FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

ADVANCED RESEARCH PROJECTS AGENCY – ENERGY (ARPA-E)
U.S. DEPARTMENT OF ENERGY
EXPLORATORY TOPICS

Announcement Type: Modification ~~09~~ 10
Funding Opportunity No. DE-FOA-0002784
CFDA Number 81.135

Funding Opportunity Announcement (FOA) Issue Date:	September 13, 2022
FOA Close Date:	Open continuously until otherwise amended.
Application Due Date:	See Exploratory Topics Table for topic-specific application due dates.
Total Amount to Be Awarded	Approximately $~~75~~ 85 million, subject to the availability of appropriated funds to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785. See Exploratory Topics Table for topic-specific information.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. See Exploratory Topics Table for topic-specific award amount requirements.

- For eligibility criteria, see Section III.A of the FOA.
- For cost share requirements under this FOA, see Section III.B of the FOA.
- To apply to this FOA, Applicants must register with and submit application materials through ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/Registration.aspx). For detailed guidance on using ARPA-E eXCHANGE, see Section IV.G.1 of the FOA.
- Applicants are responsible for meeting the submission deadline associated with each Exploratory Topic. Applicants are strongly encouraged to submit their applications at least 48 hours in advance of the Exploratory Topic submission deadline.
- For detailed guidance on compliance and responsiveness criteria, see Sections III.C.1 through III.C.3 of the FOA.

Questions about this FOA? Check the Frequently Asked Questions available at http://arpa-e.energy.gov/faq. For questions that have not already been answered, email ARPA-E-CO@hq.doe.gov (with FOA name and number in subject line); see FOA Sec. VII.A. Problems with ARPA-E eXCHANGE? Email ExchangeHelp@hq.doe.gov (with FOA name and number in subject line).

MODIFICATIONS

All modifications to the Funding Opportunity Announcement (FOA) are highlighted in yellow in the body of the FOA.

Mod No.	Date	Description of Modification
1	02/08/2023	• Inserted new Exploratory Topic, Topic B: INcreasing Transportation Efficiency and Resiliency through MODeling Assets and Logistics (INTERMODAL). See Table 1. Exploratory Topics , Appendix B and Total Amounts to be awarded on Cover Page. • Updated Responsive Criteria in Section III.C.2 Responsiveness Criteria. • Updated language in Section IV.C Content and Form of Full Applications. • Updated language in Section IV.C.1 First Component: Technical Volume. • Updated language in Section V.C Anticipated Announcement and Award Dates.
2	02/17/2023	• Inserted new Exploratory Topic, Topic C: Creating Revolutionary Energy And Technology Endeavors (CREATE). See Table 1. Exploratory Topics, Appendix C, and Total Amounts to be awarded on Cover Page.
3	2/23/2023	• Inserted new Exploratory Topic, Topic D: Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS). See Table 1. Exploratory Topics, Appendix D and Total Amounts to be awarded on Cover Page.
4	3/31/2023	• Updated Topic D: Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS) Submission Deadline for Replies to Reviewer Comments to June 1, 2023. See Table 1. Exploratory Topics and Appendix D.
5	4/28/2023	• Inserted new Exploratory Topic, Topic E: Critical Mineral Extraction from Ocean Macroalgal Biomass (Algal Mining). See Table 1. Exploratory Topics , Appendix E and Total Amounts to be awarded on Cover Page. • Updated language in Section IV.C.3 Third Component: Budget Justification Workbook/SF-424A. • Updated language in Section IV.C.6 Sixth Component Budget Assurances and Disclosure Form. • Updated language in Section IV.F.8 Technology Transfer and Outreach. • Updated language in Appendix D.
6	5/30/2023	• Inserted new Exploratory Topic, Topic F: Novel Superconducting Technologies for Conductors. See Table 1. Exploratory Topics, Appendix F, and Total Amounts to be awarded on Cover Page. • Updated language in Section II.C.4 Other Transactions Authority. • Updated language in Section IV.C.6 Sixth Component Budget Assurances and Disclosure Form. • Updated language in Section IV.F.7 Purchase of New Equipment.

		• Inserted Section IV.F.13 Buy America Requirement for Public Infrastructure Projects. • Inserted Section IV.F.14 Requirement for Financial Personnel. • Inserted Section VI.B.14 Commercialization Plan and Software Reporting. • Inserted Section VIII.K Export Control.
7	9/7/2023	• Inserted new Exploratory Topic, Topic G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes. See Table 1. Exploratory Topics, Appendix G, and Total Amounts to be awarded on Cover Page. • Inserted new Exploratory Topic, Topic H: Subsurface Engineering for Hydrogen Reservoir Management. See Table 1. Exploratory Topics, Appendix H, and Total Amounts to be awarded on Cover Page. • Updated language in Section VI.B.10 Applicant Risk Analysis. • Updated language in Section VIII.K Export Control Information. • Updated language in Section IX Glossary.
8	9/26/2023	• Updated dates in Table 1. Exploratory Topics and in the first page of Appendix E. • Updated language and citations in Appendix G Section 3.A and Appendix G Section 4. • Updated language in Appendix H Section 4.
9	3/7/2024	• Inserted new Exploratory Topic, Topic I: Field Evaluations of Vehicle Energy Efficiency for NEXTCAR Phase II Technologies. See Table 1. Exploratory Topics, Appendix I, and Total Amounts to be awarded on Cover Page.
10	3/21/2024	• Inserted new Exploratory Topic, Topic L: Plant HYperaccumulators TO MIne Nickel-Enriched Soils (PHYTOMINES). See Table 1. Exploratory Topics, Appendix L, and Total Amounts to be awarded on Cover Page.

Table 1. Exploratory Topics

Appendix	Exploratory Topic Title	Issue Date	Deadline for Questions to ARPA-E CO	Full Application Submission Deadline	Submission Deadline for Replies to Reviewer Comments	Total Federal Funds to be Awarded (subject to availability)	Anticipated Awards	Max Period of Performance	Expected Date for Notifications
A	Low-Energy Nuclear Reactions	9/13/2022	5 PM ET, 11/4/2022	9:30 AM ET, 11/15/2022	5:00 PM ET, 12/20/2022	Approximately $10M total	5-8 awards	30 months	February 2023
B	Increasing Transportation Efficiency and Resiliency Through Modeling Assets And Logistics	2/8/2023	5 PM ET, 3/31/2023	9:30 AM ET, 4/11/2023	5:00 PM ET, 5/18/2023	Approximately $10M total	5-8 awards	30 months	June 2023
C	Creating Revolutionary Energy And Technology Endeavors	2/17/2023	5 PM ET, 3/10/2023	9:30 AM ET, 3/21/2023	N/A	Approximately $10M total	20-30 awards	24 months	June 2023
D	Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky	2/23/2023	5 PM ET, 4/14/2023	9:30 AM ET, 4/25/2023	5:00 PM ET, 6/1/2023	Approximately $10M total	4-6 awards	18 months	July 2023
E	Critical Mineral Extraction from Ocean Macroalgal Biomass	4/28/2023	5:00 PM ET, 5/15/2023	9:30 AM ET, 5/31/2023	5:00 PM ET 7/6/2023	Approximately $5M total	2-4 awards	24 months	October 2023
F	Novel Superconducting Technologies for Conductors	5/30/2023	5:00 PM ET, 7/18/2023	9:30 AM ET, 7/25/2023	5:00 PM ET 8/24/2023	Approximately $10M total	2-4 awards	36 months	September 2023
G	Production of Geologic Hydrogen Through Stimulated Mineralogical Processes	9/7/2023	5:00 PM ET, 10/13/2023	9:30 AM ET, 10/24/2023	5:00 PM ET 11/27/2023	Approximately $10M total	4-6 awards	24 months	January 2024
H	Subsurface Engineering for Hydrogen Reservoir Management	9/7/2023	5:00 PM ET, 10/13/2023	9:30 AM ET, 10/24/2023	5:00 PM ET 11/27/2023	Approximately $10M total	4-6 awards	24 months	January 2024
I	Field Evaluations of Vehicle Energy Efficiency for NEXTCAR Phase II Technologies	3/11/2024	5:00 PM ET, 4/1/2024	9:30 AM ET, 4/10/2024	5:00 PM ET, 4/16/2024	Approximately $2.5M total	1 award	12 months	May 2024
J	<Reserved>								

Questions about this FOA? Check the Frequently Asked Questions available at http://arpa-e.energy.gov/faq. For questions that have not already been answered, email ARPA-E-CO@hq.doe.gov (with FOA name and number in subject line); see FOA Sec. VII.A. Problems with ARPA-E eXCHANGE? Email ExchangeHelp@hq.doe.gov (with FOA name and number in subject line).

K	<Reserved>	[redacted]							
L	[Plant HYperaccumulators TO MIne Nickel-Enriched Soils (PHYTOMINES)]()	3/21/2024	5:00 PM ET, 4/26/2024	9:30 AM ET, 5/7/2024	5:00 PM ET, 6/12/2024	Approximately $10M total	4-6 awards	36 months	October 2024

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REQUIRED DOCUMENTS CHECKLIST

Unless an exception or exceptions are described under a particular Exploratory Topic, the following are applicable to all Exploratory Topics published under this FOA.

- For an overview of the application process, see Section IV.A of the FOA.
- For guidance regarding requisite application forms, see Section IV.B of the FOA.
- For guidance regarding the content and form of Full Applications see Sections IV.C of the FOA.

SUBMISSION	COMPONENTS	OPTIONAL/ MANDATORY	FOA SECTION
Full Application	• Each Applicant must submit a Technical Volume in Adobe PDF format by the stated deadline. The Technical Volume must include the following: o Executive Summary (1 page max.) o Sections 1-5 (14 pages max.) • 1. Innovation and Impact • 2. Proposed Work • 3. Team Organization and Capabilities • 4. Technology to Market • 5. Budget o Bibliographic References (no page limit) o Personal Qualification Summaries (each Personal Qualification Summary limited to 3 pages in length, no cumulative page limit) • The Technical Volume must be accompanied by: o SF-424 (no page limit, Adobe PDF format); o Budget Justification Workbook/SF424A (no page limit, Microsoft Excel format); o Summary for Public Release (250 words max., Adobe PDF format); o Summary Slide (1 page limit, Microsoft PowerPoint format; o Completed and signed Business Assurances & Disclosures Form (no page limit, Adobe PDF format)	Mandatory	IV.C
Reply to Reviewer Comments	• As set forth in Table 1, each Applicant may submit a Reply to Reviewer Comments in Adobe PDF format. This submission is optional. The Reply may include: o Up to 2 pages of text; and o Up to 1 page of images.	Optional	IV.D

I. FUNDING OPPORTUNITY DESCRIPTION

A. AGENCY OVERVIEW

The Advanced Research Projects Agency – Energy (ARPA-E), an organization within the Department of Energy (DOE), is chartered by Congress in the America COMPETES Act of 2007 (P.L. 110-69), as amended by the America COMPETES Reauthorization Act of 2010 (P.L. 111-358), as further amended by the Energy Act of 2020 (P.L. 116-260) to:

"(A) to enhance the economic and energy security of the United States through the development of energy technologies that—

(i) reduce imports of energy from foreign sources;

(ii) reduce energy-related emissions, including greenhouse gases;

(iii) improve the energy efficiency of all economic sectors;

(iv) provide transformative solutions to improve the management, clean-up, and disposal of radioactive waste and spent nuclear fuel; and

(v) improve the resilience, reliability, and security of infrastructure to produce, deliver, and store energy; and

(B) to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies."

ARPA-E issues this Funding Opportunity Announcement (FOA) under its authorizing statute codified at 42 U.S.C. § 16538. The FOA and any Grants or Cooperative Agreements made under this FOA are subject to 2 C.F.R. Part 200 as supplemented by 2 C.F.R. Part 910.

ARPA-E funds research on and the development of transformative science and technology solutions to address the energy and environmental missions of the Department. The agency focuses on technologies that can be meaningfully advanced with a modest investment over a defined period of time in order to catalyze the translation from scientific discovery to early-stage technology. For the latest news and information about ARPA-E, its programs and the research projects currently supported, see: http://arpa-e.energy.gov/.

ARPA-E funds transformational research. Existing energy technologies generally progress on established "learning curves" where refinements to a technology and the economies of scale that accrue as manufacturing and distribution develop drive improvements to the cost/performance metric in a gradual fashion. This continual improvement of a technology is important to its increased commercial deployment and is appropriately the focus of the private sector or the applied technology offices within DOE. In contrast, ARPA-E supports transformative research that has the potential to create fundamentally new learning curves. ARPA-E technology projects typically start with cost/performance estimates well above the level of an incumbent technology. Given the high risk inherent in these projects, many will fail to progress, but some may succeed in generating a new learning curve with a projected cost/performance metric that is significantly better than that of the incumbent technology.

ARPA-E funds technology with the potential to be disruptive in the marketplace. The mere creation of a new learning curve does not ensure market penetration. Rather, the ultimate value of a technology is determined by the marketplace, and impactful technologies ultimately become disruptive – that is, they are widely adopted and displace existing technologies from the marketplace or create entirely new markets. ARPA-E understands that definitive proof of market disruption takes time, particularly for energy technologies. Therefore, ARPA-E funds the development of technologies that, if technically successful, have clear disruptive potential, e.g., by demonstrating capability for manufacturing at competitive cost and deployment at scale.

ARPA-E funds applied research and development. The Office of Management and Budget defines "applied research" as an "original investigation undertaken in order to acquire new knowledge…directed primarily towards a specific practical aim or objective" and defines "experimental development" as "creative and systematic work, drawing on knowledge gained from research and practical experience, which is directed at producing new products or processes or improving existing products or processes."[1] Applicants interested in receiving financial assistance for basic research (defined by the Office of Management and Budget as "experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts")[2] should contact the DOE's Office of Science (http://science.energy.gov/). Office of Science national scientific user facilities (http://science.energy.gov/user-facilities/) are open to all researchers, including ARPA-E Applicants and awardees. These facilities provide advanced tools of modern science including accelerators, colliders, supercomputers, light sources and neutron sources, as well as facilities for studying the nanoworld, the environment, and the atmosphere. Projects focused on early-stage R&D for the improvement of technology along defined roadmaps may be more appropriate for support through the DOE applied energy offices including: the Office of Energy Efficiency and Renewable Energy (http://www.eere.energy.gov/), the Office of Fossil Energy and Carbon Management (https://www.energy.gov/fecm/office-fossil-energy-and-carbon-management), the Office of Nuclear Energy (http://www.energy.gov/ne/office-nuclear-energy), and the Office of Electricity (https://www.energy.gov/oe/office-electricity).

B. PROGRAM OVERVIEW AND OBJECTIVES

This announcement is purposely broad in scope, and will cover a wide range of topics to encourage the submission of the most innovative and unconventional ideas in energy technology. The objective of this solicitation is to support high-risk R&D leading to the development of potentially disruptive new technologies across the full spectrum of energy applications. Topics under this FOA will explore new areas of technology development that, if

[1] OMB Circular A-11 (https://www.whitehouse.gov/wp-content/uploads/2018/06/a11_web_toc.pdf), Section 84, pg. 3.

[2] OMB Circular A-11 (https://www.whitehouse.gov/wp-content/uploads/2018/06/a11_web_toc.pdf), Section 84, pg. 3.

successful, could establish new program areas for ARPA-E, or complement the current portfolio of ARPA-E programs.

Applications to this solicitation must have the potential for high impact — if successful, it could create a new class or new trajectory for an energy technology, with the potential to make a significant impact on ARPA-E's Mission Areas (see Section I.A).

Awards under this program may take the form of analyses or exploratory research that provides the agency with information useful for the subsequent development of focused technology programs. Alternatively, awards may support proof-of-concept research for a particular new technology, either in an area not currently supported by the agency or as a potential enhancement to an ongoing focused technology program.

C. EXPLORATORY TOPICS OVERVIEW

This FOA will only accept applications in prespecified Exploratory Topics. Specific areas of interest and relevant deadlines will be posted on the ARPA-E eXCHANGE website (https://arpa-e-foa.energy.gov). For your convenience you can subscribe to the ARPA-E mailing list to receive ARPA-E newsletters and news alerts, as well as updates on when new Exploratory Topics are posted.

Each Exploratory Topic announcement will be visible on ARPA-E eXCHANGE as a supporting FOA document. Exploratory Topic details will only be visible in eXCHANGE while the notice is accepting applications. Once the topic deadline has passed the notice will be taken down and ARPA-E will no longer be accepting applications in that area. ARPA-E will only review applications that are responsive to the Exploratory Topic(s) open at the time the application is submitted.

II. Award Information

A. Award Overview

See Exploratory Topic Table and Topic Appendices for total amounts and anticipated number of awards for each Topic.

ARPA-E will accept only new submissions under this FOA. Applicants may not seek renewal or supplementation of their existing awards through this FOA.

Unless otherwise stated in the Exploratory Topic, ARPA-E plans to fully fund your negotiated budget at the time of award.

B. Renewal Awards

At ARPA-E's sole discretion, awards resulting from this FOA may be renewed by adding one or more budget periods, extending the period of performance of the initial award, or issuing a new award. Renewal funding is contingent on: (1) availability of funds appropriated by Congress for the purpose of this program; (2) substantial progress towards meeting the objectives of the approved application; (3) submittal of required reports; (4) compliance with the terms and conditions of the award; (5) ARPA-E approval of a renewal application; and (6) other factors identified by the Agency at the time it solicits a renewal application.

C. ARPA-E Funding Agreements

Through Grants, Cooperative Agreements, other transactions, and similar agreements, ARPA-E provides financial and other support to projects that have the potential to realize ARPA-E's statutory mission. ARPA-E does not use such agreements to acquire property or services for the direct benefit or use of the U.S. Government.

1. Grants

A Grant is a legal instrument that is used to provide Federal financial assistance or other things of value to carry out a public purpose of support or stimulation authorized by Federal statute. Grants are distinguished from Cooperative Agreements in that they do not provide for substantial involvement between the Federal awarding agency (in this case ARPA-E) and the Recipient.

2. Cooperative Agreements

Congress directed ARPA-E to "establish and monitor project milestones, initiate research projects quickly, and just as quickly terminate or restructure projects if such milestones are not achieved."[3] Accordingly, ARPA-E has substantial involvement in the direction of every Cooperative Agreement, as described in Section II.D below.

Cooperative Agreements involve the provision of financial or other support to accomplish a public purpose of support or stimulation authorized by Federal statute. Under Cooperative Agreements, the Government and Prime Recipients share responsibility for the direction of projects.

ARPA-E encourages Prime Recipients to review the Model Cooperative Agreement, which is available at https://arpa-e.energy.gov/technologies/project-guidance.

3. Funding Agreements with FFRDCs/DOE Labs, GOGOs, and Federal Instrumentalities

Any Federally Funded Research and Development Centers (FFRDC) involved as a member of a Project Team must provide the information requested in the "FFRDC Lab Authorization" and "Field Work Proposal" section of the Business Assurances & Disclosures Form, which is submitted with the Applicant's Full Application.

When a FFRDC/DOE Lab (including the National Energy Technology Laboratory or NETL) is the *lead organization* for a Project Team, ARPA-E executes a funding agreement directly with the FFRDC/DOE Lab and a single, separate Cooperative Agreement with another entity on the Project Team. Notwithstanding the use of multiple agreements, the FFRDC/DOE Lab is the lead organization for the entire project, including all work performed by the FFRDC/DOE Lab and the rest of the Project Team.

When a FFRDC/DOE Lab is a *member* of a Project Team, ARPA-E executes a funding agreement directly with the FFRDC/DOE Lab and a single, separate Cooperative Agreement with the Prime Recipient, as the lead organization for the Project Team. Notwithstanding the use of multiple agreements, the Prime Recipient under the Cooperative Agreement is the lead organization for the entire project, including all work performed by the FFRDC/DOE Lab and the rest of the Project Team.

Funding agreements with DOE/NNSA FFRDCs take the form of Work Authorizations issued to DOE/NNSA FFRDCs through the DOE/NNSA Field Work Proposal system for work performed under Department of Energy Management & Operation Contracts. Funding agreements with non-DOE/NNSA FFRDCs, GOGOs (including NETL), and Federal instrumentalities (e.g., Tennessee Valley Authority) will be consistent with the sponsoring agreement between the U.S. Government and the Laboratory. Any funding agreement with an FFRDC or GOGO will have

[3] U.S. Congress, Conference Report to accompany the 21st Century Competitiveness Act of 2007, H. Rpt. 110-289 at 171-172 (Aug. 1, 2007).

similar terms and conditions as ARPA-E's Model Cooperative Agreement (https://arpa-e.energy.gov/technologies/project-guidance/pre-award-guidance/funding-agreements).

Non-DOE GOGOs and Federal agencies may be proposed to provide support to the Project Team members on an applicant's project, through a Cooperative Research and Development Agreement (CRADA) or similar agreement.

4. OTHER TRANSACTIONS AUTHORITY

ARPA-E may use its "other transactions" authority under the America COMPETES Reauthorization Act of 2010 to enter into an other transaction agreement with Prime Recipients, on a case-by-case basis.

ARPA-E may negotiate an other transaction agreement when it determines that the use of a standard cooperative agreement, grant, or contract is not feasible or appropriate for a project.

The federal share of other transactions agreements should meet or exceed $3,000,000. In general, an other transaction agreement would normally requires a minimum cost share of 50%. See Section III.B.2 of the FOA.

D. FEDERAL STEWARDSHIP

ARPA-E will exercise Federal stewardship in overseeing the project activities performed under a grant. Stewardship activities include, but are not limited to, conducting site visits; reviewing performance and financial reports; providing technical assistance and/or temporary intervention in unusual circumstances to correct deficiencies which develop during the project; assuring compliance with terms and conditions of the Award; and reviewing technical performance during and after project completion to ensure that the Award objectives are being/have been accomplished.

E. STATEMENT OF SUBSTANTIAL INVOLVEMENT

ARPA-E is substantially involved in the direction of Cooperative Agreements from inception to completion. For the purposes of an ARPA-E project, substantial involvement means:

- Project Teams must adhere to ARPA-E's agency-specific and programmatic requirements.
- ARPA-E may intervene at any time in the conduct or performance of work under an award.
- ARPA-E does not limit its involvement to the administrative requirements of an award. Instead, ARPA-E has substantial involvement in the direction and redirection of the technical aspects of the project as a whole.

- ARPA-E may, at its sole discretion, modify or terminate projects that fail to achieve predetermined Go/No Go decision points or technical milestones and deliverables.
- During award negotiations, ARPA-E Program Directors and Prime Recipients mutually establish an aggressive schedule of quantitative milestones and deliverables that must be met every quarter. In addition, ARPA-E will negotiate and establish “Go/No-Go” milestones for each project. If the Prime Recipient fails to achieve any of the “Go/No-Go” milestones or technical milestones and deliverables as determined by the ARPA-E Contracting Officer, ARPA-E may – at its discretion - renegotiate the statement of project objectives or schedule of technical milestones and deliverables for the project. In the alternative, ARPA-E may suspend or terminate the award in accordance with 2 C.F.R. §§ 200.339 – 200.343.
- ARPA-E may provide guidance and/or assistance to the Prime Recipient to accelerate the commercial deployment of ARPA-E-funded technologies. Guidance and assistance provided by ARPA-E may include coordination with other Government agencies and nonprofits[4] to provide mentoring and networking opportunities for Prime Recipients. ARPA-E may also organize and sponsor events to educate Prime Recipients about key barriers to the deployment of their ARPA-E-funded technologies. In addition, ARPA-E may establish collaborations with private and public entities to provide continued support for the development and deployment of ARPA-E-funded technologies.

[4] The term “nonprofit organization” or “nonprofit” is defined in Section IX.

III. ELIGIBILITY INFORMATION

A. ELIGIBLE APPLICANTS

This FOA is open to U.S. universities, national laboratories, industry, and individuals.

1. INDIVIDUALS

U.S. citizens or permanent residents may apply for funding in their individual capacity as a Standalone Applicant,[5] as the lead for a Project Team,[6] or as a member of a Project Team. However, ARPA-E will only award funding to an entity formed by the Applicant.

2. DOMESTIC ENTITIES

For-profit entities7, educational institutions8, and nonprofits9 that are incorporated in the United States, including U.S. territories, are eligible to apply for funding as a Standalone Applicant, as the lead organization for a Project Team, or as a member of a Project Team.

FFRDCs/DOE Labs are eligible to apply for funding as the lead organization for a Project Team or as a member of a Project Team that includes institutions of higher education, companies, research foundations, or trade and industry research collaborations, but not as a Standalone Applicant.

State, local, and tribal government entities are eligible to apply for funding as a member of a Project Team, but not as a Standalone Applicant or as the lead organization for a Project Team.

Federal agencies and instrumentalities (other than DOE) are eligible to apply for funding as a member of a Project Team, but not as a Standalone Applicant or as the lead organization for a Project Team.

3. FOREIGN ENTITIES

Foreign entities, whether for-profit or otherwise, are eligible to apply for funding as Standalone Applicants, as the lead organization for a Project Team, or as a member of a Project Team. Foreign entities must designate in the Full Application a subsidiary or affiliate incorporated (or

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[5] A Standalone Applicant is an Applicant that applies for funding on its own, not as part of a Project Team.

[6] A Project Team consists of the Prime Recipient, Subrecipients, and others performing or otherwise supportingwork under an ARPA-E funding agreement.

[7] For-Profit Organizations (Other than Small Businesses) (or *large businesses*): Means entities organized for-profit other than small businesses as defined elsewhere in this Glossary.

[8] Institutions of Higher Education (or educational institutions): Has the meaning set forth at 20 U.S.C. 1001.

[9] Nonprofit organizations described in section 501(c)(4) of the Internal Revenue Code of 1986 that engaged in lobbying activities after December 31, 1995 are not eligible to apply for funding as a Prime Recipient or Subrecipient.

otherwise formed or to be formed) under the laws of a State or territory of the United States to receive funding. The Full Application must state the nature of the corporate relationship between the foreign entity and domestic subsidiary or affiliate. All work under the ARPA-E award must be performed in the United States. The Applicant may request a waiver of this requirement in the Business Assurances & Disclosures Form, which is submitted with the Full Application and can be found at https://arpa-e-foa.energy.gov/ (see "View Template Application Documents"). Refer to the Business Assurances & Disclosures Form for guidance on the content and form of the request.

4. Consortium Entities

Consortia, which may include domestic and foreign entities, must designate one member of the consortium as the consortium representative to the Project Team. The consortium representative must be incorporated in the United States. The eligibility of the consortium will be determined by reference to the eligibility of the consortium representative under Section III.A of the FOA. Each consortium must have an internal governance structure and a written set of internal rules. Upon request, the consortium entity must provide a written description of its internal governance structure and its internal rules to the Contracting Officer (ARPA-E-CO@hq.doe.gov).

Unincorporated consortia must provide the Contracting Officer with a collaboration agreement, commonly referred to as the articles of collaboration, which sets out the rights and responsibilities of each consortium member. This collaboration agreement binds the individual consortium members together and shall include the consortium's:

- Management structure;
- Method of making payments to consortium members;
- Means of ensuring and overseeing members' efforts on the project;
- Provisions for members' cost sharing contributions; and
- Provisions for ownership and rights in intellectual property developed previously or under the agreement.

B. Cost Sharing[10]

Applicants are bound by the cost share proposed in their Full Applications.

1. Base Cost Share Requirement

ARPA-E generally uses Cooperative Agreements to provide financial and other support to Prime Recipients (see Section II.C of the FOA). Under a Cooperative Agreement or Grant, the Prime

[10] Please refer to Section VI.B.3-4 of the FOA for guidance on cost share payments and reporting.

Recipient must provide at least 20% of the Total Project Cost[11] as cost share, except as provided in Sections III.B.2 or III.B.3 below.[12]

2. Increased Cost Share Requirement

Large businesses[13] are strongly encouraged to provide more than 20% of the Total Project Cost as cost share. ARPA-E may consider the amount of cost share proposed when selecting applications for award negotiations (see Section V.B.1 of the FOA).

Under an "other transaction" agreement, the Prime Recipient is normally expected to provide at least 50% of the Total Project Cost as cost share. ARPA-E may reduce this cost share requirement, as appropriate.

3. Reduced Cost Share Requirement

ARPA-E has reduced the base cost share requirement for the following types of projects:

- A domestic educational institution or domestic nonprofit applying as a Standalone Applicant is required to provide at least 5% of the Total Project Cost as cost share.

- Project Teams composed exclusively of domestic educational institutions, domestic nonprofits, and/or FFRDCs/DOE Labs/Federal agencies and instrumentalities (other than DOE) are required to provide at least 5% of the Total Project Cost as cost share.

- Small businesses – or consortia of small businesses – may provide 0% cost share from the outset of the project through the first 12 months of the project (hereinafter the "Cost Share Grace Period").[14] If the project is continued beyond the Cost Share Grace Period, then at least 10% of the Total Project Cost (including the costs incurred during the Cost Share Grace Period) will be required as cost share over the remaining period of performance.

- Project Teams where a small business is the lead organization and small businesses perform greater than or equal to 80%, of the total work under the funding agreement (as measured by the Total Project Cost) are entitled to the same cost share reduction and Cost Share Grace Period as provided above to Standalone small businesses or consortia of small businesses.[15]

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[11] The Total Project Cost is the sum of the Prime Recipient share and the Federal Government share of total allowable costs. The Federal Government share generally includes costs incurred by GOGOs and FFRDCs.
[12] Energy Policy Act of 2005, Pub.L. No. 109-58, § 988.
[13] The term "For-Profit Organizations (Other than Small Businesses)" or "large business" is defined in Section IX.
[14] The term "small business" is defined in Section IX.
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- Project Teams where domestic educational institutions, domestic nonprofits, small businesses, and/or FFRDCs perform greater than or equal to 80%, of the total work under the funding agreement (as measured by the Total Project Cost) are required to provide at least 10% of the Total Project Cost as cost share. However, any entity (such as a large business) receiving patent rights under a class waiver, or other patent waiver, that is part of a Project Team receiving this reduction must continue to meet the statutory minimum cost share requirement (20%) for its portion of the Total Project Cost.

- Projects that do not meet any of the above criteria are subject to the base cost share requirements described in Sections III.B.1 and III.B.2 of the FOA.

4. LEGAL RESPONSIBILITY

Although the cost share requirement applies to the Project Team as a whole, the funding agreement makes the Prime Recipient legally responsible for paying, or ensuring payment of the entire cost share. The Prime Recipient's cost share obligation is expressed in the funding agreement as a static amount in U.S. dollars (cost share amount) and as a percentage of the Total Project Cost (cost share percentage). If the funding agreement is terminated prior to the end of the period of performance, the Prime Recipient is required to contribute at least the cost share percentage of total expenditures incurred through the date of termination.

The Prime Recipient is solely responsible for managing cost share contributions by the Project Team and enforcing cost share obligations assumed by Project Team members in subawards or related agreements.

5. COST SHARE ALLOCATION

Each Project Team is free to determine how much each Project Team member will contribute towards the cost share requirement. The amount contributed by individual Project Team members may vary, as long as the cost share requirement for the project as a whole is met.

6. COST SHARE TYPES AND ALLOWABILITY

Every cost share contribution must be allowable under the applicable Federal cost principles, as described in Section IV.F.1 of the FOA.

Project Teams may provide cost share in the form of cash or in-kind contributions. Cash contributions may be provided by the Prime Recipient or Subrecipients. Allowable in-kind contributions include but are not limited to personnel costs, indirect costs, facilities and administrative costs, rental value of buildings or equipment, and the value of a service, other resource, or third party in-kind contribution. Project Teams may use funding or property received from state or local governments to meet the cost share requirement, so long as the funding or property was not provided to the state or local government by the Federal Government.

The Prime Recipient may not use the following sources to meet its cost share obligations:

- Revenues or royalties from the prospective operation of an activity beyond the period of performance;
- Proceeds from the prospective sale of an asset of an activity;
- Appropriated Federal funding or property (e.g., Federal grants, equipment owned by the Federal Government); or
- Expenditures that were reimbursed under a separate Federal program.
- Add IR&D and then reference the section where it is described in more detail

In addition, Project Teams may not use independent research and development (IR&D) funds[16] to meet their cost share obligations under Cooperative Agreements. However, Project Teams may use IR&D funds to meet their cost share obligations under "other transaction" agreements.

Project Teams may not use the same cash or in-kind contributions to meet cost share requirements for more than one project or program.

Cost share contributions must be specified in the project budget, verifiable from the Prime Recipient's records, and necessary and reasonable for proper and efficient accomplishment of the project. Every cost share contribution must be reviewed and approved in advance by the Contracting Officer and incorporated into the project budget before the expenditures are incurred.

Applicants may wish to refer to 2 C.F.R. Parts 200 and 910, and 10 C.F.R Part 603 for additional guidance on cost sharing, specifically 2 C.F.R. §§ 200.306 and 910.130, and 10 C.F.R. §§ 603.525-555.

7. COST SHARE CONTRIBUTIONS BY FFRDCS AND GOGOS

Because FFRDCs are funded by the Federal Government, costs incurred by FFRDCs generally may not be used to meet the cost share requirement. FFRDCs may contribute cost share only if the contributions are paid directly from the contractor's Management Fee or a non-Federal source.

Because GOGOs/Federal Agencies are funded by the Federal Government, GOGOs/Federal Agencies may not provide cost share for the proposed project. However, the GOGO/Agency

[16] As defined in Federal Acquisition Regulation SubSection 31.205-18.

costs would be included in Total Project Costs for purposes of calculating the cost-sharing requirements of the applicant.

8. Cost Share Verification

Upon selection for award negotiations, Applicants are required to provide information and documentation regarding their cost share contributions. Please refer to Section VI.B.3 of the FOA for guidance on the requisite cost share information and documentation.

C. Other

1. Compliant Criteria

Full Applications are deemed compliant if:

- The Applicant meets the eligibility requirements in Section III.A of the FOA;
- The Full Application complies with the content and form requirements in Section IV.C of the FOA; and
- The Applicant entered all required information, successfully uploaded all required documents, and clicked the "Submit" button in ARPA-E eXCHANGE by the Exploratory Topic submission deadline stated in Table 1 of this FOA.

Full Applications found to be noncompliant may not be merit reviewed or considered for award. ARPA-E may not review or consider noncompliant Full Applications, including Full Applications submitted through other means, Full Applications submitted after the applicable deadline, and incomplete Full Applications. A Full Application is incomplete if it does not include required information and documents, such as Forms SF-424 and SF-424A. ARPA-E will not extend the submission deadline for Applicants that fail to submit required information and documents due to server/connection congestion.

If applicable to the Exploratory Topic (refer to Table 1), Replies to Reviewer Comments are deemed compliant if:

- The Applicant successfully uploads its response to ARPA-E eXCHANGE by the deadline stated in the Exploratory Topic Table 1; and
- The Replies to Reviewer Comments comply with the content and form requirements of Section IV.D of the FOA.

ARPA-E will not review or consider noncompliant Replies to Reviewer Comments, including Replies submitted through other means and Replies submitted after the applicable deadline. ARPA-E will not extend the submission deadline for Applicants that fail to submit required information due to server/connection congestion. ARPA-E will review and consider each compliant and responsive Full Application, even if no Reply is submitted or if the Reply is found to be noncompliant.

2. Responsiveness Criteria

ARPA-E performs a preliminary technical review of Full Applications. The following types of submissions may be deemed nonresponsive and may not be reviewed or considered:

- Submissions that fall outside the technical parameters specified in the Exploratory Topic Appendix
- Submissions that have been submitted in response to currently issued ARPA-E FOAs.
- Submissions that are not scientifically distinct from applications submitted in response to currently issued ARPA-E FOAs.
- Submissions for basic research aimed solely at discovery and/or fundamental knowledge generation.
- Submissions for large-scale demonstration projects of existing technologies.
- Submissions for proposed technologies that represent incremental improvements to existing technologies.
- Submissions for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Submissions for proposed technologies that are not transformational, as described in Section I.A of the FOA.
- Submissions for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress.
- Submissions that are not distinct in scientific approach or objective from activities currently supported by or actively under consideration for funding by any other office within Department of Energy.
- Submissions that are not distinct in scientific approach or objective from activities currently supported by or actively under consideration for funding by other government agencies or the private sector.
- Submissions that do not propose a R&D plan that allows ARPA-E to evaluate the submission under the applicable merit review criteria provided in Section V.A of the FOA (unless the applicable Topic Appendix states otherwise).

Each Exploratory Topic may also include a section entitled "Submissions Specifically not of Interest." Submissions that propose items contained within this section in each Exploratory Topic may be deemed nonresponsive and may not be reviewed or considered.

3. LIMITATION ON NUMBER OF SUBMISSIONS

ARPA-E is not limiting the number of submissions from Applicants. Applicants may submit more than one application to each Exploratory Topic attached to this FOA, provided that each application is scientifically distinct.

Small business Applicants that qualify as a "Small Business Concern"[17] may apply to only one of the two ARPA-E, Exploratory Topics FOAs for each Exploratory Topics: DE-FOA-0002785 (Exploratory Topic SBIR/STTR), or DE-FOA-0002784 (Exploratory Topic). Small businesses that qualify as "Small Business Concerns" are strongly encouraged to apply under the former (SBIR/STTR FOA). To determine eligibility as a "Small Business Concern" under DE-FOA-0002785 (SBIR/STTR), please review the eligibility requirements in Sections III.A – III.D of that FOA.

[17] Please refer to the U.S. Small Business Administration (SBA) website. A Small Business Concern is a for-profit entity that: (1) maintains a place of business located in the United States; (2) operates primarily within the United States or makes a significant contribution to the United States economy through payment of taxes or use of American products, materials or labor; (3) is an individual proprietorship, partnership, corporation, limited liability company, joint venture, association, trust, or cooperative; and (4) meets the size eligibility requirements set forth in 13 C.F.R. § 121.702. Where the entity is formed as a joint venture, there can be no more than 49% participation by foreign business entities in the joint venture.

IV. Application and Submission Information

A. Application Process Overview

1. Registration in ARPA-E eXCHANGE

The first step in applying to this FOA is registration in ARPA-E eXCHANGE, ARPA-E's online application portal. For detailed guidance on using ARPA-E eXCHANGE, please refer to Section IV.G.1 of the FOA and the "ARPA-E eXCHANGE User Guide" (https://arpa-e-foa.energy.gov/Manuals.aspx).

2. Full Applications

Applicants must submit a Full Application by the Exploratory Topic Full Application Submission Deadline stated in Table 1 of this FOA. Section IV.C of the FOA provides instructions on submitting a Full Application.

ARPA-E performs a preliminary review of Full Applications to determine whether they are compliant and responsive, as described in Section III.C of the FOA. Full Applications found to be noncompliant or nonresponsive may not be merit reviewed or considered for award. ARPA-E makes an independent assessment of each compliant and responsive Full Application based on the criteria and program policy factors in Sections V.A.1 and V.B.1 of the FOA.

3. Reply to Reviewer Comments

If applicable to the Exploratory Topic (refer to Table 1), once ARPA-E has completed its review of Full Applications, reviewer comments on compliant and responsive Full Applications are made available to Applicants via ARPA-E eXCHANGE. Applicants may submit an optional Reply to Reviewer Comments, which must be submitted by the deadline stated in the FOA. Section IV.D of the FOA provides instructions on submitting a Reply to Reviewer Comments.

ARPA-E performs a preliminary review of Replies to determine whether they are compliant, as described in Section III.C.1 of the FOA. ARPA-E will review and consider compliant Replies only. ARPA-E will review and consider each compliant and responsive Full Application, even if no Reply is submitted or if the Reply is found to be non-compliant.

4. Pre-Selection Clarifications and "Down-Select" Process

Once ARPA-E completes its review of Full Applications (and Replies to Reviewer Comments, if applicable), it may, at the Contracting Officer's discretion, conduct a pre-selection clarification process and/or perform a "down-select" of Full Applications. Through the pre-selection clarification process or down-select process, ARPA-E may obtain additional information from select Applicants through pre-selection meetings, webinars, videoconferences, conference calls, written correspondence, or site visits that can be used to make a final selection determination. ARPA-E will not reimburse Applicants for travel and other expenses relating to pre-selection meetings or site visits, nor will these costs be eligible for reimbursement as pre-award costs.

ARPA-E may select applications for award negotiations and make awards without pre-selection meetings and site visits. Participation in a pre-selection meeting or site visit with ARPA-E does not signify that Applicants have been selected for award negotiations.

5. SELECTION FOR AWARD NEGOTIATIONS

ARPA-E carefully considers all of the information obtained through the application process and makes an independent assessment of each compliant and responsive Full Application based on the criteria, risk reviews, and program policy factors in Sections V.A.1, V.B.1, and VI.B.10 of the FOA. The Selection Official may select all or part of a Full Application for award negotiations. The Selection Official may also postpone a final selection determination on one or more Full Applications until a later date, subject to availability of funds and other factors. ARPA-E will enter into award negotiations only with selected Applicants.

Applicants are promptly notified of ARPA-E's selection determination. ARPA-E may stagger its selection determinations. As a result, some Applicants may receive their notification letter in advance of other Applicants. Please refer to Section VI.A of the FOA for guidance on award notifications.

B. APPLICATION FORMS

Required forms for Full Applications are available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov), including the SF-424 and Budget Justification Workbook/SF-424A. A sample Summary Slide is available on ARPA-E eXCHANGE. Applicants may use the templates available on ARPA-E eXCHANGE, including the template for the Technical Volume of the Full Application, the template for the Summary Slide, the template for the Summary for Public Release, the template for the Reply to Reviewer Comments and the template for the Business Assurances & Disclosures Form. A sample response to the Business Assurances & Disclosures Form is available on ARPA-E eXCHANGE.

C. CONTENT AND FORM OF FULL APPLICATIONS

Full Applications must conform to the following formatting requirements:

- Each document must be submitted in the file format prescribed below.
- The Full Application must be written in English.
- All pages must be formatted to fit on 8-1/2 by 11 inch paper with margins not less than one inch on every side. Single space all text and use Times New Roman

typeface, a black font color, and a font size of 12 point or larger (except in figures and tables).

- The ARPA-E assigned Control Number, the Lead Organization Name, and the Principal Investigator's Last Name must be prominently displayed on the upper right corner of the header of every page. Page numbers must be included in the footer of every page.

Full Applications found to be noncompliant or nonresponsive may not be merit reviewed or considered for award (see Section III.C of the FOA).

Each Full Application should be limited to a single concept or technology. Unrelated concepts and technologies should not be consolidated in a single Full Application.

Fillable Full Application template documents are available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov.

Full Applications must conform to the content requirements described below.

Component	Required Format	Description and Information
Technical Volume	PDF	The Technical Volume is the centerpiece of the Full Application. Provides a detailed description of the proposed R&D project and Project Team.
SF-424	PDF	Application for Federal Assistance. Applicants are responsible for ensuring that the proposed costs listed in eXCHANGE match those listed on forms SF-424 and SF-424A. Inconsistent submissions may impact ARPA-E's final award determination.
Budget Justification Workbook/SF-424A	XLS	Budget Information – Non-Construction Programs
Summary for Public Release	PDF	Short summary of the proposed R&D project. Intended for public release.
Summary Slide	PPT	A four-panel project slide summarizing different aspects of the proposed R&D project.
Business Assurances & Disclosures Form	PDF	Applicants should provide comprehensive responses to the questions on this form. Requires the Applicant to make responsibility disclosures and disclose conflicts of interest within the Project Team. Requires the Applicant to describe the additionality and risks associated with the proposed project, disclose applications for funding currently pending with Federal and non-Federal entities, and disclose funding from Federal and non-Federal entities for work in the same technology area as the proposed R&D project. If an Applicant Team Member is a FFRDC/DOE Lab, the lab is required to provide written authorization from the cognizant Federal agency and, if a DOE/NNSA

		FFRDC/DOE Lab, a Field Work Proposal. This form allows the Applicant to request a waiver or modification of the Performance of Work in the United States requirement. A sample response to the Business Assurances & Disclosures Form is also available on ARPA-E eXCHANGE.

