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A Public Path to Building a Star on Earth

Until fusion technologies can meet society's goals, government-supported research should remain broad, and stakeholders should resist attempts to narrow its reach.

Although it has been compared to "creating a star on earth," fusion technology faces many earthbound challenges if it is to fulfill its promise of producing low-carbon energy. At times, public trust in fission has been eroded by accidents and perceived risks; by contrast, fusion has much working in its favor. Fusion doesn't rely on a chain reaction process, and avoids the potential for accidental releases of highly radioactive fission products, which is what happened in Fukushima and Chernobyl. Furthermore, most fusion designs rely on fuel sources that are nearly unlimited, and the technology does not generate high-level waste. This addresses one of the problems to wider deployment of fission, which is that although nuclear waste storage and disposal may be more political than technical, it has not been solved in the United States. Similarly, the possibility of building a foundation for the social acceptance of fusion underlies its potential to solve multiple challenges for low-carbon energy: balancing a future grid, mitigating the need for a broad expansion of transmission infrastructure or storage solutions, and decarbonizing sectors that are challenging for renewable energy sources. However, for fusion to achieve these goals will take careful work between the public and private sectors to further develop the technology, while assuring its proper regulation, public acceptance, and certainly its affordability.

The funding of future fusion research now requires particular attention from decisionmakers. Federal funding has long underwritten fusion research—although the longstanding emphasis has been on developing a better understanding of plasma, the fourth state of matter. That almost singular focus on the science of plasma physics is changing as the technology reaches a new level of viability for energy production. Four times in the last 18 months, the National Ignition Facility at Lawrence Livermore National Laboratory has exceeded "scientific breakeven," meaning that more energy came out of a fusion reaction than was input by the test device's 192 lasers. Though that output is still two orders of magnitude removed from a commercial breakeven standard—where the grid energy needed to drive the device is exceeded by energy to the grid from the fusion reaction—these are remarkable scientific achievements. In February 2022, researchers at the Joint European Torus in the United Kingdom set a new record for producing controlled fusion energy when a five-second test produced 59 megajoules of energy, demonstrating further progress toward viable magnetic-confinement fusion. On the commercial path, there have been noteworthy technical achievements that may accelerate progress to a commercially viable fusion energy system, including demonstration of a high magnetic field in a large-bore model magnet constructed using high-temperature superconducting material.

These fusion research milestones have led to a growing narrative that the necessary science is proven, and fusion energy providing electricity to the grid is just around the corner. Some startups have already begun to sign contracts for fusion-based electricity production before the end of the decade. In commercial efforts, there are now more than 40 companies pursuing a wide range of concepts, including standard tokamak designs, mirrors, and stellarators as well as less well-explored concepts such as flow-stabilized Z-pinches. Total funding for these companies exceeds $6 billion. Recognizing the opportunity to advance some aspects of fusion research and development more quickly, the US Department of Energy (DOE) initiated a Milestone-Based Fusion Development Program and has contracted to provide funding to eight companies to help augment their research and development efforts with public support. This is an encouraging step. But growth in public budget levels is necessary to ensure that this type of program doesn't pull money away from open research efforts at labs and universities at a time when even the most viable fusion concepts are still unproven.

Momentum for fusion is clearly building, and everyone should be hopeful that it will lead to discoveries for best-case, long-term solutions to global clean-energy needs. However, this progress is occasionally accompanied by premature calls to truncate or close existing US public research facilities or pull support for the international ITER effort, an experimental fusion system being constructed in France through a collaboration of 35 nations. Although shifting support and focus to private efforts may seem politically and financially attractive to some, it is far too early to reduce funding for the ongoing efforts at national laboratories and universities in the United States. Such a move would not only narrow advancement in crosscutting technologies, but it could also impact development of the workforce needed by both the public and private sectors and hamper efforts to build public trust in the technology more broadly.

At this early stage in the development of fusion technology, a coordinated plan for public and private funding is necessary. Successfully deploying new energy technologies at scale requires more than just technical development. Three critical and equally important areas must be carefully attended to: the underlying science and material challenges; a thorough and clear regulatory structure that manages safety concerns without placing undue burden on commercial development; and public acceptance and energy equity. The future of fusion depends on a coordinated effort across all stakeholders to build a robust scientific, regulatory, and social infrastructure around the technology. Already, there have been worrying signs of possible disconnects, as well as challenges in building a public-private architecture, that will require continuous attention.

