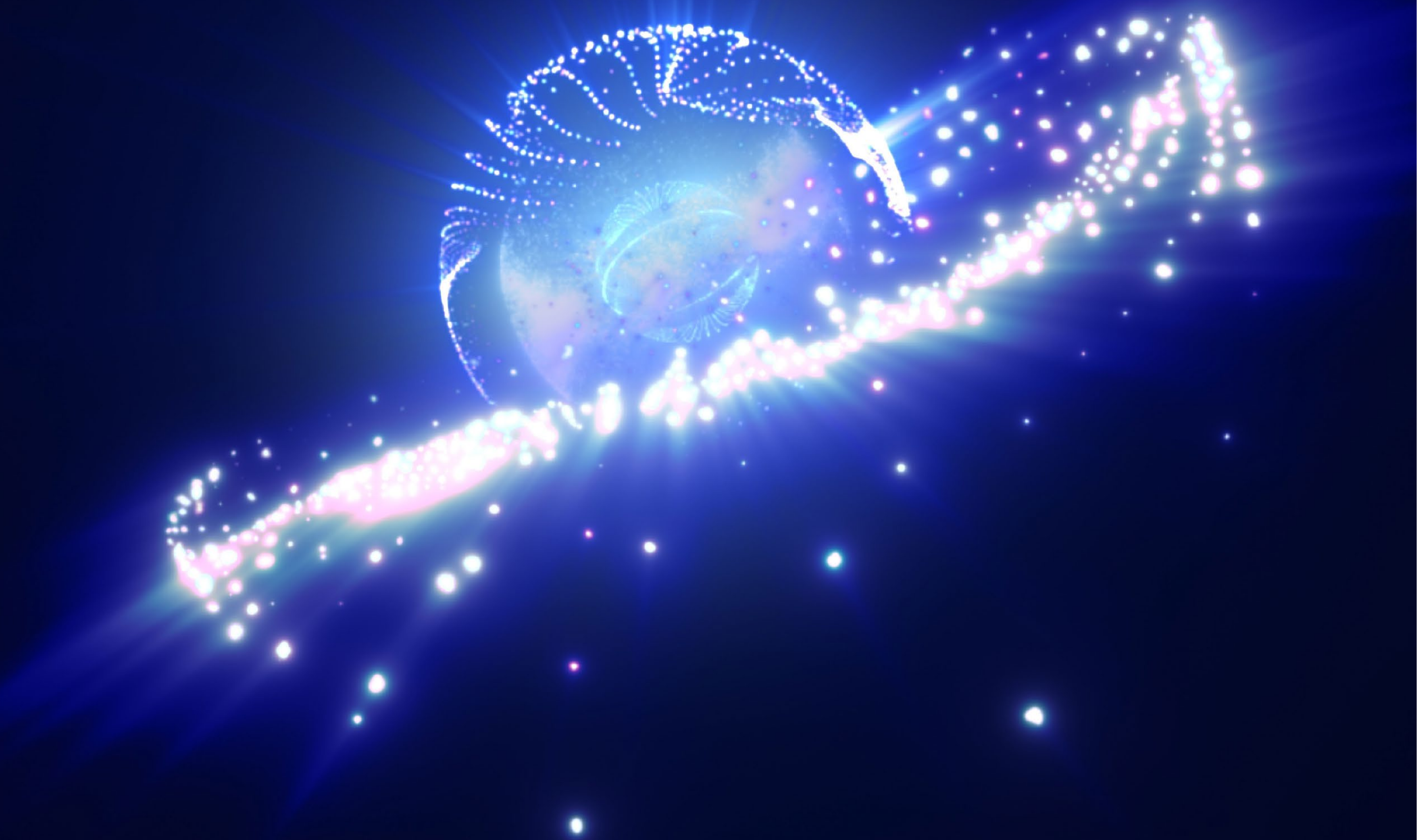
PNNL-37903

Development of a Western U.S. Fusion Energy Commercialization Hub

Report of the October 23, 2024, workshop supported by the U.S. Department of Energy Office of Fusion Energy Sciences



U.S. DEPARTMENT of ENERGY

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Executive Summary

Fusion energy, if successfully commercialized and globally adopted, could substantially increase U.S. energy dominance and provide essentially unlimited baseload power for the national grid. It also stands to provide the U.S. with a strong source of economic growth through the 2030s and 2040s, giving the U.S. a new and highly internationally competitive industry for export. Fusion can also provide the increased electrical power generation capacity required to power current and future artificial intelligence (AI) activities.

In October 2024, the CleanTech Alliance[1] held a fusion energy commercialization regional hub workshop alongside its annual Seattle Fusion Week conference. The event brought together fusion companies, researchers, economic development experts, federal and state government representatives, and power utilities from the western states of Washington, California, Colorado and Nevada. Attendees discussed the potential of regionally focused commercialization of fusion energy in three pillars: technology, workforce, and economic development.

Mel Clark, President & CEO, CleanTech Alliance, and Dr. Javier Garay, Associate Dean for Research and Professor of Mechanical and Aerospace Engineering, at the University of California San Diego (UCSD) and Founding Director of the UCSD Fusion Engineering institute, are co-PIs for this project. The project is sponsored by the U.S. Department of Energy's Office of Fusion Energy Sciences (FES) through a Field Work Proposal to Pacific Northwest National Laboratory (PNNL) with Karl Mueller as point-of-contact. Chris Ajemian (Principal, Ajemian Consulting, LLC) and Dr. Christopher Keane (Professor of Physics and former Vice-President for Research, Washington State University) co-organized the workshop and were the editors for this report.

This report details the current state of the work of the four western states to develop industry-led collaboration with national laboratories, universities, and government at all levels to hasten the commercialization of fusion energy. It provides a summary of fusion energy R&D needs, presents the ideas the attendees at the workshop identified for deepening regional collaboration, and makes findings and recommendations for next steps.

The introduction outlines the evolution of fusion public-private partnerships (PPPs) and the rise of private fusion companies. DOE's ARPA-E programs, such as ALPHA, BETHE and GAMOW, provided critical early support for those companies. For many decades prior, FES provided support via its longstanding baseline program activities with an emphasis on

[1] https://www.cleantechalliance.org/

magnetic confinement. Recent milestones, including the 2022 ignition achievement at Lawrence Livermore National Laboratory (LLNL),[2] funded by the National Nuclear Security Administration (NNSA), accelerated momentum for fusion commercialization. Under new leadership, FES launched the Milestone program[3] and FIRE Collaboratives[4] that support magnetic, inertial, and hybrid fusion approaches. Future strategies may include regional hubs and consortia that support broader industry economic development.

This report then examines the Sematech consortium, launched in 1987, as a potential model for fusion regional hubs. Sematech made gains in revitalizing the U.S. semiconductor industry by focusing on upstream supply chain improvements, fostering collaboration, and avoiding or mitigating intellectual property conflicts. Lessons for fusion public-private partnerships (PPPs) include: (1) prioritizing upstream, earlier stage, industry-wide technology challenges in materials science and other areas, (2) ensuring flexible industry-led, hub leadership, and (3) conducting effective road mapping to identify and address high-priority technical needs.

These lessons could be utilized by the Public Private Consortium Framework (PPCF) for Fusion Energy, announced by DOE in June 2024.[5] The PPCF aims to enhance collaboration between federal agencies, private companies, and other stakeholders to address common engineering challenges in fusion energy. It supports R&D on small to medium scale projects such as fusion-oriented neutron sources and tritium research that benefit multiple companies but are too costly for one entity independently. It also encourages the development of regional hubs to promote workforce development, public outreach, and economic development.

The success of Seattle Fusion Week, organized by the CleanTech Alliance, shows how regionally focused fusion initiatives can provide a foundation for implementing the commercialization goals of the PPCF. The annual Seattle conference brings together

Seattle Fusion Week

CleanTech Alliance™

Focus on Fusion

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[2] https://www.llnl.gov/article/49301/shot-ages-fusion-ignition-breakthrough-hailed-one-most-impressive-scientific-feats-21st

[3] See https://science.osti.gov/-/media/funding/pdf/Awards-Lists/2809-FES-Fusion-Milestone-Awards-List.pdf

[4] See https://science.osti.gov/Funding-Opportunities/-/media/funding/pdf/Awards-Lists/2025/Awards-List-Spreadsheet-3361-FIRE-Collaboratives-v2.pdf

[5] Federal Register / Vol. 85, No. 76 / Monday, April 20, 2020 / Notices; (https://www.federalregister.gov/documents/2020/04/20/2020-08312/cost-sharing-partnerships-with-the-private-sector-in-fusion-energy#footnote-1-p21842).

regional elements in the Washington state fusion energy commercialization ecosystem. It has grown significantly since 2021 by showcasing private sector progress, involving expert technical and economic development discussions, and providing communication and outreach to the region that a new strategic technology is beginning to commercialize. Notable speakers such as U.S. Senator Maria Cantwell, former Washington Governor Jay Inslee, and FES Director Dr. Jean Paul Allain have participated.

This report concludes with findings, recommendations, and proposed next steps. These are listed in the appendix and are summarized by this primary recommendation: DOE and the fusion community should continue to further develop the concept of industry-led fusion commercialization hubs through implementing the PPCF, including executing pilot projects to gain experience and "lessons learned" with the concept.

Introduction

Brief History of Fusion Public-Private Partnerships and the Rise of Private Companies

The Department of Energy changed its traditional public science approach to fusion energy R&D by creating public private partnerships (PPPs) through its ARPA-E agency and the fledgling fusion energy private sector. These partnerships emphasized faster paced, time limited, more narrowly focused projects than in the past. The first example was its Accelerating Low-Cost Plasma Heating and Assembly (ALPHA) program. ALPHA catalyzed[6] the growth of the modern fusion industry by supporting : (1) development of sheared-flow Z-pinches that led to the creation of Zap Energy, (2) efforts at Sandia National Laboratories and the University of Rochester to advance the MagLIF concept, work that is now being built upon by companies such as Fuse Energy Technologies and Pacific Fusion, and (3) early startups like Helion Energy. ARPA-E followed its ALPHA program with BETHE GAMOW, and CHADWICK. Other fusion companies such as Type One Energy, First Light Fusion, Tokamak Energy, CTFusion, Realta Fusion, and Avalanche Energy formed around this time.

Before ARPA-E's commercialization emphasis, DOE's FES had a major focus on tokamaks. For decades, it spent hundreds of millions of dollars annually on programs like DIII-D, NSTX-U, and ITER, the international tokamak project. One of FES' early PPPs was its Innovation Network for Fusion Energy (INFUSE),[7] a program that emphasizes small collaborations between private companies and DOE laboratories or federally funded universities.

In 2022, the National Academies of Science report "Bringing Fusion to the U.S. Grid" asserted that the knowledge developed through decades of fusion research was sufficiently advanced to propose a pathway for the Department of Energy to move forward with development of a commercially viable fusion power plant in the 2035-2040 timeframe.[8] FES responded to this challenge by implementing new programs to support

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[6] Tom Mehlhorn, "From KMS Fusion to HB11 Energy and Xcimer Energy, A Personal 50-year IFE Perspective," Phys. Plasmas 31, 020602 (2024); doi: 10.1063/5.0170661 (published online 28 February 2024).

[7] https://infuse.ornl.gov/

[8] National Academies of Sciences, Engineering, and Medicine. 2021. Bringing Fusion to the U.S. Grid¡ Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

the private sector,[9] including the Milestone program on the principles of NASA's Commercial Orbital Transportation Services (COTS) program to commercialize low Earth orbit launch rocket technology.