1. FIRST COMPONENT: TECHNICAL VOLUME

The Technical Volume must be submitted in Adobe PDF format. A Technical Volume template is available at https://arpa-e-foa.energy.gov. Exploratory Topics may have topic-specific Technical Volumes. The Technical Volume must conform to the content and form requirements included within the template, including maximum page lengths. If Applicants exceed the maximum page lengths specified for each section, ARPA-E may review only the authorized number of pages and disregard any additional pages, or ARPA-E may determine that the submission as a whole is noncompliant per Section III.C of the FOA.

Applicants must provide sufficient citations and references to the primary research literature to justify the claims and approaches made in the Technical Volume. ARPA-E and reviewers may review primary research literature in order to evaluate applications. However, all relevant technical information should be included in the body of the Technical Volume.

2. SECOND COMPONENT: SF-424

The SF-424 must be submitted in Adobe PDF format. This form is available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov.

The SF-424 includes instructions for completing the form. Applicants must complete all required fields in accordance with the instructions. Applicants may identify and include in Block 14 the entities, their addresses, and corresponding census tract numbers for any project activities that will occur within any designated Qualified Opportunity Zone (QOZ). To locate Qualified Opportunity Zones go to: https://www.cdfifund.gov/opportunity-zones.

Prime Recipients and Subrecipients are required to complete SF-LLL (Disclosure of Lobbying Activities), available at https://www.grants.gov/forms/post-award-reporting-forms.html, if any non-Federal funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any Federal agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with your application or funding agreement. The completed SF-LLL must be appended to the SF-424.

ARPA-E provides the following supplemental guidance on completing the SF-424:

- Each Project Team should submit only one SF-424 (i.e., a Subrecipient should not submit a separate SF-424).

- The list of certifications and assurances in Block 21 can be found at http://energy.gov/management/downloads/certifications-and-assurances-use-sf-424.
- The dates and dollar amounts on the SF-424 are for the entire period of performance (from the project start date to the project end date), not a portion thereof.
- Applicants are responsible for ensuring that the proposed costs listed in eXCHANGE match those listed on forms SF-424 and SF-424A. Inconsistent submissions may impact ARPA-E's final award determination.

3. THIRD COMPONENT: BUDGET JUSTIFICATION WORKBOOK/SF-424A

Applicants are required to complete the Budget Justification Workbook/SF-424A Excel spreadsheet. This form is available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov. Prime Recipients must complete each tab of the Budget Justification Workbook for the project as a whole, including all work to be performed by the Prime Recipient and its Subrecipients and Contractors. The SF-424A form included with the Budget Justification Workbook will "auto-populate" as the Applicant enters information into the Workbook. Applicants should carefully read the "Instructions and Summary" tab provided within the Budget Justification Workbook.

Subrecipient information must be submitted as follows:

- Each Subrecipient incurring greater than or equal to 10% of the Total Project Cost must complete a separate Budget Justification workbook to justify its proposed budget. These worksheets must be inserted as additional sheets within in the Prime Recipient's Budget Justification.
- Subrecipients incurring less than 10% of the Total Project Cost are not required to complete a separate Budget Justification workbook. However, such Subrecipients are required to provide supporting documentation to justify their proposed budgets. At a minimum, the supporting documentation must show which tasks/subtasks are being performed, the purpose/need for the effort, and a sufficient basis for the estimated costs.

ARPA-E provides the following supplemental guidance on completing the Budget Justification Workbook/SF-424A:

- Applicants may request funds under the appropriate object class category tabs as long as the item and amount requested are necessary to perform the proposed work, meet all the criteria for allowability under the applicable Federal cost principles, and are not prohibited by the funding restrictions described herein.
- If Patent costs are requested, they must be included in the Applicant's proposed budget (see Section IV.F.3 of the FOA for more information on Patent Costs).

- Unless a waiver is granted by ARPA-E, each Project Team must spend at least 5% of the Federal funding (i.e., the portion of the award that does not include the recipient's cost share) on Technology Transfer & Outreach (TT&O) activities to promote and further the development and deployment of ARPA-E-funded technologies (applies for Topics dated April 18, 2023 and later).
- All TT&O costs requested must be included in the Applicant's proposed budget and identified as TT&O costs in the Budget Justification Workbook/SF-424A with the costs being requested under the "Other" budget category. All budgeted activities must relate to achieving specific objectives, technical milestones and deliverables outlined in Section 2.4 Task Descriptions of the Technical Volume (applies for Topics dated April 18, 2023 and later).
- For more information, please refer to the ARPA-E Budget Justification Guidance document at https://arpa-e-foa.energy.gov.

4. FOURTH COMPONENT: SUMMARY FOR PUBLIC RELEASE

Applicants are required to provide a 250 word maximum Summary for Public Release. A Summary for Public Release template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov). The Summary for Public Release must be submitted in Adobe PDF format. This summary should not include any confidential, proprietary, or privileged information. The summary should be written for a lay audience (e.g., general public, media, Congress) using plain English.

250 Words	**SUMMARY FOR PUBLIC RELEASE**	Briefly describe the proposed effort, summarize its objective(s) and technical approach, describe its ability to achieve the "Program Objectives" (see Section I.B of the FOA), and indicate its potential impact on "ARPA-E Mission Areas" (see Section I.A of the FOA). The summary should be written at technical level suitable for a high-school science student and is designed for public release. **INSTRUCTIONS:** (1) The Summary for Public Release shall not exceed 250 words and one paragraph. (2) The Summary for Public Release shall consist only of text—no graphics, figures, or tables. (3) For applications selected for award negotiations, the Summary may be used as the basis for a public announcement by ARPA-E; therefore, **this Cover Page and Summary should not contain confidential or proprietary information**. See Section VIII.I of the FOA for additional information on marking confidential information.

5. FIFTH COMPONENT: SUMMARY SLIDE

Applicants are required to provide a single PowerPoint slide summarizing the proposed project. The slide must be submitted in Microsoft PowerPoint format. This slide will be used during

ARPA-E's evaluation of Full Applications. A summary slide template and a sample summary slide are available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov).

Summary Slides must conform to the content requirements described below:

- Exploratory Topic Name
- A Technology Summary;
  - Bullet points that describe novel aspects of the proposed technology and technology approach;
- A description of the technology's impact;
  - Quantitative description (through text or graphic) of the impact the proposed project will provide to the market and ARPA-E mission areas;
- Proposed Targets;
  - Including any important technical performance metrics and/or impact categories;
  - Including quantitative description of the state of the art;
  - Including quantitative descriptions of the proposed targets;
- Any key graphics (illustrations, charts and/or tables) summarizing technology development and/or impact;
- The project's key idea/takeaway;
- Project title and Principal Investigator information; and
- Requested ARPA-E funds and proposed Applicant cost share.

6. SIXTH COMPONENT: BUSINESS ASSURANCES & DISCLOSURES FORM

Applicants are required to provide the information requested in the Business Assurances & Disclosures Form. The information must be submitted in Adobe PDF format. A fillable Business Assurances & Disclosures Form template is available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov. A sample response to the Business Assurances & Disclosures Form is also available on ARPA-E eXCHANGE.

As described in the Business Assurances & Disclosures Form, the Applicant is required to:

- Disclose conditions bearing on responsibility, such as criminal convictions and Federal tax liability;
- Disclose conflicts of interest within the Project Team and provide the Applicant's up-to-date, written, and enforced conflict of interest policy in accordance with DOE Interim COI Policy guidance at https://www.energy.gov/management/financial-assistance-letter-no-fal-2022-02;
- If the Applicant is a FFRDC/DOE Lab, submit written authorization from the cognizant Federal agency; and
- If the Applicant is a DOE/NNSA FFRDC/DOE Lab, submit a Field Work Proposal.

In addition, ARPA-E is required by statute to "accelerat[e] transformational technological advances in areas that industry is by itself not likely to undertake because of technical and financial uncertainty."[18] In accordance with ARPA-E's statutory mandate, the Applicant is required to:

- Describe the additionality and risks associated with the proposed R&D project;
- Disclose any applications for the same project or related work currently pending with any Federal or non-Federal entities; and
- Disclose all funding for work in the same technology area as the proposed project received from any Federal or non-Federal entity within the last 5 years.

Finally, the Applicant may use the Business Assurances & Disclosures Form to:

- Request authorization to perform some work ~~overseas~~ outside of the United States; and
- Request a waiver of the TT&O spending requirement (applies for Topics dated April 18, 2023 and later).

D. CONTENT AND FORM OF REPLIES TO REVIEWER COMMENTS

If Applicable to the Exploratory Topic (refer to Table 1), written feedback on Full Applications is made available to Applicants before the submission deadline for Replies to Reviewer Comments. Applicants have a brief opportunity to prepare a short Reply to Reviewer Comments responding to one or more comments or supplementing their Full Application. A fillable Reply to Reviewer Comments template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov).

Replies to Reviewer Comments must conform to the following requirements:

- The Reply to Reviewer Comments must be submitted in Adobe PDF format.
- The Reply to Reviewer Comments must be written in English.
- All pages must be formatted to fit on 8-1/2 by 11 inch paper with margins not less than one inch on every side. Use Times New Roman typeface, a black font color, and a font size of 12 points or larger (except in figures and tables).
- The Control Number must be prominently displayed on the upper right corner of the header of every page. Page numbers must be included in the footer of every page.

[18] America COMPETES Act, Pub. L. No. 110-69, § 5012 (2007), as amended (codified at 42 U.S.C. § 16538).

ARPA-E may not review or consider noncompliant Replies to Reviewer Comments (see Section III.C.1 of the FOA). ARPA-E will review and consider each compliant and responsive Full Application, even if no Reply is submitted or if the Reply is found to be noncompliant.

Replies to Reviewer Comments must conform to the following content and form requirements, including maximum page lengths, described below. If a Reply to Reviewer Comments is more than three pages in length, ARPA-E may review only the first three pages and disregard any additional pages, or ARPA-E may determine that the submission as a whole is noncompliant.
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SECTION	PAGE LIMIT	DESCRIPTION
Text	2 pages maximum	• Applicants may respond to one or more reviewer comments or supplement their Full Application.
Images	1 page maximum	• Applicants may provide graphs, charts, or other data to respond to reviewer comments or supplement their Full Application.

E. INTERGOVERNMENTAL REVIEW

This program is not subject to Executive Order 12372 (Intergovernmental Review of Federal Programs).

F. FUNDING RESTRICTIONS

1. ALLOWABLE COSTS

All expenditures must be allowable, allocable, and reasonable in accordance with the applicable Federal cost principles. Pursuant to 2 C.F.R. § 910.352, the cost principles in the Federal Acquisition Regulations (48 C.F.R. Part 31.2) apply to for-profit entities. The cost principles contained in 2 C.F.R. Part 200, Subpart E apply to all entities other than for-profits.

2. PRE-AWARD COSTS

ARPA-E will not reimburse any pre-award costs incurred by Applicants before they are selected for award negotiations. Please refer to Section VI.A of the FOA for guidance on award notices.

Upon selection for award negotiations, Applicants may incur pre-award costs at their own risk, consistent with the requirements in 2 C.F.R. Part 200, as modified by 2 C.F.R. Part 910, and other Federal laws and regulations. All submitted budgets are subject to change and are typically reworked during award negotiations. ARPA-E is under no obligation to reimburse pre-award costs if, for any reason, the Applicant does not receive an award or the award is made for a lesser amount than the Applicant expected, or if the costs incurred are not allowable, allocable, or reasonable.

3. Patent Costs

For Subject Inventions disclosed to DOE under an award, ARPA-E will reimburse the Prime Recipient – in addition to allowable costs associated with Subject Invention disclosures - up to $30,000 of expenditures for filing and prosecution of United States patent applications, including international applications ("PCT application") submitted to the United States Patent and Trademark Office (USPTO).

The Prime Recipient may request a waiver of the $30,000 cap. Note that, patent costs are considered to be Technology Transfer & Outreach (TT&O) costs (see Section IV.F.8 of the FOA below), and should be requested as such.

4. Construction

ARPA-E generally does not fund projects that involve major construction. Recipients are required to obtain written authorization from the Contracting Officer before incurring any major construction costs.

5. Foreign Travel

ARPA-E generally does not fund projects that involve foreign travel. Recipients are required to obtain written authorization from the ARPA-E Program Director before incurring any foreign travel costs and provide trip reports with their reimbursement requests.

6. Performance of Work in the United States

ARPA-E strongly encourages interdisciplinary and cross-sectoral collaboration spanning organizational boundaries. Such collaboration enables the achievement of scientific and technological outcomes that were previously viewed as extremely difficult, if not impossible.

ARPA-E requires all work under ARPA-E funding agreements to be performed in the United States. However, Applicants may request a waiver of this requirement where their project would materially benefit from, or otherwise requires, certain work to be performed overseas.

Applicants seeking a waiver of this requirement are required to include an explicit request in the Business Assurances & Disclosures Form, which is part of the Full Application submitted to ARPA-E. Such waivers are granted where there is a demonstrated need, as determined by ARPA-E.

7. PURCHASE OF NEW EQUIPMENT

All equipment purchased under ARPA-E funding agreements must be made or manufactured in the United States, to the maximum extent practicable. This requirement does not apply to used or leased equipment. The Prime Recipients are required to notify the ARPA-E Contracting Officer reasonably in advance of purchasing any equipment that is not made or manufactured in the United States with a total acquisition cost of $250,000 or more. Purchases of foreign equipment with a total acquisition cost of $1,000,000 or more require the approval of the Head of Contracting Activity (HCA). The ARPA-E Contracting Officer will provide consent to purchase or reject within 30 calendar days of receipt of the Recipient's notification.

8. TECHNOLOGY TRANSFER AND OUTREACH

ARPA-E is required to contribute a percentage of appropriated funds to Technology Transfer and Outreach (TT&O) activities. In order to meet this mandate every Project Team must spend at least 5% of the Federal funding (i.e., the portion of the award that does not include the recipient's cost share) provided by ARPA-E on TT&O activities to promote and further the development and deployment of ARPA-E-funded technologies. Project Teams must also seek a waiver from ARPA-E to spend less than the minimum 5% TT&O expenditure requirement.

All TT&O expenditures are subject to the applicable Federal cost principles (i.e., 2 C.F.R. 200 Subpart E and 48 C.F.R. Subpart 31). Examples of TT&O expenditures are as follows:

- Documented travel and registration for the ARPA-E Energy Innovation Summit and other energy-related conferences and events;
- Documented travel to meet with potential suppliers, partners, or customers;
- Documented work by salaried or contract personnel to develop technology-to-market models or plans;
- Documented costs of acquiring industry-accepted market research reports; and
- Approved patent costs.

ARPA-E will <u>not</u> reimburse recipients for TT&O costs considered to be unallowable in accordance with the applicable cost principles. Examples of unallowable TT&O expenditures include:

- Meals or entertainment;
- Gifts to potential suppliers, partners, or customers;
- TT&O activities that do not relate to the ARPA-E-funded technologies;
- Undocumented TT&O activities; and
- TT&O activities unrelated and/or unallocable to the subject award.

Applicants may seek a waiver of the TT&O requirement by including an explicit request in the Business Assurances & Disclosures Form. Please refer to the Business Assurances & Disclosures Form for guidance on the content and form of the waiver request. ARPA-E may waive or modify the TT&O requirement, as appropriate.

For information regarding incorporation of TT&O costs into budget documentation, see Section IV.C.3 of the FOA.

9. LOBBYING

Prime Recipients and Subrecipients may not use any Federal funds, directly or indirectly, to influence or attempt to influence, directly or indirectly, congressional action on any legislative or appropriation matters pending before Congress, other than to communicate to Members of Congress as described in 18 U.S.C. § 1913. This restriction is in addition to those prescribed elsewhere in statute and regulation.

Prime Recipients and Subrecipients are required to complete and submit SF-LLL, "Disclosure of Lobbying Activities" (https://www.gsa.gov/forms-library/disclosure-lobbying-activities) if any non-Federal funds have been paid or will be paid to any person for influencing or attempting to influence any of the following in connection with your application:

- An officer or employee of any Federal agency,
- A Member of Congress,
- An officer or employee of Congress, or
- An employee of a Member of Congress.

10. CONFERENCE SPENDING

Prime Recipients and Subrecipients may not use any Federal funds to:

- Defray the cost to the United States Government of a conference held by any Executive branch department, agency, board, commission, or office which is not directly and programmatically related to the purpose for which their ARPA-E award is made and for which the cost to the United States Government is more than $20,000; or
- To circumvent the required notification by the head of any such Executive Branch department, agency, board, commission, or office to the Inspector General (or senior ethics official for any entity without an Inspector General), of the date, location, and number of employees attending such a conference.

11. INDEPENDENT RESEARCH AND DEVELOPMENT COSTS

ARPA-E does not fund Independent Research and Development (IR&D) as part of an indirect cost rate under its financial assistance awards. IR&D, as defined at FAR 31.205-18(a), includes cost of effort that is not sponsored by an assistance agreement or required in performance of a contract, and that consists of projects falling within the four following areas: (i) basic research, (ii) applied research, (iii) development, and (iv) systems and other concept formulation studies.

ARPA-E's goals are to enhance the economic and energy security of the United States through the development of energy technologies and ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies. ARPA-E accomplishes these goals by providing financial assistance for energy technology projects, and has well recognized and established procedures for supporting research through competitive financial assistance awards based on merit review of proposed projects. Reimbursement for independent research and development costs through the indirect cost mechanism could circumvent this competitive process.

To ensure that all projects receive similar and equal consideration, eligible organizations may compete for direct funding of independent research projects they consider worthy of support by submitting proposals for those projects to ARPA-E. Since proposals for these projects may be submitted for direct funding, costs for independent research and development projects are not allowable as indirect costs under ARPA-E awards. IR&D costs, however, would still be included in the direct cost base that is used to calculate the indirect rate so as to ensure an appropriate allocation of indirect costs to the organization's direct cost centers.

12. PROHIBITION ON CERTAIN TELECOMMUNICATIONS AND VIDEO SURVEILLANCE SERVICES OR EQUIPMENT

Per 2 C.F.R. § 200.216, recipients and subrecipients are prohibited from obligating or expending project funds to: (1) procure or obtain; (2) extend or renew a contract to procure or obtain; or (3) enter into a contract (or extend or renew a contract) to procure or obtain equipment, services, or systems that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. As described in Public Law 115–232, section 889, covered telecommunications equipment is telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities). Refer to 2 C.F.R. § 200.216 for possible additional prohibitions and limitations.

13. Buy America Requirement for Public Infrastructure Projects

Projects funded through this FOA that are for, or contain, construction, alteration, maintenance, or repair of public infrastructure in the United States undertaken by applicable recipient types, require that:

- All iron, steel, and manufactured products used in the infrastructure project are produced in the United States; and
- All construction materials used in the infrastructure project are manufactured in the United States.

However, ARPA-E does not anticipate soliciting for or selecting projects that propose project tasks that are for, or contain, construction, alteration, maintenance, or repair of public infrastructure. If a project selected for award negotiations includes project tasks that may be subject to the Buy America Requirement, those project tasks will be removed from the project before any award is issued – i.e., no federal funding or Recipient cost share will be available for covered project tasks.

This "Buy America" requirement does not apply to an award where the Prime Recipient is a for-profit entity.

14. Requirement for Financial Personnel

ARPA-E requires Small Business or Nonprofit applicants to identify a finance/budget professional (employee or contracted support) with an understanding of Federal contracting and/or financial assistance and cost accounting (including indirect costs, invoicing, and financial management systems) that will support the team in complying with all applicable requirements.

G. Other Submission Requirements

1. Use of ARPA-E eXCHANGE

To apply to this FOA, Applicants must register with ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/Registration.aspx). Full Applications and Replies to Reviewer Comments must be submitted through ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/login.aspx). ARPA-E will not review or consider applications submitted through other means (e.g., fax, hand delivery, email, postal mail). For detailed guidance on using ARPA-E eXCHANGE, please refer to the "ARPA-E eXCHANGE Applicant Guide" (https://arpa-e-foa.energy.gov/Manuals.aspx).

Upon creating an application submission in ARPA-E eXCHANGE, Applicants will be assigned a Control Number. If the Applicant creates more than one application submission, a different Control Number will be assigned for each application.

Once logged in to ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/login.aspx), Applicants may access their submissions by clicking the "My Submissions" link in the navigation on the left side of the page. Every application that the Applicant has submitted to ARPA-E and the corresponding Control Number is displayed on that page. If the Applicant submits more than one application to a particular FOA, a different Control Number is shown for each application.

Applicants are responsible for meeting each submission deadline in ARPA-E eXCHANGE. **Applicants are strongly encouraged to submit their applications at least 48 hours in advance of the Exploratory Topic Submission Deadline.** Under normal conditions (i.e., at least 48 hours in advance of the Close Date), Applicants should allow at least 1 hour to submit a Full Application. In addition, Applicants should allow at least 15 minutes to submit a Reply to Reviewer Comments. Once the application is submitted in ARPA-E eXCHANGE, Applicants may revise or update their application until the expiration of the applicable deadline.

Applicants should not wait until the last minute to begin the submission process. During the final hours before the submission deadline, Applicants may experience server/connection congestion that prevents them from completing the necessary steps in ARPA-E eXCHANGE to submit their applications. **ARPA-E will not extend the submission deadline for Applicants that fail to submit required information and documents due to server/connection congestion.**

ARPA-E may not review or consider incomplete applications and applications received after the Exploratory Topic submission deadline stated in the FOA. Such applications may be deemed noncompliant (see Section III.C.1 of the FOA). The following errors could cause an application to be deemed "incomplete" and thus noncompliant:

- Failing to comply with the form and content requirements in Section IV of the FOA;
- Failing to enter required information in ARPA-E eXCHANGE;
- Failing to upload required document(s) to ARPA-E eXCHANGE;
- Failing to click the "Submit" button in ARPA-E eXCHANGE by the deadline stated in the FOA;
- Uploading the wrong document(s) or application(s) to ARPA-E eXCHANGE; and
- Uploading the same document twice, but labeling it as different documents. (In the latter scenario, the Applicant failed to submit a required document.)

ARPA-E urges Applicants to carefully review their applications and to allow sufficient time for the submission of required information and documents.

V. Application Review Information

A. Criteria

ARPA-E performs a preliminary review of Full Applications to determine whether they are compliant and responsive (see Section III.C of the FOA). If applicable, ARPA-E also performs a preliminary review of Replies to Reviewer Comments to determine whether they are compliant.

ARPA-E considers a mix of quantitative and qualitative criteria in determining whether to select a Full Application for award negotiations.

1. Criteria for Full Applications

Full Applications are evaluated based on the following criteria:

(1) *Impact of the Proposed Technology* (30%) - This criterion involves consideration of the following:

- The potential for a transformational and disruptive (not incremental) advancement in one or more energy-related fields;
- Thorough understanding of the current state-of-the-art and presentation of an innovative technical approach to significantly improve performance over the current state-of-the-art;
- Awareness of competing commercial and emerging technologies and identification of how the proposed concept/technology provides significant improvement over these other solutions; and
- A reasonable and effective strategy for transitioning the proposed technology from the laboratory to commercial deployment.

(2) *Overall Scientific and Technical Merit* (30%) - This criterion involves consideration of the following:

- Whether the proposed work is unique and innovative;
- Clearly defined project outcomes and final deliverables;
- Substantiation that the proposed project is likely to meet or exceed the technical performance targets identified in this FOA;
- Feasibility of the proposed work based upon preliminary data or other background information and sound scientific and engineering practices and principles;
- A sound technical approach, including appropriately defined technical tasks, to accomplish the proposed R&D objectives; and
- Management of risk, to include identifying major technical R&D risks and feasible, effective mitigation strategies.

(3) *Qualifications, Experience, and Capabilities of the Proposed Project Team* (30%) - This criterion involves consideration of the following**:**

- The PI and Project Team have the skill and expertise needed to successfully execute the project plan, evidenced by prior experience that demonstrates an ability to perform R&D of similar risk and complexity; and
- Access to the equipment and facilities necessary to accomplish the proposed R&D effort and/or a clear plan to obtain access to necessary equipment and facilities.

(4) *Soundness of Management Plan* (10%) - This criterion involves consideration of the following:

- Plausibility of plan to manage people and resources;
- Allocation of appropriate levels of effort and resources to proposed tasks;
- Reasonableness of the proposed project schedule, including major milestones; and
- Reasonableness of the proposed budget to accomplish the proposed project.

Submissions will not be evaluated against each other since they are not submitted in accordance with a common work statement.

The above criteria will be weighted as follows:

Impact of the Proposed Technology	30%
Overall Scientific and Technical Merit	30%
Qualifications, Experience, and Capabilities of the Proposed Project Team	30%
Soundness of Management Plan	10%

2. Criteria for Replies to Reviewer Comments

ARPA-E has not established separate criteria to evaluate Replies to Reviewer Comments. Instead, Replies to Reviewer Comments are evaluated as an extension of the Full Application.

B. Review and Selection Process

1. Program Policy Factors

In addition to the above criteria, ARPA-E may consider the following program policy factors in determining which Full Applications to select for award negotiations:

I. **ARPA-E Portfolio Balance**. Project balances ARPA-E portfolio in one or more of the following areas:
   a. Diversity of technical personnel in the proposed Project Team;
   b. Technological diversity;
   c. Organizational diversity;
   d. Geographic diversity;
   e. Technical or commercialization risk; or
   f. Stage of technology development.

II. **Relevance to ARPA-E Mission Advancement.** Project contributes to one or more of ARPA-E's key statutory goals:
   a. Reduction of U.S. dependence on foreign energy sources;
   b. Stimulation of U.S. manufacturing; and/or software development
   c. Reduction of energy-related emissions;
   d. Increase in U.S. energy efficiency;
   e. Enhancement of U.S. economic and energy security; or
   f. Promotion of U.S. advanced energy technologies competitiveness.

III. **Synergy of Public and Private Efforts**.
   a. Avoids duplication and overlap with other publicly or privately funded projects;
   b. Promotes increased coordination with nongovernmental entities for demonstration of technologies and research applications to facilitate technology transfer; or
   c. Increases unique research collaborations.

IV. **Low likelihood of other sources of funding.** High technical and/or financial uncertainty that results in the non-availability of other public, private or internal funding or resources to support the project.

V. **High-Leveraging of Federal Funds**. Project leverages Federal funds to optimize advancement of programmatic goals by proposing cost share above the required minimum or otherwise accessing scarce or unique resources.

VI. **High Project Impact Relative to Project Cost.**

VII. **Qualified Opportunity Zone (QOZ).** Whether the entity is located in an urban and economically distressed area including a Qualified Opportunity Zone (QOZ) or the proposed project will occur in a QOZ or otherwise advance the goals of QOZ. The goals include spurring economic development and job creation in distressed communities throughout the United States. For a list or map of QOZs go to: https://www.cdfifund.gov/opportunity-zones.

2. ARPA-E Reviewers

By submitting an application to ARPA-E, Applicants consent to ARPA-E's use of Federal employees, contractors, and experts from educational institutions, nonprofits, industry, and governmental and intergovernmental entities as reviewers. ARPA-E selects reviewers based on their knowledge and understanding of the relevant field and application, their experience and skills, and their ability to provide constructive feedback on applications.

ARPA-E requires all reviewers to complete a Conflict-of-Interest Certification and Nondisclosure Agreement through which they disclose their knowledge of any actual or apparent conflicts and agree to safeguard confidential information contained in Full Applications, and Replies to Reviewer Comments. In addition, ARPA-E trains its reviewers in proper evaluation techniques and procedures.

Applicants are not permitted to nominate reviewers for their applications. Applicants may contact the Contracting Officer by email (ARPA-E-CO@hq.doe.gov) if they have knowledge of a potential conflict of interest or a reasonable belief that a potential conflict exists.

3. ARPA-E Support Contractor

ARPA-E utilizes contractors to assist with the evaluation of applications and project management. To avoid actual and apparent conflicts of interest, ARPA-E prohibits its support contractors from submitting or participating in the preparation of applications to ARPA-E.

By submitting an application to ARPA-E, Applicants represent that they are not performing support contractor services for ARPA-E in any capacity and did not obtain the assistance of ARPA-E's support contractors to prepare the application. ARPA-E will not consider any applications that are submitted by or prepared with the assistance of its support contractors.

C. Anticipated Announcement and Award Dates

ARPA-E expects to announce selections for negotiations for each Exploratory Topic in the month indicated in Table 1. ARPA-E anticipates that it will execute a funding agreement approximately 120 days after notifying an Applicant that its application has been selected for negotiations.

VI. AWARD ADMINISTRATION INFORMATION

A. AWARD NOTICES

1. REJECTED SUBMISSIONS

Noncompliant and nonresponsive Full Applications are rejected by the Contracting Officer and are not merit reviewed or considered for award. The Contracting Officer sends a notification letter by email to the technical and administrative points of contact designated by the Applicant in ARPA-E eXCHANGE. The notification letter states the basis upon which the Full Application was rejected.

2. FULL APPLICATION NOTIFICATIONS

ARPA-E promptly notifies Applicants of its determination. ARPA-E sends a notification letter by email to the technical and administrative points of contact designated by the Applicant in ARPA-E eXCHANGE. The notification letter may inform the Applicant that its Full Application was selected for award negotiations, or not selected. Alternatively, ARPA-E may notify one or more Applicants that a final selection determination on particular Full Applications will be made at a later date, subject to the availability of funds and other factors.

If authorized per Table 1, written feedback on Full Applications is made available to Applicants before the submission deadline for Replies to Reviewer Comments. By providing feedback, ARPA-E intends to guide the further development of the proposed technology and to provide a brief opportunity to respond to reviewer comments.

a. SUCCESSFUL APPLICANTS

ARPA-E has discretion to select all or part of a proposed project for negotiation of an award. A notification letter selecting a Full Application for award negotiations does not authorize the Applicant to commence performance of the project. **ARPA-E selects Full Applications for award negotiations, not for award.** Applicants do not receive an award until award negotiations are complete and the Contracting Officer executes the funding agreement. ARPA-E may terminate award negotiations at any time for any reason.

Please refer to Section IV.F.2 of the FOA for guidance on pre-award costs.

b. *Postponed Selection Determinations*

A notification letter postponing a final selection determination until a later date does not authorize the Applicant to commence performance of the project. ARPA-E may ultimately determine to select or not select the Full Application for award negotiations.

Please refer to Section IV.F.2 of the FOA for guidance on pre-award costs.

c. *Unsuccessful Applicants*

By not selecting a Full Application, ARPA-E intends to convey its lack of programmatic interest in the proposed project. Such assessments do not necessarily reflect judgments on the merits of the proposed project. ARPA-E hopes that unsuccessful Applicants will submit innovative ideas and concepts for future FOAs.

B. Administrative and National Policy Requirements

The following administrative and national policy requirements apply to Prime Recipients. The Prime Recipient is the responsible authority regarding the settlement and satisfaction of all contractual and administrative issues, including but not limited to disputes and claims arising out of any agreement between the Prime Recipient and a FFRDC contractor. Prime Recipients are required to flow down these requirements to their Subrecipients through subawards or related agreements.

- If a subaward is made to a DOE/NNSA National Laboratory, all Disputes and Claims will be resolved in accordance with the terms and conditions of the DOE/NNSA National Laboratory's management and operating (M&O) contract, as applicable, in consultation between DOE and the prime awardee.
- If a subaward is made to another Federal agency or its FFRDC contractor, all Disputes and Claims will be resolved in accordance with the terms and conditions of the interagency agreement in consultation between DOE and the prime awardee.

1. Unique Entity Identifier and SAM, FSRS, and FedConnect Registrations

Prime Recipients must register with the System for Award Management (SAM) at www.sam.gov/SAM prior to submitting an application, at which time the system will assign (if newly registered)a Unique Entity Identifier (UEI). As of April 4, 2022, the UEI replaces the old Dun and Bradstreet Data Universal Numbering System (DUNS) number requirement.

Prime Recipients must:

- Maintain an active SAM registration with current information, including information on a its immediate and highest-level owner and subsidiaries, as well as on all predecessors that have been awarded a Federal contract or financial assistance award within the last three years, if applicable, at all times during which it has an active Federal award or an application or plan under consideration by a Federal awarding agency;
- Remain registered in the SAM database after the initial registration;
- Update its information in the SAM database as soon as it changes;
- Review its information in the SAM database on an annual basis from the date of initial registration or subsequent updates to ensure it is current, accurate and complete; and not make a subaward to any entity unless the entity has provided its UEI.

Subrecipients are not required to register in SAM, but must obtain a UEI.

Prime Recipients and Subrecipients should commence this process as soon as possible in order to expedite the execution of a funding agreement. Registering with SAM and obtaining the UEI could take several weeks.

Prime Recipients are also required to register with the Federal Funding Accountability and Transparency Act Subaward Reporting System (FSRS) at https://www.fsrs.gov/.[19] Prime Recipients are required to report to FSRS the names and total compensation of each of the Prime Recipient's five most highly compensated executives and the names and total compensation of each Subrecipient's five most highly compensated executives. Please refer to https://www.fsrs.gov/ for guidance on reporting requirements. Prime Recipients are required to keep the FSRS data current throughout the duration of the project.

ARPA-E may not execute a funding agreement with the Prime Recipient until it has obtained a UEI and completed its SAM and FSRS registrations.

Finally, Prime Recipients are required to register with FedConnect in order to receive notification that their funding agreement has been executed by the Contracting Officer and to obtain a copy of the executed funding agreement. Please refer to https://www.fedconnect.net/FedConnect/ for registration instructions.

2. NATIONAL POLICY ASSURANCES

Project Teams, including Prime Recipients and Subrecipients, are required to comply with the National Policy Assurances attached to their funding agreement in accordance with 2 C.F.R. § 200.300. Refer to Attachment 6 of ARPA-E's Model Cooperative Agreement https://arpa-e.energy.gov/technologies/project-guidance/pre-award-guidance/funding-agreements) for information on the National Policy Assurances.

[19] The Federal Funding Accountability and Transparency Act, P.L. 109-282, 31 U.S.C. 6101 note.

3. PROOF OF COST SHARE COMMITMENT AND ALLOWABILITY

Upon selection for award negotiations, the Prime Recipient must confirm in writing that the proposed cost share contribution is allowable in accordance with applicable Federal cost principles.

The Prime Recipient is also required to provide cost share commitment letters from Subrecipients or third parties that are providing cost share, whether cash or in-kind. Each Subrecipient or third party that is contributing cost share must provide a letter on appropriate letterhead that is signed by an authorized corporate representative.

4. COST SHARE PAYMENTS[20]

All proposed cost share contributions must be reviewed in advance by the Contracting Officer and incorporated into the project budget before the expenditures are incurred.

The Prime Recipient is required to pay the "Cost Share" amount as a percentage of the total project costs in each invoice period for the duration of the period of performance. Small Businesses should refer to Section III.B.3 of the FOA.

ARPA-E may deny reimbursement requests, in whole or in part, or modify or terminate funding agreements where Prime Recipients (or Project Teams) fail to comply with ARPA-E's cost share payment requirements.

5. ENVIRONMENTAL IMPACT QUESTIONNAIRE

By law, ARPA-E is required to evaluate the potential environmental impact of projects that it is considering for funding. In particular, ARPA-E must determine before funding a project whether the project qualifies for a categorical exclusion under 10 C.F.R. § 1021.410 or whether it requires further environmental review (i.e., an environmental assessment or an environmental impact statement).

To facilitate and expedite ARPA-E's environmental review, Prime Recipients are required to complete an Environmental Impact Questionnaire during award negotiations. This form is available at https://arpa-e.energy.gov/technologies/project-guidance/pre-award-guidance/required-forms-and-templates. Each Prime Recipient must wait to complete the Environmental Impact Questionnaire (EIQ) until after ARPA-E has notified them that Attachment 3 Statement of Program Objectives is in final form. The completed EIQ is then due back to ARPA-E within 14 calendar days.

[20] Please refer to Section III.B of the FOA for guidance on cost share requirements.

6. TECHNOLOGY-TO-MARKET PLAN

During award negotiations, Prime Recipients are required to negotiate and submit an initial Technology-to-Market Plan to the ARPA-E Program Director, and obtain the ARPA-E Program Director's approval prior to the execution of the award. Prime Recipients must show how budgeted Technology Transfer and Outreach (TT&O) costs relate to furthering elements of the Technology-to-Market Plan. During the period of performance, Prime Recipients are required to provide regular updates on the initial Technology-to-Market plan and report on implementation of Technology-to-Market activities. Prime Recipients may be required to perform other actions to further the commercialization of their respective technologies.

ARPA-E may waive or modify this requirement, as appropriate.

7. INTELLECTUAL PROPERTY AND DATA MANAGEMENT PLANS

ARPA-E requires every Project Team to negotiate and establish an Intellectual Property Management Plan for the management and disposition of intellectual property arising from the project. The Prime Recipient must submit a completed and signed Intellectual Property Management plan to ARPA-E within six weeks of the effective date of the ARPA-E funding agreement. All Intellectual Property Management Plans are subject to the terms and conditions of the ARPA-E funding agreement and its intellectual property provisions, and applicable Federal laws, regulations, and policies, all of which take precedence over the terms of Intellectual Property Management Plans.

ARPA-E has developed a template for Intellectual Property Management Plans https://arpa-e.energy.gov/technologies/project-guidance/post-award-guidance/project-management-reporting-requirements so as to facilitate and expedite negotiations between Project Team members. ARPA-E does not mandate the use of this template. ARPA-E and DOE do not make any warranty (express or implied) or assume any liability or responsibility for the accuracy, completeness, or usefulness of the template. ARPA-E and DOE strongly encourage Project Teams to consult independent legal counsel before using the template.

Awardees are also required, post-award, to submit a Data Management Plan (DMP) that addresses how data generated in the course of the work performed under an ARPA-E award will be preserved and, as appropriate, shared publicly. The Prime Recipient must submit a completed and signed DMP - as part of the Team's Intellectual Property Management Plan - to ARPA-E within six weeks of the effective date of the ARPA-E funding agreement.

8. U.S. COMPETITIVENESS

A primary objective of DOE's multi-billion dollar research, development and demonstration investments – including ARPA-E awards - is advancement of new energy technologies, manufacturing capabilities, and supply chains for and by U.S. industry and labor. Therefore, in exchange for receiving taxpayer dollars to support an applicant's project, the applicant must agree to the following U.S. Competitiveness Provision as part of an award under this FOA.

U.S. Competitiveness

> The Contractor (Prime Recipient in ARPA-E awards) agrees that any products embodying any subject invention or produced through the use of any subject invention will be manufactured substantially in the United States unless the Contractor can show to the satisfaction of DOE that it is not commercially feasible. In the event DOE agrees to foreign manufacture, there will be a requirement that the Government's support of the technology be recognized in some appropriate manner, e.g., alternative binding commitments to provide an overall net benefit to the U.S. economy. The Contractor agrees that it will not license, assign or otherwise transfer any subject invention to any entity, at any tier, unless that entity agrees to these same requirements. Should the Contractor or other such entity receiving rights in the invention(s): (1) undergo a change in ownership amounting to a controlling interest, or (2) sell, assign, or otherwise transfer title or exclusive rights in the invention(s), then the assignment, license, or other transfer of rights in the subject invention(s) is/are suspended until approved in writing by DOE. The Contractor and any successor assignee will convey to DOE, upon written request from DOE, title to any subject invention, upon a breach of this paragraph. The Contractor will include this paragraph in all subawards/contracts, regardless of tier, for experimental, developmental or research work.
>
> A subject invention is any invention of the contractor conceived or first actually reduced to practice in the performance of work under an award. An invention is any invention or discovery which is or may be patentable. The contractor includes any awardee, recipient, sub-awardee, or sub-recipient.

As noted in the U.S. Competitiveness Provision, at any time in which an entity cannot meet the requirements of the U.S. Competitiveness Provision, the entity may request a modification or waiver of the U.S. Competitiveness Provision. For example, the entity may propose modifying the language of the U.S. Competitiveness Provision in order to change the scope of the requirements or to provide more specifics on the application of the requirements for a particular technology. As another example, the entity may request that the U.S. Competitiveness Provision be waived in lieu of a net benefits statement or U.S. manufacturing plan. The statement or plan would contain specific and enforceable commitments that would be beneficial to the U.S. economy and competitiveness. Commitments could include manufacturing specific products in the U.S., making a specific investment in a new or existing U.S. manufacturing facility, keeping certain activities based in the U.S. or supporting a certain number of jobs in the U.S. related to the technology. If DOE, in its sole discretion, determines that the proposed modification or waiver promotes commercialization and provides substantial U.S. economic benefits, DOE may grant the request and, if granted, modify the award terms and conditions for the requesting entity accordingly.

The U.S. Competitiveness Provision is implemented by DOE pursuant to a Determination of Exceptional Circumstances (DEC) under the Bayh-Dole Act and DOE Patent Waivers. See Section VIII.A, "Title to Subject Inventions", of this FOA for more information on the DEC and DOE Patent Waiver.

9. CORPORATE FELONY CONVICTIONS AND FEDERAL TAX LIABILITY

In submitting an application in response to this FOA, the Applicant represents that:

- It is not a corporation that has been convicted of a felony criminal violation under any Federal law within the preceding 24 months; and
- It is not a corporation that has any unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or have lapsed, and that is not being paid in a timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

For purposes of these representations the following definitions apply: A Corporation includes any entity that has filed articles of incorporation in any of the 50 states, the District of Columbia, or the various territories of the United States [but not foreign corporations]. It includes both for-profit and non-profit organizations.

10. APPLICANT RISK ANALYSIS

If selected for award negotiations, ARPA-E may evaluate the risks posed by the Applicant using the criteria set forth at 2 CFR §200.206(b)(ii). ARPA-E may require special award terms and conditions depending upon results of the risk analysis.

Further, as DOE invests in critical infrastructure and funds critical and emerging technology areas, DOE also considers possible vectors of undue foreign influence in evaluating risk. If high risks are identified and cannot be sufficiently mitigated, DOE may elect to not fund the applicant. As part of the research, technology, and economic security risk review, DOE may contact the applicant and/or proposed project team members for additional information to inform the review.

ARPA-E will not make an award if ARPA-E has determined that:

- The entity submitting the proposal or application:
  - has an owner or covered individual that is party to a malign foreign talent recruitment program;
  - has a business entity, parent company, or subsidiary located in the People's Republic of China or another foreign country of concern; or

  - o has an owner or covered individual that has a foreign affiliation with a research institution located in the People's Republic of China or another foreign country of concern; and

- The relationships and commitments described above:
  - o interfere with the capacity for activities supported by the Federal agency to be carried out;
  - o create duplication with activities supported by the Federal agency;
  - o present concerns about conflicts of interest;
  - o were not appropriately disclosed to the Federal agency;
  - o violate Federal law or terms and conditions of the Federal agency; or

  pose a risk to national security.

11. Recipient Integrity and Performance Matters

Prior to making a Federal award ARPA-E is required to review and consider any information about Applicants that is contained in the Office of Management and Budget's designated integrity and performance system accessible through SAM (currently the Federal Awardee Performance and Integrity Information System or FAPIIS) (41 U.S.C. § 2313 and 2 C.F.R. 200. 206).

