U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002720
on
Improving reliability of electric power distribution by cost-competitive undergrounding and high-performance maintenance technologies

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research program focused on technologies to improve the resilience, reliability, and security of the medium voltage (MV) electric power distribution system by undergrounding power lines. The goals of this research effort would be to develop 1) reliable and safe construction and installation technologies for underground MV distribution systems that are cost-competitive to constructing overhead systems, 2) technologies for robust health monitoring and predictive maintenance of existing and new underground power distribution systems, and 3) approaches to enable rapid repair with minimal surface disruptions. ARPA-E is seeking information at this time regarding transformative, scalable, and rapidly deployable technologies that could:

(a) Reduce the cost of civil works associated with overhead-to-underground conversion or the construction of new underground power lines close to existing buildings and active surface use (e.g. road traffic) while minimizing surface disruption.
(b) Construct underground vaults and install conduits in various terrain types and geologic conditions cost-effectively while avoiding damage to existing underground infrastructure such as subways, gas pipes, potable water and sewer pipes, and telecommunication wires.
(c) Dramatically reduce errors in the underground cable installation processes where failures are prone to occur (e.g. cable splices, installation of cables).
(d) Improve the performance of installed systems with advanced sensing and data tools (e.g. monitoring and analyzing system health, locating point of failure quickly and precisely, detecting and categorizing incipient failures before they cause a catastrophic failure).
(e) Repair a point of failure quickly and safely with minimal surface disruption for prompt power restoration in the event of a failure.

ARPA-E is interested in learning about the barriers to implementing underground MV distribution systems and technological innovations required to overcome such barriers. ARPA-E would also like to be informed about the priorities of potential technology development areas in order to create the most impactful potential program to overcome such barriers.

The reliability of electric power distribution

The recent increase in the frequency and severity of extreme weather events is exacerbating weather-related power outages across the United States.[1] The U.S. electric power distribution system has over

[1] Billion-Dollar Weather and Climate Disasters, NOAA (https://www.ncdc.noaa.gov/billions/)

5.5 million line-miles and over 180 million power poles that can be damaged by weather or tree-related incidents, which accounts for 62% of all power outages in the U.S.[2,3,4] Undergrounding power lines is a proven method to improve grid reliability as highlighted in Figure 1. Overhead circuits typically fail about 90 times/100 mi/year, whereas underground circuits fail less than 10 times/100 mi/year.[5] However, high capital costs make underground lines on average 3-5 times more expensive than overhead power lines despite lower maintenance costs.[1,6,7,8] In addition, once the power lines have been undergrounded, it is more difficult to locate faults and provide necessary maintenance and repair than on overhead power lines.

