting and facilitating voluntary consensus standards and conformity assessment systems, and safeguarding their integrity [1].

The pre-standardization engagement process (PSEP) is defined in this report by reference, both to the Standards Readiness Continuum (SRC) and framing outlined in materials developed by the *Advancing Standardization for Critical and Emerging Technologies* Center of Excellence (ASCET CoE).

The SRC outlines the overarching process, from pre-standardization to the implementation of a standard. Standards can be thought of as living documents, subject to revision over time, to maintain relevance and support innovation. As standards are implemented, conformity assessment processes are developed to ensure adherence to the relevant standards. As standards are voluntary, consensus-based, and market-driven, they may become mandatory only when referenced in law or included in government regulations, or related to employers who are using skills-based hiring.

	PRE-STANDARDIZATION		**STANDARDS DEVELOPMENT**		**IMPLEMENTATION**
	STANDARDS READINESS PHASES				
	PREMATURE	**EXPLORATORY**	**PLANNING**	**DEVELOPMENT**	**IMPLEMENTATION**
Standardization Activity	- No discussions or interest in standardization	- Identification & evaluation of existing related standards & conformity assessment programs of similar technologies - Benchmarking	- Landscape & gap analysis - Terminology development - Soliciting stakeholder engagement	- Standards committee(s) formed - Soliciting leadership and stakeholder engagement - Standards drafted, approved & maintained	- Standards approved, maintained & utilized - Conformity assessments - Referenced in law or regulation, as applicable
Information Sharing & Awareness	- Internal prototyping/research has begun - Stakeholders working independently - Consortia/Association discussions not taking place, or do not exist for a particular technology	- Collaborative research takes place - Like-minded stakeholders sharing minimal information - Consortia/Association discussions & evaluation begin	- Research is being strategized - Like-minded stakeholders collaborating & sharing minimal information more broadly - Consortia/Association position/issue papers developed	- Research is ongoing - Balanced representation of stakeholders collaborating - Stakeholders investing resources to draft & vote on standards - Consortia/Association recommendations issued	- Research is ongoing - Balanced representation of stakeholders collaborating & doing business - Stakeholders investing resources to draft & vote on standards - Consortia/Association advocating for standards adoption

The SRC explains the processes of *standardization activity* as well as *information sharing & awareness* as the standardization lifecycle matures. Material adopted from the *Enabling Standards Development Through Public-Private Partnerships* report, published by ANSI, originally labeled as "ANSI Notional Standards Readiness Phases" [2].

The ASCET CoE website lists seven main points under its definition of the PSEP: creating and maintaining standardization roadmaps; intentionality when convening groups; broad representation of those convened; information sharing; landscape assessment; engaging industry and other relevant stakeholders; and directing research to meet or anticipate a specific standardization goal. The use of this term can include more than these seven points, however, these have been explicitly outlined and should be viewed as necessary for an appropriate PSEP [3].

All of these points are important and should converge upon one another; individual *silos* of work are counterproductive to the overarching process, and create the potential for duplication of work. Throughout the process, it's especially crucial to secure broad representation among those convened when seeking input from industry partners and SDOs, as well as those in academia and government. Groups composed of stakeholders, representative of the greater population, meet the necessary qualities of openness, coordination, harmonization, and consideration of views and objections; all of which are part of ANSI's *Essential Requirements for Due Process* [4]. The ASCET CoE has the potential to facilitate this representation and successfully realize this convergence across industry.

At the time of writing, quantum technology was still in the "Exploratory" phase of the SRC; there were ongoing initiatives to develop metrics and benchmarks to quantify performance, both domestically and internationally, along with industry and government research into the technology. In the U.S., the National Quantum Initiative (NQI) was created to boost research and development related to quantum technology and quantum information science (QIS), through the National Quantum Initiative Act. The program aims to develop the technology to promote U.S. economic and national security. Additionally, NIST has two laboratory divisions whose research is directly related to the technology, the Quantum Measurement Division (N-QMD) and Quantum Sensors Division (N-QSD). The former of the NIST divisions aims to explore and better understand the future capabilities of quantum technologies, specifically the ability to measure, compute, and simulate. Additionally, N-QMD seeks to create accurate, precise measurement tools "beyond the standard quantum limit" [5]. This work is supported by the Sensors Division, whose efforts focus on developing advanced cryogenics to support quantum electronics and measurement devices for materials analysis. The goal of N-QSD's work is to "support U.S. industries that develop or use cryogenics, quantum sensors, and quantum computing" [6].

ANSI is uniquely positioned, not only in standardization, but also in the PSEP, to coordinate with industry partners, SDOs, and government agencies to accelerate standards readiness. Convening these stakeholder groups to prioritize, develop and revise standards promotes U.S. leadership in the standards realm and beyond, an essential component in driving U.S. dominance on the global stage – crucially, as the convergence of quantum technology and other CETs becomes more apparent. Importantly, ANSI represents the U.S. internationally to the International Organization for Standardization (ISO) and (via the U.S. National Committee; USNC) the International Electrotechnical Commission (IEC). This is especially relevant as both the U.S. and E.U. (among other nations) seek to be the de facto authority, in light of the European Commission announcing initiatives to "make Europe the 'quantum continent'" [7]. ANSI Government Affairs staff are critical for understanding and supporting relevant federal policy, vitally bridging the gap between the public and private sectors. This work, alongside the educational resources ANSI provides, is essential for helping U.S. leadership drive innovation in both the technology and standards spaces, especially if the U.S. wishes to achieve and maintain technological prowess across the convergence of quantum and other CETs.

