FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

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

SOLICITATION ON TOPICS INFORMING NEW PROGRAM AREAS

Announcement Type: Modification ~~18~~ 19
Funding Opportunity No. DE-FOA-0001953
CFDA Number 81.135

FOA Issue Date:	December 20, 2018
FOA Close Date:	Open continuously until otherwise amended.
Application Due Date:	See Targeted Topics Table for topic-specific application due dates.
Total Amount to Be Awarded	Approximately $114.75million, subject to the availability of appropriated funds to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954. See Targeted Topics Table for topic-specific information.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. See Targeted Topics Table for topic-specific award amount requirements.

- For eligibility criteria, see Section III.A – III.C 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.F.1 of the FOA.
- Applicants are responsible for meeting the submission deadline associated with each Targeted Topic. Applicants are strongly encouraged to submit their applications at least 48 hours in advance of the Targeted Topic submission deadline.
- For detailed guidance on compliance and responsiveness criteria, see Sections III.C.1 through III.C.4 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 Modifications
01	2/13/2019	• Revised Full Application Deadlines for Topics A, B, & C. See Table 1. Targeted Topics and Appendices A, B & C. • Inserted information regarding Renewal Awards. See Section II.B of the FOA. • Inserted new Targeted Topic. Topic D: Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion-Energy Concepts. See Table 1. Targeted Topics, Appendix D and Total Amount to be awarded on Cover Page.
02	3/12/2019	• Inserted new Targeted Topic. Topic E: Quantification of Effectiveness of Nutrient Bioextraction by Seaweed. See Table 1. Targeted Topics, Appendix E and Total Amount to be awarded on Cover Page.
03	5/21/2019	• Inserted new Targeted Topic. Topic F: High Value Methane Pyrolysis. See Table 1. Targeted Topics, Appendix F and Total Amount to be awarded on Cover Page.
04	7/12/2019	• Updated FOA to include "Replies to Reviewer Comments".
05	9/17/2019	• Inserted new Targeted Topic. Topic H: Establishing validation sites for field-level emissions quantification of agricultural bioenergy feedstock production. See Table 1. Targeted Topics, Appendix H and Total Amount to be awarded on Cover Page. • Extended FOA Close Date, see cover page of the FOA.
06	10/23/2019	• Revised Submission Deadline for Replies to Reviewer Comments and Expected date for Notifications for Topic H. See Table 1. Targeted Topics and Appendix H.
07	11/14/2019	• Inserted new Targeted Topic. Topic I: Electricity System Models for Carbon Capture Resources. See Table 1. Targeted Topics, Appendix I and Total Amount to be awarded on Cover Page.
08	12/6/2019	• Clarified language on Applicant eligibility with regards to the FLECCS program and the Solicitation on Topics Informing New Program Areas Topic I. See section IX: Appendix I of the FOA.
09	3/4/2020	• Inserted new Targeted Topic. Topic J: Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy. See Table 1. Targeted Topics, Appendix J and Total Amount to be awarded on Cover Page.
10	4/2/2020	• Inserted new Targeted Topic. Topic K Recycle Underutilized Solids to Energy (REUSE). See Table 1. Targeted Topics, Appendix K and Total Amount to be awarded on Cover Page. • Inserted an additional Program Policy Factor in Section V.B.1

Mod. No.	Date	Description of Modifications
11	5/20/2020	• Updated Section VI.B.8 U.S. Manufacturing Requirement. • Inserted new Targeted Topic L: Insulating Nanofluids and Solids to Upgrade our Large Ageing Transformer Equipment (INSULATE). • Inserted new Targeted Topic M: Mining Incinerated Disposal Ash Streams (MIDAS). • Inserted new Targeted Topic N: Waste into X (WiX). • Inserted new Targeted Topic O: Direct Removal of Carbon Dioxide from Oceanwater (DOC). • Inserted new Targeted Topic P: Direct Removal of Carbon Dioxide from Ambient Air (DAC). • See Table 1. Targeted Topics, Appendix L-P and Total Amount to be awarded on Cover Page.
12	6/1/2020	• Revised Full Application Deadlines for Topic K. See Table 1. Targeted Topics and Appendix XI, Topic K.
13	9/17/2020	• Inserted new Targeted Topic. Topic Q: Connecting Aviation By Lighter Electric Systems (CABLES). See Table 1. Targeted Topics, Appendix Q and Total Amount to be awarded on Cover Page. • Removed References to Reply to Review Comments Template.
14	9/23/2020	• Inserted new Targeted Topic. Topic R: Lowering CO2: Models to Optimize Train Infrastructure, Vehicles, and Energy Storage (LOCOMOTIVES). See Table 1. Targeted Topics, Appendix R and Total Amount to be awarded on Cover Page.
15	10/8/2020	• Inserted new Targeted Topic. Topic S: Topology Optimization and Additive Manufacturing for Performance Enhancement of High Temperature and High Pressure Heat Exchangers (Topology). See Table 1. Targeted Topics, Appendix S and Total Amount to be awarded on Cover Page. • Updated Section III.B.2 Reduced Cost Share Requirements.
16	11/23/2020	• Extended the Targeted Topic deadline for Topic S: Topology Optimization and Additive Manufacturing for Performance Enhancement of High Temperature and High Pressure Heat Exchangers (Topology) until December 1, 2020. • Updated Targeted Topic Appendix S: Topology Optimization and Additive Manufacturing for Performance Enhancement of High Temperature and High Pressure Heat Exchangers (Topology) Section B. Technical Performance Targets. • RESERVED Appendix T.
17	5/21/2021	• Updated Anticipated Award Amounts. See Cover Page of the FOA. • Inserted new Targeted Topic. Topic U: SF_6-Free Routes for Electrical Equipment. See Table 1. Targeted Topics, Appendix U and Total Amount to be awarded on Cover Page.
18	7/29/21	• Updated due date for Replies to Reviewer Comments for Topic U: $SFSF_6$-Free Routes for Electrical Equipment, see Table 1. Targeted Topics and Appendix U, Section XXI of the FOA.

		• Updated expected date for Selection Notifications for Topic U: SF_6-Free Routes for Electrical Equipment, see Table 1. Targeted Topics and Appendix U, Section XXI of the FOA..
19	8/25/21	• Updated due date for Replies to Reviewer Comments for Topic U: SF_6-Free Routes for Electrical Equipment, see Table 1. Targeted Topics and Appendix U, Section XXI of the FOA.

TABLE 1. TARGETED TOPICS

Appendix	Targeted Topic Title	Issue Date	Deadline for Questions to ARPA-E CO	Full Application Submission Deadline	Submission Deadline for Replies to Reviewer Comments	Total Amount to be Awarded (subject to the availability of funds)	Anticipated Awards	Max Period of Performance	Expected date for Notifications
A	EXTREMELY DURABLE CONCRETES AND CEMENTITIOUS MATERIALS	12/20/2018	5 PM ET, 2/8/2019	9:30 AM ET, 2/19/2019	N/A	Approximately $8M total	5-8 awards	24 months	May 2019
B	LEVERAGING INNOVATIONS SUPPORTING NUCLEAR ENERGY	12/20/2018	5 PM ET, 2/8/2019	9:30 AM ET, 2/19/2019	N/A	Approximately $8M total	3-5 awards	24 months	May 2019
C	DOWNHOLE TOOLS TO ENABLE ENHANCED GEOTHERMAL SYSTEMS	12/20/2018	5 PM ET, 2/8/2019	9:30 AM ET, 2/19/2019	N/A	Approximately $2M total	2-4 awards	24 months	May 2019
D	Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion-Energy Concepts	2/13/2019	5 PM ET, 4/5/2019	9:30 AM ET, 4/15/2019	N/A	Approximately $5M total	3-5 awards	24 months	June 2019
E	Quantification of Effectiveness of Nutrient Bioextraction by Seaweed	3/12/2019	5 PM ET, 5/1/2019	9:30 AM ET, 5/13/2019	None	Approximately $1M total, maximum $300K per award	3-5 fixed amount grants	24 months	July 2019
F	High Value Methane Pyrolysis	5/21/2019	5 PM ET, 7/16/2019	9:30 AM ET, 7/26/2019	5 PM ET, 9/4/2019	Approximately $5.5M total	3-5 awards	24 months	October 2019
G	<RESERVED>								
H	Establishing validation sites for field-level emissions quantification of agricultural bioenergy feedstock production	9/19/2019	5 PM ET, 11/7/2019	9:30 AM ET, 11/18/2019	5 PM ET, 12/11/2019	Approximately $10.0M total	3 awards	36 months	January 2020
I	Electricity System Models for Carbon Capture Resources	11/14/2019	5 PM ET, 1/10/2020	9:30 AM ET, 1/22/2020	5 PM ET, 3/4/2020	Approximately $750,000 total	1-2 awards	24 months	April 2020

Appendix	Targeted Topic Title	Issue Date	Deadline for Questions to ARPA-E CO	Full Application Submission Deadline	Submission Deadline for Replies to Reviewer Comments	Total Amount to be Awarded (subject to the availability of funds)	Anticipated Awards	Max Period of Performance	Expected date for Notifications
J	Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy	3/4/2020	5 PM ET, 4/27/2020	9:30 AM ET, 5/7/2020	5 PM ET, 6/22/2020	Approximately $5.0M total	5-10 awards	24 Months	August 2020
K	Recycle Underutilized Solids to Energy	4/2/2020	5 PM ET, 5/21/2020	10:30 AM ET, 6/2/2020	5 PM ET, 7/13/2020	Approximately $4.0M total	4-8 awards	18 Months	August 2020
L	Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment	5/20/2020	5 PM ET, 7/10/2020	9:30 AM ET, 7/22/2020	5 PM ET, 9/2/2020	Approximately $3.5M total	1-5 awards	24 Months	October 2020
M	Mining Incinerated Disposal Ash Streams	5/20/2020	5 PM ET, 7/10/2020	9:30 AM ET, 7/22/2020	5 PM ET, 9/2/2020	Approximately $4.0M total	1-5 awards	24 Months	October 2020
N	Waste into X	5/20/2020	5 PM ET, 7/10/2020	9:30 AM ET, 7/22/2020	5 PM ET, 9/2/2020	Approximately $5.0M total	5-10 awards	24 Months	October 2020
O	Direct Removal Of Carbon Dioxide From Oceanwater	5/20/2020	5 PM ET, 7/10/2020	9:30 AM ET, 7/22/2020	5 PM ET, 9/2/2020	Approximately $2.0M total	1-5 awards	24 Months	October 2020
P	Direct Removal of Carbon Dioxide From Ambient Air	5/20/2020	5 PM ET, 7/10/2020	9:30 AM ET, 7/22/2020	5 PM ET, 9/2/2020	Approximately $2.0M total	1-5 awards	24 Months	October 2020
Q	Connecting Aviation By Lighter Electric Systems	9/17/2020	5 PM ET, 11/06/2020	9:30 AM ET, 11/17/2020	5 PM ET, 1/11/2021	Approximately $10.0M total	2-6 awards	36 Months	February 2021
R	Lowering CO2: Models to Optimize Train Infrastructure, Vehicles, and Energy Storage	9/23/2020	5 PM ET, 11/13/2020	9:30 AM ET, 11/23/2020	5 PM ET, 1/11/2021	Approximately $5.0M total	2-6 awards	12 Months	February 2021
S	Topology Optimization and Additive Manufacturing for Performance Enhancement of High Temperature and High Pressure Heat Exchangers	10/8/2020	5 PM ET, 11/13/2020	9:30 AM ET, 12/1/2020	5 PM ET, 1/15/2021	Approximately $4.0M Total	4-6 awards	18 Months	March 2021

T	<RESERVED>								
U	SF_6-Free Routes for Electrical Equipment	5/21/2021	5 PM ET, 7/13/2021	9:30 AM ET, 7/23/2021	5 PM ET, ~~8/24/2021~~ 8/27/2021	Approximately $10M total	3-5 awards	36 months	September 2021

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REQUIRED DOCUMENTS CHECKLIST

Unless an exception or exceptions are described under a particular Targeted Topic, the following are applicable to all Targeted 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.

<table>
<tr><th>SUBMISSION</th><th>COMPONENTS</th><th>OPTIONAL/ MANDATORY</th><th>FOA SECTION</th></tr>
<tr><td>Full Application</td><td>• Each Applicant must submit a Technical Volume in Adobe PDF format by the stated deadline. Applicants may use the Technical Volume template available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov). The Technical Volume must include the following:
○ Executive Summary (1 page max.)
○ Sections 1-5 (14 pages max.)
• 1. Innovation and Impact
• 2. Proposed Work
• 3. Technology to Market
• 4. Team Organization and Capabilities
• 5. Budget
○ Bibliographic References (no page limit)
○ Personal Qualification Summaries (each PQS limited to 3 pages in length, no cumulative page limit)
• The Technical Volume must be accompanied by:
○ SF-424 (no page limit, Adobe PDF format);
○ Budget Justification Workbook/SF424A (no page limit, Microsoft Excel format);
○ Summary for Public Release (250 words max., Adobe PDF format);
○ Summary Slide (1 page limit, Microsoft PowerPoint format) – Applicants may use the Summary Slide template available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov);
○ Completed and signed Business Assurances & Disclosures Form (no page limit, Adobe PDF format)
○ U.S. Manufacturing Plan (1 page limit, Adobe PDF format)</td><td>Mandatory</td><td>IV.C</td></tr>
<tr><td>Reply to Reviewer Comments</td><td>• 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:
○ Up to 2 pages of text; and
○ Up to 1 page of images.</td><td>Optional</td><td>IV.D</td></tr>
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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) to:

"(A) to enhance the economic and energy security of the United States through the development of energy technologies that result in—
(i) reductions of imports of energy from foreign sources;
(ii) reductions of energy-related emissions, including greenhouse gases; and
(iii) improvement in the energy efficiency of all economic sectors; 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 the programmatic authorizing statute codified at 42 U.S.C. § 16538. The FOA and any awards made under this FOA are subject to 2 C.F.R. Part 200 as amended by 2 C.F.R. Part 910.

ARPA-E funds research on and the development of high-potential, high-impact energy technologies that are too early for private-sector investment. 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 down 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 and it can be spurred by early-stage R&D supported by the applied energy offices in DOE. By contrast, ARPA-E supports high-risk, potentially transformative research that has the potential to create fundamentally new learning curves. ARPA-E R&D projects typically start with cost/performance estimates for the proposed technology that are well above the level of the competitive 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 lower 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 the 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 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 (http://fossil.energy.gov/), the Office of Nuclear Energy (http://www.energy.gov/ne/office-nuclear-energy), and the Office of Electricity Delivery and Energy Reliability (http://energy.gov/oe/office-electricity-delivery-and-energy-reliability).

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 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).

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

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. Targeted Topics Overview

This FOA will only accept applications in prespecified Targeted 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 Targeted Topics are posted.

Each technology specific Targeted Topic announcement will be visible on ARPA-E eXCHANGE as a supporting FOA document. Targeted 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 scientifically aligned with the Targeted Topic(s) open at the time the application is submitted.

II. AWARD INFORMATION

A. AWARD OVERVIEW

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

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 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. ARPA-E expects to award Grants for research funded under this FOA up to $300,000.

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."[2] Accordingly, ARPA-E has substantial involvement in the direction of every Cooperative Agreement.

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

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/?q=site-page/funding-agreements.

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 the rest of 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 rest of 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 a FFRDC or GOGO will have similar terms and conditions as ARPA-E's Model Cooperative Agreement (https://arpa-e.energy.gov/?q=site-page/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.

In general, an other transaction agreement would require a 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 this Award. 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.

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,[3] as the lead for a Project Team,[4] 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 entities, educational institutions, and nonprofits[5] 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

U.S. incorporated subsidiaries of foreign entities, whether for-profit or otherwise, are eligible to apply for funding under this FOA as a Standalone Applicant, as the lead organization for a Project Team, or as a member of a Project Team, subject to the requirements in 2 Code of

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

[4] The term "Project Team" is used to mean any entity with multiple players working collaboratively and could encompass anything from an existing organization to an ad hoc teaming arrangement. A Project Team consists of the Prime Recipient, Subrecipients, and others performing any of the research and development work under an ARPA-E funding agreement, whether or not costs of performing the research and development work are being reimbursed under any agreement.

[5] 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.

Federal Regulation (CFR) 910.124, which includes requirements that the entity's participation in this FOA's Program be in the economic interest of the U.S. The Full Application must state the nature of the corporate relationship between the foreign entity and domestic subsidiary or affiliate.

Entities not incorporated in the U.S., whether for-profit or otherwise, are not eligible to apply for funding, but may be proposed by an Applicant as a member of a Project Team.

All work under an ARPA-E award must be performed in the U.S. The Applicants 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/. Please refer to the Business Assurances & Disclosures Form for guidance on the content and form of the request.

Also, refer to Section VIII.B which addresses U.S. manufacturing requirements for inventions arising from research projects funded by this Program.

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[6]

Cost sharing will not be required for any project with Federal Project Funding of $300,000 or less. Otherwise, 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 Recipient must provide at least 20% of the Total Project Cost[7] as cost share, except as provided in Sections III.B.2 or III.B.3 below.[8]

2. INCREASED COST SHARE REQUIREMENT

Large businesses 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 must provide at least 50% of the Total Project Cost as cost share. ARPA-E may reduce this minimum cost share requirement, as appropriate.

3. REDUCED COST SHARE REQUIREMENT

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

- *(Effective for Topics issued after September 29, 2020)* 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.

- *(Effective for Topics issued after September 29, 2020)* Project Teams composed exclusively of domestic educational institutions, domestic nonprofits, FFRDCs/DOE Labs, and/or 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 – will provide 0% cost share from the outset of the project through the first 12 months of the project (hereinafter the

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[6] Please refer to Section VI.B.3-4 of the FOA for guidance on cost share payments and reporting.
[7] 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.
[8] Energy Policy Act of 2005, Pub.L. No. 109-58, § 988.

"Cost Share Grace Period").[9] 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%, but less than 100%, of the total work under the funding agreement (as measured by the Total Project Cost) the Project Team 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.[10]

- 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 minimum 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.

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[9] Small businesses are generally defined as 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). Applicants that are small businesses will be required to certify in the Business Assurances & Disclosures Form that their organization meets the SBA's definition of a small business under at least one NAICS code.

[10] See the information provided in previous footnote.

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.E.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 <u>not</u> 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;
- Federal funding or property (e.g., Federal grants, equipment owned by the Federal Government); or
- Expenditures that were reimbursed under a separate Federal program.

In addition, Project Teams may not use independent research and development (IR&D) funds[11] 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.

[11] As defined in Federal Acquisition Regulation Subsection 31.205-18.

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 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 Targeted 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.

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 Targeted Topic Appendix
- Submissions that have been submitted in response to other currently issued ARPA-E FOAs.
- Submissions that are not scientifically distinct from applications submitted in response to other 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.

Each Targeted Topic may also include a section entitled "Submissions Specifically not of Interest." Submissions that propose items contained within this section in each Targeted 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 Targeted Topic attached to this FOA, provided that each application is scientifically distinct.

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.F.1 of the FOA and the "ARPA-E eXCHANGE Applicant Guide" (https://arpa-e-foa.energy.gov/Manuals.aspx).

2. Full Applications

Applicants must submit a Full Application by the Targeted 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 Targeted 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.E 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 and program policy factors in Sections V.A.1 and V.B.1 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, 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 content requirements described below.

Component	Required Format	Description and Information

Technical Volume	PDF	The centerpiece of the Full Application. Provides a detailed description of the proposed R&D project and Project Team. A Technical Volume template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov).
SF-424	PDF	Application for Federal Assistance (https://arpa-e-foa.energy.gov). 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 (https://arpa-e-foa.energy.gov)
Summary for Public Release	PDF	Short summary of the proposed R&D project. Intended for public release. A Summary for Public Release template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov).
Summary Slide	PPT	A four-panel project slide summarizing different aspects of the proposed R&D project. A Summary Slide template is available on ARPA-E eXCHANGE (https://arpa-e-foa.energy.gov).
Business Assurances & Disclosures Form	PDF	Requires the Applicant to make responsibility disclosures and disclose potential 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 the Applicant is a FFRDC/DOE Lab, requires the Applicant to provide written authorization from the cognizant Federal agency and, if a DOE/NNSA FFRDC/DOE Lab, a Field Work Proposal. Allows the Applicant to request a waiver or modification of the Performance of Work in the United States requirement and/or the Technology Transfer & Outreach (TT&O) spending requirement. This form 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.
U.S. Manufacturing Plan	PDF	As part of the application, Applicants are required to submit a U.S. Manufacturing Plan. The U.S. Manufacturing Plan represents the Applicant's measurable commitment to support U.S. manufacturing as a result of its award. See detailed U.S. Manufacturing Plan instructions and examples in the Seventh Component description below.

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.

ARPA-E provides detailed guidance on the content and form of each component below.

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. 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 will review only the authorized number of pages and disregard any additional pages.

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, ARPA-E and reviewers are under no obligation to review cited sources (e.g., Internet websites).

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/Pages/Opportunity-Zones.aspx.

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.E.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.
- 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.
- 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:

- Targeted 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 potential conflicts of interest within the Project Team;

- 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."[12] 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; and
- Request a waiver of the TT&O spending requirement.

7. SEVENTH COMPONENT: U.S. MANUFACTURING PLAN

As part of the application, Applicants are required to submit a U.S. Manufacturing Plan that should not exceed one page in length. The U.S. Manufacturing Plan represents the Applicant's measurable commitment to support U.S. manufacturing as a result of its award. U.S. Manufacturing Plans are a Program Policy Factor during the review and selection process. See Section V.B.1 of the FOA.

A U.S. Manufacturing Plan should contain the following or similar preamble: "If selected for funding, the Applicant agrees to the following commitments as a condition of that funding:" and, after the preamble, the plan should include one or more specific and measurable commitments. For example, an Applicant may commit particular types of products to be manufactured in the U.S. **These plans should not include requirements regarding the source of inputs[13] used during the manufacturing process.** In addition to or instead of making a commitment tied to a particular product, the Applicant may make other types of commitments still beneficial to U.S. manufacturing. An Applicant may commit to a particular investment in a new or existing U.S. manufacturing facility, keep certain activities based in the U.S. (i.e., final

[12] America COMPETES Act, Pub. L. No. 110-69, § 5012 (2007), as amended (codified at 42 U.S.C. § 16538).
[13] For purposes of this FOA, an input refers to something which is used during the manufacturing process which (1) was in existence prior to or first produced outside of an ARPA-E award; (2) does not embody a subject invention, or technology which is developed or improved under an ARPA-E award; and (3) was not produced through the use of a subject invention, or technology which is developed or improved under an ARPA-E award.

assembly) or support a certain number of jobs in the U.S. related to the technology and manufacturing. For an Applicant which is likely to license the technology to others, especially universities for which licensing may be the exclusive means of commercialization the technology, the U.S. manufacturing plan may indicate the Applicant's plan and commitment to use a licensing strategy **for both exclusive and nonexclusive** licensing that would likely support U.S. manufacturing.

When an Applicant that is a domestic small business, domestic educational institution, or nonprofit organization is selected for an award, the U.S. Manufacturing Plan submitted by the Applicant may become part of the terms and conditions of the award **in addition to the requirements attaching to subject inventions described in VI.B.8 below.** See Section VI.B.8 of the FOA for U.S. Manufacturing Requirements applicable to large businesses. The Applicant/Awardee may request a waiver or modification of the U.S. Manufacturing Plan from DOE upon a showing that the original U.S. Manufacturing Plan is no longer economically feasible.

Class patent waivers usually apply to domestic large businesses as set forth in Section VIII.F of the 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 that any products embodying or produced through the use of an invention conceived or first actually reduced to practice under the award will be substantially manufactured in the United States, unless DOE agrees that the commitments proposed in the U.S. Manufacturing Plan are sufficient. The U.S. Manufacturing Plan submitted by the Applicant may become part of the terms and conditions of the award i**n addition to the requirements attaching to subject inventions**.

D. CONTENT AND FORM OF REPLIES TO REVIEWER COMMENTS

If Applicable to the Targeted 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.

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.

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 will review only the first three pages and disregard any additional pages.

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. ARPA-E generally does not accept budgets as submitted with the Full Application. Budgets 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.

Please refer to the "Applicants' Guide to ARPA-E Award Negotiations" (https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance) for additional guidance on pre-award costs.

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. Because all patent costs are considered to be Technology Transfer & Outreach (TT&O) costs (see Section IV.E.8 of the FOA below), the waiver request is subject to approval by ARPA-E.

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.

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 – i.e., Prime Recipients must expend 100% of the Total Project Cost 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. 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 not 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.

Please refer to the "Applicants' Guide to ARPA-E Award Negotiations" (https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance) for additional guidance on TT&O requirements.

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" (http://www.whitehouse.gov/sites/default/files/omb/grants/sflllin.pdf) 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.

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 Targeted 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 Targeted 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).

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 US dependence on foreign energy sources;
   b. Stimulation of domestic manufacturing/U.S. Manufacturing Plan;
   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. *Effective April 2, 2020:* **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/Pages/Opportunity-Zones.aspx*.

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 contractor 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 on a rolling basis approximately 90 days after submission of a Full Application.

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.E.2 of the FOA for guidance on pre-award costs. Please also refer to the "Applicants' Guide to ARPA-E Award Negotiations" (https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance) for guidance on the award negotiation process.

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.E.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.

1. DUNS NUMBER AND SAM, FSRS, AND FEDCONNECT REGISTRATIONS

Prime Recipients and Subrecipients are required to obtain a Dun and Bradstreet Data Universal Numbering System (DUNS) number at http://fedgov.dnb.com/webform and to register with the System for Award Management (SAM) at https://www.sam.gov/portal/public/SAM/.
Prime Recipients and Subrecipients should commence this process as soon as possible in order to expedite the execution of a funding agreement. Obtaining a DUNS number and registering with SAM 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/.[14] 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

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

compensation of each Subrecipient's five most highly compensated executives. Please refer to https://www.fsrs.gov/ for guidance on reporting requirements.

ARPA-E may not execute a funding agreement with the Prime Recipient until it has obtained a DUNS number and completed its SAM and FSRS registrations. In addition, the Prime Recipient may not execute subawards with Subrecipients until they obtain a DUNS number and complete their SAM registration. Prime Recipients and Subrecipients are required to keep their SAM and FSRS data current throughout the duration of the project.

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. Please refer to Attachment 6 of ARPA-E's Model Cooperative Agreement (https://arpa-e.energy.gov/?q=site-page/funding-agreements) for information on the National Policy Assurances.

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. Please refer to the "Applicants' Guide to ARPA-E Award Negotiations" (https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance) for guidance on the contents of cost share commitment letters.

4. COST SHARE PAYMENTS[15]

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.

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

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 see Section III.B.3 of the FOA.

Please refer to the "Applicants' Guide to ARPA-E Award Negotiations" (https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance) for additional guidance on cost share payment requirements.

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/?q=site-page/required-forms-and-templates. The Environmental Impact Questionnaire is due within 21 calendar days of the selection announcement.

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/?q=site-page/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. The DMP must meet the minimum requirements set forth in ARPA-E's "Applicant Guide to Award Negotiations" available at the following website: https://arpa-e.energy.gov/?q=arpa-e-site-page/pre-award-guidance."

8. U.S. Manufacturing Requirement

As part of its Full Application, each applicant is required to submit a U.S. Manufacturing Plan that includes the following U.S. Manufacturing Requirements. For more information on the required U.S Manufacturing Plan, see Section IV.C.7 above.

a. Small Businesses (including Small Business Concerns)

Small businesses (and in rare cases where a non-profit might manufacture) that are Prime Recipients or Subrecipients under ARPA-E funding agreements must agree that any products embodying any subject invention or produced through the use of any subject invention will be manufactured substantially in the United States for any use or sale anywhere in the world.

Small business must also agree that, for their exclusive and nonexclusive licensees, any products that embody any subject invention or that will be produced through the use of any subject invention will be manufactured substantially in the United States for any use or sale anywhere in the world.

Small businesses must require their assignees and entities acquiring a controlling interest in the small business to apply the same U.S. Manufacturing requirements to their licensees.

b. Large Businesses

Large businesses that are Prime Recipients or Subrecipients (and in rare cases, foreign entities that are subrecipients) under ARPA-E funding agreements are required to substantially manufacture the following products in the United States: (1) products embodying subject inventions, and (2) products produced through the use of subject inventions. This requirement applies to products that are manufactured for use or sale in the United States and outside the United States.

Large businesses (and in rare cases, foreign entities that are subrecipients) must apply the same U.S. Manufacturing requirements to their assignees, licensees, and entities acquiring a controlling interest in the large business or foreign entity. Large businesses must require their assignees and entities acquiring a controlling interest in the large business to apply the same U.S. Manufacturing requirements to their licensees.

c. Educational Institutions and Nonprofits

Domestic educational institutions and nonprofits that are Prime Recipients or Subrecipients under ARPA-E funding agreements must require their exclusive and nonexclusive licensees to substantially manufacture the following products in the United States for any use or sale anywhere in the world: (1) articles embodying subject inventions, and (2) articles produced through the use of subject inventions. Educational institutions and nonprofits must require their assignees to apply the same U.S. Manufacturing requirements to their licensees.

d. FFRDCs/DOE Labs and State and Local Government Entities

FFRDCs/DOE Labs that are GOCOs and state and local government entities that are Prime Recipients or Subrecipients under ARPA-E funding agreements must require their licensees to substantially manufacture the following products in the United States for any use or sale anywhere in the world: (1) products embodying subject inventions, and (2) products produced through the use of subject inventions. They must also require their assignees to apply the same U.S. Manufacturing requirements to their licensees. GOGOs are subject to the requirements in 37 CFR § 404.5(a)(2).

e. Criteria for Waiving U.S. Manufacturing Requirements

ARPA-E seeks to "enhance the economic and energy security of the United States …" and "ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies." The preferred benefit to the U.S. economy is the creation and maintenance of manufacturing capabilities and jobs within the United States. However, an applicant or awardee may request a modification or waiver of the standard U.S. Manufacturing Requirement, or its submitted U.S. Manufacturing Plan, if the applicant/awardee can demonstrate to the satisfaction of DOE/ARPA-E that it is not commercially feasible to comply with U.S. manufacturing requirements. In addition, such requests must include a description of specific economic or other benefits to the U.S. economy which are related to the commercial use by requestor of the technology being funded by ARPA-E and which are commensurate with the Government's contribution to the proposed work. These types of benefits are more easily measured and evaluated after technical advance has been made under an award, such as by the making of a subject invention.

Such benefits may include one or more of the following:

- Direct or indirect investment in U.S.-based plant and equipment.
- Creation of new and/or higher-quality U.S.-based jobs.
- Enhancement of the domestic skills base.
- Further domestic development of the technology.
- Significant reinvestment of profits in the domestic economy.
- Positive impact on the U.S. balance of payments in terms of product and service exports as well as foreign licensing royalties and receipts.
- Appropriate recognition of U.S. taxpayer support for the technology; e.g., a quid-pro-quo commensurate with the economic benefit that would be domestically derived by the U.S. taxpayer from U.S.-based manufacture.
- Cross-licensing, sublicensing, and reassignment provisions in licenses which seek to maximize the benefits to the U.S. taxpayer.
- Any foreign manufacturing/use will occur in a country that protects U.S. patents/intellectual property.

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 §200.205(c), subparagraphs (1) through (4). ARPA-E may require special award terms and conditions depending upon results of the risk analysis.

11. RECIPIENT INTEGRITY AND PERFORMANCE MATTERS

Prior to making a Federal award with a total amount of Federal share greater than the simplified acquisition threshold (presently $250,000), 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. 200.205).

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. §200.205.

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 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.

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/?q=site-page/funding-agreements).

VII. Agency Contacts

A. Communications with ARPA-E

Upon the issuance of a Targeted 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 periodic 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 Targeted Topic 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. Typically, either by operation of law or under the authority of a patent waiver, Prime Recipients and Subrecipients may elect to retain title to their subject inventions under ARPA-E funding agreements.

- 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. If Prime Recipients/Subrecipients elect to retain title, they must file a patent application in a timely fashion, generally one year from election of title, though: a) extensions can be granted, and b) earlier filing is required for certain situations ("statutory bars," governed by 35 U.S.C. § 102) involving publication, sale, or public use of the subject invention.
- All other parties: The Federal Non-Nuclear Energy Research and Development Act of 1974, 42. U.S.C. 5908, provides that the Government obtains title to new inventions unless a waiver is granted (*see below)*.
- Class Waiver: Under 42 U.S.C. § 5908, title to subject inventions vests in the U.S. Government and large businesses and foreign entities do not have the automatic right to elect to retain title to subject inventions. However, ARPA-E typically issues "class patent waivers" under which large businesses and foreign entities that meet certain stated requirements, such as cost sharing of at least 20%, may elect to retain title to their subject inventions. If a large business or foreign entity elects to retain title to its subject invention, it must file a patent application in a timely fashion. If the class waiver does not apply, a party may request a waiver in accordance with 10 C.F.R. §784.
- GOGOs are subject to the requirements of 37 C.F.R. Part 501.
- Determination of Exceptional Circumstances (DEC): DOE has determined that exceptional circumstances exist that warrant the modification of the standard patent rights clause for small businesses and non-profit awardees under Bayh-Dole to maximize the manufacture of technologies supported by ARPA-E awards in the United States. The DEC, including a right of appeal, is dated September 9, 2013 and is available at the following link: http://energy.gov/gc/downloads/determination-exceptional-circumstances-under-bayh-dole-act-energy-efficiency-renewable. Please see Section IV.C.7 and VI.B.8 for more information on U.S. Manufacturing Requirements.

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 five years 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 Targeted Topic announcements, are also posted to these websites. 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 Targeted Topics are posted. 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, Reply to Reviewer Comments, or other submission containing confidential, proprietary, or privileged information must 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.

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 Full Application, and Reply to Reviewer Comments.

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 in accordance with 2 C.F.R. § 200.29.

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.

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

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

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

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 any of the research and development work under an ARPA-E funding agreement, whether or not costs of performing the research and development work are being reimbursed under any agreement.

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.

Targeted 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 targeted 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 Targeted 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.E.8 of the FOA for more information).

I. APPENDIX A: EXTREMELY DURABLE CONCRETES AND CEMENTITIOUS MATERIALS

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Extremely Durable Concretes and Cementitious Materials"

Topic Issue Date	December 20, 2018
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, February 8, 2019
Submission Deadline for Full Applications	9:30 AM ET, February 19, 2019
Expected Date for Selection Notifications	May 2019
Total Amount to be Awarded	Approximately $8M total funding
Anticipated Awards	5-8 awards
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust titled "Extremely Durable Concretes and Cementitious Materials." 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 advancement of concretes, precursors (*e.g*. cementitious & pozzolanic materials, aggregates, admixtures) and concrete structures, (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

ARPA-E is interested in receiving Full Applications in support of advancing extremely durable concretes and cementitious materials. This topic seeks research towards concrete that outlasts conventional concrete, reduces lifetime O&M expenses and their associated energy requirements, and therefore greatly reduces cement/concrete. Work under this program will consist of early stage research.

a. Topic Overview

Concrete is second only to water as the most widely used substance in the world,[16] largely due to the material's low cost, abundance, and relative stability in myriad environments (e.g. marine; high temperature, pressure, salinity, radiation). The ubiquity of concrete comes with a significant energy and emissions footprint, [17] which threatens to grow as domestic infrastructure degrades with age.[18] Concrete is also a critical material for U.S. energy

[16] Scrivener, Karen L., Vanderley M. John, and Ellis M. Gartner. "Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry." (2016).
[17] EIA. The cement industry is the most energy intensive of all manufacturing industries. July 1, 2013. EIA: Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=11911
[18] ASCE. 2017 Infrastructure Report Card. American Society of Civil Engineers (2017).

production, one that can have a significant impact on the cost, productivity, and resilience of key resources such as nuclear, fossil, wind, and hydroelectric power.

Over the last century, alterations to concrete mixtures – namely, the increase in cement fineness and C3S content and concomitant C2S decrease[19] - have emphasized early strength gain to accommodate an increase in the rate of construction. Several surveys have uncovered an increasing rate of deterioration for these early-strength mixtures when compared to older, higher C2S concrete blends.[20] More specifically, modern (e.g. 1950 and beyond) concrete mixes have been found to crack more easily, primarily due to lower creep, higher shrinkage and a higher elastic modulus.[20] Cracks present a critical vulnerability to any concrete structure, allowing harmful ions and gases to penetrate the structure's interior; in many cases, these harmful substances come in contact with the reinforcing steel used in most concrete structures. Corrosion of the steel rebar via the permeation of either water, air, and/or chlorine (such as from the marine environment or common de-icing salts), can result in a 12-27% reduction in usable life expectancy for the concrete structure.[21]

Rising demand for concrete – which, in the U.S., is largely driven by an aging infrastructure - could more than double the energy and emissions associated with its domestic production. Furthermore, the use of modern concrete mixtures in repair and replacement of infrastructure composed of older, more-durable concrete threatens to further drive energy use as the push for strength and speed comes at the cost of long-term durability. Without intervention, modern mixtures require more frequent repair and replacement, which translates to higher energy and emissions for both concrete production and the labor, equipment, *etc*., associated with operation and maintenance. At the same time, the low cost and operational simplicity of modern concrete represents a major hurdle to innovation as infrastructure projects face strong pressure towards low cost bids and complicated incentives between suppliers, builders, owners and operators. Attempts to introduce superior performance at a higher cost (*e.g.* materials, labor, curing time) – or without a clear value proposition - are unlikely to succeed on an impactful scale. In light of these market criteria, reverting to mixtures that improve durability at the cost of construction efficiency is not a viable option.

While previous efforts have seen some success in reducing the energy intensity of cement and concrete *production*, ARPA-E sees an opportunity to lower the energy devoted to concrete materials and infrastructure by extending the *service life/use* stage of the material's lifecycle. **Therefore, the overarching objective of this research opportunity is to develop material and**

[19] C_3S is tricalcium silicate, also known as Alite; it is a component of cement which is largely responsible for the fast-setting and initial strength development of cement. Alite is also formed at the highest cement kiln temperatures (1300+ °C) and is a contributor to the high CO_2 emissions and energy requirements from cement production. C_2S is dicalcium silicate, also known as Belite; it is less reactive at early stages, contributing to strength development at later stages, and can be produced at lower kiln temperatures (up to 100 °C lower than Alite).
[20] Mehta, P. Kumar, and Richard W. Burrows. "Building durable structures in the 21st century." Indian Concrete Journal 75.7 (2001): 437-443.
[21] Jones, Scott, *et al.* "Simulation studies of methods to delay corrosion and increase service life for cracked concrete exposed to chlorides." *Cement and Concrete Composites* **58** (2015): 59-69.

process improvements that would (1) significantly (*e.g.* 2X or more) improve the durability of concrete and cementitious materials, while (2) maintaining or lowering the energy and emissions related to production and deployment of the material, and (3) remaining cost competitive with traditional materials when accounting for the intended service life and maintenance cycle.

More durable concrete can lower the overall energy input for concrete structures by significantly delaying the need for repair and replacement; for major concrete projects, and particularly for nuclear facilities, such developments could have tremendous economic potential. Finally, there may also be opportunities to lower infrastructure investment costs through advanced mixtures and manufacturing practices that improve durability while reducing material and/or time requirements for construction. If successful, these developments would produce high value, differentiated products and processes that would better position the U.S. concrete and construction industry to lead in a growing international market.

ARPA-E seeks input from researchers, manufacturers, suppliers and end-users of such technologies (*e.g.* the construction, manufacturers, specifiers, civil, and nuclear engineering communities). Consistent with the agency's mission, ARPA-E is seeking clearly disruptive, novel technologies, early in their R&D cycle. Incremental improvements and integration strategies for existing technologies are not of interest.

b. Technical Areas of Interest & Performance Targets

ARPA-E is specifically interested in technologies within one or more of the categories below that would:

(1) significantly (*e.g.* 2X or more) improve the durability of concrete and cementitious materials, while
(2) maintain or lower the energy and emissions related to production and deployment of the material, and
(3) remaining cost competitive with traditional materials when accounting for the intended service life and maintenance cycle.