Applicants may review information in FAPIIS and comment on any information about itself that a Federal awarding agency previously entered into FAPIIS.

ARPA-E will consider any written comments provided by Applicants during award negotiations, in addition to the other information in FAPIIS, in making a judgment about an Applicant's integrity, business ethics, and record of performance under Federal awards when reviewing potential risk posed by Applicants as described in 2 C.F.R. §200.206.

12. Nondisclosure and Confidentiality Agreements Representations

In submitting an application in response to this FOA the Applicant represents that:

(1) **It does not and will not** require its employees or contractors to sign internal nondisclosure or confidentiality agreements or statements prohibiting or otherwise restricting its employees or contractors from lawfully reporting waste, fraud, or abuse to a designated investigative or law enforcement representative of a Federal department or agency authorized to receive such information.

(2) **It does not and will not** use any Federal funds to implement or enforce any nondisclosure and/or confidentiality policy, form, or agreement it uses unless it contains the following provisions:

a. *"These provisions are consistent with and do not supersede, conflict with, or otherwise alter the employee obligations, rights, or liabilities created by existing statute or Executive order relating to (1) classified information, (2) communications to Congress, (3) the reporting to an Inspector General of a violation of any law, rule, or regulation, or mismanagement, a gross waste of funds, an abuse of authority, or a substantial and specific danger to public health or safety, or (4) any other whistleblower protection. The definitions, requirements, obligations, rights, sanctions, and liabilities created by controlling Executive orders and statutory provisions are incorporated into this agreement and are controlling."*

b. The limitation above shall not contravene requirements applicable to Standard Form 312, Form 4414, or any other form issued by a Federal department or agency governing the nondisclosure of classified information.

c. Notwithstanding the provision listed in paragraph (a), a nondisclosure confidentiality policy form or agreement that is to be executed by a person connected with the conduct of an intelligence or intelligence-related activity, other than an employee or officer of the United States Government, may contain provisions appropriate to the particular activity for which such document is to be used. Such form or agreement shall, at a minimum, require that the person will not disclose any classified information received in the course of such activity unless specifically authorized to do so by the United States Government. Such nondisclosure or confidentiality forms shall also make it clear that they do not bar disclosure to congress, or to an authorized official of an executive agency or the Department of Justice, that are essential to reporting a substantial violation of law.

13. INTERIM CONFLICT OF INTEREST POLICY FOR FINANCIAL ASSISTANCE

The DOE interim Conflict of Interest Policy for Financial Assistance (COI Policy) can be found at https://www.energy.gov/management/financial-assistance-letter-no-fal-2022-02. This policy is applicable to all non-Federal entities applying for, or that receive, DOE funding by means of a financial assistance award (e.g., a grant, cooperative agreement, or technology investment agreement or similar other transaction agreement) and, through the implementation of this policy by the entity, to each Investigator who is planning to participate in, or is participating in, the project funded wholly or in part under the DOE financial assistance award. DOE's interim COI Policy establishes standards that provide a reasonable expectation that the design, conduct, and reporting of projects funded wholly or in part under DOE financial assistance awards will be free from bias resulting from financial conflicts of interest or organizational conflicts of interest. The applicant is subject to the requirements of the interim COI Policy and within each application for financial assistance, the applicant must certify that it is, or will be by the time of receiving any financial assistance award, compliant with all requirements in the interim COI Policy. For applicants to any ARPA-E Funding Opportunity Announcement, this certification, disclosure of any managed or unmanaged conflicts of interest, and a copy of (or link to) the applicant's own conflict of interest policy must be included with the information provided in the Business Assurances & Disclosures Form. The applicant must also flow down the requirements of the interim COI Policy to any subrecipient non-Federal entities.

14. COMMERCIALIZATION PLAN AND SOFTWARE REPORTING

If your project is selected and it targets the development of software, you may be required to prepare a Commercialization Plan for the targeted software and agree to special provisions that require the reporting of the targeted software and its utilization. This special approach to projects that target software mirrors the requirements for reporting that attach to new inventions made in performance of an award.

C. REPORTING

Recipients are required to submit periodic, detailed reports on technical, financial, and other aspects of the project, as described in Attachment 4 to ARPA-E's Model Cooperative Agreement https://arpa-e.energy.gov/technologies/project-guidance/pre-award-guidance/funding-agreements).

VII. AGENCY CONTACTS

A. COMMUNICATIONS WITH ARPA-E

Upon the issuance of an Exploratory Topic, only the Contracting Officer may communicate with Applicants. ARPA-E personnel and our support contractors are prohibited from communicating (in writing or otherwise) with Applicants regarding the FOA. This "quiet period" remains in effect until ARPA-E's public announcement of its project selections.

During the "quiet period," Applicants are required to submit all questions regarding this FOA to ARPA-E-CO@hq.doe.gov. Questions and Answers (Q&As) about ARPA-E and the FOA are available at http://arpa-e.energy.gov/faq. For questions that have not already been answered, please send an email with the FOA name and number in the subject line to ARPA-E-CO@hq.doe.gov. Due to the volume of questions received, ARPA-E will only answer pertinent questions that have not yet been answered and posted at the above link.

- ARPA-E will post responses on a weekly basis to any questions that are received that have not already been addressed at the link above. ARPA-E may re-phrase questions or consolidate similar questions for administrative purposes.
- ARPA-E will cease to accept questions approximately 10 business days in advance of the Exploratory Topic submission deadline. Responses to questions received before this cutoff will be posted no later than three business days in advance of the submission deadline. ARPA-E may re-phrase questions or consolidate similar questions for administrative purposes.
- Responses are published in a document specific to this FOA under "CURRENT FUNDING OPPORTUNITIES – FAQS" on ARPA-E's website (http://arpa-e.energy.gov/faq).

Applicants may submit questions regarding ARPA-E eXCHANGE, ARPA-E's online application portal, to ExchangeHelp@hq.doe.gov. ARPA-E will promptly respond to emails that raise legitimate, technical issues with ARPA-E eXCHANGE. ARPA-E will refer any questions regarding the FOA to ARPA-E-CO@hq.doe.gov.

ARPA-E will not accept or respond to communications received by other means (e.g., fax, telephone, mail, hand delivery). Emails sent to other email addresses will be disregarded.

During the "quiet period," only the Contracting Officer may authorize communications between ARPA-E personnel and Applicants. The Contracting Officer may communicate with Applicants as necessary and appropriate. As described in Section IV.A of the FOA, the Contracting Officer may arrange pre-selection meetings and/or site visits during the "quiet period."

B. Debriefings

ARPA-E does not offer or provide debriefings. If authorized per Table 1, ARPA-E provides Applicants with reviewer comments on Full Applications before the submission deadline for Replies to Reviewer Comments.

VIII. OTHER INFORMATION

A. TITLE TO SUBJECT INVENTIONS

Ownership of subject inventions is governed pursuant to the authorities listed below.

- Domestic Small Businesses, Educational Institutions, and Nonprofits: Under the Bayh-Dole Act (35 U.S.C. § 200 et seq.), domestic small businesses, educational institutions, and nonprofits may elect to retain title to their subject inventions;
- All other parties: The federal Non-Nuclear Energy Act of 1974, 42. U.S.C. 5908, provides that the government obtains title to new subject inventions unless a waiver is granted (see below):
- Class Patent Waiver for Domestic Large Businesses: DOE has issued a class patent waiver that applies to this FOA. Under this class patent waiver, domestic large businesses may elect title to their subject inventions similar to the right provided to the domestic small businesses, educational institutions, and nonprofits by law. In order to avail itself of the class patent waiver, a domestic large business must agree to the U.S. Competitiveness Provision in accordance with Section VI.B.8. of this FOA.
- Advance and Identified Waivers: For applicants that do not fall under the class patent waiver or the Bayh-Dole Act, those applicants may request a patent waiver that will cover subject inventions that may be made under the award, in advance of or within 30 days after the effective date of the award. Even if an advance waiver is not requested or the request is denied, the recipient will have a continuing right under the award to request a waiver for identified inventions, i.e., individual subject inventions that are disclosed to DOE within the time frames set forth in the award's intellectual property terms and conditions. Any patent waiver that may be granted is subject to certain terms and conditions in 10 CFR 784.
- DEC: On June 07, 2021, DOE approved a DETERMINATION OF EXCEPTIONAL CIRCUMSTANCES (DEC) UNDER THE BAYH-DOLE ACT TO FURTHER PROMOTE DOMESTIC MANUFACTURE OF DOE SCIENCE AND ENERGY TECHNOLOGIES. In accordance with this DEC, all awards, including sub-awards, under this FOA made to a Bayh-Dole entity (domestic small businesses and nonprofit organizations) shall include the U.S. Competitiveness Provision in accordance with Section VI.B.8 of this FOA. A copy of the DEC may be found on the DoE website. Pursuant to 37 CFR § 401.4, any Bayh-Dole entity affected by this DEC has the right to appeal it by providing written notice to DOE within 30 working days from the time it receives a copy of the determination.

B. GOVERNMENT RIGHTS IN SUBJECT INVENTIONS

Where Prime Recipients and Subrecipients retain title to subject inventions, the U.S. Government retains certain rights.

1. Government Use License

The U.S. Government retains a nonexclusive, nontransferable, irrevocable, paid-up license to practice or have practiced for or on behalf of the United States any subject invention throughout the world. This license extends to contractors doing work on behalf of the Government.

2. March-In Rights

The U.S. Government retains march-in rights with respect to all subject inventions. Through "march-in rights," the Government may require a Prime Recipient or Subrecipient who has elected to retain title to a subject invention (or their assignees or exclusive licensees), to grant a license for use of the invention. In addition, the Government may grant licenses for use of the subject invention when Prime Recipients, Subrecipients, or their assignees and exclusive licensees refuse to do so.

The U.S. Government may exercise its march-in rights if it determines that such action is necessary under any of the four following conditions:

- The owner or licensee has not taken or is not expected to take effective steps to achieve practical application of the invention within a reasonable time;
- The owner or licensee has not taken action to alleviate health or safety needs in a reasonably satisfactory manner;
- The owner has not met public use requirements specified by Federal statutes in a reasonably satisfactory manner; or
- The U.S. Manufacturing requirement has not been met.

C. Rights in Technical Data

Data rights differ based on whether data is first produced under an award or instead was developed at private expense outside the award.

- Background or "Limited Rights Data": The U.S. Government will not normally require delivery of technical data developed solely at private expense prior to issuance of an award, except as necessary to monitor technical progress and evaluate the potential of proposed technologies to reach specific technical and cost metrics.
- Generated Data: The U.S. Government normally retains very broad rights in technical data produced under Government financial assistance awards, including the right to distribute to the public. However, pursuant to special statutory authority, certain categories of data generated under ARPA-E awards may be protected from public disclosure for up to ten years (or more, if approved by ARPA-E) in accordance with provisions that will be set forth in the award. In addition,

invention disclosures may be protected from public disclosure for a reasonable time in order to allow for filing a patent application.

D. PROTECTED PERSONALLY IDENTIFIABLE INFORMATION

Applicants may not include any Protected Personally Identifiable Information (Protected PII) in their submissions to ARPA-E. Protected PII is defined as data that, if compromised, could cause harm to an individual such as identity theft. Listed below are examples of Protected PII that Applicants must not include in their submissions.

- Social Security Numbers in any form;
- Place of Birth associated with an individual;
- Date of Birth associated with an individual;
- Mother's maiden name associated with an individual;
- Biometric record associated with an individual;
- Fingerprint;
- Iris scan;
- DNA;
- Medical history information associated with an individual;
- Medical conditions, including history of disease;
- Metric information, e.g. weight, height, blood pressure;
- Criminal history associated with an individual;
- Ratings;
- Disciplinary actions;
- Performance elements and standards (or work expectations) are PII when they are so intertwined with performance appraisals that their disclosure would reveal an individual's performance appraisal;
- Financial information associated with an individual;
- Credit card numbers;
- Bank account numbers; and
- Security clearance history or related information (not including actual clearances held).

E. FOAS AND FOA MODIFICATIONS

FOAs are posted on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/), Grants.gov (http://www.grants.gov/), and FedConnect (https://www.fedconnect.net/FedConnect/). Any modifications to the FOA, including Exploratory Topic announcements, are also posted to these websites. You can receive an email when a modification or a new Exploratory Topic is posted by registering with FedConnect as an interested party for this FOA. It is recommended that you register as soon as possible after release of the FOA to ensure that you receive timely notice of any modifications or other announcements. More information is available at https://www.fedconnect.net.

F. Obligation of Public Funds

The Contracting Officer is the only individual who can make awards on behalf of ARPA-E or obligate ARPA-E to the expenditure of public funds. A commitment or obligation by any individual other than the Contracting Officer, either explicit or implied, is invalid.

ARPA-E awards may not be transferred, assigned, or assumed without the prior written consent of a Contracting Officer.

G. Requirement for Full And Complete Disclosure

Applicants are required to make a full and complete disclosure of the information requested in the Business Assurances & Disclosures Form. Disclosure of the requested information is mandatory. Any failure to make a full and complete disclosure of the requested information may result in:

- The rejection of a Full Application, and/or Reply to Reviewer Comments;
- The termination of award negotiations;
- The modification, suspension, and/or termination of a funding agreement;
- The initiation of debarment proceedings, debarment, and/or a declaration of ineligibility for receipt of Federal contracts, subcontracts, and financial assistance and benefits; and
- Civil and/or criminal penalties.

H. Retention of Submissions

ARPA-E expects to retain copies of all Full Applications, Replies to Reviewer Comments, and other submissions. No submissions will be returned. By applying to ARPA-E for funding, Applicants consent to ARPA-E's retention of their submissions.

I. Marking of Confidential Information

ARPA-E will use data and other information contained in Full Applications, and Replies to Reviewer Comments strictly for evaluation purposes.

Full Applications, Replies to Reviewer Comments, and other submission containing confidential, proprietary, or privileged information should be marked as described below. Failure to comply with these marking requirements may result in the disclosure of the unmarked information under the Freedom of Information Act or otherwise. The U.S. Government is not liable for the disclosure or use of unmarked information, and may use or disclose such information for any purpose.

The cover sheet of the Full Application, Reply to Reviewer Comments or other submission must be marked as follows and identify the specific pages containing confidential, proprietary, or privileged information:

> Notice of Restriction on Disclosure and Use of Data:
>
> Pages [___] of this document may contain confidential, proprietary, or privileged information that is exempt from public disclosure. Such information shall be used or disclosed only for evaluation purposes or in accordance with a financial assistance or loan agreement between the submitter and the Government. The Government may use or disclose any information that is not appropriately marked or otherwise restricted, regardless of source.

The header and footer of every page that contains confidential, proprietary, or privileged information must be marked as follows: "Contains Confidential, Proprietary, or Privileged Information Exempt from Public Disclosure." In addition, every line and paragraph containing proprietary, privileged, or trade secret information must be clearly marked with double brackets or highlighting.

J. COMPLIANCE AUDIT REQUIREMENT

A prime recipient organized as a for-profit entity expending $750,000 or more of DOE funds in the entity's fiscal year (including funds expended as a Subrecipient) must have an annual compliance audit performed at the completion of its fiscal year. For additional information, refer to Subpart F of: (i) 2 C.F.R. Part 200, and (ii) 2 C.F.R. Part 910.

If an educational institution, non-profit organization, or state/local government is either a Prime Recipient or a Subrecipient, and has expended $750,000 or more of Federal funds in the entity's fiscal year, the entity must have an annual compliance audit performed at the completion of its fiscal year. For additional information refer to Subpart F of 2 C.F.R. Part 200.

K. EXPORT CONTROL INFORMATION

Do not include information subject to export controls in any submissions, including Concept Papers, Full Applications, and Replies to Reviewer Comments – whether marked as subject to US export control laws/regulations or otherwise. Such information may not be accepted by ARPA-E and may result in a determination that the application is non-compliant, and therefore not eligible for selection. This prohibition includes any submission containing a general, non-determinative statement such as "The information on this page [or pages _ to__] may be subject to US export control laws/regulations", or similar. Under the terms of their award, awardees shall be responsible for compliance with all export control laws/regulations.

IX. GLOSSARY

Applicant: The entity that submits the application to ARPA-E. In the case of a Project Team, the Applicant is the lead organization listed on the application.

Application: The entire submission received by ARPA-E, including the Preliminary Application, Full Application, Reply to Reviewer Comments, and Small Business Grant Application (if applicable).

ARPA-E: Is the Advanced Research Projects Agency – Energy, an agency of the U.S. Department of Energy.

Cost Sharing: Is the portion of project costs from non-Federal sources that are borne by the Prime Recipient (or non-Federal third parties on behalf of the Prime Recipient), rather than by the Federal Government.

Covered Individual: an individual who contributes in a substantive, meaningful way to the scientific development or execution of an R&D project proposed to be carried out with an award from ARPA-E. This includes, but is not limited to, the PI, Co-PI, Key Personnel, and technical staff (e.g., postdoctoral fellows/researchers and graduate students). ARPA-E may further designate covered individuals during award negotiations or the award period of performance.

Deliverable: A deliverable is the quantifiable goods or services that will be provided upon the successful completion of a project task or sub-task.

DOE: U.S. Department of Energy.

DOE/NNSA: U.S. Department of Energy/National Nuclear Security Administration

FFRDCs: Federally Funded Research and Development Centers.

FOA: Funding Opportunity Announcement.

Foreign Affiliation: a funded or unfunded academic, professional, or institutional appointment or position with a foreign government or government-owned entity, whether full-time, part-time, or voluntary (including adjunct, visiting, or honorary).

Foreign Countries of Concern: the People's Republic of China, the Democratic People's Republic of Korea, the Russian Federation, the Islamic Republic of Iran, Burma, Eritrea, Pakistan, Saudi Arabia, Tajikistan, and Turkmenistan.

For-Profit Organizations (Other than Small Businesses) (or *large businesses*): Means entities organized for-profit other than small businesses as defined elsewhere in this Glossary.

GOCOs: U.S. Government Owned, Contractor Operated laboratories.

GOGOs: U.S. Government Owned, Government Operated laboratories.

Institutions of Higher Education (or *educational institutions*): Has the meaning set forth at 20 U.S.C. 1001.

Malign Foreign Talent Recruitment Program: the meaning given such term in section 10638 of the Research and Development, Competition, and Innovation Act (division B of Public Law 117–167) or 42 USC 19237, as of October 20, 2022.

Milestone: A milestone is the tangible, observable measurement that will be provided upon the successful completion of a project task or sub-task.

Nonprofit Organizations (or *nonprofits*): Has the meaning set forth at 2 C.F.R. § 200.70.

Prime Recipient: The signatory to the funding agreement with ARPA-E.

PI: Principal Investigator.

Project Team: A Project Team consists of the Prime Recipient, Subrecipients, and others performing or otherwise supporting work under an ARPA-E funding agreement.

Small Business: Small businesses are domestically incorporated entities that meet the criteria established by the U.S. Small Business Administration's (SBA) "Table of Small Business Size Standards Matched to North American Industry Classification System Codes" (NAICS) (http://www.sba.gov/content/small-business-size-standards).

Standalone Applicant: An Applicant that applies for funding on its own, not as part of a Project Team.

Subject Invention: Any invention conceived or first actually reduced to practice under an ARPA-E funding agreement.

Subrecipient: An entity (not an individual) that receives a subaward from the Prime Recipient to carry out part of the ARPA-E award.

Exploratory Topic: A technical area of research that is detailed in a "Special Program Announcement" at the end of this FOA as an Appendix and visible on ARPA-E eXCHANGE as a supporting FOA document. Each Exploratory Topic will have its own deadline. Once the topic deadline has passed the notice will be taken down and ARPA-E will no longer be accepting applications in that area. ARPA-E will only review applications that are scientifically aligned with the Exploratory Topic(s) open at the time the application is submitted.

Task: A task is an operation or segment of the work plan that requires both effort and resources. Each task (or sub-task) is connected to the overall objective of the project, via the achievement of a milestone or a deliverable.

Total Project Cost: The sum of the Prime Recipient share and the Federal Government share of total allowable costs. The Federal Government share generally includes costs incurred by GOGOs, FFRDCs, and GOCOs.

TT&O: Technology Transfer and Outreach. (See Section IV.F.8 of the FOA for more information).

X. APPENDIX A: Low-Energy Nuclear Reactions

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Low-Energy Nuclear Reactions

Topic Issue Date	September 13, 2022
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, November 4, 2022
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, November 15, 2022
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, Tuesday, December 20, 2022
Expected Date for Selection Notifications	February 2023
Anticipated Date of Awards	May 2023
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$2,500,000 for Category A and $500,000–$1,500,000 for Category B.
Maximum Period of Performance	30 Months

1. Introduction

This announcement describes an Exploratory Topic (ET) on Low-Energy Nuclear Reactions (LENR).[21] ARPA-E invites Full Applications for financial assistance in pursuit of hypotheses-driven approaches toward producing publishable evidence of LENR that is convincing to the wider scientific community. A goal of this Exploratory Topic is to establish clear practices to rigorously answer the question, "should this field move forward given that LENR could be a potentially transformative carbon-free energy source, or does it conclusively not show promise?". Program objectives, technical categories, and performance metrics are described further in Section 2.

ARPA-E acknowledges the complex, controversial history of LENR beginning with the announcement by Martin Fleischmann and Stanley Pons (FP) in 1989 that they had achieved

[21] We define LENR as a hypothetical energy-producing process (or class of processes) with system energy outputs characteristic of nuclear physics (>>1 keV/amu/reaction) and energy inputs characteristic of chemistry (~eV/atom). See further materials from the ARPA-E LENR workshop: https://arpa-e.energy.gov/events/low-energy-nuclear-reactions-workshop.

deuterium-deuterium (D-D) "cold fusion" in an electrochemical cell.[22] Multiple books[23] recount the history of "cold fusion" (now known as LENR). DOE reviews in 1989 and 2004 both concluded that the evidence did not support the claim of D-D fusion, but that research proposals on deuterated heavy metals should be evaluated under the standard peer-review process.[24] However, few such proposals were submitted, and none were funded by DOE.

Despite LENR being largely dismissed by the scientific research community by 1990, many groups from around the world (including the U.S., Japan, Russia, China, and the EU) continued to conduct varied LENR experiments and report evidence of excess heat and nuclear reactions (including neutrons, tritium, ^{3}He, ^{4}He, transmutation products, and isotopic shifts) in hundreds of reports/papers.[25] However, repeatability of the key evidence over multiple trials of seemingly the same experiment remains elusive to this day. This may be due to limitations in experimental or diagnostic techniques, a lack of awareness and/or control of the key triggers and independent variables of LENR experiments, and/or other reasons. Furthermore, results were typically not reported with the level of scientific rigor required by top-tier research journals. As a result, LENR as a field remains in a stalemate with uncertain prospects for scientific advances and impact.

Based on its claimed characteristics to date, LENR may support a form of nuclear energy with potentially low capital cost, high specific power and energy, and little-to-no radioactive byproducts. If LENR can be irrefutably demonstrated and scaled, it could potentially become a disruptive technology with myriad energy, defense, transportation, and space applications, all with strong implications for U.S. technological leadership. For energy applications, LENR could potentially contribute to decarbonizing sectors such as industrial heat and transportation (~50% of U.S. and global CO_2-equivalent emissions).

Within the past decade, there has been renewed interest in supporting LENR research activities in the U.S., with prominent sponsorship (e.g., Google, DARPA, NASA), that has advanced LENR-relevant state-of-the-art capabilities and methodologies.[26] Some of the teams are reporting preliminary evidence[27] of LENR that are possibly consistent with past observations but that do not yet meet the program metrics presented below in Section 2, the fulfillment of which could help break the stalemate surrounding LENR.

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[22] M. Fleischmann and S. Pons, "Electrochemically induced nuclear fusion of deuterium," *J. Electroanal. Chem. Int. Electrochem.* **261**, 201 (1989); https://doi.org/10.1016/0022-0728(89)80006-3.

[23] See, e.g., J. R. Huizenga, *Cold Fusion: The Scientific Fiasco of the Century* (University of Rochester Press, Rochester, NY, 1993); E. Storms, *The Science of Low Energy Nuclear Reaction* (World Scientific, Singapore, 2007); S. B. Krivit, *Hacking the Atom* (Pacific Oaks Press, San Rafael, CA, 2016); and S. B. Krivit, *Fusion Fiasco* (Pacific Oaks Press, San Rafael, CA, 2016).

[24] For the 1989 and 2004 DOE review reports, see https://www.lenr-canr.org/acrobat/ERABreportofth.pdf and https://www.lenr-canr.org/acrobat/DOEreportofth.pdf, respectively. For a summary presentation of the reviews, see https://arpa-e.energy.gov/sites/default/files/2021LENR_workshop_Greco.pdf.

[25] See, e.g., https://lenr-canr.org and the bibliographies of the Storms and Krivit books in footnote 4.

[26] See, e.g., C. P. Berlinguette et al., "Revisiting the cold case of cold fusion," *Nature* **570**, 45 (2019); https://doi.org/10.1038/s41586-019-1256-6.

[27] See talks from the ARPA-E LENR workshop: https://arpa-e.energy.gov/events/low-energy-nuclear-reactions-workshop.

This ARPA-E Exploratory Topic aims to build on the recent progress with strong emphases on testing/confirming specific hypotheses (rather than focusing only on replication), identifying and verifying control of experimental variables and triggers, supporting more comprehensive diagnostics and analysis, improving access to broader expertise and capabilities on research teams, and insisting on peer review and publication in top-tier scientific journals.

2. Topic Description

This Exploratory Topic invites Full Applications to advance LENR research by identifying and testing well-articulated hypotheses on how to activate/control LENR and their accompanying empirical signatures. A key goal of the ET is to obtain convincing empirical evidence of nuclear reactions[28] in an LENR experiment and publication of the evidence in a top-tier peer-reviewed research journal (see Section 2A for specific suggested criteria for what constitutes "convincing empirical evidence"). ARPA-E is seeking Full Applications that successfully address the highest-priority elements described in the sub-sections immediately below and in greater detail in the Technical Volume (TV) template, which is available for download at the ARPA-E: Funding Opportunity Exchange website (https://arpa-e-foa.energy.gov/).

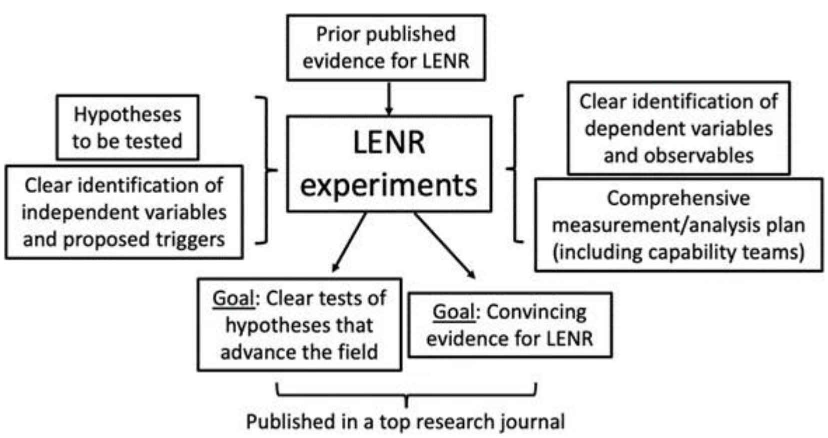
Additional overarching goals of this Exploratory Topic are to bring together new perspectives and participants, modern state-of-the-art scientific and technical capabilities, and the experiences of long-time LENR practitioners..

Applicants must select only one of the following technical categories, discussed further below:

A. LENR experiments
B. Capability teams.

A. Technical Category A: LENR experiments

The figure below summarizes Category A logic and goals.



[28] ARPA-E is agnostic at this time regarding the existence of LENR as a physical phenomenon (as defined in footnote 21), the underlying mechanism(s) of LENR, and the specific nuclear process(es) involved, if any (e.g., fusion, neutron capture, alpha or beta decay, neutronization, etc.).

For Category A, Applicants must comprehensively address the following:

- Select and justify LENR experimental platform(s) and design (i.e., methods for H and/or D loading and LENR activation/trigger; materials structure/composition; control experiments; background/contaminant characterization, etc.) with a clearly articulated connection to prior published research claiming evidence of LENR
- Articulate specific hypothesis or hypotheses to be tested, including justification at a phenomenological level of the importance and relevance of the hypothesis or hypotheses
- Identify key independent and dependent variables and their desired quantitative ranges that the proposed research will emphasize and rigorously characterize
- Propose a comprehensive diagnostic and analysis plan that minimizes the probability of inconclusive outcomes (whether the results are positive or negative); the expectation is a strong focus on detection of both prompt and secondary/delayed nuclear-reaction products, specifying the particle(s) and prompt energy ranges anticipated (and why)
- Account for uncertainties in both background and signal in the statistical analysis with all assumptions explicitly defined and justified; the correlation among all measurements should be analyzed in a single comprehensive statistical framework with all assumptions explicitly defined in mathematical terms. If multiple simultaneous measurements are made, a unified statistical framework is required with clear identification of correlated or orthogonal measurements
- Demonstrate access to the needed broad discipline expertise and the embodied knowledge of long-time LENR researchers, corresponding to the chosen experimental approach, hypotheses to be tested, and statistical analysis methodologies
- Commit to the standard peer-review process and demonstrate a willingness to submit findings to leading research journals;
- As stated in section IV.F.3, ARPA-E, for Subject Inventions disclosed to DOE under an award, ARPA-E will reimburse the Prime Recipient – in addition to allowable costs associated with Subject Invention disclosures - up to $30,000 of expenditures for filing and prosecution of United States patent applications,
- Technology-to-Market (T2M) considerations, including
    - Plausibility of proposed LENR approach to realize net energy gain and scalability to devices with useful levels of power
    - Potential first markets for a commercial system
    - Other barriers, such as obtaining IP protection, consideration for publication by top-tier journals, etc.
- Serious evaluation and mitigation/control of potential hazards (mechanical, electrical, radiological, and otherwise) associated with the proposed LENR experiments, and plans for protecting human health and property.

Please refer to the Technical Volume template (available for download at the ARPA-E: Funding Opportunity Exchange website (https://arpa-e-foa.energy.gov/)), which provides further guidance for preparing your Full Application.

To constitute convincing empirical evidence for LENR, each Applicant must describe how they will meet the following:

- Conduct experiments that demonstrably satisfy the definition of LENR given in footnote 21
- Achieve statistically significant diagnostic evidence of nuclear reactions above background and relative to control experiments, at a level greater than 99.7% (3s) statistical confidence level
- Carefully identify and eliminate "prosaic" explanations, e.g., rogue chemical reactions resulting in excess heat, material and/or environmental contaminants, natural radiation background, etc.
- Publish results in a top-tier research journal.

B. Technical Category B: Capability Teams

Applicants seeking to contribute an expert/specialist capability that could assist multiple Category-A LENR experimental teams in fulfilling program objectives should consider selecting Category B. Capabilities of interest include but are not limited to

- Diagnostic instruments expertise (e.g., detection of nuclear-reaction products, pre- and post-experimental materials elemental/isotopic analysis, etc.)
- Relevant analyses expertise, including statistical analysis and Bayesian inference techniques of "multi-messenger" datasets in low-count, high-background environments[29]
- Relevant computational codes/expertise to aid in experimental design and data interpretation
- Precision materials fabrication, handling, characterization.

The primary objectives for Category B is to bring state-of-the-art instruments and capabilities to the program and to Category-A projects that may not otherwise have access to the resources and/or expertise to quickly achieve an equivalent capability. A goal is to avoid expending time and resources in establishing capabilities/expertise that already exist elsewhere. Capability teams bring a neutral, independent perspective that will bolster the credibility of any reported evidence for LENR. ARPA-E has experience with Capability Teams in other programs.[30]

ARPA-E strongly encourages interactions between potential Category-A and Category-B Applicants throughout the application process, so that Submissions are coordinated and complementary to the extent possible. However, Category-A and Category-B Submissions will be evaluated independently.

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[29] See, e.g., J. L. Alvarez, "Poisson-based detection limit and signal confidence intervals for few total counts," Health Phys. **93**, 120 (2007); https://doi.org/10.1097/01.hp.0000261331.73389.bd.

[30] See, e.g., https://arpa-e.energy.gov/news-and-media/blog-posts/fusing-further-advancement-introducing-arpa-e-fusion-capability-teams.

Category-A Applicants are especially encouraged to partner with Category-B Applicants on capabilities requiring lengthy/nuanced experience and/or expensive instruments/diagnostics. It is acceptable for Category-A Applicants to either include a team member to fulfill the needed capability or to state that they expect to work with a known Category-B Applicant. The latter is encouraged to improve efficiency and avoid unnecessary expenses in duplicating Category-B capabilities . If the proposed capabilities are clearly articulated/justified, including appropriate quantitative technical requirements, ARPA-E will identify and encourage collaborations between Category-A and B teams during technical milestone negotiations.

ARPA-E prohibits the same person or persons being on both a Category-A and Category-B Applicant team. In order to ensure objectivity in the measurements taken by Category-B teams, Category A and Category B teams interested in partnering should ensure that there are no actual or apparent conflicts of interest within or between the the teams.

Per Section VI.B.7 of the FOA, every Project Team must negotiate and establish an Intellectual Property Management Plan for the management and disposition of intellectual property arising from the project. Every project that involves a Category-A awardee partnering with a Category-B awardee will be required to have a similar plan for the management and disposition of intellectual property arising from such a collaboration. Such a Plan will need to at least address the limtations, if any, on the use and disclosure of any data exchanged between the parties and the rights of the collaborating parties to any newly arising technology for commercialization purposes. If a Category-B awardee is partnering with more than one Category-A awardee, then both the ARPA-E award to the Category-B awardee and the Plan between the collaborating parties shall include a prohibition on the Category-B awardee sharing any data provided to it or produced by it to any other Category-A awardee without the express written permission of the partnering Category-A awardee.

C. Criteria and Metrics

Category A: LENR Experiments

Table 1 summarizes the key criteria/metrics for Category A: LENR Experiments. Applicants should clearly and concisely articulate how their Submission meets each of the criteria.

Table 1. Summary of criteria/metrics for Category A: LENR experiments.

Criteria	Metrics
Maximum input energy or voltage	• ≤ 500 eV per directly energized particle, or ≤ 500 V applied voltage anywhere in the experiment

Proposed LENR experimental platform	• Past evidence of nuclear reactions (preferred) and/or excess heat in a peer-reviewed journal paper (cite papers, show/discuss key data) • Preferably, related corroboration of key results by at least one independent group (cite papers, show/discuss key data) • Recognition and discussion of potential hazards to property and human safety, and demonstrated commitment and ability to develop a hazard mitigation/control plan
Hypotheses to be tested	• Phenomenological justification of the significance/relevance of the chosen hypothesis (hypotheses) with respect to LENR • Clear statement of independent and dependent variables to be characterized and their allowable measurement uncertainties, as well as a statement of uncontrolled/uncontrollable variables (e.g., average loading fraction may be a controllable variable, but the loading process introduces uncontrollable and possibly uncharacterized morphological changes to the sample)

Detection of nuclear-reaction products	• Justification of particles and energy ranges to be measured, and desired temporal/spatial resolutions
	• Plan for achieving statistically significant diagnostic evidence of nuclear reactions above background and relative to control experiments, at a level greater than 99.7% (3s) statistical confidence level, including
	    o Real-time detection of prompt/secondary nuclear-reaction products, including multiple detectors and positioning, etc., as appropriate, and/or pre- and post-experiment materials elemental/isotopic analysis
	    o Background/contaminant characterization with sufficient sensitivity, resolution, and time correlation to achieve the required statistical confidence
	• Inclusion of or access to state-of-the-art detectors and expertise

Calorimetry	• Calorimetry cannot be the only nor primary diagnostic, but it can be part of the diagnostic suite, provided that labor and hardware expenditures associated with calorimetry are ≤10% of the total project cost of a Category-A application • Category-A teams are encouraged to work with a Category-B Capability Team that has demonstrated capability in calorimetry • A comprehensive energy-balance model that accounts for all possible sources and sinks must be available or developed as part of the proposed work • State quantitative requirements on calorimetry detection thresholds and resolution based upon analysis of experimental uncertainty
Control experiments	• Identify and justify the control experiments needed to support a clear test of the hypotheses under consideration, and to build confidence in empirical evidence for LENR if it is observed • Describe how control experiments are not introducing new or uncontrolled variables, or how these are accounted for in reaching conclusions

Controlling impurities and contaminants	• Plan for pre- and post-experimental sample characterization for all materials, electrolytes, and/or gases • Articulation of required characterization resolution/uncertainties based on hypotheses being tested
Teaming	• Team composition includes first-hand knowledge of a past LENR experiment that is directly related to the selected experimental platform and hypotheses • PI of this Submission has a demonstrated track record of publishing in top-tier journals

Category B: Capability Teams

Several capabilities are needed for LENR experiments to fulfill the program objectives. Classes of anticipated capabilities and their desired attributes are summarized in Table 2. Category-B Applicants should clearly state the capability or capabilities they are providing (with quantitative targets wherever possible) and the class or classes of LENR experimental platforms that they envision supporting..

Table 2. Summary of criteria/attributes for Category B: Capability Teams.

Capability	Desired attributes and quantitative targets
Detection of prompt and secondary nuclear-reaction products	• Description of particles (e.g., ^{3}He, ^{4}He, tritium, neutrons, transmutation/decay products) and energy ranges that can be measured • State achievable temporal, spatial, and energy resolutions, as well as detection sensitivities and thresholds • Type of selected detectors and their strengths/weaknesses in the context of common LENR experimental platforms • Plans for placing detectors in a suitable position relative to the presumed source, including within challenging liquid or high-temperature/pressure environments
Materials fabrication and pre/post-experimental structural and elemental analysis	• Ability to fabricate materials samples with controlled microstructure (specify feature sizes, morphology, defect uniformity, etc.) • Materials handling protocols to control the introduction of contaminants • Elemental/isotopic detection thresholds and resolution • Structural and/or morphological analysis/imaging resolution, including direct measurement of H/D-loading capable of resolving spatiotemporal variations
Mass balance and spectroscopy	• Ability to provide an inventory of all species present in an LENR experiment, with mass or fractional molar resolutions adequate to differentiate from control experiments and the environmental background

Calorimetry	• Budget devoted to calorimetry should be ≤25% of total project cost[31] • Previous calorimetry data/results and calibrations by team appear in peer-reviewed publications • Achieved detection thresholds, resolutions, uncertainties of relevance to leading LENR experimental platforms • Validated energy balance model of calorimeter and all sensors with uncertainty analysis
Modeling/computation	• Relevant capabilities /codes to support the experimental design of promising classes of LENR experiments and control experiments • Relevant capabilities/codes to support diagnostic design, specification of diagnostic requirements, and data/scientific interpretations

3. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed non-responsive and may not be merit-reviewed:

- Experiments with input energies >500 eV per directly energized particle, or >500 V of applied voltage anywhere in the experiment
- No clear hypotheses to be tested
- No articulated connection to prior published evidence for LENR and of how this work builds on the earlier work
- Calorimetry as the only or primary diagnostic
- Lack of a plan for obtaining direct empirical evidence of nuclear reactions
- Purely theoretical or computational studies
- Research plans requiring substantial diagnostic or code development beyond their adaptation to specific experiments.

4. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Appendix A, LENR. All other instructions set forth at FOA Section IV.C remain unchanged.

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

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[31] Note that the limit for calorimetry is ≤10% of total project cost for Category-A applications that include calorimetry, but calorimetry can be up to ≤25% of the budget for a Category-B application.

XI. APPENDIX B: INcreasing Transportation Efficiency and Resiliency through MODeling Assets and Logistics (INTERMODAL)

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
INcreasing Transportation Efficiency and Resiliency through MODeling Assets and Logistics (INTERMODAL)

Topic Issue Date	February 8, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, March 31, 2023
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, April 11, 2023
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, Friday, May 18, 2023
Expected Date for Selection Notifications	June, 2023
Anticipated Date of Awards	October, 2023
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$2,500,000.
Maximum Period of Performance	30 Months

1. Introduction

The global freight transportation industry, including ports and warehouses, currently accounts for up to 11% of the world's greenhouse gas emissions[32]. In the US, the share of transportation emissions due to freight has been steadily increasing since 1990, up to 33% of the total in 2020[33]. This amounts to nearly 10% of the country's total emissions.

Since the middle of the last century, containerization technology has allowed the movement of goods inside twenty- or forty-foot container units, enabling the facile transfer of goods between different modes like road, rail, and water. Containerized cargo moved across multiple modes is defined here as *intermodal freight* and is the backbone of the modern domestic and international freight industries.

The US freight Class 1 rail system is an extremely efficient mode of transportation, accounting for 40% of freight movement by ton-miles while consuming 2% of the total US transportation

[32] https://climate.mit.edu/explainers/freight-transportation
[33] https://www.bts.gov/browse-statistical-products-and-data/freight-facts-and-figures/us-greenhouse-gas-emissions-domestic

energy budget[34]. Nonetheless, the greenhouse gas (GHG) emissions from rail freight movement (not accounting for passenger trains, rail yard movement, etc.) are significant—approximately 40 million tons CO_2 per year[35].

A further 400 million tons of CO_2 per year are estimated to be connected to US imports and exports[36], the vast majority of this freight being moved by ship. Much effort is rightly being put into developing ship-side technologies for maritime decarbonization, yet it has been estimated that 85% of the $1.4 trillion investment needed to decarbonize by 2050 will be in supply side (that is, land-based) infrastructure[37]. This includes fuel and electricity production, storage, and distribution technologies.

The industry has a good sense for what technology options will be available (e.g., battery energy storage, hydrogen fuel cells, zero carbon fuels), and approximate costs – but the execution and rollout strategy, on both spatial and temporal dimensions, is still unclear. These are significant financial decisions, and upcoming choices, such as on which fuel to commit a fleet to, could accelerate or delay national decarbonization timelines by years. It is vital that the industry work together and coordinate to maximize efficiency and effectiveness of this deployment. There are currently no comprehensive models of the intermodal system's energy demands and supplies, especially including overlap and shared infrastructure between modes. This will require synthesis and coordination of many different information streams.

Aside from the direct carbon emissions, the rippling and compounding effects of the COVID-19 pandemic, the Suez Canal incident[38], and other major disruptions have demonstrated the fragility of our global supply chains[39]. The past several years have demonstrated the critical need for resilience of freight transportation – the ability to adjust quickly and efficiently to changing levels and patterns of supply and demand. Decarbonization of the freight system and logistics optimization promise not only to reduce emissions, but also to increase resiliency of these networks to unexpected (or expected) shocks. For example, with more distributed and flexible energy sources such as electricity and hydrogen, the US can decrease its reliance on foreign fuels. Advanced modeling efforts should be able to ensure that these benefits are maximized, and will also help deliver the freight system resiliency needed for the next major disruption.

[34] International Energy Agency (2020), Tracking Transport 2020, available at: https://www.iea.org/reports/tracking-transport-2020/rail.