International and Domestic Efforts

In the international measurement sphere, the International Bureau of Weights and Measures (BIPM) initiated early workshops, aimed at fostering the adoption of quantum technologies, with a focus on measurements and standards – similar in nature to the work done by NIST in its role as the U.S. National Measurement Institute. The BIPM workshops were intended to facilitate information sharing, collaboration, and formulate a strategy and framework for the quantum initiative, aimed at garnering industry engagement [8]. These efforts have been proclaimed further, with BIPM naming 2025 as the International Year of Quantum Science and Technology, seeking to revolutionize the technology and create a chain-reaction of community embrace for quantum [9]. Similarly, Japan established the *Quantum STrategic industry Alliance for Revolution* (Q-STAR) in 2022, intended to facilitate the creation of quantum-related industries and businesses – an overview of their activities is provided below:

1	**Investigate and research trends in quantum technology** Investigate and research general trends in quantum technology and share information among top management within industry
2	**Investigate, research, and propose industrial applications of quantum technology** Investigate and research applicability in multiple fields
3	**Investigate and examine quantum-related technologies** Investigate, examine and share information on materials and devices required for quantum technology
4	**Investigate, plan and make proposals for required human resources** Investigate, plan, make proposals and exchange opinions on how to develop the human resources needed to make full use of quantum technology
5	**Investigate and examine systems and rules** Investigate and examine necessary information on intellectual property and standardization, ethics and trust required for the implementation of quantum technology
6	**Collaborate with quantum-related organizations in Japan and overseas** Cooperate with other organizations, both domestic and overseas, working in quantum-related areas in order to promote Q-STAR's objectives
7	**Other** Raise public awareness, make policy recommendations, etc.

Source: Q-STAR [10].

Q-STAR's activities are similar in nature to processes outlined in the SRC, with the notable exception of being a top-down approach. Japan, like most of the world, follows a top-down approach in the standardization process, wherein standardization is a high-level process. The U.S. follows a bottom-up approach instead, which facilitates input from many entities. Written testimony to the Research Subcommittee of the House Committee on Science, Space, and Technology, authored on behalf of ANSI explains this difference:

> Many countries use a top-down standardization system, meaning that a single government agency drives the standards and conformance activities that will govern its products, systems, and services. In contrast, the U.S. system is bottom-up. The views of all directly and materially interested parties, in both the public and private sectors, are considered through an open, balanced, and consensus-based process [11].

A top-down system does not necessarily facilitate input from product developers; instead, the system creates technologies and products based on the standards developed by the individual government agency. The bottom-up system, in contrast, actively facilitates input from many parties, including product developers, writing standards based on the existing technologies and products. This is important within the field of quantum technology, where American corporations have made broad strides in quantum computing (QC) and post-quantum cryptography (PQC). For example, HP is developing printers with encryption schemes resilient enough to resist PQC-based attacks. Earlier this year, Microsoft developed the first topological quantum process, Majorana 1 – one of a few different types of quantum computing being researched and developed.

In the quantum technology space, efforts to impose sweeping standards or regulations would be premature at best, and, at worst, potentially devastating to the progress made thus far. The initial AI boom has many lessons to offer, both good and bad. Certainly, AI has the potential to transform many sectors, but the technology is still young and needs to be refined. Often, human oversight is critical in ensuring the validity of the results. Criticism over attempts to regulate the technology, as seen with the EU's AI Act, suggests that premature regulations are more a of a hindrance than a helper – even with the best intentions, as it sought to protect consumers [12]–[14]. Still, good regulations – just as with good standards – should be designed with a market-informed and validated perspective, and consumers should be kept mind throughout the process. The need for, and perceived effectiveness of standards and regulations must be identified and reaffirmed throughout the process, or else they may become irrelevant and outdated.

Factors Affecting Participation – Cost, Capacity, and Risk

Even if standardization of the bleeding edge of quantum technology is premature, standardizing the enabling technologies that support the research and development of larger systems may help reduce certain technical barriers, driving down costs, increasing capacity, and mitigating the associated risks. As applications of quantum technology are incipient, much of the infrastructure and hardware are proprietary, which understandably increases the cost to manufacture a single piece needed to develop quantum computing infrastructure (e.g., a sensor), much less multiple orders of magnitude more. This becomes especially problematic when current market offerings of certain enabling technologies may not be standardized or of a high enough quality. This may result in procurement staff resorting to parts of lower quality or reduced performance with larger production volumes, that they then must modify, either internally or by outsourcing the work. Regardless of who completes the work, this process is expensive to do once, let alone at the scale needed to reasonably work on developing quantum computers. As industry professionals seek to scale up and improve upon the technology, the smaller capacity of these bespoke items hinders cost-effectiveness and adds pressure to the already constrained supply chains. Standardization of these enabling technologies may increase the supply chain pool, allowing procurement specialists to source from a variety of vendors. Aside from a lack of standards, external pressures and trade conflicts can strain the supply chain, increasing risk, which may impact funding and support from smaller private entities.