CATEGORY 1 – Materials & Mixtures:

- Molecular design of more durable cementitious materials and concrete mixtures
  - Significantly reduce (*i.e.* ≤ 100µm), or eliminate, micro-cracking
  - Improve ductility (Target 0.75% - 2%)
  - Self-healing (*e.g.* w/wo chemical additives, fibers, active aggregate, pozzolans)
  - Extremely low permeability
  - Similar or reduced set-time while improving toughness and durability
- Materials and mixtures capable of enabling additive manufacturing techniques while preserving or enhancing durability

CATEGORY 2 – Advanced Processing:

- Advanced mixing and/or pre-blending systems to enable scale up of tailored mixtures
- Novel pathways toward low-temperature processing of highly-durable materials
- Novel methods of achieving and/or verifying uniformity of mixture designs and final structures
- Novel manufacturing and/or construction approaches that would result in reduced set-time while improving concrete toughness and durability
- Technologies to enable additive manufacturing for large-scale (> 125 m^3) construction (*e.g.* system controls, precise material delivery, in-field blending or compounding)

CATEGORY 3 – Modeling, Testing, Sensing, & Maintenance:

- Structure-process-property predictive models to define degradation pathways, enable more precise mixture evaluation, and identify optimal repair timing and materials
- Accelerated durability testing for concretes and cementitious materials
- Advanced non-destructive survey and sensing techniques for monitoring concrete structures
- Novel repair methods capable of significantly extending the lifetime of existing concrete structures

In addition to the requirements stated in the FOA, please include this table in the Technical Volume. Note that this table will count towards the 14 page limit of the Technical Volume. Please provide estimates of the durability improvement, embodied energy savings, and cost of the proposed technology:

Description	Response/Comments (include references where possible)
Estimated durability improvement: Provide the anticipated application, lifetime for SOA materials and expected improvement (*e.g.* %, years) for both maintenance frequency and replacement frequency.	
Estimated embodied energy savings: Provide the estimated energy intensity of the proposed solution, the anticipated demand and associated energy savings throughout the service life cycle.	
Estimated cost: Provide the target cost and associated assumptions for your proposed technology. Should the target cost exceed that of traditional materials or approaches, please justify the cost in the context of service life, maintenance schedule, user impact, *etc.*	

3. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Approaches seeking incremental improvements to current cement and concrete materials, including OPC, geopolymers, and additives.
- Approaches seeking incremental improvements to concrete construction techniques, including marginal advances in pour-in-place and pre-casting techniques.
- Approaches seeking incremental improvements to additive manufacturing techniques, equipment and materials, including technologies specifically targeted to small-scale (<125 m^3) 'printed' structures.
- Demonstration projects that do not include a significant degree of technical risk.
- Approaches for which the capital, material, labor, and repair costs (life-cycle cost) exceed *current* life-cycle costs in the proposed application space.
- Technologies that are not suitable for use throughout the entire United States, including technologies that rely on a single, site-specific geologic material (*e.g*. limited, specific mineral only located in a particular region) are specifically not of interest.
- Primary application areas other than nuclear or infrastructure (*e.g*. commercial and residential buildings)

II. APPENDIX B: LEVERAGING INNOVATIONS SUPPORTING NUCLEAR ENERGY

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Leveraging Innovations Supporting Nuclear Energy"

Topic Issue Date	December 20, 2018
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, February 8, 2019
Submission Deadline for Full Applications	9:30 AM ET, February 19, 2019
Expected Date for Selection Notifications	May 2019
Total Amount to be Awarded	Approximately $8M total
Anticipated Awards	3-5 awards
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust titled "Leveraging Innovations Supporting Nuclear Energy." 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 development of enabling technologies which will reduce the cost of nuclear energy (2) provide a timetable for the submission of Full Applications.

2. Topic Description

For nuclear energy to support U.S. national interests in the coming decades, the next generation of nuclear reactor plants need to simultaneously achieve extremely low construction capital costs, short construction and commissioning times, and "walkaway" safe and secure operation. To attain these goals, innovative, enabling technologies for existing advanced reactor designs[22] are needed. There are many different advanced nuclear reactor designs being developed in the U.S.[23] The collection of these reactor designs has the potential to meet many different market needs of the future: flexible, dispatchable electricity generation; a variety of generation sizes; high-temperature heat; autonomous operations; etc. For these technologies to be successful, however, they need to avoid the challenges faced by the current fleet of nuclear reactors as well as domestic new build projects. Existing nuclear power plants are facing the significant challenge of having comparatively high operational and maintenance (O&M) costs that come from the high staffing level required for operation, maintenance, safety, and security.[24] Many of the Generation III+ reactors under construction have been plagued by escalating capital costs and unpredictable construction schedules. Today, only two such Gen III+

[22] Existing advanced reactor designs include classes of non-light water reactors that are being planned or have been used in the past. This includes designs that use as heat transfer media: gas, lead (or lead-bismuth alloy), molten salt, sodium, supercritical water, organics; and as nuclear fuel types: ceramic oxides, nitride, metal, triso clad, silicon carbide clad, metal clad, liq uid eutectic.
[23] https://www.thirdway.org/graphic/keeping-up-with-the-advanced-nuclear-industry
[24] Nuclear Energy Institute. *Nuclear Costs in Context*. April 2016.

Light Water Reactors (LWRs) are scheduled to come online in the U.S. by 2021, significantly behind schedule and over budget.[25]

It is clear that a substantial reduction of construction cost, O&M cost, and construction time, in combination with targeting reactor plant operation for commercial viability, is required to fundamentally enhance the competitiveness and attractiveness of nuclear energy. The ARPA-E MEITNER Program (DE-FOA-0001798)[26] is already investigating several innovative technologies that forward this goal. The purpose of this Targeted Topic is to address key technology gaps in the portfolio.

A. Technical Areas of Interest

- Approaches employing sensors, data analytics, robotics, and advanced controls (including autonomy and integration of machine learning) that limit or eliminate the need for humans to conduct regular monitoring and maintenance and enable early corrective action for abnormal conditions.
- High-performance moderators for gas-cooled reactors to enable increased power density.
- Advanced power conversion systems for ultra-high temperature (>1500 °C) reactors.
- Flexible power production via technologies that enable physically changing plant power output via sophisticated controls systems or management of reactor feedback behavior, or systems that enable variable output like storing heat for later use.
- Advanced construction techniques for faster, lower-cost construction.

3. Submissions Specifically Not of Interest

- Technologies specifically for LWRs, including Generation III or III+ LWR designs.
- Technology development that is not distinct in approach or objective from activities currently supported by or actively under consideration for funding by any office within the Department of Energy.
- Exploratory work in new nuclear reactor core concepts.
- Technologies for reactors that require fuel enriched to >20% ^{235}U (if using uranium for fuel) or fuels that are not expected to be available for large-scale commercial deployment in the foreseeable future.
- Regulatory approaches.
- Heat exchangers.

[25] http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx, https://www.scana.com/investors/nuclear/questions-answers
[26] https://arpa-e.energy.gov/?q=arpa-e-programs/MEITNER

III. APPENDIX C: DOWNHOLE TOOLS TO ENABLE ENHANCED GEOTHERMAL SYSTEMS

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Downhole Tools to Enable Enhanced Geothermal Systems"

Notice Issue Date	December 20, 2018
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, February 8, 2019
Submission Deadline for Full Applications	9:30 AM ET, February 19, 2019
Expected Date for Selection Notifications	May 2019
Total Amount to be Awarded	Approximately $2M total
Anticipated Awards	2-4 awards
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust titled "Downhole Tools to Enable Enhanced Geothermal Systems". 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 development of novel, ultra-high pressure and temperature sensors, (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for the submission of full applications.

2. Topic Description

The United States possesses a massive strategic asset in its supply of geothermal energy: deep, extremely hot (3-10 km, 150-350+ ºC) enhanced geothermal systems (EGS) represent a potential zero-carbon resource capable of delivering hundreds of gigawatts of baseload electricity with a small land footprint per unit power.[27,28] Moreover, utilizing this resource leverages many of the domestic oil & gas (O&G) industry's sophisticated subsurface techniques and sources of human capital. However, US geothermal production has been stagnant at 2-3 GW for decades, owing to difficult technical requirements, high risk profiles, long payback times, and geographic limitations for shallow (< 3 km), more easily accessible hydrothermal sites.

EGS has the potential to improve the economics and lessen the geographic restrictions on geothermal energy, but unlocking this resource will require step-changes in reservoir engineering capabilities. In particular, there is a strong need to measure rock stress state,

[27] Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E., Garnish, J., Livesay, B., Moore, M.C., Nichols, K. and Petty, S., 2006. The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century. Massachusetts Institute of Technology, 209.

[28] Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutiérrez-Negrín, L., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., Zui, V., 2011: Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

temperature, and permeability during reservoir development, as well as geofluid flow rates, temperatures, and steam fractions during operation.[29]

A wide variety of downhole sensing tools have been developed for O&G applications. Many of these tools are rated to 150–175 ºC and thus suitable for low-temperature geothermal systems, but there is a substantial technological gap in tools suitable to the high-temperature environments relevant to deep EGS.[30] Further complicating matters, when compared to traditional O&G, EGS rock formations are harder and less homogeneous, fluid compositions can be more corrosive, and operators work within tighter economic constraints.[31] Thus, while tools developed for O&G may provide sources of inspiration, they are far from uniformly transferable to EGS.

ARPA-E seeks novel low-cost sensor technologies capable of mitigating risks and lowering costs in EGS development by better characterizing rock formations and fluid enthalpy at depth. Technologies of interest include but are not limited to fiber-optic sensors and enthalpy measurement devices, as well as companion electronics and communications equipment. Successful projects will facilitate reservoir creation and maintenance, reduce unexpected reservoir behavior, and ultimately lower costs associated with EGS. Successful technologies developed for this purpose may also offer side benefits in applications including O&G, subsurface energy/CO_2 storage, aerospace and automotive engineering, nuclear energy, and space exploration.

A. Technical Areas of Interest

High-temperature downhole sensing tools for reservoir engineering, including but not limited to the following two categories:

A. Fiber-optic based sensors, such as distributed acoustic sensing (DAS), distributed temperature sensing (DTS), and distributed strain sensing (DSS).
B. Sensors that measure geofluid enthalpy; in particular, devices that measure real-time flowrate, temperature, steam fraction and pressure.

Integrated sensors that can serve more than one function over the course of operations (e.g. strain and flow measurements) are encouraged.

[29] Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F. and Sanjuan, B., 2017. Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. Geothermal Energy, 5(1), p.16.

[30] DeBruijn, G., Skeates, C., Greenaway, R., Harrison, D., Parris, M., James, S., Mueller, F., Ray, S., Riding, M., Temple, L., Wutherich, K., 2008. High Pressure, High Temperature Technologies. Oilfield Review p.46.

[31] Gehringer, M., Loksha, V., 2012. Geothermal Handbook: Planning and Financing Power Generation. ESMAP Technical Report 002/12. World Bank, Washington, DC.

B. Technical Performance Targets

Across both categories:

- Continuous (>100 hour) operation at >280 ºC/>100 bar/30,000 ppm total dissolved solids (TDS); ideally above >373 ºC/>221 bar/300,000 ppm TDS.
- Maximum diameter of 5”.
- > 99% measurement accuracy over instrument lifetime.
- Compatibility with standard signal processing equipment.
- Measurement resolution and sensitivity matching or exceeding the state-of-the-art in analogous sensors made for oil & gas applications.
- Costs, once scaled up, that are no higher than those of analogous sensors made for oil & gas applications.

Specific to Category A:

- Spatial resolution of < 1 m in 10 km.
- Scalability to > 10 km fiber length.

Specific to Category B:

- Measurement location should be precisely known or easily derived.
- Quantification of both low flowrates characteristic of small fractures (Darcy regime) and high flowrates characteristic of wellbores (> 80 kg/s).
- Flow direction measurement capabilities.

3. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Tools that have a maximum operating temperature of ≤ 280 ºC.
- Solutions applicable to only shallow (< 3km) depths.
- Incremental advances to existing tools.
- High-temperature electronics/optics without a downhole sensor.
- Models without developing a new technology.
- Development of new wells.
- Improvements to practice without developing a new technology.

B. Technical Performance Targets

Table 1 lists the design target areas for this research thrust and provides the current state-of-the-art. Note that these are the same targets as in the ARPA-E MEITNER (DE-FOA-0001798) Program. Applicants are required to address at *least one* area, providing their own targets if the entry is blank. Applicants must detail either (1) how their technology enables the performance specified, or, (2) in the case that this performance is not yet obtainable, a realistic pathway such that the performance may be obtained in a relevant timeframe. Technoeconomic analysis to support claims of impact is required.

In addition to the requirements stated in the FOA, please include this Table, along with supporting information and analysis in the Potential Impact Section of the Technical Volume. Note that this table will count towards the 14 page limit of the Technical Volume.

Table 1. Enabling technologies sought by ARPA-E must improve reactor performance in *one or more* target areas.

ID	Metric	Units	State-of-the-Art	Performance with new technology
1	Overnight construction cost	$\$/W_e$	2-7 [32]	< 2
2	On-site construction time	Months	> 60 [33]	
3	Total staffing level (on-site & off-site)	FTE/GW_e	450-750 [34]	< 50
4	Emergency planning zone (EPZ)[+]	Miles	10 and 50 [35]	
5	Time before human response required for an accident	Days	3 [36]	
6	Onsite backup power	kW_e	> 0 kW [37]	
7a	Ramp rate without steam bypass	power capacity/min	5% [38]	

[32] http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx, http://www.world-nuclear-news.org/NN-Flamanville-EPR-timetable-and-costs-revised-0309154.html

[33] http://www.world-nuclear-news.org/NN-Key-commissioning-test-completed-at-Korean-unit-1711165.html, http://www.world-nuclear-news.org/NN-Flamanville-EPR-timetable-and-costs-revised-0309154.html

[34] https://www.eucg.org/pub/3ff048c1-f842-57dd-f625-bc35440aa9c4

[35] https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html

[36] http://www.nuscalepower.com/images/our_technology/nuscale-safety-nucl-tech-may12-pre.pdf, https://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-4-8-ANRT-WS/2_USA_UK_AP1000_Westinghouse_Pfister.pdf

[37] https://www.nrc.gov/docs/ML1122/ML11229A062.pdf

[38] http://nuclear-economics.com/12-nuclear-flexibility/

7b	Process heat temperature	ºC	N/A	

+ As measured from the center of the nuclear reactor core to the boundary: location where, during an accident, radiation levels are 0.25 millisieverts/month or less above the background level.

As indicated in the Technical Volume Template heading, specify a technical category: Autonomous Operation, Gas Reactor Moderators, Advanced Power Conversion, Load Following, Advanced Construction. In addition, specify a technical subcategory based on heat transfer medium: Multiple Types / General, Gas, Heat Pipe, Lead, Molten Salt, Sodium, Other.

IV. Appendix D: Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion-Energy Concepts

Special Program Announcement for
Solicitation on Topics Informing New Program Areas
"Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion-Energy Concepts"

Notice Issue Date	February 13, 2019
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, April 5, 2019
Submission Deadline for Full Applications	9:30 AM ET, April 15, 2019
Expected Date for Selection Notifications	June 2019
Total Amount to be Awarded	Approximately $5M total
Anticipated Awards	3-5 awards
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust entitled "Diagnostic Resource Teams to Support the Validation of Potentially Transformative Fusion-Energy Concepts." The purpose of this announcement is to solicit submissions from experienced fusion researchers who have designed, implemented, and operated diagnostics for the characterization of high-temperature fusion plasmas. The immediate objectives of this Targeted Topic are:

a. Realizing plasma diagnostic systems, especially more costly or complex systems, that can be transported to and shared among different fusion experiments;
b. Enabling high-quality diagnostic measurements of plasma and fusion parameters on fusion-concept-exploration experiments supported by ARPA-E;
c. Leveraging the plasma diagnostic expertise of the entire fusion R&D community to advance potentially transformative fusion-concept research; and
d. Developing teams and experience to support a potential future expansion of diagnostic resource teams for fusion and private-public partnerships in general.

2. Topic Description

ARPA-E supports the exploration and development of potentially transformative fusion-energy concepts, with key aims of significantly lowering development costs and accelerating the timeline to commercial fusion energy. Most of the ARPA-E-supported fusion experiments would benefit from definitive diagnostic measurements to firmly establish the level of performance that has been achieved and/or to clearly identify issues if measured performance is worse than expected. In particular, several of these concepts are showing evidence of thermonuclear neutron production that could be consistent with ion temperatures above 1 keV (approximately 10 million degrees K). Measurements of key plasma parameters in these experiments are needed to confirm the observed neutron yields and determine whether they are consistent with thermonuclear plasma conditions. Such measurements would improve our understanding of these concepts and help identify and correct any deficiencies, if necessary. All of the concepts, including those not yet at keV-level temperatures, would benefit from multi-point, spatially and temporally resolved measurements of plasma parameters and their spatial profiles to experimentally infer particle, energy, and magnetic-field transport.

Many of the needed diagnostics require significant expertise and/or expensive hardware that are beyond the typical resources available to an earlier-stage fusion project. The diagnostics (and the resources to operate them and analyze the data) can cost as much as or more than the fusion experiment itself, and typically these diagnostics are available only at national-scale fusion facilities. A primary aim of this Targeted Topic is to stretch limited resources such that multiple promising, earlier-stage fusion experiments can benefit from advanced measurements to validate their performance, uncover problems, and guide research priorities.

A. Technical Areas of Interest

This Targeted Topic prioritizes establishing baseline plasma and fusion performance of ARPA-E-supported fusion concepts with the characteristics listed in Table 1, especially using diagnostics that can be transported to and shared among multiple experiments. All credible fusion approaches with a plausible pathway to commercially viable fusion energy are potentially of interest to ARPA-E. However, the list in Table 1 represents the highest priority concepts for this Targeted Topic.

Table 2 provides the *approximate* range of parameters of interest, being achieved now or possibly within the next 1–2 years, for each class of concepts. Submissions in response to this Targeted Topic should target one or both of these concept classes and corresponding parameter ranges. Conclusive measurements of the peak equilibrium values of the plasma parameters of interest (given in Table 2) are the highest priority, followed closely by time-resolved, spatial profiles of the same quantities. For neutron measurements, the chief aims are to obtain an accurate value of the total yield and to determine whether the yield is thermonuclear- or beam-dominated. It is expected that some combination of measuring both neutron energy spectra as well as spatial isotropy may be needed, depending on the class of concept. In addition, detailed Monte-Carlo modeling of neutron scattering for each experimental environment will likely be required. Diagnosis of neutron energy spectra for fusion-burn durations of order 1–10 μs is highly desirable for pulsed, intermediate-density concepts but presents challenges.

More advanced measurements to provide a deeper understanding of equilibrium, stability, and confinement (e.g., fluctuating quantities, particle distribution functions, etc.) are lower priority at this time, but remain of interest for a potential future expansion of this program. Similarly, activities to generate synthetic data are low priority under this Targeted Topic, but may be of interest in the future.

Submissions including scopes of work to help facilitate more routine use of shared diagnostics in the future, e.g., design and implementation of standardized chamber-to-diagnostic port interfaces for use on all smaller-scale fusion experiments, are encouraged. It would be desirable for the fusion R&D community to agree on standard ports for particular diagnostics going into the future.

Table 1. Priority concepts for which diagnostic measurements are solicited under this Targeted Topic.

Concept	**Class**	**Plasma size/ duration**	**Priority measurements**
Flow-shear-stabilized Z pinch [1–3]	Pulsed, intermediate-density	L=50 cm r≈0.15 cm τ_{plasma}≈ 50 μs $\tau_{neutrons}$≈5 μs	T_e, neutron energy spectrum, internal B-field, ion velocity and T_i
Staged Z pinch (gas-puff liner compressing a gas-puff Z pinch) [4–6]	Pulsed, intermediate-density	L=1 cm r≈2→0.02 cm τ_{plasma}≈120 ns $\tau_{neutrons}$≈2 ns	Neutron isotropy and energy spectrum, T_e, T_i, n_e, internal B-field
Magnetic compression of merged FRCs [7,8]	Pulsed, intermediate-density	L=30 cm r≈4 cm τ_{plasma}≈ 100 μs $\tau_{neutrons}$≈10 μs	n_e ,T_e , T_i, Z_{eff} (in D plasma), radiated power
FRC sustained and heated by rotating magnetic field [9,10]	Magnetically confined	L≈15 cm r≈5 cm τ_{plasma}≈300 ms	n_e and T_e profiles, B-field polarity and profile, density fluctuations (0.01–1 cm; 0.1–200 MHz)
Spheromak sustained by imposed dynamo current drive [11–14]	Magnetically confined	R≈34 cm r≈24 cm elong.≈1.2 τ_{plasma}≈2–5 ms	n_e ,T_e , T_i profiles

B. Submissions Specifically Not of Interest

- Significant development to demonstrate diagnostic feasibility or new diagnostic approaches (i.e., successful proposals should focus on adapting or extending proven diagnostic methods to the ARPA-E fusion experiments and in "packaging" the diagnostic for versatility, adaptability, and transportability)
- Generation of synthetic diagnostic signals from numerical simulations that require significant effort.

Table 2. Parameters of interest and their approximate range of values for the two classes of priority concepts given in Table 1.

Parameter of interest	Magnetically confined	Pulsed, intermediate density
Ion and electron density	10^{13}–10^{14} cm^{-3}	10^{16}–10^{21} cm^{-3}
Electron temperature	10–2000 eV	100–3000 eV
Ion temperature	10–2000 eV	100–10000 eV
Magnetic field	0.1–3 T	1–1000 T
Neutron yields	N/A	10^6–10^{12} (DD)
Neutron energy	N/A	2.3–2.8 MeV w/few-keV resolution
Neutron duration	N/A	10 ns – 10 µs
Desired time resolution	< 100 µs	1–1000 ns
Desired spatial resolution	< 1 cm	< 1 mm

3. Modifications to Technical Volume Template

Due to the narrow focus of this Targeted Topic on diagnostics in support of ongoing ARPA-E-sponsored fusion experiments, please follow these instructions in using the required Technical Volume template.

- Address Sec. 1, Innovation and Impact, in the narrow context of the diagnostics and measurements being proposed, and not in the context of the fusion concept/experiment for which the measurements are intended. The innovation being sought (Sec. 1.3) is in packaging proven diagnostic technologies for versatility, adaptability, and transportability.
- In Sec. 2.2, please include diagnostic design and implementation, as well as involvement in fielding the diagnostic and performing data analysis on the remote experiment(s), with a commensurate budget request. Please include the following table summarizing your proposed measurements and diagnostics.

Quantity measured	Diagnostic method	Range and resolution	Concept(s)	Spatial/ temporal resolutions	How many spatial points?
#1		e.g., $T_{e,low}$–$T_{e,high}$ ($\pm\,\delta T_e$)	Sustained spheromak and FRC, etc.	$\delta \boldsymbol{x}$, δt	
#2					
etc…					

- In Sec. 2.3, please indicate the schedule to readiness for the first measurement, and the minimum interval time required between take-down and readiness for the next measurement at a different experiment. Proposing teams are strongly encouraged to aim for

very aggressive schedules, with first measurement in < 9 months and interval time measured in days or a few weeks, with a commensurate budget request.
- Skip Secs. 4.1 and 4.2, and address Sec. 4.3 as instructed in the Technical Volume template, with a commensurate reduction in overall length of Sec. 4 from the original suggested total of 2 pages.

Submissions are *not* expected to provide highly detailed diagnostic designs, as ARPA-E recognizes that this is possible only after an Award Recipient is able to work closely with a fusion-concept team to determine the details of the plasma parameters, port positions and access, etc. ARPA-E will facilitate interactions between Award Recipients and the fusion-concept groups. It is expected that a mutually agreeable arrangement to manage the treatment of existing data and to manage the data and intellectual property arising from those interactions will be developed between the Award Recipients and fusion-concept groups.

The merit review criteria is defined in Section V.A.1 of the FOA. The following will be considered as part of the evaluation under Merit Review Criteria (1), Impact of the Proposed Technology (30%): ability to enable measurements on the priority concepts listed in Table 1. The following will be considered as part of the evaluation under Merit Review Criteria (2), Overall Scientific and Technical Merit (30%): versatility, adaptability, and transportability of the proposed diagnostics per cost, aggressiveness of schedule to first and subsequent measurements, and minimum development with regard to diagnostic feasibility/principle. Funds for this potential Targeted Topic are limited so teams are encouraged to adopt strategies to limit costs, e.g., use of existing equipment is encouraged but not required.

References

[1] U. Shumlak et al., Nucl. Fusion **49**, 075039 (2009).
[2] U. Shumlak et al., Phys. Plasmas **24**, 055702 (2017).
[3] https://arpa-e.energy.gov/sites/default/files/03_SHUMLAK.pdf.
[4] J. Narkis et al., Phys. Plasmas 23, 122706 (2016).
[5] F. Conti et al., IEEE Trans. Plasma Sci. **46**, 3855 (2018).
[6] https://arpa-e.energy.gov/sites/default/files/04_WESSEL.pdf.
[7] J. Slough et al., Nucl. Fusion **51**, 053008 (2011).
[8] https://arpa-e.energy.gov/sites/default/files/05_KIRTLEY.pdf
[9] P. Jandovitz et al., Phys. Plasmas **25**, 030702 (2018).
[10] C. Swanson et al., AIP Advances **8**, 025222 (2018).
[11] T. R. Jarboe et al., Nucl. Fusion **52**, 083017 (2012).
[12] B. S. Victor et al., Phys. Plasmas **21**, 082504 (2014).
[13] D. B. Elliott et al., Rev. Sci. Instrum. **87**, 11 (2016).
[14] A. C. Hossack et al., Nucl. Fusion **57**, 076026 (2017).

V. Appendix E: Quantification of Effectiveness of Nutrient Bioextraction by Seaweed

Special Program Announcement for

Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)

"Quantification of Effectiveness of Nutrient Bioextraction by Seaweed"

Topic Issue Date	March 12, 2019
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, May 1, 2019
Submission Deadline for Full Applications	9:30 AM ET, May 13, 2019
Expected Date for Selection Notifications	July 2019
Total Amount to be Awarded	Approximately $1M total, maximum $300K per award
Anticipated Awards	3-5 fixed-amount grants
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust titled "Quantification of Effectiveness of Nutrient Bioextraction by Seaweed". The purpose of this announcement is to (1) solicit proposals focused on the development of enabling solutions capable of quantifying fate and transport of biologically relevant nitrogen species with high-spatial and high-temporal resolution in the context of seaweed farms in the marine environment, and (2) provide a timetable for the submission of Full Applications.

2. Topic Description

Nitrogen migration from anthropogenic sources, such as agricultural runoff or wastewater discharge, is responsible for eutrophication of marine systems causing anoxia, ecological disruption and reduction in productivity of natural systems and fisheries. Eutrophication can result in widespread "dead zones" and contribute to proliferation of toxic microalgae and/or cyanobacteria, as recently seen on Florida's Gulf Coast.

One potential solution is the large-scale cultivation of nitrogen-fixing seaweeds in these eutrophic marine systems. Seaweeds are non-vascular macroalgae plants capable of rapid growth via carbon fixation and effective uptake of nitrogen, predominately in the form of nitrate. When deployed in eutrophic marine systems, cultivation of seaweeds on a large scale may provide local, and possibly regional, mitigation of excess nutrient concentration via bioextraction. ARPA-E's MARINER program targets the development and deployment of new technologies for the economically viable production of seaweeds on a scale sufficient for bioenergy production.

The effectiveness of deploying seaweed farms for nutrient concentration extraction will be significantly influenced by local and regional geographic conditions. It is therefore important to identify the geographies along US coastlines that are the most suitable candidates for testing and deploying this eutrophication mitigation strategy.

In addition to the revenue from the harvested seaweed, seaweed farms deployed in eutrophic marine areas could generate additional benefits – and potentially revenue – for the ecosystem services they provide. In order to appropriately value the nutrient mitigation services provided by seaweed cultivation, appropriate methodologies are needed for accurate, low-cost nitrogen monitoring within the context of seaweed farming systems to quantify the amount of nitrogen present and assimilated by seaweed cultivation. ARPA-E seeks solutions that will add value to the MARINER program and provide technology-to-market (T2M) opportunities for large scale seaweed cultivation.

A. Technical Areas of Interest

A proposal can cover one, two, or all three technical areas of interest outlined below.

1. Identification of geographies where seaweed farms could have a proximal positive impact on nitrogen removal, including empirical assessment of nitrogen loading on a temporal basis. Specifically, ARPA-E envisions that seaweed farms should have a "local" effect to remove nitrogen and improve water quality for enhancement of ecosystem productivity. With that goal in mind, geographic areas of high nitrogen inundation need to be assessed for seaweed farm production. Target geographic areas will require temporal nitrogen assessment to quantify and compare the seasonality of nitrogen influx with the biological growing season of seaweeds.

2. Concepts for real-time assessment and validation of nitrogen flux and uptake within and around macroalgae farms. Specifically, new solutions are required for accurately monitoring the transport and fate of nitrogen in and around individual seaweed farms with appropriate spatial and temporal resolution. Current monitoring techniques mostly rely on laborious manual sampling and analysis resulting in low-to-moderate spatial and temporal resolution. Such data is a challenge to interpret and less likely to influence management decisions. ARPA-E is therefore interested in the development of solutions that integrate spatially distributed analytical monitoring with computational modeling of nitrogen transport through and uptake by seaweed farms.

3. Validated methods for rapid and reliable determination of the nitrogen tissue content of seaweed. When seaweed is harvested, the amount of nitrogen contained in its tissue is the minimal amount of nitrogen removed from the local environment. In order to attribute a proper value for this removal service, accurate and reliable measurements of the nitrogen content are crititical. The desired quantification methods need to be able to take into account and appropriately standardize the timing and conditions of harvest, the storage conditions until analysis, and any required sample preparation procedures for the species of seaweed under consideration.

B. Technical Performance Targets

Proposed solutions must address the following performance parameters. Recognizing the tradeoffs that will exist between these performance parameters, ARPA-E is not providing specific quantitative guidance, but submissions should include a justification for why the performance targets chosen by the applicant are appropriate relative to the project goals.

1. Identification and assessment of coastal geographies where seaweed farming will have high potential to locally reduce nitrogen eutrophication and improve water quality and ecosystem productivity.
   - Temporal and spatial survey of nitrogen loads in marine geographic area(s) with high potential to benefit from large scale (100+ hectares) seaweed cultivation.
   - Quantification of localized nitrogen reduction targets that need to be achieved for meeting remediation goals.
2. System-level solutions for real-time assessment and validation of nitrogen flux and uptake within and around macroalgae farms, combining computational modeling and field measurements.
   - Modelling of the rate of nitrogen uptake by a large scale seaweed farm under nutrient conditions representative of typical problem zones, and the projected nutrient levels at equilibrium conditions in farmed areas at the regional level (1 ha resolution) and farm-level (1 m^3 resolution).
   - Integration of modelling with field data acquisition, including specification of sampling frequency and analytical accuracy required.
   - Credible experimental design, including mass balances incorporating nitrogen concentration in macroalgal biomass, for validation of projected net impact of a macroalgae farm on nitrogen levels in the water column.
   - Economic analysis evaluating the cost of the solution, when deployed on an actual farm
   - Easy to deploy and operate (either as a farm-installed system or as a service)
3. Method development for quantification of nitrogen content in macroalgal biomass:
   - Highly reproducible measurement of total nitrogen content of seaweed grown in eutrophic marine environments.
   - Procedures for sample collection, storage, and preparation that can be reliably conducted in marine farm operations.
   - Benchmarking of the proposed methods to well established and validated procedures.

3. Submissions Specifically Not of Interest

- New methods for large scale macroalgae cultivation and harvesting
- Macroalgae breeding and genetics
- Processing of harvested macroalgae
- Development of completely new sensor technologies

4. ARPA-E Funding Agreement

ARPA-E anticipates awarding fixed-amount grants resulting from this Targeted Topic. ARPA-E will only award a fixed-amount grant in instances where it can be assured that the prospective awardee will not realize any increment above the actual cost of performing work. Equal payments will be made, one each upon submission and acceptance by ARPA-E of the quarterly report demonstrating sufficient technical progress. The final payment also requires certification to ARPA-E that all project activity has been completed. For additional information about fixed-amount awards refer to 2 C.F.R. § 200.45 and 2 C.F.R. § 200.201.

In addition to the aforementioned certification, awardees will be required, *inter alia*, to submit a final technical report to ARPA-E and 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 Targeted Topic is $300,000. As set forth at FOA Section III.B, cost share is not required for awards resuting from this Targeted Topic.

5. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, the content of Full Applications are limited to the following:

Component	Required Format	Description and Information
Technical Volume (Fixed-Amount 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/).
SF-424	PDF	Application for Federal Assistance (https://arpa-e-foa.energy.gov/). Applicants are responsible for ensuring that the proposed amounts listed in eXCHANGE match those listed on forms SF-424 and SF-424A. Inconsistent submissions may impact ARPA-E's final award determination.
SF-424A (Fixed-Amount Grant)	XLS	Budget Information – Non-Construction Programs (https://arpa-e-foa.energy.gov/)
Business Assurances & Disclosures Form	PDF	Requires the Applicant to make responsibility disclosures and disclose potential conflicts of interest within the Applicant Team. Requires the Applicant to 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 the Applicant is a FFRDC/DOE Lab, requires the Applicant to provide written authorization from the cognizant Federal agency and, if a DOE/NNSA FFRDC/DOE Lab, a Field Work Proposal. Allows

Component	Required Format	Description and Information
		the Applicant to request a waiver or modification of the Performance of Work in the United States requirement. This form 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.
U.S. Manufacturing Plan	PDF	As part of the application, Applicants are required to submit a U.S. Manufacturing Plan. The U.S. Manufacturing Plan represents the Applicant's measurable commitment to support U.S. manufacturing as a result of its award. See detailed U.S. Manufacturing Plan instructions and examples in the Seventh Component description below.

Detailed guidance on the content of the Technical Volume, SF-424, Business Assurances & Disclosures Form, and U.S. Manufacturing Plan can be found in FOA Section IV.C at paragraphs One, Two, Six and Seven respectively. Guidance on the content of the SF-424A can be found on its p.2.

Templates for preparing Full Applications under this Targeted Topic may be found on ARPA-E Exchange at ARPA-E-CO@hq.doe.gov.

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VI. APPENDIX F: HIGH VALUE METHANE PYROLYSIS

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"High Value Methane Pyrolysis"

Topic Issue Date	May 21, 2019
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, July 16, 2019
Submission Deadline for Full Applications	9:30 AM ET, July 26, 2019
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 4, 2019
Expected Date for Selection Notifications	October 2019
Total Amount to be Awarded	Approximately $5.5 million, subject to the availability of appropriated funds.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $500,000 and $2.0 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust entitled "High Value Methane Pyrolysis". The purpose of this announcement is to (1) focus the attention of the scientific and technical community on specific areas of interest related to methane pyrolysis, (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for the submission of full applications.

2. Topic Description

The United States currently produces about 10 million tons of hydrogen per year, primarily for use at petroleum refineries and for the production of ammonia and methanol. Today, nearly all of hydrogen produced in the US is derived from natural gas via steam methane reforming, a process which converts natural gas and water into hydrogen and carbon dioxide. Steam methane reforming, which is done almost exclusively in centralized facilities, offers the lowest factory gate cost of hydrogen (~$1.0-$1.2/kg), but also produces large quantities of carbon dioxide (9-14 $kgCO_2/kgH_2$).[39] While the market demand for hydrogen from steam methane reforming has remained relatively steady over the last few years, there is a significant growth potential for hydrogen with a small CO_2 footprint in electricity production, transportation, and novel chemical processes. Already, hydrogen use in the transportation sector has seen rapid

[39] Department of Energy Office of Energy Efficiency and Renewable Energy. Fuel Cell Technologies Market Report 2016. [https://www.energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf]

growth with 500 megawatts of fuel cells shipped worldwide in 2016.[40] Current options for producing hydrogen with little or no release of carbon dioxide include electrolysis of water to hydrogen and oxygen and steam methane reforming with CO_2 capture and sequestration.

A third option is to split methane directly into hydrogen and elemental carbon at high temperatures. *The hydrogen produced in this process, which is also known as methane pyrolysis or methane cracking, would contain roughly half the embodied energy of the natural gas feedstock, while the carbon could be used as a product.* Carbon products that have been produced via methane pyrolysis include metallurgical coke, carbon black, graphite, carbon nanotubes, and carbon fiber.[39]

The economics for methane pyrolysis is made more favorable when the carbon byproduct is valuable[41], or when the process is made more efficient and/or economical by the use of novel catalyzed processes. Methane can be pyrolized with high yields at moderate temperatures on supported or molten metal catalysts (Ni, Co, Fe, Pt, Pd); however, catalysts are rapidly deactivated by solid carbon.[42] Another complication is that processes optimized for hydrogen production may not produce valuable carbon products; optimizing processes for both hydrogen and valuable carbon products concurrently is a daunting challenge. Furthermore, it is important to recognize that, in the context of hydrogen production on an energy-relevant scale, the volumes of co-produced carbon would be very large. For perspective, to produce the amount of hydrogen required to produce 1 quadrillion (10^{15}) BTU (1 quad) of energy, over 22 million tons of carbon would be generated. Therefore, potential applications for the resulting carbon products at scale have to be on a correspondingly large scale, e.g., on the scale of the construction sector or large-scale manufacturing industries. These applications will require the carbon materials to have useful macroscopic properties with regard to thermal, electrical, and/or mechanical performance.

While ARPA-E has already selected for award negotiations a small number of methane pyrolysis projects as part of the OPEN 2018 funding opportunity, ARPA-E has identified an ongoing need to better understand the formation and control the production of specific carbon structures in a process environment that is simultaneously suitable for the economical production of hydrogen <u>at scale</u> (> 10,000 tons/yr.) with a low CO_2 footprint.

The functional performance of the carbon materials derived by methane pyrolysis will be determined by the molecular structure of the carbon, as well as by the arrangement and alignment of substructures at the nano-or meso-scale. Processes capable of selectively controlling the molecular structure, e.g. via rearrangement of carbon-carbon bonds, and/or the solid phases (i.e. crystal structure or molecular ordering) may have the potential to shift from a

[40] Department of Energy Office of Energy Efficiency and Renewable Energy. R&D Opportunities for Development of Natural Gas Conversion Technologies. [https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26726.pdf]
[41] Keipi, T., Hankalin, V., Nummelin., and Raiko, R., Techno-economic analysis of four concepts for thermal decomposition of methane: Reduction of CO2 emissions in natural gas combustion. Energy Conversion and Management, 2016. 110: p 1-12.
[42] Amin, A. M., Croiset, E., Epling, W. Review of methane catalytic cracking for hydrogen production, International Journal of Hydrogen Energy, 2011, 36, 2904.

lower value carbon to a higher value carbon product. In addition, there is a critical need for high-quality experimental data to better understand, and ultimately control, the elemental steps of forming carbon-carbon bonds and carbon structure development under methane pyrolysis conditions. Probing for chemical and/or structural information using non-intrusive in-situ methods at a time scale applicable for realistic process control at scale is a challenge, as are intrusive sampling and ex-situ measurement techniques. Therefore, *ARPA-E is also interested in combining novel integrated catalytic processes to pyrolyze methane with in-situ advanced monitoring and analytical techniques* to enable material development and process optimization to produce low cost hydrogen coupled with higher value carbon products at scale.

A. Technical Area of Interest

ARPA-E is specifically interested in *integrated and scalable catalytic approaches that can economically convert natural gas to both fuel cell-grade hydrogen and higher value carbon materials* such as carbon fiber or other structural materials with a low CO_2 footprint**.** **(**Table 1)

While scalable hydrogen production is the ultimate goal, the emphasis is to advance the identification, understanding, and control of new reaction conditions and processes necessary to direct carbon formation towards desirable product targets. Critical consideration should also be given to both (i) the separation techniques required to economically recover the targeted grades of carbon, and (ii) advanced monitoring tools (in-situ and ex-situ) to enable fundamental understanding of carbon-carbon bond formation, rearrangement, and intermolecular aggregation into valuable carbon products under current methane pyrolysis conditions (20 bar; 800–1100 ^{o}C), *in ways that are applicable for real-time process monitoring and control* (i.e. low latency).

B. Technical Performance Targets

Table 1: Catalytic processes to pyrolyze methane to hydrogen and carbon: Performance Targets

Performance Metric	Target
Net H2 Yield% (of theoretical)[(a)]	> 25
Hydrogen Cost ($/kg)[(b)]	< 1.5
(CAPEX+OPEX) Increase Factor vs SMR+CCS[(b)]	< 2.5
Carbon Product Price ($/kg)	< 5
CO_2 Emissions (kg CO_2 / kg H_2)	< 3

[(a)] Net H_2 Yield = (mol H_2 produced-mol H_2 used in process)/(2 mol CH_4).
[(b)] Input parameters, product specifications and methodology as defined in H2A DOE model, 380 t H_2 / day centralized H_2 generation.[43,44]

Note that these targets are intentionally flexible. For example, a higher cost process that also produced higher value carbon may be more attractive than a lower cost process that can't be controlled well enough to produce a high value carbon product. Applicants are expected to utilize the methodology described in the H2A DOE model (centralized hydrogen production models)[43,44] to project the performance metrics listed in Table 1 for their proposed process, and specify the size of the intended market and expected properties (i.e. electrical, mechanical) for the carbon co-product. Applicants must also include a description of the separating techniques and any advanced monitoring tools , as described in Section 2.A. above, that would be necessary for successful completion of the proposed approach.

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Approaches that produce carbon materials primarily intended as filler in composites where the performance properties of the composite are defined primarily by the binder and not the carbon material.
- Approaches that produce carbon materials from non-gaseous feedstocks, e.g. pitch or polyacrylonitrile (PAN).
- Approaches that are unscalable.
- Approaches based on solar-thermal methane pyrolysis.
- Standard IR, Raman, UV-Vis, microscopy techniques for ex-situ analysis of polyaromatic hydrocarbons.