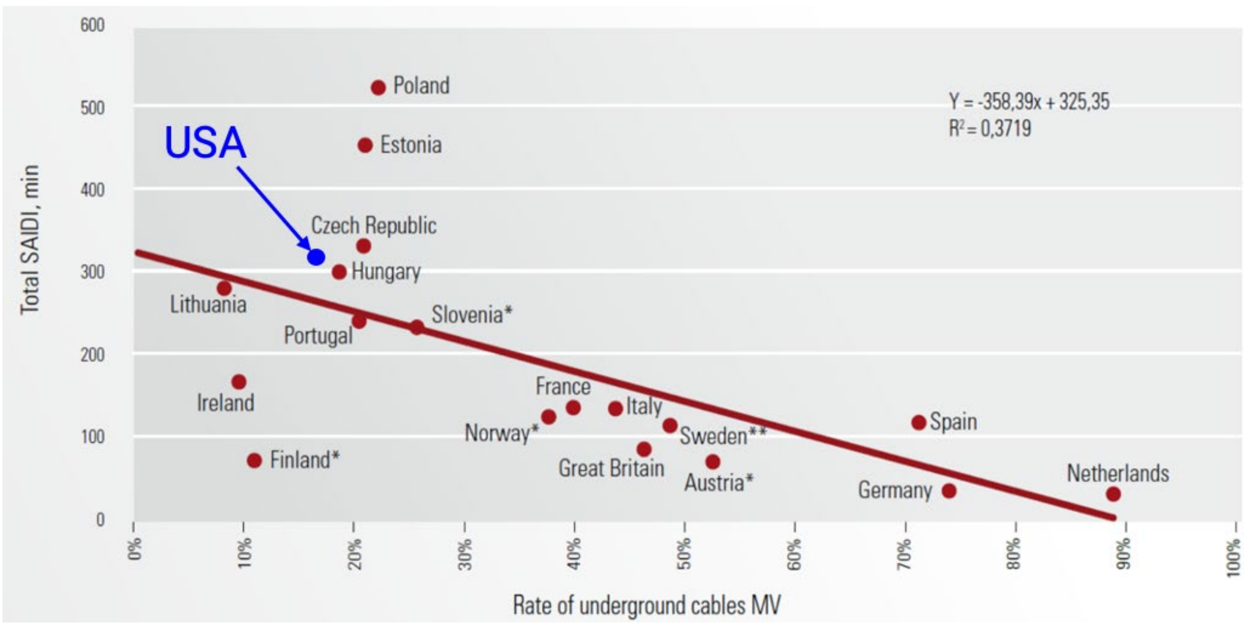

Figure 1. Statistical correlation between the percentage of underground cables in MV networks and "total SAIDI" (unplanned SAIDI including exceptional events plus planned SAIDI) averaged over 3 years. The data point for the U.S. is from the EIA data. SAIDI (System Average Interruption Duration Index) is calculated as the sum of all customer interruption durations divided by total number of customers served.[9, 10, 11]

Underground Survey and Construction

The conventional method of undergrounding powerlines entails digging a trench, laying the powerline,

[2] https://www.eei.org/issuesandpolicy/transmission/Pages/default.aspx

[3] The BRIDGE, National Academy of Engineering, Linking Engineering and Society, vol. 48(2), Summer 2018, (https://www.nae.edu/File.aspx?id=183084)

[4] https://sustainablesolutions.duke-energy.com/resources/resiliency-plan/

[5] Overhead vs. Underground Residential Distribution Circuits. Which One Is 'Better'? (https://electrical-engineering-portal.com/overhead-vs-underground)

[6] https://www.wdsu.com/article/start-making-the-investment-today-after-ida-a-push-to-harden-the-power-grid/37712492

[7] Study of the Feasibility and Reliability of Undergrounding Electric Distribution Lines in the District of Columbia, July 2010

[8] https://www.pgecurrents.com/2017/10/31/facts-about-undergrounding-electric-lines/

[9] Out of Sight, Out of Mind – An Updated Study on the Undergrounding Of Overhead Power Lines, Edison Electricity Institute, 2012

[10] Benchmarking of Reliability: North American and European Experience, J. McDaniel, W. Friedl, H. Caswell, 23rd International Conference on Electricity Distribution, 2015

[11] US data derived from EIA 2021 report (https://www.eia.gov/todayinenergy/detail.php?id=50316)

and backfilling the trench in a shallow depth range (from just below the frost line to about 30 feet depth) from the surface.[12] Trenchless methods are now commonly used for powerline installation when trenching is impractical, such as when crossing a body of water, highways, or railroads. Despite the rapid decrease in the cost of horizontal directional drilling (HDD) and tunnel boring, the cost to drill by trenchless methods can range from $300/ft[12] to $18,000/ft[13], and this high cost primarily contributes to the up to eleven-fold price increase for undergrounding powerlines using trenchless methods. Although various trenchless methods (e.g., horizontal directional drilling, microtunneling, auger boring) are used to underground powerlines, no single method possesses the high steerability, rapid penetration rate, bore diameter, and ability to drill continuously in all geologic media key to reducing overall cost. In comparison to the oil and gas industry, where advanced drilling and subsurface surveying technologies are widely used, underground infrastructure construction presents a unique set of challenges due to the shallow depth and proximity to various surface activities (e.g., traffic and noise), largely horizontal drilling, changes in surface terrains, and the presence of other underground infrastructure requiring high-resolution sensing and high-steerability to avoid them.