One example of a research area where supply chain constraints are an issue at present relates to the use of magnets in quantum computing, particularly with information storage and processing. Though there are several different magnetic materials, some of the strongest magnets are composed of Rare Earth Metals (REMs). One research experiment focused on applying quantum theory to facilitate qubit coupling (an essential, but tricky process needed for quantum computers to operate) utilized REMs such as yttrium (Y, element 39) and gadolinium (Gd, element 64). In this experiment, gadolinium wasn't used as a magnet, but as a substrate used to help stabilize and support the yttrium-based magnetic film, as the film was 3 μm thick and the gadolinium-based substrate was 500 μm thick [15]. To illustrate this, a *single* red blood cell is roughly 7-8 μm, and a single piece of paper is about 100 μm – almost half the size of a red blood cell and close to five sheets of paper thick [16], [17]. While the experimental setup is very thin, and the technology may change rapidly over the next few years, attempting to scale this technology may require a large volume of REMs – which China possesses, having exported close to 300,000 tons of neodymium magnets (another REM) [18].

In 2023, it was estimated that China has close to 70% of the global Rare Earth production, with the U.S. making up only 12% of that total. Despite the U.S. having some production capacity, China is said to have 100% production of Heavy Rare Earth Metals (HREMs), which includes yttrium and dysprosium (Dy, element 66; another element used in magnets) [19], [20]. Neodymium (Nd, element 60) and Samarium (Sm, element 62) are considered Light Rare Earth Metals (LREMs), and are also used in magnets – China has a large supply of both. In addition to having a sizeable share of global REMs, and the entirety of HREM production capacity, China has also imposed export restrictions on seven REMs: **samarium**, **gadolinium**, terbium, **dysprosium**, lutetium, scandium, and **yttrium**, as of April 4, 2025 (per the Center for Strategic & International Studies) [18]. According to that article, the new restrictions require entities to apply for an export license, with some U.S. companies being placed on an export control list. After this licensing system was introduced, exports drastically decreased, according to a June 2025 *Wall Street Journal* article:

> Total export volumes of rare-earth magnets from China fell 74% in May from a year earlier… 1.2 million kilograms of rare-earth magnets exported in May marked the lowest level since February 2020, during the Covid pandemic [21].

As of June 2025, China reportedly approved several U.S. firms to hold export licenses for REMs, however, their commerce ministry "declined to give further details such as the exact amount and how many had been extended to U.S. firms" [22]. Depending on the type of quantum computing researched, and the materials needed, the import restrictions could be a potential bottleneck for researchers, although there have been efforts in recent years to ramp up production of REMs in the U.S., most notably from DOD funding in 2021 and 2022, provided to Lynas Rare Earths to process LREMs and HREMs, with contract amounts totaling $30 million and $120 million, respectively [23]. According to that C&EN article, the DOD is looking to continue its efforts to rely less on China for its REM supply chain, with a reported $400 million investment (including a 15% stake) in MP Materials, a California-based company. The article reports that MP Materials intends to begin production of RE magnets in 2028, just two years after Lynas Rare Earths is projected to begin separating HREMs in the U.S. – noting that the latter company "has started producing heavy rare earth oxides at a plant in Malaysia" – which is intended to bolster U.S. supply chains of REMs, relieving the pressure China has on the U.S. with its heightened exports control. In a July 2025 Project Blue report, referenced in the article, analysts believe this could be the impetus needed to spur a new global rare earth industry, not dominated by China [24]. Magnets are, of course, only one of many material components used to research and develop quantum computers that have direct potential supply chain constraints, highlighting just one of the many risks associated with early investments in quantum technology. Aside from magnets, REs may be used to develop optical memory for quantum computers, which provides another potential need to source and produce RE products en masse domestically [25]. This, of course, depends on future implementations of memory for quantum computers, and what the eventual state-of-the-art systems use, although it's likely a safe bet that RE products will be used in some capacity. The considerations are important and necessary for current and future discussions, and may be relevant to the impact enabling technologies have on the ability to research and develop quantum technology.

Stakeholder Interviews – Topics and Key Takeaways

Representatives of various relevant organizations were interviewed to gain insight into the different practices and perspectives within the standards world. These discussions were intended to supplement the information synthesized from internet research. These representatives comprise industry, SDOs, and government agencies. Included in these three groups were representatives from ASTM, IEEE, NIST, HP, QED-C, and JTC 3 [26]–[31]. Several topics were discussed throughout the interviews, with the goal of guiding standards acceleration efforts: the standardization process generally, with focus on pre-standardization; determining standards readiness and what constitutes a quality standard; the role of the public sector and its relationship with the private sector; building up workforce capacity for standardization efforts; considerations for creating national or international standards; and, most importantly, the future of the sector and standards.