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[43] https://www.nrel.gov/hydrogen/h2a-production-models.html, centralized hydrogen production model, v3 2018.
[44] https://www.nrel.gov/hydrogen/h2a-production-case-studies.html, case study: central natural gas, future central hydrogen production from natural gas with CO2 sequestration version 3.2018

VII. Appendix G: Reserved

VIII. APPENDIX H: Establishing validation sites for field-level emissions quantification of agricultural bioenergy feedstock production

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Establishing validation sites for field-level emissions quantification of agricultural bioenergy feedstock production"

Topic Issue Date	September 17, 2019
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, November 7, 2019
Submission Deadline for Full Applications	9:30 AM ET, November 18, 2019
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday December 11, 2019
Expected Date for Selection Notifications	January 2020
Total Amount to be Awarded	Approximately $10.0 million, subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $100,000 and $3.61 million.
Maximum Period of Performance	36 Months

1. Introduction

This announcement describes a research thrust titled "Establishing validation sites for field-level emissions quantification of agricultural bioenergy feedstock production." The purpose of this announcement is to (1) focus attention of technical and research communities on the challenges and benefits of establishing "ground truth" sites in feedstock production environments as a means to validate emerging sensors and sensor systems capable of quantifying field-level emissions, (2) encourage dialogue amongst technology developers, feedstock producers and relevant agricultural stakeholders about leveraging these field sites, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

The United States produces ~16 billion gallons of ethanol annually, meeting ~1% of our nation's energy needs.[45] The primary feedstock for ethanol production is starch from corn and sorghum, making the ethanol industry one of the largest consumers of domestic grain (38% in 2018).[46]

[45] EIA Monthly Energy Review, Table 10.3 from the U.S. Energy Information Administration
[46] United States Department of Agriculture Economic Research Service Feed Grain Yearbook. Total Production category and Feed and Residual Use category collected from Table 4, Produced for Other Uses category and Used for Ethanol category collected from Table 31. Last Accessed 1/10/2019

Ethanol and other bio-based fuels have the potential to provide an emissions-free source of energy on a net basis[47], but not without a shift in feedstock production practices. Current feedstock production practices are driven by yield, and low profit margins leave feedstock growers with limited options for increasing productivity; often, this comes in the form of over-fertilization, which produces unnecessary emissions,[48] impacts water quality,[49] and has uncertain returns (e.g. an estimated $267–702 million dollars of fertilizer value is lost each year[50]). While these impacts become clear when aggregated to the regional or national scale, field-level contributions remain unknown. This lack of visibility, combined with the absence of economic incentives beyond yield, leaves feedstock producers to estimate and assume the risk of new management practices to their primary revenue stream (i.e. yield). By establishing sites and protocols for measuring the impact of management practices on both yield and emissions (CO_2 equivalent), this funding opportunity aims to bridge the technology gap between feedstock producers and existing market incentives that can de-risk sustainable management practices and defray the cost of monitoring their impact.

Analysis by Argonne labs using the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model provides a complete lifecycle analysis (LCA) of transportation fuels including gasoline and ethanol derived from multiple different feedstocks.[51] On average, grain production accounts for 36% of the fuel production life cycle; however, there is a broad range of yields and efficiencies across different regions and significant room for improvement to both. New developments in digital agriculture, analytics, sensor engineering, and identity preservation developed for medical and security purposes are primed for adaption to agricultural production systems to create new monitoring and decision support systems.[52] These datasets have the potential to drive new value streams through ecosystem service markets focused on reducing emissions and improving soil quality. While downstream stages of ethanol production are already realizing significant value through existing markets (e.g. California's Low-Carbon Fuel Standard), grain producers do not have access to those markets because they lack reliable, and cost-effective, methods of quantifying ecosystem impacts. Accurate quantification of field-level inputs, emissions, and yield would allow producers to participate in these existing markets, complementing existing yield-based revenues with economic incentives for input efficiency and restorative practices. While initially applying to existing markets, which could extend to biomass crop feedstocks, these tools could also be applied to production agriculture more broadly to improve its energy balance.

[47] Includes assumptions about soil organic carbon storage potential – see the ARPA-E ROOTS FOA (DE-FOA-0001565) for more details.
[48] EPA. 2019. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 (Chapter 5: Agriculture).
[49] USGS. Nitrogen and Water. https://www.usgs.gov/special-topic/water-science-school/science/nitrogen-and-water?qt-science_center_objects=0#qt-science_center_objects
[50] Basso, Bruno, et al. "Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest." *Scientific reports* 9.1 (2019): 5774.
[51] https://greet.es.anl.gov/
[52] ARPA-E 2018 Workshop: The Energy-Smart Farm: Distributed Intelligence Networks for Highly Variable and Resource Constrained Crop Production Environments. https://arpa-e.energy.gov/?q=workshop/energy-smart-farm-distributed-intelligence-networks-highly-variable-and-resource

Precision agriculture, including variable prescriptions for seed and chemical inputs, is critical to improving production efficiency. Economic forces have hindered adoption of technology for grain production, and decision support and agronomic advice based on sensor data is lacking as innovators from other communities have only recently become interested in working in agriculture. Furthermore, the R&D community lacks methods for validating the performance of new technologies, particularly in large-scale feedstock production environments. Establishing methods for validating commercial solutions for field-level emissions quantification is essential to building stakeholder trust in these technologies and the markets they feed into.

ARPA-E will provide financial support to teams that include production farms that could market directly to ethanol and other biofuel producers to develop datasets of current production inputs (e.g. fertilizer, chemicals, fuel) and outcomes (e.g. yield, emissions, water quality) in a commercial production environment. In doing so, this funding opportunity aims to fund the creation of "gold-standard" datasets to (i) pilot data capture and transfer methods for supply-chain-wide LCA, (ii) validate new, low-cost technology approaches to measuring and improving feedstock production efficiency, and (iii) provide new high-resolution data to the R&D community for technology development (e.g. remote sensing to reduce physical footprint of high-resolution monitoring; new modeling, prediction and extrapolation techniques).

A. Technical Areas of Interest & Performance Targets

ARPA-E seeks to fund the development of "ground truth" solutions that establish measurements and protocols for emissions monitoring at the field level and provide agronomic insight. The primary goal of this targeted topic is to fund project teams to establish publically available open-source, high-resolution datasets to support testing and validation of emerging biofuel production monitoring technologies. A submission to this Targeted Topic must include an applicable commercial field site (described in more detail below) and describe the Applicant's ability to:

- Establish a data protocol (e.g. modality, spatial resolution, and frequency) for quantifying field-level emissions, including soil carbon storage.
- Develop clear methods for assessing commercial solutions for emissions quantification at the field level.
- Garner stakeholder input and collaboration across the supply chain.
- Secure and share field-level datasets (i.e. open access data) both during and after the period of performance.
- Engage community members across the energy-water-food nexus to share best practices, collaborate on technology challenges, and encourage data standardization and transparency.

Data requirements: The data requirements listed below are intended to serve as a framework and should be considered a minimum requirement for quantifying (i) fertilizer-induced emissions, (ii) biomass-induced emissions, (iii) biomass nitrogen content, and (iv) soil organic carbon (SOC) sequestered at high accuracy and precision.

Applicants must define how they will ensure data quality and data security. Applicants must also describe how and for how long they will make the data sets publically available. ARPA-E Is agnostic to the measurement approach used to monitor yields, crop status, and agronomic inputs.

Sampling requirements for soil and plant data verification:

Sample	Requirement
Soil (health/nutrient monitoring)	3-5 stratified samples per acre (0-30, 30-60, and 60-100 cm) every year
Plant (nutrient monitoring)	Minimum of 5 tissue samples per acre per year
Plant composition (fiber, ash, etc.)	Minimum of 3 plant sample per acre post harvest per year

Additional measurement requirements*:

Data	Unit	Minimum resolution	Minimum Frequency
Yield	kg/acre (dry)	Acre	Seasonal
Soil pH	pH	Subacre	Seasonal
Soil carbon (1 m depth; measurements at 0-30, 30-60, and 60-100 cm)	%	Acre	Annual
Soil temperature	C/F	Subacre	Daily
Soil moisture	%	Subacre	Daily
Gas exchange** - CO_2, N_2O, CH_4	ppb (N_2O); ppm (CO_2, CH_4)	Field	Continuous (i.e. >90% data capture on a second-by-second basis)
Wind speed & direction	m/s	Field	Continuous
Solar radiation	w/m^2	Field	Continuous
Water quality - Sediment, NO_{3-}, NH_{4+}	ppm	Field	Per flow event

*This table is intended to provide a minimum set of data requirements for the validation sites; it is not a comprehensive list.
**Gas exchange should be monitored according to the state of the art methods described in: Nemitz, Eiko, et al. "Standardisation of eddy-covariance flux measurements of methane and nitrous oxide." International agrophysics 32.4 (2018): 517-549.

Site requirements: Project funds should be used to support measurements and protocols for emissions monitoring at the field level, which can include farm auditing by life cycle experts to verify the data quality and estimate production efficiency. Teams must be willing to provide access to their sites for the purpose of deploying sensing technologies on a seasonal basis for the duration of the project.

ARPA-E is specifically interested in field sites for biofuel feedstock production that are:

(1) Directly marketing to biofuel producers
(2) Geographically representative (e.g. different climates, soils)
(3) Capable of meeting the site and equipment requirements listed below:

"Ground Truth" Component	**Requirement(s)**
Site Selection	• Commercial feedstock production setting • 3-4 representative sites per crop/team • Minimum 85 acres per site • Minimum of 1 letter of support for land lease
Equipment	• Eddy covariance for GHG flux measurement • Weather station for real-time data • Yield, management and input mapping* • High speed data coverage across the test sites

* Additional information such as planting, fertilization, and harvest timing; input type (e.g. manure, ammonium nitrate) and application method; soil management practices (e.g. tillage, cover crops and residues, etc.); and pesticide/herbicide/fungicide type and application rates and timing, must be captured.

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not be merit reviewed or considered:

- R&D, pilot, or any other non-commercial field sites
- Monitoring approaches that solely, or heavily, rely on novel and unproven sensing techniques
- Approaches that solely, or heavily, rely on simulation-based monitoring
- Incomplete teams (e.g. sensor developers without production and/or analytics partners) or measurement frameworks (e.g. soil monitoring without aboveground emissions monitoring)

IX. Appendix I: Electricity System Models for Carbon Capture Resources

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Electricity System Models for Carbon Capture Resources"

Topic Issue Date	November 14, 2019
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, January 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, January 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday March 4, 2020
Expected Date for Selection Notifications	April 2020
Total Amount to be Awarded	Approximately $750,000 subject to the availability of appropriated funds.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $100,000 and $750,000.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust titled, "Electricity System Models for Carbon Capture Resources." The purpose of this announcement is to (1) solicit Full Applications for the development of modeling tools which can evaluate the value of fossil-fueled power plants with carbon capture and storage (CCS) technology in future electricity grids under a range of scenarios and (2) provide a timetable for the submission of Full Applications. These tools will be used to analyze the value of various CCS technologies in an electricity grid with a large share of variable renewable energy (VRE) generators such as wind and solar power; they are not meant to be policy proscriptions or market predictions of any kind.

2. Topic Description

The main objective of this Special Program Announcement is to develop electricity system models and associated analysis that can inform technology development for new grid resources, including the ability to model CCS-enabled power plants with more fidelity as well as model negative-emission resources such as direct air capture (DAC) systems. Another objective of this Special Program Announcement is to generate a set of electricity price signals that will allow CCS technology developers to appropriately value the operating characteristics of their systems, and to evaluate how technology tradeoffs will impact total system costs of electricity under a range of carbon emissions constraints.

Electricity system models such as capacity expansion models are used to study the evolution of the electricity-generating portofio of a grid as a function of time and across various technology and policy scenarios. Such models have shown that fossil-fueled power generators with CCS can reduce the cost of a net-zero carbon electricity system, if certain cost and performance attributes are realized[53,54,55]. To enable computations to be performed in a reasonable amount of time, researchers typically make abstractions and simplifications in terms of spatial, temporal, and technology attribute resolution.

CCS processes have historically been designed and optimized for 90% capture of the CO_2 emanating from a baseload power plant. However, technology and policy changes—especially increasing VRE penetration—are changing patterns in the time-dependent value of electricity, as represented by a locational marginal price (LMP). An example of the impact of fluctuating LMPs on the dispatch of a natural gas combined cycle (NGCC) power plant is shown in Figure 1. In response to the LMP fluctuations, the power plant varied its output between 200 and nearly 600 MW on a daily basis. Although this is only an example for one power plant and and one month in 2018, it portends the impact of changing market conditions on power plant operations, and the need to reconsider the design and operation of CCS processes accordingly.

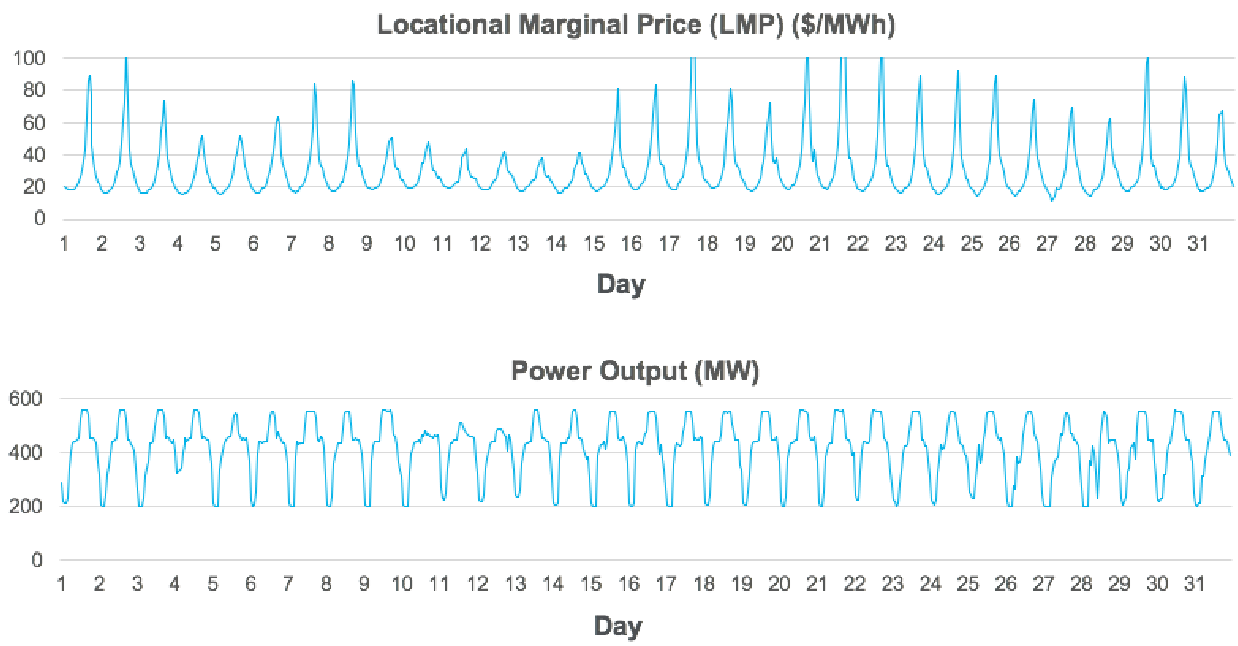

Figure 1: Day-ahead LMP[56] and the power output[57] of the Wolf Hollow II Generating Station in August 2018

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[53] N.A. Sepulveda, et al., Joule 2, 1-18 (2018)
[54] C.F. Heuberger, et al., Energy Procedia 114, 7564-7572 (2017)
[55] A. Boston, et al., Managing Flexibility Whilst Decarbonising Electricity, http://anlecrd.com.au/wp-content/uploads/2017/07/Managing-Flexibility-NEM-2017-Report.pdf (2017)
[56] Data from http://www.energyonline.com/Data/GenericData.aspx?DataId=23&ERCOT___Day-Ahead_Price
[57] Data from https://ampd.epa.gov/ampd/

This Special Program Announcement is being released concurrently with separate FOAs, FLExible Carbon Capture and Storage (FLECCS) DE-FOA-0002220 and FLExible Carbon Capture and Storage SBIR/STTR (FLECCS SBIR/STTR) DE-FOA-0002221 (collectively, the "FLECCS Program"), which seek to fund the development of CCS processes that enable fossil-fueled power plants to be responsive to a grid with a large share of VRE generators. The Project Team(s) funded under this Special Program Announcement will support the FLECCS Program in several ways. First, the Project Team(s) will generate publicly available electricity pricing data for a future grid with a large share of renewables under a range of carbon prices; this electricity pricing data will be used by Project Teams in the FLECCS Program to design and optimize CCS systems. Predicting future market structures (and therefore, precisely what future price signals will look like) as VRE generators continue to be added is impossible. However, operational requirements and market structures will impact the development and deployment of technologies such as CCS-equipped electricity generators. Even though the discussion above of LMP trends does not capture all the revenue streams an electricity generator could receive, such as ancillary services and capacity payments, data from grid modeling tools can be used to infer general characteristics that inform technology development in the FLECCS Program so that it is relevant in a future energy system.

Second, the Project Team(s) will develop open-source electricity system models that include greater fidelity for CCS-equipped power plants and the ability to model negative emission resources, in order to evaluate the impact of process designs in a future electricity system that are developed in the FLECCS Program.

A. Technical Areas of Interest

A model developed under this Special Program Announcement must, at minimum, return a price signal for one year of hourly, zonal, day ahead clearing prices (8760 hours). This analysis can be produced through a unit commitment model, production cost model, or other suitable mechanism for achieving this level of detail. The results generated by the initial analysis must be available to Project Teams under the FLECCS Program. The price signals will serve as inputs to these teams as they work to optimize designs for a range of possible future market conditions.

Furthermore, the tool or set of tools developed under this Special Program Announcement must be able to perform a capacity expansion analysis. This capacity expansion model must capture the cost and performance attributes of several technology types and be capable of projecting the level of investment in each asset type. The Project Team(s) may leverage existing models, but will likely require development of additional capabilities, including increased detail around technology specific parameters. Ideally, the Project Team will already have, or will be able to produce in the near term, hourly LMP data for a representative year (8760 hours) from existing "base case" model runs that can be used to evaluate of a first-of-a-kind plant deployment.

Both the hourly price and asset deployment models must be configurable to test a number of technology and market scenarios. The range of parameters to be explored in the scenarios include the following:

- Market
  - CO_2 price: Model a range of CO_2 prices (e.g. $100, $200, $300/ton)
  - Geography: Explore/describe zones from multiple geographic regions – with different weather and load profiles
  - Load: Consider both high and moderate electrification scenarios, to encompass both electrification potential of transportation and industry.
  - Fossil fuel pricing: Low, medium, and high fossil fuel prices
  - Price Cap / Capacity Market: Explore scenarios with a high price cap ($9,000/MWh) and no capacity market, as well as a scenario with a moderate price cap ($1,500/MWh) and a capacity market
  - Reserves: The scenarios should be able to be run with and without a reserves requirement
- CCS technology attributes
  - Capital cost: Includes a range of possibilities for both retrofit or new-build technologies
  - Heat rate/marginal cost: Analysis must handle generators equipped with CCS that respond to a highly variable pricing environment, e.g. variable heat rates and CO_2 capture rates
  - Flexibility modes: Analysis must handle designs developed under the FLECCS Program that may include, but are not limited to: load-following (startup, turndown, ramp rate), and buffering (running the power plant and CCS plant under more steady-state conditions but shifting when electricity is exported to the grid)
  - Scenarios may include multiple CCS plant types that represent different capex/opex/flexibility tradeoffs

The model analysis performed under this Special Program Announcement must generate the following outputs:
- Total system cost of energy as a function of system carbon intensity (gCO_2/kWh). This result will be generated from model runs performed at various CO_2 costs, each which will result in a different optimal system cost and carbon intensity.
  - The sensitivity of this curve to technology development pathways is of particular interest
- Capacity deployed of each CCS plant type
- Utilization of CCS fleet, including dispatch profiles of individual units
- 8,760 hours of day-ahead marginal pricing data
- Capacity market clearing price (if applicable)

To enable transparency for Project Teams under the FLECCS Program and the broader public in terms of the model results, ARPA-E is requiring the capacity expansion tool to be made open-source. In particular, each Project Team funded under this Special Program Announcement must agree to distribute the capacity expansion tool that is to be developed under this award as Open Source Software using a generally recognized open software standard such as for example those approved at http://opensource.org/osd. To the extent the capacity expansion tool to be distributed as Open Source requires access to additional software not available as compatible open source, such additional software must be readily available at a reasonable cost to any users of the capacity expansion tool.

After an initial phase of process development, each Project Team under the FLECCS Program will return a set of technology attributes (those listed in the bulleted CCS technology attribute section above) to the Project Team(s) funded under this Special Program Announcement. The Project Team(s) will evaluate these proposed technologies using the capacity expansion capabilities to determine the extent of deployment of the proposed technologies over the range of scenarios being considered. Any entity receving a Financial Assistance Award from ARPA-E under this Solicitation on Topics Informing New Program Areas: Topic I (DE-FOA-0001953), will be required to sign a non-disclosure agreement with respect to data received from each FLECCS Project Team unless a FLECCS Project Team agrees otherwise.

B. Technical Performance Targets

Applicants must clearly state how they will:

- Generate, at minimum, one year of hourly day-ahead electricity prices, under different renewable penetration levels and carbon prices within three months of the project's commencement.
- Develop capacity expansion tools with greater resolution for CCS-specific process attributes such as variable heat rate and CO_2 capture rate
- Include negative emission resources such as DAC systems
- Balance model accuracy and computational efficiency, e.g. simplifications regarding spatial, temporal, and techonology attribute resolution that minimize the impact on model accuracy.
- Interact with FLECCS Project Team, in order to provide feedback on process designs during and at the conclusion of FLECCS Phase I
- Develop an open-source capacity expansion tool. Applicants must state how they would address:
    - The user interface
    - Documentation
    - User training
- Report to ARPA-E at the end of FLECCS Phase 1 the extent of deployment of the FLECCS technologies over the range of scenarios being considered.

3. Submissions Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not be merit reviewed or considered:

- Original concepts for developing CCS systems optimized for a grid with a large share of renewables and fluctuating LMPs; this will be the scope of the FLECCS FOA

4. Eligibility with Respect to the FLECCS FOA

An entity may submit separate applications to this Solicitation on Topics Informing New Program Areas: Topic I, DE-FOA-0001953 and the FLExible Carbon Capture and Storage (FLECCS) DE-FOA-0002220 and/or FLExible Carbon Capture and Storage SBIR/STTR (FLECCS SBIR/STTR) DE-FOA-0002221 (collectively, the "FLECCS Program"). However, any individual participating on a Financial Assistance Award from ARPA-E under Solicitation on Topics Informing New Program Areas: Topic I, DE-FOA-0001953, will be prohibited from participating on any FLECCS Project Team.

5. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, the content of Full Applications are limited to the following:

Component	Required Format	Description and Information
Technical Volume (Grant) Topic I	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.**
SF-424	PDF	Application for Federal Assistance (https://arpa-e-foa.energy.gov/). Applicants are responsible for ensuring that the proposed amounts listed in eXCHANGE match those listed on forms SF-424 and SF-424A. Inconsistent submissions may impact ARPA-E's final award determination.
SF-424A (Grant)	XLS	Budget Information – Non-Construction Programs (https://arpa-e-foa.energy.gov/)
Business Assurances & Disclosures Form	PDF	Requires the Applicant to make responsibility disclosures and disclose potential conflicts of interest within the Applicant Team. Requires the Applicant to 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

Component	Required Format	Description and Information
		proposed R&D project. If the Applicant is a FFRDC/DOE Lab, requires the Applicant to provide written authorization from the cognizant Federal agency and, if a DOE/NNSA FFRDC/DOE Lab, a Field Work Proposal. Allows the Applicant to request a waiver or modification of the Performance of Work in the United States requirement. This form 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.
U.S. Manufacturing Plan	PDF	As part of the application, Applicants are required to submit a U.S. Manufacturing Plan. The U.S. Manufacturing Plan represents the Applicant's measurable commitment to support U.S. manufacturing as a result of its award. See detailed U.S. Manufacturing Plan instructions and examples in the Seventh Component description below.

Detailed guidance on the content of the Technical Volume, SF-424, Business Assurances & Disclosures Form, and U.S. Manufacturing Plan can be found in FOA Section IV.C at paragraphs One, Two, Six and Seven respectively. Guidance on the content of the SF-424A can be found on its p.2.

Templates for preparing Full Applications under this Targeted Topic may be found on ARPA-E Exchange at ARPA-E-CO@hq.doe.gov.

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X. APPENDIX J: Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Biotechnologies to Ensure a Robust Supply of Critical Materials for Clean Energy"

Topic Issue Date	March 4, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Monday, April 27, 2020
Submission Deadline for Full Applications	9:30 AM ET, Thursday May 7, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Monday June 22, 2020
Expected Date for Selection Notifications	August 2020
Total Amount to be Awarded	Approximately $5,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $500,000 and $1,500,000.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes an exploratory research thrust titled "Biotechnologies to Ensure a Robust Mineral Supply Chain for Clean Energy." The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to address mining supply challenges on the exploration/sensing, extraction, separation, recovery and purification of critical materials (CMs) using a variety of feed-mineral sources, (2) encourage partnerships with existing mining stakeholders, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of addressing mining industry challenges. The broad objective of this topic is to identify research that supports a robust supply of certain metals and elements in the U.S. via biological-based/bio-augmented processes across the entire mining supply chain including exploration and sensing, mining (extraction), separation, recovery, refining, and recycling.

C. Topic Overview

With global competition for minerals in emerging tech, defense, and energy applications, any shortage of critical resources "constitutes a strategic vulnerability for the security and prosperity of the United States."[58] The U.S. Department of the Interior (DOI) has recently issued a list of such materials, which include[59]: 1) Rare Earth Elements (REEs) consisting of the Lanthanide series (La-Lu) as well as yttrium and scandium; 2) The Platinum Group Metals (PGMs); and 3) Select members of the CM list as follows: cobalt, fluorspar (CaF_2), manganese, niobium and tin.

In addition to the CMs identified by DOI, other base transition metals of interest for this ARPA-E program are Nickel (Ni) and Copper (Cu). In 2018, the global Ni demand for Li-ion batteries was 85,000 tons and this is expected to increase by 30-40% per year[60]. The U.S. nickel production represents less than 1% (19,000 tons) of the total global production.

While the U.S. is the third largest global copper producer - with 1.2 million tons produced in 2018 - just behind Chile and Peru[61], the unique thermal and electrical properties of this metal make it a crucial element for energy efficiency applications. The issues around this material are production costs due to declining domestic ore grades and the associated energy along with environmental concerns around Cu extraction and processing.

Bio-based mining technologies offer potential advantages of lower energy requirements and production of less amounts of hazardous by-products, making them a potentially promising option for domestic CM, Ni, and Cu production. However, these techniques remain largely unproven, especially at scale.

D. Technical Areas of Interest

ARPA-E seeks novel and transformative technical approaches in microbiology, synthetic biology, and process engineering to harness nature's tools[62] to produce a robust, clean, non-toxic, and low-cost supply of CMs identified above, Ni, and Cu. **For all categories in this FOA,** applicants

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[58] "Interior Seeks Public Comment on Draft List of 35 Minerals Deemed Critical to U.S. National Security and the Economy", U.S. DOI press release, February 16, 2018. [https://www.doi.gov/pressreleases/interior-seeks-public-comment-draft-list-35-minerals-deemed-critical-us-national]
[59] "Final List of Critical Minerals 2018". U.S. DOI, Office of the Secretary, Federal Register/ Vol. 83, No 97 p. 23295 May 18, 2018 [https://www.govinfo.gov/content/pkg/FR-2018-05-18/pdf/2018-10667.pdf]
[60] Written Testimony of Simon Moores, Managing Director, Benchmark Mineral Intelligence, before US Senate Committee on Energy and Natural Resources, February 5, 2019. [https://www.energy.senate.gov/public/index.cfm/files/serve?File_id=9BAC3577-C7A4-4D6D-A5AA-33ACDB97C233]
[61] *Ibid*
[62] It is estimated that about half of all proteins in nature have a metal co-factor.

are encouraged to discuss in their Technical Volume how their proposed concept will impact any one or more of the following:

- The advancement of the fundamental understanding of the complex functionality of multispecies consortia in biomining;
- The understanding of fundamental reaction mechanism and thermodynamic constants;
- The development of new or advancement of existing analytical techniques;
- the potential for concurrent extraction and recovery of “non-critical” elements like manganese, gold, iron[63], and phosphorous, or compounds like limestone and silicates, or radioactive materials, like uranium and thorium, that may become associated co-products in the proposed extraction of the CMs, and
- The potential development of a bioinformatic database on biomining.

CATEGORY 1 – *Mineral Pre-processing*

Mineral pre-processing may include exploration approaches to better understand the ores and beneficiation steps that would ultimately improve the economic outlook of the entire mining operation.

- Novel ideas for the use of microbes to pretreat potential mining sites. For example, injecting microbes into mining sites to increase mining yields once the production cycle starts.
- Novel bio-comminution techniques. Mineral-feed weakening and breakage (i.e., crushing, grinding and pulverizing) is usually the most energy intensive and costly step in the mining process accounting for 65 to 80% of the total energy consumption. E.g., geomicrobiology.[64]
- Novel bio-beneficiation techniques to pre-concentrate materials and minimize the size of downstream treatment. For example, the use of biopanning (phage display)[65] to produce biosurfactants to selectively float mineral particles; REE-presorption using macroorganisms such as macroalgae and duckweed; among others.
- Novel low cost, portable, minimal interference spectrometers for sensing of CMs. For example, bio-inspired luminescence-based sensors that can rapidly and selectively screen between REE-rich and REE-poor sources.

CATEGORY 2 – *Biomining*

Biomining, also known as bioleaching (dissolution of the target-metal) or biooxidation (dissolution of the target-metal surrounding matrix), is a process where an electron interplay takes place between metal-containing materials (like ores) and microorganisms (like bacteria or

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[63] For example, the utilization of Ferredox-type processes (e.g., combination of elemental sulfur oxidation with ferric iron reduction to obtain nickel from goethite or limonite ores) that would yield recovered iron.

[64] Gadd G.M. “Metals, minerals and microbes: geomicrobiology and bioremediation”, *Microbiology* (2010) 156 p. 628 [https://doi.org/10.1099/mic.0.037143-0].

[65] Phage display refers to the use of virus to infect bacteria (bacteriophages) to produce selective peptides.

fungi) with the objective to facilitate the solubilization and recovery of metals. These biotechnological processes could significantly facilitate the extraction of critical metals. The extraction may occur by secretion of organic acids, cell metal intake, or via metabolic use of metal in aerobic or anaerobic respiration.

a) Natural cell approach

- Discovery and identification of relevant biomining microbes and consortia candidates living in habitats like mine waters or degraded gas & oil pipelines that demonstrate high biocatalytic activity towards CM extraction/oxidation (e.g., microbial-mediated metal leaching), high electron exchange capacity with CMs, high resistance to extreme conditions like metallic ions, metabolic dependences (e.g. REE-dependent bacteria like *M. extorquens*).
- Understanding the functionality of naturally occurring microbial communities in biomining, as opposed to single-species systems. The whole-community genetic capacity could be studied by metagenomics and metatranscriptomics sequencing analysis to better understand the performance of multispecies assemblages. For example, the understanding of biopassivation effects whereby one strain solubilizes a CMs while another irreversibly sequesters it to inhibit the formation of a toxic environment.
- Methods to increase resistance and adaptation of natural cells. For example, adaptive evolution, acclimation, natural mutagenesis followed by selection of media containing metals.
- Novel mineral-concentration methods that can be employed in combination with biomining to minimize the amount of materials being processed downstream. For example, microorganims that demonstrate high mineral bioaccumulation rates (hyperaccumulation) inside the cell (as pure metal, metal compounds, nanoparticles) or outside the cell (selective CM-biosorption).

b) Engineered cell approach

- Synthetic biology to target the design of specific metal-binding proteins, enzymes, chelators, siderophore-like molecules (e.g., lanthanophores), or sequestration systems. For example, the metabolic engineering of microbes to over produce REE-binding proteins, similar to lanmodulin.
- Engineered microbes that overproduce acid biolixiviants solutions of organic acids (e.g., citric, oxalic, tartaric, gluconic) and acid combination suites.
- Identification and regulation of genes/gene clusters associated with stress-responses - to the presence of acid, metal, osmotic stress and temperature – and genetic modifications to prevent/disrupt passivation effects. For example, genetic engineering of candidate genes into a microbial extremophile that already have a desired level of environmental tolerance to pH and/or temperature; engineered-cells for the production of passivation-inhibitors.
- Genetic modifications that allow for enhanced bioleaching, surface-mediated biomining, selective bioaccumulation, immobilization, and mineralization of CMs. For example, genetically-modified microalgae to enhance metal recovery.

CATEGORY 3 – *Mineral Post-processing*

CMs post-processing may involve costly recovery, separation, and concentration steps. These steps may be integrated to the previous step (biomining), done separately or even eliminated. Under this category, we seek solutions involving:

- Novel microbial reduction and recovery techniques that transform critical elements into valuable, saleable products. For example, a process where a microorganism reduces $PdCl_4^{2-}$ into its metallic nanoparticle form (Pd^0) that can be used directly in the manufacturing of palladium-supported catalysts.
- The separation of individual rare earths elements remains a significant challenge. The refining of mixed metals into individual metals is of interest. For example, the use of selective natural or bioengineered proteins or cell surfaces[66] that can allow bioaffinity-based purification processes.
- Processes that minimize the energy intensity for the recovery of CMs from highly dilute streams. For example, phytomining[67], biomining/bioassembly approaches, living filters, and other bioseparation matrices, such as membranes.

CATEGORY 4 – *Supplementary Abiotic Processing*

ARPA-E recognizes that hybrid approaches that couple one (or more) abiotic steps in the CM sourcing pathway may provide a more concentrated, economical, and scalable solution. Examples of such supplementary processes may include but are not limited to the use of robots for surgical extraction of CM-containing components from electronic waste; electrochemical or electromagnetic treatment that transforms primary or secondary mineral sources into amenable bioleaching feed-material; acoustic dissolution to produce aqueous solutions rich in CMs; selective lixiviant extractions; carbon dioxide extractions (e.g., mineral carbonations to produce metal-carbonates, CM supercritical CO_2 extractions); task-specific ionic liquids (TSILs); fabrication processes that make use of chemical states as presented by bio-extraction.

E. Technical performance targets

In addition to the requirements stated in this FOA, please include all items listed on Tables 1 and 2 in the Technical Volume. Note that these tables will count toward the 14-page limit of the Technical Volume. Also, if the proposed solution applies to more than one category (e.g., process intensification), clearly indicate so in the Technical Volume.

[66] Chang E. et al. "Surface complexation model of rare earth element adsorption onto bacterial surfaces with lanthanide binding tags" *Applied Geochemistry* 112 (2020) 104478 p.1 [https://doi.org/10.1016/j.apgeochem.2019.104478]

[67] Plants that accumulate high concentrations of metals.

Guidance on the cost ($/kg) of some CMs is publicly available[68]. However, in this FOA, we assume that mining costs will closely follow both material and energy (M&E) balance performance and the metric space is built around these fundamental concepts. Use **1 tonne of product** as the basis for calculation.

Table 1. Performance targets

Metric	Applicable to Category	State-of-the-art (SOA)	Performance target with proposed technology
Material balance [a]	1-4	To be derived in detail and submitted by applicant	* Zero toxic tailings left behind [b] * Concurrent liberation of ≥ 90% beneficial coproducts (if any)
Energy balance [a]	1-4	To be derived in detail and submitted by applicant	≥ 50% energy savings over SOA[c]

[a] Applicants are expected to follow standard chemical engineering guidelines to produce the material & energy balances for both the SOA and proposed technology processes. Please review **Example 1** below and note that ARPA-E expects to review a complete pathway (e.g., ore-to-refined CM) not just a single unit operation. While M&E balances emphasis can be given to the proposed step(s), the respondent is responsible to provide a complete M&E balance for the pathway and is encouraged to use conventional/SOA processes to complete the processing steps in the pathway.
[b] The material balance has to be detailed enough to allow the reviewing team to quantify the amount of left over materials (e.g., tailings) (if any) for the proposed process.
[c] The energy target may be flexible for tradeoffs where, for example, the CM extraction yield or CM level of concentration is substantially increased over the SOA while maintaining the same level of energy demand of SOA (i.e., no energy savings).

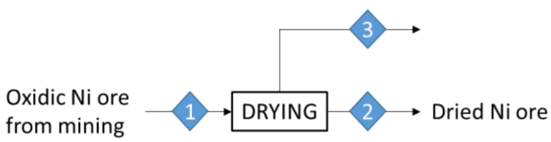
Example 1. Material & Energy Balance in the Conventional Production of Nickel

The conventional pathway for producing metallic nickel from oxidic nickel minerals involves ore mining, drying or calcination, pyrometallurgical steps (roasting and smelting), followed by hydrometallurgical and refining steps. The following diagram details the drying step of a low grade oxidic nickel ore (please note that the FOA response should include a complete pathway). The drying step will remove most of the moisture in the ore. The M&E balance basis is 1 tonne of nickel product.

[68] Leader A. et al. “The effect of critical material prices on the competitiveness of clean energy technologies” *Materials for Renewable and Sustainable Energy* (2019) 8:8 p.1-17 [https://doi.org/10.1007/s40243-019-0146-z]

Material Balance for ore drying

All units in kg:



Material*	Stream 1	Stream 2	Stream 3	**
Ni	1,000	1,000	-	
Si	70,540	70,540	-	
Mg	43,782	43,782	-	
Fe	33,472	33,472	-	
Ca	20,944	20,944	-	
S	4,891	4,891	-	
H_2O (moisture and chemically bound)	77,989	19,497 (chemically bound)	58,492	
SO_2	-	-	-	
O_2 (from air)	-	-	-	
Other minerals	20,345	20,345	-	
Total	**272,963**	**214,471**	**58,492**	

* Add as many materials as needed.
** Add as many streams as needed

Energy Balance for ore drying

The theoretical amount of energy required (Q_{drying}) to dry the nickel ore is:
$Q_{drying} = m_{ore} \cdot c_{p\ ore} \cdot \Delta T + m_{moisture} \cdot c_{p\ water} \cdot \Delta T + m_{moisture} \cdot \Delta H_{vap}$

Where m_{ore} is the dry mass of the ore (214,471 kg), c_p is the average heat capacity of the ore (0.4 kJ/kg · K), ΔT is the temperature difference (373 K-293 K= 80 K), $m_{moisture}$ is the mass of moisture (58,492 kg), $c_{p\ water}$ is the heat capacity of water (4.187 kJ/kg · K) and ΔH_{vap} is the specific heat of vaporization of water (2.26 MJ/kg). Therefore, Q_{drying} is 161.7 GJ.

Additional guidance on M&E balances for complete mining processes can be found in the published literature. [69] In response to this FOA, provide an overall energy requirement in units of **GJ per one tonne of product**, see Table IX in reference [70] for examples.

[69] ANL/ESD-15/11 "Material and Energy Flows Associated with Select Metals in GREET2: Molybdenum, Platinum, Zinc, Nickel, Silicon" Sept 2015. [Material and Energy Flows Associated with Select Metals in GREET2: Molybdenum, Platinum, Zinc, Nickel, Silicon].
[70] Talens-Pieró L., Villalba-Méndez G. "Material and Energy Requirement for Rare Earth Production" JOM vol. 65, No 10, 2013. [doi: 10.1007/s11837-013-0719-8].

Table 2. Concept summary table

Variable	Response (include references where possible)
End-product(s)	List all relevant material(s) to be produced and % recovery (e.g., 56% Nd recovery)
Source of the critical material(s)	Specify the U.S. available source (primary/native or secondary/artificial) of CMs and comment on the source sustainability (abundance, concentration, and variability for economic viability). Examples: ores (ARPA-E is particularly interested in bastnäsite, ultramafic ores71 and phosphate rock72), mining wastes (mine tailings), coal waste streams73 (coal ash, acid mine drainage74), waste-to-energy combustion residues (fly and bottom ashes), sea nodules, post-consumer wastes (electronic waste, electric motors, batteries, permanent magnets), landfill and ashfill wastes, medical waste, spent catalysts, steel slags, drill cuttings, produced waters (oil & gas), wastewater, seawater, other.
Biology	Provide description of the microorganism, consortia or biological solution approach. Describe relevant metabolism. Why was this biology selected? Vigorous? Well-adapted? Highly selective?
Reactor/system type and operation mode (continuous, semi-continuous, batch, other)	Specify, sketch, and describe the reactor/system configuration and operation mode: (multiple) continuous stirred tank reactor(s), leach column, fluidized-bed reactor (e.g., gravity assisted), biofilms (e.g., bioleaching heap, membrane biofilm reactors), air lift reactor (Pachuca tank), living filter, electrochemical reactor, bioelectrochemical reactor, wetland, vat, lagoon, raceway pond, in-situ bioleaching, hierarchical reactor design (e.g., 3D printed structure, microfluidic systems), other.
Current scale	Provide current scale and proof-of-concept reaction/recovery yield(s).
Proposed TRL – scale up factor	Provide and justify new TRL, reactor scale and expected reaction/recovery yield(s). Also provide scale up factor as compared to current proof-of-concept scale (e.g., x 10).
Carbon source, growth media, and carbon sequestration	What is the planned organic nutrition (e.g., spent brewer grain) that the microorganism will consume to grow and reproduce? Is nutrition locally available (e.g., decomposing plant matter in a wetland)? Is growth media expected to be a significant price tag in the economics of the process? Is there any associated CO2 mineralization/storage potential?
Energy source	What is the source of energy for metabolism (e.g., sunlight, ferric iron)?
Oxygen source and diffusion	If O2 is needed in the process, describe how the system will optimize gas transfer into the liquid and circumvent mass transfer diffusion limitations. If the proposed system is located in a constrained location (e.g., deep in-situ biomining), what are the anticipated challenges to oxygen supply?
Residence time	Provide estimate of residence times. How will the configuration/time proposed be optimized to minimize residence time while providing sufficient time to grow, reproduce and metabolize the materials undergoing bioleaching-extraction?