[35] https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WUHR.pdf

[36] https://www.itf-oecd.org/sites/default/files/docs/cop-pdf-06.pdf

[37] https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping

[38] https://www.nytimes.com/2021/03/25/world/middleeast/suez-canal-container-ship.html

[39] https://www.morganstanley.com/ideas/supply-chain-disruption-outlook

Previous ARPA-E programs such as LOCOMOTIVES[40] and TRANSNET[41] have addressed route optimization for single modes (rail and light duty passenger vehicles, respectively). Other government, academic, and private modeling efforts have targeted portions of the freight system and specific modes (reference examples provided[42,43,44,45,46,47]), but none so far have addressed its deeply interconnected nature, including the challenges and opportunities the intermodal system presents. In other words, there is no systematic government or private modeling effort for the complete intermodal system with an emphasis on both decarbonization and increased resiliency. An ideal model should provide the optimum route for moving goods across maritime, rail and road transportation systems with the lowest CO_2 emissions. Considering the interwoven yet fragmented nature of logistics and freight transportation, with poor data sharing, misaligned incentives, and many different stakeholders, there is a need for top-down modeling efforts that cross intermodal boundaries.

Given the many challenges associated with modeling the extreme complexity of the freight system, there exists no comprehensive plan to direct how freight decarbonization should be achieved. The new transportation energy systems (battery electric, hydrogen, etc.) studied to date are not viewed by all stakeholders to have a reasonable technical or economic viability, and it is not obvious which choice would be optimal to pursue considering other variabilities in the system.

These considerations lead to the twofold goals of this Exploratory Topic:

1) Support the development of models of the national intermodal freight transportation network (i.e., moving freight by two or more modes of transportation -- e.g., trucks, trains, and cargo ships) that enable prioritization for energy infrastructure deployment, along with data required for the effective deployment of this optimized distribution system

2) Support the development of models of the national intermodal freight transportation system that enable predictive and responsive optimization of modal choice, inter- or intra- modal transfer, or routing.

2. Topic Description

The overarching goal of this program is to demonstrate deployment and operational strategies that bring freight transportation in line with national net-zero-by-2050 targets. The specific

40 https://arpa-e.energy.gov/technologies/exploratory-topics/rail-ghg-reduction
41 https://arpa-e.energy.gov/technologies/programs/transnet
42 https://www.sciencedirect.com/science/article/pii/S2590198222000033
43 https://www.rit.edu/gccis/lecdm/GIFT_Overview.pdf
44 https://www.wabteccorp.com/digital-electronics/network-logistics/port-optimizer
45 https://www.railvision.ca/
46 https://nautiluslabs.com/
47 https://convoy.com/

objectives of this program are to identify and quantify infrastructure and logistical developments of the intermodal freight system that:

- Identify the most cost-effective transition pathways to a net-zero GHG emissions freight transportation system, including water, rail and road. Air freight modeling is not included in scope.
- Identify new intermodal routes that involve different combinations of road, rail and water for better overall system performance, and develop new methodologies for assessing these routes.
- Reduce the overall energy usage per ton-mile of freight transport while minimizing levelized cost of ton-kilometers (LCOTKM).
- Optimize freight logistics for energy use reduction and increased supply chain resiliency.
- Provide a comprehensive freely distributed modeling ecosystem, as described below, including user friendly interface with inputs that are easily modified, and outputs in human readable/usable form with standard database support.

Funding recipients must produce a fully operational computational model which includes an executable program. The recipient must publicly distribute (1) the executable program at no more than a nominal cost to the user, with no restriction on further use and (2) along with associated documentation and user interface. Topic B: Technical Volume – Intermodal includes further details on the requirements of such executable programs.

The recipient may assert a copyright in any distributed program subject to provisions that will be contained in the award.

Once selected for award, each selectee must develop a Software Commercialization Plan as a milestone during performance of their award, the contents of which are subject to the approval of ARPA-E. Such plan must include a commitment to report to ARPA-E the software program, algorithms or data sets that are the intended target of the award, and address how such items, in accordance with the above criteria, will be commercialized and which Intellectual Property rights will be asserted. ARPA-E will be open to considering modification of the license retained by the government in copyright to support acceptable Plans. An Awardee may request a modification of the Software Commercialization Plan from ARPA-E at any time.

Further, such Software Commercialization Plan must include the expected strategy for distribution, support, and maintenance of developed models, as further described in Topic B: Technical Volume – Intermodal. The Technical Volume should include at least a summary of how the applicant expects their Software Commercialization Plan will address these factors.

3. Technical Areas of Interest

There are two categories of targeted outcomes of this Exploratory Topic:

- Category 1: Intermodal Infrastructure Model - A complete validated model of the national intermodal freight transportation network that enables prioritization for low-carbon energy infrastructure deployment. All modes (water, rail and road transportation) must be included with explicitly defined external inputs (e.g., GREET transportation models), modeling methodology and validation method. The model must include new low-carbon transportation energy sources (battery electric, hydrogen, biofuels, e-fuels such as ammonia and methanol, direct electrification) with realistic estimates of availability, costs and other factors affecting deployment. Data required for the effective deployment and validation of this optimized distribution system must be identified along with the means for acquisition, consolidation, and analysis of data. Category 1 efforts are encouraged to incorporate detailed present and future logistics flows as modeled in Category 2.
- Category 2: Intermodal Logistics Model - A complete and validated set of logistics models of the national intermodal freight transportation system that enable predictive and responsive optimization of modal choice, inter- or intramodal transfer, and routing. The logistic model must operate both as a full intermodal system planning tool and a quasi-real-time dynamic scheduler. Category 2 efforts are encouraged to consider and enable optimization around likely future infrastructure rollout as modeled in Category 1.

Further details regarding the categories may be found in Topic B: Technical Volume – Intermodal.

The two categories of interest comprise an interconnected set of modeling and simulation tools for the US intermodal freight transportation system. Applicants should develop modeling and simulation tools that represent disruptive advancements in analytical and predictive capabilities for intermodal infrastructure deployment models (Category 1), for intermodal logistics models (Category 2), or for both infrastructure and logistics models (combination of Category 1 and Category 2). Applicants can submit to a single or both categories. Figure 1 schematically lays out the overall structure of this program and the interrelationships between external data sets and the two technical categories. The following sections summarize the overall objectives and scope of each category and required external data sets.

Modeling efforts that collect and merge disparate data sources or encourage data sharing within and across modes will be of particular interest. Models that factor in future operational strategies and efficiency opportunities such as connected and autonomous vehicle technologies (see the ARPA-E NEXTCAR program[48]), including platooning,[49] will also be of high interest.

Disaggregation, or the de-scaling of cargo vehicles into smaller, faster, and more flexible moving units, is a nascent movement taking place in the rail and water transport industries[50]. This is

[48] https://arpa-e.energy.gov/technologies/programs/nextcar

[49] https://highways.dot.gov/research/laboratories/saxton-transportation-operations-laboratory/Truck-Platooning

[50] https://www.freightwaves.com/news/viewpoint-moving-toward-disaggregation-in-the-maritime-and-rail-industries

enabled in part by recent technological developments in vehicle autonomy and electrification, eliminating the need for large scales to achieve labor efficiency and allowing for the construction of low cost, modular vehicles. Another important piece to enable disaggregation is route planning and scheduling, which becomes much more complex with smaller units traveling more frequently between a wider array of terminals, possibly also involving forming, joining, or breaking convoys. Currently, there are no suitable tools to model and optimize such a future intermodal system, or to understand the realistic energy, GHG, and service tradeoffs. Efforts in this space are especially encouraged.

All modeling efforts (energy infrastructure deployment and intermodal freight logistics) should attempt to minimize levelized cost of ton-kilometers (LCOTKM). Models should also be able to demonstrate 1) lowest cost and greenhouse gas (GHG) emission infrastructure deployment pathways to decarbonization or 2) ability to minimize cost and GHG emissions via system-level logistical efficiency improvements.

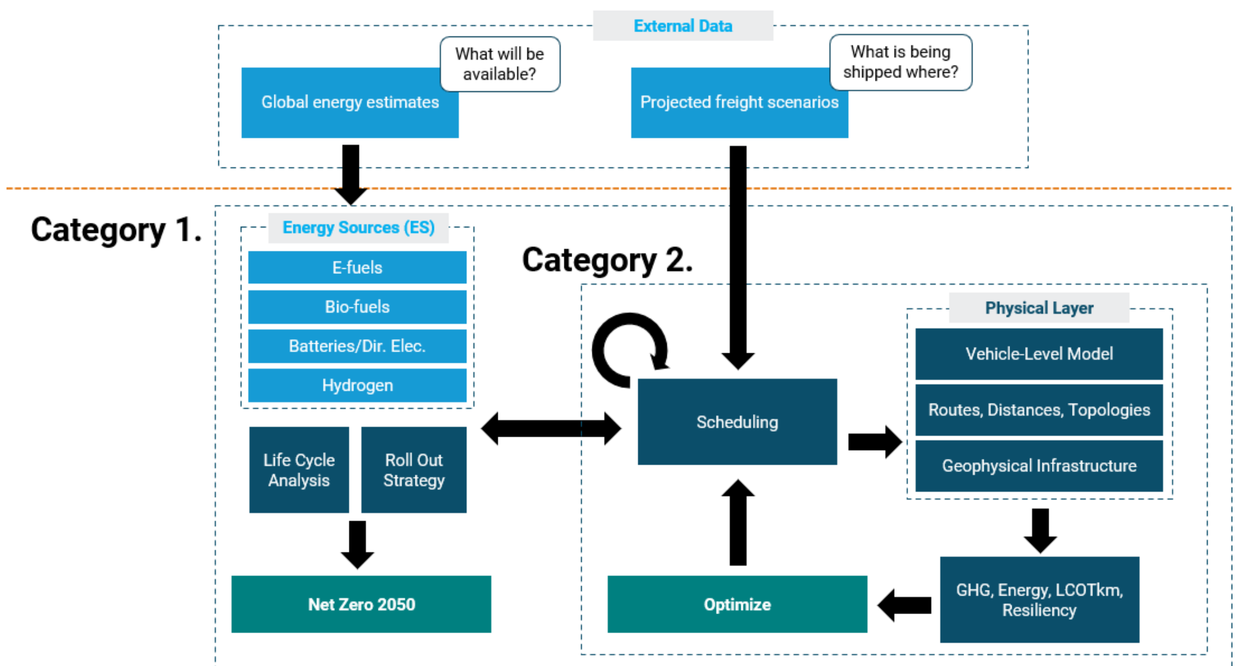

Figure 1: Interrelated Modeling Structure of Technical Categories

A. Category 1: Intermodal Infrastructure Model

Over the next several decades, hundreds of billions of dollars will be deployed to decarbonize the US transportation system, including zero-carbon fuel production, transport and storage, electrification build-out, next-gen vehicle asset purchases, and more.

The primary goal of Category 1 is to create a decision-making support tool for freight transportation energy infrastructure deployment: an optimized “roadmap” to decarbonization of the US intermodal system. Figure 2 illustrates the main components of this technical category.

The scope of this category includes modeling infrastructure related to both low-carbon fuels and electrification for freight transportation (water, rail and road), as well as intermodal transfer infrastructure. Aviation freight modeling is not in scope. The model must include full life cycle analysis (full description given in the technical volume) for low-carbon fuel production, transport, storage, and bunkering/refueling. For modes of transport that may use only electricity (i.e., battery-powered, or direct electrification of rail), the scope includes electricity generation, transmission and distribution infrastructure, charging stations, and/or battery swapping infrastructure. Only infrastructure within US borders should be considered, however, fueling for international maritime at US ports is in scope.

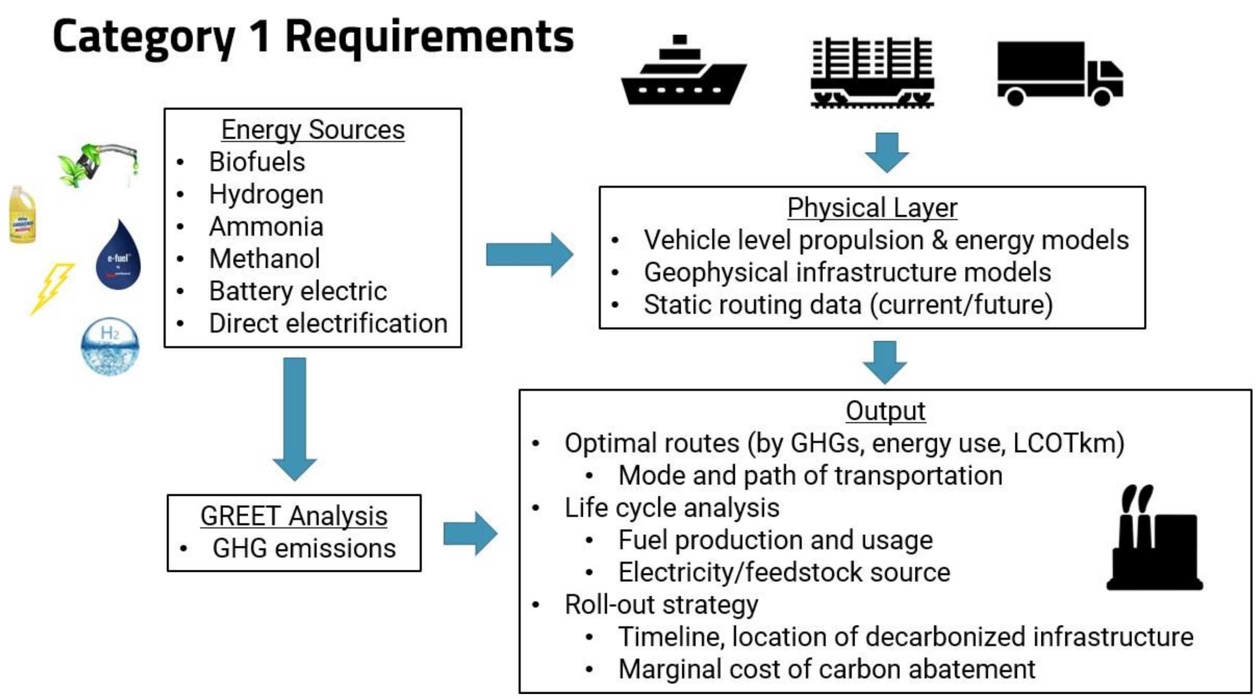

Figure 2: System Level Infrastructure Model

B. Category 2: Intermodal Logistical Model

It is expected that the transportation system will be decarbonized through a combination of electrification and zero-carbon fuels. However, for the near future, there will likely be a limited supply of zero-carbon fuels. it is expected that the electric grid will not be 100% green for decades, and electrification of heavy freight is more difficult than for passenger vehicles. Until there is an unlimited amount of cheap green energy, the combination of these factors means that operational efficiency will continue to be important to minimize transportation emissions. Specifically, there are significant opportunities in optimizing logistics and the interplay between different modes to increase operational efficiency by slowing down the moving segments of travel[51].

Furthermore, the past few years have demonstrated the fragility of the modern supply chain. With the rise of industrial philosophies like "just-in-time manufacturing"[52] and "precision scheduled railroading"[53], along with massively increasing demand on an aging and overburdened infrastructure, the freight transportation system has become more sensitive and less resilient to disruptions. At the same time, increasing availability of data and powerful computational tools allow for new opportunities in top-down management of these enormously complex systems, enabling rapid response and re-optimization after disruptive events (whether foreseen or unforeseen).

The goal of Category 2 is to create a full system and real-time model for optimization of national intermodal logistics scheduling, for the purpose of increasing system-wide operational energy efficiency. Figure 3 illustrates the main components of this technical category.
The scope of this category includes freight transportation by water, rail, and road. Inputs may include vessel arrival data (i.e., at a port) but models should not assume routes that originate outside the US can be modified easily nor should data from non-US ports or points of origin be required.

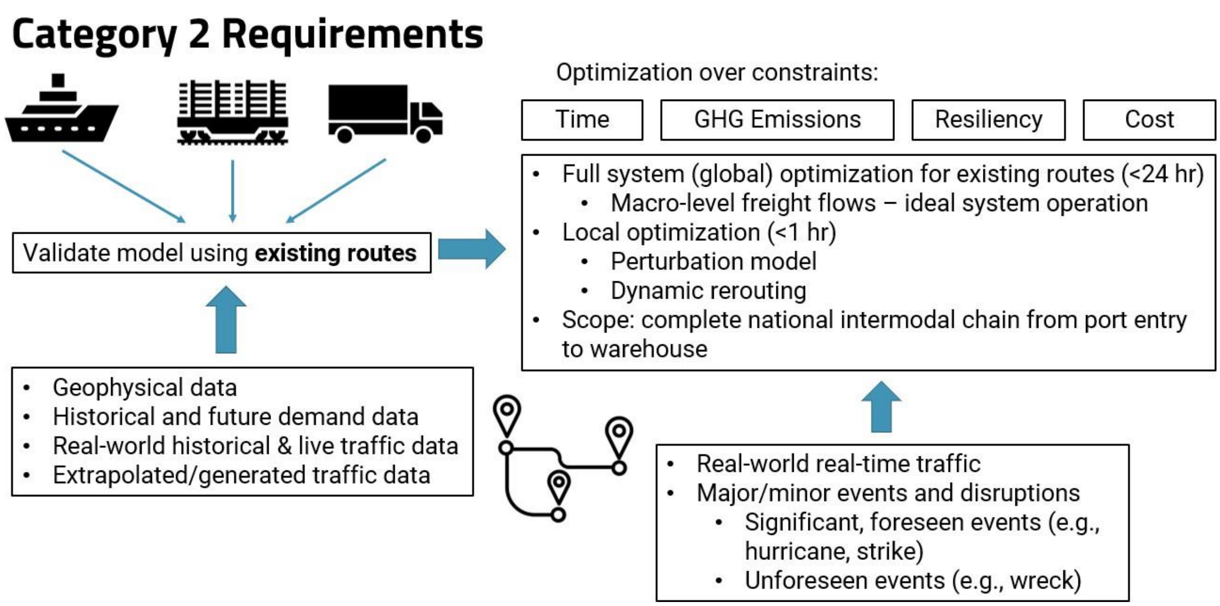

Figure 3: Logistics Model

51 https://www.mdpi.com/1996-1073/14/22/7487/pdf
52 https://www.techtarget.com/whatis/definition/just-in-time-manufacturing-JIT-manufacturing
53 https://www.freightwaves.com/news/what-is-precision-scheduled-railroading-psr

C. Sources of External Data

External Data required for completion of categories 1 and 2 fall into two major classes:

A. LCA, emissions, and energy estimates
B. Projected intermodal freight scenarios

Many publicly available data sets can be found at https://catalog.data.gov/ and https://www.bts.gov/browse-statistical-products-and-data.

Examples of publicly available data sets are given below. The applicant is not limited to these data sources. All required data sets must be explicitly stated in the application.

1. Sources of External Energy Data

Category 1 external data should provide validated transportation propulsion models, accurate estimates of GHG emissions, energy consumption and costs for each transport mode projected through 2050.

Publicly available data sets are preferred, but proprietary data sets are acceptable if they are adequately sourced, documented and made available for inspection by ARPA-E, but not delivered to ARPA-E.

Examples of Category 1 data sources include:

- Life Cycle Analysis (LCA), emissions, and energy estimates
    - Road
        - GREET: https://greet.es.anl.gov/greet_1_series
        - VECTO: https://ec.europa.eu/clima/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/vehicle-energy-consumption-calculation-tool-vecto_en
        - T3CO: https://www.nrel.gov/transportation/t3co.html
    - Maritime
        - GREET marine: https://greet.es.anl.gov/greet_marine
    - Rail
        - GREET rail: https://greet.es.anl.gov/files/rail-module
- Current and projected energy costs: regional and global
    - NREL renewable cost projections: https://www.nrel.gov/docs/fy22osti/83064.pdf
    - EIA US Annual Energy Outlook: https://www.eia.gov/outlooks/aeo/
    - IEA World Energy Outlook: https://iea.blob.core.windows.net/assets/88dec0c7-3a11-4d3b-99dc-8323ebfb388b/WorldEnergyOutlook2021.pdf

2. Sources of Projected Intermodal Freight Scenarios

Category 2 external data should provide current freight flows to the route level, as well as projected freight scenarios out to 2050.

Publicly available data sets are preferred, but proprietary data sets are acceptable if they adequately sourced, documented and made available for inspection by ARPA-E, but not delivered to ARPA-E. Furthermore, artificial or constructed "test sets" of real-time data flows are acceptable if transparent in their creation and validation.

Examples of Category 2 data sources include:

- Freight Analysis Framework (FHWA) - https://faf.ornl.gov/faf5/dtt_total.aspx
- Congestion: https://ops.fhwa.dot.gov/freight/freight_analysis/freight_story/congestion.htm
- Rail routes:
  - LOCOMOTIVES projects are open source and available for class 1 rail lines.
  - https://www.intermodal.org/resource-center/intermodalsystem
  - https://data-usdot.opendata.arcgis.com/datasets/usdot::north-american-rail-network-lines/explore
- Maritime routes:
  - MARAD: https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics
  - Global Shipping Routes: https://www.arcgis.com/home/webmap/viewer.html?layers=12c0789207e64714b9545ad30fca1633&useExisting=1
  - AIS historical data: https://marinecadastre.gov/ais/
- Highway and port truck routes:
  - FWHA: https://ops.fhwa.dot.gov/freight/infrastructure/nhs_connect/index.htm
  - Top truck bottlenecks (ATRI): https://truckingresearch.org/2021/02/23/2021-top-truck-bottlenecks/
- Existing energy infrastructure
  - Alternative fueling stations: https://afdc.energy.gov/stations/#/find/nearest
  - Charging station planning: https://www.nrel.gov/transportation/evi-x.html

4. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed non-responsive and may not be merit-reviewed:

- Models of only specific freight transportation modes
- Models that focus exclusively on non-freight transportation sectors, or on non-containerized freight
- Models that focus on last-mile delivery of goods

- Models that focus on aviation
- Proposals for the development of new and novel energy systems or fuel technologies

5. Content and Form of Full Applications

Notwithstanding the instructions at FOA Section IV.C, "Topic B: Technical Volume – Intermodal" is replacing the "Technical Volume Template" provided.

Component	Required Format	Description and Information
Topic B: Technical Volume – Intermodal	PDF	The centerpiece of the Full Application. Provides a detailed description of the proposed R&D project and Applicant Team. A Technical Volume template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/). **Note – Section and page maximums for this Topic's Technical Volume differ from the standard Technical Volume Template under this FOA.**

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XII. APPENDIX C: Creating Revolutionary Energy And Technology Endeavors

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Creating Revolutionary Energy And Technology Endeavors

Topic Issue Date	February 17, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, March 10, 2023
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, March 21, 2023
Submission Deadline for Replies to Reviewer Comments:	Not Applicable
Expected Date for Selection Notifications	June, 2023
Anticipated Date of Awards	September, 2023
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $200,000 and $500,000. Awards are issued as grants, with a go/no-go milestone.
Maximum Period of Performance	24 Months

1. Introduction

The objective of CREATE is to identify and support disruptive energy-related technologies. Projects funded through CREATE should have the potential for large-scale impact. If successful, projects should create new paradigms in energy technology and have the potential to achieve significant advances in any of the following ARPA-E Mission Areas:

- reducing energy imports
- improving energy efficiency of all economic sectors
- reducing energy-related emissions, including greenhouse gas emissions
- improving management, clean-up and disposal of radioactive waste and spent nuclear fuel
- improving resilience, reliability and security of infrastructure to produce, deliver and store energy

Awards under this program will support research projects that establish potential new areas of technology development and provide ARPA-E with information that could lead to new focused funding programs. Awards may support exploratory research to establish viability, proof-of-concept demonstration for new energy technology and/or modeling and simulation efforts to guide development of new energy technologies.

2. Areas of Interest

Applications that address one or more of ARPA-E's Mission Areas (see above and Section I.A.). Applicants must explain how the proposed concept represents a transformative approach. Applicants may propose technology development efforts with the potential for high impact in any of the ARPA-E Mission Areas.

3. ARPA-E Funding Agreement

ARPA-E anticipates awarding cost-reimbursable grants resulting from this Exploratory Topic. This FOA and any such grants made under this FOA are subject to 2 C.F.R. Part 200 as supplemented by 2 C.F.R. Part 910.

Awardees will be required, inter alia, to obtain prior approval of the ARPA-E Contracting Officer for changes in principal investigator, project partner, or scope of project effort.

The maximum amount of any grant awarded under this Exploratory Topic is $500,000.

4. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, "Topic C: Technical Volume (Cost-Reimbursable Grant)" is replacing the "Technical Volume Template" and "Topic C: SF-424A (Cost-Reimbursable Grant)" is replacing the "Budget Justification Workbook/SF-424A" provided.

Component	**Required Format**	**Description and Information**
Topic C: Technical Volume (Cost-Reimbursable Grant)	PDF	The centerpiece of the Full Application. Provides a detailed description of the proposed R&D project and Applicant Team. A Technical Volume template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov/). **Note – Section and page maximums for this Topic's Technical Volume differ from the standard Technical Volume Template under this FOA.**
Topic C: SF-424A (Cost-Reimbursable Grant)	XLS	Budget Information – Non-Construction Programs (https://arpa-e-foa.energy.gov/)

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

Commercialization Plan

An award that targets the development of software, algorithms or data bases that are intended for use by others and not just intended for internal use by the awardee may be required to develop a Commercialization Plan as a milestone during performance of their award. A Commercialization Plan must include a commitment to report to ARPA the targeted item and address how software, algorithms or data sets that are the intended target of the award will be commercialized and which Intellectual Property rights will be asserted. ARPA-E will be open to considering modification of the license retained by the government in copyright to support acceptable Plans. An Awardee may request a modification of the Commercialization Plan from ARPA-E at any time.

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XIII. Appendix D: Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS)

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
"Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS)"

Topic Issue Date	February 23, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, April 14, 2023
Submission Deadline for Full Applications	9:30 AM ET, April 25, 2023
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, June 1, 2023
Expected Date for Selection Notifications	July 2023
Anticipated Date of Awards	November 2023
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $500,000 and $2,500,000.
Maximum Period of Performance	18 Months

1. Introduction

This announcement describes an Exploratory Topic (ET): Predictive Real-time Emissions Technologies Reducing Aircraft Induced Lines in the Sky (PRE-TRAILS). The purpose of this announcement is (1) to solicit Full Applications for the development of new technologies and tools related to improving the prediction of contrails that form Aircraft Induced Cirrus (AIC) clouds to reduce the environmental impact of aviation, (2) to focus the attention of the scientific and technical community on the specific area of interest and encourage dialogue amongst those interested, and (3) to provide a timetable for the submission of full applications.

2. Topic Description

Aviation is an important part of our domestic and international transportation networks. Fuel consuming aircraft emit a range of emissions. From a climate-forcing standpoint, the most significant are carbon dioxide and water vapor. The Schmidt-Appleman criterion describes specific temperature, pressure and humidity conditions where the mixing of aircraft exhaust water with colder ambient humid air can result in the formation of condensation trails (contrails).[54] Fortunately, most contrails dissipate in under 10 minutes and are of no concern.

However, when nucleation sites and specific atmospheric conditions exist (such as Ice Super-Saturated Regions (ISSR)), engine exhaust can cause the formation of persistent contrails, which can in turn produce persistent cirrus clouds known as aircraft-induced cirrus (AIC). These upper atmospheric clouds can last for hours and may grow to span several hundreds of kilometers. Recent studies have indicated that contrails likely contribute to global radiative forcing at a level that is roughly equivalent to that of the CO_2 emissions from the entire aviation sector, which is estimated to be about 2% of total global CO_2 emissions.[55] Submissions funded under this ET will focus on the following ARPA-E mission area:

1. **Reduce Energy-Related Emissions**: Projects will develop the diagnostics and predictive tools needed to explore further mitigation of contrail-related global warming. If successful, a total radiative forcing emission equivalent to all CO_2 emissions from aviation could potentially be mitigated[55].

Unfortunately, at present, pilots, air traffic controllers, and aerospace system designers have little to no information on whether a specific flight may result in persistent cirrus clouds. ARPA-E envisions the development of a system to predict aviation contrails (hereinafter referred to as an “Aviation Contrail Predictive System”) that would be capable of informing pilots and ground controllers in real-time whether an airplane is likely to produce persistent AIC. This new system could foster the development of a) avoidance strategies – allowing re-direction of airplanes by ground control to more favorable (non-AIC) flight trajectories – and/or b) on-board mitigation technologies.

The development of an Aviation Contrail Predictive System will be particularly challenging – in part because AIC can form several hours after the passage an aircraft. Thus, these predictive models will need to consider both dynamic atmospheric conditions and engine emissions. This may require, for example, the assimilation of *in-situ* data from onboard sensor systems as well as off-aircraft observational data from ground- and/or satellite-based sources and previous flight reports.

[54] Schumann, U., 1996. On conditions for contrail formation from aircraft exhausts. Meteorologische Zeitschrift, 5, pp.4-23.
[55] Lee, D.S., Fahey, D.W., Skowron, A., Allen, M.R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J. and Gettelman, A. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244, p.117834 (2021).

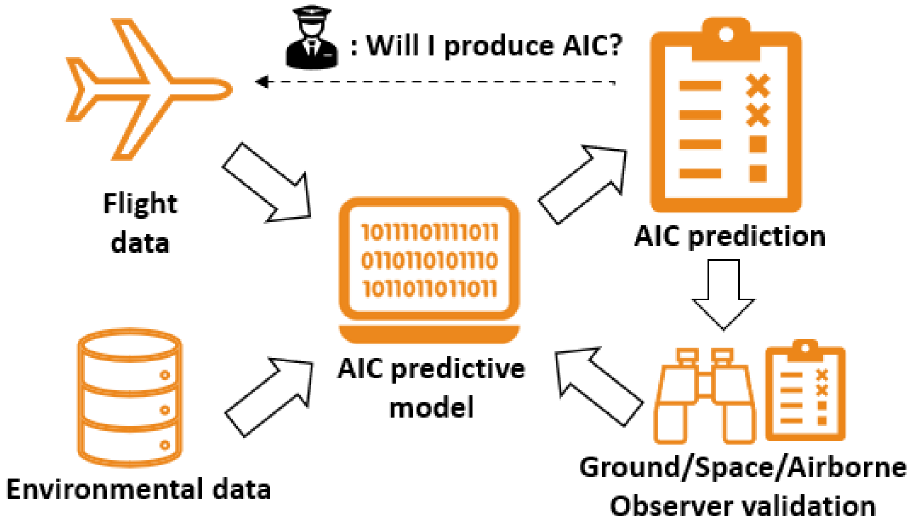

Figure 1. An envisioned use of a near real-time AIC predictive model. Flight data and other environmental data sources are assimilated into a best-guess AIC predictive model during flight planning. Further *in-situ* data from the current flight, *in-situ* data from previous or following flights, and observational data from satellite or ground-based sources would constrain and improve the model output, resulting in improved predictions and better in-flight decision support either via simple monitoring and reporting to the pilot/flight operator or via continuously optimized tactical flight routing. The program outcome is the AIC predictive model and data or sensors needed to make an accurate AIC prediction validated using observations.

One potential approach to explore is the use of predictive modeling through machine learning to analyze data on past and present contrail formation, atmospheric conditions, and onboard sensor systems. A computationally inexpensive, continually updated AIC predictive model could improve forecast accuracy and thus provide feedback and decision support to flight planners, whether prior to takeoff or while underway (Figure 1).

This ARPA-E ET aims to fund project teams that will improve the prediction of AIC resulting from contrail formation. It is hoped that these efforts will provide valuable tools for airlines and other stakeholders in the aviation industry to create and improve detailed techno-economic analyses, quantify efficiencies, and more accurately estimate the environmental impacts associated with the adoption of alternative fuels such as SAF or hydrogen.

3. Technical Areas of Interest

The aim of this new Exploratory Topic is to support the development of a predictive capability that in "real-time" and with high confidence could inform a pilot or flight operator whether an aircraft is likely to produce persistent aircraft induced cirrus clouds (AIC), even hours before they are fully developed. Each submission must address the following three technology areas to develop an Aviation Contrail Predictive System:

- **Aircraft, Environmental Data, and Sensor Development:** New sensors or environmental data sources may be needed to provide sufficient training and validation data for the envisioned predictive capabilities. Contrail forming conditions are identified by the Schmidt-Appleman criterion: where water vapor content reaches liquid saturation under specific temperature and saturation conditions in the presence of nucleation sites.[56,57,58] Especially important are persistent contrails formed when airplanes travel through atmospheric Ice Super-Saturated Regions (ISSR), leading to AIC.[57] As the persistent contrail formation regime is a combination of Schmidt-Appleman and ISSR criteria, sensors capable of identifying these parameters accurately in real-time are of particular interest, *e.g.* sensor systems capable of measuring upper atmospheric humidity at or below 10 ppm.

- **Predictive Modeling:** Advanced machine learning computational methods developed in the past decade allow the exploration of larger sets of input data and explore complex multivariate correlations to solve more complex problems than ever before. ARPA-E is interested in project teams that explore whether such methods can be leveraged to develop a real-time predictive system for AIC development. To inform avoidance and mitigation strategies, it is important that any predictive model gives reasonably accurate results, minimizing false positive (type I) and false negative (type II) errors. For the purposes of this Exploratory Topic, this can be captured in the balanced F-score (F_1-score) which is the harmonic mean of precision and recall. It is important that sufficient confidence in the model exists to inform avoidance and mitigation solutions, while minimizing unnecessary and burdensome rerouting.
- **Observer Data**: A predictive model needs to be trained and validated. For an Aircraft Contrail Predictive System, this will likely require observers and additional sensors. It is anticipated that teams will need to obtain sufficient relevant flight and observer data from available sources or dedicated flight tests to provide true AIC observations and validation, rather than theoretical studies alone. Additionally, ARPA-E envisions a contrail reporting and observational data aggregation mechanism that mimics current tools for turbulence reporting and could further serve to continuously refine and improve AIC predictive modeling capabilities going forward.

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[56] Appleman, H., 1953: The formation of exhaust condensation trails by jet aircraft. Bull. Amer. Meteor. Soc., 34, 14–20.
[57] Kärcher, B. 2018. Formation and radiative forcing of contrail cirrus. Nature Communications, 9, 1824.
[58] Teoh, R., Schumann, U., Majumdar, A. and Stettler, M.E., 2020. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. Environmental Science & Technology, 54(5), pp.2941-2950.

4. Technical Performance Targets

A. *Model F_1-score of at least 0.8*: The developed models should be able to forecast persistent aircraft induced cirrus (AIC) cloud with an accuracy (as defined by the F_1-score) of at least 0.8 for a period of at least 5-12 hours after the passage of an aircraft.

Additionally, proposed AIC predictive model frameworks should be able to provide forecasts for a wide range of atmospheric conditions, including both clear and cloudy skies, and will prove their ability to provide real-time updates to pilots and flight controllers. While the feedback mechanism is undefined for the purpose of this Exploratory Topic, applicants are strongly encouraged to define in their application how these model predictions will be used to inform the pilot or air traffic control to allow for in-flight tactical decisions. This will allow airlines to adjust their flight routes and altitudes to avoid contrail formation and minimize their environmental impact.

B. Final demonstration of the AIC predictive model to achieve a minimum of five (5) true positive predictions of persistent aircraft induced cirrus (AIC) cloud for relevant flights at cruise altitude while satisfying the F_1-score criterion.

The performance of the developed AIC predictive models must be demonstrated before the end of project via a minimum of five (5) true positive predictions of persistent aircraft induced cirrus (AIC) cloud while satisfying the F_1-score criterion. For this target, persistence is defined as greater than five (5) hours and a cirrus cloud as a cloud system which spans ≥ 1 km in width at relevant cruise altitude. This will require observer validation, whether using onboard test flights, ground- or satellite-based.

C. Enabling technologies/Transformational Sensors: if novel sensors are proposed as enabling technologies, describe how they are transformational and relevant for the AIC predictive model to reach the outcome listed above

Any additional sensors that are needed beyond existing sensors on aircraft need to have size, weight, and power requirements that allow them to be easily integrated with existing airframes.

5. Criteria and Metrics

ARPA-E has an ambitious technical target: model performance with a validated F_1-score of at least 0.8. There are several other criteria of interest in each of the relevant areas that support that target:

1. **Aircraft and environmental data and sensor development:** relevant data factors need to be identified and measured with sufficient accuracy. This might be a combination of aircraft speed, altitude, aircraft and engine model, fuel type, humidity, pressure, weather

forecast, or other relevant atmospheric data. If current sensors are insufficient, new sensors might need to be explored. Target sensor performance metrics should be described in the submitted application within the context of meeting the F_1-score ≥ 0.8 metric.

2. **Predictive modeling approaches:** it is anticipated that advanced predictive analytical methods are required to identify relevant parameters and develop correlations which can yield a reasonably high accuracy, *e.g.* F_1-score ≥ 0.8, strongly reducing the number of false positives and false negatives. These predictive models require validation of their performance by identifying probable AIC ≥ 1 km in width, persisting for no fewer than five (5) hours at relevant cruise flight altitude.

3. **Observer data to validate and train the predictive model:** relevant observer methods need to be deployed, developed, or invented to provide feedback on whether aircraft contrails lead to AIC, and will play a critical role in validating model predictions. This can be a set of ground observer systems near relevant flight corridors, aircraft mounted observing sensors, or space-based observer data, as well as any other available aviation data sources. For the purposes of this new Exploratory Topic, limited relevant test flights for data gathering and model validation might be required.

Successful projects will develop a single AIC predictive model, and will incorporate two interim Go/No-Go decision points at intermediate steps, delimitating three distinct project performance focus periods:

Period 1: Development of sensors and predictive model framework: identify any sensor data sources, sensor development needs, and flight and/or other data requirements and explicitly state them with Pass/Fail metrics for each. These Pass/Fail metrics must be directly attributable to successfully meeting the overall model prediction metric of F_1-score of at least 0.8.

Period 2: Gathering of test and observer data and development of AIC predictive model: effective training of the AIC predictive model using the gathered data and exploration on how to integrate such systems within the aircraft to provide feedback to pilot, air traffic control, and other relevant aerospace system design teams.

Period 3: AIC predictive model demonstration: flight testing or other demonstration in relevant conditions of the proposed approach, including a minimum of 5 successful true positive AIC predictions, while satisfying the F_1-score criterion. This can include flight tests or demonstration on available and validated datasets. The criterion for validation is prediction of contrail cirrus and observation of the resultant AIC persisting for no fewer than 5 hours and spanning at least 1 km in width.

6. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed non-responsive and may not be merit-reviewed:

- *Incomplete solutions:* any system or systems that do not result in a predictive capability that meets the aforementioned F_1-score criterion. This includes sensors solely for atmospheric measurement, or models for a single component of the AIC forming conditions (*e.g.,* models of single parameters such as convection, temperature, humidity, *etc.*).
- *Solutions not relevant to majority of commercial flights:* any technologies that operate solely outside of currently accepted flight commercial flight paths (whether altitude, aircraft or flight path) are not of interest.

7. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: DE-FOA-0002784. All other instructions set forth at FOA Section IV.C remain unchanged.

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

Commercialization Plan and Software Reporting:

All projects funded under this ET target the development of a software model. Therefore, if your project is selected and awarded following award negotiations, you will be required, as a milestone, to prepare a Commercialization Plan for the targeted software and agree to special provisions that require the reporting of the targeted software and its utilization. This special approach to projects that target software mirrors the requirements for reporting that attach to new inventions made in performance of an award. Because the Plan is called a Commercialization Plan does not mean that an awardee will be required to make the software publicly available. An acceptable Plan may indicate that the awardee will use the software internally within its own enterprises.

XIV. Appendix E: Critical Mineral Extraction from Ocean Macroalgal Biomass (Algal Mining)

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
"Critical Mineral Extraction from Ocean Macroalgal Biomass (Algal Mining)"

Topic Issue Date	April 28, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, May 15, 2023
Submission Deadline for Full Applications	9:30 AM ET, May 31, 2023
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, July 6, 2023
Expected Date for Selection Notifications	~~August 2023~~ October 2023
Anticipated Date of Awards	~~November 2023~~ February 2024
Total Amount to be Awarded	Approximately $5,000,000 subject to the availability of appropriated funds for this Exploratory Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $500,000 and $2,500,000.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes an exploratory research thrust entitled Critical Mineral Extraction from Macroalgal Biomass. The purpose of this announcement is to (1) solicit Full Applications for the evaluation of the feasibility of extracting critical minerals from macroalgae cultivated in the U.S. Exclusive Economic Zone, (2) encourage partnerships between seaweed farmers and scientists, marine microbiologists, geologists, critical mineral experts, and the mining community, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

ARPA-E is interested in receiving full applications investigating the feasibility of extracting critical minerals, specifically Rare Earth Elements (REEs) critical for the production of electric motors and generators, and high-value Platinum Group Metals (PGMs), from macroalgae cultivated and/or harvested within the U.S. Exclusive Economic Zone (EEZ). See Table 1 for a complete list of elements within the scope of this announcement. The targeted outcomes of this topic are:

1) An understanding of what environmental, temporal and ecological factors influence the PGM/REE metal content of ocean-grown macroalgae. Factors including but not limited to cultivation region, cultivation mechanism, the effects of water quality and proximity of natural mineral sources, and harvest strategy are of interest.
2) Identification of the mechanism of biological metal absorption and hyperaccumulation by ocean macroalgal biomass, including the maximum capacity and absorption rate thereof, variability and location of mineral concentration within the macroalgal

holobiont, variation among species, impact of harvesting strategies, and underlying cellular and molecular mechanisms.

3) Development of methods to extract critical minerals from the macroalgae at high output purities that can dovetail with existing and nascent macroalgal valorization streams developed for the other components of macroalgae such as carbon compounds, macro- and micro-nutrients, utilizing existing waste streams from seaweed biorefineries. Within scope is continuous mineral extraction from growing macroalgae without destruction of the plant. Note that the research thrust described is only concerned with adding value to existing or nascent macroalgal processing streams that already valorize aspects of the biomass other than the PGM/REE metals of interest.
4) A techno-economic analysis of these methods, considering the sensitivity to the inputs investigated in items (1), (2) or (3).

Table 1. *List of metals of interest to ARPA-E*[59]

Relevant PGMs/REEs	Required purities for Technical Area 2 (TA2)	Relevant PGMs/REEs	Required purities for TA2	Relevant PGMs/REEs	Required purities for TA2
cerium	99%	lanthanum	99%	ruthenium	99%
dysprosium	99%	lutetium	99%	samarium	99%
erbium	99%	neodymium	99.9%	scandium	99%
europium	99%	palladium	99%	terbium	99%
gadolinium	99%	platinum	99%	thulium	99%
holmium	99%	praseodymium	99%	ytterbium	99%
iridium	99%	rhodium	99%	yttrium	99.9%

[59] Elements in Table 1 qualify for [credits] under the Inflation Reduction Act of 2022 at the elemental purity levels shown. Text - H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022 | Congress.gov | Library of Congress

3. Background

REEs and PGMs are critical in the manufacture of modern energy and national security technologies. For example, REEs are required for the fabrication of high-performance magnets required for wind turbines, electric vehicles, high-energy-density battery electric storage, high-efficiency lighting, solar panels, and other technologies either core or ancillary to the renewable energy industry. Though demand continues to increase, economically and environmentally viable deposits are difficult to realize and extraction from existing terrestrial deposits remains costly in terms of energy inputs and emissions outputs. Many of these deposits are located outside the United States, creating supply chain vulnerabilities for the energy goals and national security of the country. Some of the critical minerals most important to decarbonization are also the most vulnerable to disruptions in trade, including three minerals critical to the production of the permanent magnets used in wind turbine generators and electric vehicles: Neodymium, Dysprosium, and Praseodymium (Fig. 1).