Each group has a different role in general standardization, especially with respect to the pre-standardization engagement process. SDOs have slightly different processes across organizations, although they share some similarities. A proposal identifying the need for a new standard is typically submitted, which is the first step in the process. Depending on the SDO, there may be more intricacies such as requiring internal sponsorship for that proposal to be reviewed by an internal standards board, before advancing. In other processes, a three-stage approach may be followed, that includes exploration, planning, and organization; a project can be stopped at any part of the process, regardless of progress. Accordingly, there are no commitments to follow through with a project, even if it advances to any subsequent stage, which can mitigate the cost of time and resources invested into a project if it isn't viable. This proposal process should identify a clear industry need, as well as the scope and type of standard the project seeks to create (e.g., test methods). In both cases, once greenlit, Working Groups (WGs) comprising experts from various fields are created to author a draft of the standard. Drafts are circulated internally and must meet a minimum consensus requirement to then open the draft up to public comment, typically comprised of other stakeholders. Before the standard is sent out for public comments, further validation of the proposed standard should be conducted. When the standard is sent out for public comments, all comments must be addressed by the working group, though there is no obligation to accept any or all critiques, based on the feasibility of implementing changes or the need of the standard. NIST may have several few roles in support of standardization, which comprise the following:

> Assisting U.S. industry in evaluating whether and how to get started in a new technical committee; taking a leadership role in a CET field to ensure access to information and input in developing the standards for these industries; developing a measurement method to enable the development of a standard; contributing to the conceptual and measurement science as it pertains to a CET; and working with industry to relate measurement results to actual performance in products based on technological innovation.

The above quote block was referenced directly from communications with NIST. These support roles reaffirm the clear need for consensus, as objective, scientific support helps to facilitate discussion and support the requirements within a standard. Subsequently, as consensus is an important tenet of the process, voting rights must be delegated accordingly to allow interested members who wish to participate the ability to do so. Again, the exact process may differ between SDOs, but in some cases, voting rights are conferred initially upon the first meeting for a new project, although stakeholders who join later in the cycle can earn voting rights through active and consistent participation in meetings. If an entity wants a standard developed, then the voting changes slightly, so each entity has one vote, rather than each individual working on the development. While the SDOs spearhead development, industry and corporate entities may offer contributions to the process, and will work with competitors toward the development of a standard. In the interest of protecting a company's IP, competitors working together often bring their "pre-competitive" IP to the table, which is to say that they work to ensure interoperability and certain baseline metrics to be included in the standard's requirements. This facilitates future competition, as companies can work to improve upon the baseline requirements by "accessorizing" their products to market them as more attractive options to consumers. Accordingly, a well-made standard is one that clearly identifies a need and serves a clear purpose, which is to benefit the consumer or end user – standards on products should spur innovation and market competition, which is why it's incredibly important to recognize when the time is right to standardize.

Determining standards readiness is crucial in achieving this goal and involves multiple considerations. For SDOs, there need to be enough technical experts supporting the body of work throughout the process and the technology itself must be capable of being standardized, or else any time spent drafting standards may be wasted if the technology changes rapidly or if the potential impacts of the technology are not well understood. These latter points must be considered, or else the drafted standards could risk stifling innovation and may be either too narrow or too ambitious in scope. Additionally, if the technology doesn't deliver the desired results or products, then standardization doesn't serve a purpose because both the technology and standard won't be utilized by industry or end users. The perspective offered by NIST echoes the approach taken by ASTM and IEEE – the current state of the technology must be well understood, even if the technology is nascent, and market-side and community readiness need to be gauged appropriately. Market-side readiness may be current or potential, which is an important element to consider; that is, the likelihood of a technology changing rapidly in the short term can affect the ability to make informed predictions about the needs a standard should address, as these needs, and even the technology itself, can change greatly over this short period of time. The other important consideration is community readiness, pertaining to either consumers or end users, and interested stakeholders. Even with an existing, mature technology, standardization can't properly occur if there's no consumer or market interest, nor can it occur without the technical expertise required to support discussions and standard-writing.