[71] Sun J-Z, et al. "Mechanism of Mg^{2+} dissolution from olivine and serpentine: Implication for bioleaching of high-magnesium nickel sulfide ore at elevated temperature pH" *International Journal of Minerals, Metallurgy and Materials* 26, 9 (2019) p. 1069 [https://doi.org/10.1007/s12613-019-1823-8].
[72] Liang H. et al. "Rare-earth leaching from Florida phosphate rock in wet-process phosphoric acid production" *Minerals & Metallurgical Processing*, 2017, Vol. 34, No. 3, p. 146 [https://doi.org/10.19150/mmp.7615]
[73] DOE (2017)"High Concentrations of rare earth elements found in American coal basins" [www.energy.gov/articles/high-concentrations-rare-earth-elements-found-american-coal-basins]
[74] Vass, C.R., Noble, A. & Ziemkiewicz, P.F. "The Occurrence and Concentration of Rare Earth Elements in Acid Mine Drainage and Treatment By-products: Part 1—Initial Survey of the Northern Appalachian Coal Basin" *Mining, Metallurgy & Exploration* (2019) 36: 903. [https://doi-org.proxy.scejournals.org/10.1007/s42461-019-0097-z].

Control of competitors and contaminants	Describe how the competition of mutated forms, unrelated organisms, the presence of toxins (e.g., salt, jarosite) will be controlled. In other words, how will the proposed system outgrow competitors, inhibit contamination, evade toxicity? How long is the system expected to run without interruption?
Environmental impact	Are the environmental impacts of the proposed biomining approach significantly better than those of conventional approaches (hydrometallurgy and pyrometallurgy)?
Circular economy	Do you anticipate that the proposed process would be integrated into an existing facility, like a mine, landfill, waste-to-energy plant, wastewater treatment plant, other?

4. Program Structure

The maximum period of performance of this program is 24 months. It is expected that all programs will undergo a midpoint review (Go/No Go gate).

5. Submissions specifically not of interest

Submissions that propose the following may be deemed nonresponsive and may not be merit reviewed or considered:

- Approaches seeking incremental improvements – rather than transformational solutions – to current mining applications.
- Scale-up projects for existing technologies that do not have significant technical risk.

XI. APPENDIX K: Recycle Underutilized Solids to Energy

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Recycle Underutilized Solids to Energy"

Topic Issue Date	April 2, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Thursday, May 21, 2020
Submission Deadline for Full Applications	10:30 AM ET, Tuesday, June 2, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Monday July 13, 2020
Expected Date for Selection Notifications	August 2020
Total Amount to be Awarded	Approximately $4,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $100,000 to $1,000,000
Maximum Period of Performance	18 Months

1. Introduction

This announcement describes an exploratory research program, "Recycle Underutilized Solids to Energy" (REUSE). The purpose of this announcement is to (1) focus the attention of the scientific and technical community on specific areas of interest related to converting high-energy materials currently going into landfills into high-energy content liquid product capable of displacing energy imports used for fuel or chemical production, (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for submission of full applications.

ARPA-E seeks to screen a wide range of feeds, products, and processes. This exploratory program has a duration of 12-18 months.

2. Topic Description

ARPA-E is interested in receiving Full Applications in support of the exploratory REUSE program. Under the REUSE Topic, ARPA-E seeks to fund the development of technologies to convert high-energy materials currently going to landfills into a high-energy content liquid product. The high-energy materials include plastics (#1-7 polymers, rubber, and composites) and paper.

ARPA-E anticipates deployment of multiple low-cost, simple, flexible, small-scale (100-500 ton per day) regional facilities using modular plants ("REUSE facilities"). This scale is consistent with the sources for high-energy materials, which include ~300 Material Recovery Facilities and industrial waste sources.

ARPA-E-funded processes under this Topic will create a high-energy content liquid that can be easily shipped to and stored at points of aggregation. The liquid product could be used as a fuel blend stock or an intermediate for further conversion to fuels or chemicals. It does not need to be a highly-refined fuel such as gasoline or diesel. The ultimate end products could represent down-cycling or up-cycling the feeds.

The assumption is that REUSE facilities can be more economical than the paradigm of large-scale facilities making purity products, due to cost of transporting and aggregating waste and the high operating cost (OPEX) and high capital cost (CAPEX) for product purification. We assume it will be more economical to transport the liquid product to existing large-scale facilities, such as chemical plants, refineries, or fuel depots, than to transport waste to a central processing plants.

The critical issues for REUSE are demonstrating simple, flexible "liquefaction chemistry" and meeting economic targets for low-cost, small scale "liquefaction" plants. "Liquefaction chemistry" means converting solid high-energy materials to a high-energy content liquid product. It implies cracking carbon-carbon bonds, which requires some combination of heat, chemical reactants, and/or catalysts. REUSE processes will need to be robust -- tolerant to a wide range of feed composition and quality. The second critical issue is economic viability of small-scale facilities. We hypothesize costs will be lowered by "economies of numbers", developing simple, repeatable, modular units, versus through "economies of scale" with large, field-erected, custom-engineered facilities designed to produce a limited number of high-purity products.

ARPA-E is interested in submissions which offer disruptive, vs incremental, advances compared to current technology. Applicants can propose novel chemical routes; novel hardware, process integration, and/or process simplification using known chemical routes; or a combination of novel chemistry and hardware/process design.

Projects funded under this Topic will have two primary tasks. In the first task, lab-scale tests will develop performance and design criteria for proposed processes. In the second task, the experimental results will be used to develop a preliminary process design and techno-economic analysis for a 250 ton per day (feed) facility.

A. Target Feeds

ARPA-E seeks to divert high-energy materials from landfills. The target high-energy materials include plastics (#1-7 polymers, rubber, and composites) and paper. These feeds include:

- Plastic waste from manufacturing sites (pre-consumer waste), estimated at 1-2 MM ton/yr
- Ag waste: From irrigation tubing, silage, greenhouses, and mulching, 0.4 MM ton plastic in 2018[75]
- Tires: The US Tire Manufacturing Association reported 0.6 MM ton tires were landfilled in 2017,[76] much lower than the Environmental Protection Agency estimate of 4.95 MM ton for 2017.[77]
- Auto shredder residue, 1.9 MM ton/yr plastics and 1.1 MM ton/yr rubber, and a growing amount of composite materials (glass fiber, natural fiber, and carbon fiber).[78]
- ~ 300 Material Recovery Facilities (MRF). More than 90% of the US population has access to curbside recycling, and/or drop-off centers,[79] which send recyclables to MRFs for separation and baling. Potential feeds include low-value MRF bales and MRF bales rejected to landfills.

Economics of REUSE facilities depend on feed costs. Materials sent to landfills are valued at the average US tipping fee, -$55/ton.[80] Table 1, from the 2020 Curbside Recycling Report, shows prices for plastics and paper bales produced by MRFs.[81] As discussed below, some plastics and paper materials separated at MRFs are landfilled due to contamination, lack of market, or both. We assume all materials sent from MRFs to landfill are valued at -$55/ton.

Table 1 Material Price per Ton[81]

Material	Price per ton
#1 PET Bottles (includes thermoforms)	$188
#2 HDPE Natural Bottles and Jars	$1008
#2 HDPE Colored Bottles and Jars	$262
"#3-7" Other Plastic Packaging	$5
Bulk Rigid Plastics	$48

[75] Recovering Agricultural Plastics: Obstacles and Opportunities, Waste Advantage Magazine, Sept 1, 2018
[76] 2017 U.S. Scrap Tire Management Summary, U.S. Tire Manufacturers Association, July 18, 2018
[77] Rubber and Leather: Material-Specific Data, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/rubber-and-leather-material-specific-data
[78] 2014 ENERGY AND ECONOMIC VALUE OF MUNICIPAL SOLID WASTE (MSW), INCLUDING NON-RECYCLED PLASTICS (NRP), CURRENTLY LANDFILLED IN THE FIFTY STATES, Nickolas J. Themelis and Charles Mussche, July 9, 2014 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.645.7112&rep=rep1&type=pdf
[79] Perceptions and realities of recycling vary widely from place to place, Drew DeSilver, Pew Research Center, https://www.pewresearch.org/staff/drew-desilver/
[80] EREF releases analysis on national landfill tipping fees, https://www.wastetodaymagazine.com/article/eref-releases-analysis-national-msw-landfill-tipping-fees/
[81] 2020 STATE OF CURBSIDE RECYCLING REPORT, THE RECYCLING PARTNERSHIP, https://recyclingpartnership.org/stateofcurbside/

Mixed Paper	-$2

In addition to the industrial sources cited above, REUSE target feeds include the following materials from MRFs:

- "#3-7" plastics (PVC, LDPE, PP, PS, and other, respectively).
- Films, which overlaps the #3-7 category because films include #2 HDPE, #4 LDPE, and #5 PP. The 2020 Curbside Recycling Report estimates 3.6 MM tons of film material is available. Most of the 0.4 MM ton/yr agricultural plastic use is film, and has a low recycle rate.
- Bulk rigid plastics, which are primarily injection molded HDPE and PP. Bales are likely to contain smaller amounts of other #3-7 polymers, depending on the MRF processing system.[82]
- Mixed paper, essentially paper that does not meet specifications for corrugated cardboard or newspaper. It includes phone books, magazines, junk mail, and office paper.
- MRF bales that are rejected to landfills due to low quality. China's ban on recycled paper or plastics with more than 0.5% contamination has led to a collapse of prices for bales that do not meet this requirement. Recently the price of mixed plastic dropped to zero.[83] Yasar et al reported that the majority of newsprint and cardboard bales were outside ISRI specifications.
- Residual bales from MRF. Typically 15-30% of the MRF incoming material is rejected as residuals.[84] These bales contain enough plastic and paper to support "secondary" MRF processing. However, they also contain dirt, food, and other contaminants.
- Plastics that cannot be recycled with currently available technology, particularly due to presence of impurities.

Additional information about Target Feeds is available on the ARPA-E website in the REUSE Webinar and REUSE Background Information document found here: https://arpa-e.energy.gov/?q=news-item/trash-treasure-reuse-creates-feedstock-plastic-waste.

B. Target Products

As discussed above, ARPA-E is interested in liquid products that can be easily shipped to and stored at points of aggregation. The value of potential products varies widely, impacting the economics of potential technologies developed under this Topic. The price for hydrocarbon

[82] National Mixed Rigid Plastic Bale Composition Study Executive Summary – Summer 2015, https://plasticsrecycling.org/images/pdf/resources/reports/Executive_Summary_Bale_Sort_2015.pdf
[83] Update on International & Domestic Recycling Markets, J Semrau, MRF Stakeholder meeting Oct 7, 2019
[84] Measuring Composition and Contamination at the MRF, John Culbertson, Northeast Recycling Conference, October 31 2018

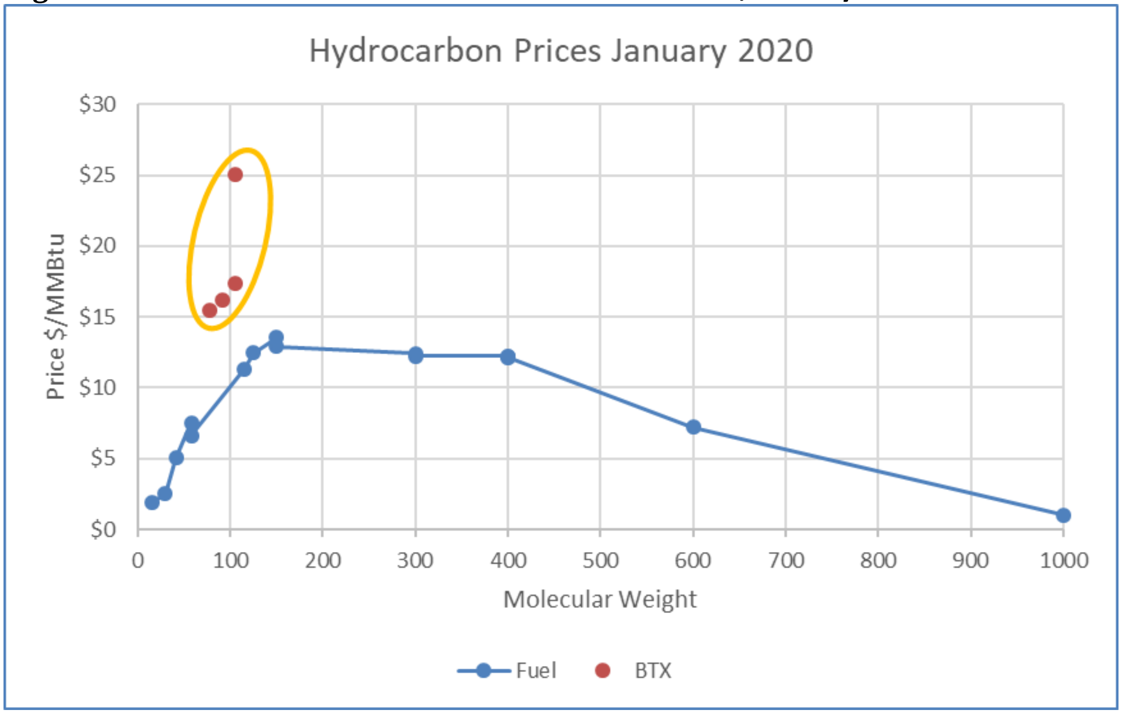
products are shown in Table 2, based on January 2020 US Gulf Coast,[85,86,87] and shown graphically in Figure 1. The price increases with carbon number/boiling point from the light gases (methane, ethane, propane, butane) to vacuum gas oil and light cycle oil, and then drops again for heavy products, such as #6 fuel oil and petroleum coke.

Table 2 Gulf Coast Value for Fuels and Chemical Feeds, January 2020

Hydrocarbon Stream	$/MMBtu	Description/Use
West Texas Intermediate (WTI)	11.85	Crude
Natural Gas	1.92	Fuel gas
Ethane	2.50	Fuel gas Cracker feedstock
Propane	5.04	
Isobutane	7.54	Fuel gas Cracker feedstock Gasoline blendstock
Normal Butane	6.65	
Naphtha	11.29	Gasoline Cracker feedstock
CBOB	12.45	
Ultra low sulfur diesel	13.53	Diesel, Marine blendstock
No. 2 Oil	12.92	
Low sulfur Light Cycle Oil	12.41	Gasoline feedstock Marine blendstock
Light Cycle Oil	12.26	
Vacuum Gas Oil (Low Sulfur)	12.26	Diesel feedstock Marine blendstock
Vacuum Gas Oil (Med Sulfur)	12.22	
Vacuum Gas Oil (High Sulfur)	12.13	
No. 6 Oil 3% S, Gulf Coast	7.23	Marine blendstock
Petroleum Coke	1.02	Solid fuel
Benzene	15.94	Chemical feedstock
Toluene	16.15	
m-Xylene	17.85	
p-Xylene	25.05	

85 OPIS International Feedstocks Intelligence Report, Jan 9, 2020
86 BTX Market Report and Price Trend, Fiber2Fashion.com, https://www.fibre2fashion.com/market-intelligence/textile-market-watch/benzene-price-trends-industry-reports/18/
87 EIA Table 4.12.A. Average Cost of Petroleum Coke Delivered for Electricity Generation by State, November 2019 and 2018, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_4_12_a

Figure 1 Gulf Coast Value for Fuels and Chemical Feeds, January 2020



Ethane, propane, and butanes can be used as feeds for crackers, which produce plastic precursors. Consequently these products represent a path to "close the loop" on plastics recycling. However, transporting the lighter ethane, propane, and butanes is relatively more expensive, and their value is lower than heavier hydrocarbons.

Naphtha and heavier hydrocarbons through Light Cycle Oil (LCO) and Vacuum Gas Oil (VGO) are significantly more valuable, easier to transport, and also can be used as or converted to cracker feeds. Liquids in these boiling point ranges could also be used as a refinery feedstock, essentially substituting for low-sulfur (sweet) crude.

Heavier hydrocarbon streams may be useful as low-sulfur bunker fuel. The International Marine Organization (IMO) mandates to lower fuel sulfur content to 0.5% by weight creates new demand for Marine Gas Oil (MGO), a mix of distillates; and Very Low Sulfur Fuel Oil, which can be made from blending LCO and/or VGO. IMO compliant fuels are priced $10-20/bbl higher than WTI.[88]

In comparison with fuel products, chemical feedstocks such as benzene, toluene, and xylene (BTX) have significantly higher value. These chemicals are precursors to plastics, and can also be an option for "closing the loop" on plastics recycling.

ARPA-E is open to other liquid products not shown in Table 2. Oxygenated compounds, including ketones, aldehydes, alcohols, and/or acids are generally more valuable than their

[88] https://shipandbunker.com/news/world/391062-imo-2020-no-large-speed-bump-thus-far

hydrocarbon counterparts. These can be used in chemical or biological processes. ARPA-E also encourages processes that depolymerize composites, producing recyclable matrix components capable of being shipped to a central location.

Table 2 shows the importance of minimizing light gases and very heavy liquids or char. Applicants with significant light gas and/or char production need to discuss the impact on their process economics.

ARPA-E discourages processes that produce high acid (acid number >0.5mg KOH/g) hydrocarbon liquids, and is not interested in high TAN (acid number >1.0mg KOH/g) liquids. REUSE discourages chemically unstable liquids (ie gum-forming liquids produced in some biomass pyrolysis processes), or processes that produce harmful co-products such as certain polycyclic aromatic hydrocarbons (PAH). Applicants with processes that produce these materials must discuss how these processes can be commercially viable.

C. Target Technologies

Cracking carbon-carbon bonds is a common step for all processes converting plastics, paper, or plastic/paper mixtures into liquid products. Cracking carbon-carbon bonds requires some combination of heat, chemical reactants, and/or catalysts. The discussion below highlights some processes and critical issues. These processes are discussed in further detail on the ARPA-E website in the REUSE Webinar and REUSE Background Information document found here: https://arpa-e.energy.gov/?q=news-item/trash-treasure-reuse-creates-feedstock-plastic-waste.

Using intermediate refinery streams to slurry plastics and/or paper may facilitate incorporating the liquid products into downstream refinery and petrochemical processes. Slurrying the solid wastes may improve material handling and enhance reactivity. Several hydrocarbon refinery streams, including crude oil, vacuum gas oil (VGO), heavy cycle oil (HCO), light cycle oil (LCO), benzene/toluene/xylene (BTX), naphtha, and middle distillates, are potential slurrying agents.

ARPA-E encourages submissions that address innovations for developing repeatable, modular units, and/or designs that reduce CAPEX by reducing engineering and/or construction costs. In addition to modularization, it may be necessary to simplify unit operations (ie flash separations vs distillation, firing light ends in process heaters vs recovering and selling a full product slate, etc). Costs for feeds such as hydrogen and costs for managing wastes such as sulfur, nitrogen, and waste water will need careful consideration. It may be advantageous to build REUSE projects adjacent to other facilities, such as upstream MRFs or downstream refineries or chemical plants. However, for the REUSE program the process economics will be evaluated on a stand-alone basis.

There are several potential technical issues common to all these processes which Applicants must address:

- Ability to configure the process for continuous operation, or strategy to manage multiple batch operations.

- Tolerance of the process for likely contaminants.
- Degree of feed pre-treatment required to feed plastic/paper (ie size reduction), manage contaminants (ie washing), etc.
- Monetizing or disposing light gases – ie combustible co-products which cannot be incorporated into the liquid product
- Emissions (sulfur and/or nitrogen compounds, wastewater)
- Potential to form hazardous co-products (ie polycyclic aromatic hydrocarbons)
- Need to dispose by-products (ie insoluble materials separated from the liquid product, char, salts)

The discussion below highlights some particular concerns for each process option. Applicants must address these issues for the specific technology they propose.

Hydrotreating/hydrocracking/hydrogenolysis

Hydrotreating has been demonstrated with plastics slurried in hydrocarbon liquids in tests dating back to the 1970's. There is considerable literature on hydrotreating biomass and biomass-derived liquids, but less work on hydrotreating paper.

There are several technical challenges with hydrotreating/hydrogenolysis. The first is the relatively high cost of hydrogen for small-scale facilities. The second is the relatively small size of the reactors. The third is the thermal balance associated with hydrogenation reactions, particularly for high oxygen content feeds such as PET and paper. The fourth is catalyst life. Applicants proposing hydrotreating/hydrocracking/hydrogenolysis processes must address these issues.

Thermal cracking

Thermal cracking in this context covers processes that slurry the plastic and/or paper feed in a refinery intermediate stream and use an indirectly heated reactor operating under reducing conditions. From the 1970's through about 2000 there were numerous studies to convert plastics to fuel, often starting with a thermal cracking step. Starting in the 1970's researchers also investigated thermal cracking of cellulosic materials.

ARPA-E is less interested in processes that use slurrying materials that must be recovered to be economical, such as donor solvent processes using decalin or tetralin. Submissions using expensive solvents must address expected solvent losses and solvent recovery process(es).

One of the technical challenges with thermal cracking is the potential to generate harmful co-products, such as polycyclic aromatic hydrocarbons (PAH), from waste materials under reducing conditions.[89] A second issue is the potential to form coke or carbon deposits on fired heaters or heat exchangers. Applicants proposing Thermal Cracking processes must address these issues.

[89] Polycyclic aromatic hydrocarbons (PAH) formation from the pyrolysis of different municipal solid waste fractions, Hui Zhou, et al, Waste Management, October 2014, 36

Torrefaction/Pyrolysis/Solvolysis/Hydrothermal liquefaction

Torrefaction/Pyrolysis in this context covers processes that use an indirectly heated reactor operating under reducing conditions (i.e., allothermal reactor). Solvolysis refers to a process in which the solvent is the primary reactant with the substrate. Hydrothermal liquefaction refers to sub- or supercritical reactions with water. There is extensive literature on pyrolysis, solvolysis, and hydrothermal liquefaction of composites,[90] plastics, cellulosic materials, and mixtures of plastics and cellulosic materials. ARPA-E is not encouraging submissions for these processes, unless the Applicants can demonstrate a disruptive aspect of their technology, and/or a significant techno-economic breakthrough compared to current state of art.

Autothermal pyrolysis/gasification

Autothermal pyrolysis/gasification in this context covers the continuum of processes that use substoichiomeric quantities of air/oxygen to produce liquid-range products. The equivalence ration, ϕ (moles oxidant fed/moles oxidant for complete combustion) ranges from about 0.05 for autothermal operations to about 0.4 for gasification. ARPA-E is interested in processes that directly produce liquids; consequently ϕ will typically be less than 0.2. ARPA-E is not interested in processes that produce light gases or syngas that are subsequently converted to liquids using chemical or biological processes.

There are several challenges associated with autothermal pyrolysis/gasification. The first issue is managing thermal profiles/gas distribution in fixed- or moving-bed reactors. The second issue is attrition, agglomeration, and erosion in fluidized bed reactors. Applicants proposing autothermal pyrolysis/gasifier processes must address these issues.

Fluid catalytic cracking (FCC)

There are many investigations using plastics or paper/cellulosic materials in FCC processes. Some processes co-feed waste materials with refinery streams; however, not all FCC processes require a slurry media.

There are several technical challenges with catalytic cracking plastics. The first issue is the need to achieve thermal balance in the reactor/regenerator. The second issue, for paper and plastics such at PET contain significant oxygen, is minimizing carbon losses/maximizing liquid fuel production. The third issue is economically maintaining catalyst life. The fourth is scaling down FCC reactor equipment to the scale anticipated in REUSE. Applicants proposing cracking processes must address these issues.

Oxidative processes

Oxidation using reactants other than oxygen can produce liquids from hydrocarbons to highly-oxygenated products including ketones, aldehydes, and acids. Examples include NO and NO_2; nitric acid; $Ca(OH)_2$; and solid sulfur.

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[90] Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties, G. Oliveux et al, Progress in Materials Science 72 (2015) 61–99

There are several technical challenges with oxidative processes. The first is the cost of reactants. The second is the materials of construction. The third is the thermal balance and methods for maintaining reactor temperature. Applicants proposing oxidative processes must address these issues.

Other Processes
ARPA-E is interested in other novel and disruptive processes that can convert plastics and paper to a stable, easily transportable liquid product, ideally with high energy yield and minimal production of light gases and/or char.

D. Task 1: Test Considerations

As discussed above, the first task will be lab-scale tests to quantify performance and design criteria for the proposed processes. In the second task, the experimental results will be used to develop a preliminary process design and techno-economic evaluation for a 250 ton per day (feed) facility.

To ensure the testing program supports the second task, Applicants must provide a preliminary process flow diagram and a preliminary heat and material balance for their process. ARPA-E expects Applicants to justify estimated quantities for feeds, products, emissions, wastes, and any deleterious co-products based on experimental results, extrapolations from the literature, modeling, or reasoning from chemical principles.

Applicants must list the critical design issues for their technology, as presently understood. Applicants must discuss how their test program addresses their design issues, the common issues for all technologies, and technical issues specific for a given technology as discussed above. The scale and duration of testing needs to be appropriate to quantify performance and design criteria. For example, test units should be at the gram scale and larger. Applicants should note their experience with scaling up test results from their proposed units to commercial units. Applicants proposing to use milligram or smaller scale systems need to address potential limited ability to analyze products or assess thermal effects.
Test duration should be sufficient to span the expected residence time distribution of the scaled-up process, and long enough to address catalyst deactivation, if appropriate. If catalyst deactivation dictates excessively long tests, ARPA-E is open to testing programs with appropriately pre-aged catalysts.

Applicants must specify the feeds they plan to test. ARPA-E strongly encourages processes and test programs with a wide range of feeds/co-feeds.

E. Task 2: Preliminary Process Design and Techno-economic Evaluation

The second task is development of a preliminary process design and techno-economic analysis based on the experimental results for a 250 ton per day (feed) facility. Project Teams will develop a preliminary process design, and create a process model using Aspen or similar modelling tools. The process design will incorporate the critical design parameters, or ranges of parameters, as determined in the first task. The process model will include a detailed heat and material balance with a summary of inputs (feeds, utilities) and products/co-products and emissions from the process. It will also be used to develop an equipment list.

The heat and material balance and equipment list will be used to develop a preliminary estimate of the CAPEX and OPEX for the "inside battery limits" (ISBL) or core unit operations of the process. CAPEX and OPEX are expected to be in the range of +/-30% based using typical costing tools such as Aspen ICARUS or equivalent. An example of this type of analysis is available at https://www.nrel.gov/docs/fy19osti/71949.pdf.. Applicants can request assistance from ARPA-E for access to process modeling and/or costing tools in their submission.

ARPA-E anticipates facilities that can compete economically using repeatable, simple, and modular designs. Applicants should identify potential concepts for process simplification, modularity, thermal integration, managing light gases, and minimizing costs for rejecting heteroatoms and char.

3. Progress Reporting

To aid in assessing the Recipient's technical progress under any cooperative agreement resulting from this Targeted Topic, ARPA-E requires quarterly reporting throughout an agreement's performance period. This includes reporting on the following subject matter:

- Test results, including
  - feed and product characterization,
  - test operating conditions
  - yields for gas, liquid, and solid products
  - material balance closure

- Process summary, including
  - Process flow diagram(s)
  - Heat and material balance for "best operating condition(s)"
  - Preliminary equipment sizing

- Summary of process economic model, including
  - CAPEX
  - OPEX
  - Revenue

- Assessment of commercial potential

- Discussion of common and specific technical issues for Awardee's technology
- Recommendations for next steps for Awardee's technology development

4. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Submissions that do not include a process flow diagram and preliminary heat and material balance
- Submissions that do not incude a list of target feeds.
- Processes that are exclusively mechanical recycling, i.e. milling, grinding, etc.
- Torrefaction/Pyrolysis/Solvolysis/Hydrothermal liquefaction, per note in Process Technology section
- Gasification processes in which light gases (H_2, CO, methane, C2 and C3 hydrocarbons) account for more than 20% of the heating value of the products
- Combustion/incineration processes
- Anaerobic digestion or biological decomposition processes
- Incremental modifications to current deinking/paper recycling processes
- Processes that require multiple conversion steps to produce a liquid product, ie gasification + Fischer-Tropsch
- Processes that cannot be deployed widely throughout the United States, including technologies that rely on a single, site-specific resource.
- Submissions that focus solely on PET and/or HDPE bottles.

5. Modifications to Technical Volume Template

The Technical Volume template for the REUSE Topic has multiple modifications. Cumulative page limits for Sections 1-5 is 14 pages, excluding the required process flow diagram and the heat and material balance, and optional cost model.

6. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, "Technical Volume: Topic K" is replacing the "Techncial Volume Template" provided. All other Components remain the same and can be found in Section IV.C.

Component	Required Format	Description and Information
	PDF	The centerpiece of the Full Application. Provides a detailed description of the proposed R&D project and Applicant Team. A Technical Volume

Component	Required Format	Description and Information
Technical Volume: Topic K		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 L: Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment (INSULATE)"

Topic Issue Date	May 20, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, July 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 2, 2020
Expected Date for Selection Notifications	October 2020
Total Amount to be Awarded	Approximately $3,500,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $100,000 to $3.5 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes an exploratory research thrust titled "Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment (INSULATE)." The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to address innovations in transformer insulation reliability, (2) encourage partnerships with existing insulation component manufacturers, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of exploring vital insulating elements in large power transformers (LPTs) in order to increase their resilience. In particular, the objective of this topic is to explore solutions related to increasing the life expectancy of the transformer, including: (i) high-performance solid insulation materials, (ii) advanced insulating fluids with improved dielectric strength, thermal conductivity, and aging performance, and (iii) Kraft paper rejuvenating additives.

A. Topic Overview

Transformers are an essential element in the power transmission-distribution system. Whether electricity is generated using fossil, renewable, or nuclear resources, transformers are needed to perform the basic function of voltage conversion by either stepping-up or stepping-down the voltage for efficient transmission between power generation and end-user. There exist about 2500 LPTs in the power grid which carry more than 90% of our nations power.[91]

With the few exceptions of lightning and switching surges, transformer failure is fundamentally caused by insulation issues. Electrical (transient and overvoltage damage, corona discharge, static electrification), mechanical (winding deformation/rupture of paper, magnetically induced EM forces, conductor tipping, telescoping, spiral tightening, end ring crushing, failed coil clamping, displacement of loads), and thermal issues (pyrolysis of the cellulose material) ultimately cause damage to the insulation. The 2015 CIGRE survey of 964 prominent tranformer failures found that the major reason for transformer collapse was dielectric (i.e., insulation failure).[92] DOE estimates that power outages may cost the U.S. economy \$18-\$33 billion annually[93] (2003-2012, adjusted for inflation).

Depending on the type of insulation employed, transformers can be categorized as dry transformers where air is the cooling medium, or oil-immersed transformers, also known as oil-cooled transformers. This latter type is most commonly used in LPTs and it comprises a paper-oil pair system where a thin solid insulating material (usually cellulose-derived) serves as the interface between the copper windings and the oil bath. The oil serves a dual function as electrical insulation and as heat dissipation medium, usually in a passive cooling radiator system as shown in **Figure 1**. A transformer operating at a cooler temperature would have increased longevity, efficiency performance, reliability, and safety. There can also be a significant economic upside for grid operators if the transformer assets have a longer lifetime as shown for other emerging grid technologies. This is driven primarliy by reduced operation and maintenace costs as well reduced transfer replacement costs over a given period.[94]

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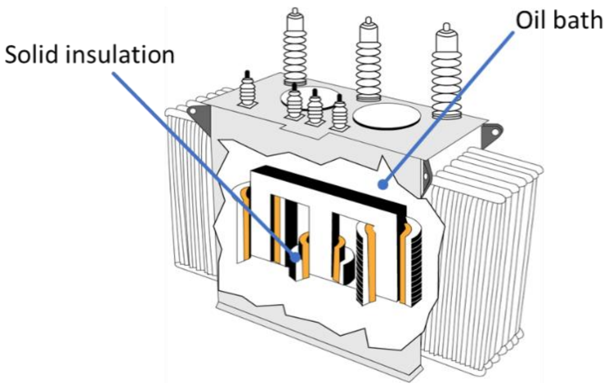
[91] U.S. Department of Energy, Office of Electricity, "Transformer Resilience and Advanced Components (TRAC) Program," https://www.energy.gov/oe/services/technology-development/transformer-resilience-and-advanced-components-trac-program.

[92] Rafiq M. et al. "*The impacts of nanotechnology on the improvement of liquid insulation of transformers: Emerging trends and challenges*" **J. Mol. Liq.** 302 2020 112482 p.1-2 [https://doi.org/10.1016/j.molliq.2020.112482]

[93] DOE Executive Office of the President "*Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*" 2013 [https://www.energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf].

[94] D W. Cunningham, E P. Carlson, J S. Manser, I C. Kizilyalli. "Impacts of Wide Band Gap Power Electronics on Photovoltaic System Design", IEEE Journal of Photovoltaics Vol. 10, Issue 1, Jan. 2020 [https://doi.org/10.1109/JPHOTOV.2019.2950592]



(a)


(b)

Figure. 1 Oil-immersed, 3-phase core-type power transformer: **(a)** Schematic highlighting the insulating elements, **(b)** picture showing degraded solid insulation inside a transformer.[95,96]

Oil-immersed transformer technology was installed in the U.S. during the 1960s and 1970s, and consequently many of these assets are approaching the end of their designed service life (~ 40 years). Temperature spikes (pyrolytic degradation), oxygen (oxidative degradation), sulfur[97] and moisture contamination (hydrolytic degradation)[98] play a key role in the overall degradation of the transformer insulating elements. However, due to the significant capital cost ($15/kVA), customized design[99], and long lead time for delivery (up to 18-24 months when demand is high)[100] it is less desirable to replace these LPT assets. Instead, ARPA-E is interested in exploring novel insulation systems that may be used to upgrade existing oil-immersed LPTs.

Kraft papers are the preferred solid insulation material in oil-immersed LPTs. Direct experimental methods like accelerated thermo-oxidative aging have been explored in order to predict the degradation of Kraft papers.[101] However, direct measurements are often not possible, therefore

95 [http://engineering.electrical-equipment.org/electrical-distribution/top-10-causes-for-power-system-failures-part1.html]. Last accessed 4/6/2020.
96 Messard L.C. et al., "Transformer Post-Mortem Analysis" 735 Task Force A2.45 (2018) [ISBN: 978-2-85873-438-2]
97 Du D., Tang C., Zhang J. Hu D., "*Effects of hydrogen sulfide on the mechanical and thermal properties of cellulose insulation paper: A molecular dynamics simulation*" **Materials Chemistry and Physics** 240 (2020) 122153 [https://doi.org/10.1016/j.matchemphys.2019.122153].
98 V. Vasovic et al., "*Aging of transformer insulation of experimental transformers and laboratory models with different moisture contents: Part II — moisture distribution and aging kinetics*," in **IEEE Transactions on Dielectrics and Electrical Insulation**, vol. 26, no. 6, p. 1847-1852 2019. [https://ieeexplore.ieee.org/document/8924115]
99 Department of Energy, Office of Electricity, DE-FOA-0001876 "*Next Generation Transformers – Flexible and Adaptable Designs*" [https://www.fedconnect.net/FedConnect/PublicPages/PublicSearch/Public_Opportunities.aspx]
100 U.S. Department of Energy "*Large Power Transformers and the U.S. Electric Grid*" 2014 [https://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf]
101 Polanský R., et al, "*Quantifying the Effect of Catalysts on the Lifetime of Transformer Oil*" **Appl. Sci.** 2020, 10, 1309; [doi: 10.3390/app10041309]

other methods[102] like the *loading guide model* (IEC 60076-7) and the *paper degradation model* are used to produce an estimate of remaining life. *The paper degradation model* utilizes a convenient and practical approach based on the Kraft paper's degree of polymerization (DP), a measure of the average cellulose chain size, which correlates well with various mechanical properties, like tensile strength. The classical kinetic model relates the rate of degradation and temperature by an Arrhenius equation:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = Ate^{-\frac{E_a}{RT}} \qquad \text{[Eq. 1]}$$

where *t* is the time in hours, DP_t is the degree of polymerization at time t, DP_0 is the initial degree of polymerization, E_a is the activation energy for the oxidation and hydrolysis reactions in J per mol, the pre-exponent value *A* is a constant depending on the chemical environment (typically a function of the water content, oxygen, and acidity), *R* is the ideal gas constant (8.314 $J{\cdot}mol^{-1}{\cdot}K^{-1}$), and *T* is the hot-spot temperature in K.

The DP_0 for new Kraft paper is about 1200 and a paper is considered to be at the end of its service life when a DP_t value of ~200 is reached. The E_a for degradation of cellulose in oil is in the range of 85 to 120 kJ/mol.[103] Ariannik and collaborators recently proposed enhancements to the *paper degradation model* to more accurately predict remanent transformer lifetime. Their analysis included loading factor increases over time, temperature variations in the field, and moisture accumulation.[104] Technology enhancements for solid paper insulation include thermal upgrading, the utilization of better pulps, hygroscopicity reduction, hybrid insulations, and cellulose composites.[105]

For the oil bath, petroleum-based mineral oils (MOs) have been typically used. However, flammability and sustainability concerns have motivated an interest in investigatigating alternative base-fluids like silicone oil, natural ester oils,[106] synthetic esters, [107] and nanofluids (NFs). [108] This latter research area has focused on the investigation of engineered colloidal

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[102] Gorgan B. et al., "*Calculation of the remaining lifetime of power transformers paper insulation*," 2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Brasov, 2012, pp. 293-300. [DOI: 10.1109/OPTIM.2012.6231792].
[103] Lungard L.E. et al., "Aging of Cellulose in Mineral Oil Insulated Transformers" 323 Task Force D1.01.10 (2007) [ISBN: 978-2-85873-018-6].
[104] Ariannik M., Razi-Kazemi A.A., Lehtonen M. "*An approach on lifetime estimation of distribution transformers based on degree of polymerization*", **Reliability Engineering and System Safety** 198 (2020) 106881. [https://doi.org/10.1016/j.ress.2020.106881].
[105] R. Chandrashekar, S. Chaudhari, P. Bajpai, R. Mehta, "*Developments in Insulating Paper for Power Transformers*" [http://www.academia.edu/6851508/Developments in Insulating Paper for Power Transformers]
[106] Azizie N. A. & Hussin N., "*Preparation of vegetable oil-based nanofluid and studies on its insulating property: A review*", 2020 **J. Phys.**: Conf. Ser. 1432 012025 [doi: 10.1088/1742-6596/1432/1/012025]
[107] Guide for Transformer Maintenance, Council on Large Electric Systems (CIGRE-445) Working Group A2.34 February 2011.
[108] Muhammad R. et al, "*The impacts of nanotechnology on the improvement of liquid insulation of transformers: Emerging trends and challenges*" **Journal of Molecular Liquids**, v.302, 2020 112482. [https://doi.org/10.1016/j.molliq.2020.112482].

suspensions of nanometer-sized (one dimension in the 10-100 nm range) solid particles in concentrations of a few wt.% dispersed in a fluid. Some of the most promising nanoparticles have been found to be iron oxides (Fe_2O_3, Fe_3O_4), TiO_2, Al_2O_3, CdS, ZnO, ZrO_2, among others.[109] The breakdown voltages of NFs have been found to be twice of that of MOs[110].

B. Technical Areas of Interest

ARPA-E is interested in advancing the performance of transformer insulation/cooling components in order to increase LPTs service life, reliability, efficiency, and survivability.

Technical area A. High-performance Solid Insulating Materials

a) Novel chemistries. Polymers beyond cellulose, for example Nomex®.
b) Directional configurations. At the micro-level, examples are two-dimensional materials (2D) like graphene and hexagonal boron nitride (h-BN). At the macro-level, different winding configurations that can accommodate conductors operating at higher loads.
c) Bioinspired materials. Including but not limited to nanocellulose.
d) Nanocomposites. Including but not limited to organic-inorganic composites.
e) Hybrid insulations. Combinations of different materials.

Technical area B. Advanced Dielectric Nanofluids

a) NF formulations. Identification and selection of cost-competitive base-oils, nanoparticles or their combinations (multi-nanoparticles systems), and dispersants/surfactants to improve base-oil/nanoparticle compatibilities.
b) NF synthesis. Methods for the long-term stability of the suspensions to avoid agglomerations

Technical area C. Oil Additives

a) Novel oil additives that can be used on existing LPT assests that enhance the chemical state of the cellulose, reverse aging of the solid insulation, lower maintenance requirements (e.g., oil reclamation), provide infiltration protection, etc. For example, cross-linking agents that can periodically rejuvinate the Kraft paper.

** Responses that combine technical areas are of particular interest**

C. Technical Performance Targets

The goal of the FOA is to increase the transformer median service lifetime from a few decades to at least **80 years**. ARPA-E expects a transformer demonstration at the end of each project using the solid/fluid insulation components or additives that are capable of meeting the energy

[109] Suhaimi S. N. et al. "*A Review on Oil-Based Nanofluid as Next-Generation Insulation for Transformer Application*" **Journal of Nanomaterials**, v. 2020 ID 2061343 p. 1-17 [https://doi.org/10.1155/2020/2061343].
[110] Contreras J. E., Rodriguez E. A., Taha-Tijerina J., "*Nanotechnology applications for electrical transformers—A review*" **Electric Power Systems Research** 143 (2017) 573–584 [http://dx.doi.org/10.1016/j.epsr.2016.10.058]

conservation standards specified in the Code of Federal Regulations at 10 CFR 431.196. The demonstration transformer will be used for experimental validation of the projected lifetime.