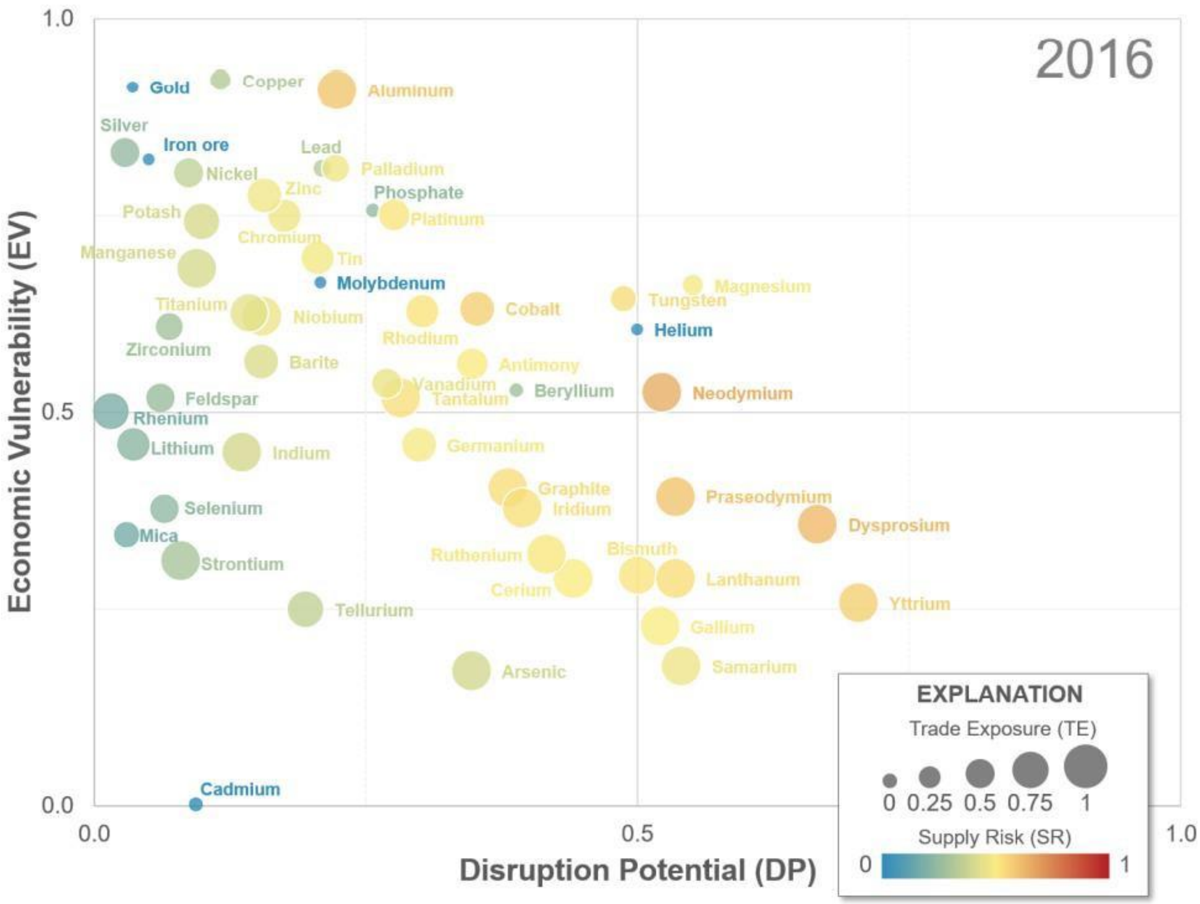

Figure 1. *Economic vulnerability vs. disruption potential for critical minerals in 2016. The REEs of concern to this work include Neodymium, Dysprosium, Praseodymium, and Terbium (not depicted). PGMs including Platinum and Palladium are of secondary importance in terms of disruption potential, but offer opportunities toward economic feasibility due to their high value. Figure from USGS 2019 Critical Minerals Review.*

The U.S. Government aims to significantly increase the quantity of renewable power production supporting our country's grid, with a priority on wind and offshore wind energy, as well as an interest in decarbonizing the transport sector through electric vehicles. As these developments progress, it is paramount that the U.S. identify new and independent sources of rare earth elements that ensure this progress is protected against supply chain uncertainties.

Research has shown that macroalgae may be an effective bioaccumulator of critical minerals.[60,61,62,63,64] There is evidence that macroalgae may be particularly well suited to absorbing neodymium and dysprosium, minerals already identified as both critical and vulnerable. However, much of this research has primarily focused on macroalgae exposed to contaminated seawater featuring anthropogenically enhanced concentrations of specific types of critical minerals associated with industrial pollution. These studies have also indicated that different species may absorb different metals at varying rates, and that the positive indicators of absorption strength vary by species or desired mineral. ARPA-E wishes to reduce this uncertainty and refine our scientific understanding of bioaccumulation in macroalgae in an effort to consider the mechanisms, technical, and the economic feasibility of adding a critical minerals extraction processing chain to existing cultivated macroalgae processing streams.

Little is known regarding the effects environmental and biological variables have on critical mineral bioaccumulation in macroalgae in-situ. This topic seeks to understand the variability in critical mineral absorption based on species, cultivation region, water properties, harvest timing, and other variables that may ultimately influence mineral concentration. For example, PGM/REE concentrations in near-surface rock within a watershed adjacent to coastal areas may cause higher levels of these minerals in the tissue of coastal macroalgal populations. An example of such a region may be the Bokan-Dotson Ridge Zone in the Prince of Wales Island region of Alaska[65], a region known for macroalgal cultivation. However, even if terrestrial runoff does influence PGM/REE concentrations in macroalgal tissues, it is important to understand

[60] Thainara Viana, Bruno Henriques, Nicole Ferreira, Cláudia Lopes, Daniela Tavares, Elaine Fabre, Lina Carvalho, José Pinheiro-Torres, Eduarda Pereira, Sustainable recovery of neodymium and dysprosium from waters through seaweeds: Influence of operational parameters, Chemosphere, Volume 280, 2021, 130600, ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2021.130600.

[61] João Pinto, Bruno Henriques, José Soares, Marcelo Costa, Mariana Dias, Elaine Fabre, Cláudia B. Lopes, Carlos Vale, José Pinheiro-Torres, Eduarda Pereira, A green method based on living macroalgae for the removal of rare earth elements from contaminated waters, Journal of Environmental Management, Volume 263, 2020, 110376, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2020.110376.

[62] Jéssica Jacinto, Bruno Henriques, A.C. Duarte, Carlos Vale, E. Pereira, Removal and recovery of Critical Rare Elements from contaminated waters by living Gracilaria gracilis, Journal of Hazardous Materials, Volume 344, 2018, Pages 531-538, ISSN 0304-3894, https://doi.org/10.1016/j.jhazmat.2017.10.054.

[63] Nora Shenouda Gad, Biosorption of rare earth elements using biomass of Sargassum on El-Atshan Trachytic sill, Central Eastern Desert, Egypt, Egyptian Journal of Petroleum, Volume 25, Issue 4, 2016, Pages 445-451, ISSN 1110-0621, https://doi.org/10.1016/j.ejpe.2015.10.013.

[64] Wang, M., Hu, C., Barnes, B. B., Mitchum, G., Lapointe, B., & Montoya, J. P. (2019). The great Atlantic sargassum belt. *Science*, *365*(6448), 83-87.

[65] Barker, J. C., and Van Gosen, B. S. (2012) "Alaska's rare earth deposits and resource potential," Mining Engineering, 64(1), pp20-32

how far from the source this increased concentration may extend, the nature of REE transport through natural erosion and transportation, and the mechanisms by which REEs may be absorbed by local species of macroalgae. An understanding of the total viable harvest yield and requisite farm size is also important in answering questions regarding scalability.

Other sources of PGM/REEs, such as from upwelled deep seawater or riverine runoff that influences the growth of floating pelagic macroalgae may also be suitable for large scale critical mineral extraction. For example, sargassum has shown to be a potentially excellent bioaccumulator of metals[66], and there is a naturally occurring source of pelagic sargassum in the Atlantic Ocean. In this case, cultivation may be unnecessary as due to a dramatic increase in natural biomass production in recent years[67].

The extraction of REEs is a potential additional market for U.S. macroalgal growers. It allows for the generation of revenue from what are currently waste streams in seaweed processing (the ash and wastewater fractions), while providing the U.S. with resources that are critical to the country's national security. In addition, it is a market that can scale along with the U.S. macroalgae industry. The separate increasing demand for critical minerals and the importance of the U.S. maintaining its own national critical mineral reserve will align well with an increasing scale of seaweed. This dual-purpose market can enable the cultivation volume needed to grow macroalgal biomass on a scale relevant for ocean Carbon Dioxide Removal (CDR) and/or ocean biomass uses for other energy related applications. In this scenario, where the U.S. would produce millions of tons of macroalgal biomass each year, it is important that the farmers are able to extract as much value from the biomass as possible. This topic will fund investigations that may enable farmers in the future to extract critical minerals from their harvests in addition to also supplying industries that reduce emissions and/or draw down carbon from the planet's atmosphere.

Aside from its potential use as a bio-accumulator, cultivated macroalgae could be an important part of both the green energy transition and a future carbon negative industry. Cultivated seaweed extracts carbon from the ocean and may then be sunk to the deep ocean or converted through other methods to sequester that carbon for long periods of time. The National Academy of Sciences report on ocean CDR[68] lists seaweed sinking as one of the six potential avenues for ocean CDR. In addition to carbon removal, cultivated seaweed can potentially be used as a biofuel feedstock, an environmentally beneficial additive to animal feed, and a critical ingredient in soil remediation methodologies. Given the potential scale of the macroalgae

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[66] Jéssica Jacinto, Bruno Henriques, A.C. Duarte, Carlos Vale, E. Pereira, Removal and recovery of Critical Rare Elements from contaminated waters by living Gracilaria gracilis, Journal of Hazardous Materials, Volume 344, 2018, Pages 531-538, ISSN 0304-3894, https://doi.org/10.1016/j.jhazmat.2017.10.054.

[67] Nora Shenouda Gad, Biosorption of rare earth elements using biomass of Sargassum on El-Atshan Trachytic sill, Central Eastern Desert, Egypt, Egyptian Journal of Petroleum, Volume 25, Issue 4, 2016, Pages 445-451, ISSN 1110-0621, https://doi.org/10.1016/j.ejpe.2015.10.013.

[68] National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.

industry, and the rapid increase in both interest and active farmers in the U.S., it is crucial to identify additional markets that farmers can use to generate revenue. One of the challenges in valorizing macroalgae biomass is the significant waste in any current seaweed processing approach. Between the ash fraction and wastewater stream, up to 60% of the biomass is currently unutilized[69]. ARPA-E considers finding pathways to valorize these waste streams an enabling mechanism for the growth of the macroalgae industry by opening up additional revenues streams for biomass that is currently discarded. In addition, ARPA-E considers finding pathways to extract critical minerals without creating a waste stream (e.g., without harvesting or burning the plant) vital in the reduction of carbon emissions.

Several methods of elemental or metal extraction from algal biomass exist. Pyrolysis and gasification are known methods of conversion but require drying of the biomass prior. Hydrothermal liquefaction (HTL) is a method that allows the whole macroalgal biomass to be processed without dewatering, thus eliminating drying step necessary for pyrolysis and gasification. HTL is a thermochemical method that uses low temperatures (<400C) and high pressure to convert biomass into biocrude that can then be used for a range of applications, such as biofuels[70]. The method allows water in the macroalgae to be kept in a liquid or supercritical state, lowering its dielectric constant and allowing it to act as polar solvent to penetrate and assist the degradation of the macroalgae[71]. HTL is able to convert both lipid and nonlipid fractions of algae, while making recovery of nutrients and metals easier. HTL has been accomplished in both small batch and continuous reactor systems[72], though most work to-date using HTL has been carried out in small batch reactors. However, HTL may be cost prohibitive and processing times may be longer than what is scalable. In addition, all these methods rely on destruction of the macroalgae to recover metals and other valorizable components.

4. Technical Areas of Interest

The goal of this topic is to support the investigation of the REE and PGM content of marine macroalgae and the variation of that content across different cultivation conditions, the identification of the absorption mechanism and storage location of minerals within different macroalgae species, and the development of new extraction processes for the mineral fraction of macroalgal biomass. To achieve this, ARPA-E seeks to fund projects in two Technical Areas:

Technical Area 1 (TA1): Macroalgae Composition

This Technical Area seeks to fund projects to investigate the critical mineral composition of marine macroalgae, and the variation and nature of that composition based on species, environmental factors, and harvest timing factors. Investigation to identify the mechanism of

[69] Bavington, Charles (*pers. Comm*, 3/18/22)

[70] Yulin Hu, ... Chunbao (Charles) Xu, in Future Energy (Third Edition), 2020

[71] Lin Mei Wu, ... Wei Hua Yu, in Bioenergy Research: Advances and Applications, 2014

[72] S.N. Sahu, ... D.M. Mahapatra, in Bioreactors, 2020

absorption for the species being investigated, and the location of minerals of interest[73] within the biomass (i.e., exudate, stipe, holdfast, blade, or other location) is within scope. This topic calls for projects that investigate brown or red marine macroalgal species cultivated and/or harvested in a scalable manner, in either temperate or tropical waters within the U.S. EEZ. Environmental scenarios of interest are:

1) Marine macroalgae cultivated in the proximity of known and characterized terrestrial REE/PGM mineral sources. It is hypothesized that the runoff from the watershed that encompasses these sources may drive an increase in the mineral content of ambient seawater in associated coastal areas. Projects investigating this type of mineral source should assess the impact of the terrestrial minerals on seawater REE/PGM concentration, the scales associated with any impact on the seawater mineral concentration (i.e. how far from the terrestrial source is the water impact, and what is the spatial attenuation of the impact), dependence on rainfall and other weathering processes, and how the proximity to a terrestrial source impacts REE/PGM concentrations in macroalgae harvested from nearby waters at different times of the year.
2) Macroalgae grown using upwelled deep-sea water. This type of water is a potential source of nutrients that is being investigated for offshore macroalgal cultivation. In addition to a high macronutrient content important for macroalgal growth, deep sea water contains higher concentrations of REE/PGM6. Projects investigating this nutrient source may leverage deep sea water that is upwelled to macroalgae located in surface waters or macroalgae that is depth cycled periodically to deeper waters for nutrient access and weather impact mitigation purposes. Regardless of the approach, projects should quantify the concentration of minerals in deep sea water compared to surface waters and the impact on the mineral composition of macroalgae grown using that deep sea water.
3) Sargassum harvested from the Atlantic Sargassum Belt, a recently developed excessive seasonal bloom of sargassum that spans the Atlantic Ocean from the Western coast of Africa to the Caribbean. There are some indications that that this biomass may contain a high concentration of PGEs in comparison to other macroalgal stocks. Projects investigating this mineral source should quantify the metal concentration of Caribbean sargassum as a function of location and seasonality. An investigation of hypotheses that seek to determine the origin of these PGEs is also within scope.
4) Macroalgae cultivated in the exposed ocean, not within proximity of any specific known source of metals. Projects investigating this macroalgae source should quantify the concentration of seawater in the region being considered, and the variation in metal content of cultivated macroalgae over the course of a growing season. The goal of these projects is to understand potential harvest and cultivation strategies to maximize the metal content of macroalgae and the quantify the potential scale of critical mineral extraction as an additional value stream from a large-scale macroalgae industry.

[73] Minerals of interest for this FOA include primarily rare earth elements, and platinum group elements. Additional extraction of critical minerals either separately or in combination with the REEs and/or PGEs will be viewed favorably for this FOA.

Regardless of the nutrient or biomass source being considered, projects in this Technical Area should identify the species being cultivated, the region being considered, temporal variations in REE/PGM concentration, and the source of both nutrient and metals impacting the macroalgae. In addition, projects should identify the mechanism of absorption for the species being considered and the location of the minerals within the biomass (i.e., in the exudate, in the stipe tissue, blade tissue, holdfast tissue, or other location).Underlying mechanisms for bioaccumulation, such as changes in the expression of specific enzymes and proteins that drive mineral absorption are also of interest. Projects should describe their approach for acquiring biomass such as teaming with an existing farmer, wild harvest in a specific region, or small-scale cultivation in targeted locations. They should also describe their sampling and analysis plan for the seawater, compositional analysis of seaweed biomass and the approach that will be used to identify the mechanisms and location of absorbed minerals. It is encouraged that performers in this category be prepared to provide a minimum 10kg of dry biomass for Performers funded under TA2 along with collection and specimen identifying documentation, including date, time and location of collection, who collected the specimen, positive species ID, and the part(s) of the plant the specimen is from (if the specimen is a sub-sample). This information and material to be shared may be subject to restrictions on use or disclosure authorized by the TA1 award. If any data that is exchanged is subject to any authorized restriction the TA1 and TA2 will be expected to reach an agreement following selection regarding the handling of such data. This topic seeks to fund projects in TA1 between $500,000 and $2,500,000 and have a period of performance of no more than 24 months.

Technical Area 2: Element Extraction from Macroalgae

This Technical Area seeks to fund projects that will develop new processes for the efficient extraction and processing of REE/PGM elements into usable forms from macroalgal biomass and also terrestrial plant mass if applicable. This topic is interested in projects that investigate extraction from marine brown or red seaweed species, cultivated and/or harvested in either temperate or tropical waters of the U.S. EEZ. This topic is also interested in dual-use processes that also enable the refinement of REEs from hyperaccumulating terrestrial plant mass, such as pokeweed, that contain rare earth elements and other elements listed as of interest in this FOA. Specific developments of interest are:

1) Low-energy, scalable methods of element extraction and processing in general, suitable for macroalgal 'bio-ore' feedstocks and terrestrial hyperaccumulator feedstocks.
2) Methods of element extraction and processing that accommodate the refinement of multiple REE/PGM metals.
3) Methods of element extraction and processing that incorporate the capture and reuse of macroalgal and terrestrial plant carbon for applications other than human consumption (destructive extraction).
4) If applicable, methods of continuous extraction and processing from macroalgae without substantially interrupting macroalgal growth, that involve preservation of the macroalgae in the field.

Projects in this Technical Area should also provide a preliminary technoeconomic analysis (TEA) of the proposed extraction technology, assuming cultivation and harvest quantities scaling from 1000 tons to 1 Gigaton of wet macroalgae per year and expect to update the TEA during the funding period if selected for an award. Projects in this category should expect to deliver a lab-scale demonstration of the extraction method along with an experimentally supported TEA of the proposed technology. Projects targeting a destructive method of extraction should target an extraction efficiency 99% or higher. Projects targeting a continuous extraction method should target an extraction efficiency of 80% or higher. This topic seeks to fund projects in TA2 between $500,000 and $2,500,000 and have a period of performance of no more than 24 months. Performers in TA2 focused on macroalgae are expected to collaborate with those funded in TA1 for facilities siting and to obtain enough macroalgae for experimental processing.

5. Timeline

Given that optimized hyperaccumulating biomass must first be identified and developed before representative processing outputs can be experimentally determined, Table 2 indicates a prospective timeline for a project that incorporates TA1 and TA2 (applicants may submit applications under TA1, TA2, or both). The topic timeline requires simultaneous investigation of natural PGM/REE sources and hyperaccumulation mechanisms as well as development of an efficient metal extraction process, which may necessitate the development of the extraction process using non-optimized, representative macroalgal samples. It is expected that samples of macroalgae that contain the highest concentrations of PGM/REE naturally obtainable will be available at the end of Y1/beginning of Y2. These samples would thus ideally be processed through already developed methods, in order to yield metals extraction rates and efficiencies that would feed into a technoeconomic analysis at the culmination of the two-year effort.

Table 2. *Anticipated timeline with tasks from both TA1 and TA2. Asterisks denote go/no-go milestones for TA1.*

	Year 1 (Y1)				Year 2 (Y2)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
TA1 Tasks								
Evaluate environmental inputs to PGM/REE concentration				*				
Evaluate seasonal effects				*				
Evaluate biological effects				*				
Investigate mechanism of PGM/REE accumulation								
Obtain samples of optimal hyperaccumulating macroalgae								
TA2 Tasks								
Develop refinement process with non-optimized, representative macroalgal samples								
Apply 'optimized' biomass to refinement process								
Perform technoeconomic analysis and projected values using results from processing optimized biomass								

6. Technical Performance Targets

If responding to TA1, respondents are required to include the following in their proposal:

Discovery Mechanisms:

1) Hypothesize what variables (environmental, biological, genetic, etc.) may impact metal hyperaccumulation and ultimately concentrations in raw harvested biomass, with reasoned justification.
2) For each variable hypothesized to be an influencing factor, a proposed experimental approach that will obtain correlative information between the factor and metals concentration in harvested macroalgae.
3) A multivariate analysis approach that will indicate the optimal combination of variables that would result in the highest PGM/REE concentrations in harvested macroalgae, along with the capture of uncertainties associated with each variable. In addition, the analysis should investigate the synergistic effects between variables such as multi-metal interaction, if observed.
4) Hypothesize and test for identifying the absorption method and distribution of the PGM/REE mineral content on the surface of or within the macroalgal specie(s) under consideration. This approach must be outlined in sufficient detail including experimental method, variable matrix, and an uncertainty analysis.

Metrics:

1) Proposers should strive to include the experimental testing of a comprehensive set of variables that may influence metals concentration in ocean-grown macroalgae. At minimum, four environmental variables (geographic location, water depth, species, harvest time) should be considered. More are desirable, especially if a strong correlative relationship between the variable and PGM/REE concentrations can be reasonably hypothesized.
2) Investigation of the bioaccumulation for the minerals Neodymium, Praseodymium, Terbium and Dysprosium (minerals important to the manufacture of electric motors) are mandatory, in addition to at least **five** other minerals featured in the list provided in Table 1 of this document. Preference will be given to minerals known to be critical for green energy technologies or of high value, and at risk of supply disruption through geopolitical uncertainties.
3) The optimal combination of variables should result in bioconcentration factors on the order of **>10^6** (compared to ambient seawater at the collection site), when considering species of macroalgae that could be economically cultivated at megaton annual scales for valorization in ways additional to PGM/REE markets.

If responding to TA2, respondents are required to include the following in their proposal:

1) A description of the proposed technology, including estimates of energy requirements per gram of PGM/REE produced.
2) Describe how the proposed technology will accomplish one of the following targets with elements of interest to this FOA present in the macroalgae at bioconcentration levels required in TA1 (whole plant considered) either alone or in presence of other elements:
    a. Extraction efficiency of 99% or higher for technologies targeting a destructive method of extraction.
    b. Extraction efficiency of 80% or higher for technologies providing a continuous extraction method (e.g., extracting metals from the surface of macroalgae, without destruction of the macroalgae feedstock).
3) The selected algal species required as the input material and approximate quantities required for minimum laboratory R&D/demonstration processes.
4) An initial technoeconomic analysis that includes consideration of both the extraction/processing technology as well as the feedstock, and any other additional markets that could be served through valorization of carbon in any waste generated.

7. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed inappropriate and may not be merit reviewed nor considered:

- Submissions that are only suitable for land-based macroalgae cultivation (submissions may include the use of land-based tanks to systematically test specific inputs and their corresponding effect on macroalgae; however, they must be aimed at ultimately enabling offshore cultivation of macroalgae and critical mineral extraction).
- Submissions for TA1 that feature algal species that are not associated with any scaled macroalgal feedstock industry, either existent or nascent.
- Submissions aimed solely at growing and cultivating macroalgae, without consideration of minerals processing.
- Submissions for TA2 that do not cover at least five (5) elements listed in Table 1 of this document.
- Submissions for TA1 or TA2 that consider fewer than the minimum number of critical minerals under consideration.
- Submissions for TA2 that do not consider valorization of macroalgal carbon content and/or ash fraction in addition to REE/PGM metals.
- Submissions for TA2 focused on extraction from green algal species, unless scaled marine production opportunities and valorization avenues for green macroalgae are explicitly identified.
- Submissions for TA 2 that include terrestrial plants or macroalgae for which the presence of elements deemed of interest in this FOA has not been confirmed.

- Submissions that focus on developing new biological organisms.

8. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Appendix E, Algal Mining. All other instructions set forth at FOA Section IV.C remain unchanged.

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

XV. Appendix F: Novel Superconducting Technologies for Conductors

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Novel Superconducting Technologies for Conductors

Topic Issue Date	May 30, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 18, 2023
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, July 25, 2023
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, Thursday August 24, 2023
Expected Date for Selection Notifications	September, 2023
Anticipated Date of Awards	December, 2023
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$10,000,000.
Maximum Period of Performance	36 Months

1. Introduction

This announcement describes a research and development thrust titled "Novel Superconducting Technologies for Conductors." The purpose of this announcement is to (1) focus the attention of the scientific and technical community on specific areas of interest related to the manufacturing processes of high-performance, rapidly produced superconducting tapes, (2) encourage dialogue among those interested in this area, and (3) provide a timetable for the submission of full applications.

2. Topic Description

Widely available low-cost high-temperature superconducting (HTS) tapes would encourage their use into several energy-related applications that could have major implications in the energy transition. The superconductors targeted in this Topic are expected to help enable the market growth and proliferation of nuclear fusion,[74] superconducting cables for the electric grid,[75,76] electric aviation,[77] and superconductor-based electric generators/motors.[78,79]

[74] X. Wang, S. A. Gourlay, and S. O. Prestemon, "Dipole magnets above 20 Tesla: research needs for a path via high-temperature superconducting REBCO conductors," *Instruments*, vol. 3, no. 4, 62, 2019, doi: 10.3390/instruments3040062.
[75] T. Stamm, P. Cheetham, C. Park, C. H. Kim, L. Graber, and S. Pamidi, "Novel gases as electrical insulation and a new design for gas-cooled superconducting power cables," IEEE Electr. Insul. Mag., vol. 36, no. 5, pp. 32–42, 2020, doi: 10.1109/MEI.2020.9165697.
[76] B. Marchionini et al., "High temperature superconductivity application readiness map - energy delivery - transmission, substation and distribution," IEEE Trans. Appl. Supercond., vol. 33, no. 5, 5401405 , 2023, doi: 10.1109/TASC.2023.3242226.
[77] https://arpa-e.energy.gov/technologies/exploratory-topics/aviation-power-distribution
[78] L. Ybanez et al., "ASCEND: The first step towards cryogenic electric propulsion," IOP Conf. Ser.: Mater. Sci. Eng., vol. 1241, no. 1, 012034, 2022, doi: 10.1088/1757-899X/1241/1/012034.
[79] https://arpa-e.energy.gov/technologies/programs/ascend

Superconductors are materials that have zero electrical resistance when operated at temperature T, electrical current I, and magnetic field B below a critical temperature T_c, a critical current I_c, and a critical field B_c, respectively. This triad of critical parameters are interdependent such that, at lower temperatures, superconductors may be able to operate at higher currents or under a higher magnetic field before quenching occurs, i.e., before they lose their superconducting properties. HTS such as $YBa_2Cu_3O_{7-x}$, which is part of a larger family of compounds known as Rare Earth Barium Copper Oxides (REBCO), are a particularly attractive technology because if they are processed appropriately they can maintain high critical current in high magnetic fields (i.e., > 20 T) at low temperatures (i.e., 20 K with LH_2) for applications such as high-energy physics and nuclear fusion,[74] or can work at higher temperatures (i.e., up to 77 K with LN_2) in lower magnetic fields (< 2 T) for applications such as electric motors and generators, transformers, high-speed maglev transportation, and electric power transmission.[75,76,80]

Although they have superior performance, HTS are more difficult to manufacture than low-temperature superconductors (LTS). LTS such as niobium–titanium are simple metal alloys which are malleable and are easily and cheaply manufactured into wires or tapes. However, they generally have critical temperatures less than 30 K, use liquid helium cooling (i.e., ≈ 4 K) to improve their critical current I_c, and are not capable of operating in very high magnetic fields.[74] Conversely, the most promising high-temperature superconductors, such as REBCO, are brittle ceramics which often require a combination of multiple sequential processing steps, multiple layers of sequential deposition, and highly controlled growth processes. These factors lead to difficult and costly manufacturing for HTS tapes.

The manufacturing process of REBCO tapes starts with a substrate layer which typically consist of a thin, long, flexible, metal foil that provides mechanical support as well as thermal stability (see Fig. 3a of Ref.[81], for example). The width and thickness of the substrate can vary depending on manufacturing process capabilities and customer requirements. Currently, the substrates are ≈ 30-150 μm thick and 12 mm wide. Wider substrates could be an area for manufacturing improvement. In terms of customer requirements, thicker substrates may allow for higher proof strength which could be needed when tapes experience large electromagnetic forces during operation, while thinner substrates can allow for smaller bending radii before critical current degradation which is a consideration when wrapping HTS tapes onto formers for cables.[82,83] The substrate is processed to provide a smooth, aligned crystalline structure for the REBCO layer epitaxial growth through the use of various oxide buffer layers combined with ion-beam assisted deposition (IBAD), inclined substrate deposition (ISD), or a rolling assisted biaxially textured substrate (RABiTS) method.

[80] K. Mizuno, M. Sugino, M. Tanaka, and M. Ogata, "Development of a real-scale REBCO Coil for the demonstration of a magnetomotive force of 700 kA," Q. rep. RTRI, vol. 58, no. 4, pp. 318–323, 2017, doi: 10.2219/rtriqr.58.4_318.

[81] L. MacManus-Driscoll and S. C. Wimbush, "Processing and applications of high temperature superconducting coated conductors," Nature Review Materials, vol.6, pp. 587-604, 2021, doi: 10.1038/s41578-021-00290-3.

[82] G. Jiang et al., "Recent development and mass production of high Je 2G-HTS tapes by using thin hastelloy substrate at Shanghai Superconductor Technology," Supercond. Sci. Technol., vol. 33, no. 7, 074005, 2020, doi: 10.1088/1361-6668/ab90c4.

[83] X. Wang, D. Arbelaez, S. Caspi, S. O. Prestemon, G. Sabbi, and T. Shen, "Strain distribution in REBCO-coated conductors bent with the constant-perimeter geometry," IEEE Trans. Appl. Supercond., vol. 27, no. 8, 6604010, 2017, doi: 10.1109/TASC.2017.2766132.

Once the substrate is ready, the REBCO is then applied with several passes through deposition processes such as Pulsed Laser Deposition (PLD), reactive sputtering/evaporation, metal organic deposition (MOD), or metal organic chemical vapor deposition (MOCVD) with precise temperature, chemical, and dopant controls. As the REBCO layer gets thicker, high-quality growth is difficult to maintain and control. Thus, the critical current density J_c – defined as the ratio of I_c to the cross-sectional area of the REBCO layer – generally decreases with each pass of the tape through the deposition process. Preventing degradation in J_c as the REBCO layer gets thicker is an active area of research. [84,85] Outcomes of this research and development could result in less chemical species needed, fewer or faster passes through the deposition processes, and longer lengths of tape without critical current dropouts leading to cost savings, faster production, or improved capability to meet customer performance requirements such as uniform current density over long lengths to eliminate end tape connections and improve current balancing in parallel tapes. Other process adjustments in the buffer and HTS layer to improve J_c can also relate to the creation of field pinning defects for high magnetic field operation.[811,86,87,88,89]

Once the REBCO layer is complete, the sheet can be slit into narrower tapes typically 1-6 mm wide. Burrs or cracks resulting from the mechanical slitting of these wider tapes into narrower widths for specific applications can lead to a reduction in I_c. Laser slitting is becoming more common and generally causes less degradation though could still have a small heat-affected zone (HAZ) of a few tens of micrometers where the tape can be damaged.[90,91] A few micrometers thick silver layer is generally deposited to protect the HTS layer before and/or after slitting. Finally, the entire conductor is usually coated with a copper stabilization layer that can be as thick as 50 µm depending on customer specifications which are often related to quenching requirements.

The performance of the HTS can be defined by (i) its critical current per unit width, $I_{c/w}$ (in A/cm-width) and/or (ii) its engineering current density J_e (in A/mm^2) defined as the ratio of I_c at a given temperature and magnetic field and the cross-sectional area A of the completed tape including all layers, i.e., $J_e = I_c/A$. The engineering current density J_e is an important parameter particularly for high-density magnets as it indicates how tightly coils can be packed.[92] The reported tape

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[84] S. Chen et al., "Scale Up of high-performance REBCO tapes in a pilot-scale advanced MOCVD tool with In-line 2D-XRD system," IEEE Trans. Appl. Supercond., vol. 31, no. 5, 6600205, 2021, doi: 10.1109/TASC.2021.3058868.

[85] A. Markelov *et al.*, "2G HTS wire with enhanced engineering current density attained through the deposition of HTS layer with increased thickness," *Progress in Superconductivity and Cryogenics*, vol. 21, no. 4, pp. 29–33, 2019, doi: 10.9714/PSAC.2019.21.4.029.

[86] K. Tsuchiya et al., "Critical current measurement of commercial REBCO conductors at 4.2 K," Cryogenics, vol. 85, pp. 1–7, 2017, doi: 10.1016/j.cryogenics.2017.05.002.

[87] W. O'Neill, "Ultrafast machining of high temperature superconductor nanostructures for novel mesoscale physics," Final Technical Report. AFRL-AFOSR-UK-TR-2023-0012.

[88] N. M. Strickland et al., "Tunable dimensionality of pinning centers from silver-ion irradiation of REBCO coated conductors," IEEE Trans. Appl. Supercond., vol. 33, no. 5, 8000205, 2023, doi: 10.1109/TASC.2023.3240384.

[89] M. Paidpilli et al., "Growth of high-performance 4-5 µm thick film REBCO tapes doped with hafnium using advanced MOCVD," IEEE Trans. Appl. Supercond., vol. 31, no. 5, 6600405, 2021, doi: 10.1109/TASC.2021.3060366.

[90] Z. Yang, Y. Li, P. Song, M. Guan, F. Feng, and T. Qu, "Effect of edge cracks on critical current degradation in REBCO tapes under tensile stress," *Superconductivity*, vol. 1, 100007, 2022, doi: 10.1016/j.supcon.2022.100007.

[91] W. N. Hartnett *et al.*, "Characterization of edge damage induced on REBCO superconducting tape by mechanical slitting," *Eng. Res. Express*, vol. 3, no. 3, 035007, 2021, doi: 10.1088/2631-8695/ac0fc3.

[92] R. C. Duckworth *et al.*, "Conceptual design and performance considerations for superconducting magnets in the material plasma exposure experiment," *IEEE Trans. Plasma Sci.*, vol. 48, no. 6, pp. 1421–1427, 2020, doi: 10.1109/TPS.2020.2985948.

length achieving a given $I_{c/w}$ or J_e is also a key metric as it indicates if uniformity can be maintained over a substantial length of tape through the manufacturing process. Various state-of-the-art metrics have been reported in recent literature. While statistical uniformity between batches is also a very important metric, data is sparse. The reader is also referred to recent publications as cited in this Topic for further review of state-of-the-art HTS fabrication and manufacturing trends.

While there are many areas of improvement and investigation associated with HTS that may be inextricably related, **the primary focus of this Topic is on novel fabrication methods for HTS tape or wire that can concurrently (i) increase the continuous tape or wire length, (ii) reduce the electrical variation along the tape or wire, and (iii) increase the overall production rate while (iv) significantly reducing the production costs and (v) maintaining a high level of tape performance characterized by $I_{c/w}$ and J_e**. Therefore, ARPA-E seeks proposals for novel scalable superconducting manufacturing methods that can increase the production rate of high-quality superconducting tapes or wires with uniform performance parameters.

A. Technical Areas of Interest

Technical areas of interest could include methods to improve the speed and quality of manufacturing with faster deposition, fabricate higher quality tapes with higher $I_{c/w}$ or J_e reduce processing steps, increase tape width, and/or reduce required chemical species and verifiably translate these improvements to tape production with clear reductions in cost by a factor 10x, per the Topic metrics, and an increase in production speed for a single production line. Applicants must discuss limiting factors that exist in today's production processes in their technical volume as well as how they propose to greatly improve those processes. In order to achieve the ambitious cost metric, such improvements should be for a single HTS tape or wire production line rather than counting on economies of scale with multiple production lines. Other manufacturing aspects such as reducing performance degradation due to axial strains, improving slitting processes and cable production methods, or expanding fabrication into multi-tape or multi-wire structures are also important for the overall performance in the different applications and should be considered as they relate to the Topic objectives or proving out the metrics; however, they should not be the singular focus of any proposal.

The areas of interest include novel manufacturing techniques and processes such as those discussed above that will demonstrably increase superconducting tape output from a single production line for tape operation either:

A. at high magnetic fields (10-20 T) in the temperatures range of 20-40 K, or
B. at low magnetic fields (< 1 T) in the temperatures range of 65-77 K accessible to liquid nitrogen.

B. Technical Performance Targets

Superconductor tape metrics and goals of this Topic are outlined in Table below. Every submission must describe how the proposed technology will be abel to comply with the metrics A.1-A.6 and report the remaining metrics in Table A. In addition, each submission must specify the intended application(s) and the associated, relevant metrics for the proposed technology and support these metrics via justifications in the body of their technical volume. The applicant should also describe how the tape will be handled and used in producing the final product(s) in the application of interest. In particular, the pathway to achieving the aggressive cost metric must be described in detail. If a metric is not considered or is changed from the Topic suggested goal, the applicant must describe in detail the reason for the omission or change, respectively. For example, if a tape has exceptional performance at 77 K, the applicant may be able to provide justification as to why a tape with lower critical current density at 20 T, 20 K should be acceptable or if the proposed solution is for wider tapes and/or those with higher ampacity, the applicant may be able to justify a lower production rate per year.

Table A. Comparison of the HTS tape manufacturing Topic goals and proposed solution.

ID	Performance parameter	Production-level SOA	Topic goals	Proposed solution and justification
A.1	Production Cost (in $/kA m)	100	< 10	
A.2	Continuous tape or wire length (m)	500	> 500	
A.3	Variation along continuous length of 300 m as percentage of A.5 or A.6	-	< 10%	
A.4	J_e (A/mm^2)*	~600	> 600	
A.5	$I_{c/w}$ (A/cm-width)*	~500	> 500	
A.6	Tape fabrication width pre-slitting (mm)	12	> 12	
A.7	Projected production rate for single process line (in km/year)	-	Applicant specified	
A.8	Magnetic Field (T)	0.01-20	Applicant specified	
A.9	Temperature (K)	20-77	Applicant specified	
A.10	Allowed compressive strain without degradation to I_c	1.25%	Applicant specified	
A.11	J_e consistency between 3 lots of 300 m (%)	-	Applicant specified	
A.12	HAZ, crack, or burr size due to slitting (µm)	10-50	Applicant specified	
A.13	SC epitaxial film growth rate (nm/s)	3-50	Applicant specified	
A.14	SC epitaxial layer thickness (µm)	1-5	Applicant specified	
A.15	Substrate thickness (µm)	30-50	Applicant specified	
A.16	Copper plating thickness (µm)	5-50	Applicant specified	

*at the temperatures and magnetic fields specified by the application in A.8 and A.9.

XVI. Appendix G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Production of Geologic Hydrogen Through Stimulated Mineralogical Processes

Topic Issue Date	September 7, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, October 13, 2023
Submission Deadline for Full Applications	9:30 AM ET, October 24, 2023
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, November 27, 2023
Expected Date for Selection Notifications	January 2024
Anticipated Date of Awards	April 2024
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$2,500,000.
Maximum Period of Performance	24 Months

1. Introduction

It is anticipated that hydrogen (H_2) will be critical to our efforts to mitigate the climate impact of our energy system through its use as a reductant or energy source in applications that have typically been served by fossil fuels. However, to have the desired climate impact, hydrogen must be produced via climate-neutral means. Current global hydrogen demand is approximately 100 million tonnes (Mt)/year, but the International Energy Agency's (IEA) Net Zero by 2050 Roadmap requires 500 Mt/year of hydrogen by 2050.[93] At present, steam methane reforming (SMR) is used to produce "gray" hydrogen at low cost ($1.50/kg) but generates ~10 kg CO_2/kg H_2. "Blue" (SMR with carbon capture) and "green" (renewable energy powered water electrolysis) hydrogen are more climate-neutral alternatives to "gray" hydrogen. "Blue" and "green" hydrogen are being actively pursued and estimated to cost $2.00+/kg and $3.00+/kg, respectively. In addition to producing hydrogen at a higher cost than traditional SMR, both have approach-specific challenges:

"Blue" Hydrogen:

- Storage of gigatonnes (Gt) of CO_2/year;

[93] Inflation Reduction Act of 2022

- Greenhouse gas (GHG) emissions through losses in carbon capture and upstream methane leaks corresponding to about 10% of that of "gray" hydrogen.

"Green" Hydrogen:

- Competition for carbon-free electricity with other decarbonization efforts, and overall emission mitigation will depend on the electricity supply;
- Critical mineral availability to meet requirements for both electrolyzer production and the wind/solar generation capacity to power it.

Thus, it is important to develop alternate routes to low cost (<\$1/kg H_2) and low emissions (<0.45 kg CO_2e/kg H_2) hydrogen.[94]

The subsurface continuously generates and consumes hydrogen through natural geochemical and biological processes.[95] There has been recent interest in the discovery of naturally accumulating deposits of subsurface hydrogen, such as efforts by the United States Geologic Survey (USGS).[96] Estimates vary from as little as 500,000 tonnes/year[97] to as much as billions of tonnes/year[98,99,100] of hydrogen being produced in the subsurface and accumulating in areas where mineralogical production processes are faster than consumptive biological processes. While the supply of naturally accumulating hydrogen, in and of itself, is potentially impactful on the U.S. energy economy, iron in the earth's crust has the theoretical potential to produce around 150,000 Gt H_2 from the reaction of Fe(II) within 3 km of the surface.[101] Exploiting a small percentage of this source through stimulated mineralogical processes could yield larger quantities of hydrogen than what are produced naturally. For reference, 1 Gt H_2 has enough energy to power the entire U.S. for a year.[102] Thus, engineering the production of subsurface hydrogen could potentially enable the production of substantial amounts of clean energy.

ARPA-E, under a combination of Exploratory Topics (ETs) G and H (hereinafter referred to as the Geologic H_2 effort), seeks to fund the development and validation of technologies that can stimulate the generation of hydrogen within the subsurface by enhancing/accelerating natural

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94 Hydrogen Shot | Department of Energy

95 N. Dopffel, B.A. An-Stepec, J.R. de Rezende, D.Z. Sousa and A. Koerdt, Editorial: Microbiology of underground hydrogen storage, (2023).

96 G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

97 B. Sherwood Lollar, T.C. Onstott, G. Lacrampe-Coulome, C.J. Ballantine. The contribution of Precambrian continental lithosphere to global H_2 production. *Nature.* **516**, 379–382 (2014).

98 E. Hand, Hidden hydrogen. *Science*. **379**, 630–636 (2023).

99 F. Klein, J.D. Tarnas, W. Bach, Abiotic sources of molecular hydrogen on earth. *Elements.* **16**, 19–24 (2020).

100 V. Zgonnik, The occurrence and geoscience of natural hydrogen: A comprehensive review. *Earth Sci Rev.* **203**, 103140 (2020).

101 G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

102 The lower heating value of H_2 is ~33 kWh/kg, 1 Gt of H would yield ~33,000 TWh (~112.6 quads, greater than U.S. energy consumption (EIA))

mineralogical processes. *Given the substantial resource potential of materials in the earth's crust, successful technologies developed under this new effort will lead to hydrogen production with the lowest cost (<$1 kg/$H_2$), emissions (<0.45 kg CO_2e/H_2), and resource consumption with minimal disruption to the surrounding environment.* This outcome supports the goals set for ARPA-E under 42 U.S.C. § 16538(c) to (1) reduce imports by minimizing the need for critical minerals for "green" hydrogen; (2) improve efficiency by utilizing hydrogen as a primary energy source for electricity (as opposed to as an energy carrier with a 30% energy loss); and (3) reduce emissions via the provision of ultra-low-GHG emission H_2.