Clarifying the role of the public and private sectors throughout this process enriches public knowledge and support in these efforts, and inherently delegates the responsibilities and oversight of each entity. The general position is that the private sector is meant to spearhead the work of researching and developing the technology as well as with standardization, once a technology is mature enough to be effectively standardized. This is readily apparent by current efforts from companies, like Microsoft, Google, HP, and IBM, among others. DARPA's Quantum Benchmarking Initiative (QBI) is a great current example of this, as companies like Hewlett Packard Enterprise (separate from HP) and IBM are currently participating, building upon DARPA's previous Underexplored Systems for Utility-Scale Quantum Computing (US2QC) program, in which Microsoft is a participant in the final phase of the program. According to *Quantum Computing Report*, QBI's third phase, Stage C, shares the same goals with the final phase of US2QC, "to verify and validate whether a company has developed an industrially useful quantum computer" [32]. On the public sector side, QBI is a great example of how a coordinated effort supported by the federal government can enable the private sector to innovate and develop new technologies. The strength of the program lies in its mission, which is to assess the viability of the technology at an industrial scale. This inherently focuses on demonstrating performance and value proposition, rather than requiring private sector to focus on achieving a specific desired outcome. Rewarding companies for their work in demonstrating market-scale viability incentivizes small and medium enterprises (SMEs) to contribute, despite the associated risks. Public-sector investments in the private sector intended to spur innovation, rather than fulfill a specific requirement, are preferred, according to the discussions held. Accordingly, there is consensus that this is the proper relationship between the public and private sectors: the latter spearheads research and innovation, while the former can provide various modes of support. Policymakers may be encouraged to create laws or acts, based on constituent support, that direct funds from the federal budget to support these fields in a few ways. Federal research funding is one such method of supporting the research and development of nascent technologies and bodies of knowledge, such as quantum technology, as academia has helped pioneer many discoveries – even unintended discoveries have led to new technologies or a better understanding of numerous fields. Supporting these efforts, NIST has a few responsibilities: helping with measurement sciences and documentation, providing training via the Standards Coordination Office for the U.S. Government, and offering informal consulting work. Their metrology work establishes a baseline for the private sector to work with, especially as future consortia are stood up and further discussions are held. Federal government technical experts can also play a role in technical committees, which may make it easier for the private sector to have a role in discussions and the development of the technology.

As quantum technology matures to the point that standardization is practical, industry experts with knowledge of standardization and standards-writing will be needed. Accordingly, the topic of building up workforce capacity regarding standards is top of mind for stakeholders. Each group is tackling this issue differently, with private corporations facilitating internal training systems in addition to talent acquisition efforts. SDOs like ASTM help by hosting workshops at conferences or hosting specific training conferences for professionals. Similarly, ANSI provides a range of training and education programs, including programs focused on participation in ISO and IEC. NIST, as previously mentioned, provides training through the Standards Coordination Office for employees within various government agencies, allowing many professionals and experts from many different organizations to apply and be selected for the training. All of these initiatives help train experts from various fields for standards, and these trainings should help when creating standards, as those participating in the process will have technical expertise as well as the ability to engage in standard writing, making the standards technically accurate and market-informed, and should make the overall process more efficient.

Discussions of strategy touched on the topic of developing standards for quantum technology as American National Standards (ANS) or international standards, which included the benefits and drawbacks of pursuing one route over the other. Domestically, the ANS designation is highly desirable and offers legitimacy to the developed standard, as it was developed in accordance with ANSI's Essential Requirements. However, developing a standard solely as an ANS may not be preferable for certain technological fields, such as AI, quantum technology, and other CETs, because of the impacts of the technologies, individually and collectively. On the international level, there may be pushback from other countries seeking to advance their own interests as well. Additionally, within working bodies like IEC/ISO JTC 3, it makes more sense to develop international standards first, rather than introduce a previously developed ANS (or another country's national standard), as there will likely be less pushback (conversely, the bar is much higher on the international level, which may be another source of resistance to an ANS). The magnitude of the converging technologies, as mentioned previously, is another important factor to consider, and supports the notion of prioritizing international collaboration and developing international standards. In lieu of this, a lot of the driving work can be shouldered by one national standards body, even on the international level, especially if that NSB has representation across many SCs and WGs, which can then strengthen discussions during National Committee meetings. The U.S., for example, has representation comprising physicists, industry professionals, academics, and scientists from National Laboratories, which ensures a voice in most projects within JTC 3, so there are myriad perspectives and sources of information to consider during National Committee meetings. Regardless, the work done internationally should be representative of all participating member-nations, and, more importantly, it should be industry-led; the SDOs shouldn't solely decide what is important, but rather those participating in standardization efforts (which will likely include industry) will make that decision. By and large, the most important aspect of international standards action is that the work is industry-led.

There is still a lot of work on the horizon for quantum technology (and other CETs), which includes both advancements for the technology – a necessary next step before broad standardization is practical – and potential paradigm shifts to current work methods. Moving forward, the project call process can be revised such that a new component of standards proposals is included, in which existing standards are identified that will support the work of a new standard being drafted. In addition, embedding standards-writers to help identify research that can help with creating new standards, updating existing standards, and supporting lagging standards in development should be factored into this process. Furthermore, a more consistent effort for the standards and the research and development communities to work in tandem, as much as is feasible, may prevent one process from lagging behind the other. In turn, this may help maintain or improve the pace of the R&D arm, particularly when focusing on enabling technologies and how they can accelerate that work.

Consequently, public understanding and support is crucial in this process, as lawmakers should be inclined to address the concerns of their constituents, and educating the public about the potential capabilities of quantum technology is an important body of work that needs to be addressed in conjunction with any technical and standards-related advancements made. Incidentally, the work of educating the public is highly time-sensitive and cannot be ignored, or quantum may repeat some of the same failures and mistakes of AI when it was first implemented; societal fears and misinformation should be addressed early. Generally, more discussions involving experts are needed, but these discussions should involve efforts to educate and include the public as much as possible. Future discussions should also determine what critical materials are needed for large-scale deployment, which will likely include REEs, based on the recent efforts in the U.S. to ramp up sourcing and production of REMs and RE products.