Later in 2022 on December 5, the LLNL National Ignition Facility achieved ignition (more energy out of a fusion reaction than used to create, heat, and confine the plasma). This was a major scientific achievement and increased momentum in not only laser-based inertial confinement approaches, but magnetic concepts as well. Acknowledging this accomplishment, FES created the Inertial Fusion Energy Science & Technology Accelerated Research (IFE-STAR) program.[10] While not strictly a PPP, IFE-STAR provided funding for inertial fusion energy (IFE) research at universities and national laboratories that would soon be working with companies that were pursuing inertial fusion energy commercialization.

Up until this time, most private fusion companies belonged in the magnetic confinement category, which included concepts like tokamaks, stellarators, spheromaks, and magnetic mirrors. Some had augmented their approaches with the advent of cheaper, smaller and more powerful high-tech superconducting magnets. The Milestone program brough both magnetic fusion energy (MFE) and IFE companies under the same publicly funded roof. A variety of magnetic, inertial, and magneto-inertial hybrid approach companies, such as Xcimer Energy, Focused Energy, Longview Fusion, HB11 Energy, Thea Energy, Marvel Fusion, and Blue Laser Fusion had been established by this time.

Dr. Jean Paul Allain became the new director of FES in 2023 and began revising the federal government's fusion energy strategy with a new DOE Decadal Fusion Energy Strategy[11] and his "Building Bridges" vision.[12] The Fusion Innovation Research Engines (FIRE) Collaboratives program later augmented the Milestone program with additional support to private companies with thinking begun under the first Trump administration.

FES' next partnership with the private sector could be a program that achieves the DOE goals outlined in the June 2024 PPCF for Fusion Energy Commercialization Request for Information,[13] which is discussed below. Regional economic development hubs, such as the Western United States Fusion Commercialization Initiative discussed at the Oct. 23,

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[9] White House Fact Sheet Mar. 15, 2022 (https://www.whitehouse.gov/ostp/news-updates/2022/03/15/fact-sheet-developing-a-bold-vision-for-commercial-fusion-energy/).

[10] See https://science.osti.gov/-/media/funding/pdf/Awards-Lists/3044-FES-IFE-STAR-Awards-List.pdf

[11] https://www.energy.gov/doe-fusion-energy-strategy-2024-executive-summary

[12] https://www.energy.gov/sites/default/files/2024-12/fes-building-bridges-vision_0.pdf

[13] Federal Register (https://www.federalregister.gov/documents/2024/06/07/2024-12539/fusion-energy-public-private-consortium-framework).

2024, Everett, WA workshop, are candidates for such a program. These hubs could adapt principles of the privately led Sematech consortium that had some successes regaining US market share in semiconductor production in the late 1980s/early 1990s. (See Appendix C for an extended version of this section.)

Public-Private Partnerships: The Example of Sematech[14]

The U.S. has a long history of effective PPPs, from infrastructure projects pursued since the Nation's founding to the more recent USA Manufacturing Institutes and activities supported by the CHIPS and Science Act. One of these partnerships, Sematech, has several lessons important for fusion energy.

Sematech was launched in 1987 in response to America's rapidly eroding position in the world semiconductor market, national security concerns arising from loss of domestic chip manufacturing capacity, and failing competition with Japan. By mid-1987, Japan had a nearly 10% lead over the U.S. in world semiconductor market share, compared to the situation in 1981 where the U.S. held the lead by a similar margin. The Sematech consortium started with 14 semiconductor firms representing 85% of U.S. chip manufacturing capacity with $200M in funding that was split between industry and the Defense Advanced Research Projects Agency (DARPA). Due to Sematech's efforts the U.S. semiconductor market share position was largely reversed by 1993.

In later years Sematech became less effective due to the companies going their own ways and a lack of adequate government long term support. However, Sematech's work from the late 80's through the early 90's has several lessons for fusion:

1. Focus on the partnership enhancing value in the supply chain, particularly upstream, vs. collaborative research on end products. Sematech got off to a difficult start. Its original strategy was to build its own fabrication facilities ("fabs") and share knowledge

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[14] The information on Sematech in this section is primarily drawn from the following sources:

a) "Sematech: A Public-Private Partnership for Spurring Domestic Manufacturing," David M. Hart, Bipartisan Policy Center, February 2024. https://bipartisanpolicy.org/wp-content/uploads/2024/02/Sematech-A-public-private-partnership-for-spurring-domestic-manufacturing.pdf

b) "Implementing the CHIPS Act: Sematech's Lessons for the National Semiconductor Technology Center," Charles Wessner and Thomas Howell, Center for Strategic and International Studies, May 2023. https://www.csis.org/analysis/implementing-chips-act-sematechs-lessons-national-semiconductor-technology-center

c) "Sematech 1987-1997: A Final Report to the Department of Defense," Executive Services Directorate, February 1997. https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/Science_and_Technology/10-F-0709_A_Final_Report_to_the_Department_of_Defense_February_21_1987.pdf from those fabs with consortium members. That method did not succeed, however, as it relied on sharing sensitive intellectual property between consortium members. When this problem became apparent, Sematech pivoted its effort upstream to cooperative research and development activities aimed at improving the machines and materials used by semiconductor manufacturers, with a goal of minimizing production costs to member companies. This enabled all members of the consortium to profit from joint research efforts and avoided impinging on individual manufacturers' intellectual property. Sematech's efforts also strengthened partnerships between chip manufacturers and supply chain members, leading to the setting of agreed standards and improved quality across the industry.

The lesson here for fusion is that public-private partnerships should focus on fundamental "upstream" technology issues relevant to all companies. Examples discussed at length at this workshop and elsewhere include development of damage resistant materials, tritium handling, energy conversion (including blanket operation), and common supply chain technologies. Examples of the latter include high temperature superconducting (HTS) magnets, divertors and edge plasma control devices, pulsed power systems, capacitors, solid state switches, laser diodes, and optical components. Topics with sensitive intellectual property, such as core fusion plasma confinement and fusion performance, are less likely to be supported by public-private partnerships.

2. The consortium (or hub) should be industry-run, with flexible and innovative leadership drawn from both the public and private sectors. It can be expected that a cooperative venture among fusion industry members operating on the technological edge will run into technical dead-ends and other problems. Consortium leaders must be empowered to change direction rapidly based on the needs of the fusion industry as opposed to being tied to the normal program, project, and financial management practices appropriate for the public science model (incremental longer-term federally funded research and development programs).
3. Effective road mapping is key. The productive research relationship between equipment manufacturers and chipmakers was developed through extensive joint "road mapping" sessions where the industry's technology needs were discussed and debated in an open, honest way. Joint commitment to the highest priority technical needs at the end of the process was essential. DOE is now leading similar road mapping exercises to commercialize fusion energy. These efforts must continue until difficult decisions are made and top priority technical solutions are recognized and financially supported, even if other worthy projects are not pursued due to constrained budgets.

These are the most important lessons fusion can draw from Sematech. Additional insights can be gained by reading the reports cited in this document, and other sources.

DOE Public-Private Consortium Framework (PPCF)

The Public Private Consortium Framework (PPCF), mentioned above, provides for a discussion and program of public private collaboration to amplify federal funding for the major common engineering tasks that face the fusion energy private sector and its ability to provide the U.S. with energy dominance. It would fund a variety of activities from small to medium test stands that would conduct R&D to address science and technology gaps through consortia of interested private investors, philanthropy, and federal and state government. In an era of constrained federal budgets, low technology readiness and limited investor funds in most instances, the fusion private sector needs to find ways to cooperate in common technical areas where it is premature to generate intellectual property. Examples include technical projects or initiatives like a fusion oriented neutron source, diagnostics, pulsed power and other technologies mentioned above that can benefit many companies, but which no one company can afford alone. Sematech has been suggested as a source of inspiration for an entity that would perform this role. A major difference with fusion is that its fledgling private sector is venture funded and not yet selling fusion energy since its technology readiness level is much lower than semiconductors were during the Sematech era.

Additionally, a PPCF could support regional economic development hubs that address workforce and economic development needs necessary for building fusion supply chains. A hub would make use of the physical proximity of multiple assets in a commercialization ecosystem, e.g. private companies, universities, NGOs, and state and local governments. A fusion specific hub would also incorporate DOE national laboratories and potential future customers such as power utilities and private data center companies or industrial users such as concrete or aluminum producers or fossil fuel companies. A hub would be a private, nonprofit entity able to accept various sources of funding and fund projects according to its charter. Several existing fusion centers in the U.S. could transform their membership into hubs, such as a western states entity, a Wisconsin entity, and an effort in the Atlantic region. A fusion hub's region would be self-defined.

As stated in the executive summary, on October 23rd, 2024, FES sponsored the Western United States Fusion Energy Commercialization Hub workshop, which examined these principles to assess the efficiency of focusing resources in the four western states of Washington, California, Colorado, and Nevada. Subjects included regional workforce, common technology, and economic development stemming from a future fusion energy industry. This workshop report is meant to support DOE as it develops specific plans to implement the PPCF.

The Need for Broad Engagement and Seattle Fusion Week

The need for a regionally focused fusion hub workshop was made apparent through the organic success of the CleanTech Alliance's Seattle Fusion Week conference. The annual conference facilitates interaction between the various actors in the fusion energy commercialization ecosystem, such as fusion energy companies, the burgeoning fusion supply chain companies, federal and state governments, representatives from DOE national laboratories, federally funded universities and community colleges, and power utilities, one of the most likely future customers for fusion energy power plants.

The inaugural Seattle Fusion Week conference took place in 2021. It included a breakout session on fusion energy for space propulsion, a debate about fusion versus hydrogen and other renewable energies, as well as other early, curated conversations.

In 2022, programming expanded to include panels on:

- Plasma Physics for Politicians
- Utility Integration, Deployment, and Readiness
- STEM Education and Workforce Development
- Accessibility of fusion energy and jobs for all communities

The third annual Seattle Fusion Week conference in 2023 attracted over 175 attendees from more than 90 organizations and featured remarks from U.S. Senator Maria Cantwell.

The fourth annual Seattle Fusion Week took place in October of 2024 and featured speakers including Washington Governor Jay Inslee and the U.S. Department of Energy's Fusion Energy Sciences Director, Dr. Jean Paul Allain. Programming in 2024 expanded to three days and included breakout tracks with sessions geared towards supply chain companies, students, educators, and policymakers. Seattle Fusion Week received additional support from the City of Everett, Washington State University, and the Washington State Department of Commerce's Innovation Cluster Accelerator Program (ICAP), in addition to the CleanTech Alliance's Focus on Fusion Cluster. The CleanTech Alliance will continue to build on past success and prioritize what the fusion industry needs as the event evolves in 2025. The CleanTech Alliance hopes to contribute to the western regional hub by partnering with the other fusion centers in California, Colorado and Nevada.

Fusion Commercialization Hub Workshop Development

FES provided funding for a one-day workshop, held October 23, 2024, to explore the concept of a Western U.S. Fusion Energy Commercialization Hub. This development was a logical outgrowth of:

- The three annual Seattle Fusion Week conferences, held each fall since 2021
- The September 2023 University of California (UC) system wide workshop on fusion commercialization; and
- Numerous subsequent discussions with academic, industrial, national laboratory, and governmental leaders.