- If responding to **Technical area A. High-performance Solid Insulating Materials**, respondents are required to include in their Technical Volume **Metric Table 1** and **Metric Table 2** with all the required information. Respondents should use the appropiate SOA product standard (IEC, ASTM, IEEE, ISO etc.) that is applicable or comparable to the proposed solution. Example SOA metrics for solid dielectrics using IEC 60641 are provided below in Metric Table 2. If the proposed solution performance is below any SOA, justify the tradeoff. The transformer demonstration for Technical Area A is required to be an oil-filled transformer of at least 100 kVA in rating using the developed solid insulating material. Respondents should indicate in their Technical Volume the specifications for their transformer demonstration and the method they will use to experimentally validate the model used to predict an 80 year lifetime.

- If responding to **Technical area B. Advanced Dielectric Nanofluids** , respondents are required to include in their Technical Volume **Metric Table 1** and **Metric Table 3** with all the required information. Respondents should use the appropiate SOA product standard (IEC, ASTM, IEEE, ISO etc.) that is applicable or comparable to the proposed solution. Example SOA metrics for fluid dielectrics using various ASTM standards are provided below in Metric Table 3. If the proposed solution performance is below any SOA, justify the tradeoff. The transformer demonstration for the Technical Area B should be a commercial transformer of at least 100 kVA in rating filled with the developed advanced dielectric nanofluid. Respondents should indicate in their Technical Volume the specifications for their transformer demonstration and the method they will use to experimentally validate the model used to predict an 80 year lifetime.

- If responding to **Technical area C. Oil Additives**, respondents are required to include in their Technical Volume **Metric Table 1** with all the required information. Respondents should indicate in their Technical Volume how the proposed solution will be able to recover (reverse aging) and/or maintain the SOA properties for the solid dielectric over the life of the transformer. Example SOA properties for solid and fluid dielectics are provided below in Metric Tables 2 and 3, respectively. The transformer demonstration for the Technical Area C should be an existing commercial transformer of at least 100 kVA in rating where the developed additive can be added to the existing oil. Respondents should indicate in their Technical Volume the specifications of transformer demonstration and the method they will use to experimentally validate the model used to predict an 80 year lifetime.If the proposed solution applies to more than one technical area indicate that clearly in the Technical Volume and include all the required Metric Tables from each technical area.

Metric Tables to be inlcuded in the Technical Volume are below. Note that the tables will count toward the 14-page limit of the Technical Volume.

Metric Table 1. Comparison of the service life technical specifications for state-of-the-art (SOA), INSULATE FOA goal, and proposed insulation solution (*italics*).

Performance parameter	**SOA**	**INSULATE goal**	**Proposed solution**
Transformer median service life (years)	40	80	*Projected lifetime estimation*
Transformer aging curve	N/A		*Provide projected aging curve here. Y-axis: Degree of Polymerization (# units) vs. x-axis: time (years)*
Provide key aging model assumptions here. If the aging curve is experimental provide detailed methodology here. Discuss failure mechanism and acceleration factors like electric field, temperature, oxygen, etc.			

Metric Table 2. Comparison of the technical specs for SOA, INSULATE goal, and proposed solid insulation.

Performance parameter	**SOA (Standard IEC 60641, Use Appropriate Type)**	**INSULATE goal**	**Proposed solution**
Electrical properties			
Electrical strength in oil (kV/mm)	Min. 45.0 (≤ 1.6 mm) Min. 35.0 (> 1.6 mm)	90.0 70.0	
Conductivity of aqueous extract (mS/m)	< 10.0	Same or better	
Other physical and mechanical properties			
Nominal operating temperature (°C)	95	> 95	
Activation Energy (kJ/mol)	85 – 120		
Apparent density (g/cm^3)	1.0 – 1.3	Same or better	
Tensile strength MD (MPa)	> 100.0	Same or better	
Tensile strength CMD (MPa)	> 75.0	Same or better	
Elongation at fracture MD (%)	> 2.5	Same or better	
Elongation at fracture CMD (%)	> 3.5	Same or better	
Compressibility C (%)	< 10.0	Same or better	
Compressibility reversible Crev. (%)	> 45.0	Same or better	
Oil absorption (%)	> 6.0	Same or better	
Moisture content (%)	< 6.0	Same or better	
pH of aqueous extract	6.0 – 9.0	Same or better	

Metric Table 3. Comparison of the technical specifications for MO, INSULATE goal, and proposed nanofluid.

Performance parameter	**Mineral Oil**	**INSULATE goal**	**Proposed solution**
Electrical Properties			
Breakdown voltage (kV) [ASTM D1816]	> 20 (1 mm electrode gap) > 40 (2 mm electrode gap)	> 30 > 50	

Thermal Properties			
Flash point (°C) [ASTM D92]	> 145	≥ 165	
Flammability	Combustible	Non-flammable	
Pour point (°C) [ASTM D97]	< -40	Same or better	
Other Properties			
Density 60/60 [ASTM D1298, ASTM D4052]	0.910	Same or better	
Biodegradability [ASTM D5864]	Poor	Same or better	
Water Content (ppm) [ASTM D3487]	< 50	Same or better	
Viscosity (mm^2/sec) [ASTM D3487]	< 12	Same or better	

3. Program Structure

The maximum period of performance for this program is 24 months. It is expected that all projects will undergo a midpoint review (Go/No Go gate) during the program. Successful projects may be eligible for award extensions, renewals, and new awards in accordance with Section IIB of this FOA.

4. Submissions Specifically Not Of Interest

Submissions that propose the following may be deemed non responsive and may not be merit-reviewed nor considered:

- Insulation technologies that are incompatible with existing oil-immersed LPTs infrastructure and/or their respective maintenance protocols
- Solid State Transformers (SSTs) and High frequency transformers
- Other LPT components such as surge arresters

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XIII. Appendix M: Mining Incinerated Disposal Ash Streams

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Mining Incinerated Disposal Ash Streams (MIDAS)"

Topic Issue Date	May 20, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, July 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 2, 2020
Expected Date for Selection Notifications	October 2020
Total Amount to be Awarded	Approximately $4,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $250,000 to $1.5 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes an exploratory research thrust titled "Mining Incinerated Disposal Ash Streams (MIDAS)." The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to explore the use of Municipal Solid Waste Incineration (MSWI) ash[111] as a source of critical materials (CMs), alloys (e.g., brass and bronze), valuable base metals (e.g., Al, Cu) and other precious metals (e.g., Au, Ag); (2) encourage partnerships with waste-to-energy[112] (WTE) stakeholders, downstream processors, reclaimed materials up takers; and (3) provide a timetable for the submission of Full Applications.

[111] MSWI ash is a generic term used to reference bottom ashes (BAs) and fly ashes (FAs) produced in the waste combustion process. MSWI ash is produced at an average yield is 0.25 ton MSWI ash per ton of wet MSW. According to European Suppliers of Waste to Energy Technology (ESWET), BA is defined as the unburnable fraction of waste like sand stones, glass, minerals, etc. collected at the end of the grate. FA is the particulate residue conveyed with the flue gas and removed from the boiler, the fabric filter or the electrostatic precipitator. The distribution between BAs and FAs is dependent on the type of combustor and the combustion conditions. However, in a typical operation BAs would constitute about 85% of the MSWI ash and FAs would constitute the remaining 15%.

[112] Waste-to-Energy, also known as Energy from Waste (EfW) is a waste management option where MSW is combusted at temperatures of about 850°C-1000°C in a controlled air atmosphere. The heat of combustion is used to produce steam that can be employed to generate electricity or to provide heat to buildings or production processes.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of advancing the recovery and reclamation of CMs and other valuable elements from MSWI ashes. The broad objective of the MIDAS topic is to explore (i) real-time, cost-effective elemental identification techniques for MSWI ash, (ii) economically feasible methods of concentrating and extracting elements that may initially be in low concentrations (e.g., Sc, La, Ce, Pr, Nd) in the MSWI ash, and (iii) refining technologies for upcycling scrap metals within the waste processing facilities.

A. Topic Overview

The global demand for CMs and other metals continues to grow while their production from primary ore resources is limited. These elements are used in emerging tech, defense, and energy applications, and any shortage of critical resources "constitutes a strategic vulnerability for the security and prosperity of the United States."[113] The CMs list provided by the U.S. Department of the Interior (DOI), includes Rare Earth Elements (REEs) consisting of the Lanthanide series (La-Lu) as well as yttrium and scandium, Platinum Group Metals (PGMs), cobalt, fluorspar (CaF_2), manganese, niobium, tin, among others.[114] Other metals of interest to ARPA-E are copper, gold, silver, and nickel.

With nearly 2 billion tons of MSW generated globally, this feedstock may constitute the largest resource for the recovery of CMs and other metals. Gutiérrez-Gutiérrez and collaborators recently assessed the availability of extracting CMs from four closed UK landfills. Their findings suggested that the concentrations of REEs (58 ± 6 mg kg^{-1}), scandium and PGMs (3 ± 1 mg kg^{-1} each) were too low for commercial viability[115] as the concentration of these elements was lower than their primary ores. A subsequent study also found REEs concentration in landfills to be low, in the range of 40-80 mg kg^{-1}.[116]

Therefore, urban mining of ashfills and MSWI ashes may be a more attractive alternative than landfill mining for the reclamation of CMs and other metals, as the combustion or gasification processes concentrate the valuable products. In Japan, significant quantities of scarce metals

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113 "Interior Seeks Public Comment on Draft List of 35 Minerals Deemed Critical to U.S. National Security and the Economy", U.S. DOI press release, February 16, 2018. [https://www.doi.gov/pressreleases/interior-seeks-public-comment-draft-list-35-minerals-deemed-critical-us-national].
114 "Final List of Critical Minerals 2018". U.S. DOI, Office of the Secretary, Federal Register/ Vol. 83, No 97 p. 23295 May 18, 2018 [https://www.govinfo.gov/content/pkg/FR-2018-05-18/pdf/2018-10667.pdf].
115 Gutiérrez-Gutiérrez S., Coulon F., Jiang Y., Wagland S. "*Rare earth elements and critical metal content of extracted landfilled material and potential recovery opportunities*" **Waste Management** 42 (2015) 128-136 [https://doi.org/10.1016/j.wasman.2015.04.024].
116 Burlakovs J. et al. "On the way to 'zero waste' management: Recovery potential of elements, including rare earth elements, from fine fraction of waste" **Journal of Cleaner Production** 186 (2018) p. 85 [https://doi.org/10.1016/j.jclepro.2018.03.102].

have been accumulated over the years in fly ashes and slags. It is believed that these reserves may already be larger than the ones in the countries where these elements first originated.[117]

Within the MSW stream the largest source of the materials of interest comes from appliances and electronics. This appliances and electronics are broadly classified as electronic waste often referred to as *e-waste* or *e-scrap*. While the definition of *e-waste* is quite complex, the widely adopted definition in different *e-waste* studies is by the European Union Waste Electrical and Electronic Equipment (EU WEEE) directive, defined as *"Electrical and Electronic Equipment (EEE) which is waste, including all components, sub-assemblies, and consumables, which are part of the product at the time of discarding".*[118] EEE comprises the six categories[119] listed below:

- **Temperature exchange equipment.** More commonly referred to as cooling and freezing equipment. Includes refrigerators, freezers, air conditioners, heat pumps, etc.
- **Screens & monitors**. Includes TVs, monitors, laptops, notebooks, tablets, etc.
- **Lamps**. Includes fluorescent lamps, high intensity discharge lamps, LED lamps, etc.
- **Large equipment**. Includes washing machines, clothes dryers, dish-washers, large stoves, large printing/copying machines, photovoltaic panels, etc.
- **Small equipment**. Includes vacuum cleaners, microwaves, small electric & electronic tools, etc.
- **Small IT and telecommunication equipment**. Like mobile phones, Global Positioning Systems, routers, etc.

Each product of the six *e-waste* categories has a different lifetime profile leading to different waste quantities, economic values, and potential environmental and health impacts if recycled inappropriately.
Many states regulate the disposal of *e-waste* and existing recycling recovers about 15 to 30%[120] of the EEE. The economic value of the disposed metals can be appreciated when considering the tens of millions of personal electronic devices entering the waste stream. The Institute of Scrap Recycling Industries estimates that for each 1 million cellphones, 33 lbs. of palladium, 75 lbs. of gold, 772 lbs. of silver, and 35,274 lbs. of copper[121] can be theoretically recovered.

The U.S. WTE infrastructure processes about 30 million tons of MSW annually, or about 10% of the MSW generated in the U.S. while producing nearly 7.5 million tons of MSWI ash and 14

[117] Dodson J. R., et al. " Elemental Sustainability: Towards the total recovery of scarce metals" **Chemical Engineering and Processing** 51 (2012) p.71 [doi:10.1016/j.cep.2011.09.008].
[118] D. Mmereki, B. Li, A. Baldwin, and L. Hong, "The Generation, Composition, Collection, Treatment, and Disposal System, and Impact of E-Waste", *Chapter 4* [http://dx.doi.org/10.5772/61332]
[119] "*What is E-waste*?" Chapter 1 [https://www.itu.int/en/ITU-D/Climate-Change/Documents/GEM%202017/Global-E waste%20Monitor%202017%20-%20Chapter%201.pdf]
[120] http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures_on_EWaste_and_Recycling.pdf
https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_fs.pdf
[121] https://www.isri.org/recycling-commodities/recycling-industry-yearbook

million MWh[122] of electricity (~ 0.05 Quads) for the grid. WTE revenues from the generation of electricity and/or steam are vulnerable to the decreasing costs of natural gas and the increasing penetration of both subsidized and unsubsidized renewable energies, like wind and solar. The diminishing profits associated with the decreasing electricity revenues in combination with increasing MSWI ash disposal costs (national average fee is ~$50 per ton of MSWI ash), may quickly evolve into a financial situation of net negative cash flow. Consequently, the U.S. WTE industry has invested in researching various technologies to improve both energy and resource recovery.

Recent efforts have been focused in turning the MSWI ash liability into an asset. Two new state-of-the-art ash recovery plants have been built in Pennsylvania. The first one was built by the York County Solid Waste Authority, pioneering MSWI bottom ash recovery with the installation of an Ash Recycling and Processing Facility (ARPF)[123] that is co-located with their WTE plant in York, PA. Here, MSWI bottom ash is fractionated into oversized non-combustible materials, mixed ferrous metals, mixed non-ferrous metals, small and large aggregate fractions, sand, filter cake (fine residue), ferritic dirt, char, and tailings. The second plant is being built by Covanta in Fairless Hills, PA. The Total Ash Processing System (TAPS)[124] plant is expected to be able to process 400,000 tons of MSWI combined ash[125] per year sourced from different WTE plants.

Typical unit operations and equipment present in ash recovery plants may include manual sorting, sieving, crushing/milling, magnetic separations, eddy current separators, induction sorting separators, jiggers, hydrocyclones, decanters, and press filters. In order to maximize valuable materials recovery, some modifications to the WTE upstream processing may be required. A change in the typical ash quenching process from wet (water quenching) to a dry cooling system (air) enables the MSWI ash to remain disperse rather than aggregating into clumps. For example, the KEZO plant in Hinwil Switzerland,[126] can recover 99% of the valuable materials (like Au, Cu and Al) using the Thermo-recycling (Thermo-Re®) process. Here, MSW is combusted at 850°C and the produced MSWI ash is cooled with air before entering the metals recycling system.

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[122] Michaels T. & E Krishnan K. "*2018 Directory of Waste-to-Energy Facilities*", **Energy Recovery Council (ERC)** p. 5 [http://energyrecoverycouncil.org/wp-content/uploads/2019/10/ERC-2018-directory.pdf]. Last accessed 3/25/2020.

[123] Ash Recycling and Processing Facility (ARPF). [https://www.ycswa.com/ash-processing-and-recycling-facility/]. Last accessed 3/25/2020.

[124] Total Ash Processing System (TAPS) press release. [https://www.covanta.com/News/Press-Releases/2019/2019/01/Jan-07]. Last accessed 3/30/2020

[125] Combined ash is the mixture of bottom and fly ashes, also known as total ash.

[126] "In Hinwil, KEZOs alchemists turn waste into gold" Climate Magazine No. 6 p.11 [https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Medien/EN_Zurich_Climate_Magazine_Nr_6_Gold_from_Waste.pdf]. Last accessed 4/15/2020.

ARPA-E believes we may be amid a complete paradigm shift on how we view MSW, no longer as trash but as an abundant and sustainable source of energy and valuable elements like Al, Cu, Pt, Ag, Au, In, Nd, Pr, etc. The challenge is to economically reclaim these elements.

In addition, the extraction of CMs and other metals from primary ores is usually energy intensive and may have a large environmental footprint. Taking gold as an example, primary production via conventional or *in situ* leaching methods is estimated to have a carbon footprint of about 29 tonnes of CO_2-eq kg^{-1}.[127] This carbon footprint could be substantially reduced by using secondary sources like MSWI ash. In the case of austenitic stainless steel obtained solely from recycled sources, it has been estimated that the energy requirements and carbon footprint would be reduced by 67% and 70%[128], respectively.

ARPA-E's environmental goal is to aid in the development of pathways that would result in zero waste going to landfill which may also substantially reduce GHG emissions associated with primary ore mining.

B. Technical Areas of Interest & Technical Performance Targets

Respondents can select the most suitable material stream(s) available from the WTE plant (Figure 1). The proposed solutions may also employ the energy generated by the mass burn.[129]

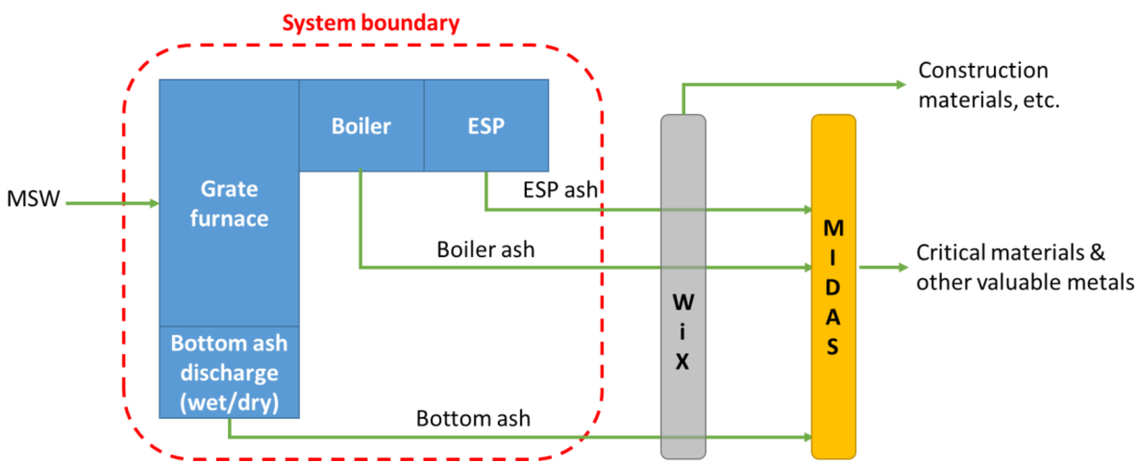

Figure 1. Schematic showing the solid streams in ARPA-E's conceptualization of zero waste going to landfill. ESP stands for electrostatic precipitator. The Waste into X (WiX) FOA is being published co-currently with this FOA. WiX focuses on the development of construction

[127] Haque N. & Norgate T. "*The greenhouse gas footprint of in-situ leaching of uranium, gold and copper in Australia*" **Journal of Cleaner Production** 84 2014 p. 382 [https://doi.org/10.1016/j.jclepro.2013.09.033].
[128] Johnson J., Reck B.K., Wang T., Graedel T.E. "*The energy benefit of stainless steel recycling*" **Energy Policy** 36 2008 p.181 [doi:10.1016/j.enpol.2007.08.028].
[129] Heat of combustion available is ~20 MMBTU per ton of MSWI ash. For electricity use, 1 ton of MSW yields 550 kwh and respondents should assume a current parasitic load of ~12% for the WTE plant.

materials. Note that proponents may or may not need a WiX intermediate step. The WTE diagram (blue boxes) was modified from Morf and collaborators.[130]

It should be noted that the composition of the ashes will vary from facility to facility and from day to day, reflecting both the technology deployed by the WTE facility and the varying composition of the MSW stream. Any proposed solution should address the expected variability within a given facility and be adaptable to additional facilities. ARPA-E seeks novel and transformative technical solutions within the following technical areas:

Technical area 1. *e-waste* thermal conversion products. In practice, unrecycled *e-waste* ends up being processed in WTE facilities and little is known about the chemical and physical transformations that these materials undergo during WTE processing. A fundamental understanding of *e-waste* conversion products is needed to better inform the subsequent ash processing steps (Technical areas 2 and 3).

- Determination of *e-waste* combustion products. Combustion of *e-waste* in the presence of "formulations" (ratios of paper/food waste/plastics/target e-waste) should align with national averages identified by the U.S. EPA.[131] The identification of toxic products[132] like the ones originating from Li-ion batteries is also of interest.

The technical performance target is to complete a physical (shape, particle size distribution) and chemical (metal, oxide, or derivative) characterization of the MSWI ash product and create a list of recommendations for downstream processing.

Technical area 2. Pretreatment, Identification, and Sorting

- Preliminary treatments that improve downstream recovery, including but not limited to comminution, sieving, density-based separations, selective ageing.
- In-line, real time identification and quantification of metals. Optical devices can discriminate amongst copper, bronze, and brass from aluminum based on color but it is still challenging to separate within different gray non-ferrous metals. The in-line metal analysis goal is to achieve an identification accuracy of +/- 2%.
- Enhancement of magnetic and eddy current-type separations. State-of-the-art equipment has a particle size limitation (e.g., better detection/separation for particle sizes < 3 cm).

[130] Morf L.S., et al. "*Precious metals and rare earth elements in municipal solid waste – Sources and fate in a Swiss incineration plant*" **Waste Management** 33 (2013) p.636 [http://dx.doi.org/10.1016/j.wasman.2012.09.010].
[131] *ibid*
[132] **Stewart, E.S., Lemieux, P.M. "**Emissions from the incineration of electronics industry waste**"** IEEE International Symposium on Electronics and the Environment, 2003. https://ieeexplore.ieee.org/document/1208088

- Identification of contaminants with the objective to remove the carriers[133] of elements of environmental concern, like Cd, Pb, Hg, etc.

Technical area 3. Extraction and Recovery. Novel and benign methods (and their combinations) to systematically target the recovery of each element. Solution needs to show environmental benefit relative to the processing of primary ores. Methods can include but are not limited to the following:

- *Chemical.* Chemical leaching with organic and inorganic acids.
- *Electrorefining.* Electrochemical processes that convert metal oxides into metals.
- *Biological*. Biotechnological solutions with microbes[134] and macrobes.
- *Mechanical*. Operations like wet gravity separation, etc.
- *Thermal.* Ash melting and ash gasification.[135]
- *Process intensification.* Sequential removal of other valuable materials like non-metals to afford a metal concentrate for further processing. CMs (REEs, PGMs, etc.) in MSWI ash may be in very low concentrations[136] but once fractionation of other materials occurs (e.g., WiX), the concentration of CMs may be enough to perform their economic recovery.

The technical performance targets for all of the above extraction and recovery methods are to:

- Remain within the energy available from a WTE operation.
- Minimize hazardous emissions to air, water, and soil.
- Leave residual MSWI ashes (if any) in a powdered or slurry form.
- Recover at least 95% of all CMs as pure compounds or as smeltable concentrate.
- Recover at least 90% of other metallic species within the MSWI ash.

3. Program Structure

The maximum period of performance for this program is 24 months. It is expected that all projects will undergo a midpoint review (Go/No Go gate) during the program.

To aid in assessing the Recipient's technical progress under any project resulting from this Targeted Topic, ARPA-E requires quarterly reporting throughout an agreement's performance period. This includes reporting on the following subject matter:

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[133] Viczek, S.A., Aldrian A., Pomberger, R. Sarc R. "*Origins and carriers of Sb, As, Cd, Cl, Cr, Co, Pb, Hg, and Ni in mixed solid waste – A literature-based evaluation*" **Waste Management** 101 (2020) 87-112 [https://doi.org/10.1016/j.wasman.2019.12.009]

[134] Wu H.-Y. & Ting Y.-P., "*Metal extraction from municipal solid waste (MSW) incinerator fly ash —Chemical leaching and fungal bioleaching*" **Enzyme and Microbial Technology** 38 (2006) p. 839 [doi:10.1016/j.enzmictec.2005.08.012].

[135] Jung C.-H. & Osako M. "*Metal resource potential of residues from municipal solid waste (MSW) melting plants*" **Resources, Conservation and Recycling** 53 (2009) p. 301 [doi:10.1016/j.resconrec.2009.01.004].

[136] Allegrini E. et al. "*Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes*" **Waste Management** 34 (2014) p. 1633 [http://dx.do.org/10.1016/j.wasman.2014.05.003].

- Test results, including
  - feed and product characterization
  - test operating conditions
  - material balance and yield of desired products
- Process summary, including
  - process flow diagram(s)
  - heat and material balance for anticipated deployment
  - operating and capital cost estimates as available

4. Coordination with other DOE Activities

This funding announcement has been specifically coordinated with the Advanced Manufacturing Office (AMO) and Basic Energy Sciences (BES) program in DOE's Office of Science (SC). The focus on alternatives and extraction/separations crosscut the DOE technology areas for REEs. The proposals to this funding announcement should take into consideration possible leverage with the programs supported by other DOE offices. There are extensive opportunities for synergistic exchange of information among the sponsored projects for a greater leverage of knowledge emerging from novel and transformative technical approaches in the recovery of critical materials. Projects funded by ARPA-E as a result of this FOA will be encouraged to explore opportunities to coordinate with projects funded by other DOE Offices, including AMO, BES-SC and FE, in order to maximize the scientific and technological impact.

The AMO supports recovery of critical materials from e-waste through the Critical Materials Institute, a DOE innovation hub led by Ames Laboratory (https://www.ameslab.gov/cmi), and recovery of precious metals from e-waste through the Reducing EMbodied-Energy And Decreasing Emissions (REMADE) Institute (https://remadeinstitute.org/). CMI focuses on diversifying and expanding the availability of critical materials throughout their supply chains, reducing wastes by increasing the efficiency of manufacturing and recycling, and reducing demand by identifying substitutes for critical materials. The REMADE Institute focus its efforts on addressing knowledge gaps that will eliminate and/or mitigate the technical and economic barriers that prevent greater material recycling, recovery, remanufacturing, and reuse of materials including metals, fibers, polymers, and electronic waste.

5. Submissions Specifically Not Of Interest

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

- Reclaiming solutions that do not involve WTE.
- Solutions focused on the recovery of MSWI ash materials other than the CMs and metals identified above. See DE-FOA-0001953 and DE-FOA-0001954 Appendix XIV. Appendix N: Waste into X for minerals open FOA.

XIV. APPENDIX N: WASTE INTO X

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Waste into X (WiX)"

Topic Issue Date	May 20, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, July 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 2, 2020
Expected Date for Selection Notifications	October 2020
Total Amount to be Awarded	Approximately $5,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $250,000 to $1.5 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes an exploratory research thrust titled "Waste into X (WiX)." The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to address the beneficiation of Municipal Solid Waste Incineration (MSWI) ash[137] for the production of value-added products (X) such as, engineered-pumice, zeolites, supplementary cementitious materials (SCMs), clinker substitutes, among others, (2) encourage partnerships with waste-to-energy[138] (WTE) stakeholders, downstream processors, and value-added products uptakers, and (3) provide a timetable for the submission of Full Applications.

[137] MSWI ash is a generic term used to reference bottom ashes (BAs) and fly ashes (FAs) produced in the waste combustion process. MSWI ash is produced at an average yield is 0.25 ton MSWI ash per ton of wet MSW. According to European Suppliers of Waste to Energy Technology (ESWET), BA is defined as the unburnable fraction of waste like sand stones, glass, minerals, etc. collected at the end of the grate, and FA is the particulate residue conveyed with the flue gas and removed from the boiler, the fabric filter or the electrostatic precipitator. The distribution between BAs and FAs is dependent on the type of combustor and the combustion conditions. However, in a typical operation BAs would constitute about 85% of the MSWI ash and FAs would constitute the remaining 15%.

[138] Waste-to-Energy, also known as Energy from Waste (EfW) is a waste management option where MSW is combusted at temperatures of about 1000°C in a controlled air atmosphere. The heat of combustion is used to produce steam that can be employed to generate electricity or to provide heat to buildings or production processes.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of advancing the beneficiation of MSWI ash into valuable products. The broad objective of the WiX topic is to explore (i) real-time, cost-effective characterization techniques for the MSWI ash output stream, (ii) the feasibility of adding co-feeds to waste pre-combustion, or to the MSWI ash post-combustion to yield a consistent product independent of MSW composition variability, and (iii) cost-competitive technologies for the upcycling of MSWI ash fractions into novel valorized products.

A. Topic Overview

The EPA waste management hierarchy prioritizes 1) source reduction & reuse, 2) recycling/composting, 3) energy recovery (i.e., WTE), and lastly 4) treatment and disposal (i.e., landfilling).[139] However, according to 2017 EPA statistics,[140] more than a half of the 268 million tons per year of the Municipal Solid Waste (MSW) generated in the U.S. is sent to landfills (139 million tons per year)**,** with the remainder being diverted to recycling, composting, and waste to energy (WTE) processes. However, there is an indication that the amount of waste sent to landfills may be substantially larger as other reports by Themelis, Powell, and their collaborators have found that landfills in the U.S. accepted 262 million tons in 2012[141] (when EPA reported only 122 million tons for the same year) and that EPA may be consistently underestimating annual tonnage going to landfill by more than 100 million tons every year.[142]

The average U.S. recycling rate is estimated to be around 25%[143] and while this is an important link in our sustainable waste management hierarchy, this alternative has limitations. Challenges include consumer compliance and confusion during the segregation process (leading to higher processing and transportation costs), contamination by composite and other materials (not everything is recyclable), challenges with international recycling markets, like the Chinese import ban on plastic waste,[144] and in many cases the costs of recycling (inclusive of revenues)

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[139] EPA "*Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy*" [https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy]. Last accessed 4/6/2020

[140] *National Overview: Facts and Figures on Materials, Wastes and Recycling*, EPA [https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#Landfilling]. Last accessed on 3/24/2020.

[141] Themelis N. J., & Shin D., "*Survey of MSW Generation and Disposition in the US. MSW Management*." (2015). [https://www.mswmanagement.com/collection/article/13019760/survey-of-msw-generation-and-disposition-in-the-us]. Last accessed on 3/24/2020.

[142] Powell J. T., Townsend T. G., & Zimmerman J. B., "*Estimates of solid waste disposal rates and reduction targets for landfill gas emissions*". **Nature Climate Change**, 6 (2), p. 162 (2016). [https://doi-org.proxy.scejournals.org/10.1038/nclimate2804]

[143] https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

[144] Brooks L. A. et al. *"The Chinese import ban and its impact on global plastic waste trade"* **Science Advances** 20 p. 1-7 [https://doi.org/10.1126/sciadv.aat0131]

exceeding the costs of landfilling. These challenges have given rise to "wishcycling", a situation where recyclables are segregated and collected just to be later landfilled or combusted, as opposed to being actually recycled.

Landfilling is currently the most economical alternative for waste disposal in the U.S. However, this technology presents several environmental disadvantages as it consumes land resources, still carries significant public health risks, is incompatible with a circular economy philosophy, and despite the efforts to recover energy from the biodegradable fraction of the waste, landfills have been found to be a major contributor to Greenhouse Gas (GHG) emissions. In California, some landfills are deemed to be methane *super-emitters,*[145] accounting for more than 40% of the state's methane emissions, followed by the dairy and oil & gas sectors.

Given the environmental challenges associated with recycling and landfilling, the possibility of generating a significant amount of energy via WTE, and the potential for reducing embodied energy in commonly used materials via the use of end-products, ARPA-E is interested in exploring the energy and resource potential of WTE. The U.S. WTE infrastructure only processes about 30 million tons of MSW annually, or about 10% of the waste generated in the U.S., while producing about 14 million MWh[146] of electricity (~ 0.05 Quads) for the grid.

The U.S. WTE industry has invested in researching various technologies for both energy and resource recovery. Recent efforts have been focused in turning the MSWI ash liability into an asset. For example, the York County Solid Waste Authority has pioneered MSWI bottom ash recovery with the installation of an Ash Recycling and Processing Facility (ARPF)[147] that is co-located with their WTE plant in York, PA. Here, MSWI bottom ash is fractionated into oversized non-combustible materials, different sizes of ferrous metal and non-ferrous metals, small and large aggregate fractions, sand, filter cake (fine residue), ferritic dirt, char, and tailings.

Another more recent example is Covanta's Total Ash Processing System (TAPS)[148] being built in Fairless Hills, PA. The plant is expected to be able to process 400,000 tons of MSWI combined ash[149] per year sourced from different WTE plants. Currently there is no commercial outlet for the ash after metal recovery.

ARPA-E believes we may be in the midst of a complete paradigm shift on how we view MSW, no longer as trash but as an abundant source of valuable energy, metals, and mineral components

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[145] Duren R. M., Thorpe A. K., Foster K. T. et al. *"California's methane super-emitters"* **Nature** 575 p. 180 (2019) [https://doi.org/10.1038/s41586-019-1720-3]
[146] Michaels T. & E Krishnan K. "*2018 Directory of Waste-to-Energy Facilities*", **Energy Recovery Council (ERC)** p. 5 [http://energyrecoverycouncil.org/wp-content/uploads/2019/10/ERC-2018-directory.pdf]. Last accessed 3/25/2020.
[147] Ash Recycling and Processing Facility (ARPF). [https://www.ycswa.com/ash-processing-and-recycling-facility/]. Last accessed 3/25/2020.
[148] Total Ash Processing System (TAPS) press release. [https://www.covanta.com/News/Press-Releases/2019/2019/01/Jan-07]. Last accessed 3/30/2020
[149] Combined ash is the mixture of bottom and fly ashes, also known as total ash.

like Ca, Mg, Si, etc. The challenge is to economically separate and re-engineer these recovered materials into value-added products (X). ARPA-E's environmental goal is to aid in the development of pathways that would result in zero waste going to the landfill which not only reduces GHG but also harnesses the energy embedded in MSWI ash.

B. Technical Areas of Interest & Technical Performance Targets

ARPA-E seeks novel and transformative technical solutions within the three technical areas detailed below. For all proposed solutions the respondents should assume an MSWI ash that has been stripped of ferrous and non-ferrous metal fractions by existing magnetic separation and eddy current methods,[150] respectively.

Technical Area 1. Real-time analysis of MSWI ash

Real-time data analytical techniques, including but not limited to XRD, XRF, chemical characterization, or optical techniques that can be combined with technologies such as artificial intelligence (deep learning, machine learning), IoT, etc. to characterize MSWI ash in real time. It is expected that the respondent's solution will address MSWI ash-specific challenges such as sintering[151] and color blending (e.g., ash may be covered by a layer of uncombusted carbon products or cement-like compounds) which may hinder the accurate identification of materials.

The goal is to produce either an approximate compositional analysis (± 2%) or predictive performance correlation that can help ascertain MSWI ash downstream processing needs and/or end-use applications.

Technical Area 2. Pre- and/or Post-combustion additions (co-feeds)

Solutions may include but are not limited to the addition of clays, glass, coal combustion residues, feldspars, crushed cements, carbonates, slags, rice husks, and other waste streams, like biosolids. All proposals should address how these co-feeds could be added *dynamically to afford a consistent product independent of MSW compositional variations*. ARPA-E is interested in exploring these additions:

a) <u>Before combustion</u> (pre-combustion) with the objective of reducing slag, co-calcination of cement precursors, etc. Solutions should not increase the amount of controlled emissions nor increase equipment maintenance costs. Any potential for the co-feeds to decrease emissions of persistent organic pollutants (POPs), NO_X, SO_X, HCl or per- or polyfluoroalkyl substances (PFAs) should be identified.

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[150] Holm O. & Simon F.-G., "*Innovative treatment trains of bottom ash (BA) from municipal solid waste incineration (MSWI) in Germany*" **Waste Management** 59 (2017) p.230. [http://dx.doi.org/10.1016/j.wasman.2016.09.004]
[151] Refers to the process where either bottom ash or fly ash compacts into a solid mass upon heating, without melting to the point of liquefaction.

b) After combustion (post-combustion) to synthesize value-added construction materials, dilute clinker formulations so as to properly manage any hazardous materials, etc.

For both cases a) and b), the proposed solution may take advantage of the heat available from the mass burn unit,[152] and the impact of combustion/thermal treatment variations can be evaluated.

The goal is to enable the controlled-addition of co-feeds to the MSWI ash to afford a product with consistent performance in a value added end use. Respondents should estimate the cost of the additives to be evaluated relative to the value of the final application.

Technical Area 3. MSWI ash upcycling

Under technical area 3, ARPA-E seeks the development of novel products from MSWI ash mineral fractions that will meet industrial specifications, such as content of heavy metals, chlorine,[153] etc. The solutions may include but are not limited to:

- Construction materials,[154] such as the production of cement clinkers,[155] SCMs, pre-cast blocks, and aggregates.
- Glass-derived products, such as engineered-pumice, sands, and refractory materials.
- Solid fuels. In practice, the incomplete combustion of MSW gives rise to production of char-like by-products. Thus, the upgrading of these char-materials into practical solid fuels is of interest as part of an overall MSWI ash utilization plan.

The metric for technical area 3 is to meet the appropriate ASTM (or equivalent) standard for the proposed end-use of the value-added product. For example, the ASTM C1697-18 Standard Specification for Blended Supplementary Cementitious Materials, or the ASTM C1825-19 Standard Guide for Developing Specifications for Masonry Units. Respondents should supply specific standards that need to be addressed and incorporate attainment of that standard in the project plan.

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[152] Assume a current parasitic load of ~12% for the WTE plant operation. For this FOA, respondents are welcomed to propose solutions that may employ the remaining energy (~88%) produced by the mass burn in the WiX solution. Assume heat of combustion available of 20 MMBTU per ton of MSWI ash (e.g., high pressure steam at ~600 °C).

[153] Ko M.-S., Chen Y.-L., Wei P.-S., "*Recycling of municipal solid waste incinerator fly ash by using hydrocyclone separation*", **Waste Management** 33 (2013) p. 617 [http://dx.doi.org/10.1016/j.wasman.2012.10.009].

[154] Joseph A. M., et al. "*The Use of Municipal Solid Waste Incineration Ash in Various Building Materials: A Belgian Point of View*" **Materials** 2018, 11, 141 p. 1-30. [https://www.mdpi.com/1996-1944/11/1/141].

[155] Monroy Sarmiento L., et al. "*Critical examination of recycled municipal solid waste incineration ash as a mineral source for Portland cement manufacture – A case study*" **Resource, Conservation & Recycling** 148 (2019) 1-10. [https://doi.org/10.1016/j.resconrec.2019.05.002]

As MSWI ash may contain certain toxic metals or components that may lead to environmental releases if extracted, respondents should discuss this risk and applicability of the U.S. EPA's LEAF protocol[156] to determine leaching potential of the chosen valorized end products.
As indicted earlier, MSWI ash is comprised of two distinct streams: bottom ash (BA) and fly ash (FA). Though the intent is to use all of the combustion residues, respondents can propose solutions for either BA or FA fractions, as well as solutions for the combined fraction.

It should be noted that the composition of the ash will vary from facility to facility and from day to day, reflecting both the technology deployed by the WTE facility and the varying composition of the MSW stream. Any proposed solution should address the expected variability within a given facility and be adaptable to to additional facilities.

3. Other Available Resources

- Energy Recovery Council – Industry organization for waste to energy operations with good background information and information about existing facilities. http://energyrecoverycouncil.org/
- U.S. Environmental Protection Agency MSW energy recovery website https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw
- U.S. Environmental Protection Agency LEAF testing website https://www.epa.gov/hw-sw846/leaching-environmental-assessment-framework-leaf-methods-and-guidance

4. Submissions Specifically Not of Interest

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

- MSW upcycling solutions that do not involve WTE.
- Solutions focused simply on fractionation of ash for use as aggregate replacement
- Solutions that require extensive waste stream segregation or pretreatment before entering the combustion process.
- Solutions focused on metals recovery from MSWI ash. See DE-FOA-0001953 and DE-FOA-0001954 Appendix XIII. Appendix M: Mining Incinerated Disposal Ash Streams

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[156] EPA's Leaching Environmental Assessment Framework (LEAF) Methods and Guidance [https://www.epa.gov/hw-sw846/leaching-environmental-assessment-framework-leaf-methods-and-guidance].

XV. APPENDIX O: Direct Removal of Carbon Dioxide from Oceanwater

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Direct Removal of Carbon Dioxide from Oceanwater"

Topic Issue Date	May 20, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, July 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 2, 2020
Expected Date for Selection Notifications	October 2020
Total Amount to be Awarded	Approximately $2,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $250,000 to $1.5 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust entitled "Direct removal of carbon dioxide from oceanwater." The purpose of this announcement is to (1) focus the attention of the scientific and technical communities on specific areas of interest related to CO_2 capture from oceanwater (or other natural waters), (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

Capture of dispersed greenhouse gases (GHGs) is an important part of a diversified portfolio of technologies to mitigate U.S. GHG emissions. A large portion of the 5.2 gigatons (Gt)[157] of CO_2 emitted each year in the United States[158] is released in relatively small quantities from distributed sources (e.g., from small point sources or some transportation sources). For such emissions, point source capture may be infeasible. In those cases, capture of dispersed CO_2 serves as a crosscutting and complementary approach to achieving economy-wide net-zero emissions.