ARPA-E seeks Full Applications to develop technologies that can lead to the production of stimulated geologic hydrogen at low cost and with low emissions. The Agency is specifically interested in:

1. *ET G: Technologies that stimulate hydrogen production from mineral deposits found in the subsurface* including developing our understanding of hydrogen-producing geochemical reactions (*e.g.*, serpentinization) and of how to enhance or control the rate of hydrogen production through external stimuli (*e.g.*, physical, chemical, or biological), and
2. *ET H: Technologies relevant to the extraction of geologic hydrogen* including improvements in subsurface transport methods and engineered containment, reservoir monitoring and/or modeling during production and extraction (*e.g.*, strain, leakage, and/or other risks).

ARPA-E targets for geologic hydrogen production for this effort are provided in **Table 1**, with a more in-depth discussion of technological metrics that applicants must address in Section 4 of this ET.

Table 1. Overall ARPA-E Geologic H_2 targets for geologic hydrogen production.

Metric	Geologic H_2 Target
H_2 cost at the well-head	*<$1/kg H_2*
H_2 GHG *(from production)*	*<0.45 kg CO_2e/kg H_2*
Hydrogen purity	*>20% (volumetric) at the well-head*
Deposit potential	*>10 Mt H_2*
Deposit production *(from formation)*	*>1 million m^3/day H_2 (>30,000 tonnes/year H_2)*

2. Topic Description

Under the Geologic H_2 effort, ARPA-E seeks to fund the development and validation of technologies that can lead to the lowest cost and lowest GHG emission hydrogen from the subsurface. These ETs are interested in supporting the development of upstream technologies to the well-head.

This ET includes Category 1, understanding and controlling the stimulation process, and Category 2, developing tools to model, monitor, or mitigate geological processes and risks.

Engineering methods to economically extract the hydrogen through containment or separations is the focus of ET H: Subsurface Engineering for Hydrogen Reservoir Management. If successful, this effort could potentially enable the production of enough hydrogen to decarbonize the most challenging industries.

A. Topics of Interest

The following is a non-exhaustive list of technologies that are of interest for ET G. Applications can address one or more technologies:

- *Stimulation and generation:* Technologies which enhance the natural rate of serpentinization or other equivalent hydrogen producing geochemical reactions (*e.g.*, reduction of iron bearing minerals in banded iron formations, clinkers).
- *Modeling approaches:* Methods and tools to predict the viability of subsurface resources for stimulated hydrogen generation, inform reservoir management, or assist with stimulation efforts.
- *Characterization:* Methods and tools to map subsurface and ocean floor resources (*e.g.*, ultramafic formations or other candidate formations) and quantify physiochemical properties of interest, specifically total Fe content, Fe(II) concentration, Fe(II)/Fe(III) ratio, specific surface area, permeability, or other parameters relevant to stimulated hydrogen generation.

B. Topics Not of Interest

Applications that propose the following technology concepts may be deemed nonresponsive and may not be reviewed or considered:

- Methods focused on identifying, managing, and monitoring hydrogen reservoirs, as well as assessing the risk of hydrogen reservoir development. Proposals of this focus should apply to ET H: Subsurface Engineering for Hydrogen Reservoir Management.
- Gasification of existing hydrocarbon reserves in the subsurface (*e.g.*, coal, oil reserves).
- Subsurface conversion of methane into hydrogen.
- Technologies focused solely on extraction of naturally occurring/accumulating hydrogen.
- Methods of producing hydrogen that require carbon sequestration to meet the overall Geologic H_2 GHG target.
- Applications focused on generating subsurface hydrogen through electrolysis of water.
- Technologies that are fully mature in other sectors (*e.g.*, geothermal or oil and gas) and do not require substantial innovation to support subsurface hydrogen production.
- Subsequent applications and uses of hydrogen downstream of the well-head.
- Applications that do not address Category 1 (see Section 3. Technical Categories).

C. Technology-To-Market (T2M)

Current domestic hydrogen production is predominantly via SMR through merchant hydrogen producers. If the overall Geologic H_2 target of $1/kg H_2 can be reached, geologically produced hydrogen would be competitive in those markets.[103] Hydrogen demand could also evolve from local use opportunities to regional gathering, or as an input to other regional market opportunities (*e.g.*, petrochemical, ammonia, steelmaking).

For this ET, applicants should:

1. Identify a potential commercial pathway and commercial transition partners for their proposed work.
2. Show how their proposed technology contributes to meeting the overall Geologic H_2 targets for cost and emissions. The applicant should clearly identify the boundaries of their technology and provide a preliminary techno-economic assessment (TEA) and Life Cycle Assessment (LCA) in their Full Application. In their analysis or justification, applicants must show which current or conventional technologies can be directly implemented (known costs), as well as which novel technologies need to be developed (unknown costs).

3. Technical Categories

ARPA-E has identified two major technical categories. Category 1 is related to the investigation of stimulation methods to rapidly enhance the natural rate of hydrogen production from mineral sources. Category 2 is centered around the technology needed to manage the production of hydrogen through reaction modeling and monitoring.

Applications must address Category 1 and are also encouraged to address Category 2 as a complementary category to Category 1.

A. Category 1 – Stimulation

This category is focused on developing methods to enhance, control, and sustain serpentinization or other relevant processes for the generation of hydrogen, and is open to any approaches to do so in an economically feasible and sustainable way. Approaches of interest may be physical, chemical, thermal, or biological in nature, or any other approach. The final deliverable must include experimental data to show that the technology meets the overall Geologic H_2 and Category 1-specific performance targets. Computational models or simulation data are optional and encouraged.

The stimulation of subsurface hydrogen production represents a potentially much larger hydrogen source than the passive exploration/exploitation of naturally occurring hydrogen. With an average yield of 2-4 kgH_2/m^3 upon complete oxidation, the 10^{20} kg of ultramafic

[103] Inflation Reduction Act of 2022

peridotites in the earth's upper 7-km[104] of crust can generate up to 100 trillion tons of hydrogen, sufficient for 250,000 years at a rate of 400 Mt/yr. Additionally, these formations are annually refreshed at a rate of 10^{12} kg/yr through tectonic activity.[105] To stimulate the serpentinization for hydrogen production, water is injected *in situ* in identified reactive formations, from which hydrogen-saturated water can be collected from recovery wells surrounding the injection point.[106] It is estimated and supported by laboratory scale experiments that a rate of 0.1-3 MtH_2/yr for 1 km^3 of peridotite be achieved with >5 wt% Fe(II) concentration.[107] Furthermore, this process can be expanded to other rock formations that contain valuable elements (Li, Ni, Co) or *ex situ* sources (Fe-rich mine wastes and steel slags), as well as using seawater or wastewater for natural oxidation of iron. However, the engineering of serpentinization in ultramafic rocks and other hydrogen producing mineralogical processes is not well understood. Recent research has evaluated the equilibrium and kinetic dynamics of this process.[108,109]

B. Category 2 – Modeling and Characterization

This category is focused on methods to understand, predict, and monitor stimulated hydrogen using innovative modeling and characterization approaches. Proposals focused on predicting and evaluating the yield and scale of stimulation methods, as well as methods to monitor, characterize, and confirm stimulation production, are of particular interest for this category.

The subsurface dynamics of hydrogen are poorly understood. In addition, existing technologies and methods for characterizing the subsurface were originated in the oil and gas sector, where the needs are very different than stimulated H_2 generation. Oil and gas characterization and modeling methods are focused on interpreting fluid flow (*e.g.*, hydrocarbons, brine) in porous rocks (*e.g.*, sandstones, shales).[110] The subsurface generation mechanism of hydrogen is typically a mineralogical reaction, likely within crystalline rock, in which iron bearing minerals react with water to create gaseous phase hydrogen.[111] These processes are most observable in

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[104] P. B. Kelemen, J. Matter, E. E. Streit, J. F. Rudge, W. B. Curry, J. Blusztajn, Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO_2 Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545–576 (2011).
[105] P. B. Kelemen, J. Matter, E. E. Streit, J. F. Rudge, W. B. Curry, J. Blusztajn, Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO_2 Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545–576 (2011).
[106] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).
[107] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).
[108] T. M. McCollom, W. Bach, Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochim. Cosmochim. Acta*. **73**, 856–875 (2009).
[109] F. Klein, W. Bach, T. M. McCollom, Compositional controls on hydrogen generation during serpentinization of ultramafic rocks. *Lithos*. **178**, 55–69 (2013).
[110] https://wiki.aapg.org/Overview_of_routine_core_analysis
[111] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).

extreme environments, such as tectonic subduction zones, but are still being investigated.[112] The nature of ultramafic rocks is very different from that of porous clastic rocks, necessitating new approaches to characterization and modeling.

Serpentinization (or an alternative hydrogen producing geochemical reaction) necessitates a focus on different physiochemical properties, such as total iron content, Fe(II)/Fe(III) ratio, and specific surface area. Methods to characterize and map these properties that pertain to the proposed stimulation methods as well as methods to model and predict engineered mineralogical processes of interest are needed to make stimulated geologic hydrogen a viable and responsibly exploited energy source.

4. Technical Performance Targets

Under the Geologic H_2 effort, ARPA-E intends to support the development of technologies that can lead to future hydrogen production safely and responsibly at lower cost and GHG emissions when compared to current state of the art (*e.g.*, hydrogen produced from SMR, SMR with sequestration, electrolysis). Proposed methods and technologies are required to meet the overall Geologic H_2 targets (**see items Pa-Pe below**).

In addition to the overall Geologic H_2 targets *(i.e.*, those targets applicable to both ET G and ET H), proposed methods and technologies will also be required to meet category-specific targets:

Geologic H_2 Effort

The proposed model, method, or technology must be able to do one or more of the following:

Pa. Produce H_2 with a cost at the well-head of *\$1/kg H_2.*

Pb. Produce H_2 with GHG/kg H_2 of *<1 kg CO_2e/kg H_2.*

Pc. Produce H_2 with a purity of *>20% at the well-head (note – alternates can be proposed if an easy-to-separate sweeping gas is employed and justified in the Application).*

Pd. Enable H_2 deposit exploitation with a potential of *>10 Mt H_2.*

Pe. Enable H_2 deposit production of *>1 million m^3 H_2.*

ET G Category 1. Stimulation

The proposed method or technology must be able to do one or more of the following:

[112] Worman, S. L., Pratson, L. F., Karson, J. A., and Schlesinger, W. H. (2020). Abiotic hydrogen (H2) sources and sinks near the Mid-Ocean Ridge (MOR) with implications for the subseafloor biosphere. PNAS 117, 13283–13293. doi:10.1073/pnas.2002619117

1a. Increase ~~reaction~~ serpentinization rate by *>10^5×* over the rate found in the native ore being evaluated at an equivalent starting *T* and *P* (*e.g.*, rate from the Samail ophiolite, Oman reported as 8×10^{-14} s^{-1}).[113]

1b. Increase the rate of other target H_2 producing mineralogical processes to produce a *comparable amount of H_2 to* ***1a.***

ET G Category 2. Modeling/Characterization
The proposed model, method, or technology must be able to do one or more of the following:

2a. Experimentally show ways to accurately quantify Fe(II), the Fe(II)/Fe(III) ratio, and the total Fe of target candidate formations.

2b. Experimentally show models that can predict H_2 stimulation using methods proposed in **Cat. 1**.

5. Data Rights and Sharing

Awardees under this ET will be strongly encouraged to share data with one or more select ARPA-E awardees who will use the data as inputs to generate publicly available models or tools that can be used to generate outputs such as life cycle analysis that will facilitate commercial acceptance of the technologies in this ET. Shared data may include, but is not limited to, mineral composition, conditions of the reaction, kinetics of hydrogen formation, and any underlying components or inputs for a technoeconomic or life-cycle analysis.

An awardee that receives data from another awardee will be required to treat any data provided to them as confidential information unless this requirement is altered by written agreement between them and the awardee that provided the data. The awardee receiving data will be required to treat all data generated under their award as trade secret-like for 10 years subject to a mutually agreed upon list of data that may be publicly released at any time. Such a publicly releasable list will not include data that is specifically identifiable with an awardee that provided data. Data provided by one awardee to another will not be shared by the awardee receiving the data with any other awardee. Similarly, an awardee that receives data from another awardee will not share with any other awardee data they generate that is related to the awardee that provided the data.

6. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Topic G. All other instructions set forth at FOA Section IV.C remain unchanged.

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[113] J. A. Leong, M. Nielsen, N. McQueen, R. Karolyte, D. J. Hillegonds, C. Ballentine, T. Darrah, W. McGillis, P. B. Kelemen, H_2 and CH_4 outgassing rates in the Samail ophiolite, Oman: Implications for low-temperature, continental serpentinization rates. *Geochim. Cosmochim. Acta* **347**, 1–15 (2023).

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

XVII. Appendix H: Subsurface Engineering for Hydrogen Reservoir Management

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Subsurface Engineering for Hydrogen Reservoir Management

Topic Issue Date	September 7, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, October 13, 2023
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Maximum Period of Performance	24 Months

1. Introduction

It is anticipated that hydrogen (H_2) will be critical to our efforts to mitigate the climate impact of our energy system through its use as a reductant or energy source in applications that have typically been served by fossil fuels. However, to have the desired climate impact, hydrogen must be produced via climate-neutral means. Current global hydrogen demand is approximately 100 million tonnes (Mt)/year, but the International Energy Agency's (IEA) Net Zero by 2050 Roadmap requires 500 Mt/year of hydrogen by 2050.[114] At present, steam methane reforming (SMR) is used to produce "gray" hydrogen at low cost ($1.50/kg) but generates ~10 kg CO_2/kg H_2. "Blue" (SMR with carbon capture) and "green" (renewable energy powered water electrolysis) hydrogen are more climate-neutral alternatives to "gray" hydrogen. "Blue" and "green" hydrogen are being actively pursued and estimated to cost $2.00+/kg and $3.00+/kg, respectively. In addition to producing hydrogen at a higher cost than traditional SMR, both have approach-specific challenges:

"Blue" Hydrogen:

- Storage of gigatonnes (Gt) of CO_2/year;

[114] Inflation Reduction Act of 2022

- Greenhouse gas (GHG) emissions through losses in carbon capture and upstream methane leaks corresponding to about 10% of that of "gray" hydrogen.

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- Competition for carbon-free electricity with other decarbonization efforts, and overall emission mitigation will depend on the electricity supply;
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Thus, it is important to develop alternate routes to low cost (<$1/kg H_2) and low emissions (<0.45 kg CO_2e/kg H_2) hydrogen.[115]

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ARPA-E, under a combination of Exploratory Topics (ETs) G and H (hereinafter referred to as the Geologic H_2 effort), seeks to fund the development and validation of technologies that can

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[115] Hydrogen Shot | Department of Energy

[116] N. Dopffel, B.A. An-Stepec, J.R. de Rezende, D.Z. Sousa and A. Koerdt, Editorial: Microbiology of underground hydrogen storage, (2023).

[117] G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

[118] B. Sherwood Lollar, T.C. Onstott, G. Lacrampe-Couloume, C.J. Ballantine. The contribution of Precambrian continental lithosphere to global H_2 production. *Nature.* **516**, 379–382 (2014).

[119] E. Hand, Hidden hydrogen. *Science*. **379**, 630–636 (2023).

[120] F. Klein, J.D. Tarnas, W. Bach, Abiotic sources of molecular hydrogen on earth. *Elements.* **16**, 19–24 (2020).

[121] V. Zgonnik, The occurrence and geoscience of natural hydrogen: A comprehensive review. *Earth Sci Rev.* **203**, 103140 (2020).

[122] G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

[123] The lower heating value of H_2 is ~33 kWh/kg, 1 Gt of H would yield ~33,000 TWh (~112.6 quads, greater than U.S. energy consumption (EIA))

stimulate the generation of hydrogen within the subsurface by enhancing/accelerating natural mineralogical processes. *Given the substantial resource potential of materials in the earth's crust, successful technologies developed under this new effort will lead to hydrogen production with the lowest cost (<$1 kg/$H_2$), emissions (<0.45 kg CO_2e/H_2), and resource consumption with minimal disruption to the surrounding environment.* This outcome supports the goals set for ARPA-E under 42 U.S.C. § 16538(c) to (1) reduce imports by minimizing the need for critical minerals for "green" hydrogen; (2) improve efficiency by utilizing hydrogen as a primary energy source for electricity (as opposed to as an energy carrier with a 30% energy loss); and (3) reduce emissions via the provision of ultra-low-GHG emission H_2.

ARPA-E seeks Full Applications to develop technologies that can lead to the production of stimulated geologic hydrogen at low cost and with low emissions. The Agency is specifically interested in:

1. *ET G: Technologies that stimulate hydrogen production from mineral deposits found in the subsurface* including developing our understanding of hydrogen-producing geochemical reactions (*e.g.*, serpentinization) and of how to enhance or control the rate of hydrogen production through external stimuli (*e.g.*, physical, chemical, or biological), and
2. *ET H: Technologies relevant to the extraction of geologic hydrogen* including improvements in subsurface transport methods and engineered containment, reservoir monitoring and/or modeling during production and extraction (*e.g.*, strain, leakage, and/or other risks).

ARPA-E targets for geologic hydrogen production for this effort are provided in **Table 1**, with a more in-depth discussion of technological metrics that applicants must address in Section 4 of this ET.

Table 1. Overall ARPA-E Geologic H_2 targets for geologic hydrogen production.

Metric	Geologic H_2 Target
H_2 cost at the well-head	*<$1/kg H_2*
H_2 GHG *(from production)*	*<0.45 kg CO_2e/kg H_2*
Hydrogen purity	*>20% (volumetric) at the well-head*
Deposit potential	*>10 Mt H_2*
Deposit production *(from formation)*	*>1 million m^3/day H_2 (>30,000 tonnes/year H_2)*

2. Topic Description

Under the Geologic H_2 effort, ARPA-E seeks to fund the development and validation of technologies that can lead to the lowest cost and lowest GHG emission hydrogen from the subsurface. These ETs are interested in supporting the development of upstream technologies to the well-head.

This ET includes Category 1, engineering of methods to economically extract the hydrogen through containment or separations; Category 2, developing tools to model, monitor, or mitigate geological processes; and Category 3, understanding environmental risks associated with geologic H_2 production (see Section 3, Technical Categories, for full details).

Understanding and controlling the hydrogen stimulation process is the focus of ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes. If successful, this effort could potentially enable the production of enough hydrogen to decarbonize the most challenging industries.

A. Topics of Interest

The following is a non-exhaustive list of technologies that are of interest for ET H. Applications can address one or more technologies:

- *Subsurface engineering:* Technologies which are related to engineering or creating subsurface hydrogen reservoirs, or technologies which can achieve a higher concentration/pressure of hydrogen prior to the well-head.
- *Down-hole gas separation:* Down-hole/upstream-of-well-head systems capable of separating gases to enable transport of higher purity hydrogen (in the case of production of coevolved or liberated gases). An example includes low cost, high flux, high selectivity membrane systems.
- *Risk mitigation methods:* Technologies that can predict, model, or prevent harmful side effects associated with enhanced stimulation of hydrogen generating mineralogical processes (*e.g.*, serpentinization of ultramafic rocks). Focus should be given to understanding and addressing volumetric expansion, seismicity, hydrogen leakage and associated impact on GHG emissions, biological effects, and subsurface contamination.
- *Modeling approaches:* Methods to predict the viability of subsurface resources for stimulated hydrogen generation, inform reservoir management, or assist with stimulation efforts.
- *Characterization:* Methods to map subsurface and ocean floor resources (*e.g.*, ultramafic formations or other candidate formations) and quantify physiochemical properties of interest, specifically total Fe content, Fe(II) concentration, Fe(II)/Fe(III) ratio, specific surface area, permeability, or other parameters relevant to stimulated hydrogen generation.

B. Topics Not of Interest

Applications that propose the following technology concepts may be deemed nonresponsive and may not be reviewed or considered:

- Methods focused on stimulation methods, such as enhanced serpentinization or other hydrogen generating processes, as well as modeling and characterization methods focused on predicting and monitoring the yield of these stimulation methods.

Applications of this focus should apply to ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

- Gasification of existing hydrocarbon reserves in the subsurface (*e.g.*, coal, oil reserves).
- Subsurface conversion of methane into hydrogen.
- Technologies focused solely on extraction of naturally occurring/accumulating hydrogen.
- Methods of producing hydrogen that require carbon sequestration to meet the overall Geologic H_2 GHG target.
- Applications focused on generating subsurface hydrogen through electrolysis of water.
- Technologies that are fully mature in other sectors (*e.g.*, geothermal or oil and gas) and do not require substantial innovation to support subsurface hydrogen production.
- Subsequent applications and uses of hydrogen downstream of the well-head.
- Applications that only address Category 2 and/or 3 (see Section 3. Technical Categories).

C. Technology-To-Market (T2M)

Current domestic hydrogen production is predominantly via SMR through merchant hydrogen producers. If the overall Geologic H_2 target of $1/kg H_2 can be reached, geologically produced hydrogen would be competitive in those markets.[124] Hydrogen demand could also evolve from local use opportunities to regional gathering, or as an input to other regional market opportunities (*e.g.*, petrochemical, ammonia, steelmaking).

For this ET, applicants should:

1. Identify a potential commercial pathway and commercial transition partners for their proposed work.
2. Show how their proposed technology contributes to meeting the overall Geologic H_2 targets for cost and emissions. The applicant should clearly identify the boundaries of their technology and provide a preliminary techno-economic assessment (TEA) and Life Cycle Assessment (LCA) in their Full Application. In their analysis or justification, applicants must show which current or conventional technologies can be directly implemented (known costs), as well as which novel technologies need to be developed (unknown costs).

3. Technical Categories

ARPA-E has identified three technical categories for this ET. Technical Category 1 deals with technologies in subsurface engineering, including ways to contain, concentrate, and economically transport hydrogen to the well-head. Category 2 is centered around the technologies needed to manage the production of hydrogen through monitoring, and Category 3 is centered around understanding and managing environmental risks associated with geologic

[124] Inflation Reduction Act of 2022

hydrogen production. Applications must address Category 1 and are also encouraged to address Category 2 and Category 3 as complementary categories to Category 1.

A. Category 1 – Economic Extraction and Subsurface Engineering

Category 1 is focused on developing ways to effectively extract and manage hydrogen production. Applications to this category should focus on developing innovative ways to support hydrogen reservoir management, including hydrogen containment, production, and extraction/transport to the surface.

Stimulating hydrogen generation from mineral deposits is very different from the production of hydrocarbons or geothermal resources. How to manage subsurface generation, containment, and extraction will require the development of new technologies—the priorities of which are so far undefined. Consequently, there is an identified need for engineering solutions that enable geologic hydrogen to be a viable and impactful energy resource.

Obtaining a high enough pressure of hydrogen at the well-head may be a critical factor governing the economics of stimulated geologic hydrogen if gas separations are required on the surface. Depending on the rate of hydrogen production, the extraction of hydrogen to the surface may not be straightforward. For example, steam could be one of the proposed stimulation methods and could ideally act as a hydrogen carrier. However, gaseous hydrogen solubility in water is very low, even at the high pressures and elevated temperatures found in the subsurface (<1 mol H_2/kg H_2O at pressures >1000 atm).[125] This solubility is further decreased by the addition of brines or salts, which would be in waste streams or leached during the pumping process. As an example, it would require >1 tonne of water for every kilogram of hydrogen, making it an unattractive transport modality.[126] Pumped-water transport would most likely only be economical in an enhanced geothermal operation where the pumped hot water or steam is already used to generate electricity and the hydrogen can be captured as an additional product. Thus, depending on the rates of stimulation, it may be necessary to concentrate and purify the hydrogen before the well-head, which can then be extracted on-demand when it is needed for energy.

Concentration of hydrogen may involve the identification, engineering, and/or creation of new geologic reservoirs to work with stimulated hydrogen generation. Several known geologic features are currently being explored for geologic hydrogen storage, but stimulated geologic hydrogen ideally would be agnostic to the existence of geologic features. This may be in the form of creating artificial subsurface reservoirs, like those currently deployed for pumped hydroelectric storage,[127] with engineered channels to control the flow of stimulated hydrogen. In addition, these efforts are critical to the mitigation of hydrogen or other GHGs produced from leaking into the atmosphere, as discussed in Category 3.1. In addition, it is possible that

[125] Z. Zhu, Y. Cao, Z. Zheng, D. Chen, An Accurate Model for Estimating H2 Solubility in Pure Water and Aqueous NaCl Solutions. *Energies*. **15**, 5021 (2022).
[126] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).
[127] Quidnetenergy.com

there can be some synergy with H_2 stimulation and CO_2 sequestration in ultramafic rocks and may aid in releasing reactive Fe(II) species.[128] However, mineralization of CO_2 may create geologic barriers to hydrogen diffusion, and the interaction between to-be mineralized CO_2 and hydrogen in the reservoir area can be significant.

Increasing the purity of the hydrogen at the well-head may require the development of down-hole separation systems where the hydrogen is separated from any other gaseous species (geology dependent, *e.g.*, CO_2, CH_4, N_2, H_2S, *etc.*). This can be in the form of a down-hole membrane system that accepts hydrogen as a permeate gas and rejects the other retentate gases into a separate reservoir (to not dilute the stimulated hydrogen further). Other methods which can economically extract the stimulated hydrogen with high enough purity and pressure would be of interest, including any chemical or material methods which can bind and release hydrogen.

B. Category 2 – Modeling and Characterization

Category 2 is focused on methods to monitor stimulated hydrogen production and inform reservoir management through the use of innovative modeling and characterization approaches. Applications focused on the preliminary identification of target reservoirs, characterization of ultramafic rocks or other formations of interest, geophysics-informed modeling and ongoing monitoring methods to manage risk assessment or inform management decisions are of particular interest for this category.

The subsurface dynamics of hydrogen are poorly understood. In addition, existing technologies and methods for characterizing the subsurface were originated in the oil and gas sector, where the needs are very different than stimulated H_2 generation. Oil and gas characterization and modeling methods are focused on interpreting fluid flow (*e.g.*, hydrocarbons, brine) in porous rocks (*e.g.*, sandstones, shales).[129] The subsurface generation mechanism of hydrogen is typically a mineralogical reaction, likely within crystalline rock, in which iron bearing minerals react with water to create gaseous phase hydrogen.[130] These processes are most observable in extreme environments, such as tectonic subduction zones, but are still being investigated.[131] The nature of ultramafic rocks is very different from that of porous clastic rocks, necessitating new approaches to characterization and modeling. Serpentinization (or an alternative hydrogen-producing geochemical reaction) necessitates a focus on different physiochemical properties, such as total iron content, Fe(II)/Fe(III) ratio, and specific surface area. Methods to characterize and map these properties for hydrogen producing reservoir management and

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[128] P. B. Kelemen, J. Matter, E. E. Streit, J. F. Rudge, W. B. Curry, J. Blusztajn, Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO $_2$ Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545–576 (2011).

[129] https://wiki.aapg.org/Overview_of_routine_core_analysis

[130] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).

[131] Worman, S. L., Pratson, L. F., Karson, J. A., and Schlesinger, W. H. (2020). Abiotic hydrogen (H2) sources and sinks near the Mid-Ocean Ridge (MOR) with implications for the subseafloor biosphere. PNAS 117, 13283–13293. doi:10.1073/pnas.2002619117x

methods to monitor and predict production are needed to make stimulated geologic hydrogen a viable and responsibly exploited energy source. In addition to informing subsurface engineering efforts aimed at producing hydrogen, monitoring and predicting the side effects (*e.g.*, hydrogen leakage, subsurface contamination, volume expansion, development of geomechanical stress and seismicity) of the processes used to stimulate hydrogen production are also necessary to help ensure the success of this effort.

C. Category 3 – Risk Management

The nascent nature of geologic hydrogen leads to potential risks, which may require new technological development for mitigation and monitoring. Some identified risks stem from the geophysical changes that occur, while others may be from unintended releases of materials/hydrogen through leaks caused by physical and chemical reactions.

1. Category 3.1 – Leakage/Greenhouse Gas Effects

This sub-category seeks to fund research associated with understanding and developing mitigation strategies to prevent the unintended release of hydrogen to the atmosphere.

Hydrogen is a GHG and its uncontrolled release into the atmosphere is a critical concern.[132] Hydrogen's small size, coupled with the natural stress areas in geologic structures, makes it such that leakage is impossible to contain completely. However, as the amount of hydrogen leakage is driven by the pressure of subsurface hydrogen, monitoring and controlling it will be critical to acceptable environmental and economic performance. This concentration and pressure of hydrogen in the subsurface needs to be economic for extraction and further purification/use, but also cannot be so large that a high amount of leakage is found at the surface. Mitigating the release of stimulated geologic hydrogen or other natural accumulations of hydrogen into the atmosphere requires low leakage containment reservoirs (previously discussed in **Cat. 1**) and/or bio-remediation efforts for microbial consumption of any leaking hydrogen. The mitigation of hydrogen leakage may also require development of sensitive downhole sensors.

2. Category 3.2 – Subsurface Contamination

This sub-category is focused on understanding, preventing, and mitigating the threat of subsurface contamination resulting from stimulated hydrogen production. Applications should focus on subsurface contamination issues specific to the production of stimulated hydrogen through serpentinization of ultramafic rocks or proposed in complementary ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

The serpentinization and flushing of the subsurface with water (or other fluids) has the potential to leech out toxic metals or radioactive materials previously mineralized within a

[132] Environmental Defense Fund, 2022, (STUDY: Emissions of Hydrogen Could Undermine Its Climate Benefits). https://www.edf.org/media/study-emissions-hydrogen-could-undermine-its-climate-benefits-warming-effects-are-two-six

target formation.[133] If pumped water is used as a partial carrier of hydrogen gas, sensing technologies are needed to detect low concentrations of contaminants. If the pumped fluid is recycled back into the ground, interference with aquifers will need to be closely monitored to ensure that there is no contamination. In contrast, if stimulation uses an alternative mechanism that does not involve pumping water to the surface, the containment technology must prevent the migration of contaminants to aquifers or other sources which can lead to the surface. It may also be possible for toxic metals to be re-mineralized with CO_2 in areas that are not being stimulated.

3. Category 3.3 – Seismicity

This sub-category is focused on understanding, preventing, and mitigating the risk associated with volume expansion and associated seismicity resulting from enhanced serpentinization or other proposed mechanisms for stimulated hydrogen, as proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

Research focused on this subcategory should develop understanding of this risk and, where possible, propose and develop risk mitigation approaches.

Current literature reports that the serpentinization reaction can cause a volume expansion in the oxidized state by as much as 50%.[134,135] Thus, it is necessary for both safety (induced seismicity) but also for the well-controlled production of hydrogen to continuously monitor the volume changes associated with any stimulated reaction. This can be partially mitigated at the laboratory-scale by determining the conditions at which excess strain is generated within ore bodies. In addition, new methods and technologies need to be developed to predict volumetric expansion and associated risks. These advances may come in the form of new sensors (such as optimized distributed fiber optic sensing) that can measure the strain tensor or modeling efforts to predict volume expansion in advance of stimulated hydrogen production efforts. The development of any technology addressing this should be highly correlated with efforts that seek to model the stimulation process.

4. Category 3.4 – Biological Effects

This sub-category is focused on understanding, preventing, and mitigating the risks posed to the microbiome, and near surface ecology more generally, associated with enriched or depleted hydrogen concentrations.

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[133] Environmental Protection Agency, (Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)). https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm

[134] E.B. Alexander, J. DuShey, Topographic and soil differences from peridotite to serpentinite, Geomorphology, 135(3–4), 2011, 271-276.

[135] Malvoisin et al., Control of serpentinisation rate by reaction-induced cracking. Earth and Planetary Science Letters, 476, 2017, 143–152.

Hydrogen is an electron donor for subsurface bacteria and archaea, henceforth called microorganisms.[136] Thus, elevated hydrogen concentrations, through artificial stimulation, can promote the growth of these microbial communities, which can result in adverse effects on gas injectivity and extraction, reduction in hydrogen volume, and corrosion of metal infrastructure.[137] Additionally, the supply of hydrogen via natural serpentinization can lead to the growth of previously absent microbial communities and lead to adverse, unintended ecological effects.[138,139,140] Consequently, new research is needed to fully understand and determine the relation of these microbial communities to subsurface hydrogen dynamics with a focus on minimizing the ecological and microbial impacts from stimulated hydrogen production.

4. Technical Performance Targets

Under the Geologic H_2 effort, ARPA-E intends to support the development of technologies that can lead to future hydrogen production safely and responsibly at lower cost and GHG emissions when compared to current state of the art (*e.g.*, hydrogen produced from SMR, SMR with sequestration, electrolysis). Proposed methods and technologies are required to meet the overall Geologic H_2 targets (**see items Pa-Pe below**).

In addition to the overall Geologic H_2 targets (*i.e*., those targets applicable to both ET G and ET H), proposed methods and technologies will also be required to meet category-specific targets:

Geologic H_2 Effort

The proposed model, method, or technology must be able to do one or more of the following:

Pa. Produce H_2 with a cost at the well-head of *\$1/kg H_2.*

Pb. Produce H_2 with GHG/kg H_2 of *<1 kg CO_2e/kg H_2.*

Pc. Produce H_2 with a purity of *>20% at the well-head (note – alternates can be proposed if an easy-to-separate sweeping gas is employed and justified in the Application).*

Pd. Enable H_2 deposit exploitation with a potential of *>10 Mt H_2.*

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[136] N. Dopffel, B.A. An-Stepec, J.R. de Rezende, D.Z. Sousa and A. Koerdt, Editorial: Microbiology of underground hydrogen storage, (2023).

[137] E. M. Thaysen, S. McMahon, G. J. Strobel, I. B. Butler, B. T. Ngwenya, N. Heinemann, M. Wilkinson, A. Hassanpouryouzband, C. I. McDermott, K. Edlmann, Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. *Renew. Sustain. Energy Rev.* **151**, 111481 (2021).

[138] D. S. Kelley, J. A. Karson, G. L. Früh-Green, D. R. Yoerger, T. M. Shank, D. A. Butterfield, J. M. Hayes, M. O. Schrenk, E. J. Olson, G. Proskurowski, M. Jakuba, A. Bradley, B. Larson, K. Ludwig, D. Glickson, K. Buckman, A. S. Bradley, W. J. Brazelton, K. Roe, M. J. Elend, A. Delacour, S. M. Bernasconi, M. D. Lilley, J. A. Baross, R. E. Summons, S. P. Sylva, A Serpentinite-Hosted Ecosystem: The Lost City Hydrothermal Field. *Science*. **307**, 1428–1434 (2005).

[139] W. J. Brazelton, M. O. Schrenk, D. S. Kelley, J. A. Baross, Methane- and Sulfur-Metabolizing Microbial Communities Dominate the Lost City Hydrothermal Field Ecosystem. *Appl. Environ. Microbiol.* **72**, 6257–6270 (2006).

[140] M. O. Schrenk, W. J. Brazelton, S. Q. Lang, Serpentinization, Carbon, and Deep Life. *Rev. Mineral. Geochem.* **75**, 575–606 (2013).

Pe. Enable H_2 deposit production of *>1 million m^3 H_2.*

ET H Category 1. Economic Extraction and Subsurface Engineering

The proposed method or technology must be able to do one or more of the following:

1a. Experimentally show the potential to transport H_2 to the well-head with a purity of *>20% by volume* (or at a justified concentration that is economical for conventional gas separation methods).

1b. Enable the subsurface enhancement of H_2 concentration from natural accumulations up to *66% H_2 at ~10 atm* (based on proposed geologic hydrogen storage targets).[141]

1c. Experimentally show sustained and controlled production from target stimulation method with a *loss of output <25% over 1 month* (equivalent to hypothetical production loss of ~3 months of unconventional natural gas production).[142]

ET H Category 2. Modeling/Characterization

The proposed model, method, or technology must be able to do one or more of the following:

2a. Increase the success of finding enhanced serpentinization candidate formations.

2b. Decrease field work for delineating enhanced serpentinization candidate formations by *10× (e.g., 10× reduction in time, labor, cost, or other relevant parameters as interpreted by the applicant).*

2c. Increase the success of finding other H_2 producing stimulation candidate formations that do not proceed through serpentinization.

2d. Decrease field work for delineating other target H_2 producing stimulation candidate formations *comparable to **3b.***

2e. Experimentally show ways to accurately characterize pore spaces of ultramafic rocks, such as the quantification of porosity and specific surface area *(i.e., porosity<8%).*

2f. Experimentally show ways to accurately measure matrix permeability of ultramafic rocks *(i.e., $<10^{-15}$ m^2).*

2g. Experimentally show ways to accurately quantify Fe(II), Fe(II)/Fe(III) ratio, and total Fe of target candidate formations.

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[141] R.K. Ahluwali, D.D. Papadias, J-K. Peng, H.S. Roh, System Level Analysis on Hydrogen Storage Options, U.S. DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting. Project ID: ST001, (2019).

[142] https://geology.com/royalty/production-decline.shtml

ET H Category 3. Risk Management

The proposed model, method, or technology must be able to do one or more of the following:

3a. Predict volume expansion for enhanced H_2 producing mineralogical processes based on stimulation methods proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes (enhanced serpentinization of ultramafic rocks or *other* proposed method).

3b. Model induced seismicity associated with H_2 stimulation methods proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes (enhanced serpentinization of ultramafic rocks or other proposed method).

3c. Develop a list of critical ecological indicators (*i.e.*, microbiomes, flora, fauna) and quantify how each of them is impacted from hydrogen leakage and depletion in situ and at surface environments. Develop methods for determining the impact range of hydrogen leakage, monitoring the ecological indicators, and mitigating biotic effects on hydrogen yield and leakage.

3d. Investigate ways to mitigate subsurface contamination associated with methods proposed in **Cat. 1** or **2.1** (enhanced serpentinization of ultramafic rocks or other proposed method).

5. Data Rights and Sharing

Awardees under this ET will be strongly encouraged to share data with one or more select ARPA-E awardees who will use the data as inputs to generate publicly available models or tools that can be used to generate outputs such as life cycle analysis that will facilitate commercial acceptance of the technologies in this ET. Shared data may include, but is not limited to, hydrogen concentration, purification, containment, and extraction (including any input data for technoeconomic and life-cycle analyses, such as efficiency, energy, kinetics, etc.).

An awardee that receives data from another awardee will be required to treat any data provided to them as confidential information unless this requirement is altered by written agreement between them and the awardee that provided the data. The awardee receiving data will be required to treat all data generated under their award as trade secret-like for 10 years subject to a mutually agreed upon list of data that may be publicly released at any time. Such a publicly releasable list will not include data that is specifically identifiable with an awardee that provided data. Data provided by one awardee to another will not be shared by the awardee receiving the data with any other awardee. Similarly, an awardee that receives data from another awardee will not share with any other awardee data they generate that is related to the awardee that provided the data.

6. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Topic H. All other instructions set forth at FOA Section IV.C remain unchanged.

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Subsurface Engineering for Hydrogen Reservoir Management

Topic Issue Date	September 7, 2023
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, October 13, 2023
Submission Deadline for Full Applications	9:30 AM ET, October 24, 2023
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, November 27, 2023
Expected Date for Selection Notifications	January 2024
Anticipated Date of Awards	April 2024
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$2,500,000.
Maximum Period of Performance	24 Months

1. Introduction

It is anticipated that hydrogen (H_2) will be critical to our efforts to mitigate the climate impact of our energy system through its use as a reductant or energy source in applications that have typically been served by fossil fuels. However, to have the desired climate impact, hydrogen must be produced via climate-neutral means. Current global hydrogen demand is approximately 100 million tonnes (Mt)/year, but the International Energy Agency's (IEA) Net Zero by 2050 Roadmap requires 500 Mt/year of hydrogen by 2050.[143] At present, steam methane reforming (SMR) is used to produce "gray" hydrogen at low cost ($1.50/kg) but generates ~10 kg CO_2/kg H_2. "Blue" (SMR with carbon capture) and "green" (renewable energy powered water electrolysis) hydrogen are more climate-neutral alternatives to "gray" hydrogen. "Blue" and "green" hydrogen are being actively pursued and estimated to cost $2.00+/kg and $3.00+/kg, respectively. In addition to producing hydrogen at a higher cost than traditional SMR, both have approach-specific challenges:

"Blue" Hydrogen:

- Storage of gigatonnes (Gt) of CO_2/year;

[143] Inflation Reduction Act of 2022

- Greenhouse gas (GHG) emissions through losses in carbon capture and upstream methane leaks corresponding to about 10% of that of "gray" hydrogen.

"Green" Hydrogen:

- Competition for carbon-free electricity with other decarbonization efforts, and overall emission mitigation will depend on the electricity supply;
- Critical mineral availability to meet requirements for both electrolyzer production and the wind/solar generation capacity to power it.

Thus, it is important to develop alternate routes to low cost (<$1/kg H_2) and low emissions (<0.45 kg CO_2e/kg H_2) hydrogen.[144]

The subsurface continuously generates and consumes hydrogen through natural geochemical and biological processes.[145] There has been recent interest in the discovery of naturally accumulating deposits of subsurface hydrogen, such as efforts by the United States Geologic Survey (USGS).[146] Estimates vary from as little as 500,000 tonnes/year[147] to as much as billions of tonnes/year[148,149,150] of hydrogen being produced in the subsurface and accumulating in areas where mineralogical production processes are faster than consumptive biological processes. While the supply of naturally accumulating hydrogen, in and of itself, is potentially impactful on the U.S. energy economy, iron in the earth's crust has the theoretical potential to produce around 150,000 Gt H_2 from the reaction of Fe(II) within 3 km of the surface.[151] Exploiting a small percentage of this source through stimulated mineralogical processes could yield larger quantities of hydrogen than what are produced naturally. For reference, 1 Gt H_2 has enough energy to power the entire U.S. for a year.[152] Thus, engineering the production of subsurface hydrogen could potentially enable the production of substantial amounts of clean energy.

ARPA-E, under a combination of Exploratory Topics (ETs) G and H (hereinafter referred to as the Geologic H_2 effort), seeks to fund the development and validation of technologies that can

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[144] [Hydrogen Shot | Department of Energy]()

[145] N. Dopffel, B.A. An-Stepec, J.R. de Rezende, D.Z. Sousa and A. Koerdt, Editorial: Microbiology of underground hydrogen storage, (2023).

[146] G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

[147] B. Sherwood Lollar, T.C. Onstott, G. Lacrampe-Coulome, C.J. Ballantine. The contribution of Precambrian continental lithosphere to global H_2 production. *Nature.* **516**, 379–382 (2014).

[148] E. Hand, Hidden hydrogen. *Science*. **379**, 630–636 (2023).

[149] F. Klein, J.D. Tarnas, W. Bach, Abiotic sources of molecular hydrogen on earth. *Elements.* **16**, 19–24 (2020).

[150] V. Zgonnik, The occurrence and geoscience of natural hydrogen: A comprehensive review. *Earth Sci Rev.* **203**, 103140 (2020).

[151] G.S. Ellis and S.E. Gelman, A preliminary model of global subsurface natural hydrogen resource potential, Geological Society of America Annual Meeting October 9-12, 2022, Denver, Colorado, Geological Society of America Abstracts with Programs, v. 54, no. 5. https://doi.org/10.1130/abs/2022AM-380270.