Mel Clark, President & CEO, CleanTech Alliance, and Dr. Javier Garay, Associate Dean for Research and Professor of Mechanical and Aerospace Engineering, UCSD, were co-PIs of the project. FES funds will support the completion of two tasks described in previous communications with DOE:

- Task 1 included organizing and executing the full day workshop on the Hub concept, alongside the CleanTech Alliance's annual "Seattle Fusion Week." The CleanTech Alliance managed event logistics. The content was developed by a team from academia, DOE national laboratories, and the private sector. Workshop presentations will be summarized, and findings reported, including specific proposed tasks to be executed by the hub. The report will discuss how the proposed hub relates to the FES PPCF.
- Task 2 will be performed by Community Attributes, Inc. (CAI). It will develop a fusion economic cluster study. FES funds will support a phase-one study that will develop an initial model of the fusion energy economy needed for workforce planning, common technology development, and regional economic development.

The October 23rd workshop examined what the four western states of Washington, California, Colorado, and Nevada could do to accelerate commercialization of fusion energy by focusing resources within a defined geographical region. Eleven fusion companies (Avalanche Energy, Blue Laser Fusion, Fuse, General Atomics, Kyoto Fusioneering, Longview Fusion, Marvel Fusion, Pacific Fusion, Tokamak Energy, Xcimer Energy, Zap Energy) discussed:

- Workforce development
- Possible pre-IP common technology development

- The utility of a regional approach to fusion regulation and permitting
- Regional economic development, e.g. supply chain and related topics

Western U.S. Fusion Commercialization Hub – A Potential Model

Workshop participants provided extensive input which the Hub leadership team synthesized into a proposed hub model. This proposed model is summarized below.

- Mission: Lead and support a commercialization ecosystem that accelerates fusion energy
- Vision: Fusion energy commercialization hubs will accelerate bringing fusion to the grid via coordinated development and execution of workforce, technology development, communication, and economic development activities.
- Objectives:
  - Foster and support pre-competitive collaboration in fusion technologies
  - Establish shared technical infrastructure and supply chain
  - Develop a comprehensive workforce pipeline
  - Build public understanding and support of fusion energy

Fusion commercialization hubs, including the Western U.S. Hub, would perform the following tasks:

Workforce Development

1. Workforce development plan: The Hub will develop and implement a workforce plan for fusion, starting with a pilot program (see Recommendation A3). The Hub will organize a consortium consisting of representatives from educational institutions (all levels), organized labor, fusion companies, tribal nations, and STEM-related non-governmental organizations to lead development of this plan. The consortium would also host periodic “one-stop-shop" events where fusion companies, universities, and regional economic development organizations and others would gather to advance workforce development.
2. Integration with other hub elements: New curriculum and learning approaches will be needed to develop a fusion workforce plan. The Hub workforce development plan team will need to work with industry, universities, and other Hub elements to enhance

educational opportunities in fusion. This will include implementation of fusion curricula and hands-on fusion-related learning opportunities in educational institutions at all levels. Internship and apprenticeship opportunities with fusion companies will also be needed. Industry, educational, and other organizations within the Hub structure will increase the speed with which fusion educational and training opportunities can be delivered and the fusion workforce built.

3. Progress tracking: The Hub workforce development team will work with partners to track progress developing and implementing the fusion workforce development plan regionwide.

Technology and Supply Chain Development

1. Industry should lead technology development activities as their collaborative workplans must respect the individual company intellectual property arrangements; government should play a supporting role.
2. Supply Chains: The fusion companies, working with other industries, governments (federal, state, local), and other organizations, should execute a collaborative planning effort aimed at building fusion supply chains. This activity supports both the short- and long-term needs of the fusion industry and should be launched as soon as possible.
3. Centralized Testing Facilities: Similar to Blue Origin's wind tunnel model, hubs could enable testing of fusion reactor materials and systems, including blankets, first-wall materials (including liquids), and tritium science and engineering systems while ensuring intellectual property protection. This would include hub involvement in formulation and execution of a plan for a national Fusion Prototypical Neutron Source (FPNS).
4. Tools Development: Hubs could lead development of tools and technologies suitable for use in high radiation environments. This includes diagnostics, plasma-facing components, target fabrication (IFE), optical components (IFE), and other technologies. Diagnostics is a critical area currently underfunded and underdeveloped.
5. Collaborative Environment: Hubs could encourage partnerships among private companies, universities, and government agencies to tackle common, cross-cutting technology development and other challenges.
6. State and Federal Synergy: Hubs could assist in aligning state resources (e.g., WA State Clean Energy Fund RD&D segment, WA State Department of Commerce, California's Energy Commission) with federal funding initiatives to maximize

investment results. The synergy model should consider the needs of both EPSCoR and non-EPSCoR states.

7. Near-Term Applications: The hub could support companies in identifying power and non-power applications (e.g., defense, industrial heat) that could generate revenue while grid-scale fusion matures.

Outreach and Economic Development

1. Develop and execute an outreach and economic development plan for fusion for the geographical region defined by hubs: The hubs will develop and implement a fusion economic development plan for the western U.S. region. This effort will start with a pilot program in a particular local or regional area (see "Next Steps" Recommendation 1c).
2. Progress tracking: The Hub will track progress on its goals, again in coordination with other Hub efforts.
3. Communication support for hubs and in fusion general: There is a strong need for enhanced public communication about fusion, both for the western U.S. Hub and in general. The communications component of the hub team will support other elements of the hub in explaining fusion and its public outreach. Communication and outreach will be critical to the hub's success. This effort will build upon the stakeholder analysis work and other efforts performed by the hub team.

Analysis of Working Session Data

In the final session of the workshop, participants were divided into six groups, each with experts from industry, academia, government, and stakeholder organizations. The groups were tasked with identifying high priority needs and potential solutions and recording their ideas on Post-it notes. These notes were later organized into a digital format using a Miro board to facilitate further analysis. Each group was asked to focus on the three pillars—workforce, technology, and economic development planning—spending 20 minutes on each, in a rotating order. This structure was designed to surface challenges and solutions that resonated with multiple groups, highlighting shared areas of interest and fostering a collaborative discussion. This approach allowed each group to collect the insights and suggestions from expert presentations and stakeholder contributions earlier in the day.

The notes, in the above orientation, have been analyzed both by a Large Language Model (LLM) at PNNL and by human contributors to this report. This section synthesizes those two analyses.[15]

Analysis and Outcomes

Analysis of participants' notes show strong regional enthusiasm for developing a fusion energy ecosystem, with opportunities for collaboration among participants. The workshop identified critical ideas and initiatives, revealing both immediate opportunities and long-term strategic priorities. Below we will outline critical success factors, a summary of what was discussed in each pillar and then a detailed breakdown of what was shared across all groups for each pillar. Finally, we will end with recommendations for the next steps.

Success Factors for the Hub include:

- Development of shared testing facilities and supply chain infrastructure, e.g., mining and refining lithium required for all deuterium-tritium fuel cycles
- Creation of comprehensive workforce development programs
- Implementation of coordinated economic development strategies

[15] Parts of this section were developed using the assistance of a PNNL large language model (LLM). This work was done in collaboration with Nancy Washton (PNNL) and Karl Mueller (PNNL). The LLM analysis systematically processed workshop outputs and identified key themes, priorities, and recommendations. This collaborative human-AI approach enabled comprehensive analysis of 269 distinct ideas generated during the workshop while maintaining focus on the hub's core pillars of workforce development, technology advancement, and outreach/economic development.

- Establishment of sustainable funding mechanisms
- Formation of effective governance structures and intellectual property (IP) rules

Summary of Pillar Discussions

Workforce Development Pillar: Groups focused on the need to create robust educational pathways and training programs able to respond to the fusion industry's evolving needs. There was strong agreement on the value of on-the-job opportunities such as internships, apprenticeships, and specialized training initiatives. The discussions also touched on strategies for comprehensive recruitment and retention to build a skilled workforce. It was noted that many of the outreach activities suggested to attract students to learn about fusion mirrored efforts in the Outreach and Economic Development Planning pillar. This overlap presents an opportunity to develop shared materials and programs that effectively utilize the resources of employees, volunteers, and state organizations, thereby enhancing both workforce and economic development efforts such as with the “one-stop-shop” events mentioned above.

Technology Pillar: Group discussions covered a variety of topics with a focus on advancing diagnostic tools, materials development and testing (particularly neutron testing), and sharing best practices within the hub. The groups highlighted the need for developing shared facilities to test and validate new technologies. This would facilitate innovation while protecting the IP of individual companies. Further work will be required with hub participants to narrow the scope and select projects to pursue. As part of developing a hub charter and governance, determinations should be made about whether all hub members must agree or if a critical mass of members can work together on projects.

Economic Development Pillar: Economic development discussions centered on effectively communicating the benefits and impacts (positive and negative) of fusion energy to the public and fostering relationships with local stakeholders. The groups brainstormed many approaches (both specific solutions and themes) to engage communities and build support for fusion commercialization projects. It was noted above that there is an overlap between these ideas and workforce development projects. Experts shared various best practices in economic development, highlighting that fusion initiatives do not need to reinvent these processes. Instead, a hub could develop a standardized playbook that includes general materials, convene stakeholders, and provide a recommended list of experts for private industry to engage with for specialized purposes.

The table below shows the Post-it note themes that most groups identified within the three categories of workforce, technology development, and outreach/economic development.

Table 1. Post-it Note Themes

Pillar	Topics Covered by Majority (5+)	Strong Alignment (mentioned by 3+ groups)
Workforce	• Develop curriculum and courses for K-16 and alternative pathways (re-training, summer camps, veterans) • Internships, apprenticeships, co-ops	• Engage via a wide variety of outreach methods
Technology	• Groups D & E did not provide input on this topic, so there are no topics with majority consensus	• Diagnostics (plasma, radiation hardened, repetition rate) • Neutron effects testing • A repository for hub members of buyers, suppliers, collaborators, and open project lists • Establish a facility for shared testing that supports the hub's needs • Align funding needs and advocacy for the hub members • Share best technology practices
Outreach and Economic Development	• Find a well-respected "celebrity" who can make the story of fusion accessible to everyone • Engage early and often • Identify and share tangible economic benefits	• Understand the market you will be working with • Identify your stakeholders early • Engage via a wide variety of outreach methods

Findings, Recommendations, and Immediate Next Steps

The workshop spurred discussion of the issues facing fusion commercialization and how the public and private sectors, working together via fusion hubs and other means, could address these issues. These discussions as well as further meetings after the workshop resulted in numerous proposed strategies, findings, recommendations, and short-term next steps that are summarized below. Many of these arise from the panel reports, where additional information is available in the Appendices.

Findings

The workshop produced the following findings:

1. General:
    a. Regional hubs or other public-private partnership mechanisms should be industry-led and formally involved in their development.
    b. Strong partnering with state and local governments, as well as the federal government, are needed in all areas of fusion commercialization.
2. Workforce Development:
    a. Initiatives like Seattle Fusion Week have alerted educators, researchers, and industry leaders to the workforce needs of fusion companies and generated ideas on how they may be met.
    b. The best way to build the fusion workforce is via a consortium that includes industry, educational institutions, governments (federal, state, and local), advocacy groups, parents, and others.
3. Technology Development:
    a. Public-private partnerships allow fusion companies to access decades of publicly funded fusion work and will be key to the success of fusion commercialization.
    b. Regional hubs working in national collaborations as needed can help address high-priority challenges in materials science and engineering, supply chain components, and other areas, including needed investment in required projects such as neutron sources.
4. Outreach and Economic Development
    a. Outreach efforts like Seattle Fusion Week raise public awareness and local support for fusion. The Clean Tech Alliance in Seattle, WA, along with its partner

organizations in San Diego, CA, Denver, CO, and Reno, NV, are well-positioned to play a pivotal role in the rapid commercialization of fusion energy in a Western a U.S. Fusion Commercialization Hub.

b. Enhanced communication with the public is essential. People will instinctively associate nuclear proliferation, Fukushima and the Hanford clean-up with anything nuclear, including fusion. The differences between fusion and fission must be clear and understandable to the public. The public will generally trust hub communications more than those from companies or the government.

c. Collaboration with business and local and state governments ensures economic growth aligns with fusion energy adoption.