Addressing the development challenge

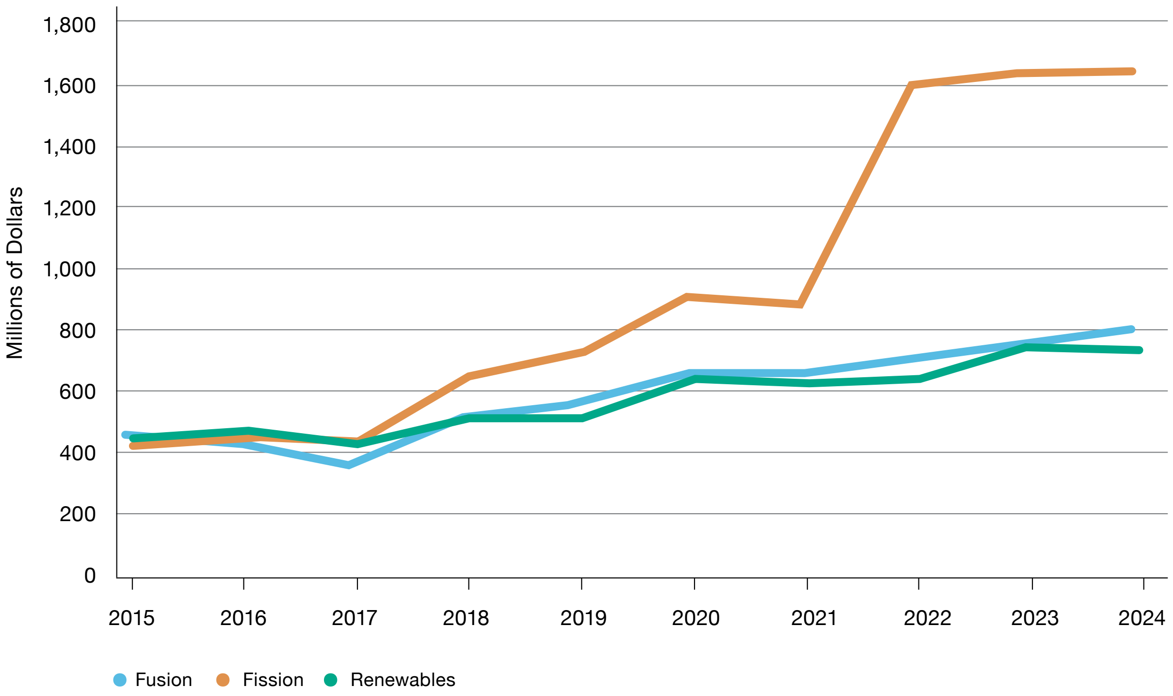
Getting to the point where commercial developers can create fusion generation that can compete with other low-carbon energy sources still requires a significant amount of research in areas such as plasma physics and materials, supported by high-performance computing, artificial intelligence, and digital engineering. To become a reliable supplier of energy, fusion needs a set of supporting technologies, including materials that will withstand very harsh environments, reliable and lower-cost high-field magnets, and sustainable fuel supplies—all of which are now at early stages of readiness. Support for the international ITER project and enhancement of national fusion R&D programs at national labs and universities is necessary for these fundamental innovations. Without this publicly funded work, pathways to a commercially viable fusion system will be much narrower, focusing on specific needs of as-yet-unproven commercial designs.

Although individual companies are attempting to solve some of the challenges that remain, they are often—and understandably—focused on approaches that are specific to their design cases. Private ventures cannot be expected to explore the broader landscape of options that could ultimately lead to more sustainable and affordable solutions. For instance, significant effort is being expended in the private sector to develop high-temperature superconducting magnet technologies. Many companies are focusing primarily on yttrium barium copper oxide superconducting tape, an option that demonstrated high magnetic field for Commonwealth Fusion Systems in the company's initial model coil tests. But it is still uncertain if this will prove to be a robust, affordable, long-term option for all designs. This is just one example of an area where a public program that examines a broad range of options may yield benefit for the full complement of fusion designs.

Ultimately, private companies are looking to capitalize on existing scientific and technological knowledge, generally adding their own particular innovations in a specific area. They are not typically focused on developing the broad, underlying science and technology that will likely be needed for many different approaches, and they are certainly not focused on making such advances publicly available—that is the job of the public program. The greater the base of publicly available fundamental scientific and technological understanding, as provided by public R&D, the more opportunities there will be for innovation by private companies.

Many of fusion's technical challenges have been detailed in reports from the US National Academies of Sciences, Engineering, and Medicine, such as a 2019 consensus report, *A Strategic Plan for US Burning Plasma Research*, and a 2021 consensus report, *Bringing Fusion to the US Grid*. The US Government Accountability office also

Figure 1. **DOE ENERGY PROGRAM R&D FUNDING**



Fusion budget shown includes all research and ITER funding. Fission budget shown includes reactor concepts R&D, fuel cycle R&D, Nuclear Energy Enabling Technologies, and Advanced Reactor Demonstration Program funding. Renewables funding includes solar, wind, water, and geothermal technology research funding.

recently released a report on fusion energy. Successfully meeting the crosscutting challenges these reports outline will augment most commercial development efforts, and will also ensure that no specific commercial design is favored while alternatives that could ultimately prove more attractive are still at low technology readiness level.