[157] 1 gigaton (Gt) = 10^9 metric tons
[158] U.S. Energy Information Administration, https://www.eia.gov/environment/emissions/carbon/

Beyond helping to achieve net-zero emissions, capture of dispersed CO_2 can lead to net-negative emissions. Recent reports[159,160] highlight the importance of negative emissions – at the Gt/y scale by midcentury – in limiting global temperature increases resulting from anthropogenic CO_2 emissions. When coupled with storage or certain utilization pathways, capture of dispersed CO_2 can meet such needs and offset historical emissions.

Capture of dispersed CO_2 can also meet industrial CO_2 demand (or be a source for CO_2 utilization) on site, eliminating the need for potentially costly transport. The market for CO_2 use is growing, with some forecasting an increase in global CO_2 demand from 300 Mt/y today to 1 Gt/y by 2040.[161] Particularly for end users demanding small quantities of CO_2, the cost of transporting CO_2 may offset the (currently) greater cost of capturing dispersed CO_2 relative to other sources.

The removal of CO_2 from oceanwater (or other natural waters), or direct ocean capture (DOC), is one method of capturing dispersed CO_2. In some cases, DOC can be advantageous relative to other emissions mitigation and negative emissions strategies. In comparison to removal of CO_2 from the ambient air, or direct air capture (DAC), dissolved inorganic carbon (DIC) exists at a higher volumetric concentration, meaning smaller volumes of fluid can move through the system per unit carbon removed. DOC also has the potential to operate offshore. Offshore operation limits competition for useful land, can allow access to oceanic CO_2 storage sites currently only reachable by pipeline, and can provide a source of CO_2 for offshore enhanced oil recovery (EOR). Finally, DOC represents a direct reversal of ocean acidification caused by anthropogenic CO_2 emissions. However, operation in an oceanic environment also includes specific challenges, such as corrosion, ecological considerations, potentially high capital and operating expenditures due to offshore implementation, and the like. All applicants should identify which of these challenges are applicable to their technology, and how they would mitigate these risks.

For this Targeted Topic, ARPA-E is focused on the CO_2 capture process; ARPA-E is not interested in proposals that focus solely on transport, storage, or utilization.

A. Technoeconomic Performance Targets

ARPA-E seeks to establish robust, energy efficient, and low-cost strategies for direct removal of carbon dioxide from oceanwater (or other natural waters). Although not all technical areas of interest include full system designs, the aim of projects funded under this solicitation is to drive

[159] National Academies of Sciences, Engineering, and Medicine, "Negative emissions technologies and reliable sequestration: a research agenda," 2018.
[160] IPCC, "Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty," 2018.
[161] R. Anderson, "CCUS Costs and Opportunities for Long-term CO_2 Disposal," Bloomberg New Energy Finance, 2020.

innovation towards a DOC system with the technoeconomic performance targets shown below. Additionally, systems should have the potential to scale to Gt-levels of CO_2 capture. Projects focused on system components or full system designs should show the potential to lower capital and/or operating expenditures below those presently available.

Applicants must describe, in a manner as detailed and quantitative as possible, how their concept, if successful, would enable the technoeconomic performance targets identified below. However, the technoeconomic performance targets are not required to be achieved by the end of the project period of performance.

Performance Metric	Target
Levelized Cost of Capture	< \$100/t CO_2
Second Law Efficiency	> 10%
Embodied Emissions (as % of lifecycle captured emissions)	< 5%

B. Technical Area of Interest

ARPA-E seeks to catalyze technology discoveries by supporting projects focused on the areas below:

1. Salt Splitting Technologies

One method to effect CO_2 removal from saltwater involves splitting the dissolved salt into its corresponding acid and base. The resulting acid is then used to reduce the pH of the saltwater, causing the DIC equilibrium to shift towards CO_2, which is then outgassed. The base is then used to return the pH to the appropriate level. The net result is the separation of dissolved CO_2 from saltwater.

For example, bipolar membrane electrodialysis (EDBM) can separate an $NaCl_{(aq)}$ stream into $HCl_{(aq)}$ and $NaOH_{(aq)}$. The resulting $HCl_{(aq)}$ is then applied to a stream of seawater, lowering its pH and driving the conversion of HCO_3^- to CO_2. After the CO_2 has been removed from the seawater stream, the $NaOH_{(aq)}$ is applied to increase the pH.

ARPA-E is specifically interested in proposals which may result in low-cost EDBM or other salt splitting systems. Technical areas of interest include, but are not limited to:

- Novel, high-efficiency process designs or other approaches to increase system efficiency
- Approaches to reduce balance-of-plant capital expenditures
- Approaches to decrease EDBM cell size, including high-recovery, low-cost brine pre-concentration

- Novel component designs
- Other salt splitting approaches not involving EDBM

Proposals must include detailed, technology-specific information to support the technoeconomic performance targets in Section 2.A. For example, proposals for novel process designs may include target values for metrics used in cost and performance models, such as:

Example Category	Example Metric	Value or Range
Capital cost estimation	Major component sizes (e.g., required heat exchanger surface area or reactor volume) [m^2, m^3]	
O&M cost estimation	Thermal and electrical energy consumption [kWh/t CO_2 captured]	
	Water or chemical consumption	
Performance estimation	Required component efficiency or effectiveness values	
	Thermodynamic states at major component boundaries	
	Outlet CO_2 state (concentration, temperature, pressure)	
	Outlet CO_2 impurities (species, concentrations)	

2. Novel Concepts Not Involving Salt Splitting

ARPA-E is specifically interested in novel approaches to CO_2 removal from natural waters that do not involve the chemical conversion of salts into acids and bases. Such approaches may include, but are not limited to:

- Novel, alternative chemistries (e.g., that more directly drive bicarbonate to CO_2 conversion, as by a bicarbonate-selective membrane)
- Biological methods for CO_2 removal
- Passive sorbent-based processes
- Hybridization with naturally occurring oceanic mineral deposits capable of long-term CO_2 storage

Proposals must include detailed, technology-specific information to support the technoeconomic performance targets in Section 2.A. For example, proposals for a membrane may include target values for metrics used in cost and performance models, such as:

Example Category	Example Metric	Value or Range
Capital cost estimation	Cost per membrane surface area	
O&M cost estimation	Membrane lifetime	
Performance estimation	Permeability to desired species	
	Rejection of undesired species	
	Chemical stability in the presence of seawater	

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Approaches that consume compounds or chemicals in stoichiometric proportion to the CO_2 captured
- Approaches that produce compounds or chemicals in stoichiometric proportion to the CO_2 captured, such as chlor-alkali technologies that co-produce chlorine gas. Exceptions may be made for approaches with co-product market sizes greater than 1 Gt/y.
- Ocean liming
- Iron fertilization
- Approaches that are not scalable
- Approaches that only incrementally improve upon state of the art technologies

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XVI. APPENDIX P: Direct Removal of Carbon Dioxide from Ambient Air

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Direct Removal of Carbon Dioxide from Ambient Air"

Topic Issue Date	May 20, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, July 10, 2020
Submission Deadline for Full Applications	9:30 AM ET, Wednesday, July 22, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Wednesday, September 2, 2020
Expected Date for Selection Notifications	October 2020
Total Amount to be Awarded	Approximately $2,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $250,000 to $1.5 million.
Maximum Period of Performance	24 Months

1. Introduction

This announcement describes a research thrust entitled "Direct removal of carbon dioxide from ambient air." The purpose of this announcement is to (1) focus the attention of the scientific and technical communities on specific areas of interest related to direct removal of carbon dioxide (CO_2) from ambient air, (2) encourage dialogue amongst those interested in this area, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

Capture of dispersed greenhouse gases (GHGs) is an important part of a diversified portfolio of technologies to mitigate U.S. GHG emissions. A large portion of the 5.2 gigatons (Gt)[162] of CO_2 emitted each year in the United States[163] is released in relatively small quantities from distributed sources (e.g., from small point sources or some transportation sources). For such emissions, point source capture may be infeasible. In those cases, capture of dispersed CO_2 serves as a crosscutting and complementary approach to achieving economy-wide net-zero emissions.

[162] 1 gigaton (Gt) = 10^9 metric tons
[163] U.S. Energy Information Administration, https://www.eia.gov/environment/emissions/carbon/

Beyond helping to achieve net-zero emissions, capture of dispersed CO_2 can lead to net-negative emissions. Recent reports[164,165] highlight the importance of negative emissions – at the Gt/y scale by midcentury – in limiting global temperature increases resulting from anthropogenic CO_2 emissions. When coupled with storage or certain utilization pathways, capture of dispersed CO_2 can meet such needs and offset historical emissions.

Capture of dispersed CO_2 can also meet industrial CO_2 demand (or be a source for CO_2 utilization) on site, eliminating the need for potentially costly transport. The market for CO_2 use is growing, with some forecasting an increase in global CO_2 demand from 300 Mt/y today to 1 Gt/y by 2040.[166] Particularly for end users demanding small quantities of CO_2, the cost of transporting CO_2 may offset the (currently) greater cost of capturing dispersed CO_2 relative to other sources.

Direct removal of CO_2 from the atmosphere, sometimes referred to as direct air capture (DAC), is the separation of CO_2 at ambient concentration (about 410 parts per million by volume fraction (ppmv)[167]) from air. In some cases, DAC can be advantageous relative to other emissions mitigation and negative emissions strategies. In comparison to removal of CO_2 from point sources, DAC has the advantage of being location independent. In comparison to negative emissions strategies that use biomass, DAC systems do not compete with agriculture for land.

For this FOA topic, ARPA-E is focused on the CO_2 capture process; ARPA-E is not interested in proposals that focus solely on transport, storage, or utilization.

Recently, the Department of Energy's Office of Science and Office of Fossil Energy released funding opportunity announcements related to capturing carbon dioxide directly from ambient air.[168] ARPA-E's effort in this space is designed to complement these funding opportunities by focusing on earlier-stage and higher-risk concepts than the Office of Fossil Energy, while including performance-driven metrics including cost which is differentiated from the Office of Science's fundamental materials research.

A. Technoeconomic Performance Targets

ARPA-E seeks to establish robust, energy efficient, and low-cost strategies for direct removal of carbon dioxide from ambient air. Although not all technical areas of interest include full system designs, the aim is to drive innovation towards a direct air capture system with the

[164] National Academies of Sciences, Engineering, and Medicine, "Negative emissions technologies and reliable sequestration: a research agenda," 2018.
[165] IPCC, "Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty," 2018.
[166] R. Anderson, "CCUS Costs and Opportunities for Long-term CO_2 Disposal," Bloomberg New Energy Finance, 2020.
[167] https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html
[168] https://www.energy.gov/articles/department-energy-provide-22-million-research-capturing-carbon-dioxide-air

technoeconomic performance targets shown below. Additionally, systems should have the potential to scale to Gt-levels of CO_2 capture. Projects focused on system components or full system designs should show the potential to lower capital and/or operating expenditures below those presently available.

Applicants must describe, in a manner as detailed and quantitative as possible, how their concept, if successful, would enable the technoeconomic performance targets identified below. However, the technoeconomic performance targets are not required to be achieved by the end of the project period of performance.

Technoeconomic Performance Target	Target Value
Levelized Cost of Capture	< \$100/t CO_2
Second Law Efficiency	> 30%
Embodied Emissions (as % of lifecycle captured emissions)	< 5%

B. Technical Area of Interest

Direct air capture may be done using solvents, sorbents, and/or membranes. ARPA-E is specifically interested in novel, high-risk DAC technology pathways with capital costs and energy and chemical intensities much lower than state of the art. Technologies able to operate across a variety of environmental and geographical constraints across the country are of particular interest. Technologies should show the potential for economically attractive system scaling to Gt-levels of CO_2 removal. Applicants are encouraged to be as detailed and quantitative as possible regarding their materials and process design.

ARPA-E seeks to catalyze technology discoveries by supporting projects focused on one or more of the following areas:

1. Capture Materials

Projects are sought on development of new materials used for CO_2 capture including, but not limited to, sorbent, solvent, membrane, biological, and biologically-inspired approaches. This technical area is meant to complement funding opportunities[168] from the Office of Fossil Energy and the Office of Science by focusing on earlier-stage and higher-risk concepts than Office of Fossil Energy while including cost and performance-driven metrics, which is differentiated from the Office of Science's fundamental materials research. ARPA-E also has a unique emphasis on novel biological and biologically-inspired approaches to DAC.

Critical consideration should be given to capture kinetics as well as the material lifetime and degradation as a function of number of cycles. Projects in this area should include details on the material supply chain and show the potential for Gt-levels of CO_2 removal.

Proposals must include detailed, technology-specific information to support the technoeconomic performance targets in Section 2.A. For example, proposals for novel sorbents may include target values for metrics used in cost and performance models, such as:

Example Category	Example Metric	Value or Range
Capital cost estimation	Active surface area per unit volume [m^2/m^3]	
	CO_2 mass : sorbent mass, fully loaded [kg/kg]	
	Cycle duration [time], including loading and unloading times	
O&M cost estimation	Sorbent lifetime [time (e.g., years) or number of cycles]	
	Rate of CO_2 sorption	
	Regeneration energy consumption (as heat and/or work)	
	Nominal regeneration conditions (temperature, pressure)	
Performance estimation	CO_2 selectivity relative to N_2, O_2, and H_2O	
	State of desorbed CO_2 (concentration, temperature, pressure)	

2. Novel Air Contactor Designs

Projects are sought on novel air contactor designs that maximize mass transfer while minimizing capital expenditures and energy demand. Current air contactor designs are energy intensive. ARPA-E is particularly interested in proposals that drastically reduce the system energy requirements relative to state-of-the-art. Proposals may focus on the design of a single air contactor or a group of air contactors. Applicants should include any overall process details relevant to the air contactor design.

ARPA-E has a particular interest in passive air collector designs. A passive DAC system relies on wind to deliver ambient CO_2 to the contactor and capture material. This strategy eliminates the need for fans and their associated energy consumption, which may be a significant fraction of total energy consumption. A passive system design must include estimates of the boundary conditions on wind speeds required as well as estimates of reactive or contactor surface area requirements as a function of wind speed per unit of CO_2 removed.

Proposals must include detailed, technology-specific information to support the technoeconomic performance targets in Section 2.A. For example, proposals for novel air contactor designs may include target values for metrics used in cost and performance models, such as:

Example Category	Example Metric	Value or Range
Capital cost estimation	Normalized capital cost [$/ [t Air/y]]	
	Geographic footprint	
	Spacing design and/or heuristics (if applicable)	
O&M cost estimation	Thermal and electrical energy consumption [kWh/t CO_2 captured]	
Performance estimation	Pressure drop	
	Volume flow (throughput)	
	Mass transfer boundary conditions	

3. Novel Process designs

Projects are sought on novel process designs and chemistries that drastically reduce thermal and electrical energy requirements as well as water and/or other chemical consumption relative to state of the art.

Proposals must include detailed, technology-specific information to support the technoeconomic performance targets in Section 2.A. For example, proposals for novel process designs may include target values for metrics used in cost and performance models, such as:

Example Category	Example Metric	Value or Range
Capital cost estimation	Major component sizes (e.g., required heat exchanger surface area or reactor volume) [m^2, m^3]	
O&M cost estimation	Thermal and electrical energy consumption [kWh/t CO_2 captured]	
	Water or other chemical consumption	
Performance estimation	Required component efficiency or effectiveness values	

	Thermodynamic states at major component boundaries	
	Outlet CO_2 state (concentration, temperature, pressure)	
	Outlet CO_2 impurities (species, concentrations)	

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not merit review or be considered:

- Approaches that focus solely on any one or combination of the following: CO_2 transport, storage, and/or utilization
- Approaches that are not scalable
- Approaches that capture CO_2 solely from point sources, where the concentration of CO_2 is greater than the concentration of CO_2 in ambient air
- Approaches that only incrementally improve upon state of the art technologies

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XVII. APPENDIX Q: Connecting Aviation By Lighter Electric Systems

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"Connecting Aviation By Lighter Electric Systems (CABLES)"

Topic Issue Date	September 16, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, November 6, 2020
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, November 17, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Monday, January 11, 2021
Expected Date for Selection Notifications	February 2021
Anticipated Date of Awards	Approximately June 2021
Total Amount to be Awarded	Approximately $10,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. The Maximum Awards is $6 Million in Federal Share
Maximum Period of Performance	36 Months

1. Introduction

This announcement describes an exploratory research thrust titled "Connecting Aviation By Lighter Electrical Systems." The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to develop medium-voltage (> 10 kV) power distribution cables, connectors, and circuit breakers for fully-electrical aviation applications (> 12.2 km altitude), (2) encourage partnerships with commercial cable/connector manufacturers, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of the development of medium-voltage interconnecting systems for power distribution in electric aviation. The broad objectives of this topic are to (i) identify appropriate wiring materials (i.e., conducting or superconducting) with optimum gravimetric power densities and minimum electrical losses, and evaluate corresponding vacuum or cryogenic systems if necessary; (ii) identify insulating materials with high dielectric strength, good thermal conductivity, low specific weight, conformality, malleability, and air-void minimization; (iii) assess connector designs; (iv) develop circuit breakers for aviation applications; and (v) for all cases address partial discharge related reliability issues that arise from low air pressure environments.

A. Topic Overview

ARPA-E has recently launched two programs on electric aviation relevant to narrow-body passenger aircrafts. The first program, ASCEND (Aviation-class Synergistically Cooled Electric-motors with integrated Drives), [169] will deal with the development of lightweight and ultra-efficient integrated electric motors, drives and thermal management systems to facilitate net-zero carbon emissions. The second program, REEACH (Range Extenders for Electric Aviation with Low Carbon and High Efficiency), [170] will develop a system for the conversion of chemical energy contained in energy dense Carbon Neutral Liquid Fuels (CNFLs) to electric power for aircraft propulsion. However, a remaining challenge, especially in all-electric aviation, is power distribution. As part of the agency's continued effort to mitigate the growing environmental burden associated with commercial air travel (10 top airlines emitted a total of 306 MT CO_2e in 2018)[171], we seek the development of electric power cable, electric cable connector, and circuit breaker technology suitable for an all-electric aircraft.

The state-of-the-art maximum onboard electric power generation capacity in operating commercial airliners is approximately 1 MW on the Boeing 787, which is supplied via low-voltage AC distribution (115-235 V_{AC}, ±270 V_{DC}) to ancillary electrical power systems such as HVAC, avionics, actuators, and anti-icing/deicing systems. Airbus' testbed design for a narrow-body, hybrid-electric distribution system, the E-Fan X, includes a distribution system at 3 kV and a 2 MW electric propulsor which replaces one of four jet engines.[172]

However, an all-electric propulsion system for twin-aisle (e.g. the notional NASA N3-X) aircraft would require at least 50 MW[173] (i.e. utility-scale power) during takeoff, which is significantly higher than the present onboard generation and power distribution system capabilities. Rolls-Royce and GE research projects funded by NASA[174,175] have concluded that even with high temperature superconductors (HTSs), voltages are optimally in the range of ±4.5-12 kV to

[169] https://arpa-e.energy.gov/?q=arpa-e-programs/ascend
[170] https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=f05ad2e5-5ef4-4079-b794-57c1146e4a14
[171] Harrison K., "*Before Covid, Largest 10 Airlines Emitted more than Poland*" BloombergNEF April 2020.
[172] https://www.airbus.com/innovation/future-technology/electric-flight/e-fan-x.html#ove
[173] National Academies of Sciences, Engineering, and Medicine. 2016. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press
[174] Armstrong M., et al., "*Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid*," NASA/CR—2015-218440
[175] Gemin P., et al. "*Architecture, Voltage and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)*," NASA/CR—2015-218713

achieve the power density required of power electronics and motors for 50 MW[176] of total system power. In order to achieve greater than 50 MW power distribution, there are various possible solution spaces as well as unique challenges that will need to be addressed.

Medium Voltage

The distribution of such a large amount of power may require the use of a prohibitive load of cables and connectors. Thus, ARPA-E is interested in evaluating transformative solutions such as the use of a medium-voltage direct current (MVDC) distribution system that would be more likely to meet weight and size requirements. Figure 1 gives an example of how increasing voltage can reduce the wiring weight of the conducting core (Cu portion) and increase the gravimetric power density of cable.

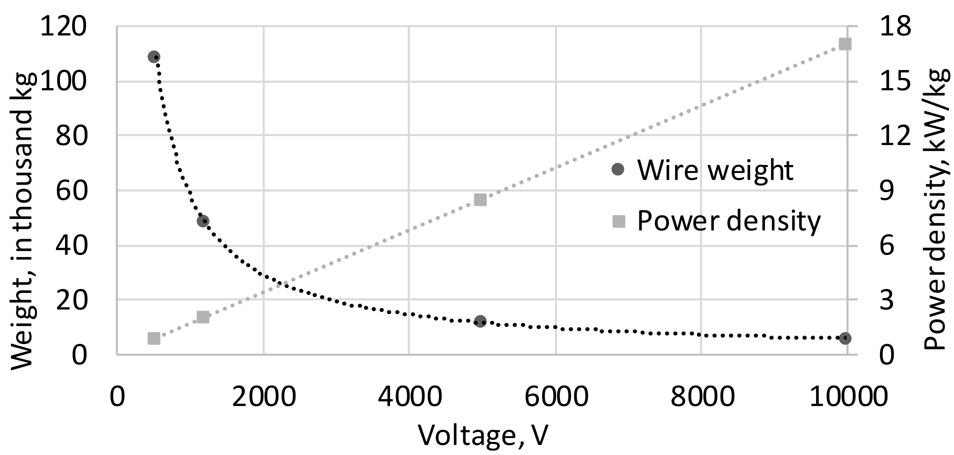

Fig. 1. Voltage *vs.* copper wiring weight (no insulation)[177] and power density.

As shown in Figure 1, at a voltage of 540 V, the weight of the copper wiring is estimated to be 108,606 kg which is almost half of the maximum total weight allowance of a Boeing 787 at takeoff, whereas at 10 kV, the weight for the copper wiring is only 5,865 kg, an 18.5-fold weight reduction. Moving to medium voltage has the additional benefit of reducing power loss which translates to reduced heat dissipation and increased efficiency. At 540 V and 10 kV the power losses are estimated to be 48 kW and 2.6 kW, respectively. Thus, performance at medium voltage may be critical to have substantial improvement in the gravimetric power density of the electrical system using traditional metals.

[176] NASA's baseline TeDP architecture with a fully redundant 25 MW minimum take-off requirement.
[177] *Weight estimation assumptions*: 8 x 45 m cables copper wires with no insulation (insulation would contribute additional weight), 100 MW notional aircraft, 2x redundancy, 2 generators.

1. Cable Core Materials

Another approach to achieve lighter systems is with novel conducting materials. Lighter materials, such as All Aluminum Alloy Conductors (AAACs) are commonly used in high-voltage overhead transmission lines due to their lower density and high tensile strength. While there is still concern about corrosion with aluminum, AAACs have been tested in subsea umbilical applications (10°C-90°C, seawater, 300 bar) and the study concluded that "wet design" AAAC medium voltage (MV) power cables were not susceptible to corrosion.[178] Materials and methods that reduce the likelihood of corrosion, such as alloys, sealants, corrosion-inhibiting finishers, and the avoidance of galvanic coupling should also be considered in any design.

Other novel conducting materials include conductive polymer composites, graphene, carbon nanotubes (CNTs) and their composites, such as CNT-Cu and CNT-Ag. These metallic CNTs have the potential for high thermal and electrical conductivity, high ampacity ($x10^2$ Cu),[179] and a low specific gravity of about 9 and 2.7 times less than copper and aluminum, respectively.[180]

Superconductors are another possible enabling technology for all-electric aviation.[181] Superconducting materials are an attractive alternative due to low resistivity below their critical temperature, T_c. High-T_c Superconductor (HTS) cables have been used in various transmission projects in Germany, Japan, and the U.S.[182] The superconductor coolant can also provide a secondary function for cabling systems. For example, low-T_c Superconductor (LTS) materials, such as MgB_2, have been assessed in cabling applications where hybrid energy delivery of fuel, such as liquid H_2, and power are combined for terrestrial applications.[183]

[178] Socariceanu M., An X., Deighton A., Friday A. "*Corrosion assessment of aluminum conductor for medium voltage cables for Subsea umbilical system*" Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE v. 5, 2018.

[179] Subramanian C., et al. "*One hundred fold increase in current carrying capacity in a carbon nanotube–copper composite"* Nat. Comm. 4 2202 [DOI: 10.1038/ncomms3202 | www.nature.com/naturecommunications].

[180] Bystricky P., Lashmore D., Kalus-Bystricky I. "*Metal matrix composite comprising nanotubes and methods of producing same*" IPN: WO2018/126191 A1 p.1.

[181] Luongo C.A. et al. "*Next Generation More-Electric Aircraft: A Potential Application for HTS Superconductors*" IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, v.19, 3 (2009). [doi: 10.1109/TASC.2009.2019021].

[182] Santosh M. "*The Promising Role of Superconductivity in Cable Power Applications*" Journal of Electrical Engineering 6 (2018) 295-298 [doi: 10.17265/2328-2223/2018.05.007].

[183] Vysotsky V.S., et al. "*Hybrid Energy Transfer Line with Liquid Hydrogen and Superconducting MgB_2 Cable—First Experimental Proof of Concept*" IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, v.23, 3, 2013. [doi:10.1109/TASC.2013.2238574].

2. Insulation Considerations

Electric insulation for cables and connectors in all-electric aircraft applications have many functions. One of which is to reduce the electric field surrounding the conductor. This can be done by increasing the effective capacitance of the cable with respect to external potentials. By increasing the effective capacitance with an improved dielectric, added layers, or increased material, more charge accumulation is required to reach the same voltage differential at a given point.

Shields may also be included to limit voltage stress on the insulation, dissipate insulation leakage current, and remove the capacitive charging current.[184] For cables with semiconducting or conductive shield layers, the electric field has a more uniform distribution throughout the cable and any accumulated charge has a return path to ground. Even with a shield, partial discharge may occur within a material if the dielectric has voids or defects that cause it to break down in the presence of a strong electric field.

In general, insulation material must be able to: (i) perform at the low atmospheric pressures of the high altitude environment (low degradability under partial discharge), (ii) provide efficient heat dissipation (thin, high thermal conductivity), (iii) alleviate the effects of dv/dt, and (iv) perform under the high electric stress arising from the increased power density (high dielectric strength, high thermal stability).

Polymeric materials, while excellent electric insulators, often present poor thermal conductivity and thermal stability. Ceramics on the other hand, present poor mechanical properties (brittleness). Therefore, composite materials like aluminum nitride (AlN)[185] and silicon carbide (SiC) have been also explored as insulation materials. However, given the considerable cable/connector insulation requirements, a single material is less likely to meet all demanded functionalities. A hybrid solution like micro-multilayered electrical insulations (MMEIs) may be more appropriate.

For example, one literature report, prototyped and tested an MMEI comprising a corona barrier layer (Kapton® CR film), EMI shielding layer (Ni alloy mu-metal foil), heat dissipation layer (eGRAF®), multiple high dielectric layers (Kapton® PI), multiple bond/moisture barrier layers (polytetrafluoroethylene PTFE and polyether ether ketone, PEEK). These MMEI configurations resulted in an increased breakdown voltage, V_B, of 70% compared to the Kapton® PI film

[184] https://www.anixter.com/en_us/resources/literature/wire-wisdom/5kv-shielded-vs-non-shielded-cables.html
[185] Yin W. et al. "*Highly Thermally Conductive Insulation for High Power Density Electric Machines*" AIAA Propulsion and Energy Forum (2019) [DOI: 10.2514/6.2019-4510].

alone.[186] This study underscored the importance of the careful selection of materials and the need for systematic design and optimization of the layered configuration.

Polypropylene laminated paper (PPLP) has been extensively examined for HTS cabling insulation applications.[187,188] It is worthwhile noting that initial NASA reports on HTS cable insulation - across examined medium voltages - indicate that the weight of the transfer line that carries the cryogen (N_2 and Ne) and the vacuum jacket may be higher (4 kg/m)[189] than that of the superconductor core itself, making the transfer line the most significant contributor to the overall cable weight.

3. State-of-the-Art Circuit Breakers

Ultrafast and efficient circuit breakers for aviation may also be needed at medium voltage. These breakers may be for high-frequency AC or DC applications and be mechanical, solid-state, or hybrid. A well-known issue in DC distribution systems is that they do not have natural zero-current crossings and therefore DC circuit breakers generally include some mechanism to create a zero-current crossing during a fault.[190] While AC breakers have the advantage of breaking at natural zero-crossings, increases in system frequency and changes in impedance ratios may likewise require more rapid detection, actuation, and coordination of aerospace protection systems than traditional AC circuit breakers. For all cases, clearing a fault quickly with minimum stress on the system and without nuisance tripping are key components of the circuit breaker design.

4. Connectors and Circuit Breakers in Aerospace

Connector and circuit breaker designs for aerospace applications are also particularly challenging not only because of the power density requirements but also due to increased demands on safety and reliability in extreme environmental conditions (pressure, temperature, vibration, shock, etc.) In particular, at medium voltage and low atmospheric pressures, creepage and clearance requirements change. The risk of partial discharge becomes a concern especially in gaps where air molecules may become ionized as a result of voltage across the

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[186] Shin E.-S. "Development of High Voltage Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System" AIAA Propulsion and Energy Forum (2019) [DOI: 10.2514/6.2019-4511].
[187] Peng C. et al. "*Insulation Characteristics of PPLP in GHe and Design of 10 kV Bipolar Coaxial HTS DC Cable*" in IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, v. 29, 5 (2019). [doi: 10.1109/TASC.2019.2898116].
[188] Kim Y.-S. et al. "*Research on insulation design of 22.9-kV high-T/sub c/ Superconducting cable in Korea*," in IEEE Transactions on Power Delivery, vol. 20, no. 2, pp. 554-559 (2005). [doi: 10.1109/TPWRD.2004.838627].
[189] Gemin P., et al. "Architecture, Voltage and Components for a Turboelectric Distributed Propulsion Electric Grid (AVC-TeDP)," NASA/CR—2015-218713
[190] Armstrong M., et al., "*Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid*," NASA/CR—2015-218440

void.[191] For example, according to Paschen's Law, a set of infinite parallel plates separated by less than 3 mm of air at sea level with a voltage differential of 10 kV will arc; however, the same plates will arc at less than 10 mm if they are at an altitude of 10 km. In practice, using IPC-2221B, the required separation distance at 10 kV for components on a printed circuit board at sea level is 50 mm – over 15 times the Paschen curve distance. This example fifteen-fold increase in spacing requirements to meet an industry standard, coupled with the increase in minimum spacing due to reduced air pressure, creates a significant design challenge for medium-voltage components in aviation applications.

B. Technical Areas of Interest & Technical Performance Targets

As part of this FOA, ARPA-E seeks novel and transformative technical solutions that will address the development of reliable power cables, connectors, and circuit breakers in a twin-aisle, all-electric aircraft. Since specific aviation standards do not exist at these voltage and current levels, it is expected that a combination of standards used in medium voltage for marine and terrestrial applications and at lower voltages and currents on aircraft will be used to validate the new technology. All technology developed under the program should at a minimum be in compliance with all relevant standards. The targeted outcome of the program is to increase the power distribution capability on electric aircraft with minimal impact on weight while maintaining the high reliability and safety requirements of aviation. Applicants are encouraged to discuss the following topics in their Technical Volumes where applicable:

- **Preliminary layout and architecture of the aircraft electrical system.** Provide an example fuselage (existing or notional) to estimate the total length of MV distribution cable, the number of MV connectors, interconnecting points, any auxiliary equipment, and approximate locations to provide a basis for technology design choices.
- **Cryostat and cryocooler technologies**. Discuss what the proposed cabling/connector solution needs from cryostat and cryocooler technologies.
- **Power Converters**. Discuss how the proposed cabling, connector, or circuit breaker design might be affected by power converters.
- **Interfaces/terminals**. Discuss what the proposed cabling/connector solution requires from the interfacing electrical connector/cabling technology.
- **Manufacturability**. Discuss any foreseeable challenges in scaling up manufacturing processes for the proposed technical solutions.
- **Capital and operating costs**. Discuss the basis for initial capital cost estimates of the proposed power conductor system including the supporting distribution system components and operating cost considerations.

[191] Christau I. Thesis: "*Optimization of High Voltage Electrical Systems for Aerospace Applications*" School of Electric and Electronic Engineering, U. Manchester (2011).

Proposed solutions must have a sound development plan to meet or exceed their stated metrics by the end of the period of performance of the proposed project in order to be considered for the award. Each proposal must include quantitative analysis, with supporting calculations and references, to demonstrate that the cable, connector, or circuit breaker developed in this program will meet the metrics. Each proposal should also provide the references to the appropriate standards (FAA, IHS, SAE, AIR, IEC, ASTM, IEEE, ISO, MIL, DO, etc.) it will comply with and/or be tested against. A cost metric has also been included in order to evaluate the future commercial viability of the power distribution technologies, including any necessary balance of plant (BOP). This cost estimate is an important requirement for the resultant technologies to be successfully deployed in an operational and intrinsically safe commercial aircraft of the future. In addition to the requirements stated in this FOA, all respondents must include information noted in **Table A**, **Table B**, or **Table C** if responding to technical area A, technical area B, or technical area C, respectively. Proposals that integrate more than one technical area are highly encouraged. If the proposed solution covers more than one technical area clearly indicate so in the Technical Volume and include **all required tables**. Note that the tables will not count toward the 14-page limit of the Technical Volume. The technical areas are outlined below.

1. Technical Area A: Electric Power Cable

Phase 1. Conceptual design

a. Cable configuration. Development of conceptual designs of the cable layer configuration (conductor, insulation, shielding, jacketing, cryostat, cryocooler, etc.) and any auxiliary devices.
b. Conducting material. Novel materials with improved specific weight, power density, power loss and heat removal are of interest.
c. Insulation materials. Novel materials with improved dielectric strength, less voids, increased thermal conductivity, and lower specific weight are of interest.
d. Electric field analysis. Computer-aided design (CAD) drawings with electric field analysis.
e. Safety analysis. Partial discharge, vibration, fire resistance, fluid absorption resistance, redundancy, and other safety considerations.

Phase 2. Build and test

a. Prototyping. Build (an) operational cable prototype(s).
b. Testing and demonstration. Proof-of-concept, laboratory-scale testing in a low-pressure environment with a cable length of three meters or more that emulates 12.2 km or greater altitudes to assess the potential of partial discharge is required. Prototypes should be tested to show compliance with applicable metrics and

standards. Test set-ups, including how the cable will be terminated, should be described in the application.

1. Technical Performance Targets Area A:Electrical Power Cable

Cable metrics are outlined in **Table A** below. The applicant must specify relevant metrics or cite relevant standards with which their technology will comply or provide an explanation if a metric is not considered or is changed from the FOA suggested goal. For example, if an HTS cabling system is used, the applicant may be able to provide justification for a system at less than 10 kV.

Table A. Comparison of the cabling FOA goals and proposed solution.

ID	Performance parameter	FOA suggested goal	Proposed solution or standard
A.1	Voltage	≥ 10 kV (or +/- 5 kV)	
A.2	System Redundancy	Applicant specified compliance	
A.3	Altitude/pressure	12.2 km/18.8 kPa	
A.4	Temperature	-55°C to 300°C	
A.5	Current rating per cable	1,000 A	
A.6	Core conductor linear density (kg/m)	Applicant specified.	
A.7	Cable linear density (kg/m)	Applicant specified.	
A.8	Resistivity (Ω·m)	Applicant specified.	
A.9	Estimated cable bend radius	Applicant specified.	
A.10	Partial Discharge	Applicant specified compliance.	
A.11	Surge withstand voltage	Applicant specified compliance.	
A.12	Surge withstand current	Applicant specified compliance.	
A.13	Fire resistance	Applicant specified compliance.	
A.14	Oil resistance	Applicant specified compliance.	
A.15	Electromagnetic interference and compatibility	Applicant specified compliance.	
A.16	Partial discharge testing	Applicant specified compliance.	
A.17	Life cycle testing	Applicant specified compliance.	
A.18	Vibration testing	Applicant specified compliance.	
A.19	Initial Capital Cost including BOP*	< $55/kW	

*This FOA goal represents the combined cost of the cable system and associated connectors.

2. Technical Area B: Electric Power Cable Connector

Phase 1. Conceptual design

a. Connector configuration. Development of conceptual designs of the connector gender, mount, insulation, etc.
b. Electric field analysis. Computer-aided design (CAD) drawings with electric field analysis.
c. Safety analysis. Partial discharge, water intrusion, vibration, shock, redundancy, and other safety considerations.

Phase 2. Build and test

a. Prototyping. Build (an) operational connector prototype(s).
b. Testing and demonstration. Proof-of-concept, laboratory-scale testing in a low-pressure environment that emulates 12.2 km or greater altitudes to assess the potential of partial discharge is required. Prototype should be tested to show compliance with applicable metrics and standards. Test set-ups should be described in the application.

1. Technical Performance Targets Area B: Electrical Power Cable Connector

Connector metrics are outlined in the table below. The applicant must specify relevant metrics or cite relevant standards with which their technology will comply or provide an explanation if a metric is not considered or is changed from the FOA suggested goal. Cable connector applicants are encouraged to team up with a power cable team or clearly outline how their proposed connector interfaces with a particular power cable solution.

Table B. Comparison of the connector FOA goals and proposed solution.

ID	Performance parameter	FOA suggested goal	Proposed solution or standard
B.1	Voltage	≥ 10 kV (or +/- 5 kV)	
B.2	System Redundancy	Applicant specified compliance.	
B.3	Altitude/pressure	12.2 km/18.8 kPa	
B.4	Temperature	-55°C to 300°C	
B.5	Current rating per connector	1,000 A	
B.6	Connector dimensions (approx.)	Applicant specified.	
B.7	Partial Discharge	Applicant specified compliance.	
B.8	Surge withstand voltage	Applicant specified compliance.	
B.9	Surge withstand current	Applicant specified compliance.	
B.10	Fire resistance	Applicant specified compliance.	
B.11	Oil resistance	Applicant specified compliance.	

B.12	Electromagnetic interference and compatibility	Applicant specified compliance.	
B.13	Partial discharge testing	Applicant specified compliance.	
B.14	Life cycle testing	Applicant specified compliance.	
B.15	Vibration testing	Applicant specified compliance.	
B.16	Initial Capital Cost including BOP*	< $55/kW	

*This FOA goal represents the combined cost of the cable system and associated connectors.

3. Technical Area C: Circuit Breakers

Phase 1. Conceptual design

a. Mechanical design. Development of conceptual mechanical designs of the circuit breaker including connection points, conductors, energy absorbers, insulation, semiconductors, mechanical switches, cooling, etc.
b. Control and electrical designs. Timing diagrams, current measurements, actuation, semiconductor devices, and EMI hardening. Methods to eliminate nuisance tripping and evaluation of system impedances on electrical and control design.
c. Electric field analysis. Computer-aided design (CAD) drawings with electric field analysis.
d. Safety analysis. Partial discharge, vibration, fire and oil resistance, redundancy, and other safety considerations.

Phase 2. Build and test

a. Prototyping. Build (an) operational circuit breaker prototype(s).
b. Testing and demonstration. Proof-of-concept, laboratory-scale testing in a low-pressure environment that emulates 12.2 km or greater altitudes to assess the potential of partial discharge during operation is required. Prototypes should be tested to show compliance with applicable metrics and standards. Test set-ups should be described in the application.

1. Technical Performance Targets Area C: Circuit Breakers

Circuit breaker metrics are outlined in **Table C** below. The applicant must specify relevant metrics or cite relevant standards with which their technology will comply or provide an explanation if a metric is not considered or is changed from the FOA suggested goal.

Table C. Comparison of the circuit breaker FOA goals and proposed solution.

ID	Performance parameter	FOA suggested goal	Proposed solution or standard
C.1	Voltage	≥ 10 kV (or +/- 5 kV)	
C.2	System redundancy	Applicant specified compliance.	
C.3	Altitude/pressure	12.2 km/18.8 kPa	
C.4	Temperature	-55°C to 175°C	
C.5	Continuous current rating	≥ 100 A	
C.6	Gravimetric power density	≥ 100 kW/kg	
C.7	Interrupt time	< 100 µs	
C.8	Efficiency	≥ 99.5 %	
C.9	Nuisance trips	Applicant specified.	
C.10	Circuit breaker dimensions (approx.)	Applicant specified.	
C.11	Energy absorption	Applicant specified.	
C.12	Cooling requirements	Applicant specified.	
C.13	Partial discharge	Applicant specified compliance.	
C.14	Surge withstand voltage	Applicant specified compliance.	
C.15	Surge withstand current	Applicant specified compliance.	
C.16	Fire resistance	Applicant specified compliance.	
C.17	Oil resistance	Applicant specified compliance.	
C.18	Electromagnetic interference and compatibility	Applicant specified compliance.	
C.19	Partial discharge testing	Applicant specified compliance.	
C.20	Life cycle testing	Applicant specified compliance.	
C.21	Vibration testing	Applicant specified compliance.	