Recommendations

Co-PI Mel Clark and the CleanTech Alliance team are planning to re-convene in a second workshop to be organized by co-PI Dr. Javier Garay. The second workshop will further develop these recommendations:

1. Strengthen Regional Fusion Commercialization Hubs
    a. Develop the industry-led regional Western U.S. Fusion Commercialization Hub to support workforce development, economic development, research and technology development, and revenue sharing.
    b. Strategically integrate current WA State Focus on Fusion Cluster activities with those of the proposed Fusion Commercialization Hub, including expanding Cluster activities to include more states and regions.
2. Enhance Technical Public-Private Partnerships
    a. Fusion leaders should apply lessons from Sematech and Washington's Innovation Cluster Accelerator program to advance technology development via adaptable, industry-led leadership. Other fusion centers in the western states of CA, CO, and NV have various entities and assets that are organized along these lines. Examples are the private companies and national laboratories in CA and CO, the CleanTech Industry Association in Denver, and the pulsed power research program in Reno, NV.
    b. Fusion leaders should develop mechanisms for industry up-stream technology information sharing and collaboration in diagnostics, materials, and other areas. These are highly effective, as demonstrated by Sematech.

c. Fusion leaders should create a roadmap for establishing collaborative multi-purpose hubs that address priority issues such as diagnostics, material development and testing, tritium science and engineering, first wall/blanket development, and development of needed testing facilities such as neutron sources. These hubs would also lead development of common-use supply chains for technologies such as HTS magnets, divertors and edge plasma control devices, pulsed power systems, capacitors, solid state switches, solid state lasers diodes, and optical components. These hubs should function via cost sharing, collaborations, use of shared facilities and infrastructure, and other partnerships mechanisms.

d. The fusion community should encourage multi-state collaborations as well as state matching of federal public-private partnership funds.

e. Fusion commercialization hubs should work with DOE and others to develop innovative new models for intellectual property management.

f. DOE should lead efforts to coordinate and enhance current international partnerships aimed at advancing fusion commercialization in the U.S., including leveraging models such as the Fraunhofer Institutes.

3. Develop Workforce Programs

a. The Hub should lead the development of a workforce plan for fusion that integrates current ongoing activities. The plan should be based on industry needs, cover all educational ranges, and integrate effectively with other STEM-based workforce plans. The plan should be based on the consortium framework discussed in section 2b of the findings.

b. Encourage industry to invest in 2-year, 4-year, and graduate educational institutions with a goal of increasing the visibility of fusion and related training/employment opportunities. Consider supporting endowed professorships, fusion-related laboratories, skilled technical staff, and fusion “career days.”

4. Expand Outreach and Economic Development

a. The Western U.S. Fusion Commercialization Hub, working with partners, should lead the development of outreach plans for fusion in the western United States. The Hub can provide communications and other materials for use by local and regional organizations.

b. The Hub should encourage policymakers and local businesses to prioritize fusion energy commercialization within regional economic development plans.

5. Align with Federal Initiatives
    a. Fusion leaders should continue to work with the DOE to maximize the ability of the Hub and other public-private entities to support the PPCF.
    b. The Hub should support the development of a western United States industry-led, multi-state regulatory initiative to adopt NRC and Organization of Agreement States regulation.
    c. DOE should provide ongoing program support for the Western U.S. Fusion Commercialization Hub and other similar efforts around the country and provide information regarding how the PPCF will be implemented following the second Hub workshop discussed below.
    d. Hub leadership should work with industry, federal, state and local governments, and other partners to identify resources for ongoing Hub activities.

Immediate Next Steps

1. General
    a. Formally add industry to commercialization hub leadership teams.
    b. The University of California San Diego and partners should host a second workshop in southern CA in 2025 to obtain input from the fusion communities in CA, NV, and CO. This workshop should include input from the biotech and semiconductor industries. DOE will be asked to provide financial support for this workshop and the associated enduring program.
    c. The Hub leadership team should develop and execute collaboratively funded pilot projects in each of the three hub “pillar areas” (workforce, technology development, outreach and economic development). These pilot programs, which require DOE support, will provide valuable experience and ensure that fusion commercialization hubs provide true added value to the companies and accomplish DOE’s PPCF goals.
    d. As a first step towards a hub governance plan, the hub leadership team should work with DOE and key stakeholders to define the mission, vision, core objective, and scope of fusion hubs that support the goals of the PPCF. This discussion should use the “Statement of proposed Fusion Commercial Hub Mission, Vision, Core Objectives, and Scope” in this report as a starting point.

2. Workforce Development
    a. The hub leadership team should start to gather information from the companies regarding their current and future workforce needs. These needs will drive the workforce plan so this data collection effort should begin now using the level of resources available. The recent NSF workshop on fusion workforce development will provide valuable insight on how to get started on a regional workforce plan.[16]
    b. Industry and educators should work together to build interest in fusion and the fusion workforce pipeline, particularly for K-12 students.
3. Technology Development
    a. Companies should partner with the public sector to develop diagnostics that operate in the high yield/high repetition rate regime and develop training programs for diagnostic developers and operators. This is a great "early win" opportunity to leverage public-sector knowledge in pursuit of private sector fusion commercialization success.
    b. Companies should encourage systemic data sharing and standardization for common-use systems, particularly for materials and diagnostics.
    c. Companies should use their ancillary capabilities to explore related markets, consistent with sponsor funding and intellectual property management requirements.
4. Outreach and Economic Development
    a. The Hub should develop communication materials for use in public outreach efforts.
    b. The Hub should perform a stakeholder analysis of selected regional areas to better understand the background and perspectives of the regions where fusion energy will be initially implemented. This could be a DOE-funded "pilot" project as discussed in "Immediate Next Step" 1c above.

[16] "Accelerating the Fusion Workforce," A Report from the National Science Foundation Funded Clean Energy Technology Conference C. Paz-Soldan, E. Belonohy, T. Carter, L.E. Coté, E. Kostadinova, C. Lowe, S. L. Sharma, S. de Clark, J. Deshpande, K. Kelly, V. Kruse, B. Makani, D. Schaffner, and K. Thome, (submitted Mon. Jan. 6, 2025; https://arxiv.org/abs/2501.03372).

Conclusion

Under the leadership of Mel Clark, Dr. Javier Garay, and colleagues, the CleanTech Alliance convened a significant workshop in October 2024, to advance fusion energy commercialization through regional collaboration that emphasized the importance of regionally focused workforce preparation, industry-led technology development, and economic development planning, all critical to developing a robust fusion commercialization ecosystem and furthering fusion energy's ability to provide energy dominance to the U.S.

The workshop drew lessons from past successful PPPs, such as the Sematech consortium for the semiconductor industry, and aligned with DOE initiatives like the Public Private Consortium Framework for Fusion Energy (PPCF), and regional hub development. It highlighted efforts such as Seattle Fusion Week, which has grown to become a model for regional collaboration, economic development, and workforce development in fusion energy. The CleanTech Alliance's Focus on Fusion Cluster, backed by Washington State's Innovation Cluster Accelerator Program (ICAP), has already begun successfully fostering broad regional collaboration, and stands as a model that could be scaled to manage a multi-state region with locally focused nodes, or replicated in more localized implementations.

Acknowledgements

This work was supported by DOE via FWP 84608 at Pacific Northwest National Laboratory. We acknowledge all involved in supporting this workshop and producing this report, including Lindsay McCormick (CleanTech Alliance), Jana Strasburg (Pacific Northwest National Laboratory), Washington State University/Everett for providing the meeting site, and members of the workshop organizing committee listed below:

Mel Clark, President & CEO, CleanTech Alliance, (co-PI)

Dr. Javier Garay, Associate Dean for Research, Founding Director of the Fusion Engineering Institute, and Professor of Mechanical and Aerospace Engineering, Jacobs School of Engineering, University of California-San Diego (co-PI)

Chris Ajemian, Principal, Ajemian Consulting, LLC (co-Organizer)

Dr. Christopher Keane, Professor of Physics, Washington State University (co-Organizer)

Dr. Farhat Beg, Director, Center for Energy Research and Professor of Mechanical and Aerospace Engineering, Jacobs School of Engineering, University of California-San Diego

Dr. E. Michael Campbell, President, MCM Consultants

Dr. Roberto Mancini, Trevor J. McMinn Endowed Research Professor in Physics, University of Nevada, Reno

Dr. Carmen Menoni, Professor of Electrical and Computer Engineering and University Distinguished Professor, Colorado State University

Dr. Karl Mueller, Director, Program Development Office, Physical and Computational Sciences Directorate, Pacific Northwest National Laboratory

Appendix A: Agenda

Introduction and Fusion Hub Description Chair: F. Beg (UCSD)		Speakers
8:30 AM	Welcome	M. Clark (Clean Tech Alliance), J. Garay (UCSD), K. Mueller (PNNL)
8:45 AM	DOE Perspective on Public-Private Partnerships	J.P. Allain (US DOE)
9:05 AM	WA State Dept. of Commerce remarks	T. Deets (WA State Dept. of Commerce)
9:20 AM	Overview of the Western US Fusion Commercialization Hub	C. Ajemian (Consultant)/C. Keane (WSU)
9:40 AM	Fusion Economic Study and Cluster	C. Mefford (Community Attributes, Inc.), M. Clark (Clean Tech Alliance)
10:00 AM	Break/networking	
Panel Discussions: Technology Development Chair: R. Mancini (UNR)		Speakers
10:20 AM	Technology Development Pillar: Panel I	Moderator: M. Campbell (MCM Consultants). Speakers: H. Freund (Marvel Fusion), C. Galloway (Xcimer Energy), E. Moses (Longview Fusion), M. Pattison (Blue Laser Fusion), B. Uppal (Kyoto Fusioneering)
11:20 AM	Break and Networking	
11:40 AM	Technology Development Pillar: Panel II	Moderator: A. Krishnan (General Atomics). Speakers: Tokamak Energy (M. Ginsberg), Avalanche (R. Langtry), Pacific Fusion (W. Regan), Zap Energy (R. Umstattd), T. Mehlhorn (Fuse)
12:40 PM	Break – Pick up lunch downstairs; transition to Room 102 and Networking	

Panel Discussions: Economic Development and Workforce Chair: M. Sushko (PNNL)		Speakers
1:00 PM	Economic Development pillar	Moderator: K. McAteer (WSU). Speakers: K. Dye (TRIDEC), A. Doyle (Altagas), T. Parr (WSU), B. Willson (CSU)
1:50 PM	Break/networking	
2:10 PM	Workforce Pillar	Moderator: M. Brummer (Centralia College). Speakers: T. Carter (ORNL), E. Kostadinova (Auburn Univ.), C. Menoni (CSU), J. Mota (Columbia Basin College), U. Shumlak (UW)
3:10 PM	Break	
Work Groups and Report Out Session Chair: J. Strasburg (PNNL)		
3:20 PM	Individual table work groups	
4:30 PM	Report out to broader group	
5:00 PM	Adjourn	