To help drive these necessary innovations, the focus of national publicly funded programs is being reevaluated, particularly at the Department of Energy. The public, through DOE and its national labs, has an interest in ensuring that potentially transformational technologies are moved forward; but it also has an interest in ensuring that public funding does not tilt the playing field excessively and serve to limit or skew the competitive landscape. Certainly, DOE must perform due diligence and only fund those companies that can meet agreed milestones. But DOE should also help keep a range of options available, as they have in programs like the Advanced Reactor Demonstration Program for advanced fission, which still funds 10 different designs. Where possible, DOE should consider teaming with other parts of the federal government in areas that overlap (e.g., materials, management of tritium, workforce) and should stay connected with international partners where appropriate.

A research roadmap to guide public investment

To guide efforts for the next decade, DOE's Fusion Energy Sciences office should create a US research and development roadmap to align the appropriate resources. Some of this work is already in progress: for example, the DOE Fusion Energy Sciences Advisory Committee's ongoing review of priority research areas and infrastructure needs recently advocated for continuing support for ITER, emphasizing research supporting fuel cycle and breeding blanket test facilities, and developing a prototypic neutron source for materials testing. To structure these efforts, DOE has published a Fusion Energy Strategy that describes the path ahead at a very high level, emphasizing three pillars focusing on closing science and technology gaps, preparing the path for commercialization and building partnerships. In executing this strategy, DOE's Fusion Energy Sciences has proferred a vision that emphasizes "building bridges." While these efforts are encouraging, they are still not obviously underpinned with a current technical assessment of the state of readiness across fusion technology development. A more formal assessment of technical readiness for key technologies is still needed to assure leadership across multiple design options. A helpful model to look to is the DOE-sponsored assessment of advanced fission reactor designs conducted by several national laboratories with support from the fission industry.

A more detailed technical assessment and roadmap would enable a better public-private alignment of technological readiness and research priorities. For example, some observers posit that the basic understanding of the fusion power source has reached Technology Readiness Level (TRL) "6," which implies readiness to move to a prototype at the systems level. But that rating typically requires that all component subsystems be at that same TRL level to move forward. Whether this is correct is unclear, and there is not even full agreement what TRL levels mean in relation to fusion systems. A roadmap, buttressed by a consensus understanding of component and system technical readiness, could assist stakeholders in determining whether this overall TRL assessment is accurate and if more robust funding for prototype development efforts is advisable. Similarly, the roadmap could guide the type of expert elicitation and synthesis that the fission community has used to develop priorities to advance technology while also building a comprehensive training and support infrastructure.

The roadmap can also direct public funds toward prudent investments. Figure 1 reflects the funding levels for research across fusion, fission, and renewables over the last 10 years. Although fusion funding has grown to about $800 million for DOE's Fusion Energy Sciences, it is still well below the level for a technology that is already proven (fission) and is only on par with research in the four primary renewable technologies (wind, solar, water, and geothermal). Over the last four years, accounting for inflation, fusion funding has essentially remained flat. If the experience of advanced fission reactor design and development is indicative, fusion funding levels will almost certainly need to double or triple in the coming years to ensure success by mid-century.

Even with bipartisan support, it will be difficult to increase public funding to the scale required. Given these limits, some have argued that the public fusion R&D program should be primarily focused on the needs of the growing commercial enterprise. But DOE's mission and goal is to ensure the technology succeeds without favoring any one company or approach. This has been successful with fission: as new technologies have been developed, DOE increased funding to ensure that critical academic and lab research continues. Similarly, as some commercial designs and technologies for fusion move ahead, the public fusion science program should continue—informed by and, where prudent, aligned with private sector efforts. Furthermore, public efforts should not be constrained by the near-term focus of private investments, which may prioritize financial returns over technological progress. Until fusion technologies can meet public goals, public research should remain broad, and stakeholders should resist attempts at narrowing its reach. Ideally, development should continue in a manner that places the United States both at the leading edge of fusion R&D *and* at the forefront of commercialization—and keeps it there.

One well-known example of a robust private venture that meets public and private needs is NASA's Commercial Orbital Transportation Services (COTS) program. COTS transitioned support for space resupply missions for the International Space Station from NASA to the commercial sector and ultimately helped fund development of a commercial space transportation ecosystem. Given the success of this model, advocating for a similar approach for fusion is tempting. However, the development of fusion technologies is not truly comparable with COTS in that, unlike the space program, there is no baseline, proven technology to be optimized and enhanced in a commercially viable and reliable form. In fact, the success of COTS might be seen as a model supporting a more robust public effort, because decades of public funding supported the development and testing of the fundamental technologies which have enabled today's multiple commercial programs to proceed with rapid iteration and development in the marketplace.