Once the underground space has been created using either trenching or trenchless methods, conduits are installed, cables are pulled through the conduits, and finally the cables are spliced. The conduits must have an adequate range of operating temperature, high thermal conductivity, low electrical conductivity, be water-resistant and corrosion-resistant, and have structural integrity.

For cable splicing, enough underground space must be secured which is often achieved by installing concrete vaults with manhole access in every 1,000 feet or so. The number of underground vaults constructed per line mile varies with customer density and is a primary driver of the overall system cost.

Subsurface surveying is employed pre-installation or concurrently with the installation of powerlines by trenching or trenchless methods. A primary requirement for either approach is proper subsurface characterization[14] to avoid cross boring[15] or delays caused by geologic obstacles, which can result in substantial additional costs. Current subsurface surveying requires multiple methods (e.g., ground-penetrating radar, seismic, magnetics) to correctly identify subsurface geologic media, materials, and object size. Additionally, no single method possesses the resolution, fast scan capabilities, and background canceling ability to identify a wide range of subsurface geologic media and obstacles while drilling.

Cable Splicing and Installation

A large proportion of underground system failures are caused by the cables themselves (56.2%), cable splices and service taps (37.1%), and the terminations (5.6%) that physically and electrically connect the cable and the equipment.[16] The root causes of these failures are largely attributed to poor workmanship (66%) followed by manufacturing defects of the cables and accessories (16%). Furthermore, splicing operations are often done in confined spaces that can cause safety issues. In order to address these issues, robotic splicing methods and faster, more automated splicing techniques are gaining traction in

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[12] Analysis of parameters affecting costs of horizontal directional drilling projects in the United States for municipal infrastructure, Vilfrant, E.C., Masters Abstracts International vol. 49(03), 2010

[13] TBM Tunnel Assumptions and Cost Estimating Output (https://www.vlhc.org/cna/hmm_appendix.pdf)

[14] The Orfeus Project (Optimised Radar for Finding Every Utility in the Street), M. Pieraccini, F. Parrini, G. de Pasquale and H. Scott, IGARSS 2008 - 2008 IEEE International Geoscience and Remote Sensing Symposium, 2008, pp. II-9-II-12, doi: 10.1109/IGARSS.2008.4778914

[15] Preventing and Eliminating Cross Bores - Increasing Safety and Reducing Risk.doc (crossboresafety.org)

[16] Medium Voltage Cable System Issues, Georgia Tech Research Corporation, 2016 (https://www.neetrac.gatech.edu/publications/CDFI/2-MV-Issues_25_with-Copyright.pdf)

the industry. New technologies are required to expand and dramatically widen their use by ensuring that they can work with a wide range of cable diameters, insulation materials, and applications, all while making them more automated.[17]

Next Generation System Diagnostics

Fault diagnostics and prognostics for detecting an impending fault, identifying the type of impending failure, and locating a failing component with high accuracy days or weeks before it fails are especially important for underground cable systems due to the lack of visual access and the longer time required for repairs. Online fault detection and location has been extensively studied in grid transmission using travelling wave methods for hard faults[18] or for offline cables using reflectometry-based methods. Wide area monitoring with phasor measurement units combined with artificial intelligence or machine learning methods, particularly at higher sampling rates, is also being investigated for diagnosing and locating incipient faults.[19] Optical fibers installed alongside underground cables can detect temperature rise, strain, and possibly partial discharge, which could help solve many detection and locating issues. However, they have not been installed with legacy cables and are only now becoming standard practice in critical applications.[20] In general, none of these options currently provide a low-cost, ubiquitous, manageable solution for locating and diagnosing a wide range of incipient faults on legacy and newly installed underground MV cables.

These examples are intended to be illustrative rather than restrictive. ARPA-E is looking for information on approaches that can meet the stated goals.