[152] The lower heating value of H_2 is ~33 kWh/kg, 1 Gt of H would yield ~33,000 TWh (~112.6 quads, greater than U.S. energy consumption (EIA))

stimulate the generation of hydrogen within the subsurface by enhancing/accelerating natural mineralogical processes. *Given the substantial resource potential of materials in the earth's crust, successful technologies developed under this new effort will lead to hydrogen production with the lowest cost (<$1 kg/$H_2$), emissions (<0.45 kg CO_2e/H_2), and resource consumption with minimal disruption to the surrounding environment.* This outcome supports the goals set for ARPA-E under 42 U.S.C. § 16538(c) to (1) reduce imports by minimizing the need for critical minerals for "green" hydrogen; (2) improve efficiency by utilizing hydrogen as a primary energy source for electricity (as opposed to as an energy carrier with a 30% energy loss); and (3) reduce emissions via the provision of ultra-low-GHG emission H_2.

ARPA-E seeks Full Applications to develop technologies that can lead to the production of stimulated geologic hydrogen at low cost and with low emissions. The Agency is specifically interested in:

3. *ET G: Technologies that stimulate hydrogen production from mineral deposits found in the subsurface* including developing our understanding of hydrogen-producing geochemical reactions (*e.g.*, serpentinization) and of how to enhance or control the rate of hydrogen production through external stimuli (*e.g.*, physical, chemical, or biological), and
4. *ET H: Technologies relevant to the extraction of geologic hydrogen* including improvements in subsurface transport methods and engineered containment, reservoir monitoring and/or modeling during production and extraction (*e.g.*, strain, leakage, and/or other risks).

ARPA-E targets for geologic hydrogen production for this effort are provided in **Table 1**, with a more in-depth discussion of technological metrics that applicants must address in Section 4 of this ET.

Table 1. Overall ARPA-E Geologic H_2 targets for geologic hydrogen production.

Metric	Geologic H_2 Target
H_2 cost at the well-head	*<$1/kg H_2*
H_2 GHG *(from production)*	*<0.45 kg CO_2e/kg H_2*
Hydrogen purity	*>20% (volumetric) at the well-head*
Deposit potential	*>10 Mt H_2*
Deposit production *(from formation)*	*>1 million m^3/day H_2 (>30,000 tonnes/year H_2)*

2. Topic Description

Under the Geologic H_2 effort, ARPA-E seeks to fund the development and validation of technologies that can lead to the lowest cost and lowest GHG emission hydrogen from the subsurface. These ETs are interested in supporting the development of upstream technologies to the well-head.

This ET includes Category 1, engineering of methods to economically extract the hydrogen through containment or separations; Category 2, developing tools to model, monitor, or mitigate geological processes; and Category 3, understanding environmental risks associated with geologic H_2 production (see Section 3, Technical Categories, for full details).

Understanding and controlling the hydrogen stimulation process is the focus of ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes. If successful, this effort could potentially enable the production of enough hydrogen to decarbonize the most challenging industries.

A. Topics of Interest

The following is a non-exhaustive list of technologies that are of interest for ET H. Applications can address one or more technologies:

- *Subsurface engineering:* Technologies which are related to engineering or creating subsurface hydrogen reservoirs, or technologies which can achieve a higher concentration/pressure of hydrogen prior to the well-head.
- *Down-hole gas separation:* Down-hole/upstream-of-well-head systems capable of separating gases to enable transport of higher purity hydrogen (in the case of production of coevolved or liberated gases). An example includes low cost, high flux, high selectivity membrane systems.
- *Risk mitigation methods:* Technologies that can predict, model, or prevent harmful side effects associated with enhanced stimulation of hydrogen generating mineralogical processes (*e.g.*, serpentinization of ultramafic rocks). Focus should be given to understanding and addressing volumetric expansion, seismicity, hydrogen leakage and associated impact on GHG emissions, biological effects, and subsurface contamination.
- *Modeling approaches:* Methods to predict the viability of subsurface resources for stimulated hydrogen generation, inform reservoir management, or assist with stimulation efforts.
- *Characterization:* Methods to map subsurface and ocean floor resources (*e.g.*, ultramafic formations or other candidate formations) and quantify physiochemical properties of interest, specifically total Fe content, Fe(II) concentration, Fe(II)/Fe(III) ratio, specific surface area, permeability, or other parameters relevant to stimulated hydrogen generation.

B. Topics Not of Interest

Applications that propose the following technology concepts may be deemed nonresponsive and may not be reviewed or considered:

- Methods focused on stimulation methods, such as enhanced serpentinization or other hydrogen generating processes, as well as modeling and characterization methods focused on predicting and monitoring the yield of these stimulation methods.

Applications of this focus should apply to ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

- Gasification of existing hydrocarbon reserves in the subsurface (*e.g.*, coal, oil reserves).
- Subsurface conversion of methane into hydrogen.
- Technologies focused solely on extraction of naturally occurring/accumulating hydrogen.
- Methods of producing hydrogen that require carbon sequestration to meet the overall Geologic H_2 GHG target.
- Applications focused on generating subsurface hydrogen through electrolysis of water.
- Technologies that are fully mature in other sectors (*e.g.*, geothermal or oil and gas) and do not require substantial innovation to support subsurface hydrogen production.
- Subsequent applications and uses of hydrogen downstream of the well-head.
- Applications that only address Category 2 and/or 3 (see Section 3. Technical Categories).

C. Technology-To-Market (T2M)

Current domestic hydrogen production is predominantly via SMR through merchant hydrogen producers. If the overall Geologic H_2 target of $1/kg H_2 can be reached, geologically produced hydrogen would be competitive in those markets.[153] Hydrogen demand could also evolve from local use opportunities to regional gathering, or as an input to other regional market opportunities (*e.g.*, petrochemical, ammonia, steelmaking).

For this ET, applicants should:

3. Identify a potential commercial pathway and commercial transition partners for their proposed work.
4. Show how their proposed technology contributes to meeting the overall Geologic H_2 targets for cost and emissions. The applicant should clearly identify the boundaries of their technology and provide a preliminary techno-economic assessment (TEA) and Life Cycle Assessment (LCA) in their Full Application. In their analysis or justification, applicants must show which current or conventional technologies can be directly implemented (known costs), as well as which novel technologies need to be developed (unknown costs).

3. Technical Categories

ARPA-E has identified three technical categories for this ET. Technical Category 1 deals with technologies in subsurface engineering, including ways to contain, concentrate, and economically transport hydrogen to the well-head. Category 2 is centered around the technologies needed to manage the production of hydrogen through monitoring, and Category 3 is centered around understanding and managing environmental risks associated with geologic

[153] Inflation Reduction Act of 2022

hydrogen production. Applications must address Category 1 and are also encouraged to address Category 2 and Category 3 as complementary categories to Category 1.

A. Category 1 – Economic Extraction and Subsurface Engineering

Category 1 is focused on developing ways to effectively extract and manage hydrogen production. Applications to this category should focus on developing innovative ways to support hydrogen reservoir management, including hydrogen containment, production, and extraction/transport to the surface.

Stimulating hydrogen generation from mineral deposits is very different from the production of hydrocarbons or geothermal resources. How to manage subsurface generation, containment, and extraction will require the development of new technologies—the priorities of which are so far undefined. Consequently, there is an identified need for engineering solutions that enable geologic hydrogen to be a viable and impactful energy resource.

Obtaining a high enough pressure of hydrogen at the well-head may be a critical factor governing the economics of stimulated geologic hydrogen if gas separations are required on the surface. Depending on the rate of hydrogen production, the extraction of hydrogen to the surface may not be straightforward. For example, steam could be one of the proposed stimulation methods and could ideally act as a hydrogen carrier. However, gaseous hydrogen solubility in water is very low, even at the high pressures and elevated temperatures found in the subsurface (<1 mol H_2/kg H_2O at pressures >1000 atm).[154] This solubility is further decreased by the addition of brines or salts, which would be in waste streams or leached during the pumping process. As an example, it would require >1 tonne of water for every kilogram of hydrogen, making it an unattractive transport modality.[155] Pumped-water transport would most likely only be economical in an enhanced geothermal operation where the pumped hot water or steam is already used to generate electricity and the hydrogen can be captured as an additional product. Thus, depending on the rates of stimulation, it may be necessary to concentrate and purify the hydrogen before the well-head, which can then be extracted on-demand when it is needed for energy.

Concentration of hydrogen may involve the identification, engineering, and/or creation of new geologic reservoirs to work with stimulated hydrogen generation. Several known geologic features are currently being explored for geologic hydrogen storage, but stimulated geologic hydrogen ideally would be agnostic to the existence of geologic features. This may be in the form of creating artificial subsurface reservoirs, like those currently deployed for pumped hydroelectric storage,[156] with engineered channels to control the flow of stimulated hydrogen. In addition, these efforts are critical to the mitigation of hydrogen or other GHGs produced from leaking into the atmosphere, as discussed in Category 3.1. In addition, it is possible that

[154] Z. Zhu, Y. Cao, Z. Zheng, D. Chen, An Accurate Model for Estimating H2 Solubility in Pure Water and Aqueous NaCl Solutions. *Energies*. **15**, 5021 (2022).
[155] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).
[156] Quidnetenergy.com

there can be some synergy with H_2 stimulation and CO_2 sequestration in ultramafic rocks and may aid in releasing reactive Fe(II) species.[157] However, mineralization of CO_2 may create geologic barriers to hydrogen diffusion, and the interaction between to-be mineralized CO_2 and hydrogen in the reservoir area can be significant.

Increasing the purity of the hydrogen at the well-head may require the development of down-hole separation systems where the hydrogen is separated from any other gaseous species (geology dependent, *e.g.*, CO_2, CH_4, N_2, H_2S, *etc.*). This can be in the form of a down-hole membrane system that accepts hydrogen as a permeate gas and rejects the other retentate gases into a separate reservoir (to not dilute the stimulated hydrogen further). Other methods which can economically extract the stimulated hydrogen with high enough purity and pressure would be of interest, including any chemical or material methods which can bind and release hydrogen.

B. Category 2 – Modeling and Characterization

Category 2 is focused on methods to monitor stimulated hydrogen production and inform reservoir management through the use of innovative modeling and characterization approaches. Applications focused on the preliminary identification of target reservoirs, characterization of ultramafic rocks or other formations of interest, geophysics-informed modeling and ongoing monitoring methods to manage risk assessment or inform management decisions are of particular interest for this category.

The subsurface dynamics of hydrogen are poorly understood. In addition, existing technologies and methods for characterizing the subsurface were originated in the oil and gas sector, where the needs are very different than stimulated H_2 generation. Oil and gas characterization and modeling methods are focused on interpreting fluid flow (*e.g.*, hydrocarbons, brine) in porous rocks (*e.g.*, sandstones, shales).[158] The subsurface generation mechanism of hydrogen is typically a mineralogical reaction, likely within crystalline rock, in which iron bearing minerals react with water to create gaseous phase hydrogen.[159] These processes are most observable in extreme environments, such as tectonic subduction zones, but are still being investigated.[160] The nature of ultramafic rocks is very different from that of porous clastic rocks, necessitating new approaches to characterization and modeling. Serpentinization (or an alternative hydrogen-producing geochemical reaction) necessitates a focus on different physiochemical properties, such as total iron content, Fe(II)/Fe(III) ratio, and specific surface area. Methods to characterize and map these properties for hydrogen producing reservoir management and

[157] P. B. Kelemen, J. Matter, E. E. Streit, J. F. Rudge, W. B. Curry, J. Blusztajn, Rates and Mechanisms of Mineral Carbonation in Peridotite: Natural Processes and Recipes for Enhanced, in situ CO_2 Capture and Storage. *Annu. Rev. Earth Planet. Sci.* **39**, 545–576 (2011).
[158] https://wiki.aapg.org/Overview_of_routine_core_analysis
[159] F. Osselin, C. Soulaine, C. Fauguerolles, E. C. Gaucher, B. Scaillet, M. Pichavant, Orange hydrogen is the new green. *Nat. Geosci.* **15**, 765–769 (2022).
[160] Worman, S. L., Pratson, L. F., Karson, J. A., and Schlesinger, W. H. (2020). Abiotic hydrogen (H2) sources and sinks near the Mid-Ocean Ridge (MOR) with implications for the subseafloor biosphere. PNAS 117, 13283–13293. doi:10.1073/pnas.2002619117x

methods to monitor and predict production are needed to make stimulated geologic hydrogen a viable and responsibly exploited energy source. In addition to informing subsurface engineering efforts aimed at producing hydrogen, monitoring and predicting the side effects (*e.g.*, hydrogen leakage, subsurface contamination, volume expansion, development of geomechanical stress and seismicity) of the processes used to stimulate hydrogen production are also necessary to help ensure the success of this effort.

C. Category 3 – Risk Management

The nascent nature of geologic hydrogen leads to potential risks, which may require new technological development for mitigation and monitoring. Some identified risks stem from the geophysical changes that occur, while others may be from unintended releases of materials/hydrogen through leaks caused by physical and chemical reactions.

5. Category 3.1 – Leakage/Greenhouse Gas Effects

This sub-category seeks to fund research associated with understanding and developing mitigation strategies to prevent the unintended release of hydrogen to the atmosphere.

Hydrogen is a GHG and its uncontrolled release into the atmosphere is a critical concern.[161] Hydrogen's small size, coupled with the natural stress areas in geologic structures, makes it such that leakage is impossible to contain completely. However, as the amount of hydrogen leakage is driven by the pressure of subsurface hydrogen, monitoring and controlling it will be critical to acceptable environmental and economic performance. This concentration and pressure of hydrogen in the subsurface needs to be economic for extraction and further purification/use, but also cannot be so large that a high amount of leakage is found at the surface. Mitigating the release of stimulated geologic hydrogen or other natural accumulations of hydrogen into the atmosphere requires low leakage containment reservoirs (previously discussed in **Cat. 1**) and/or bio-remediation efforts for microbial consumption of any leaking hydrogen. The mitigation of hydrogen leakage may also require development of sensitive downhole sensors.

6. Category 3.2 – Subsurface Contamination

This sub-category is focused on understanding, preventing, and mitigating the threat of subsurface contamination resulting from stimulated hydrogen production. Applications should focus on subsurface contamination issues specific to the production of stimulated hydrogen through serpentinization of ultramafic rocks or proposed in complementary ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

The serpentinization and flushing of the subsurface with water (or other fluids) has the potential to leech out toxic metals or radioactive materials previously mineralized within a

[161] Environmental Defense Fund, 2022, (STUDY: Emissions of Hydrogen Could Undermine Its Climate Benefits). https://www.edf.org/media/study-emissions-hydrogen-could-undermine-its-climate-benefits-warming-effects-are-two-six

target formation.[162] If pumped water is used as a partial carrier of hydrogen gas, sensing technologies are needed to detect low concentrations of contaminants. If the pumped fluid is recycled back into the ground, interference with aquifers will need to be closely monitored to ensure that there is no contamination. In contrast, if stimulation uses an alternative mechanism that does not involve pumping water to the surface, the containment technology must prevent the migration of contaminants to aquifers or other sources which can lead to the surface. It may also be possible for toxic metals to be re-mineralized with CO_2 in areas that are not being stimulated.

7. Category 3.3 – Seismicity

This sub-category is focused on understanding, preventing, and mitigating the risk associated with volume expansion and associated seismicity resulting from enhanced serpentinization or other proposed mechanisms for stimulated hydrogen, as proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes.

Research focused on this subcategory should develop understanding of this risk and, where possible, propose and develop risk mitigation approaches.

Current literature reports that the serpentinization reaction can cause a volume expansion in the oxidized state by as much as 50%.[163,164] Thus, it is necessary for both safety (induced seismicity) but also for the well-controlled production of hydrogen to continuously monitor the volume changes associated with any stimulated reaction. This can be partially mitigated at the laboratory-scale by determining the conditions at which excess strain is generated within ore bodies. In addition, new methods and technologies need to be developed to predict volumetric expansion and associated risks. These advances may come in the form of new sensors (such as optimized distributed fiber optic sensing) that can measure the strain tensor or modeling efforts to predict volume expansion in advance of stimulated hydrogen production efforts. The development of any technology addressing this should be highly correlated with efforts that seek to model the stimulation process.

8. Category 3.4 – Biological Effects

This sub-category is focused on understanding, preventing, and mitigating the risks posed to the microbiome, and near surface ecology more generally, associated with enriched or depleted hydrogen concentrations.

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[162] Environmental Protection Agency, (Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)). https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm

[163] E.B. Alexander, J. DuShey, Topographic and soil differences from peridotite to serpentinite, Geomorphology, 135(3–4), 2011, 271-276.

[164] Malvoisin et al., Control of serpentinisation rate by reaction-induced cracking. Earth and Planetary Science Letters, 476, 2017, 143–152.

Hydrogen is an electron donor for subsurface bacteria and archaea, henceforth called microorganisms.[165] Thus, elevated hydrogen concentrations, through artificial stimulation, can promote the growth of these microbial communities, which can result in adverse effects on gas injectivity and extraction, reduction in hydrogen volume, and corrosion of metal infrastructure.[166] Additionally, the supply of hydrogen via natural serpentinization can lead to the growth of previously absent microbial communities and lead to adverse, unintended ecological effects.[167,168,169] Consequently, new research is needed to fully understand and determine the relation of these microbial communities to subsurface hydrogen dynamics with a focus on minimizing the ecological and microbial impacts from stimulated hydrogen production.

4. Technical Performance Targets

Under the Geologic H_2 effort, ARPA-E intends to support the development of technologies that can lead to future hydrogen production safely and responsibly at lower cost and GHG emissions when compared to current state of the art (*e.g.*, hydrogen produced from SMR, SMR with sequestration, electrolysis). Proposed methods and technologies are required to meet the overall Geologic H_2 targets (**see items Pa-Pe below**).

In addition to the overall Geologic H_2 targets (*i.e*., those targets applicable to both ET G and ET H), proposed methods and technologies will also be required to meet category-specific targets:

Geologic H_2 Effort

The proposed model, method, or technology must be able to do one or more of the following:

Pa. Produce H_2 with a cost at the well-head of *\$1/kg H_2.*

Pb. Produce H_2 with GHG/kg H_2 of *<1 kg CO_2e/kg H_2.*

Pc. Produce H_2 with a purity of *>20% at the well-head (note – alternates can be proposed if an easy-to-separate sweeping gas is employed and justified in the Application).*

Pd. Enable H_2 deposit exploitation with a potential of *>10 Mt H_2.*

[165] N. Dopffel, B.A. An-Stepec, J.R. de Rezende, D.Z. Sousa and A. Koerdt, Editorial: Microbiology of underground hydrogen storage, (2023).

[166] E. M. Thaysen, S. McMahon, G. J. Strobel, I. B. Butler, B. T. Ngwenya, N. Heinemann, M. Wilkinson, A. Hassanpouryouzband, C. I. McDermott, K. Edlmann, Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. *Renew. Sustain. Energy Rev.* **151**, 111481 (2021).

[167] D. S. Kelley, J. A. Karson, G. L. Früh-Green, D. R. Yoerger, T. M. Shank, D. A. Butterfield, J. M. Hayes, M. O. Schrenk, E. J. Olson, G. Proskurowski, M. Jakuba, A. Bradley, B. Larson, K. Ludwig, D. Glickson, K. Buckman, A. S. Bradley, W. J. Brazelton, K. Roe, M. J. Elend, A. Delacour, S. M. Bernasconi, M. D. Lilley, J. A. Baross, R. E. Summons, S. P. Sylva, A Serpentinite-Hosted Ecosystem: The Lost City Hydrothermal Field. *Science*. **307**, 1428–1434 (2005).

[168] W. J. Brazelton, M. O. Schrenk, D. S. Kelley, J. A. Baross, Methane- and Sulfur-Metabolizing Microbial Communities Dominate the Lost City Hydrothermal Field Ecosystem. *Appl. Environ. Microbiol.* **72**, 6257–6270 (2006).

[169] M. O. Schrenk, W. J. Brazelton, S. Q. Lang, Serpentinization, Carbon, and Deep Life. *Rev. Mineral. Geochem.* **75**, 575–606 (2013).

Pe. Enable H_2 deposit production of *>1 million m^3 H_2.*

ET H Category 1. Economic Extraction and Subsurface Engineering
The proposed method or technology must be able to do one or more of the following:

1a. Experimentally show the potential to transport H_2 to the well-head with a purity of *>20% by volume* (or at a justified concentration that is economical for conventional gas separation methods).

1b. Enable the subsurface enhancement of H_2 concentration from natural accumulations up to *66% H_2 at ~10 atm* (based on proposed geologic hydrogen storage targets).[170]

1c. Experimentally show sustained and controlled production from target stimulation method with a *loss of output <25% over 1 month* (equivalent to hypothetical production loss of ~3 months of unconventional natural gas production).[171]

ET H Category 2. Modeling/Characterization
The proposed model, method, or technology must be able to do one or more of the following:

2a. Increase the success of finding enhanced serpentinization candidate formations.

2b. Decrease field work for delineating enhanced serpentinization candidate formations by *10× (e.g., 10× reduction in time, labor, cost, or other relevant parameters as interpreted by the applicant).*

2c. Increase the success of finding other H_2 producing stimulation candidate formations that do not proceed through serpentinization.

2d. Decrease field work for delineating other target H_2 producing stimulation candidate formations *comparable to **3b.***

2e. Experimentally show ways to accurately characterize pore spaces of ultramafic rocks, such as the quantification of porosity and specific surface area *(i.e., porosity<8%).*

2f. Experimentally show ways to accurately measure matrix permeability of ultramafic rocks *(i.e., <10^{-15} m^2).*

2g. Experimentally show ways to accurately quantify Fe(II), Fe(II)/Fe(III) ratio, and total Fe of target candidate formations.

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[170] R.K. Ahluwali, D.D. Papadias, J-K. Peng, H.S. Roh, System Level Analysis on Hydrogen Storage Options, U.S. DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting. Project ID: ST001, (2019).
[171] https://geology.com/royalty/production-decline.shtml

ET H Category 3. Risk Management

The proposed model, method, or technology must be able to do one or more of the following:

3a. Predict volume expansion for enhanced H_2 producing mineralogical processes based on stimulation methods proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes (enhanced serpentinization of ultramafic rocks or *other* proposed method).

3b. Model induced seismicity associated with H_2 stimulation methods proposed in ET G: Production of Geologic Hydrogen Through Stimulated Mineralogical Processes (enhanced serpentinization of ultramafic rocks or other proposed method).

3c. Develop a list of critical ecological indicators (*i.e.*, microbiomes, flora, fauna) and quantify how each of them is impacted from hydrogen leakage and depletion in situ and at surface environments. Develop methods for determining the impact range of hydrogen leakage, monitoring the ecological indicators, and mitigating biotic effects on hydrogen yield and leakage.

3d. Investigate ways to mitigate subsurface contamination associated with methods proposed in **Cat. 1** or **2.1** (enhanced serpentinization of ultramafic rocks or other proposed method).

5. Data Rights and Sharing

Awardees under this ET will be strongly encouraged to share data with one or more select ARPA-E awardees who will use the data as inputs to generate publicly available models or tools that can be used to generate outputs such as life cycle analysis that will facilitate commercial acceptance of the technologies in this ET. Shared data may include, but is not limited to, hydrogen concentration, purification, containment, and extraction (including any input data for technoeconomic and life-cycle analyses, such as efficiency, energy, kinetics, etc.).

An awardee that receives data from another awardee will be required to treat any data provided to them as confidential information unless this requirement is altered by written agreement between them and the awardee that provided the data. The awardee receiving data will be required to treat all data generated under their award as trade secret-like for 10 years subject to a mutually agreed upon list of data that may be publicly released at any time. Such a publicly releasable list will not include data that is specifically identifiable with an awardee that provided data. Data provided by one awardee to another will not be shared by the awardee receiving the data with any other awardee. Similarly, an awardee that receives data from another awardee will not share with any other awardee data they generate that is related to the awardee that provided the data.

6. Content and Form of Full Applications

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Topic H. All other instructions set forth at FOA Section IV.C remain unchanged.

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

XVIII. Appendix I: Field Evaluations of Vehicle Energy Efficiency for NEXTCAR Phase II Technologies

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0002784)
Field Evaluations of Vehicle Energy Efficiency for NEXTCAR Phase II Technologies

Topic Issue Date	March 11, 2024
Deadline for Questions to ARPA-E-CO@hq.doe.gov	April 1, 2024
Submission Deadline for Full Applications	9:30 AM ET, April 10, 2024
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, April 16, 2024
Expected Date for Selection Notifications	May 2024
Total Amount to be Awarded	Approximately $2,500,000 subject to the availability of appropriated funds
Anticipated Awards	ARPA-E may issue one or no awards under this FOA. Awards may vary between $500,000 and $2,500,000.
Maximum Period of Performance	12 months

1. Introduction

This announcement describes an Exploratory Topic (ET) on "Field Evaluations of Vehicle Energy Efficiency for NEXTCAR Phase II Technologies." ARPA-E invites Full Applications to conduct testing and validation of energy savings improvements through connected and autonomous vehicle (CAV) technologies developed under Phase II of the ARPA-E NEXT generation energy technologies for Connected and Automated on-Road vehicles (NEXTCAR) Program.[172] A goal of this ET is to support further quantification of the energy benefits of eco-driving applications over realistic real-world driving and dynamic operational scenarios that can inform development of future energy efficiency criteria for these technologies.

Team(s) funded through this announcement will provide a physical test facility, develop relevant augmented reality scenarios to complement on-track testing, and host an on-site event in Fall 2024 to evaluate the energy efficiency improvements of Society of Automotive Engineers (SAE) J3016 [173] Level 4-capable NEXTCAR Phase II light-duty vehicles. Institutions currently serving as prime recipients/lead institutions of a NEXTCAR Phase II award are not eligible to apply to this Exploratory Topic.

[172] NEXTCAR | Arpa-e.Energy.Gov.
[173] "J3016_202104: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles - SAE International."

2. Topic Description

A. Background

The automotive sector accounts for 21% of total national energy use, with light-duty passenger vehicles accounting for 54% of that total in 2021, or 12% of total U.S. energy consumption. [174] For many years, the automotive industry has developed a range of vehicle energy efficiency technologies, including engine downsizing and boosting, vehicle light-weighting, aerodynamic improvements, rolling resistance reduction, engine efficiency improvements, waste heat recovery, auxiliary and parasitic load reduction, transmission improvements, hybridization, and electrification. While vehicle efficiency has increased as automakers have implemented these advancements to maintain compliance with federal standards, vehicle miles traveled have also increased year over year, from approximately 2.5 trillion miles per month in 1997 to 3.2 trillion miles/month at the end of 2021.[175]

In addition to the transition toward powertrain electrification, automotive transportation is in the midst of further disruption as automated driving technologies (i.e., advanced driver assistance systems) increasingly integrate into the vehicle fleet, along with useful on-board information being made available through connectivity (i.e., vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-everything (V2X)). While the primary objective of automating the driving task is to increase vehicle safety,[176] vehicle dynamic controls and powertrain operation can be further optimized for energy efficiency improvements as well. Real-time vehicle-level dynamic control and powertrain calibration can be further enabled through information obtained from connectivity (e.g., preview and lookahead of route characteristics, indications of traffic density and speed, signal phase timing).

B. ARPA-E NEXTCAR Program Overview

The ARPA-E NEXTCAR Program has experimentally shown energy efficiency improvements of 20% in aggregate compared to 2016-2017 baseline (i.e., SAE J3016 Level 0[177]) vehicles for a variety of duty cycles, driving operations, and maneuvers through the development and implementation of co-optimized advanced vehicle dynamic and powertrain control technologies using connectivity and SAE J3016 Level 1 through Level 3 of automation (see **Figure 1**).

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[174] "Use of Energy for Transportation - U.S. Energy Information Administration (EIA)."
[175] "Figure 1 - Moving 12-Month Total on All Roads - December 2021 - Policy | Federal Highway Administration."
[176] Masello et al., "On the Road Safety Benefits of Advanced Driver Assistance Systems in Different Driving Contexts."
[177] J3016_202104: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles - SAE International

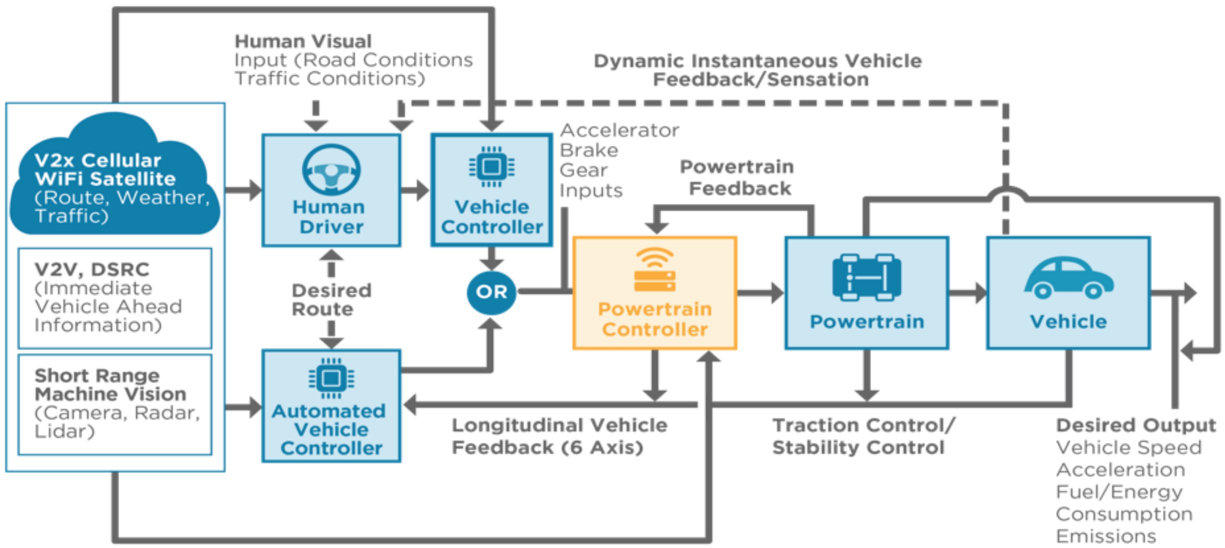

Figure 1. Schematic of powertrain and vehicle control with NEXTCAR technologies

Phase I of NEXTCAR focused on the development of transformative vehicle dynamic and powertrain (VD&PT) control technological solutions for use in all vehicle classes, including cars, trucks, and buses. Its goal was to of enable a 20% reduction in the energy consumption of future CAVs, compared to vehicles without these VD&PT control technologies. The teams moving on to Phase II of NEXTCAR are building on these goals with a specific focus on light-duty passenger vehicles, to achieve 10% reduction in energy consumption in addition to the 20% reductions achieved in Phase I. Teams in Phase II are taking vehicles to Level 4 of automation, where a vehicle can perform all driving operations on its own with optional human override.

The four NEXTCAR Phase II teams are led by Michigan Technological University (MTU), Ohio State University (OSU), Southwest Research Institute (SwRI), and the University of California-Berkeley (UCB).[178] Phase I technologies across all teams that are advancing to Phase II include eco-approach and departure at signalized intersections application (i.e. eco-AND), eco-driving, and powertrain optimization.[179] Platooning,[180] as well as eco-routing, including eco-fleet and multi-lane operation, are also being extended from Phase I by a subset of teams. Cooperative merging and intelligent parking and charging are being newly explored in Phase II. To test the claims associated with Phase II NEXTCAR technologies, an appropriate test environment is needed to facilitate Field Evaluations. This ET seeks applications that can develop the necessary capabilities to support NEXTCAR Phase II Field Evaluations which will culminate in a NEXTCAR Phase II Field Day at project end.

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[178] "NEXTCAR Phase II Project Descriptions | Arpa-e.Energy.Gov."
[179] Including road surface profiling. For ICVs and HEVs – Improvements to vehicle efficiency is derived through powertrain control optimization (including efficient modal selection) for internal combustion engines and hybrid electric vehicles. For HEVs and BEVs – Improvements to vehicle efficiency and drive range through battery state of charge optimization over a full trip for plug-in hybrid electric and battery electric vehicles.
[180] Including advanced vehicle positioning.

Each NEXTCAR Phase II project team has retrofitted their respective vehicles with a diverse array of connected and automated vehicle hardware and software. This significant effort includes the integration of various rapid prototyping testing tools alongside distinct simulation tools, culminating in unique vehicle-in-loop architectures for developing and testing energy-saving technologies across teams. Despite the uniqueness of each team's architecture, ARPA-E has identified notable commonalities between some of the vehicle-in-loop architectures. For instance, multiple teams utilized Space MicroAutobox III and Simulink within their rapid prototype testing architectures. Multiple teams also integrated traffic simulation tools such as VISSIM and SUMO within their vehicle-in-loop architecture.

To prevent duplication of effort and capitalize on the identified commonalities in existing testing architectures, ARPA-E requires the engagement of a specialized testing facility that has demonstrated the ability to support and test novel, cutting-edge technologies in the vehicles it tests. In particular, this facility must have demonstrable prior experience with NEXTCAR-developed technologies.

C. Technical Areas of Interest

Energy efficiency technologies that leverage CAV capabilities, such as those developed by the NEXTCAR Program, typically fall outside the U.S. Environmental Protection Agency (EPA) drive cycles used to evaluate vehicle energy efficiency. There are gaps in the EPA drive cycles which are geared towards Level 0 vehicle operation and prescribe vehicle trajectories and speed for every second of that trajectory to uniformly evaluate operation across all vehicles and vehicle types.[181] Energy saving technologies that rely on real-time optimization of the vehicle's trajectory in response to world driving criteria, such as traffic conditions, traffic signs and signals, turns, and driver behavior cannot be tested using these cycles. Further development is necessary to uniformly evaluate and quantify potential energy savings from CAV technologies as these vehicles become more integrated into the overall fleet.

This ET invites Full Applications to quantify the energy efficiency of NEXTCAR Phase II technologies by developing an augmented reality, vehicle-in-the-loop, testing system that can integrate a synchronized virtual environment into a real vehicle, performing testing in a simplified track environment, and guaranteeing the correlation between physical and virtual vehicle positioning. The specific needs of the testing and track environments are detailed in Tasks 1, 2, and 3 (see below). In addition, the applicant must become well-versed in the technologies created by each of the NEXTCAR Phase II teams to devising a series of driving scenarios that not only simulate but closely resemble real-world driving situations. These scenarios should incorporate elements such as the movement of nearby traffic, the geometric design of roadways, and the operation of traffic signals, among others. Such attention to detail is crucial to ensure these scenarios accurately reflect the complexities of real driving conditions and offer opportunities to verify the energy savings reported by the NEXTCAR Phase II teams. The selected field evaluation team(s) are not expected to provide SAE Level 4 CAVs for testing.

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[181] "Dynamometer Drive Schedules | US EPA." FTP UDDS @75 °F, FTP UDDS @20 °F, HWFET @75 °F, US06 @75 °F, and SC03 @95 °F.

Rather, they will need to provide a test environment, including physical and digital infrastructure where the NEXTCAR Phase II vehicles can be evaluated.

Detailed augmented reality simulation scenarios should be designed for the selected test location and include a variety of traffic conditions and maneuvers. Driving scenarios need to be crafted for both freeway and urban arterial functional road classifications. It is further expected that existing software interfaces are leveraged to show compatibility with the NEXTCAR Phase II teams.

ARPA-E anticipates that driving scenarios and simulations developed through this solicitation could further focus CAV research efforts. For example, quantifying CAV energy savings potential could clear the pathways to future regulatory credits and compliance. As such, simulated routes should also address gaps in drive cycle testing around real-world driving conditions and behavior to be relevant for future market-wide adoption.

Submitted applications should respond to the following four interrelated tasks (see **Figure 2**).

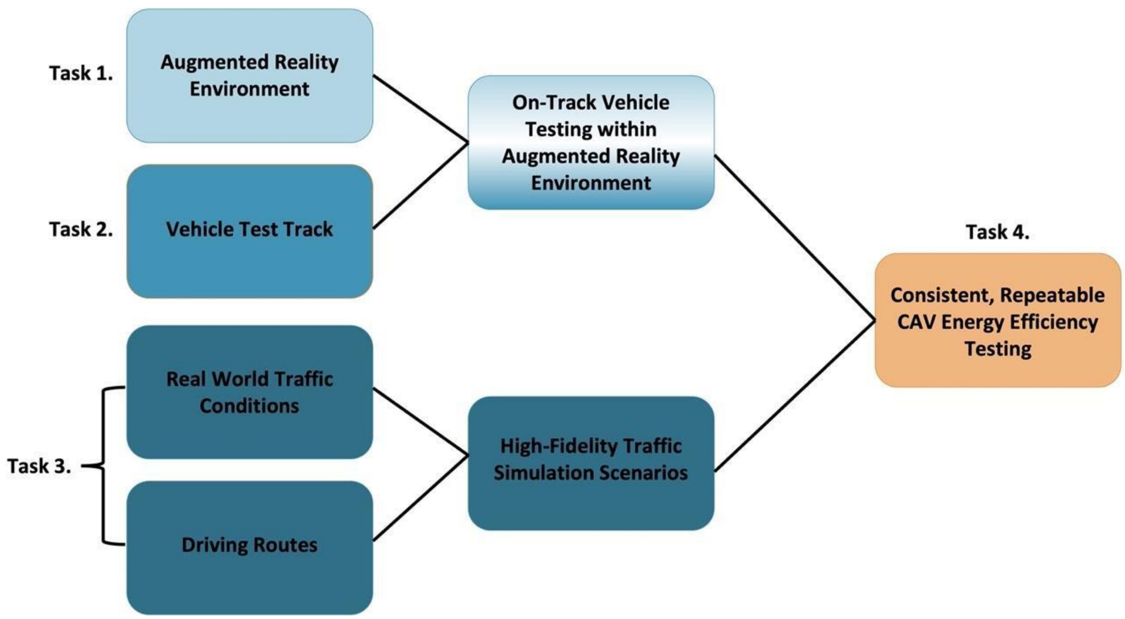

Figure 2. Schematic of overall task breakdown

1. **Task 1. Augmented reality environment**

The proposed augmented reality environment should leverage existing simulation tools or tools that are in development to streamline and accelerate the overall development process.[182] Applications should, as applicable, conduct an initial determination of the feasibility of

[182] Examples include the U.S. Department of Energy Oak Ridge National Laboratory Real-Sim platform: Shao, Y., Deter, D., Cook, A., Wang, C. et al., "Real-Sim Interface: Enabling Multi-resolution Simulation and X-in-the-Loop Development for Connected and Automated Vehicles," *SAE Intl. J CAV* 5(4):327-339, 2022, https://doi.org/10.4271/12-05-04-0026 and Real-Twin platform.

implementing available open-source cooperative driving automation platforms from the U.S. Department of Transportation.[183]

In addition to leveraging simulation tools that have shown the best performance for modeling traffic movement on freeways, arterials, and city intersections, the proposed augmented reality environment will also need to prove compatibility with NEXTCAR on-track testing and software interfaces. As such, the selected entity is expected to gain a comprehensive understanding of the tools and methodologies being employed by each of the four NEXTCAR Phase II teams in the development of their respective individual on-track testing environments. Applicants should describe their strategy for coordinating with each of the teams to assess the presence and functionality of augmented reality systems within their individual testing environments for compatibility with the unified on-track augmented reality testing environment that will be developed through this ET.

Applicants should also describe how the augmented reality environment they develop will enable NEXTCAR Phase II vehicles to complete the proposed driving route and be evaluated against traffic conditions without the liability and uncertainty that would surround relying only on physical on-road testing. The proposed approach should also offer consistency and comparability between a baseline and SAE Level 4-capable test vehicles, referred to as ego-vehicles. When navigating a specific scenario, it is essential that both types of vehicles encounter identical traffic flow and traffic signal timings along the selected route. Therefore, the platform's ability to accurately replicate the scenario, including providing consistent traffic conditions and replicating the same random seed numbers across all simulation components that inherit randomness, is critical. This precise replication enables the same vehicle to be operated first as a baseline vehicle and subsequently as a test vehicle, separately.

Simulation results will not necessarily need to be visually overlayed onto the user's view of the real-world environment, but views of both must be visible to observers and safety drivers. Ideally, heads up displays or other methods to visually combine virtual and real worlds should be used to allow for vehicle baseline testing during human driver operation. Applicants can also consider alternative methods, such as presenting the simulation results on a screen inside the vehicle. Ultimately, views of both worlds must be visible to observers and safety drivers. Applicants should collaborate with the NEXTCAR teams to clearly outline their approach for designing baseline tests that utilize each NEXTCAR Phase II vehicle.

The final version of the augmented reality environment should be scalable, with the capacity to integrate multiple actual vehicles and accommodate various study areas. For instance, the environment should have the capability to support real vehicles operating in a platoon that utilizes a Cooperative Adaptive Cruise Control (CACC)application. The environment should also be capable of communicating Basic Safety Messages (BSM), Map Data (MAP) and Signal Phase

[183] CARMA[SM] Program https://highways.dot.gov/research/operations/CARMA; Virtual Open Innovation Collaborative Environment for Safety (VOICES) https://www.transportation.gov/hasscoe/voices.

and Timing Message (SPaT) 'equivalent' information to the ego vehicle based on virtual traffic scenarios.

2. Task 2. Physical Test Track

Access to an existing CAV closed-track test facility (see requirements in Section D below) with adequate roadway to perform freeway (i.e., up to 65 mph) and urban arterial city driving routes will be necessary. The proposed location will also need to be equipped with digital and physical infrastructure for performing on-track augmented reality testing. Applicants should describe their capability for hosting a field day testing event at their facility to evaluate the energy performance of the NEXTCAR Phase II vehicles as part of the culmination of the Program. The testing facility will need to have the capacity to host 60 attendees (see Table 1). Test track viewing facilities should also allow observers to follow the vehicle's progress within the augmented reality environment directly or by streaming. Real-world testing and traffic simulation should be easily viewable by all live participants.

Applicants should include a plan for providing the necessary computing and Dedicated Short-Range Communications (DSRC) infrastructure in the creation of the augmented reality environment, described in Task 1. Behavior of real-world vehicles at the test site and simulated vehicles in the traffic simulation must be linked so that the real world vehicles can "participate" in the traffic simulation and receive BSM, MAP, and SPaT messages of the simulation environment. It is also expected that the selected entity will leverage the existing on-board units of the NEXTCAR Phase II vehicles to connect the vehicles of each of the four teams to the on-track testing environment. The selected entity may need to equip some of the NEXTCAR Phase II teams with hardware or integration equipment required to utilize the physical facility and/or augmented reality environment.

3. Task 3. Driving Scenarios

High-fidelity traffic simulations that accurately reflect real-world driving situations and road conditions will need to be developed within the augmented reality environment. These simulations are intended to identify potential energy savings through technologies developed by each NEXTCAR team. Distinct scenarios will be designed for freeway and urban arterial settings. These scenarios will serve to assess the effectiveness of eco-driving applications developed during NEXTCAR Phase II. The energy efficiency of these applications will be tested on SAE Level 4-capable vehicles by comparing their performance to that of a standard SAE Level 0 vehicle. The comparison will involve switching off the Level 4 technology suite and operating the vehicle as if it were Level 0. Depending on the processing units available on each of the NEXTCAR Phase II team vehicles, the same scenario may also need to be designed in multiple working environments.

Applications should propose a technical approach to develop multiple driving scenarios within the augmented reality simulation that represent real-world scenarios with which to evaluate the energy efficiency of the NEXTCAR Phase II vehicles. A plan for designing driving scenarios that, at a minimum, incorporate the following Phase II maneuvers should also be included. Roundabouts and unprotected left turns are outside the scope of all listed maneuvers.