Public funding to build public support

Beyond meeting fusion's R&D challenges, it will be important for private developers to have regulatory certainty and public trust as they evaluate their designs. In advancing regulatory development, there are many notable examples of thoughtful mixtures of public and private funding that have supported both the development of technologies and their acceptance and integration with society. Rocket systems, the Global Positioning System, the internet, microchips, and LED lights have all started with public funding that led to broad understanding of the technology, regulatory strategies, and workforce development. In electricity generation, for example, fission energy as a power source was led at its early stages by academia and the US Department of Defense—creating a regulatory regime as well as workers versed in the technology—before it was expanded to commercial scale by private industry. A similar period and level of public support is necessary to achieve an appropriate level of social readiness for fusion.

On the regulatory front, work is already underway. The US Nuclear Regulatory Commission is developing a comprehensive regulatory and licensing process in keeping with the timelines laid out in the Nuclear Energy Innovation and Modernization Act, which requires a final rule by the end of 2027. In meeting this regulatory challenge, care must be taken to consider all voices and avoid taking pathways that could undercut public acceptance and energy equity. Public funding of research and appropriate outreach at this stage of development can make sure that safety, security, safeguards, and social license are well examined. When it comes to regulations related to waste and nonproliferation, issues that have troubled the development of fission energy, national laboratories provide the backbone of experience and analytical

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tools that are needed for careful, thorough analysis. As regulation is developed for near-term fusion designs, private developers will want to be aware that regulators may need to change course as they gain a greater understanding of design specifics from pilot plant development. If this is not carefully managed, industry may miss the mark in balancing speed and cost of development with public acceptance.

The question of building public trust should be given special priority. Even though the risks of fusion are different and of lower consequence than they are with fission, they are not zero. In particular, both public researchers and industry should be wary of understating risks because in the long run, that could erode public support. Any sense that industry is misrepresenting risks of, for example, proliferation or accidental release could affect the public's perception of the entire class of technology.

Care should also be taken to engage the public early and often to ensure there are no unanticipated hurdles in deploying the technology when it is ready. For example, there has been significant public concern around releases of tritium, a radioactive isotope of hydrogen, including the global reaction to releases of tritiated water from Fukushima in 2023. Opposition to the releases is vocal and has been strongest within Japan's fishing community, which is concerned that radiation could prevent them from selling seafood internationally. Korea and China have also expressed concerns regarding environmental effects in their territories. Arguably, some of this concern is wrapped up in regional politics, but even though the International Atomic Energy Agency indicates that there will be "negligible radiological impact on the environment and people" from the releases, the government of Japan is still on the defensive.

The Fukushima accident highlights the risks posed by the global nature of the relationship between nuclear development and public trust: accidents anywhere in the world, on any design, may affect public acceptance of this class of technologies elsewhere. As the US Nuclear Regulatory Commission works through domestic criteria, the government should also take a leading role with the International Atomic Energy Agency to clarify global safeguards and security guidelines. In particular, the US government should lead by improving detection and accounting standards for tritium. Risks of tritiated water release may actually be greater at fusion facilities that use a deuterium/tritium fuel cycle due to the very large quantities of tritium involved; these risks should be addressed explicitly and not underplayed. The Fukushima tritium releases will total 2.2 grams over 20–30 years. A single gigawatt-scale fusion energy system will burn over 50 kilograms of tritium in a full power year.

Finally—and importantly—a key part of ensuring public acceptance, regulatory steadiness, and a smooth path to commercialization lies in developing a well-trained, robust, and diverse workforce. Today's public research is helping to build an initial core workforce, but significantly more effort is needed to build out the supporting infrastructure of skilled trades, operations staff, and engineering teams to construct these complex facilities. More research scientists and engineers are also a critical need. A recent National Academies study examining development of advanced fission reactors recommended a broader whole-of-government approach to building the necessary workforce to support expansion of fission, similar to the approaches taken in the multi-agency National Network for Manufacturing Innovation. An equally ambitious approach should be considered for fusion.

A careful path to deployment

Amid the excitement around the potential for fusion, it has been suggested that development of stringent rules that might affect the cost of commercialization should be balanced against the urgent need to transition to a low-carbon energy system. This type of balancing must be done with care. Policymakers can and must support low-carbon development while also taking reasonable steps to ensure those low-carbon solutions do not generate their own risks. They also must ensure these technologies are deployed equitably. A robust plan for development must incorporate public facilities designed specifically to examine new approaches and new materials with a parallel effort to explore risks.

The last 75 years of experience with nuclear fission demonstrates that a complex technology cannot succeed without both technology improvements and global public trust. If development is properly managed, deployment of fusion can provide the long-term, low-carbon solution the world desperately needs. But we must not lose sight of that long-term goal or be distracted by claims that success is assured.

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