Appendix B: Attendee List

Last	First	Organization
Ajemian	Christopher	Ajemian Consulting
Albrecht	MariAnn	Lawrence Livermore National Laboratory
Allain	JP	U.S. Department of Energy
Beg	Farhat	University of California, San Diego
Brummer	Monica	Centralia College
Campbell	Michael	MCM Consultants
Cardillo	Carlos	University of Nevada, Reno
Carter	Troy	Oak Ridge National Laboratory
Clark	Mel	CleanTech Alliance
Deets	Tammy	WA State Dept. of Commerce
Doyle	Andrea	AltaGas
Drobnicki	Christopher	Puget Sound Energy
Dye	Karl	Tri-Cities Development Council
Freund	Heike	Marvel Fusion
Galloway	Conner	Xcimer Energy Corporation
Garay	Javier	University of California, San Diego
Ginsberg	Michael	Tokamak Energy
Gregoire	Don	Energy Northwest
Hickernell	Laura	CO CleanTech Trade Association
Keane	Christopher	Washington State University
Kelly	Kate	Avalanche Energy
Kostadinova	Eva	Auburn University
Langtry	Robin	Avalanche Energy
Mancini	Roberto	University of Nevada, Reno
McAteer	Kate	Washington State University
McCarrick	James	Lawrence Livermore National Laboratory
McCormick	Lindsay	CleanTech Alliance
Mefford	Christopher	Community Attributes, Inc.
Mehlhorn	Tom	Fuse Energy Technologies
Menoni	Carmen	Colorado State University
Mota	Jesus	Columbia Basin College
Moses	Ed	Longview Fusion Energy Systems
Mueller	Karl	Pacific Northwest National Laboratory
Nanda	Rabindra	Washington State University
Pattison	Morgan	Blue Laser Fusion
Parr	Terri	Washington State University
Regan	Will	Pacific Fusion

Last	First	Organization
Schulz	Noel	Washington State University
Shumlak	Uri	University of Washington
Strasburg	Jana	Pacific Northwest National Laboratory
Sushko	Maria	Pacific Northwest National Laboratory
Umstattd	Ryan	Zap Energy
Uppal	Bibake	Kyoto Fusioneering
Van Dyk	Greg	Altrusion
Willson	Bryan	Colorado State University
Zare	Arezoo	Washington State University

Appendix C: Fuller History of Fusion Public Private Partnerships and the Rise of Private Companies

In his 50-year perspective treatise on fusion energy R&D, Tom Mehlhorn states the guiding principle of U.S. fusion strategy is that private industry will drive the commercialization of fusion energy and public-private partnerships will accelerate the development of fusion energy concepts overall. Public private partnerships in fusion are now experiencing a quickening as confidence grows that the technology will soon be available. In the 2010s venture capital investment in companies like TAE Technologies and General Fusion birthed the first significant private sector activity. Larger rounds of capital helped companies like Commonwealth Fusion Systems and Helion Energy spin out of MIT and the University of Washington. These developments, along with successful magneto-inertial confinement fusion (MIF) experiments at Sandia National Laboratory in 2014, gave rise to changes in the long standing "public science" model of federal funding for fusion research that had provided steady incremental progress in the understanding of fusion science over many decades.[17]

ARPA-E Gains a Fusion Mission

DOE's ARPA-E agency changed the public science approach by funding faster paced, time limited, narrowly focused projects that gave crucial early support to the fledgling fusion private sector. The first example was its Accelerating Low-Cost Plasma Heating and Assembly (ALPHA) program. ALPHA catalyzed the growth of the modern fusion industry in several ways, including: (1) funding University of Washington research on flow Z-pinches that led to the creation of Zap Energy, (2) supporting efforts at Sandia National Laboratories and the University of Rochester to advance the MagLIF concept, work that is now being built upon by companies such as Fuse Energy Technologies and Pacific Fusion, and (3) providing early support to startups like Helion Energy.[18] Other fusion companies such as Type One Energy, First Light Fusion, Tokamak Energy, CTFusion, Realta Fusion, Xcimer Energy, and Avalanche Energy formed around this time. ARPA-E followed its ALPHA program with BETHE (Breakthroughs Enabling Thermonuclear-fusion Energy), which expanded the number of awards and provided some follow-on projects for prior awardees,

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[17] Tom Mehlhorn, "From KMS Fusion to HB11 Energy and Xcimer Energy, A Personal 50-year IFE Perspective," Phys. Plasmas 31, 020602 (2024); doi: 10.1063/5.0170661 (published online 28 February 2024).

[18] See Tom Mehlhorn, "From KMS Fusion to HB11 Energy and Xcimer Energy, A Personal 50-year IFE Perspective," Phys. Plasmas 31, 020602 (2024); doi: 10.1063/5.0170661 (published online 28 February 2024), the ALPHA program page, and Retrospective of the ARPA-E ALPHA Fusion Program.

and GAMOW (Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts), which supported high-duty fusion drivers, advanced materials, and additive manufacturing. ARPA-E's current program is CHADWICK (Creating Hardened And Durable fusion first Wall Incorporating Centralized Knowledge), which pursues the discovery of advanced materials for plasma facing first walls.

FES Programs

Before ARPA-E's commercialization emphasis, DOE's Office of Fusion Energy Science was the traditional source of public funding for fusion energy science R&D with a major focus on tokamaks. One of its early PPPs was its Innovation Network for Fusion Energy (INFUSE), a program that emphasizes small collaborations between private companies and DOE laboratories or federally funded universities.

In 2022, the National Academies of Science report "Bringing Fusion to the U.S. Grid" asserted that the knowledge developed through decades of fusion research was now sufficiently advanced to propose a path to demonstrate fusion-generated electricity and that the Department of Energy should move forward to develop a commercially viable fusion power plant in the 2035-2040 timeframe.[19] These recommendations inspired the DOE's Office of Science to proclaim a Bold Decadal Vision to develop a strategy "to accelerate the viability of commercial fusion energy in partnership with the private sector." To realize this vision, under the first Trump administration FES proposed what would become the Milestone program on the principles of NASA's Commercial Orbital Transportation Services (COTS) program to commercialize low Earth orbit launch rocket technology.

Later, on December 5th, 2022, the National Ignition Facility at Lawrence Livermore National Laboratory reported ignition (more energy out of a fusion reaction than was used to create, heat and confine the plasma) as defined by the National Academy of Sciences. This development was a major scientific achievement and increased momentum in not only laser-based inertial confinement approaches, but magnetic concepts as well. Acknowledging this accomplishment, FES created the Inertial Fusion Energy Science & Technology Accelerated Research (IFE-STAR) program. While not an actual PPP, IFE-STAR provided funding for IFE research at universities and national laboratories that would soon be working with companies that were pursuing inertial fusion energy commercialization.

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[19] National Academies of Sciences, Engineering, and Medicine 2021. "Bringing Fusion to the U.S. Grid." Washington, DC: The National Academies Press (https://doi.org/10.17226/25991).

Up until this time, most private fusion companies belonged to the magnetic confinement camp, which included concepts like tokamaks, stellarators, spheromaks, and magnetic mirrors. Some had augmented their approaches with the advent of more powerful high temperature superconducting magnets. But the Milestone program brough both MFE and IFE companies under the same public fusion roof. By this time, a variety of magnetic, inertial and magneto-inertial hybrid approaches, such as Longview Fusion, HB11 Energy, Thea Energy, Marvel Fusion, Xcimer Energy, and Blue Laser Fusion had been established. In fact, commercialization allowed several alternate fusion concepts to experience a resurgence, thereby broadening the range of approaches available to U.S. industry.

While the Milestone and IFE-STAR programs represented great progress in fusion science that justified the beginning of commercialization, many in the fusion community recognized the need for more experimental data, which entails the construction of a new generation of larger, more expensive and highly capable demonstration fusion machines. Moreover, the new private sector focused on speed, intellectual property, and in some cases, noncooperative vertical alignment. It criticized FES and ARPA-E programs for their cumbersome contracting and partnering requirements (such as CRADA agreements), IP constraints, and the low level of funding that prevented significant leaps in scientific and technological understanding.

New FES Director

Dr. Jean Paul Allain became the new director of FES in 2023 and began revising the federal government's fusion energy strategy with a new DOE Decadal Fusion Energy Strategy Since FES has a science mission, the DOE office had to confront a separate commercialization need without significant new funding. The Fusion Innovation Research Engines (FIRE Collaboratives) program later augmented the Milestone program with additional support to private companies. It focused on burning plasma technology, advanced materials, and balance of plant technologies that would be required to create fusion fuel and generate electricity.

Looking Ahead

The remaining tasks for the commercialization of fusion energy are large. The fusion community must now turn from learning the science of fusion plasmas to developing the engineering of future fusion power plants. In a time of tight federal budgets, it is hoped that the financial burden for this phase be born through partnership between the public and private sectors. Additionally, government, the private sector as well as the general public, must now commence the broad economic development required to support fusion industrialization and power plant construction. Like the other phases of fusion energy development, it will be a monumental undertaking that requires a decade or more of planning and execution. Fortunately, many of the needs for fusion commercialization are not unique to fusion and have been established in adjacent fields like aerospace, power electronics, artificial intelligence and others.

PPCF

FES' next partnership with the private sector could be a program that implements the Public Private Consortium Framework (PPCF) for Fusion Energy Commercialization Request for Information. A regional economic development hub, such as the Western United States Fusion Commercialization Hub discussed at the October 23rd, 2024, workshop in Everett, WA, could adapt principles from the privately led Sematech consortium. This consortium provided for competing U.S. semiconductor firms to cooperate to answer the competition from Japanese firms in the 1980s. The Sematech model was not perfect and eventually faltered. It ground to a halt when various firms began to act independently. Ultimately, the CHIPS Act was required to correct its flaws. But it provided an example of how individual members of an industry could cooperate in creating central suppliers to manage the extraordinary costs of semiconductor design and fabrication.

Appendix D: Public-private Partnerships and the Fusion Workforce

Moderator: Monica Brummer, Director of the Pacific NW Center of Excellence for Clean Energy Centralia College

Creating a Fusion-Ready Workforce: Summary of workforce discussions, Seattle Fusion Week 2024

Economists have shared that the overall U.S. workforce pool is shrinking; and between now and 2030, we will see the lowest growth of the working-age population since the Civil War.[20] Businesses are seeing fewer applicants; and there is an increasing knowledge gap as experienced workers retire.

The workforce landscape has changed. Applicants bring varied values and skills. Our workforce is in an era that includes opportunities for workers to live anywhere and earn remotely, to earn high wages without a degree, and to become a high-wage social media influencer.

So, how do emerging technologies such as fusion energy recruit from an increasingly changing workforce pool? How do fusion companies prepare workers for delivering clean electricity within the next decade? How do we train and motivate the next generation of workers? Students who are now in the third grade will be entering the workforce at the time fusion enters its commercialization phase.

2024 Seattle Fusion Week: Collaboration is key

The CleanTech Alliance, the nation's largest clean technology industry association, gathered experts during 2024 Seattle Fusion Week to share best practices and solutions. Presenters and panelists discussed technologies, supply chain development, economic development planning, and workforce development strategies. At the top of the lists of strategies was the need for industry to collaborate, create a consortium, and share.

Accelerating the Fusion Workforce, a Report from the National Science Foundation funded Clean Energy Technology Conference, led by UCLA, was included within the workforce panel discussion. According to the report, the workforce needs of the nascent fusion

[20] Economist and Forbes online contributor, Bill Conerly, PhD.

industry are growing at a rate that academic workforce development programs are not currently able to match.[21]

How do we, as industry and education partners, work together to solve this dilemma? Industry needs to collaborate and be proactive in building an ecosystem in an intentional way that includes foresight.