- Power split and model blending technologies
- Eco-approach and -departure at signalized intersections
- Urban eco-driving
- Platooning and cooperative adaptive cruise control on highways[184]
- Eco-lane changes
- Cooperative lane merging on highways
- Grade optimizer

The driving scenarios will be executed on the track of the identified facility within the augmented reality simulation platform. This platform will map the testing site to the virtual environment, and traffic will be simulated virtually. Applicants should include a rationale behind the proposed simulation environment relative to the test facility. The technical approach, at minimum, must explicitly address all factors in the following bulleted specification.

Driving Scenario Requirements:

- Driving route types (freeways and urban arterials): Maximum of four urban arterials routes and two freeway routes. The exact number and length of routes can be negotiated with the performer after reviewing the NEXTCAR teams' technologies;
- Speed limits, frequency of intersections, control methods, and other relevant factors to be immersed in the augmented reality environment such that the scenarios provide energy savings opportunities while presenting realistic driving conditions in urban and suburban locations;
- Details of the chosen driving routes, including their spatial and temporal dimensions, must be provided along with the rationale for these selections. The evaluation should focus on assessing the potential for energy savings and emission reductions for plug-in hybrid and battery electric vehicles;
- Longitudinal grades of the routes; and
- Justification for the maneuvers selected to evaluate the listed energy efficiency behaviors and their frequency.

Traffic Interaction Requirements:

- Utilized traffic infrastructure: Fixed traffic signals and others;
- Levels of traffic congestion to evaluate for each roadway type;
- Detail the behavior of the surrounding traffic to navigate;
- Data utilized to build scenario(s), including a detailed description of the anticipated input data set(s), and whether the applicant currently has access; and
- For each planned route, a variety of driving scenarios will be developed, reflecting different levels of traffic density and variations in traffic light patterns. The designer must employ

[184] Physical test vehicles may need to be provided by the test facility.

creativity to ensure these scenarios closely mimic actual traffic conditions and provide potential for energy efficiency improvements.

Additional Requirements:

- Provide a plan for NEXTCAR vehicle interfaces and integration;
- Provide supporting documentation and training for the NEXTCAR Phase II teams;
- Report on data sources used for scenario/simulation development;
- Explain the rationale behind chosen traffic conditions, traffic levels, vehicle maneuvers, and speed limits;
- Explain how the scenarios could apply to or enhance future CAV efficiency technologies.
- Outline the design document deliverable detailing the approach for diverse driving scenario identification; and
- Develop scenarios within augmented reality simulations to reflect real-world conditions for testing energy efficiency in Level 4 CAVs.

4. Task 4. Energy Efficiency Test Procedures

The selected entity will need to develop vehicle test procedures at their field test site and methods to quantify energy consumption of the NEXTCAR Phase II Level 4 vehicle, as well as its baseline version when operating as Level 0 vehicle with Level 4 features deactivated. As such, the proposed technical approach should account for blocking factors including variables like the time of day, atmospheric conditions, wind patterns and velocity, tire inflation levels, vehicular weight, and the battery's state of charge. A statistical methodology should be proposed to determine the number of runs needed per driving route to assess the difference between baseline vehicles and SAE J3016 Level 4 vehicles with an acceptable statistical confidence level. Applicants can design a testing methodology that spans multiple days instead of limiting testing to a single day. ARPA-E is focused on mitigating the impact of different blocking factors rather than evaluating energy savings under varying conditions caused by these factors. ARPA-E’s interest lies in ensuring that the influence of such variables is controlled and minimized when comparing baseline and test scenarios. Applications should also explain how repeatability will be achieved across the four NEXTCAR Phase II teams (i.e., vehicles and timeframes) to account for weather differences between runs and measurement of travel times for all trips under each driving scenario, along with a plan for mitigating any differences.

At the conclusion of the NEXTCAR Phase II Field Day, preparation of a final report is expected that analyzes the energy efficiency performance of the NEXTCAR technologies tested under the developed driving scenarios. As such, applications should include as part of their test plan a list of the results that are envisioned to be collected and reported to show the efficacies of the NEXTCAR Phase II technologies tested.

D. Test Requirements

The minimum facility requirements listed in Table 1 are intended to serve as an initial framework. In addition to hosting the NEXTCAR Phase II Field Day, the selected entity will need to budget for any additional time, equipment, and expertise that might be required to prepare the NEXTCAR Phase II team vehicles for testing both on the physical track facility and within the simulation environment (see Table 2 for possible user support requirements). As noted in Section C, the selected entity will also be encouraged to consider tools that can be easily integrated with the algorithms and on-board units of the NEXTCAR Phase II teams.

The testing facility must be centrally located within the United States. This central positioning is crucial to facilitate equitable access for all participating teams and stakeholders from different regions of the country. It is also imperative that the testing facility is accessible within a 1-hour drive from a major airport. This proximity ensures efficient and convenient travel for teams, especially for those requiring frequent in-person visits or transporting equipment and materials.

Applicants must have access to a testing facility equipped with advanced vehicle-in-the-loop (VIL) capabilities. The facility should be capable of simulating L4 autonomous vehicle (AV) environments and include augmented reality systems for realistic testing scenarios. The testing track must be equipped with high-fidelity sensors and data acquisition systems to accurately measure vehicle performance and energy savings.

Applicants should showcase a proven track record in the following areas:

- Conducting field tests for connected and automated vehicles (CAVs), with a particular focus on energy efficiency.
- Proficiency in using augmented reality systems, vehicle dynamics, energy systems, and CAV technologies.

Previous experience in testing energy consumption for electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) is mandatory. Only applications that demonstrate previous collaboration with industry, academia, government agencies, and specifically with NEXTCAR teams on similar projects will be considered. This criterion is to ensure the best applicant capable of leveraging commonalities between the existing testing methodologies of NEXTCAR teams to minimize testing cost will be selected.

Table 1 Facility Requirements

Category	Description
Physical Infrastructure	○ At least two miles of multi-lane arterial and five miles of multi-lane freeway for the design of driving scenarios. While the use of multiple laps is acceptable to achieve these values, any constraints considered (e.g., executing U-turns) should be clearly reported. ○ A garage capable of servicing all NEXTCAR teams where the teams can simultaneously perform on-site maintenance for any issues occurring during the Field Day testing. ○ Availability of the facility to NEXTCAR teams for use one week before and during field day testing, including nighttime access.
V2X Communication Capabilities	○ DSRC infrastructure that meet SAE J2945 requirements and can transmit both SPaT and MAP messages that meet SAE J2735 requirements.
Digital Infrastructure	○ High resolution site maps, Point Cloud Data, and HD maps. ○ Strong GPS/GNSS signal to support precise navigation using only GPS/GNSS technology (e.g., differential GPS/GNSS) without need for additional location tracking systems.
Test Vehicles	○ Two test vehicles, ideally an SUV, minivan, or full-size sedan, should be equipped to interface with the augmented reality setup and capable of transmitting BSM to the NEXTCAR ego vehicle for evaluating technologies like platooning, cooperative adaptive cruise control, and cooperative lane merging on highways.
Vehicle Efficiency Measurements	○ Energy and fuel measurement capability for NEXTCAR vehicles (kilowatt-hours, miles per gallon, miles per gallon equivalent). ○ Travel time measurement capability for trips performed by NEXTCAR vehicles.
Augmented Reality and Simulation	○ Ability to define multiple simulations of traffic and roadway users, including traffic signals, that mimic the same roadway geometry as the real-world test site. ○ Ability to simulate AV Level 4 sensors and operation. ○ Ability to integrate multiple signalized intersections into the augmented reality at variable locations and spacings. ○ Ability to track the position and velocity of real-world vehicles and adjust the behavior of actors in the simulation based on real-world vehicle actions. ○ Ability to simulate a range of low- to high-density traffic flow conditions with 100 milliseconds maximum latency.

Audience and Broadcasting	○ Ability to host 60 attendees. ○ Area for either direct test track viewing or streaming of the simulated vehicle that allows attendees to follow progress within the augmented reality environment. ○ Large screens or other similar broadcasting methods for attendees to be able to view the real-world testing and traffic simulation.
Additional Requirements	○ Measurement of local wind (i.e., velocity and direction) and ambient temperature. ○ Monitoring and recording instances of any safety violations made by the NEXTCAR vehicles (e.g., near crashes and running red lights). ○ Track access and management procedures to ensure safety.

Table 2 Potential User Support Requirements

	SwRI	OSU	UCB	MTU
Vehicle Model	• 2021 Honda Clarity Plug-in Hybrid	• 2021 Chrysler Pacifica Plug-in Hybrid	• 2023 Ioniq 5 Sel Electric AWD	• 2021 Chrysler Pacifica Plug-in Hybrid • 2019 Chevrolet Bolt Electric • 2020 RAM 1500 eTorque mild Hybrid
Powertrain Details	• 1.5-L L-4 DOHC 16V Hybrid: 103 hp • AC Permanent -Magnet Synchronous Electric Motor 181 hp [Main Traction motor]	• 260 hp 3.6L V6 Engine • Front Wheel Drive with eFlite Hybrid Electric Drivetrain	• AWD - Electric Motors (74 kW + 165 kW)	• Powersplit hybrid. 191 kW 3.6L V6 + 84 kW + 63 kW • 1Motor EV. 150 kW PM traction motor • Mild hybrid. 290 kW 5.7L V8 + 12 kW BAS
Battery Size	• 17 kWh • 6.6 kW Onboard 32-Amp charger	• 16kWh 360V Lithium-Ion Battery Pack	• 77.4 kWh	• 360 Volt, 16 kW-h • 360 Volt, 60 kW-h • 48 Volt, 0.43 kW-h

Driving Mode	• Sport, Deceleration Paddle Selectors, HV Mode, EV Mode, HV Charge Mode		• Eco Mode, Sport Mode, Normal Mode	• Drive, Low (higher regen rates) • Drive, Low. 2WD, 4WD high/low • Normal, Sport, One Pedal Driving, Regen on Demand
AV/CAV Hardware and Software Instrument-ation	• SwRI Ranger localization system • LIDAR and camera systems • Cohda DSRC radio • SwRI L4 autonomy stack	• dSPACE MicroAutoBox III • AutonomouStuff Spectra • AutonomouStuff Speed and Steering Controller (ROS-based) • New Eagle Drive-by-Wire System with Power Distribution Module • Cohda MK6 On-Board Unit (for V2V and V2I communication via DSRC) • CAV Sensors o 2 Cameras o1 32-bit LiDAR o1 Mobileye o1 Electronically Scanning Radar (ESR) o1 NovAtel Position Kit (GPS/IMU) • CARMA Messenger (support SAE-J2735 compliant DSRC communication) • Autoware.AI ROS-based Vehicle Automation Stack	• Linux Rugged Embedded PC • Cohda (for V2V and V2I comms via DSRC) • dGPS, Lidars, Camera • MicroAutoBox II	• DBW, Autoware.AI w/ LiDAR, RTK-GPS, IMU, Radars, Forward Camera, cV2X
Rapid Prototyping System Components	•dSPACE Microautobox with SwRI eco-driving algorithm •NI cRIO – based DBW system	• dSPACE MicroAutoBox III • AutonomouStuff Spectra (Industrial-grade Linux PC) with ROS-based packages	•MicroAuto Box II (dSPACE), •Rugged Fanless Linux PC (Neousys Technology)	•Autoware.AI, dSPACE MABiii

Additional Simulation Tools	• Integration with VISSIM traffic simulator toolsets	• Integration with Simulation of Urban Mobility (SUMO) • RoadRunner • Matlab/Simulink	• Mixed Reality On-Road Vehicle Setup Using CARLA	• Matlab/Simulink, • CARLA, LG SVL, & Autoware WF Simulator

E. Reporting Requirements

Proposed field evaluation solutions must address the above technical areas of interest while working within the bounds and requirements outlined in Sections C and D above. Applicants should clearly show how their proposed methodologies address the above technical tasks while adhering to the relevant stipulations and any additional considerations not explicitly listed.

The selected field evaluation team will host individual NEXTCAR Phase II awardees' test vehicles, which may have confidential data on board. The selected field evaluation team will not access any such data unless necessary for test performance, in which case the selected field evaluation team shall assure that such confidentiality is maintained through appropriate means, which may include the execution of a user agreement or non-disclosure agreement.[185]

The ideal outcome of this program is the sustained advancement and application of the developed environment and simulation scenarios beyond the conclusion of the performance period. As such, Applicants should describe their preliminary strategy for broad dissemination of their framework, along with stakeholder outreach across the CAV industry (i.e., OEMs, communication providers, vehicle fleets, etc.) in sharing results, collaborating on inputs, and encouraging data transparency and driving scenario standardization.

In addition to a final report that synthesizes the project outputs, an implementation plan in the form of a technical memo will be expected at the conclusion of the award that identifies next steps, action items, and stakeholders to create awareness and enable the research community to adopt the on-track augmented reality testing environment and driving scenarios developed as part of this research effort.

F. Workplan

The selected entity will be expected to complete the following workplan in fulfillment of the tasks described in Section C. Applicants can also include interim milestones as desired.

[185] Per Section 5 below, an example of such a user agreement or non-disclosure agreement must be submitted with the application to this FOA.

Milestone		Due Date (quarter)
1.	Comprehensive design document that assesses capabilities and compatibility of each NEXTCAR Phase II team's testing environment. The document outlines the proposed unified on-track augmented reality testing environment and approach for identifying diverse driving scenarios that mirror real-world situations.	1
2.	Augmented reality environment for evaluating the energy efficiency of SAE Level 4 CAV technologies completed.	2
3.	Driving scenarios within the augmented reality environment developed and appropriate test procedures designed to validate the energy efficiency of SAE Level 4 eco-driving applications developed by the NEXTCAR Phase II teams.	3
4.	Full integration of NEXTCAR vehicles and technologies with the selected testing platform and infrastructure	3
5.	Field Day testing event	4
6.	Final report	4

5. Submissions Specifically Not of Interest

- Simulation or scenario development for autonomous vehicles outside of SAE Levels 4 and 5.
- Facilities and scenarios that require NEXTCAR teams to provide or acquire equipment not specified within NEXTCAR Phase II.
- Vehicle evaluation on real-world roads in live traffic.
- Testing locations which require special permitting or permissions.
- Testing that does not include evaluation on all roadway types: Arterials (urban and semi-urban) and freeways.
- Testing that only accounts for a single traffic scenario.
- Testing scenarios that do not account for all maneuvers and driving behaviors listed in Section C.

6. Eligibility

Eligibility for this FOA is restricted to applicants that have demonstrable prior experience working with one of the four NEXTCAR Phase II teams described in Section 2.B above, excluding those entities which are currently NEXTCAR Phase II Prime Recipients or lead institutions. As described in Section 2.B, eligible entities will already be aware of the technologies developed by the NEXTCAR Phase II teams, which will ensure that applicants are capable of supporting those technologies by leveraging methods and building upon the existing tools to develop a unified testing environment meeting the requirements shown in Tables 1 and 2 above. Also, engaging an entity with demonstrated expertise with any of the four NEXTCAR Phase II teams' unique solutions will minimize delays associated with adapting the facility and test environment to those novel technologies, ensuring a more streamlined and efficient testing phase.

7. Content and Form of Full Application

The content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Topic I. All other instructions set forth at FOA Section IV.C remain unchanged.

In addition to the requirements in Section IV.C, Applicants are required to upload their organization's user agreement, or non-disclosure agreement, in Exchange.[186]

Templates for preparing Full Applications under this Exploratory Topic may be found on ARPA-E Exchange at https://arpa-e-foa.energy.gov/.

8. Technology Transfer and Outreach

Applicants for this FOA are not required to include Technology Transfer and Outreach (TT&O) activities in their budget, and are not required to seek a waiver from ARPA-E.

[186] Please refer to Section 2.E.

XIX. Appendix L: Plant HYperaccumulators TO MIne Nickel-Enriched Soils (PHYTOMINES)

Special Program Announcement for
Exploratory Topics (DE-FOA-0002784)
Plant HYperaccumulators TO MIne Nickel-Enriched Soils (PHYTOMINES)

Topic Issue Date	March 21, 2024
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, April 26, 2024
Submission Deadline for Full Applications	9:30 AM ET, May 7, 2024
Submission Deadline for Replies to Reviewer Comments:	5:00 PM ET, June 12, 2024
Expected Date for Selection Notifications	July 2024
Anticipated Date of Awards	October 2024
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0002784 and DE-FOA-0002785 for this Exploratory Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between approximately $1,000,000–$2,500,000.
Maximum Period of Performance	36 Months

1. Introduction

This announcement describes the exploratory research effort Plant HYperaccumulators TO MIne Nickel-Enriched Soils (PHYTOMINES). The purpose of this announcement is to (1) evaluate the feasibility of systems that use plants to extract nickel from soils, and (2) encourage partnerships between farmers, agronomists, plant scientists, microbiologists, engineers, data scientists, soil scientists, battery manufacturers, and those working in the mining and steel industries.

2. Topic Description

ARPA-E is interested in funding research projects that investigate the feasibility of cost-competitive and low carbon-footprint extraction of nickel by terrestrial plants. The nickel-rich bio-ore derived from such plants could establish a competitive domestic supply chain to supplement conventional mining methods and reduce nickel imports. The targeted outcomes of this topic are:

i. The development of phytomining technologies that optimize the biotic systems which regulate the availability and uptake of nickel by hyperaccumulator (HA) plants.[187]

[187] Nicoletta Rascio and Flavia Navari-Izzo, "Heavy Metal Hyperaccumulating Plants: How and Why Do They Do It? And What Makes Them so Interesting?," *Plant Science* 180, no. 2 (February 2011): 169–81, https://doi.org/10.1016/j.plantsci.2010.08.016.

Technologies could be interventions in the soil or plant microbiome or the development of plant traits that enable the accumulation of nickel at an enhanced rate. We envision these projects as early-stage proof-of-concepts likely to take place in closed or open-air laboratories, greenhouses, or confined fields where light, humidity, and temperature regimes can be fully programmed. Open field trials are outside the scope of this FOA.

ii. Understanding the interrelationships of the geologic, ecological, and economic factors that affect the potential of phytomining to complement traditional mining as a source of nickel and other critical materials for energy listed in the DOE's 2023 Critical Materials Assessment (the DOE CMA).[188] Possible projects include mapping HA species of interest, scaling phytomining opportunities, and technoeconomic and lifecycle analyses (TEAs and LCAs) of phytomining projects.

3. Background

As the United States expands its investment in clean energy technology, the demand for clean energy minerals from viable sources will increase. Among the critical materials named by the DOE CMA, nickel serves as an ideal target to validate the viability of phytomining in the U.S. due to the large number of documented nickel HA plants globally (more than 500 species).[189] Nickel is used in the cathodes of lithium-ion batteries present in electric vehicles, consumer electronics, stationary storage, stainless steel, metallurgy, coatings, electroplating, and other alloys. Nickel is crucial to global clean energy technology supply chains and its future demand is expected to grow considerably due to nickel's use in batteries for electric vehicles and stationary storage and for solid oxide electrolyzers and fuel cells.[190,191] The DOE CMA found the supply risk for nickel is moderate in the short term and high in the long term, given the challenges of matching rapid demand increases, the presence of some sensitive countries among the list of global suppliers, and the reliance of the U.S. market on imports to meet domestic demand.[192] At present, nickel is only mined in the U.S. at Eagle Mine in Champion, Michigan.

[188] https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals.

[189] Roger D. Reeves, Alan J. Backer, Tanguy Jaffré, Peter D. Erskine, Guillaume Echevarria, and Antony van der Ent, "A global database for plants that hyperaccumulate metal and metalloid trace elements", *New Phytologist* 218:407–411 (2018), https://doi.org/10.1111/nph.14907.

[190] US DOE, "2023 Critical Materials Assessment," 2023.

[191] IEA, "The Role of Critical Minerals in Clean Energy Transitions," 2022.

[192] US DOE, "2023 Critical Materials Assessment."

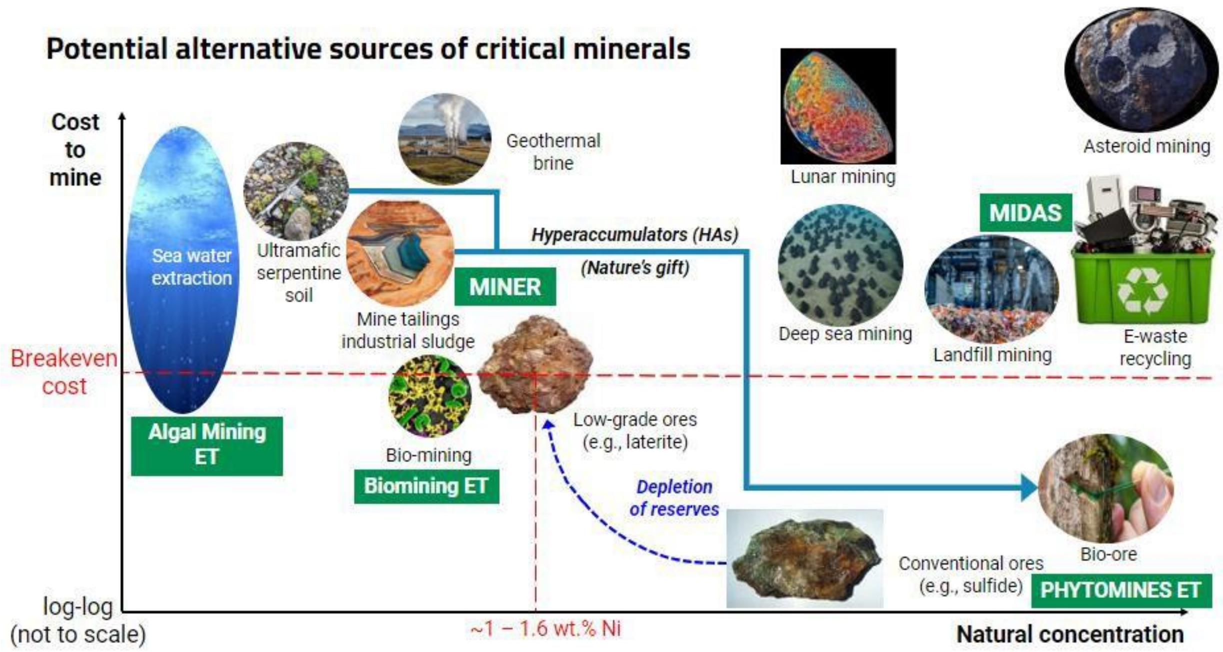

Figure 1 . Alternative sources of critical minerals and ARPA-E programs to develop these sources.

Traditionally, agriculture has been deployed to produce food, fuel, or fiber. However, plants also accumulate minerals from the soils in which they grow. The ability of plants to accumulate metals is used currently to detoxify soils and water in a process known as phytoremediation.[193] Phytoremediation, however, has not focused on the deployment of plants to accumulate and collect minerals for downstream use—a possibility that is described as 'phytomining'.[194] ARPA-E seeks applications for extracting dilute terrestrial nickel in soils using phytomining which are sub-economic for conventional mining (Figure 1).[195]

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[193] Sumira Jan and Javid Ahmad Parray, "Heavy Metal Uptake in Plants," in *Approaches to Heavy Metal Tolerance in Plants*, by Sumira Jan and Javid Ahmad Parray (Singapore: Springer Singapore, 2016), 1–18, https://doi.org/10.1007/978-981-10-1693-6_1.
[194] Rufus Chaney, J. Scott Angle, C. Leigh Broadhurst, Carinne Peters, Ryan Tappero, and Donald Sparks, "Improved Understanding of Hyperaccumulation Yields: Commercial Phytoextraction and Phytomining Technologies," *Journal of Environmental Quality* 36: 1429-1443 (2007), doi.org/10.2134/jeq2006.0514.
[195] Antony Van Der Ent et al., eds., *Agromining: Farming for Metals: Extracting Unconventional Resources Using Plants*, Mineral Resource Reviews (Cham: Springer International Publishing, 2021), https://doi.org/10.1007/978-3-030-58904-2.

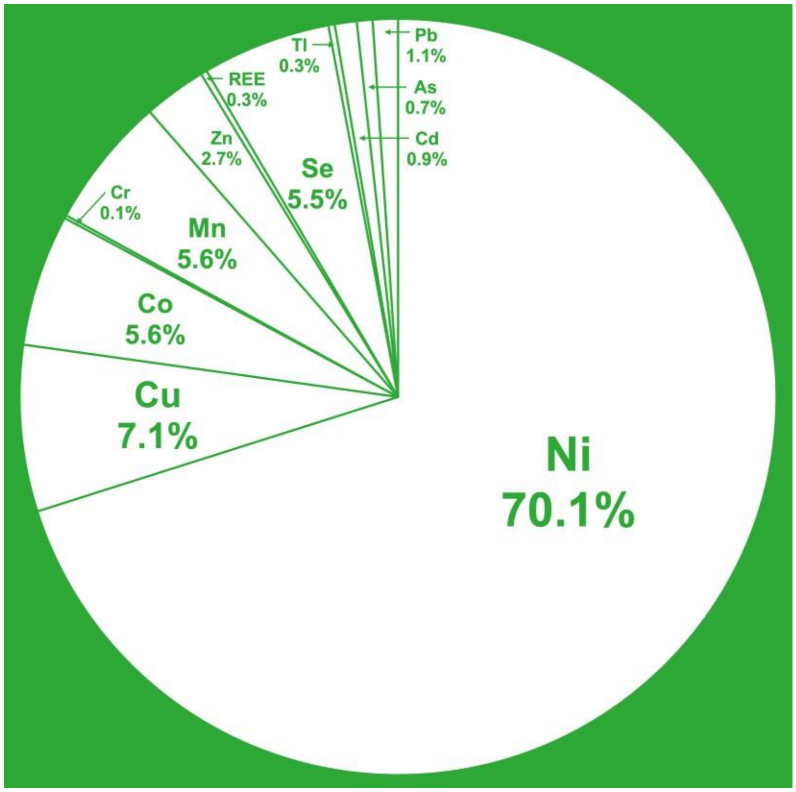

Figure 2. Most known hyperaccumulators accumulate nickel, but plants that hyperaccumulate other critical materials have also been identified.[196]

As shown in Figure 2, over 500 species of plants have been documented to hyperaccumulate nickel, which is generally defined as accumulating greater than 1 milligram of nickel per gram of total dry plant biomass (mg Ni/gdpb). Plants such as *Berkheya coddii* are reported to accumulate more than 30 mg Ni/gdpb in dry leaves.[197] Initial experiments to harvest nickel at small scale from HA plants have been conducted in Asia.[198] In Europe, several companies seek to produce and market nickel-rich bio-ore[199]. In the U.S., phytomining is not currently pursued commercially.[200]

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[196] A. van der Ent, ARPA-E Workshop, 2023.

[197] Marie Rue, Adrian L D Paul, Guillaume Echevarria, Antony van der Ent, Marie-Odile Simonnot, and Jean Louis Morel "Uptake, translocation and accumulation of nickel and cobalt in *Berkheya coddii*, a 'metal crop' from South Africa" *Metallomics*, 12(8): 1278–1289 (2020), https://doi.org/10.1039/d0mt00099j.

[198] Philip Nkrumah, Romane Tisserand, Rufus L. Chaney, Alan Baker, Jean-Louis Morel, Romain Goudon, Peter Erskine, Guillaume Echevarria, and Antony van der Ent, "The first tropical 'metal farm': Some perspectives from field and pot experiments," *Journal of Geochemical Exploration* 198: 114-122 (2019), https://doi.org/10.1016/j.gexplo.2018.12.003.

[199] Bani, A. et al. (2021). Element Case Studies in the Temperate/Mediterranean Regions of Europe: Nickel. In: van der Ent, A., Baker, A.J., Echevarria, G., Simonnot, MO., Morel, J.L. (eds) *Agromining: Farming for Metals. Mineral Resource Reviews*. Springer, Cham. https://doi.org/10.1007/978-3-030-58904-2_16.

[200] Philip Nti Nkrumah et al., "Current Status and Challenges in Developing Nickel Phytomining: An Agronomic Perspective," *Plant and Soil* 406, no. 1–2 (September 2016): 55–69, https://doi.org/10.1007/s11104-016-2859-4.

This Exploratory Topic supports the technological development of phytomining in the U.S. that could complement current and future domestic sources of nickel and catalyze phytomining for critical minerals beyond nickel.[201] ARPA-E seeks to de-risk future investments in the improvement of phytomining systems technologies, to optimize nickel accumulation rates in plants that could grow in nickel-rich soils, and to improve awareness of phytomining's potential utility in underutilized and nonagricultural lands.

Both the concentration and bioavailability (or phytoavailability) of nickel within soils are key drivers of the productivity and economic viability of phytomining.[202] Between these two factors, nickel's bioavailability is variable and governed by the combined outcomes of natural biotic systems.[203] At present, knowledge of those systems is insufficient to optimize their management. Activity and composition of rhizobial communities, including nematodes, mycorrhizal fungi, and the microbiome, have been shown to affect the availability and uptake of metals of interest in harvestable plants.[204] Endophyte and viral activity in above-ground plant tissues can alter hyperaccumulation activity. Plant traits, such as root or gene expression phenotypes, and plant exudates interact and alter the system.[205] ARPA-E seeks to reduce the scientific uncertainty associated with the technologies used to optimize biotic systems that regulate nickel availability to HA plants. Such understanding and control of biological systems would potentially improve future phytomining economics such that they are competitive with traditional mining.

ARPA-E has recognized that a major obstacle to investment in phytomining is the lack of knowledge regarding key considerations, including environmental impacts.[206] Such considerations include the uncertainty regarding availability of viable phytomining resources in

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[201] A. Joseph Pollard and Alan J.M. Baker, "Quantitative Genetics of Zinc Hyperaccumulation in *Thlaspi caerulescens*," *New Phytologist* 132, no. 1 (January 1996): 113–18, https://doi.org/10.1111/j.1469-8137.1996.tb04515.x; V Bert et al., "Genetic Basis of Cd Tolerance and Hyperaccumulation in *Arabidopsis halleri*," n.d.; A. G. L. Assunção et al., "Elevated Expression of Metal Transporter Genes in Three Accessions of the Metal Hyperaccumulator *Thlaspi Caerulescens*: Zinc Transporters of *Thlaspi Caerulescens*," *Plant, Cell & Environment* 24, no. 2 (February 2001): 217–26, https://doi.org/10.1111/j.1365-3040.2001.00666.x.

[202] Petra Susan Kidd et al., "Developing Sustainable Agromining Systems in Agricultural Ultramafic Soils for Nickel Recovery," *Frontiers in Environmental Science* 6 (June 8, 2018): 44, https://doi.org/10.3389/fenvs.2018.00044; Yin-M Li et al., "Development of a Technology for Commercial Phytoextraction of Nickel: Economic and Technical Considerations," n.d.

[203] Adrian L. D Paul and Rufus L. Chaney, "Influence of Subsoil and Soil Volume on the Accumulation of Nickel by *Odontarrhena corsica* Grown on a Serpentine Soil," *International Journal of Phytoremediation*, November 28, 2023, 1–8, https://doi.org/10.1080/15226514.2023.2282055.

[204] Jianfeng Hua et al., "Interactions between Arbuscular Mycorrhizal Fungi and Fungivorous Nematodes on the Growth and Arsenic Uptake of Tobacco in Arsenic-Contaminated Soils," *Applied Soil Ecology* 84 (December 2014): 176–84, https://doi.org/10.1016/j.apsoil.2014.07.004.

[205] Michael W. Persans, Ken Nieman, and David E. Salt, "Functional Activity and Role of Cation-Efflux Family Members in Ni Hyperaccumulation in *Thlaspi goesingense*," *Proceedings of the National Academy of Sciences* 98, no. 17 (August 14, 2001): 9995–10000, https://doi.org/10.1073/pnas.171039798.

[206] Kidd et al., "Developing Sustainable Agromining Systems in Agricultural Ultramafic Soils for Nickel Recovery"; Li et al., "Development of a Technology for Commercial Phytoextraction of Nickel: Economic and Technical Considerations"; Nkrumah et al., "Current Status and Challenges in Developing Nickel Phytomining."

the U.S. —including the inventory of native HA plants, mineral characteristics in soil, land ownership data for natural habitats and adjacent areas viable for phytomining.[207,208] ARPA-E seeks to promote the development of data and tools that will reduce these uncertainties and investment risk.

4. Technical Areas of Interest

The goal of this topic is to support the investigation of nickel phytomining to complement existing U.S. mining of nickel ore. To achieve this, ARPA-E seeks to fund projects in two Technical Areas:

Technical Area 1 (TA1): Systemic approaches to improve the phytomining of nickel on U.S. marginal lands

ARPA-E is interested in supporting proof-of-concept studies that utilize biotic phytomining systems to recover nickel from soils. These biotic systems include HA plants, their associated microorganisms, and the soil environment.[209] ARPA-E would consider modifications in system components, including plants as well as biota within rhizobial or above-ground biomes, that lead to increased collection of nickel and enhance the economic viability of phytomining.[210] Projects should take a systems approach that investigates interactions between underlying soil geochemistry, HA plants, and the organisms that mediate interactions between the plant and soil environment.[211] Technologies of interest could include those that introduce additions or deletions to the activity and composition of rhizobial, endophyte, viral, or multicellular communities or that alter activity or traits in plant tissues that increase plant hyperaccumulation activity.[212] Technologies at the biome, organismal, or metagenomic scale will be considered. While research using model organisms/systems could be a complementary work stream, applications that focus on non-model organisms or have potential to translate to non-model organisms with strong commercialization pathways are encouraged.

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[207] Justin A. Mistikawy et al., "Chromium, Manganese, Nickel, and Cobalt Mobility and Bioavailability from Mafic-to-Ultramafic Mine Spoil Weathering in Western Massachusetts, USA," *Environmental Geochemistry and Health* 42, no. 10 (October 2020): 3263–79, https://doi.org/10.1007/s10653-020-00566-7; Jean M. Morrison et al., "A Regional-Scale Study of Chromium and Nickel in Soils of Northern California, USA," *Applied Geochemistry* 24, no. 8 (August 2009): 1500–1511, https://doi.org/10.1016/j.apgeochem.2009.04.027.
[208] Van Der Ent et al., *Agromining*.
[209] Paul and Chaney, "Influence of Subsoil and Soil Volume on the Accumulation of Nickel by *Odontarrhena corsica* Grown on a Serpentine Soil."
[210] Assunção et al., "Elevated Expression of Metal Transporter Genes in Three Accessions of the Metal Hyperaccumulator *Thlaspi caerulescens*"; Martina Becher et al., "Cross-Species Microarray Transcript Profiling Reveals High Constitutive Expression of Metal Homeostasis Genes in Shoots of the Zinc Hyperaccumulator *Arabidopsis halleri*: Transcript Profiling in Shoots of *A. halleri*," *The Plant Journal* 37, no. 2 (January 2004): 251–68, https://doi.org/10.1046/j.1365-313X.2003.01959.x.
[211] Aida Bani et al., "The Effect of Plant Density in Nickel-Phytomining Field Experiments with *Alyssum murale* in Albania," *Australian Journal of Botany* 63, no. 2 (2015): 72, https://doi.org/10.1071/BT14285.
[212] Jitendra Mishra, Rachna Singh, and Naveen K. Arora, "Alleviation of Heavy Metal Stress in Plants and Remediation of Soil by Rhizosphere Microorganisms," *Frontiers in Microbiology* 8 (September 6, 2017): 1706, https://doi.org/10.3389/fmicb.2017.01706.

Applications should identify the molecular mechanism through which the phytomining system is expected to enhance plant hyperaccumulation of nickel. Further, applicants should indicate the mechanisms through which the phytomining system will alter the existing biota and soil geochemistry and the likely duration of that alteration. Applications should provide information on the prevalence of the environments in which the phytomining system is potentially applicable and the potential relevance of that system to nickel accumulation at commercial scale. While scalability is a critical factor to long-term commercial potential, risk management is an equally critical consideration. As such, from their initial design, applicants should consider the environmental impacts of the proposed phytomining system. The applicants should explain methods for containing the system to a geographic area of interest. Designing phytomining systems to be self-containing (e.g., self-regulating microbe accumulation or plant sterility) will be a key consideration to project funding decisions.

Genetic modification is within the scope of this Technical Area. Should a new genetically modified material arise from the performance of an award, it must be reported in iEdison, the government-wide portal for reporting new inventions. iEdison allows for the reporting of biological materials that are going to be either patented by the awardee or not patented. If not patented, the new genetically modified material may be reported in iEdison as "Designated as Unpatented Biological Material or Research Tool." Awards made under TA1 will require that such new materials that the awardee does not intend to patent be so reported in iEdison, and will also require follow-on reporting on the utilization of such materials.

Applications should specifically address the present accumulation rate of nickel in the proposed plant-soil system, the targeted enhanced accumulation rate proposed, and the biological hypothesis through which the accumulation rate will be increased. Optionally, applicants can indicate the likely methodology or methodologies that will be used to extract nickel from biomass and the cost and greenhouse gas (GHG) emissions associated with these extraction processes; projects will be expected to not exceed and, ideally, reduce both cost and emissions versus current nickel mining technologies. Trials are expected to take place in highly controlled lab or green house environments, where light, humidity, and temperature regimes can be programmed, and the characteristics of the soil system (either native or artificial) are fully defined. Applicants shall explain the relevance of laboratory metrics to nickel accumulation rates that would be observed in situ. ARPA-E seeks to fund multiple projects in TA1 where each project is between $1 million to $2.5 million and has a period of performance of no more than 36 months. To support TEA/LCA in TA2, as described below, TA1 teams may share information with TA2 teams, such as cost information and process details. Metrics and technical performance criteria for TA1 are listed below in Table 1.

Technical Area 2 (TA2): Enhancing phytomining's enabling knowledge base

ARPA-E seeks to promote the development of data and tools that will support continued technology investment and community building for phytomining in the U.S. A priority outcome is the creation of a publicly available database of phytomining sites for nickel and rare earth/platinum group metals or other critical metals.[213] The publicly available database must not be subject to any restriction of further modification, use or disclosure. The database will be publicly accessible and identify the realizable scope of phytomining in the U.S.; it will at a minimum unite currently separated geospatial data and a range of metadata including the descriptions of the geologic, environmental, ecological, and ownership status of high-value target sites for hyperaccumulation. As nickel is likely to be the near-term target, it will be acceptable to prioritize creating more granular data on nickel soil content rather than a diversity of data on the soil content of rare earth/platinum group metals or other critical metals. ARPA-E recognizes that the existing catalog of native HA plants in North America is highly likely to be incomplete and seeks to narrow this gap, including potentially through the screening of existing plant collections (e.g., herbaria surveys) to identify new native HA plants. Such screenings should provide genomic and phenotypic information on hyperaccumulators and closely related non-hyperaccumulators to enhance understanding of the genetic mechanisms and regulation of hyperaccumulation. Applicants should provide a detailed plan to make these data publicly available. Finally, project developers and investors need to generate data validating the technoeconomic model of phytomining. Therefore, under TA2, ARPA-E also seeks to support analyses that evaluate phytomining technologies arising from TA1. To support TA1 projects and facilitate potential collaborations for TEA/LCA work under TA2, teams in different technical categories may share information such as cost information, process details, and TEA/LCA. Similarly, ARPA-E anticipates that LCAs that establish a carbon profile on par or less than traditional mining will be an important enhancement to these projects' eventual investment theses. ARPA-E seeks to fund projects in TA2 where each project can be up to $1 million with a period of performance of no more than 24 months. Metrics and technical performance criteria for TA2 are listed below in Table 1.

5. Metrics and Technical Performance Criteria

Table 1. Description of primary metrics for Technical Areas 1 and 2.

Technical Area 1 (TA1): Systems approaches to improve the phytomining of nickel on U.S. marginal lands	
Phytomining system development: hypothesis and description (must be included in the Application)	• Description of system initial conditions and the prevalence of the system in U.S. (ultra)mafic soils. • Molecular-level mechanism of action to enhance phytomining is proposed.

[213] Paulo J.C. et al., "Phytoremediation of Soils Contaminated with Metals and Metalloids at Mining Areas: Potential of Native Flora," in *Environmental Risk Assessment of Soil Contamination*, ed. Maria C. Hernandez Soriano (InTech, 2014), https://doi.org/10.5772/57469.

Target Effectiveness of phytomining system (must be verified by experimentation)	• Improved (experimental) phytomining system produces 200% of nickel yield of unimproved system and is greater than 30 mg Ni/gdpb. • At lab or confined field scale of no less than 1,000 cubic feet of soil, phytomining system should accumulate more than 250 kg of nickel per hectare per year (kg Ni/hectare/year) in harvestable plant biomass. • Project also describes a technology pathway to accumulation of greater than 500 kg Ni/hectare/year.
Information from selected downstream processing (must be included in the Application)	• Description of likely methodology for extraction of nickel from the HA plant, including an estimate of GHG emissions associated with the extraction of 1,000 kg of nickel from plant biomass using the indicated methodology.
Technical Area 2 (TA2): Enhancing phytomining's enabling knowledge base	
Mapping HA species of interest and scaling phytomining opportunities	• Identification of U.S. native HA species and their current population distribution, as well as the range and types of reported nickel and other critical materials accumulation (mg Ni/gdpb) in the species. For each sample, include DNA sequencing of HA species and a closely related species, and a measure of the accumulation of nickel in leaf tissue. • Integrated publicly available database that identifies natural or anthropogenic soils with more than 50 parts per million nickel concentration, ecological, climactic, and ownership data.
TEA/LCA of phytomining	• Studies of the GHG impacts and economic viability of phytomining of nickel using systems described in TA1.

If responding to TA1, applicants are required to submit:

1. An initial discussion of the relevance and likely robustness of the proposed technology system to phytomining of nickel in diverse ecosystems.
2. A description of likely changes to the geographic range of the system that may result from changes introduced within the project.
3. Current accumulation rate of nickel in the proposed system, the targeted accumulation rate, and the biological hypothesis through which the accumulation rate will be increased.
4. Description of likely downstream processing methodologies to yield bio-ore and estimates of the TEA/LCA of the proposed bio-ore generation process.
5. Target nickel production cost and a plan to conduct TEA/LCA studies of the combined phytomining/bio-ore generation and selected downstream processing method.

6. Submissions Specifically Not of Interest

- Applications that envision field testing HA plant systems. Trials are expected to take place in highly controlled lab or greenhouse environments, where light, humidity, and temperature regimes can be fully programmed.
- To maintain focus on the soil-plant interface, projects that focus exclusively on modification of above-ground endophytes and their interactions with plants.
- Submissions aimed solely at growing and cultivating terrestrial plants, without consideration of extracting and refining metals from hyperaccumulated plant biomass.
- Submissions aimed solely at processing of hyperaccumulated plant biomass to extract and refine metals.
- Submissions that include species listed as Federal noxious weeds or invasive species by the U.S. Department of Agriculture.[214]
- Projects under Technical Area 1 that anticipate nickel extraction that will produce GHG emissions greater than the emissions associated with nickel mining technology (approximately 20 kg carbon dioxide equivalent (CO2e) per kg nickel).
- Submissions that clearly compete with existing land use for food and fuel crops.
- Approaches that cannot be scaled up at a reasonable cost and time.

[214] Noxious weeds: www.aphis.usda.gov/plant_health/plant_pest_info/weeds/downloads/weedlist.pdf.
Invasive species: www.invasivespeciesinfo.gov/species-profile-list.