Recommendations

To reach these goals, a variety of short-term and long-term strategies should be developed. As discussed, public support is vital for this technology, so education and transparency are invaluable. In addition, executing the following would enhance current activities: facilitating discussions relating to standardization efforts for various enabling technologies; expanding upon existing SD-PPPs; industry efforts to enhance the standards community's preparedness; and supporting policy that could bolster standardization activities and provide more apparent leadership in America when the technology has matured enough to make standards activities feasible – maximizing the consumer and market benefits of standardizing the technology across all of its subcategories.

Recommendation 1: Increased Education and Transparency

The creation of a centralized information source explaining quantum technology could be implemented to support this broader goal. A "Quantum Technology 101" webpage could be developed with resources to facilitate learning. There should be multiple layers to the resources, intended to target and educate Americans broadly, meeting them where they are, and mitigating barriers to understanding, e.g., level of education, reading proficiency, or learning disabilities. In other words, such a resource should allow users to specify their highest level of education (e.g., no high school, some college (no degree), bachelor's degree, etc.), so the content can educate them at their level of knowledge on what quantum technology has the potential to achieve, compared to classical computing – meeting them where they are.

According to the Digest of Education Statistics, published in 2023 by the National Center for Education Statistics, 90.6% of Americans 18 and over had attained at least a high school diploma or equivalent (e.g., a GED), 61.8% had attended at least some college (though they did not necessarily earn a degree), and 35.4% had earned at least a Bachelor's degree [33]. The data suggest that, in 2023, the median American adult had earned a high school diploma or completed an equivalency program and had attended at least some college, but did not necessarily earn a degree. Thus, it's assumed that in the current year, similar trends carry over, such that the median American has earned a high school diploma or equivalent and has attended at least some college, though not necessarily earned a degree. As the data are two years old, the actual percentages are likely different, albeit marginally. If these trends in educational attainment are analogous to more modern developments, then the present-day proportions should be similar; thus, the percentages presented should be used as proxy in the absence of current data.

Therefore, a centralized, verified resource that can be used to educate interested parties in a manner relevant to their general level of education should be developed and implemented to inform the general public about quantum technology, which may comprise details of what a quantum computer is, the basic principles behind quantum computing (i.e., explaining quantum superposition in such a way that is easily digestible for the most Americans), and potential capabilities quantum technology is expected to possess. This resource should be something that scientists, technical experts, and technical or scientific communicators can pull from and contribute to, as the body of knowledge pertaining to quantum mechanics and quantum technology matures and expands, so the information is relevant and accurate – it's imperative that the public is not delivered false or exaggerated expectations, or the risk of losing public interest and support may increase, which could impede progress altogether. Regardless of education, the average American is likely less concerned with the intricate details of how a quantum computer (much less a classical computer) works; rather, Americans need to know what quantum computers have potential to achieve – quantum computing may unlock faster drug and material discovery, better-optimized traffic, and improved weather simulation and modeling, among several other useful regimes in which the technology has the potential to make an impact [34]–[36]. More importantly to the average American are the specific potential outcomes of these advances:

> Faster drug discovery may lead to cheaper, more effective treatments and, better yet, cures. Similarly, faster material discovery could help across a range of fields – longer-lasting batteries at a lower cost to the consumer might make EV technology more practical and enticing. Furthermore, smart devices could last longer or be more powerful – smart phones that can last more than one day on a single charge, even with generous use, is especially crucial in the wake of worsening natural disasters. Using materials with greater corrosion-resistance could promise a savings of hundreds of *billions* of dollars annually, in the U.S. alone [37]. Materials with greater corrosion-resistant properties can be used to increase the lifespan of American naval fleets, savings taxpayers' money without weakening U.S. National Defense capabilities. Conversely, better materials equipped to operate in extreme environments may enhance the capabilities of the military, providing for the common defense and promoting the general welfare. Materials developed for advanced energy sources can offset the need for fossil fuels and provide greater baseline energy stability and security – fossil fuels kill, and air quality plays a significant role in personal health, especially for children [38]–[40]. Better-optimized traffic would reduce travel times, save on gas and toll costs, and could reduce rush-hour stress during early-morning and evening commutes. More accurate weather forecasting is an obvious benefit, as more predictability brings greater peace of mind and can increase emergency preparedness ahead of heavy storms and other natural weather phenomena.