The workforce panel, which was the final panel before groups broke out into workgroups, included:

- Troy Carter, Director of Fusion Energy Division at Oak Ridge National Laboratory, professor of Physics, Director of Basic Plasma Science Facility and Plasma Science and Technology Institute, UCLA
- Carmen Menoni, Professor of Electrical and Computer Engineering, Colorado State University
- Evdokiya Kostadinova, Assist. Professor in Physics, research in plasma physics, Auburn University, Alabama
- Uri Shumlak, Professor of Aeronautics & Astronautics University of Washington; Fellow, American Physical Society; Associate Fellow, American Institute of Aeronautics and Astronautics; Senior Member, Institute of Electrical and Electronics Engineers; Co-founder, Zap Energy, a spin-out company from UW to develop commercial fusion applications.
- Jesus Mota, Dean of Career & Technical Education, Columbia Basin College, overseeing nuclear technology, manufacturing technology, automotive, occupational health and welding.
- Panel moderator: Monica Brummer, Director of the Pacific Northwest Center of Excellence for Clean Energy, and co-chair of local and global hydrogen workforce committees.

The panel reviewed the UCLA report and gathered comments specifically for the West Coast region. The following is a summary of topics, questions and discussions.

[21] "Accelerating the Fusion Workforce," A Report from the National Science Foundation Funded Clean Energy Technology Conference C. Paz-Soldan, E. Belonohy, T. Carter, L.E. Coté, E. Kostadinova, C. Lowe, S. L. Sharma, S. de Clark, J. Deshpande, K. Kelly, V. Kruse, B. Makani, D. Schaffner, and K. Thome, (submitted Mon. Jan. 6, 2025; https://arxiv.org/abs/2501.03372).

The Phases of Fusion and its Workforce

Fusion can be categorized into two phases: scientific exploration and commercial exploration.

New science discoveries are still occurring, which means industry needs physicists and engineers to work on theory (historically, fusion energy education has only been offered through physics and nuclear engineering). Mechanical engineering has climbed to the top of fusion needs, followed closely by physics and electrical and aerospace engineering.

Machinists are needed to create new parts and widgets as theories are tested. Machinists and advanced manufacturing technicians will need to be trained to replicate successful theories for the commercial phase. Those in manufacturing will support commercialization as the second phase continues to expand.

Panelists agreed that there is a lot of work to do. There needs to be a workforce pipeline for technicians, fusion/plasma curriculum and lesson plans, 10-course graduate degrees that focus on fusion, dual credit courses for high schools and colleges, and methods of tracking graduates.

As we track changes within industry, we also need to note that building a pipeline of educated and trained workers takes time. Two to four years are needed to build and launch full degree programs.

State of Workforce Planning

What is the state of workforce planning for fusion—across all educational levels—as you see it? Name some strategies for engaging diverse academic institutions in the four-state fusion hub.

We, as industry and education partners, need to understand:

- What is already in place? Surveys are needed across the region to gather information about existing programs, programs that can be bridged between research and existing coursework, certificated programs (often in other college departments), and gaps. For example:
  - Within Washington State’s 34 community and technical colleges: 26 offer programs in advanced manufacturing, machining, welding and related fields; 28 offer physics and engineering; and three offer baccalaureate degrees that include Advanced Manufacturing and Design, Engineering Technology and Manufacturing Engineering Technology.

    - Colleges located near fusion development can strategically incorporate fusion curriculum into existing programs to begin exposing students to emerging technology.

- Gaps in workforce training. Surveys may also reveal gaps within plasma physics, materials science, vacuum technologies, pulse power, and lasers. A one-stop-shop is needed for industry and future students.
- Alignment. Follow-up is needed to align stackable credits and certificated programs. The value of education needs to align with careers. Nuclear education is successful because graduates earn high-wage salaries that compete with other industries.
- Timelines. Who is being hired today? What about the future? How many people are needed to be trained and hired? What skills are needed to support this industry?
- Who will teach? Educators need training too. They need tours, externships, and tool kits to be able to incorporate new technologies and new science theories into existing courses.

Incentives are needed—such as internships and apprenticeships that will build workforce pipelines, offer experience, and provide mobility. Internship opportunities are extremely rare—especially for undergraduate students.

Workforce Mobility

How are technologies enabling other fields, thus allowing for workforce mobility in and out of fusion?

Panelists encouraged the development of a workforce taskforce that includes industry, organized labor, tribal members, and educators. The taskforce should:

- Invite physicists, engineers, machinists, electricians (capacitor and pulse power operators), and plasma specialists.
- Hold listening sessions/DACUM (Developing a Curriculum) that allow educators to listen to industry representatives to learn about skills that are needed within the region.
- Identify roles within the region: What are the roles of universities, colleges, and industry partners, and what are companies pioneering in the region?
- Identify skills that are transferable from other industries – such as aerospace and manufacturing. Offer short-term credentials that allow workers to layer fusion into their knowledge base.

- Develop targeted recruitment of mid-career professionals.
- Invite industry reps to become adjunct faculty. Those who work in industry will have an advantage of meeting and recruiting students into openings.

The discussion continued to include what can be done to incorporate curriculum on a national level. The example of hydrogen hubs can provide many lessons learned:

> Hydrogen hubs are facing curriculum gaps at the two-year college level. The commercialization of green electrolytic hydrogen is new, even for organized labor. There are safety concerns that need to be addressed. It makes sense that a national lab, such as the Pacific Northwest National Laboratory (PNNL), takes the lead at coordinating national level work to avoid duplication in hubs across the nation. PNNL is collaborating with representatives of national unions, community colleges and the Center for Hydrogen Safety on how to create green hydrogen safety curriculum for training.

Next Steps

What are the key next steps to developing a western U.S. fusion workforce plan? Discuss key local, regional, and national components, including the role of the PPCF.

As stated earlier, collaboration rises to the top. All fusion companies should have representation within a consortium to share needs and best practices. This leads to:

- Combined networking, common recruitment sites, and a local chapter of something national.
  - The National Hydropower Foundation supports chapters called Waterpower Clubs[22] in higher education that include students in other academic areas such as marketing, design, welding, and accounting. These students gain knowledge of hydropower careers and often apply for jobs in that industry.
  - Can the physics groups have a fusion focused chapter?
- Increased partnerships, such as:
  - Industry at local colleges. Serve on advisory boards, donate equipment for training, visit classrooms, become mentors, encourage retirees to stay in industry by sharing experience as an adjunct.

[22] https://waterpowerclub.hydrofoundation.org/hydropower-industry-partners/; https://waterpowerclub.hydrofoundation.org/.

  - Two-year college faculty enrollment in university research programs.
  - Connections between manufacturers and educators for training and equipment.
  - College-Training-Registered Apprenticeship agreements.
- Enhanced communication such as sharing job openings.
- Colleges need job data, SOC codes, and job descriptions. Build a fast-track path into a fusion career, such as a one-year master's degree that is connected to an apprenticeship program.
- Alignment of all strategies listed within this document – as well as developing trust between industry, unions, and higher education.

Building a national consortium was also the answer to how states can contribute to a national strategy for fusion curriculum.

K-12 Strategies

Consider the upcoming workforce. What specific strategies for K-12 outreach and public engagement exist or should be developed in a four-state regional hub?

All too often, industry and educators look to each other to solve career awareness problems when they should be working together to build interest and a workforce pipeline. How?

- Recognize this isn't a "one and done thing" and that the efforts of all parties need to be continued.
- Identify existing outreach tools that can be easily updated, such as the Foundation for Water & Energy Education's (FWEE) NW Sources of Electricity Activity Guide[23] and summer STEM academies.
  - During the summer, energy/STEM academies led by FWEE, organizers added hydrogen fueled cars that allowed participants to make small amounts of hydrogen. Students were encouraged to keep the cars and use them at home (to educate parents and family).
- Emphasize interdisciplinary skills in STEM such as critical thinking, collaboration and engineering principles.

[23] https://fwee.org/education/northwest-sources-of-electricity/

- Invite educators, such as superintendents, Career and Technical Education (CTE) directors and science faculty, to visit emerging technologies through site tours or longer excursions, such as externships.
  - Columbia Basin College (CBC) secured an advanced manufacturing NSF grant that involved 3-D printing. The program invited teachers, offered free 3-D printers and training. Teachers incorporated the printers into their classroom. One CBC faculty is working in high schools and leading dual credit (high school and college) for those classes.
- Find a way to get fusion into the existing curriculum that will also give students college credit. Talk about fusion in the concept and sense of stars. Have the science embedded so students hear the word fusion and want to know more about it so that fusion becomes a common word.
- Build career awareness programs such as tool kits that include safe, engaging classroom experiments.
- Showcase professionals in the fusion field, especially those from unique backgrounds, who can make careers more relatable and attainable.
- Visit classrooms and offer Fusion 101.
  - Fusion company employees visit middle and high school classrooms and lead a hands-on learning activity that promotes fusion and safety. They do this to ensure students do not become afraid of fusion.
- Offer tours and events that accommodate students.
  - The University of Washington (UW) hosts annual discovery days for 4th–8th grade students who tour all labs—starting with the UW College of Engineering. The tour includes a few wow-factor demonstrations such as using pulse power to electromagnetically crush aluminum cans, and the Los Alamos famous Z-pinch.
- Survey various institutions, collect information, and build an engaging traveling show that reaches students in rural communities.
- Connect to families to build interest, passion, and support. If parents don’t know about it, then they cannot advocate for it.

Challenges and Barriers

What are barriers to developing and executing an effective fusion workforce development plan?

The panelists didn't want to end the discussion without discussing barriers. They are passionate about fusion; and using quotes best describes the discussion.

- "If we start building from scratch today, it will be very difficult."
- "Let's be clear – it takes money to get this done."
- "Getting institutions to work together. Getting two departments to work across an institution is hard enough. We need to encourage people to work together. We need to find a way to break down barriers. A consortium can do that to increase educational opportunities."
- "Universities are underutilized. Plasma programs need fusion faculty. Universities need to increase engagement with high schools, students, teachers, and parents. A lot of work needs to be done at the pre-college level."
- "We don't have the skill steps internally to start training programs or to purchase equipment. Most of our faculty are from industry. We don't want to burn out industry."
- "We struggle with image. It's not just about fusion innovation. There's a lot of science involved. Fusion comes from space and the stars. There's fear of nuclear weapons and energy dependence."
- "We have industries poaching our students before they graduate. It's hard to stand up a new program and even more difficult when big businesses, such as Boeing and Amazon, ask for specific training that only fits their needs (and then hire the students before they finish the program). Note: poaching lowers enrollment and funding to colleges."

It's in the Stars (conclusion)

All participants agreed that creating a consortium is the best way to build the fusion workforce; and industry tackling this topic in silos won't be effective or efficient. Collaborating best practices, resources, and ideas between industry, educators and trainers will fill gaps and keep our workforce in our region.

Collaboration is needed to solve the declining trends in STEM. In a separate panel during 2024 Seattle Fusion Week, the following statistics were shared:

STEM by the numbers in Snohomish Region: By 2030, 75 percent of high-demand, family-sustaining wage jobs in this region will require a postsecondary degree or credential. Forty-three percent of those jobs will be STEM or STEM literacy-based occupations. Trends show that only 41 percent of the high school class of 2021 was projected to be on track to attain postsecondary credentials by the age of 26. To meet the 2030 labor market demand, 281 students each year will need to be on track to earn credentials by the age of 26.

Forty-one percent of graduates attending college is a high percentage in many rural areas within our region. We need to maintain a student's point of view and train students for careers. Educational institutions should add credentials and ongoing continuing education opportunities to make students more marketable.

Using star power to explain fusion, building traveling demonstrations to reach rural areas, inviting educators into research facilities, and educating families to build advocacy are all components of building a workforce. It is a team effort.

Industry needs to step up and incentivize workforce development programs at institutions that serve diverse populations and ensure there are jobs for students after they complete their training.