Quick Repair with Less Disruption

Underground power line failures often take longer to restore power than overhead power line failures due to the lack of visibility and difficulty in accessing the underground point of failure. The current method is to dig a trench over a large area in order to locate and repair the fault, which causes surface disruptions over a large area. Advanced fault locating technologies could help to avoid large-area trenching. However, gaining quick access to the underground power lines and repairing them without excavating the entire area continue to be major challenges.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an

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[17] https://ulctechnologies.com/technologies/electric-cable-splicing-machine/
[18] Use of Traveling Wave Signatures in Medium-Voltage Distribution Systems for Fault Detection and Location, NREL Technical Report, 2021 (https://www.nrel.gov/docs/fy21osti/78057.pdf)
[19] Fault Diagnosis for Electrical Systems and Power Networks: A Review, C. M. Furse, M. Kafal, R. Razzaghi and Y. -J. Shin, IEEE Sensors Journal, vol. 21, no. 2, pp. 888-906, 15 Jan.15, 2021, doi: 10.1109/JSEN.2020.2987321
[20] EPRI Program on Technology Innovation: Fiber Optic Primary Power Cable Feasibility Analysis, 3002017804, 2020

opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on March 31, 2022** Emails should conform to the following guidelines:

- Please insert "Response to DE-FOA-0002720 - <your organization name>" in the subject line of your email
- In the body of your email, include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential processes.

Questions

The questions posed in this section are classified into several different groups as appropriate. Please provide responses and information about any of the following. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Citations are encouraged as appropriate. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

Technology Prioritization

1) What could have the greatest impact on facilitating the implementation of underground distribution lines: lowering capital costs, increasing installation reliability/resilience, or improving operational performance that leads to reduced maintenance and operating cost over time?
2) What is the most expensive aspect of burying distribution lines? Please be as specific as possible and differentiate between rural, suburban, and urban areas.
3) To what extent could each of the following technologies, if available, allow for significant cost savings in the installation of underground distribution lines? Please rank them, if possible, and provide justifications for your answer(s), and consider categorizing them as rural, suburban, or urban.
    a. Drilling technologies that are faster than the current state of the art
    b. Technologies abolishing the use of vaults
    c. Technologies to reduce splicing time
    d. Dependable splicing technologies (e.g. reduce human errors by automation)
    e. Technology advancement in subsurface surveying (i.e. before drilling for geologic survey and during drilling to avoid obstacles)

f. Conduit installation technologies with less time
g. Any other technological advancements (please specify)

4) What is the ideal depth for underground distribution lines when cost, ease of installation, ease of repair, and other existing underground structures are taken into account? Please provide specific reasons for your response.
5) What new technologies would it take to install underground distribution line taps in the absence of an underground vault? Is this even a possibility?
6) What are the components of an underground electrical distribution system's operating and maintenance costs?
7) What are the components of an overhead electrical distribution system's operating and maintenance costs?
8) To what extent could putting overhead distribution lines on the ground improve reliability? Are there any technology gaps that could be filled to expedite the deployment?
9) Who are the key experts in underground distribution line installation or repair?

Construction & Civil Works

10) What factors influence the size of underground vaults, and what are the ranges? To what extent could underground vault size be reduced if splicing could be done remotely with a small robotic system? What other technologies could potentially reduce the size of the vault?
11) Is it possible to ream vaults instead of digging them? If so, how would this work and why is it not done already?
12) To what extent could trenchless drilling and reaming vaults reduce the cost of undergrounding when compared to traditional trenching-based conduit and vault construction?
13) Aside from cost, what are the current barriers to laying a single 5,000-foot run of underground distribution cable? These impediments could be technical, logistical, or other in nature.
14) What diameter hole or tunnel is required if multiple lines/conduits are being installed? Please provide specific conduit numbers and diameters as examples. Is it possible to install these larger tunnels or conduits without trenching, for example, by modifying horizontal directional drilling or a similar method?
15) If trenchless drilling technologies are used to build underground MV distribution systems, how important is it to have a high penetration rate and/or to operate as continuously as possible in order to reduce overall construction costs?
16) What percentage of the cost of underground installation for MV primary distribution (PD) lines can be attributed to pre-construction ground surveying?
17) How are soils removed in trenchless underground MV distribution system construction? Is it possible to leave the soil in place using compaction or other methods?
18) What other drilling technologies from the oil and gas industry could be used to build underground MV distribution systems (cable conduits as well as underground space for splices and taps) in a variety of terrains and duct diameters? What would be the most difficult technical challenge in transferring such technologies?