Recently, the ASCET CoE determined that it would shift its focus toward 4 of the 17 CETs - *Quantum Technology*, *Artificial Intelligence* (AI), *Biotechnology* (biotech), and *Semiconductors*. Recalibrating the scope of work will allow the Center to prioritize these technologies, accelerating its efforts and enhancing its mission. On ASCET's website is a section labeled "Information and Data Sharing Hub," which states that the Center plans to "develop and implement tools and resources to enable the U.S. private sector to engage and influence international standardization more efficiently and effectively" [41]. The Information and Data Sharing Hub could be leveraged over the short-term to host existing educational resources regarding quantum technology, as previously mentioned, alongside future resources intended to improve American standardization efforts on an international stage, pairing "Quantum Technology 101" with "U.S. Standards Engagement 101." Heightened efforts to educate the public and enhance the private sector standards community could promote technical expertise, standards readiness, and greater support across the intersections of each community. Strengthening the workforce and general public would make the remaining bodies of work much more palatable, ideally mitigating technical barriers and improving the overall quality of work carried out across these key domains (i.e., R&D and standardization).

As much potential as the ASCET CoE may have, because it is federally-funded, and federal funding priorities may shift over time, a more stable, long-term home for these educational resources may be necessary. ANSI may therefore play an essential role on this front, in offering and maintaining these resources under its Education Research Center [42]. ANSI has established long-standing relationships with numerous SDOs, industry members, and government agencies, placing the organization toward the center of this network of relevant stakeholders. Because of ANSI's history with convening and facilitating collaboration (in line with its *Essential Requirements*, no less), these responsibilities are well within its wheelhouse. As such, ANSI may consider proactively housing these educational resources, broadly serving the general public.

Recommendation 2: Facilitating Discussions about Standardization for Enabling Technologies

Increasing the pace of R&D work is intrinsic to standards acceleration; standardizing a nascent technology is trivial as the technology is likely to experience many major changes over a short period of time, meaning any standards created will likely be quickly outdated, if not before the standard is even finished. This would be an unnecessary expenditure of time and resources, especially if standards writers were to invest them elsewhere and have a larger impact.

The standardization of enabling technologies may address the issues of cost, capacity, and risk, introduced previously in this report, which are central to the developmental workflow for not just quantum technology but the other CETs the ASCET CoE will focus on. As mentioned, proprietary components used to develop quantum computers are costly, and if an enabling technology that supports this development cannot be made in-house, it must be procured from a third party. At best, current market offerings meet the needs of R&D specialists; at worst, if very few needs are met by current offerings, then a lot of money may be spent on procurement and modification so the enabling technology can meet the project needs. One example of this is lasers, which play several crucial roles, and are used to manipulate qubits. For the sake of this example, it is assumed only five market offerings are realistic candidates for adoption based on the needs of R&D specialists. Even though these five are the most viable, the R&D specialists need a laser with certain characteristics of each of the current offerings, though no single offering satisfies these requirements. The specialists might need to buy one or a few of the offerings and make modifications, either in-house or externally to meet their requirements. This process takes time and money, and may add additional work for the specialists. Another enabling technology is cryogenics, as quantum computers necessitate very low temperatures, close to absolute zero (0 K, -273.15 °C, -459.67 °F), underscoring the critical function this technology serves in supporting the development and eventual usage of quantum computers. In both cases, standardizing enabling technologies may help to improve the quality, performance, and cost, making it more cost-effective to procure from future market offerings that meet the need of researchers and technicians.

Of course, the needs of researchers may change over time, and they may have a different list of requirements for various supporting products, which could mean lasers with the earlier specific characteristics are cheaper, but they may not be ideal or relevant anymore. Even though enabling technologies are less likely to undergo major design changes or revisions in a short period of time, the use cases for them may shift as the broader technology advances. In lieu of this, the need to facilitate further discussions relevant to this issue is apparent. These discussions should address exactly this possibility and determine the most strategic way to support standardization for enabling technologies, and create a landscape of relevance and utility over time, through coordination between professionals in the standards community, technical experts, and scientists working to develop these technologies and definitions (the latter of which NIST has worked on and will continue to expand upon and revise).

Recommendation 3: Expanding upon Existing Public-Private Partnerships and Industry Collaboration

The Quantum Economic Development Consortium (QED-C) was established in 2019 to "enable the real-world application of quantum technology, and, in turn, grow a robust commercial industry and supply chain." The QED-C framework could be expanded upon to directly address standards-related issues. Additionally, QED-C could engage with the ASCET CoE to help facilitate information sharing, communicate notices of new project calls, funding opportunities, and develop detailed project summaries with the intention of informing and providing motivation for scientists to undertake new projects. Accordingly, a broad, well-connected industry network will need to be further developed. The goal of these expansions should be to encourage professionals with standards expertise and other experts within the scientific community to collaborate on standardization efforts. This touches upon the earlier issue of the need to create technically accurate and market-informed standards, which may then facilitate competition and promote American leadership within the field.

Recommendation 4: Policy to Promote American Leadership and Engagement for Quantum Technology and CETs

To support U.S. quantum leadership and engagement, new policies may help lay the foundation for future work and facilitate U.S. leadership globally in technological development and standards activities. Congressional action could advance and institutionalize current federal efforts, including federal R&D programs focused on quantum technology, for example via a renewed National Quantum Initiative. One proposed standards-focused bill (*S. 1269 – Promoting United States Leadership in Standards Act of 2025*) seeks to bolster American leadership in standards, allowing NIST and the Department of State (DOS) to lead efforts to "encourage and enable United States participation in developing standards and specifications" for CETs [43]. This bill specifies that NIST and the Secretary of State must provide a briefing meant to aid the Federal Government in supporting "industry-led efforts in the development of technical standards for artificial intelligence and other critical and emerging technologies." Additionally, the bill outlines the creation of an easy-to-access portal to help stakeholders navigate and actively engage in international standardization efforts (which could be addressed through the ASCET CoE *Information and Data Sharing Hub* in the future).