Appendix E: Summary of Tech Panel I – Advancing Fusion Technology Development

Moderator: Dr E. Michael Campbell, President, MCM Consultants

The workshop on developing a Western U.S. Fusion Commercialization Hub featured two technology development panels. The panel discussed here consisted of E. Michael Campbell (moderator), Conner Galloway, Edward Moses, Morgan Patterson, Heike Freund, and Bibake Uppal. Campbell, President of MCM Consultants, has recently retired as the Director of the University of Rochester's Laboratory for Laser Energetics (LLE) and is presently a Professor of Practice at UCSD, Conner Galloway is a founder and chief scientific officer of the fusion company, Xcimer Energy, Edward Moses is the founder and CEO of Longview Fusion, Morgan Patterson is a consultant to the fusion energy company, Blue Light Fusion, Heike Freund is the COO of Marvel Fusion and Bibake Uppal is the chief executive of Kyoto Fusioneering-USA.

A goal of this workshop was to develop a vision and strategy for a Fusion Commercialization Hub that would bring together state/local government, private, philanthropic funding, and partnerships to accelerate fusion energy research, development, demonstration, and deployment. By motivating funding and support from non-federal entities, it is hoped that federal support will be catalyzed and amplified.

With the exception of Kyoto Fusioneering, the panel membership and focus were on Inertial Fusion Energy (IFE) concepts driven by lasers. Kyoto has an interest in IFE, but the company's strategy is to address the broad range of engineering challenges for all fusion concepts based on deuterium-tritium fuel. The more recent interest in IFE has been motivated by the demonstration of scientific gain (Q_{sci}), defined as fusion energy output divided by the incident energy to heat, compress and confine the plasma. The highest performing National Ignition Facility (NIF) experiment had a Q_{sci} of ~2.4 with over 5 Megajoules (MJ) of fusion being produced with an incident laser energy of ~2.2 MJ. NIF of course is a science facility, funded to support national security and is not a prototype of an IFE plant. No other fusion process has achieved Q_{sci} greater than 1, with ~ 0.75 being the highest value from a tokamak. The SPARC tokamak under construction by Commonwealth Fusion Systems (CFS) hopes to achieve Q_{sci} greater than one later in this decade.

The panel discussion began with each member describing their role and the company's approach to fusion. Conner Galloway described Xcimer's approach to develop low cost (~$50/joule), high energy KrF lasers and leverage chamber designs that utilized liquid walls to breed the tritium and protect structural materials from the fusion radiation. This approach is leveraging significant work previously done for heavy ion drivers and national security. The high energy (~10 MJ) of the 248 nm laser relaxes target physics issues and should produce the fusion gains needed for IFE. Xcimer Energy is one of the companies funded by DOE's Milestone program. Longview's fusion approach described by Ed Moses is based on the LIFE project funded at Lawrence Livermore National Laboratory (LLNL) and utilizes the targets that NIF has employed to achieve fusion gain. The driver is a diode pumped solid state laser with on target energy ~3 MJ designed to produce adequate gain for IFE. A positive feature of the laser driver is that wall plug efficiencies in the range of 15% are credible. Blue Light Fusion, founded by Shuji Nakamura, 2014 Nobel Prize winner, is a relatively new company that is developing a novel temporal pulse stacking laser architecture. Morgan Patterson briefly described their efforts to date.

Heike Freund briefly discussed Marvel's innovative target concept that utilizes high intensity ($I > 10^{20}$watts/cm^2, 532 nm) light to irradiate nanostructured targets containing fusion fuel. Marvel is based in Germany and has an office and growing relationship with Colorado State University in Fort Collins. Bibake Uppal described Kyoto Fusioneering whose strategy is to look at the full fusion power plant and develop common fuel systems, such as tritium, and thermal and exhaust systems. A tritium cycle is common to both inertial and magnetic concepts, and they are looking to develop common systems and then adapt/modify them to specific concepts.

Since advancing the commercialization of fusion is a major goal of the proposed Hub, the focus of the panel discussion was to explore any technologies or science that is shared by the various fusion companies. These "shared" topics would help motivate the development, the infrastructure, and supply chains that would be required for both the near-term development of fusion and the long term if fusion is to have a significant impact on the world's growing demand for energy. The topics that were discussed in the panel are the following:

1. driver technology and any related pulsed power.
2. target fabrication.
3. tritium and the related issue of plasma facing components that must survive the radiation from DT fusion and enable economic production of power.

Laser Drivers

The two most compelling lasers for IFE are pulsed power (high energy electron beams) driven excimer lasers (Xcimer) and diode pumped solid state lasers (Longview, Blue Light Fusion and Marvel). The technologies and supply chain issues are very different for the various lasers. For example, excimer lasers are driven by pulsed power (capacitors and switches driving high energy electron beams). These technologies share many common features to IFE companies driven by impedance matched MARX generators such as Pacific Fusion and Fuse. There is also technology overlap with companies with different fusion approaches (Zap with velocity shear stabilized Z-pinches and Helion with colliding FRC plasmas). While there will be somewhat different requirements, all the companies will need high energy storage, long lifetime capacitors, and solid-state switches with rep-rates ranging from a fraction of a Hertz to 10 Hertz that are affordable, and with an infrastructure that can handle the supply needs in a reasonable time. The capacitor supply chain during the cold war was ten times what it is today and must be rebuilt. One goal of the workshop as mentioned above was to address infrastructure and supply chain issues. This area would clearly benefit from companies working together to supply the requirements and to seek funding from a variety of sources (including DOE and DOD). A position being explored (and taken) by the companies requiring pulsed power is to “do it alone” for their own needs. In the absence of dedicated funding and committed interest from the present pulsed power companies, this is the fallback position that most fusion companies will pursue.

A major need for solid-state laser drivers is cost reduction for laser diodes. As Ed Moses described, the cost of laser diodes has fallen dramatically over the past decade from approximately $10/watt to $1/watt. This drop in prices has been driven by industrial use of lasers and somewhat by DOD’s need for directed weapons, but not by fusion. Fusion has some different requirements from those used presently in industry and defense, in that they must be pulsed and not a continuous wave as used in these other applications. There are additional challenges on lifetime and thermal management where there is less “industrial experience.” Nonetheless, getting the diode cost to a few cents per watt is credible and would benefit from companies working together with the existing manufacturing base to seek funding and work to this goal. Advancements in diode fabrication and reliability are also needed.

Perhaps the most difficult challenge for solid state lasers is the gain media. The large apertures (>~10 cm) required for IFE systems require the development of doped glass, crystals, or ceramics that can handle high energy and high power. Significant research and infrastructure development were required for the “single shot” NIF laser glass over two to three decades ago and this capability no longer exists. LLNL is proposing an energy upgrade to NIF that is only possible because of existing Nd doped glass left over from production from the Laser Megajoule (LMJ) laser in France. Recognizing supply chain issues of critical materials (rare earth materials) must be a component of the solid-state laser strategy. Another supply chain challenge for solid state drivers is the need for nonlinear crystals to frequency up-concert the near infrared light of Nd to the ultraviolet (~350 nm) required for target physics.

Another major issue for all laser-based approaches is the optical components that are the elements of any laser architecture. These components, including gratings for approaches that use psec pulses such as fast ignition or Marvel nanostructure targets, must be able to handle the pulse fluence (Joules/cm^2), the average power, and long duration lifetime (10^4 to 10^6 pulses/day) for the optical components of the IFE laser system. The impact of radiation on the components in proximity to the chamber is an additional concern.

Targets

Commercial IFE plants will require several 10^4 to 10^6 targets per day that are capable of the fusion gain required for the plant. Numerous economic studies on IFE have concluded that the total cost of a target (material, fabrication, characterization) should be less than a dollar (Ed Moses of Longview stated confidence for target costs in the range of $0.25–$0.30). Most IFE laser companies are focused on wetted foam targets with foam densities in the range of 50 mg/cm^3 or less compared to the ~200 mg/cm^3 of liquid DT. The interest in foams is severalfold-the major interest is the more rapid filling of targets and resulting in-plant DT inventory of less than one kilogram. Other reasons are the ability to shape the foam to compensate for low mode drive asymmetries and the potential for foam mass production via fabrication using two photon printing. IFE approaches that rely on targets other than foams are also being pursued.

In addition to fabrication, the targets must survive injection into the fusion chamber and be tracked and irradiated by the laser beams. Since ICF has been primarily funded for national security, there has been little investment in mass producing targets and injection. (Targets at NIF and OMEGA at the University of Rochester's Laboratory for Laser Energetics (LLE), the only facilities in the U.S. that conduct implosion experiments, place the targets on stalks and conduct ~100 high performing implosion experiments a year). Research and engineering on these two topics are critical for the successful development of laser driven IFE. DOE has recently funded a FIRE collaborative, led by General Atomics, to address IFE target fabrication and target engagement issues.

Tritium

While some companies are exploring fusion fuels that are not DT, first generation fusion reactors will almost certainly rely on this fuel. A GW electric plant will "burn" about a kilogram of equimolar DT fuel a day. Tritium is radioactive (beta emitter with end point energy ~18 keV) with a half-life of ~12 years and must be bred in the fusion plant. The

14.1 MeV fusion neutrons interaction with lithium will breed tritium and all DT fusion concepts will have breeding blankets containing lithium. Blankets that have been suggested include FLIBE (lithium fluoride and beryllium-fluoride), lead-lithium, pure lithium, and solid ceramics. Key metrics that influence the plant economics include the fuel "burn-up" fraction per pulse (or discharge), the breeding fraction (ratio of tritium bred to tritium consumed), and the potential need for enriching Li-6 (lithium-6 and lithium -7 are the two natural isotopes of lithium with relative abundances of ~8% and~ 92% respectively). Neutrons interacting with lithium-6 produces tritium in an exothermic reaction and adds energy to the blanket whereas neutrons interacting with lithium-7 is an endothermic reaction.

In IFE, high gain targets burn up ~30% of the fuel so in addition to breeding, the unburnt fuel must also be recovered. In most magnetic fusion approaches, only ~1–2% of the fuel is burnt. Breeding fractions must be greater than one, and most approaches aim for values in the range of 1.1. The tritium of course must be separated from the breeding blanket, and this is an area that also has not received adequate attention. In IFE approaches, the fusion takes place in ~1 cm^3 region in the center of the chamber and this enables a variety of "plasma facing first wall" concepts including liquid walls which serves to protect any structural walls, breed tritium, minimize activation of structural components, and serve as the energy carrying fluid to the heat exchanger. A fusion event will vaporize some of the liquid wall (depending on yield per pulse and liquid composition) with estimates in the range of tens of kilograms and there must be time for the chamber to "reset" before the next pulse. Xcimer Energy is developing this approach whereas Longview is focused on a ceramic breeder wall that must be replaced every several years. IFE also produced x-rays and ions in addition to the neutrons and methods to protect (or extract this energy) from the structures from this additional radiation are also a challenge and feature of IFE.
The panel discussed this topic, including the need to adequately evaluate the waste stream from any DT fusion concept. Recognizing supply chain issues of critical materials (i.e., lithium) must be a component of the tritium strategy.

What role/value is there in a fusion hub to advance the commercialization of fusion?

A coordinated, multi-state fusion hub could serve as a catalyst for technology advancement by providing shared resources and facilities and motivate both state and federal funding to address common challenges shared by fusion companies (recognizing IP issues). A hub would involve national laboratories, industry (fusion companies), those in the "supply chain," and universities.