Surveying

19) Is subsurface surveying used only for distribution line route planning or also for drilling?
20) What technological advances would enable concurrent drilling and subsurface characterization (i.e. 'measure-while-drilling')? What are the difficulties in translating such technologies for shallow subsurface underground construction?
21) To what extent could less common methods, such as ambient noise seismology or gravimeters, be used to characterize the shallow depth subsurface in preparation for drilling?
22) What other subsurface surveying technologies from the oil and gas industry could be used in the

construction of near-surface underground power lines for all terrain types and various active surface conditions that could cause noise? What would be the most difficult technical challenge in transferring such technologies?

<u>Conduits & Cables</u>

23) What new methods could be developed to drill and concurrently place conduits for underground utilities?
24) What technical innovations would be required to enable the conduits or cables to be manufactured on-site (e.g. additive manufacturing) to allow for continuous drilling, conduit construction, and cable installation with a minimum number of splices?

<u>Splicing</u>

25) What technical advancements are required such that an automated or robotic splicing technique could be more agnostic in terms of cable rating, insulation type, and environment while requiring the least amount of human intervention? What specifications would be needed for such a tool or robot, such as the minimum amount of underground space in which to splice, diameters, insulation materials, etc.?
26) What is the longest cable run before a splice is required in rural/suburban/urban underground MV PD electrical systems? What are the constraints?
27) What new innovations would allow the installation of underground MV PD cable splices or taps without using underground vaults?
28) Are there opportunities to redesign the underground cables to make them more easily spliced by a machine?
29) Are there any non-mechanical or non-traditional methods for underground splicing (e.g., lasers, chemical solvents, explosives for compression, etc.) that could be used (e.g., layer removal or layer deposition)?

<u>Diagnostics</u>

30) What commercial products are currently used or under development for monitoring and diagnosing overhead and underground MV PD cables and equipment? Please provide information about the detection range, accuracy, and breadth for these tools. What features or capabilities are missing in these tools that would allow for comprehensive monitoring and diagnostics of all types of cable degradation, faults, and failures?
31) Is there any detection method or application used in other fields or applications that could be applied to underground cable monitoring to improve the locating of underground cable faults and incipient failures?
32) Is there currently a database of typical failure precursors for MV PD underground electrical cabling systems, such as impedance change or partial discharge electrical signatures, that could aid in cable fault diagnostics?
33) Why is it not a *de facto* standard to install a fiber optic sensing element with MV PD underground cables? Are there limits to what a fiber optic sensing element can detect? How could such limitations be overcome?

<u>Repair</u>

34) Is it possible to quickly access underground faults from the surface at the point of failure? If so, what methods could be utilized to accomplish this? If not, what technical advancements are required?
35) Is it possible to use keyhole technologies to repair underground power lines while causing

minimal surface disruption? What are the technical challenges of implementing keyhole repair methods?

T2M (Technology to Market)

36) To what extent does the existing power line configuration (overhead or underground) determine or influence how fiber optic lines are installed?
37) How would capital costs be affected if the cost of undergrounding could be shared with another utility? How much of the undergrounding cost premium can be offset by cost-sharing?
38) How are undergrounding lines prioritized? What is the cost-benefit ratio of resiliency?
39) How are the economic impact and expected frequency of future events considered when deciding whether to rebuild overhead or convert to underground after a weather event?
40) What data would utilities and/or regulators require to determine what an allowable expense to pass through to ratepayers would be for an undergrounding project?
41) Are there any metrics for improving reliability that would be used to evaluate an undergrounding project? Is it solely based on the cost and useful life of existing equipment?
42) Are weather-related investments planned for, or are they only evaluated after the fact?
43) Is the current method of calculating the benefits of undergrounding taking into account secondary effects such as lost kWh revenue, ratepayer health, and productivity?