3. Program Structure

Topic Q is a program offered in two separate programmatic phases. Applicants must provide detailed budgets and task descriptions that cover both Topic Q: Phase 1 and Topic Q: Phase 2.

Topic Q: Phase 1 can be proposed for a maximum of 12 months, based on the Applicant's individual assessment and the proposed project schedule. Based on each individual project's technical success, including meeting technical targets of Topic Q: Phase 1, ARPA-E may select one or more projects to continue to Topic Q: Phase 2, subject to the availability of appropriated funds.

Projects are anticipated to be between 12 and 36 months. It is expected that all projects will undergo a review (Go/No Go gate) during the program. The Go/No Go gate will most likely coincide with the completion of Topic Q: Phase 1. It is possible that an applicant is in advance stages of development of a cable/connector design (Topic Q: Phase 1) and could move immediately onto Topic Q: Phase 2. Successful projects may be eligible for award extensions, renewals, and new awards in accordance with Section II.B of this FOA.

4. Submissions Specifically Not of Interest

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

- Development of other electric aviation components - such as motors, inverters, power electronics, etc. - that are not directly related to cables, connectors, or circuit breakers.

5. Modifications to Technical Volume Template

The Technical Volume template for the CABLES Topic requires an additional Table. Cumulative page limits for Sections 1-5 is 14 pages, excluding the required table.

6. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, "Technical Volume: Topic Q" is replacing the "Techncial Volume Template" provided. All other Components remain the same and can be found in Section IV.C.

Component	Required Format	Description and Information
Technical Volume: Topic Q	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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XVIII. APPENDIX R: LOWERING CO2: MODELS TO OPTIMIZE TRAIN INFRATSTRUCTURE, VEHICLES AND ENERGY STORAGE

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
"LOwering CO2: Models to Optimize Train Infrastructure, Vehicles, and Energy Storage (LOCOMOTIVES)"

Topic Issue Date	September 23, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, November 13, 2020
Submission Deadline for Full Applications	9:30 AM ET, Monday November 23, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Monday, January 11, 2021
Expected Date for Selection Notifications	February 2021
Anticipated Date of Awards	Approximately June 2021
Total Amount to be Awarded	Approximately $5,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no reimburseable grants under this FOA. The Maximum Award is $1.5 Million in Federal Share.
Maximum Period of Performance	12 Months

1. Introduction

The US freight Class 1 rail system is a large transportation sector, responsible for the movement of a significant amount of freight throughout the country. It is an extremely efficient mode of transportation, accounting for 40% ton-miles[192] of freight movement while consuming 2% of the total US transportation energy budget.[193] Nonetheless, the GHG emissions from freight movement (not accounting for passenger trains, rail yard movement, etc.) are very large; approximately 40 million tons CO_2 per year.[194]

A long series of incremental advancements have made it one of the most efficient modes of transportation, and thus one of the cleanest (GHG/ton-km) today. Its average efficiency is approximately 180 km-metric ton (MT)/liter diesel using a fleet of diesel-electric locomotives[195], i.e., diesel AC generators driving electric motors. This transportation efficiency is comparable

[192] Bureau of Transportation Statistics (2017), U.S. Ton-Miles of Freight, available at: https://www.bts.gov/us-ton-miles-freight.
[193] International Energy Agency (2020), Tracking Transport 2020, available at: https://www.iea.org/reports/tracking-transport-2020/rail.
[194] United States Environmental Protection Agency (2019), Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions 1990–2017, available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WUHR.pdf.
[195] CSX Transportation (2016), Fuel Efficiency, available at: https://www.csx.com/index.cfm/about-us/the-csx-advantage/fuel-efficiency/.

to that of large vessel maritime and is almost four times more efficient than truck transport. This high efficiency has been driven by improvements not just in the locomotive propulsion systems but also multiple hardware components of the system: rail/wheel optimization, aerodynamics of rail cars, power electronics, etc. Logistical software has also played a role by reducing idle time, maximizing rail car loads and car numbers by route.

As a result, there is limited opportunity to further reduce rail GHG emissions associated with rail freight via efficiency and logistics improvements alone. This has been borne out in recent years by the observed flattening of the efficiency curve[196]. Deep decarbonization analyses show that, as with most of the transportation sector, fuel switching represents the biggest opportunity for significant further reductions in GHG associated with rail freight[197].

If full decarbonization of fleet GHG emissions is to be achieved, new propulsion and energy storage (referred to generally as ES systems) technologies, as well as the charging/fueling infrastructure, must be developed. However, this will be more difficult for the rail freight sector than for much of the rest of the transportation sector since the unique operational and financial characteristics of the rail freight sector combine to drive very challenging requirements:

- Very high energy storage requirements > GJ
- High power drive systems: Rail freight requires high propulsion power (> 10 MW provided by multiple locomotives)
- Must operate in extreme environmental conditions
- Need for widely distributed infrastructure
- Industry moving to larger trains
- High capital costs → long lifecycle for new technology
- Mostly privately owned → short term ROI

Given the many challenges discussed above along with the complex nature of the system as a whole, no comprehensive plan has been formulated to direct how rail decarbonization should be achieved. The new ES systems 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 the best to pursue taking into account other variabilities in the system.

A global rollout plan must be developed to replace or modify the existing fleet of approximately 25,000 locomotives[198] and expand the fraction of cargo moving by rail if rail is to become an integral part of full de-carbonization in the next decades. Fortunately, the rail sector includes a manageable number of routes, well characterized trains and infrastructure systems, predictable

[196] Association of American Railroads (2019), The Environmental Benefits of Moving Freight by Rail, available at: https://www.aar.org/wp-content/uploads/2018/07/AAR-Environmental-Benefits-Movig-Freight-by-Rail.pdf.
[197] Taptich, Michael N., Arpad Horvath, and Mikhail V. Chester (2016), Worldwide Greenhouse Gas Reduction Potentials in Transportation by 2050, Journal of Industrial Ecology 20.2: 329-340.
[198] Statista (2019), U.S. class I railroad locomotive fleet from 1995 to 2018, available at: https://www.statista.com/statistics/185222/us-class-i-railroad-locomotive-fleet-since-1990.

schedules, and diesel-electric propulsion. As a result, at least theoretically, this enables optimal planning for potential technology infusion into the sector.

2. Topic Description

As an important step towards realization of such a global rollout plan, the targeted outcome of the LOCOMOTIVES Topic is a set of publicly available planning tools for identification, evaluation, and prioritization of ES-related technology developments whose deployment would significantly reduce GHG emissions from the rail freight sector. These tools must be informed by and consistent with the economic and logistical constraints of the rail freight system or reasonable extrapolation thereof.

ARPA-E envisions LOCOMOTIVES as a critical precursor to a potential future program focused on developing the rail freight ES technologies themselves. Modelling tools developed through LOCOMOTIVES will enable analyses that ensure that ES development for rail freight ultimately addresses the crucial technical and logistical issues required for complete decarbonization of this transportation sector, and will inform the priorities in ES technologies development and deployment utilizing a common validated tool or tools.

A. Technical Areas of Interest

Through this LOCOMOTIVES Topic, ARPA-E seeks the development of validated planning and simulation tools that are able to model the deployment of a wide range of ES technologies in the Class 1 Rail Freight sector and that determine associated lifecycle GHG emissions and levelized cost of Mt-km (LCOTKM) values over various time scales (e.g., 10, 20, 30 years). ARPA-E seeks the development of these tools via two categories: i) a comprehensive, route-by-route model ("Full Roll-out Model (FRM)"), and ii) a reduced-scope model ("Bounding Model (BM)"), which is a solution to the required validated physical and economic core model. The functional diagram for this modeling scheme is given in Figure 1 where the FRM represents the full diagram and the BM is the core physical/economic model subcomponent.

Please note that although Class 1 freight is the primary focus, proposals that *additionally* consider commuter railroads and/or shorter haul freight routes that intersect with Class 1 operations, such as sharing a section of track along one or more Class 1 freight route(s), for example, are also responsive to this Topic.

At the conclusion of work sponsored under this Targeted Topic, ARPA-E envisions one or more models will be publically available for use by third-parties to study and support the cost-benefit analysis of fleet GHG emission decarbonization. The models will also be available to applicants and awardees under a future ARPA-E program, if any, to assist with concept development and optimization. ARPA-E may use these models, combined with information from other sources, to inform potential future program development, including a prioritization of ES technologies to pursue.

Technical Categories

1. Full Roll-out Model (FRM)

One goal of LOCOMOTIVES is to support the development of one or more comprehensive, route-by-route models ("Full Roll-out Model (FRM)") of Class 1 freight rail that incorporate assumptions from a realistic roll-out plan. As such, the FRM is expected to include many time-dependent parameters, including but not limited to projected ES performance and cost, freight rail fleet turnover, manufacturing scale/capacity, infrastructure buildout, diesel and other fuel costs, etc. The FRM would enable the most accurate evaluation of (1) which ES technology options actually get implemented, when, and at what level of relative performance/cost to other options, (2) decarbonization impact of potential ES technology developments, and (3) strategic business planning activities.

ARPA-E envisions the FRM as a simulation tool that would enable automated optimization of the technology deployment at specific target levels of GHG emissions and/or LCOTKM reductions. The LCOTKM model should be defensible based on historical analysis of investments, new technology deployment and regulatory compliance in the rail freight industry. A realistic physical model that can accommodate a wide range of ES technologies should be built and system performance and energy consumption on a route-by-route basis should be validated.

The FRM is likely to require teams with expertise in multiple areas, including (1) transportation network optimization and/or systems engineering, (2) ES technology including both state-of-the-art and novel proposed solutions, and (3) business, financial risk management, and/or project management.

2. Reduced-Scope Bounding Model (BM)

Another objective of LOCOMOTIVES is to support the development of multiple validated physical and economic models - "Bounding Models" (BM). A BM would not consider the specifics of the roll-out plan, and thus would not include time-dependent roll-out parameters or attempt to enable time-dependent analysis. Instead, it would incorporate realistic predictions of the values of the input parameters at a snapshot in time in the future, close to when full implementation of new ES technologies could be expected (e.g. 2050). It would then allow for optimization of the full freight rail fleet as if the fleet turned over instantaneously, all at that moment in time or at a simple deployment/year. Though this roll-out scenario is likely unrealistic, the results from optimization analyses via the BM model would nonetheless be valuable in *bounding* the maximum possible impact that could be achieved by development and full implementation of various ES technologies. As such, ARPA-E envisions one or more BMs will be developed under this Topic.

With multiple BMs, each utilizing different underlying physical and economic models, approximations, and assumptions, the BMs can be cross-validated and compared. This will allow for an evaluation of the relative efficacy of each BM in areas such as accuracy, computational burden, flexibility in updating physical and economic data, realistic implementation of ES infrastructure, etc.

Applicants must specify the category they intend to pursue; i) the Full Roll-out Model (FRM), or ii) Reduced-Scope Bounding Model (BM).

B. Rail Modeling and Validation

A function diagram of a possible FRM modeling scheme is given in Figure 1 below. The inputs of the model include a set of global goals for the rail system, ES sources to be considered in the rollout and technical, logistical and economic constraints. The next stage of the modeling is a rollout strategy model which includes ES and associated infrastructure properties and a time sequenced implementation. This is followed by a module that takes this ES rollout implementation and calculates energy usage and costs through a physical or empirical transportation model and computes the LCOTKM, GHG (time) and associated energy usage and economic metrics by route. This "Physical and Economic Modeling" is the equivalent of the BM module, and is thus a minimum requirement of the LOCOMOTIVES Topic. These outputs are compared to global input goals, e.g., GHG reduction, and the rollout plan adjusted to better align with these goals.

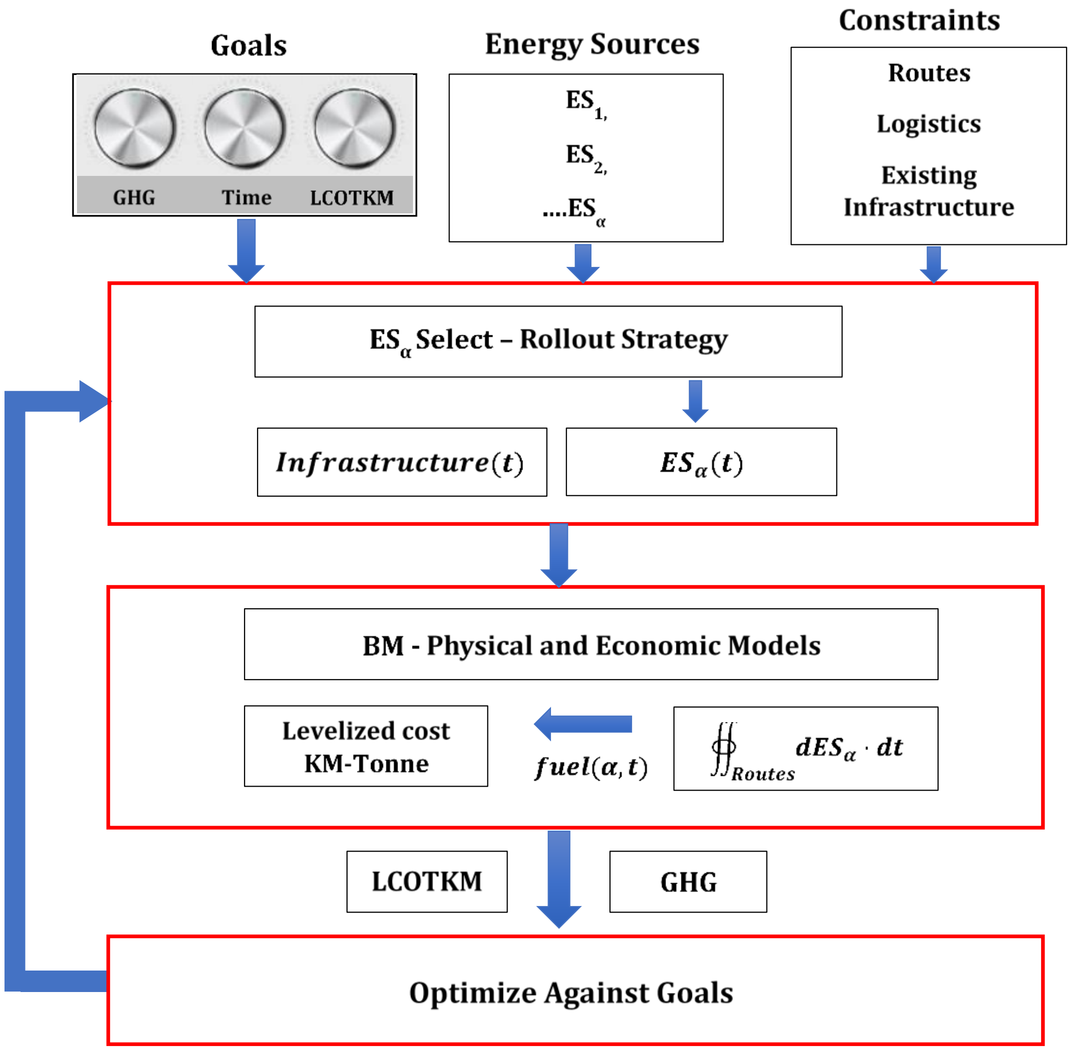

Figure 2: Function diagram of a possible modeling scheme

The inputs to the model fall into three main classes: ES properties, rail route constraints and logistics, economic model assumptions. Table 1 provides notional categories for each input class. Since the logistics will often include a consist (group of locomotives on one train), multiple ES technologies should be explored. The proposed inputs, to be explicitly documented in the application, must support quantitative modeling of the output quantities as specified in Table 2 and Section C.

Table 1: Example of rail freight model input parameters

ES Technology	Rail Constraints	LCOTKM
• *Nature of the Energy storage system (single ES or hybrid ES) • Non-propulsion electrical loads • Volumetric energy density (Wh/L) • Gravimetric energy density (Wh/kg) • Specific Power (W/kg) • Charge acceptance (max C-rate) • CO2/TKm • $/kWh of energy storage • $Capital deployed unit • $Infrastructure deployed unit • $O&M • CO2 production/life cycle • +$kwh regenerative • Reliability (% in service) • Service lifetime	• Definition of locomotive consist • Locomotive specifications • Locomotive type utilization • Train specifications • Rail Car Specifications • Regenerative Braking • Route distribution • Infrastructure distribution and characteristics (refueling stations, etc.) • Seasonal variations • Idle time • Freight and Passenger Demand • Weather constrains (i.e. air temperature and humidity) • Stations (departure, terminal, intermediate) • The maximum service capability of stations • Safety requirements (e.g. headway between successive dispatches and • bottleneck problems on limited track capacity) • Ability to add new routes	• $ ES capital • $ locomotive/upgrade • Discount rate/depreciation • $ ES technology development (OEM) • $ ES infrastructure • $ fuel/TKm with geographical distribution • $ O&M – excluding fuel • $ logistical modification (e.g. Tender/car revenue loss) • $ revenue model • $ Cost/benefit of adding new routes

*A nonproprietary description of the each ES used to validate the model should be included

Some of the input data sets are publicly available. The North America rail lines[199] and nodes[200] data set is one example. This rail network dataset is a comprehensive database of North America's railway system at 1:24,000 to 1:100,000 scale as of April 15, 2020. The data set covers all 50 States plus the District of Columbia. Additionally, the Intermodal Freight Facilities Marine Roll-on Roll-off (Ro/Ro) dataset[201] is another example of the publicly available data. The

[199] Available at: http://osav-usdot.opendata.arcgis.com/datasets/f15d9e40cd1d4170a36bf31d4e6a3c28_0.
[200] Available at: http://osav-usdot.opendata.arcgis.com/datasets/a3de9d3cac5345fca767cd8e74ec92ff_0.
[201] Available at: http://osav-usdot.opendata.arcgis.com/datasets/f5b340dce0e9459abebcbc95bd734b35_0.

major Ro/Ro intermodal facilities data is current as of July 1, 2019. Every facility is associated with a port and assumed to be served by both marine and truck, and those facilities which support rail operations, the reporting code for the operating rail company is also identified. The dataset also includes at least one Navigation Unit ID from the U.S. Army Corps of Engineers (USACE) Port Facilities dataset which is associated with the Ro/Ro terminal. However, applicants are encouraged to identify additional high-fidelity data they will use as inputs, including the relevant Association of American Railroads' (AAR) publication packages[202] such as actual fuel consumption, known train speed, etc. All applications must provide a detailed description of the input data set(s).

Table 2 provides a summary of the minimum output requirements for any model developed under this Topic (whether FRM or BM). The GHG accounting will utilize the standard DOE recommendations contained in https://greet.es.anl.gov/. Submissions to this Topic should also describe how the proposed model will quantify uncertainty in the output values.

Table 2: Minimum set of output requirements

ES - Propulsion	Infrastructure	Potential Impact

• Power delivered to wheels, P(t): - acc., + regen
• Acceleration (t): + acc, - deacc
• Energy expended by ES(t), - delivered for propulsion, + regenerative
• Fuel(t) expended (same signage as ES(t)) for each propulsion source
• Impact of refueling/recharging time on schedule: + increases route time, - decreases route time
• GHG(t) for each source
	• Distance required between refuel for each ES
	• Time between refueling for each ES
	• Fueling time
	• Fuel quantity and cost of each refueling
	• Refueling/recharging yard size and capacity
	• Train size (# cars, weight of freight)
	• Energy content for each refueling
	• Cost associated with transportation and storage of Fuel if not directly included in fuel cost
		• ES option chosen by route
		• % ES option chosen
		  - On a per-route basis
		  - On a per unit energy basis
		• Lifecycle GHG +/- for each route vs baseline (today), based on chosen ES
		• Cost (LCOTKM) +/- for each route vs baseline, based on chosen ES
		• Cost (LCOTKM) of operations;
		• Scheduling and logistics
		• Aggregate impact: lifecycle GHG and cost
		• Operating Ratio

[202] Available at: https://my.aar.org/Pages/AllProducts.aspx.

C. Technical Performance Targets

The Project Team(s) funded under this Topic will generate a publicly available model that *at least* meets the objectives of 2.a.ii Reduced-Scope Bounding Model (BM).

The model must feature a robust physical submodel, which includes the proper dynamics in train cars. ARPA-E intends to support the development of a microscopic[203] flexible model that replicates the longitudinal train dynamics. The details of the proposed model must be described along with the spatial and temporal scales over which it is valid. The model must include all resistive forces including journal, flange, aerodynamic, dynamic and mechanical braking and others relevant for accurate evaluation of train dynamics and required propulsive forces. The model also must be continuous in that it tracks the system dynamics instantaneously and thus is able to replicate transient train motion, although a discrete model that can calculate transients at an appropriate time scale is acceptable. A method of model validation against existing train fuel consumption data along multiple exemplary routes must be included in the model description. The model must have flexible input to assemble hybrid consists as well as variable train car number and type. A method of adding new routes with proper physical characteristics must be provided. The main physical inputs of the model, listed in Table 1, should be used to calibrate the output parameters, listed in Table 2.

In addition, the model must include a defensible economic model for the ES technology categories given in Table 3. Wherever possible, it is desirable to validate the model using ES technologies for which both technical and economic data exists. The Applicant is not limited to modeling these illustrative ES categories and is encouraged to provide a general framework for the introduction of novel ES. With regards to ES, the model must consider capital and operational/maintenance costs for both the ES system and supporting infrastructure. For battery-based ES, as an example, the economics for “recharging” must be considered, which includes both costs for constructing new infrastructure, modifying existing infrastructure, etc., as well as the price of electricity. Alternatively, a model that emphasizes ES technologies that rely on fuels other than diesel such as hydrogen (fuel cells, for example) must include a detailed analysis of fuel economics that considers production, transport logistics, storage, losses, etc. At the same time, any projections for future pricing for hydrogen (or other fuel) should be supported by compelling data and/or widely accepted trends. Regardless of the specific ES technology, the model must capture all economic impacts from the development stage to implementation, the latter of which may include the requirement for specialty containment vessels and/or strategies to enable safe operation/storage of the ES system itself, fuel(s), or perhaps both. Separately, a proposal that considers new routes must include a quantitative assessment of economic and/or other impacts.

[203] Microscopic models should simulate single train motion for each route, and thus can describe detailed dynamic motions of trains using detailed inputs such as speed, road gradient, curvature, and other train specifications.

Table 3: Required ES categories

ES Technology Class	Representative Examples
Battery	Lithium-ion / Sodium-ion
	Sodium-sulfur
	Lead-Acid
	Metal-Air (Li, Na, Zn, Al)
	Alternative secondary battery chemistries
Redox Flow Battery and Hybrid Flow Battery	Metal ion (vanadium, iron)
	Organic / organometallic
	Zinc-bromine
	Alternative flow battery chemistries
	Alternative hybrid flow battery chemistries
Fuel Cell	Polymer Electrolyte Membrane Fuel Cell (PEMFC)
	Alkaline Fuel Cell (AFC)
	Phosphoric Acid Fuel Cell (PAFC)
	Molten Carbonate Fuel Cell (MCFC)
	Solid Oxide Fuel Cell (SOFC)
	Other fuel cell types
Super Capacitors	
Hybrid Energy Storage System	Combination of ES technologies working together, either serially or in parallel

In summary, applicants must clearly state:

- Whether they are proposing to Category i) Full Roll-out Model (FRM), ii) Reduced-Scope Bounding Model (BM).
- Detailed description of the anticipated input data set(s), including which the team does/does not currently have access to. See section 2.b for more detail.
- The proposed outputs of the model, including the minimum required outputs and the anticipated uncertainties in those outputs. See table 2 in sections 2.b and 2.c for more detail.

- A detailed process for validating the output accuracy against known route data, including the set of exemplary routes that will be used in the validation.
- How they will develop a robust physical model, which includes the proper dynamics in train cars. The details of the proposed model must be described along with the spatial and temporal scales over which it is valid.
- How they will enable flexible input to assemble hybrid consists as well as variable train car number and type.
- How they will allow for future addition of new routes with proper physical characteristics
- How they will build their model for each required ES category so that its performance and energy consumption on a route-by-route basis is validated.
- Whether the model will be a continuous or a discrete model. If discrete, the team must state how it will calculate transients at an appropriate time scale.
- Balance model accuracy and computational efficiency, e.g. simplifications regarding spatial, temporal, and technology attribute resolution that minimize the impact on model accuracy.
- How they intend to make the model available as open-source. See section 2.d for more detail.
- How they will address the user interface, documentation, and user training. See section 2.e for more detail.
- Their willingness to present their model at a future ARPA-E workshop, if applicable
- Their willingness to interact with Project Teams funded under a potential future program focused on ES technology development, in order to ensure that the software can accommodate their technical solutions

D. Open Source Requirements

To enable productive utilization for Project Teams under a potential follow on program on Class 1 RR ES technologies and the broader public in terms of the model results, ARPA-E is requiring that any models developed under this Topic be made open-source. In particular, each Project Team funded under this Topic must agree to distribute the model that is to be developed under this award as Open Source Software using a generally recognized open software standard such as those approved at http://opensource.org/osd. To the extent the model to be distributed as Open Source requires access to additional software not available as compatible open source, such additional software must be publically available at a reasonable cost to any users of the model.

E. User Support Requirements

Applicants should propose open source models which have interfaces that allow for “low overhead” utilization for public users. A well-defined user interface, not necessarily graphical, must be provided that allows for manipulation of all I/O. The I/O must be in an open source format allowing for simple input in text processors and spreadsheets. A user manual and a FAQ tool must be provided with the software distribution.

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not be merit reviewed or considered:

- Approaches seeking incremental improvements – rather than transformational solutions – to the ES inputs
- Scale-up projects for existing technologies that do not have significant technical risk.
- Original concepts for developing ES technologies optimized for rail freight themselves; this would be the scope of a potential future FOA.
- Models that focus exclusively on other segments of the rail sector (e.g. passenger rail) or other transportation networks.
- Models that focus exclusively on network-level analysis.
- Proposals for the development of new and novel ES technologies.

4. Content and Form of Full Applications

Not withstanding the instructions at FOA Section IV.C, "Technical Volume: Topic R" is replacing the "Technical Volume Template" provided and the content and form of Full Applications for Topic R is revised to require a Commercialization Plan instead of a U.S. Manufacturing Plan.

Component	Required Format	Description and Information
Technical Volume: Topic R	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/).
Commercialization Plan	PDF	As part of the application, Applicants are required to submit a Commercialization Plan. The Commercialization Plan represents the Applicant's measurable commitment to support U.S. manufacturing or provide other benefits to the U.S. economy as a result of its award.

Commercialization Plan

As part of the application, Applicants are required to submit a Commercialization Plan that should not exceed three pages in length. A template Commercialization Plan is available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov. The Commercialization Plan represents the Applicant's measurable commitment to support U.S. manufacturing of subject inventions and distribution of any data, namely software and data sets, resulting from its award in a manner that benefits the U.S. economy. Commercialization Plans are a Program Policy Factor during the review and selection process. See Section V.B.1 of the FOA.

A Commercialization Plan must contain a commitment to the U.S manufacturing requirements stated in Section VI.B.8. A Commercialization Plan must also include a plan for how data will be commercialized and which Intellectual Property rights will be asserted. Additionally, the Commercialization Plan should include a description of specific economic or other benefits to the U.S. economy related to the commercial use by the Applicant of the technology being funded by ARPA-E. For example, an Applicant may commit particular types of products to be manufactured in the United States or include restrictions on licensing of software to use in the United States. (These plans should not include requirements regarding the source of inputs used during the manufacturing process.) In addition to or instead of making a commitment tied to a particular product, the Applicant may make other types of commitments beneficial to U.S. manufacturing or utilization of software. For example, an Applicant may commit to the creation of new and/or high-tech U.S.-based jobs such as those associated with maintaining the software, offering services related to the use of the software, or further domestic development of the software by the Applicant or third parties. ARPA-E is open to considering modification of the license retained by the government in copyright to support acceptable Plans. Assertion of copyright is automatically allowed for domestic educational institutions and nonprofits; for-profit entities must request authorization from ARPA-E to assert copyright.

When an Applicant is selected for an award, the Commercialization Plan submitted by the Applicant will become part of the terms and conditions of the award. It is important to note that the Commercialization Plan is in support of and not a replacement for the U.S. Manufacturing Requirement described in Section VI.B.8. The Applicant/Awardee may request a waiver or modification of the Commercialization Plan from DOE/ARPA-E upon a showing that the original Commercialization Plan is no longer economically feasible.

Class patent waivers usually apply to domestic large businesses as set forth in Section VIII.A of the 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 that any products embodying or produced through the use of an invention conceived or first actually reduced to practice under the award will be substantially manufactured in the United States, unless a waiver is granted by DOE/ARPA-E. The Commercialization Plan submitted by the Applicant will become part of the terms and conditions of the award in addition to the requirements attaching to subject inventions.

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XIX. APPENDIX S: TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING FOR PERFORMANCE ENHANCEMENT OF HIGH TEMPERATURE AND HIGH PRESSURE HEAT EXCHANGERS

Special Program Announcement for Solicitation on Topics Informing New Program Areas (DE-FOA-0001953) "Topology Optimization And Additive Manufacturing For Performance Enhancement Of High Temperature And High Pressure Heat Exchangers (Topology)"

Topic Issue Date	October 8, 2020
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Friday, November 13, 2020
Submission Deadline for Full Applications	9:30 AM ET, Tuesday, December 1, 2020
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, Friday, January 15, 2021
Expected Date for Selection Notifications	March 2021
Anticipated Date of Awards	Approximately June 2021
Total Amount to be Awarded	Approximately $4,000,000 subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no reimburseable grants under this FOA. The Maximum Award is $1 Million in Federal Share.
Maximum Period of Performance	18 Months

1. Introduction

This announcement describes a research thrust entitled "Topology Optimization and Additive Manufacturing for Performance Enhancement of High Temperature and High Pressure Heat Exchangers." The purpose of this announcement is to (1) solicit Full Applications for the development of new technologies and tools related to the design, fabrication, and performance enhancement of high temperature and high pressure heat exchangers via topology optimization and additive (and/or other advanced) manufacturing techniques, (2) focus the attention of the scientific and technical community on the specific area of interest and encourage dialogue amongst those interested, and (3) provide a timetable for the submission of full applications.

2. Topic Description

The Special Program Announcement is a supplemental funding opportunity in support of ARPA-E's recently launched HITEMMP (High Intensity Thermal Exchange through Materials and Manufacturing Processes) Program, and aims to support the development of new approaches and technologies for the design and manufacture of high-temperature, high-pressure, efficient, and compact heat exchangers (HXs). The specific objective sought through this Topic is to fund further improvements in HITEMMP heat exchanger designs to enable superior thermo-mechanical performance and increased power density, life cycle durability, and cost effectiveness through the combined utilization of the twin technologies of topology optimization (TO) and additive manufacturing (AM).

Heat exchangers are critical to efficient thermal energy exchange in numerous industrial applications and everyday life, with significant applications in electricity generation, transportation, petrochemical processing, waste heat recovery, and much more. The HITEMMP Program is targeting heat exchangers capable of operating for tens of thousands of hours at temperatures and pressures exceeding 800°C (1470 °F) and 80 bar (1,160 psi), respectively. This new class of hardware, designed and manufactured using novel techniques, topologies, and materials, would enable far greater exchanger efficiency, thus boosting the performance of many important industrial processes. Additional details on HITEMMP can be found in the HITEMMP FOA (DE-FOA-0001970) and on ARPA-E's website.[204]

The desired heat exchangers present unique challenges in materials and manufacturing due to the difficulty of finding the optimum balance between enhanced heat transfer rates without excessive pressure drop penalties while meeting the thermo-mechanical and life cycle durability and cost requirements. Moreover, depending on the operating temperature and pressure, high-temperature materials can vary from ferritic steels to Ni-based alloys and ceramics. However, there is a substantial cost increase as one shifts from materials such as ferritic steel to Ni-based alloys.[205] Fortunately, an optimum manufacturing process and shape topology can reduce material consumption, machine fabrication time, and post processing operations, among other benefits. These interrelated materials and manufacturing challenges provide a unique opportunity to utilize recent advances in additive manufacturing (AM), multi-scale design and topology optimization, integrated/conformal thermal management architectures, and multi-material fabrication and joining technologies to implement a substantial enhancement to the state-of-the-art HXs for high-temperature and high-pressure applications.

Significant progress has been achieved in the areas of topology optimization and AM in recent years[206], particularly for structural optimization purposes. With the recent advancement of AM and the high degree of freedom it offers, fabrication of complex geometries and conformality is a new and enabling technology for transformative advancements in fabrication of hard-to-manufacture materials and design geometries. Topology optimization (TO) and additive manufacturing (AM) are twin-technologies that allow the design and fabrication of complex

[204] https://arpa-e.energy.gov/?q=arpa-e-programs/hitemmp
[205] Brun, K., Friedman, P., & Dennis, R. (Eds.) (2017). Fundamentals and applications of supercritical carbon dioxide (sCO2) based power cycles. Woodhead Publishing.
[206] M.P. Bendsoe, O. Sigmund, *Topology Optimization – Theory, Methods and Applications*, 2nd ed., Springer Verlag, Berlin, 2003.

geometries with superior thermo-mechanical performance and high-power density, among other features. However, in the area of thermal topology optimization (TTO) substantial deficiencies must be overcome before its meaningful implementation to HX design and enhancement; including the following:

- Lack of a public domain or commercially available software tool that addresses the comprehensive multi-physics/multi scale structural, fluid dynamics, thermal, and manufacturing aspects of heat/mass transfer topology optimization.
- Most of the previous work has been limited to rather simple configurations of fluid-solid heat exchange such as that of a heat sink configuration, or pressure drop reduction in the heat exchanger header. Thus, they lack combined coupling of the three fields of structural, fluid dynamics, and thermal with a minimum of 4 materials (hot and cold streams, solid, and void space) in a typical heat exchanger.
- Simulation of the complex interactions among fluid flow, heat transfer, and geometry optimization is computationally intensive and far from being fully understood. It requires innovation in modeling and computational schemes. Most of the previous work in TTO particularly lacks proper modeling of the conjugate heat transfer as a function of the complex fluid flow and thermal regimes on a geometrically optimized surface configuration.

Though not the focus of this Topic, combined TO and AM can yield more impressive enhancements for mass transfer-driven applications, in which for many processes the mass transfer coefficients and the heat generated vs. removed by conduction for exothermic reactions depend *quadratically* on the characteristic size[207,208]. Example applications for substantial energy savings and CO_2 footprint reduction can be found elsewhere[207-210].

A. Technical Area of Interest

ARPA-E is specifically interested in supporting projects that will utilize topology optimization (TO) integrated with advanced manufacturing techniques such as additive manufacturing (AM) to fully tap the combined benefits of the two technologies. Specifically of interest is the combined use of these technologies to aid in the development of cost-effective high-temperature heat exchangers with superior thermo-mechanical operational performance while delivering desired high specific and volumetric power density (kW/kg and kW/L), among other requirements, as further described below and outlined in Table 1 in the next section.

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[207] M. S. Mettler, G. D. Stefanidis, and D. G. Vlachos, Scale out strategies for microchemical devices: Application to natural gas to syngas conversion. Ind. Eng. Chem. Res. 49, 10942–10955 (2010).
[208] P. Desir, B. Saha, and D.G. Vlachos, Ultrafast flow chemistry for the acid-catalyzed conversion of fructose. Energy Environ. Sci. 12, 2463–2475 (2019).
[209] H. Ganapathy, A. Shooshtari, S. Dessiatoun, M. Ohadi, M. Alshehhi, Hydrodynamics and mass transfer performance of a microreactor for enhanced gas separation processes, Chemical Engineering Journal 266, 258-270.
[210] H. Ganapathy, A. Shooshtari, S. Dessiatoun, M. Alshehhi, M. Ohadi, Fluid flow and mass transfer characteristics of enhanced CO_2 capture in a minichannel reactor, Applied energy 119, 43-56.

While AM technology has in recent years evolved from research and development projects to printing high volumes of metallic components of complex shape and high added-value with enhanced performance requirements, its enabling features can only be fully tapped through its combination with topology optimization[206,212-216]. TO can optimally distribute materials within a given design domain for optimal performance, yet yielding more durable, lighter and stronger structures at the component and system level[206,211-214], while also facilitating AM manufacturing processes to reduce fabrication time and cost. For example, the build orientation plays a critical role in additive manufacturing, as it not only affects the amount of supports needed during the printing process, but also affects the microstructure, thermo-mechanical properties, and quality of the printed parts[215,216]. Realizing the importance of the overhang angle with respect to the build plate, it is of interest to reduce or eventually eliminate complex support structures by optimizing the build orientation through enabling features of combined AM and TO, thus yielding lower fabrication cost and reduced post-processing requirements. The concept was demonstrated in a recent study involving an approach that can simultaneously optimize build orientation and the topological layout of the component[214].

AM-enabled topology optimization has the potential for substantial improvement in heat transfer rates, without imposing high pumping power requirements. In a recent study[217] on a chip cooling/heat sink application, a TO-optimized heat sink geometry demonstrated the potential for more than three-fold reduction in the pumping power for a given thermal performance compared to a conventional parallel plate fin design. In a separate study[218], the heat transfer and fluid flow performance of an AM-fabricated optimized heat sink were experimentally evaluated, and the results indicated a higher coefficient of performance (COP) relative to the benchmark heat sink designs. Advanced thermal management systems enabled by the combination of innovative designs, topology optimization, and AM can offer significant advantages for energy conversion systems across multiple industrial sectors, particularly for aerospace applications in which integrated, high-power density thermal management plays a critical role.

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[212] M. Leary, L. Merli, F. Torti, M. Mazur, M. Brandt, Optimal topology for additive manufacture: a method for enabling additive manufacture of support-free optimal structures, Mater. Des. 63 (2014) 678–690.
[213] A.T. Gaynor, N.A. Meisel, C.B. Williams, J.K. Guest, Topology optimization for additive manufacturing: considering maximum overhang constraint, 15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference (2014).
[214] C. Wang, X. Qian, Simultaneous optimization of build orientation and topology for additive Manufacturing, Additive Manufacturing, Volume 34, August 2020, 101246.
[215] L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, J.-P. Kruth, A study of the microstructural evolution during selective laser melting of ti-6al-4v, Acta Mater. 58 (9) (2010) 3303–3312.
[216] X. Zhang, R. Tiwari, A. H. Shooshtari, and M. Ohadi. An additively-manufactured metallic manifold-microchannel heat exchanger for high temperature applications. Applied Thermal Engineering, 143:899-908, 2018.
[217] Sun, Sicheng, Piotr Liebersbach, and Xiaoping Qian. "3D Topology Optimization of Heat Sinks for Liquid Cooling." Applied Thermal Engineering (2020): 115540.
[218] https://asmedigitalcollection.asme.org/mechanicaldesign/article/137/11/111403/474784/Topology-Optimization-Additive-Layer-Manufacturing

B. Technical Performance Targets

The performance metrics listed in Table 1, below, intend to simultaneously achieve superior thermo-mechanical performance and increased power density, life cycle durability, and cost effectiveness for the heat exchangers of interest to the HITEMMP program. Applicants are also required to provide the information identified in Table 2, given at the end of this document, adapted from the HITEMMP FOA. While Table 1 focuses on specific improvements of importance to the HITEMMP Program, Table 2 provides a summary of the general design parameters for a selected heat exchanger. Both existing HITEMMP performers, as well as new participants are welcome to apply for this funding opportunity. New participants can apply as a separate new team or in collaboration with an existing HITEMMP team. Existing HITEMMP performers that apply for funding under this Topic are encouraged to seek out additional partners to fill any gap in their existing team to specifically address technical needs of this Topic. A list of current HITEMMP performers and contact information of the principal investigators are available on ARPA-E's website[204].

Table 1: Performance targets for this special program announcement. Applicants are expected to fill the table in its entirety and include it with their submission.

ID	Metric Name	Base case design (before application of AM-enabled TO)	Advanced Design (after application of AM-enabled TO)	Description and rationale
1	Topology optimization and the respective selected computational technique(s) and unique advantages			Designer choice, key innovations and the specific technique(s) needs to be described.
2	Heat exchanger specific power density (includes core, headers, and any other applicable flow distribution structures)	kW_{th}/kg	kW_{th}/kg	This is a required design outcome parameter. It may vary based on the selected design and the targeted application area. Comparison with respective existing solutions must be provided in your submission.
3	Heat exchanger volume-based power density (includes core, headers, and any other applicable flow distribution structures)	kW_{th}/m^3	kW_{th}/m^3	This is a required design outcome parameter. It may vary based on the selected design and the targeted application area. Comparison with respective existing solutions must be provided in your submission.

ID	Metric Name	Base case design (before application of AM-enabled TO)	Advanced Design (after application of AM-enabled TO)	Description and rationale
4	Quantified improvement in the heat exchanger structural capability (e.g., thermal fatigue and creep life improvement, among other benefits)	Meantime before failure (MTBF)		Describe the specific remedy/design feature(s) and the respective quantified improvement over the base case.
5	Quantified improvement in the manufacturability/manufacturing yield, materials consumption/waste reduction, and other projected benefits and their effect on the cumulative cost of the heat exchanger, [$/UA]	[$/UA]		High-level details of your cost model and the projected cost reductions because of the AM-TO enabling technology (ies) should be summarized briefly here, with full details provided in the submission.