Other relevant bills focus on enhancing international cooperation via research exchanges (*S. 1397 – International Quantum Research Exchange Act*); and monitor advancements made to the field of quantum information science and technology (*S. 1746 – Quantum LEAP Act of 2025*), to consider and make necessary investments to advance the field in the interest of national and economic security [44], [45]. Continued bipartisan support in promoting U.S. interests for the advancement of quantum technology and other CETs will be crucial in achieving and maintaining global leadership across all fields related to quantum technology.

Summary of Recommendations and Concluding Remarks

Overall, The ASCET CoE Information and Data Sharing Hub has the potential to become a versatile tool for experts to contribute information and resources to over the short-term, informing the field of new advancements relating to each of the four CETs it will shift its focus to, moving forward. However, ANSI may play a key role in housing these educational resources over the long-term, if federal funding priorities shift in the coming years. Critically, engaging scientists and building up workforce capacity for standardization from the pool of technical experts, scientists, and industry professionals is necessary to realize a paradigm shift from the current standardization process – research and development work operating in tandem with standardization efforts, as much as is feasible. Offering educational resources that meet the public's needs, regardless of educational disparities, is an essential next step needed to garner interest and bolster support for quantum technology and the other CETs. Realizing quantum technology's true potential may lead to many consumer-driven improvements such as reduced costs in medicines used to treat and cure, longer-lasting electronics, better weather forecasting, less traffic congestion, and higher-performance materials that can generate cost-savings of billions of dollars annually. There are likely many potential applications that haven't been realized yet, and as these are identified, educating the public and subject matter experts will have a profound impact on the future of the technology. Expanding upon existing partnerships and consortia to support the current bodies of work, in conjunction with supporting policy will enhance the U.S. mission to maintain global leadership, promote national security, and secure its economic interests.

Accomplishing the goals outlined throughout this report will require the dissolution of work performed in silos, accepting a paradigm shift in the way work is conducted across the standards realm and industry, as technological convergence is inevitable in both the current era and the future. On that note, working in silos risks a lack of interoperability and the likelihood of bodies of work being needlessly repeated, which not only delays progress, but may instead prove deleterious to the development of the technology and efforts to bolster standards readiness. Accordingly, technological developments should be made in tandem with standardization efforts (as much as is feasible, and without limiting ourselves) to enhance U.S. leadership and expertise within the fields of quantum technology and other CETs.

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Appendix A. Acronyms and Abbreviations

ANAB – ANSI National Accreditation Board. The body responsible for all accreditation activities related to standardization for SDOs and the conformity assessment process for scheme owners.

ANS – American National Standard. A voluntary consensus standard, developed in accordance with ANSI's *Essential Requirements* such that the development of such standards is fair and responsive, open to all parties.

ASCET – Advancing Standardization for Critical and Emerging Technologies. A cooperative agreement between ASTM International and NIST. (ASCET was formerly the U.S. Standardization Center of Excellence for Critical and Emerging Technologies; SCoE, CETs). The initiative is meant to support private sector efforts within the respective standardization processes related to various CETs. The shift from SCoE to ASCET is reflective of an international effort to standardize CETs.

ASD – ANSI-accredited Standards Developer. An SDO that has been accredited by ANSI.

CA – Conformity Assessment. "A process for demonstrating that specified requirements have been fulfilled. This may include testing, calibration, inspection, validation, verification, and certifications. ANAB is a global leader in conformity assessment activities."

CET – Critical and Emerging Technology. Relates to any of several nascent technologies. These include the following terms, with the 4 CETs in ***bold italics*** being specific technologies of focus for ASCET:

- Advanced and Networked Sensing and Signature Management
- Advanced Computing
- Advanced Engineering Materials
- Advanced Gas Turbine Engine Technologies
- Advanced Manufacturing
- ***Artificial Intelligence***
- ***Biotechnology***
- Data Privacy, Data Security, and Cyber Security Technologies
- Directed Energy
- Highly Automated, Autonomous, and Unscrewed Systems, and Robotics
- Human-Machine Interfaces
- Hypersonics
- Next Generation Communications
- Positioning, Navigation, and Timing Technologies
- ***Quantum Technology***
- ***Semiconductors*** and Microelectronics
- Space Technologies and Systems

IEC – International Electrotechnical Commission

ISO – International Organization for Standardization

JTC – Joint Technical Committee

NOFO – Notice of Funding Opportunity

PSEP – Pre-Standardization Engagement Process

SC – Subcommittee

SD-PPP – Standards-Driven Public-Private Partnership(s)

SDO – Standards Developing Organization

TAG – Technical Advisory Group

TC – Technical Committee

WG – Working Group