Possible benefits include:

- Centralized and shared Testing Facilities: Hubs could enable testing of fusion blankets, first-wall materials including liquids, and tritium science and engineering (breeding or recovery). Since most tritium knowledge is in selected national laboratories and NOT in companies, this is a major opportunity for a fusion hub.
- Target fabrication (IFE) and Diagnostic Tools Development in "radiation rich environments": Creating shared diagnostic capabilities for plasma and materials testing including rep-rated experiments for any pulsed concept, is a critical area currently underfunded and underdeveloped. For IFE, the development of target fabrication science and engineering is critical and common to most companies.
- Collaborative Environment: Encouraging partnerships and developing funding strategies among private companies, universities, and government agencies to tackle common challenges across a range of topics as discussed in the text above.
- State and Federal Synergy: Aligning state resources with federal funding initiatives to maximize investment impact, including EPSCoR states such as Nevada.
- Near-Term Applications: Supporting companies to identify and develop non-grid applications for both fusion and associated technologies (e.g., defense, industrial heat, water production, hydrogen) that could generate revenue while grid-scale fusion matures.
- Public engagement: Public awareness of the benefits and challenges for fusion is an important component that a hub could provide. Public trust must be developed for both the acceptance and siting of fusion plants.

Findings and Recommendations

Technological Challenges:

- Tritium science and engineering: Fueling, breeding and recovery
- Material qualification including liquid walls and tritium retention remains a major challenge for DT fueled fusion; innovative approaches like facility sharing and early-stage testing are critical
- Development of high-repetition-rate systems (for IFE, targets driver and optical components) is essential for commercialization, requiring both technological and operational advances

- Diagnostics development needs increased attention, particularly for high-yield, radiation rich regimes and power plant conditions
- Mass production of targets

Policy and Funding Strategies:

- Encourage state-level matching of federal funds to amplify investment
- Develop opportunities in EPSCoR states
- Develop acceptance and public trust for fusion
- Advocate for systematic data sharing and standardization, particularly for materials and diagnostics
- Highlight the role of hubs in de-risking private investment by providing validation and collaboration opportunities
- Encourage investment in universities by public and private sources such as establishing endowed and named chairs for the long-term development of the needed workforce
- For ICF, explore national security applications that require high performing targets but not at the rep-rate required for commercial fusion energy

Collaboration Models:

- International cooperation initiatives with countries such as U.S., UK, Germany, Japan, South Korea, and Canada (tritium focus with Canada), could possibly accelerate development, particularly in areas like tritium science and engineering and material testing. Lessons learned from the ITER Project would be useful.

Private Sector Engagement:

- Encourage private companies to invest in shared infrastructure by demonstrating long-term cost savings and collaborative benefits.
- As mentioned above, encourage investment in universities through vehicles such as endowed chairs (at junior colleges, colleges and universities) that focus on fusion engineering, science, and trade skills needs.
- Explore open-source tools and shared diagnostics to reduce duplication of effort and promote innovation.
- Motivate and encourage federal programs like the “CHIPS and Science Act” to develop the infrastructure and supply chain needed for large scale fusion deployment.

Short-Term Next Steps

Establish Key Partnerships:

- Advocate and support alliances between federal agencies, e.g., DOE (including NNSA and NSF) and private sector players to coordinate funding and facilities.
- Facilitate multi-state collaborations and partnerships, learning and leveraging models like ARCHES and Pacific CREST to align regional resources.
- Develop a strategy vision for a multi-state hub building on the strengths of the individual states (technical, educational, and political).

Develop Shared Facilities:

- Create a roadmap for establishing multi-purpose hubs that address diagnostics, tritium S&T, material testing, target fabrication and technology validation.
- Prioritize the development of first wall (including liquid walls) and blanket testing capabilities to fast-track material qualification.

Encourage State Involvement:

- Advocate for state matching programs and regulatory frameworks that incentivize private investment with an increased focus on workforce needs.
- Advocate state and federal legislatures (Senate and House) to develop fusion funding pathways.
- Further develop multi-state public advocacy.
- Work with state energy commissions to align fusion efforts with clean energy, grid integration goals, and other energy needs (water and hydrogen).

Focus on Diagnostic Tools:

- Increase funding for diagnostic R&D, particularly those addressing plasma behavior and high-repetition-rate operations.
- Develop training programs for diagnostics and materials testing in collaboration with universities.

Promote Early Market Opportunities:

- Identify and support near-term applications for fusion and related technologies, such as defense and industrial heat.
- Encourage companies to explore ancillary markets (e.g., HTS systems and liquid metals) to build revenue streams and expertise.

Appendix F: Summary of Tech Panel II – Advancing Fusion Technology Development

1. Panel Overview

Moderator: Dr. Michael Ginsberg, President, Tokamak Energy

Participants:

- Robin Langtry (Avalanche Energy): Focused on compact, modular fusion reactors using an Orbitron-hybrid design.
- Will Regan (Pacific Fusion): Developing high-current pulse systems for inertial confinement fusion (ICF).
- Ryan Umstattd (Zap Energy): Specialized in z-pinch plasma discharges and liquid metal technologies.
- Tom Mehlhorn (Fuse): Advocating for a pulsed power approach and university-based pulsed power facility.

The panel began with an introduction by Roberto Mancini and set the stage for discussions about how a fusion commercialization hub could advance fusion technology, emphasizing technological collaboration, diagnostics development, and material qualification challenges.

2. Fusion Commercialization Hub: Advancing Technology Development

A fusion commercialization hub could serve as a catalyst for technology advancement by providing shared resources and facilities. Key benefits include:

- Centralized Testing Facilities: Similar to Blue Origin's wind tunnel model, hubs could enable testing of fusion blankets, first-wall materials, and tritium breeding systems while ensuring intellectual property (IP) protection.
- Diagnostic Tools Development: Creating shared diagnostic capabilities for plasma and materials testing, a critical area currently underfunded and underdeveloped.
- Collaborative Environment: Encouraging partnerships among private companies, universities, and government agencies to tackle cross-cutting challenges such as high-repetition-rate operations and materials degradation.

- State and Federal Synergy: Aligning state resources (e.g., WA State Clean Energy Fund, WA State Department of Commerce, California's Energy Commission) with federal funding initiatives to maximize investment impact.
- Near-Term Applications: Supporting companies to identify and develop non-grid applications (e.g., defense and industrial heat) that could generate revenue while grid-scale fusion matures.

3. Findings and Recommendations

Key findings and recommendations include:

Technological Challenges:

- Material qualification remains a bottleneck; innovative approaches like facility sharing and early-stage testing are critical.
- Development of high-repetition-rate systems is essential for commercialization, requiring both technological and operational advances.
- Diagnostics development needs increased attention, particularly for high-yield regimes and power plant conditions.

Policy and Funding Strategies:

- Encourage state-level matching of federal funds to amplify investment (e.g., WA State Clean Energy Fund, California's collaboration with ARPA-E).
- Advocate for systematic data sharing and standardization, particularly for materials and diagnostics.
- Highlight the role of hubs in de-risking private investment by providing validation and collaboration opportunities.

Collaboration Models:

- International cooperation, such as U.S., UK, Canada initiatives, could accelerate development, particularly in areas like tritium handling and material testing.
- Leverage existing models, such as Fraunhofer Institutes, to create a networked approach to manufacturing and materials science.

Private Sector Engagement:

- Encourage private companies to invest in shared infrastructure by demonstrating long-term cost savings and collaborative benefits.

- Explore open-source tools and shared diagnostics to reduce duplication of effort and promote innovation.

4. Essential Short-Term Next Steps

Establish Key Partnerships:

- Build alliances between federal agencies (e.g., DOE and DOC) and private sector players to coordinate funding and facilities.
- Facilitate multi-state collaborations, leveraging models like ARCHES and Pacific CREST to align regional resources.

Develop Shared Facilities:

- Create a roadmap for establishing multi-purpose hubs that address diagnostics, material testing, and technology validation.
- Prioritize the development of first wall and blanket testing capabilities to fast-track material qualification.

Encourage State Involvement:

- Advocate for state matching programs and regulatory frameworks that incentivize private investment.
- Work with state energy commissions to align fusion efforts with clean energy and grid integration goals.

Focus on Diagnostic Tools:

- Increase funding for R&D diagnostics, particularly those addressing plasma behavior and high-repetition-rate operations.
- Develop training programs for diagnostics and materials testing in collaboration with universities.

Promote Early Market Opportunities:

- Identify and support near-term applications for fusion technologies, such as defense and industrial heat.
- Encourage companies to explore ancillary markets (e.g., HTS systems, liquid metals) to build revenue streams and expertise.

By addressing these steps, the fusion community can accelerate progress toward commercialization while fostering a collaborative, innovation-driven ecosystem. The emerging regional hubs that responded to the PPCF RFI, such as in the NW and Pacific CREST, highlight the pivotal role of states in this transition, providing a foundation for national and international partnerships that could define the future of fusion energy.

Appendix G: Outreach and Economic Development

Moderator: Dr. Kate McAteer, Vice Chancellor for Academic & Student Affairs
Washington State University

"The need for enhanced public communication regarding fusion is well recognized"

Panel Overview

The panel opened with an overview of outreach and the economic development plan – Investment in the American Workforce. The need to identify tribes located near potential project sites is critical to include in stakeholder identification. The PNWH2 Association identified over 212 stakeholders and 15 tribes to include in the hub proposal. Over 100 stakeholders and two tribes provided letters of support for the proposal.

The panel comprised:

- Moderator: Kate McAteer, PhD, Vice Chancellor for Academic & Student Affairs,
- Panelists: Andrea Doyle, Manager, External Affairs & Tribal Relations for Washington State, AltaGas (Node 2, PNWH2 Hub)
- Karl Dye, President/CEO, TRIDEC (Tri-City Development Council, Tri-Cities, WA)
- Terri Parr, Tribal Liaison, Office of Tribals Relations, WSU
- Bryan Willson, Executive Director, CSU Energy Institute at CSU

Discussion questions included:

- The need for enhanced public communication for fusion is well recognized. How does an economic development plan for a "low TRL" activity such as fusion compared to the PNWH2 plan?
- What specific economic development projects or activities should be pursued? How would you involve the companies?
- What are the barriers to developing and executing an effective communication and economic development plan?

How a Hub Could Advance Economic Development Planning and Engagement

Specific tasks, including those the hub could pay for, would be helpful to advance the following:

- A hub is beneficial for economic development planning because of the shared resources and expertise (lessons learned from engagements).

- An information flyer from a hub or from DOE rather than from a company is often viewed as neutral, third part information, and builds trust.
- Stakeholder analysis over a multi-state region will be needed (RMI was the consultant hired to do this for the hydrogen hub).
- Development and distribution of education materials about fusion for kids and adults. These should be bilingual if regions have significant percentages of multi-lingual families. (See clean energy booklet that the Center of Excellence developed for kids, but adults love it too!)
- Having a commitment from all projects in a hub to the economic development plan ensures a cohesive plan is developed and can be implemented wherever a project is located.

Findings and Recommendations

- Build authentic relationships early with prospective stakeholders where a project may be located.
- Early engagement is key. Learn from previous projects where such discussion did not occur.
- Follow PNWH2 Association example of communicating with Tribes by attending ATNI, sending Dear Tribal Leader letters with hub status updates. Before, during and after proposal submission.
- Understand that people will think of Hiroshima/Nagasaki or waste/clean-up with anything related to nuclear. Education is critical. Outreach at the individual level and at the organized group level is needed.
- Be conscious of the “fine line” that economic development planners walk between sharing of information and the public’s desire for full transparency. Focus on the positive outcomes but explain if some information cannot be shared.

Essential Short-Term Next Steps

- Communicate early and often with the public about fusion. What it is and isn’t.
- Address safety concerns that the public may have.
- Communicate with the stakeholders now if potential sites are known.

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