In addition to the information provided in Table 1, Applicants are expected to include detailed description of the proposed specific TO technique(s), its key innovations and the advantages it offers, as well as measures such as its computational time requirements, among others. Proposed efforts under this Topic must include a heat exchanger conceptual design, TO algorithm/mathematical model development, fabrication and test/characterization, and a clear pathway to achieving the Topic objectives and performance metrics. While initial demonstrations can be on sub-scale, coupon-level, heat exchangers, the final result of any award under this Topic must be a detailed design, fabrication, testing, and characterization of the 50 kW_{th} developmental prototype as prescribed in the HITEMMP FOA and the roadmap for technology integration and insertion into the targeted HITEMMP technology. ARPA-E may assist by making testing resources available or otherwise providing funding directly to a user facility for testing of a project team's 50 kW unit if selected for award negotiations. Prospective applicants seeking ARPA-E's assistance should not include monies for testing of the 50 kW unit in their applications.

Expected Outcome: Software and publications, in support of maximizing the methodology (ies) adoption and program impact; and/or software commercialization with software vendors through technology to market (T2M) efforts. In addition, a developmental topology optimized heat exchanger with capacity of 50 kWth, meeting the requirements described in this Targeted Topic.

Table 2: HITEMMP Program targets for Category A: Metallic-based Structures (Hot-side Temperature ≥ 800°C) and Category B: Ceramic-based or other composite structures (Hot side

Temperature ≥ 1,100°C). Applicants are expected to choose either one of the categories, provide all of the information requested in this table, and include it with their submission.

ID	Metric Name	Category A Target (Metallic-based structures)	Category B Target (Ceramic-based or other composite structures)	Description and rationale
1	Targeted applications			For use in high efficiency, high temperature and pressure modular power generation systems as a recuperator for an application area(s) defined by Applicant (e.g., aviation, modular power, or industrial).
2	Hot-side inlet temperature	≥ 800°C	≥ 1,100°C	Must specify your selected hot-side inlet temperature.
3	Hot-side inlet pressure	≥ 80 bar	≥ 80 bar	Must specify your selected hot-side inlet pressure.
4	Cold-side inlet temperature	300°C	300°C	This is a fixed design parameter to be used by all applicants, regardless of the application category selected and/or other design parameters.
5	Cold-side inlet pressure	≥ 250 bar	≥ 250 bar	Must specify your selected cold-side inlet pressure.
6	Hot-side pressure drop, $(\Delta P/P_{inlet})_{hot}$	≤ 2%	≤ 4%	Must specify your design's hot-side pressure drop.
7	Cold-side pressure drop, $(\Delta P/P_{inlet})_{cold}$	≤ 2%	≤ 4%	Must specify your design's cold-side pressure drop
8	Hot-side mass flow rate	kg/sec	kg/sec	Left to the designer's choice. **However, the mass flow rate of the hot-side and the cold-side must be taken as equal** to represent the case of a high temperature recuperator in a recuperated closed Brayton cycle.
9	Cold-side mass flow rate	kg/sec	kg/sec	Left to the designer's choice. **However, the mass flow rate of the hot-side and the cold-side must be taken as equal** to represent the case of a high temperature recuperator in a recuperated closed Brayton cycle.
10	Heat exchanger effectiveness	≥ 80%	≥ 50%	Must specify your design's heat exchanger effectiveness.
11	Heat exchanger thermal duty (capacity)	≥ 50 kW_{th}	≥ 50 kW_{th}	The selected capacity recognizes the need for scalability for the high temperature applications.

ID	Metric Name	Category A Target (Metallic-based structures)	Category B Target (Ceramic-based or other composite structures)	Description and rationale
14	Heat exchanger material(s)			Left to the designer's choice. However, justification for its selection and its characterization/qualification procedure needs to be clearly outlined in the submission.
15	Working fluid			Left to the designer's choice but the hot-side and cold-side must use the same working fluid. However, one objective of this program is the development of heat exchangers that can utilize supercritical fluids such as sCO_2 and sHe due to the advantages they offer in high efficiency power generation cycles – Recuperated Closed Brayton Cycles.
16	Heat exchanger manufacturing technique			Left to the designer's choice. However, justification for the selected technique and the specific manufacturing path for successful fabrication needs to be clearly outlined in the submissions. Design parameters such as minimum feature size requirement, built volume, and surface finish quality are parameters of key importance.
18	Durability	Hours MTBF	Hours MTBF	The proposed heat exchanger is expected to have a path to commercialization. As such, for the selected application area, an explicit path toward a targeted MTBF (mean time between failures) of 40,000 hours of operation before a major overhaul is required.

3. Areas Specifically Not of Interest

Submissions that propose the following may be deemed nonresponsive and may not be merit reviewed or considered:

- Analytical and computer simulations work only, without manufacturing and experimental work that can validate the topology-optimized design and modeling.
- Similar work that is being sponsored by DOE or other federal government agencies.

- "Paper studies" of novel material, design, or heat exchanger development outside of the scope of HITEMMP FOA.
- Projects involving discovery and development of new materials and/ or manufacturing techniques.

4. Content and Form of Full Applications

Notwithstanding the instructions at FOA Section IV.C, the content and form of Applicants' Technical Volumes shall follow the instructions and be consistent with the template titled Technical Volume: Topic S. Furthermore, Applicants shall submit a Commercialization Plan, as described below, in lieu of the U.S. Manufacturing Plan described at FOA Section IV.C. All other instructions set forth at FOA Section IV.C remain unchanged.

Component	Required Format	Description and Information
Technical Volume: Topic S	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.**
Commercialization Plan	PDF	As part of the application, Applicants are required to submit a Commercialization Plan. The Commercialization Plan represents the Applicant's measurable commitment to support U.S. manufacturing or provide other benefits to the U.S. economy as a result of its award.

Commercialization Plan

As part of the application, Applicants are required to submit a Commercialization Plan that should not exceed three pages in length. A template Commercialization Plan is available on ARPA-E eXCHANGE at https://arpa-e-foa.energy.gov. The Commercialization Plan represents the Applicant's measurable commitment to support U.S. manufacturing of subject inventions and distribution of any data, namely software and data sets, resulting from its award in a manner that benefits the U.S. economy. Commercialization Plans are a Program Policy Factor during the review and selection process. See Section V.B.1 of the FOA.

A Commercialization Plan must contain a commitment to the U.S manufacturing requirements stated in Section VI.B.8. A Commercialization Plan must also include a plan for how data will be commercialized and which Intellectual Property rights will be asserted. Additionally, the Commercialization Plan should include a description of specific economic or other benefits to the U.S. economy related to the commercial use by the Applicant of the technology being funded by

ARPA-E. For example, an Applicant may commit particular types of products to be manufactured in the United States or include restrictions on licensing of software to use in the United States. (These plans should not include requirements regarding the source of inputs used during the manufacturing process.) In addition to or instead of making a commitment tied to a particular product, the Applicant may make other types of commitments beneficial to U.S. manufacturing or utilization of software. For example, an Applicant may commit to the creation of new and/or high-tech U.S.-based jobs such as those associated with maintaining the software, offering services related to the use of the software, or further domestic development of the software by the Applicant or third parties. ARPA-E is open to considering modification of the license retained by the government in copyright to support acceptable Plans. Assertion of copyright is automatically allowed for domestic educational institutions and nonprofits; for-profit entities must request authorization from ARPA-E to assert copyright.

When an Applicant is selected for an award, the Commercialization Plan submitted by the Applicant will become part of the terms and conditions of the award. It is important to note that the Commercialization Plan is in support of and not a replacement for the U.S. Manufacturing Requirement described in Section VI.B.8. The Applicant/Awardee may request a waiver or modification of the Commercialization Plan from DOE/ARPA-E upon a showing that the original Commercialization Plan is no longer economically feasible.

Class patent waivers usually apply to domestic large businesses as set forth in Section VIII.A of the 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 that any products embodying or produced through the use of an invention conceived or first actually reduced to practice under the award will be substantially manufactured in the United States, unless a waiver is granted by DOE/ARPA-E. The Commercialization Plan submitted by the Applicant will become part of the terms and conditions of the award in addition to the requirements attaching to subject inventions.

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XX. APPENDIX T: RESERVED

XXI. APPENDIX U: SF$_6$-Free Routes for Electrical Equipment

Special Program Announcement for
Solicitation on Topics Informing New Program Areas (DE-FOA-0001953)
SF_6-Free Routes for Electrical Equipment

Topic Issue Date	May 21, 2021
Deadline for Questions to ARPA-E-CO@hq.doe.gov	5 PM ET, Tuesday, July 13, 2021
Submission Deadline for Full Applications	9:30 AM ET, Friday, July 23, 2021
Submission Deadline for Replies to Reviewer Comments:	5 PM ET, ~~Tuesday August 24, 2021~~ Friday, August 27, 2021
Expected Date for Selection Notifications	September 2021
Total Amount to be Awarded	Approximately $10M subject to the availability of appropriated funds, to be shared between FOAs DE-FOA-0001953 and DE-FOA-0001954 for this Targeted Topic.
Anticipated Awards	ARPA-E may issue one, multiple, or no awards under this FOA. Awards may vary between $1M and $6M.
Maximum Period of Performance	36 Months

1. Introduction

This announcement describes an exploratory research thrust titled SF_6-Free Routes for Electrical Equipment (S-FREE). The purpose of this announcement is to (1) solicit Full Applications from the technical and research communities to address innovations in low greenhouse gas (GHG) alternatives for gas-insulated equipment in energy grids, (2) encourage partnerships with utilities, power generators, regulators, and equipment manufacturers, and (3) provide a timetable for the submission of Full Applications.

2. Topic Description

The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) is interested in receiving Full Applications in support of technology development aimed at reducing SF_6 emissions from the electric transmission and distribution sector. The targeted outcomes for this Topic include analyzing the viability and risks associated with alternative gas solutions on the market today, identifying potential new alternative gases or gas mixtures with comparable performance to SF_6 but with a much lower GWP (global warming potential), accelerating development and testing of vacuum-dry air or vacuum-solid dielectric technologies for high voltage (at or above 245 kV) applications, designing cost-effective sensors that enable early and continuous SF_6 and alternative gas leak detection, and/or creating new pathways for the permanent fixation or destruction of SF_6 for end-of-life disposal. Proposed technologies must have a focus on market-wide adoption, particularly in the short- to medium-term, addressing the technical challenges associated with market acceptance of alternative technologies. ARPA-E anticipates that any technology developed in this program could have a significant and widespread global impact as countries look to reduce, regulate, or eliminate SF_6 emissions from their electrical grids.

Today, the electric grid in the United States is responsible for distributing over 4 trillion kWh per year of electricity from generators to consumers. It forms an integrated network that has become an indispensable asset to the nation's economy, infrastructure, and security. The physical infrastructure of this network depends on a combination of specialized equipment including transformers, switchgear, circuit breakers, converters, switches, circuit switches, and coupling capacitor potential devices. A critical component for the safety and reliability of the electric grid is a man-made gas, sulfur hexafluoride (SF_6). In 1937, GE introduced SF_6 as an insulation gas in the electric industry; since then, SF_6 has become ubiquitous in medium-voltage (MV) and high-voltage (HV) equipment. Among its many key attributes are its intrinsic non-toxic, non-corrosive, and non-flammable nature, in addition to its superior stability over a wide operating window, good thermal conductivity, high dielectric strength, and excellent arc quenching capabilities. These properties make it particularly amenable as an insulating and arc-quenching gas in electrical equipment.[219] As a result, over 90% of gas-insulated switchgear globally uses SF_6 as the insulating gas.[220] However, SF_6 emissions from the electric transmission and distribution sector pose a significant climate risk as a potent and long-lived greenhouse gas (GHG). One ton of SF_6 emitted to the atmosphere has an equivalent 100-year global warming potential (GWP) of 22,800-26,700 tons of carbon dioxide and has an estimated atmospheric lifetime of 3,200 years.[221] As the U.S. and individual states set increasingly ambitious emissions targets, emissions of all GHGs, particularly from the electric grid, will be scrutinized. Furthermore, regulations being considered in places like California and the EU aim to completely phase out SF_6 from electrical equipment, necessarily setting a timeline to develop alternative solutions to SF_6-insulated equipment.[222,223] Alternative solutions developed today could define the market for decades to come, both in the US and globally.

[219] Wang, Y., *et al.* Processes. **2019**, *7*, 216.
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[222] Kurz, R. EU Reports Highlights Sulphur Hexaflouride Countdown, Replacements. *T&D World*. [Accessed April 2021]; https://www.tdworld.com/test-and-measurement/article/21146560/eu-report-highlights-sulphur-hexafluoride-countdown-replacements
[223] California Air Resources Board. (2020). 2020 SF6 ISOR Reducing Sulfur Hexaflouride Emissions from Gas Insulated Switchgear. https://ww3.arb.ca.gov/regact/2020/sf6/isor.pdf

Equipment leaks are a major source of SF_6 emissions from the electrical transport and distribution sector. This is particularly true for aging equipment which, due to natural deterioration, is more prone to gas leaks.[224] A study presented at the 2000 International Conference on SF_6 and the Environment suggests that 10% of circuit breakers in the U.S. leak; of that 10%, 15% were identified as minor leaks and 85% were identified as major leaks or leaks that required operations to schedule repairs.[225,226] The National Electrical Manufacturers Association (NEMA) estimates leak rates of 0.1% per year and the International Electrotechnical Commission (IEC) sets the standard for equipment leakage at 0.5%.[224,227,228] Across the entire life cycle of the equipment, however, SF_6 emissions may be as high as 15%[229] and potentially underreported by at least a factor of two.[230] In addition to the emissions associated with equipment service life, losses due to poor gas handling practices are also to blame. The operation and maintenance of SF_6 gas carts are considered a major source of handling-related losses.[231]

Today, significant effort is dedicated towards supplanting fossil fuel-derived electricity generation with wind and solar power, with the concomitant effect of the grid becoming increasingly decentralized.[232] Barring any disruptive technological advances or policy-driven trends, more gas-insulated equipment (GIE) employing SF_6 will be added to the grid, increasing the emissions risks and, ironically, potential climate impacts. As more clean energy is integrated onto the grid, SF_6 emissions from the transmission and distribution (T&D) sector (0.25% of combined emissions from SF_6 and power generation; 0.07% of total GHG emissions from US in 2019[233]) will constitute a larger proportion of emissions from the electric grid (**Figure 3**).

[224] SF6 Leak Rates from High Voltage Circuit Breakers - U.S. EPA Investigates Potential Greenhouse Gas Emissions Source

[225] McCreary, J.D., "AEP: A Case Study," presented at the International Conference on SF6 and the Environment: Emission Reduction Technologies, November 2-3, 2000, San Diego, CA. [Online].

[226] D. Keith, J. Fisher, and T. McRae, "Experience with Infrared Leak Detection on FPL Switchgear," presented at the International Conference on SF6 and the Environment: Emission Reduction Technologies, November 2-3, 2000, San Diego, CA. [Online]

[227] IEC, International Electrotechnical Commission Standard 62271-1, 2004

[228] NEMA, "Management of SF6 Gas for Use in Electrical Power Equipment," Ad-Hoc Task Group on SF6, Switchgear Section (8-SG), February, 1998.

[229] McGrath, M. "Climate Change: Electrical Industry's 'Dirty Secret' Boosts Warming". BBC. September 13, 2019. https://www.bbc.com/news/science-environment-49567197 [Online]

[230] Weiss, R. F. and Prinn, R. G. Phil. Trans. R. Soc. A. **2011**, *369*. 1925-1942.

[231] Blackman, J., Averyt, M., and Taylor, Z. **2016**. https://www.epa.gov/sites/production/files/2016-02/documents/leakrates_circuitbreakers.pdf [Accessed April 2021].

[232] Sanghera, S. and Sekine, Y. Power Grid Long-Term Outlook 2021. **February 2021**. BloombergNEF

[233] EPA 2019 Inventory of GHGs.

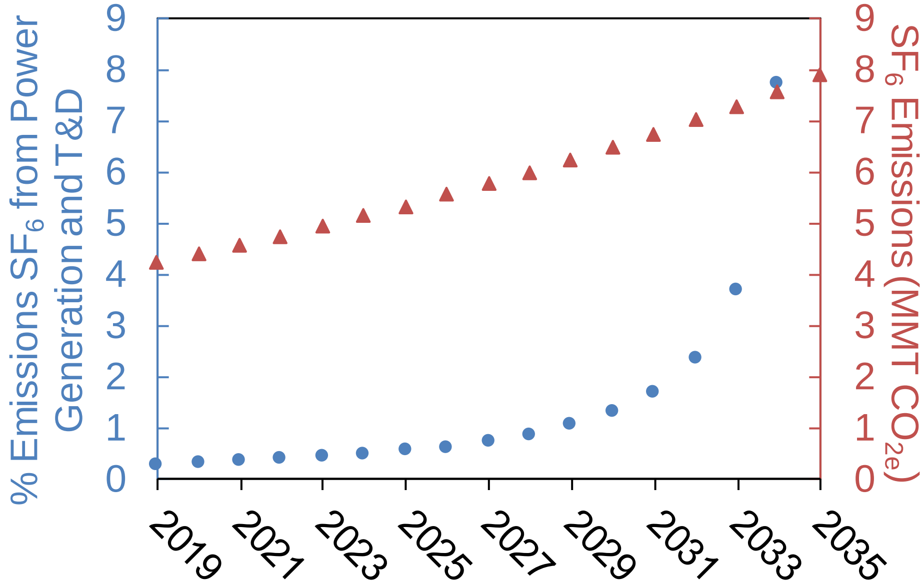

Figure 3. Projected SF_6 emissions as a percentage of the emissions from power generation and T&D and in real terms, expressed as MMT CO_{2e}. Calculations based on emissions from power generation decreasing linearly to zero by 2035 and SF_6 nameplate capacity increasing by 4% per year (consistent with the average historical increase between 1999-2013) and SF_6 emissions rates of 1.5% consistent with EPA reported values (recent SF_6 emissions rates have plateaued since 2015).[234] Note: SF_6 emissions rates may be underreported by a factor of two,[230] as one study suggested, based on atmospheric concentrations.

In addition, a large portion of the U.S. grid was built in the 1960s and 1970s[232], implying that the equipment currently in use is approaching or exceeding its useful life span. The aging infrastructure has two important implications. First, older equipment tends to leak more SF_6 or require more volumes of SF_6 which pose a significant climate risk.[224] Second, within the next few decades, much of this equipment will be replaced and will require large investments. Precluding any market-ready alternatives, this equipment will be replaced with new equipment that still uses SF_6, potentially locking in this potent greenhouse gas in the grid for the next 20-50 years over the lifetime of the grid equipment and increasing the risk of future SF_6 emissions. Because of the environmental challenges associated with using SF_6 in the electric grid, a few states, including California and Massachusetts, are updating requirements to address SF_6 emissions reporting and to set new, more stringent, emissions limits.[223,235] Given the age of the equipment, the investment needed to update and expand the grid, and the stricter policy measures, new technologies and/or alternative gases that minimize or eliminate SF_6 and SF_6 emissions from gas-insulated equipment (GIE) will be required.

[234] https://www.epa.gov/sites/production/files/2016-02/documents/sf6_annrep_2015_v9.pdf; https://www.epa.gov/sites/production/files/2021-02/documents/us-ghg-inventory-2021-main-text.pdf;

[235] Massachusetts Department of Environmental Protection (2017). Reducing Sulfur Hexafluoride (SF6) Emissions from Gas-Insulated Switchgear (Report 310 CMR 7.72). [Accessed April 2021]; https://www.mass.gov/service-details/reducing-sulfur-hexafluoride-sf6-emissions-from-gas-insulated-switchgear-310-cmr

State of the Art and Alternatives to SF_6 Technology

SF_6 is used extensively as the insulating and arc quenching medium in MV and HV (12kV to 720kV) electrical power systems due to its high dielectric strength. Research by Rabie and Franck compared the dielectric strength of SF_6 to 2611 carbonyl compounds as a pre-selection process to identify potential SF_6 alternatives. Dielectric strength is a sought-after characteristic in SF_6 replacements for GIE because it strongly correlates with certain key performance metrics.[236] **Figure 2a** shows the 2611 molecules grouped into 3 classes of C_{3-}, C_{4-} and C_{5-} carbonyl compounds looking at their predicted dielectric strength (E_r), the dielectric strength relative to SF_6, and T_B, the molecules' boiling point. The most promising candidate molecules, due to their relatively high values of E_r and low values of T_B, are captured in the black box. However, none of the molecules surveyed in this study met or exceeded the performance of SF_6, illustrating how finding suitable alternatives for this gas is difficult.

A critical performance metric for insulating gases used in GIE is the breakdown voltage, V_b, which is a function of both the type of gas and pressure (**Figure 2b**). As can be seen in **Figure 2b**, air under vacuum (0.02 kPa-cm) and SF_6 under pressure (1-2 kPa-cm) have equivalent breakdown voltages; both vacuum-based and SF_6-insulated GIE are used on the grid today but are not always interchangeable due to space constraints and/or equipment costs. The breakdown voltages of alternative gases as a function of pressure will similarly need to be characterized before they are introduced onto the grid at large scale.

[236] M. Rabie, D. A. Dahl, S. M. A. Donald, M. Reiher, C. M. Franck "Predictors for Gases of High Electric Strength", accepted for publication in IEEE TDEI, 2013

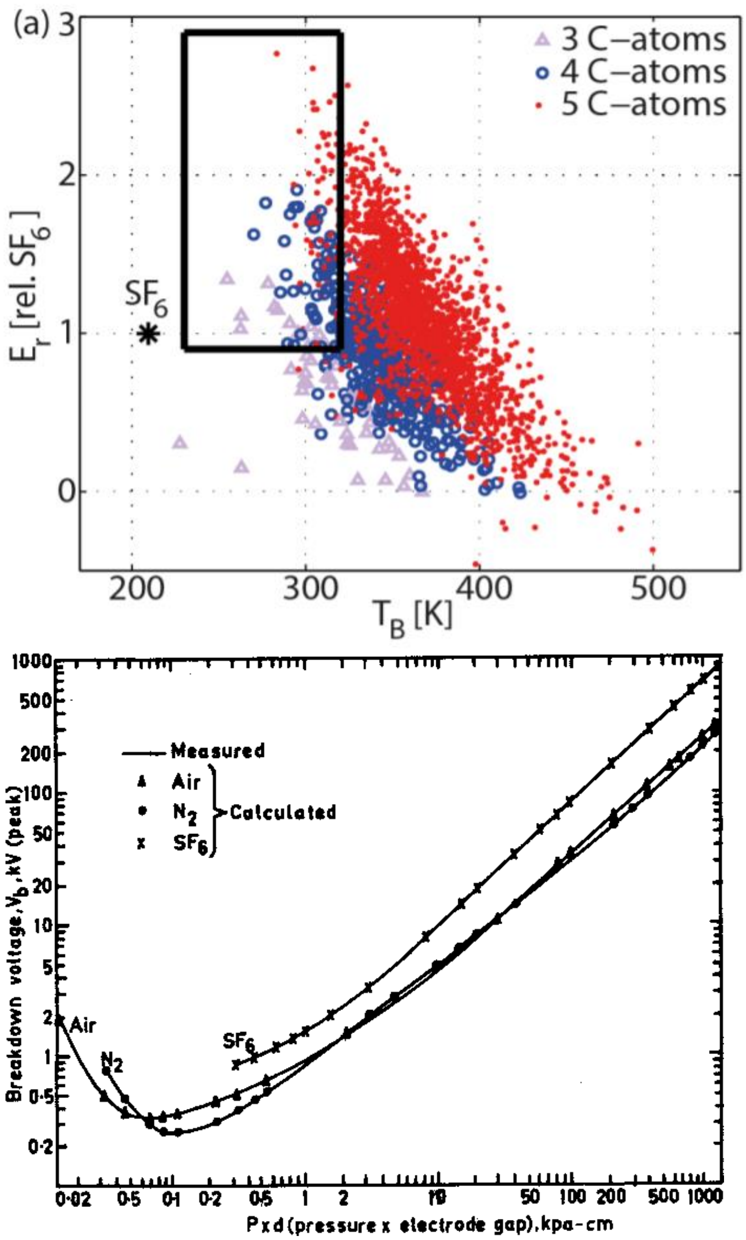

Figure 2. (a) Predicted dielectric strength E_r vs predicted boiling point T_B for 2,611 carboxyl compounds. The complete list of molecules is split into carbonyl compounds containing 3 (triangles), 4 (circles) and 5 carbon atoms (dots).[237] **(b)** Breakdown voltage (kV) versus pressure-gap length product (kPa-cm) for air, nitrogen, and SF_6. [238]

[237] M. Rabie, C. M. Franck, "Predicting the electric strength for proposed SF6 replacement gases by means of density functional theory", ISH 2013

[238] Husain, E. Nema, R. IEEE Transactions on Electrical Insulation. **1982**. *EI-17*. 350-353.

The search for SF_6 alternative gases with a lower environmental impact has been an area of focus for decades.[239] Key technical requirements for these alternatives include high dielectric strength, low GWP, zero ozone depletion potential (ODP), low toxicity, non-flammability, high arc quenching and heat dissipation capability, long-term stability, and material compatibility.[240] 3M's Novec™ dielectric gases, Novec™ 4710 and Novec™ 5110, are widely known as SF_6 gas alternatives for power utility applications. Original equipment manufacturers (OEMs) use mixtures of these Novec™ dielectric fluids to enhance performance properties. For example, GE developed Green Gas for Grid (g^3) using CO_2 and O_2 mixed with Novec™ 4710 for gas insulated substation (GIS) and gas insulated line (GIL) applications. ABB developed AirPlus™ combined dry air with Novec™ 5110, also for GIL and GIS applications.

Although potential gas alternatives like those previously mentioned have demonstrated promising results, several challenges exist in accomplishing full replacement of SF_6. For example, though these alternative gases can reduce the GWP by over 99% relative to SF_6, a 99% reduction still leaves many alternatives with a GWP >100. Furthermore, alternative gas and gas mixtures are not necessarily drop-in solutions for SF_6. Some gas mixtures are not suitable for colder climate zones due to their higher boiling points, posing a potential performance risk at lower temperatures. Alternative gases and gas mixtures also require new equipment specially designed to use these gases and, unlike SF_6 which boasts widespread market adoption, alternative gas and gas mixtures do not have mature end-of-life disposal or recycling processes. Furthermore, it has been difficult for utilities to overlook the uncertainty regarding the decomposition products of alternative gases during typical equipment operation or after accidental release to the environment and there is still a degree of uncertainty around the potential of future regulations which may impact future adoption. Even if these points are addressed, market adoption would still require overcoming challenges associated with workforce training and spacing constraints, in addition to the need to assess the connection compatibility with existing equipment/infrastructure.

Vacuum-dry air or vacuum-solid dielectric circuit breakers are also seen as an SF_6 alternative, using vacuum as the arc quenching medium and either dry air or a solid dielectric as the insulator, eliminating the need for SF_6 or related gases entirely. Several manufacturers already have vacuum technologies for 38 and 72.5kV, while technologies at 145kV are expected to become available within the next year. Although these vacuum or near-vacuum technologies have a higher dielectric strength compared to SF_6 circuit breakers, OEMs consider scaling to higher voltages (i.e., 245kV) a difficult technical challenge. Therefore, developing vacuum technologies for HV is an area of interest for this FOA.

Beyond developing a gas substitute for SF_6 or any equipment replacement, there are additional opportunities for technology development at critical stages in the life cycle of the equipment. One of the most effective strategies for mitigating SF_6 emissions in existing equipment is to detect leaks early and to fix these quickly. Several technologies are currently available on the market

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[239] L. Niemeyer. A systematic search for insulation gases and their environmental evaluation. In Gaseous Dielectrics VIII, 459–464. Springer Science & Business Media, 1998.
[240] Seeger, M., *et al*. Plasma Phys. Technol. J. **2017**, *4*, 18-22.

including portable point source non-dispersive infrared (NDIR) detectors, NDIR room sensors which detect ppb and ppm SF_6 concentration levels in enclosed GIE substations, and pressure gauges interfaced with alarm systems that monitor changes in pressure in GIE.[241] While these technologies are mature and widely available, ARPA-E believes further improvements in continuous, sensitive, early-warning detection systems are merited. Cost-effective, robust sensor technologies that enable leak detection and remediation is critical to address SF_6 emissions in the near-term, both in the US and globally, and will require innovative solutions that can be deployed broadly. Of particular interest are cost-effective detection technologies with remote notification systems or systems sensitive enough to detect slow leaks in small-capacity gas-insulated equipment which pose unique challenges that demand low detection limits and high accuracy under a variety of environmental conditions. Today's continuous sensors primarily rely on pressure gauges that are not sensitive enough to detect slow leaks or leaks in small-capacity equipment. As a result, even with the technology that is on the market today, several small-capacity GIE owners responded to the proposed policy changes to the California legislation by noting that achieving 1% emissions rates on a consistent basis is challenging.[242] NDIR-based sensors offer higher sensitivity than pressure gauges, but they currently have several drawbacks. NDIR point source sensors are more sensitive and can detect ppm or ppb SF_6 concentrations but are not continuous, are cost prohibitive, and require a technician to manually check all equipment for leaks. NDIR room sensors can continuously monitor dilute SF_6 concentrations but are still costly and are only applicable for equipment housed in an enclosure. Regardless, a 1% emissions rate still corresponds to the equivalent of at least 1 Megatonne of CO_2 released per year in the US; these emissions could potentially increase five-fold by the year 2035 if SF_6 nameplate capacity continues to increase at an average of 4% per year and the emissions rate stays the same.[243] Developing sensors that combine lower cost, higher sensitivity, and continuous monitoring for all equipment settings could lead to advances in early detection technologies that reduce SF_6 emissions in the short- and medium-term as the electric grid transitions to non-SF_6 alternatives and potentially lead to more accurate accounting of emissions rates. Furthermore, cost-effective sensors designed for alternative gases and gas mixtures will be required because the alternative gases on the market today have a GWP potential that is lower than SF_6 but still significant when compared with other greenhouse gases.[244,245]

Finally, ARPA-E is interested in exploring novel end-of-life processes for SF_6. For SF_6, though destruction pathways are already established, ARPA-E believes there could be opportunities in

[241] Advances in Leak Detection in the Manufacturing Process (epa.gov) (Accessed March 30, 2021); DILO SF6 Gas Leak Detector | 3-033-R501 (Accessed March 30, 2021); SF6 Transmitter (draeger.com) (Accessed March 30, 2021); Mitigating Potential SF6 Leaks Through Early Leak Detection (epa.gov) (Accessed March 30, 2021); NDIR Infrared (IR) gas sensor for CO2, methane, SF6, refrigerants (nenvitech.com) (Accessed March 30, 2021); Gas detector - GIR-10 - WIKA USA (Accessed March 30, 2021)

[242] 2020 SF6 ISOR SF6 CARB Legislation

[243] The emissions are estimated by using a 1% emissions rate on the reported and projected SF_6 nameplate capacities (See **Figure 1**). Of note, the EPA does not require SF_6 emissions reporting for utility operators with a combined total of 17,820 lbs SF_6 nameplate capacity and therefore, the numbers available for nameplate capacity may not be complete.

[244] Blazquez, S., *et al.* Chemical Physics Letters. **2017**, *687*, 297-302.

[245] Sulbaek Anderson, M. P., *et al*. Environ. Sci. Technol. **2017**, *51*, 1321-1329.

lower-energy destruction pathways or in developing novel materials that could permanently fixate SF_6 as a solid for disposal. This aims to address SF_6 supplies which, when it is phased out from use in electrical equipment, may have limited secondary markets and will need to be properly treated or disposed of to avoid being released to the environment. For alternative gas and gas mixtures, end-of-life considerations are in their nascent stage. ARPA-E is particularly interested in proposals for recycling process designs for alternative gas and gas mixtures that can achieve equivalent performance to industry-wide practice for SF_6; namely, equivalent price and purity to virgin gas.

1. Technical Areas of Interest

The goal of the Topic is to support development of alternative technologies which substitute SF_6 in GIE with alternative gas, alternative gas mixtures, or vacuum-based technologies and address SF_6 emissions across the life cycle of the equipment. Within the scope of this program, ARPA-E expects to evaluate the viability and risks associated with alternative gas solutions, identify potential new alternative gases or gas mixtures that meet or exceed the performance of SF_6 at a GWP approximately equal to CO_2, accelerate development and testing of vacuum-dry air or vacuum-solid dielectric technologies for high voltage (at or above 245 kV) applications, design sensors that enable earlier leak detection, create new pathways for the permanent fixation of SF_6 for end-of-life disposal, and/or develop recycling processes for alternative gases and gas mixtures. To achieve this, ARPA-E seeks novel technology approaches in three technology areas, including:

Technical area A. Alternative gases and gas mixtures

- Developing SF_6 alternative gases or gas mixtures suitable for medium- and high-voltage (≥ 245 kV) GIE.

Technical area B. Vacuum-based equipment

- Developing and testing high-voltage (at 245 kV and above) vacuum-dry air or vacuum-solid dielectric equipment.

Technical area C. SF_6 and Alternative Gases life cycle equipment

- Developing technologies or processes related to life-cycle issues including: SF_6 leak detection/monitoring, alternative gas leak detection/monitoring, SF_6 decommissioning and disposal, and alternative SF_6 recycling processes.

In addition to the overall scientific and technical merit of the proposed solutions, ARPA-E also considers the impact of the proposed technology. To fully demonstrate each of these areas Applicants are encouraged to discuss the following in their Technical Volumes, where applicable:

- **State of the art metrics.** Provide a baseline for the proposed technology's performance and discuss the metrics for current state of the art technologies that the proposed technology plans to exceed.

- **Retrofit ability.** Discuss how the proposed technology could serve as a drop-in solution for SF_6-insulated GIE with existing equipment and hardware.
- **Market Adoption.** Applicants should discuss key challenges associated with the lack of market-wide adoption of current SF_6 alternatives and be able to demonstrate how their proposed solution could overcome or de-risk market acceptance challenges to achieve market-wide adoption.

Furthermore, proposed technologies must be able to soundly demonstrate an ability to meet or exceed the outlined metrics by the end of the proposed period of performance. Technical Volumes must also include quantitative analysis, with supporting calculations and references, to demonstrate that the alternative gases, vacuum-based technologies, or life cycle equipment developed in this program will meet the metrics.

2. Technical Performance Targets

If responding to **Technical area A. Alternative gas and gas mixtures**, respondents are required to include in their Technical Volume their proposed alternative gas or gas mixture. Respondents should include in their technical volume the information requested in **Metric Table 1** and list the known or anticipated performance parameters. If some performance parameters are not yet quantified, Applicants are encouraged to include in their proposal a plan to characterize or quantify those values. As part of the project, ARPA-E expects any proposed alternative gas or gas mixtures to meet or exceed the performance parameters of SF_6 with a GWP at or near 1.[246] If the alternative gas or gas mixture is not expected to/does not meet or exceed the performance parameters listed in **Metric Table 1**, Applicants are encouraged to speak to the trade-off and how their alternative gas or gas mixture may offer additional advantages over SF_6 or other alternatives. Within the Technical Volume, Applicants are expected to report a Paschen Curve, if known, comparing the performance of their alternative gas or gas mixture compared with SF_6; if Applicants do not have a Paschen Curve, they should state their plans to produce one and include it as one of the final deliverables of their project. Applicants should state the appropriate state-of-the-art product standards (IEE, IEC, ANSI, ISO, *etc.*,) they will use to test their alternative gas or gas mixture and provide a reasonable path to market strategy, identifying any potential commercial risks and potential risk mitigation strategies. If not known already, Applicants should also discuss how they will address questions regarding the decomposition products when the alternative gas or gas mixtures are exposed to a high-voltage arc or any decomposition products that might be produced if the gas is accidentally released to the environment.

If responding to **Technical area B. Vacuum-based equipment**, respondents are required to include in their Technical Volume the voltage capacity, short-circuit current rating, and footprint for their proposed vacuum-based GIE. Respondents should state the appropriate state-of-the art product standards (IEE, IEC, ANSI, ISO) they will use to test their proposed design in order to

[246] A detailed explanation for how GWP of a greenhouse gas has been calculated in the literature can be found in Hodnebrog, O., *et al.* Reviews of Geophysics. **2019**, *58*, e2019RG000691.

validate the performance and safety requirements of the GIE. Respondents should include a detailed description of the main technical and/or commercial risks for their proposed HV (at or above 245 kV) vacuum-based design and how they will minimize or mitigate these risks. For example, if the vacuum-based technology is expected to have a significantly higher CAPEX, a detailed technoeconomic analysis (TEA) outlining potential cost savings due to reduced report requirements, any changes in operating costs, and/or anticipated payback period are encouraged. The information requested in **Metric Table 2** is required in applications for **Technical area B**. The state-of-the-art technology is assumed to be SF_6-insulated GIE at an equivalent voltage rating versus the proposed vacuum-based design.

If responding to **Technical area C. SF_6 and alternative gas life cycle technologies**, respondents are required to include in their Technical Volume details of their proposed gas sensor or their design for a destruction or fixation process for SF_6. The ARPA-E performance targets will be set based on the proposed method of detection for the gas sensor and/or the stated alternative gas or gas mixture. For gas sensors, ARPA-E is specifically interested in cost-effective and continuous detectors which enable equipment operators to reduce the time when a leak (particularly a small leak) in the GIE develops and when it is addressed. The leak or monitor must be sensitive enough to enable a reduction in SF_6 or alternative gas emissions to below 1% per year across all GIE, regardless of the gas nameplate capacity. Proposals that target leak detection using a sensor that is both continuous and cost-effective for small nameplate capacity equipment is particularly of interest. ARPA-E recognizes there are several ways that leaks can be detected, including pressure gauges and NDIR sensors, which will change the metrics that are used. For example, to achieve gas emission rates below 1% per year, a temperature-corrected pressure gauge must be sensitive enough to detect a less than 1% change in pressure and an NDIR sensor (or something similar) must be a cost-effective, passive, continuous sensor which can detect SF_6 concentrations in an open space at ppb or ppm levels. Applicants should also include plans to address the long-term stability of the gas detector; sensors that are autonomous and/or self-calibrating are preferred. For new sensor technologies, ARPA-E is interested in path to market considerations and Applicants should address any commercialization risks and how these risks might be mitigated. For SF_6 destruction or fixation pathways, Applicants should be prepared to describe the destruction pathway compared to the current practice or the fixation mechanism by which SF_6 may be permanently fixated into a solid material. The information requested in **Metric Table 3** is required; for the gas sensors, the ARPA-E performance targets will be set by the state-of-the-art gas sensor with an equivalent method of detection.

Above-referenced metric tables are below. <u>Note that the tables will count toward the 14-page limit of the Technical Volume</u>. Proposed solutions must meet the performance metrics outlined. However, if a metric is not considered, is changed, or if a trade-off is identified, an explanation must be provided.

Metric Table 1. Gas properties to meet or exceed technical specifications for state-of-the-art (SOA).

Performance Parameter	ARPA-E Performance Targets[1]	Proposed Solution
Toxicity[2]	Practically Non-Toxic	
$CO2_e$ (GWP)	1	
Atmospheric Lifetime (Years)	-	Applicant Specified
Lowest Operating Temperature (°C)	-30	
Boiling Point (°C)	-64	
Dielectric Strength at optimized pressure conditions relative to SF_6	1.00	
Decomposition Products	-	Applicant Specified
Toxicity of Decomposition Products[2]	Slightly Toxic	
Ozone Depletion Potential	0	

[1]Based on performance parameters for SF_6 but with a GWP of 1.
[2]Hodge-Sterner Toxicity Scale reference

Metric Table 2. Required performance parameters for vacuum-based alternatives.

Performance Parameter	State-of-the-Art (SF_6-Insulated GIE with equivalent voltage rating)	Proposed Solution
Voltage capacity (kV)	Applicant Specified	
Short-Circuit Rating (kA)	Applicant Specified	
GIE Footprint (m^2)	Applicant Specified	
Weight of Equipment (lb.)	Applicant Specified	
CAPEX (USD)	Applicant Specified	

Metric Table 3. Required performance parameters for proposed sensor technologies

Performance Parameter	ARPA-E Performance Targets	Proposed Solution
Leak Detection/Monitoring*		
Method of Detection	Applicant Specified	
Analyte Gas (can be SF_6 or alternative gas)	Applicant Specified based on State-of-the-Art	
Sensitivity (Ex. if pressure-based solution, the minimum change in pressure that can be detected.)	Applicant Specified based on State-of-the-Art	
Cost of Gas Sensor (USD/Year)	At or Below Equivalent Sensor Technology	

Continuous Monitoring? (Y/N)	Yes	

*ARPA-E performance targets compared to state-of-the-art technology with same method of detection

3. Program Structure

The maximum period of performance for this program is 36 months. It is expected that all projects will undergo a midpoint review (Go/No Go gate) during the program. Successful projects may be eligible for award extensions, renewals, and new awards in accordance with Section IIB of this FOA.

4. Submissions Specifically Not Of Interest

Submissions that propose the following may be deemed non responsive and may not be merit-reviewed nor considered:

- Incremental modifications rather than transformational changes to SF_6 alternative gases or gas mixtures. Approaches including existing solutions or incremental improvements to current vacuum-dry air or vacuum-solid dielectric technologies.
- Technologies only suitable for voltage ranges outside those indicated in Technical Areas of Interest.
- Submissions that do not include the information requested in the metric tables applicable to the chosen Technical Area
- Submissions that do not include a plan for market-wide adoption across the United States

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