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

Request for Information (RFI) DE-FOA-0002419 on Reducing Environmental Methane Everyday of the Year (REMEDY)

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research program focused on technologies to prevent and/or abate methane emissions. The goal is to reverse the rate of accumulation of methane in the atmosphere, resulting in a decrease in atmospheric methane concentration. ARPA-E is seeking information at this time regarding transformative and implementable technologies that could:

(a) Prevent methane emissions from anthropogenic activities. Examples include addressing improperly abandoned coal mines and oil and gas wells; plugged oil and gas wells that leak; uncontrolled landfill gas; and agricultural-related emissions from farming and ruminants. Emphasis will be on preventing energy-related emissions, but ARPA-E is interested in approaches that could be broadly applied which intervene before methane escapes into the atmosphere.

(b) Abate methane emissions at the source (stack, vents, leaks, etc.). Sources may have steady or variable flow rates and/or concentration. Source temperatures may range from ambient to elevated (i.e. >200 C). System-level approaches are encouraged (*i.e.* integrated methane collection/capture, reactor, and monitoring/control system).

(c) Remove methane from the air. Examples include approaches which enhance methane oxidation reactions in the troposphere, mineralization (*i.e*. biological oxidation of methane to CO_2) in soils, or recover methane for use as a fuel or chemical reactant.

Note that some approaches may fit several categories. For example, biological enhancement of methanotropes could be used to prevent methane emissions from coal mines, abate emissions from leaks, and remove methane from air. Priority is oxidation of methane to CO_2. Technologies that recover or beneficially use methane will need to show ability to address at least 1 billion standard cubic feet/yr economically.

ARPA-E is interested in processes that reduce methane emissions by >90% on a life-cycle basis. Inputs, including energy and water, need to be quantified. The performance metrics for cost[1] and water inputs[2] are intended to allow comparison of methane prevention and abatement processes to CO2 control processes. Performance targets include:

a) Net greenhouse gas reduction >90% based on a lifecycle analysis, calculated using 100 year greenhouse gas warming potentials for all relevant species.
b) Freshwater consumption <3 m^3/ton CO_2 equivalent
c) Methane reduction cost $150/ton CO_2 equivalent

[1] https://netl.doe.gov/projects/files/CostandPerformanceofBituminousCoalandNGPlantswithCCSRev4_091020.pdf
[2] Rosa, L., et al. Nat Sustain 3, 658–666 (2020).

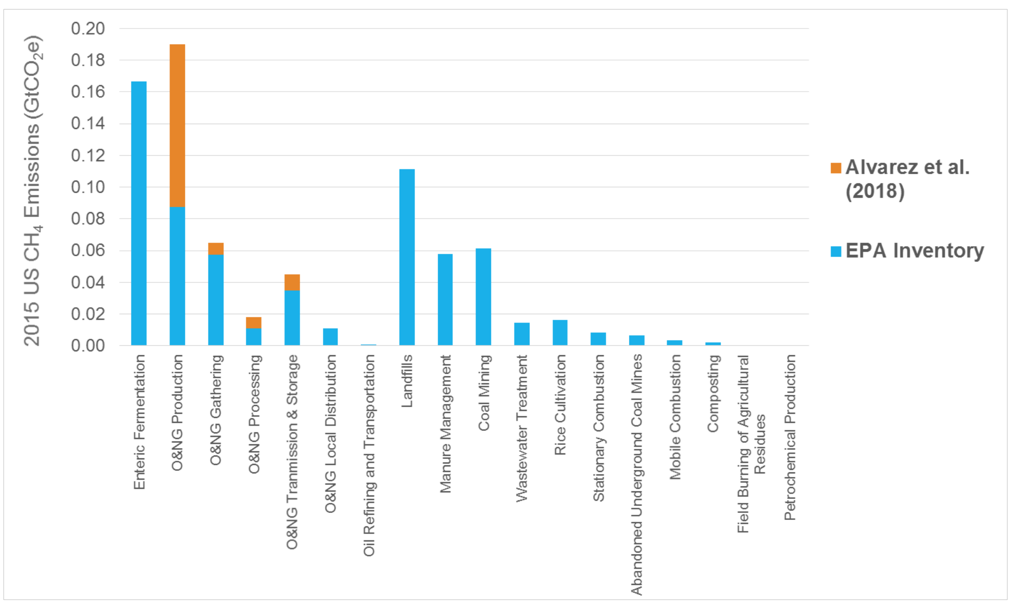
d) No emission of toxic or environmentally harmful substances

Anthropogenic Methane Emission Sources

The Saunois *et al*. update on the global methane budget quantifies sources and sinks for methane in the atmosphere, and the environmental implications[3]. Anthropogenic activities account for 50-60% of global methane sources, particularly from agriculture and the use of fossil fuels. Natural sinks in the atmosphere and soils remove the majority of methane. However, there is a net accumulation of methane in the atmosphere, resulting in concentration increase ~2.6 times to ~2 ppm during the recent industrialization period. They note that due to methane's ~9 year lifetime in the atmosphere, stabilization or reduction in methane emissions can lead to a rapid decline in methane concentration. ARPA-E seeks approaches which can foster this decline in atmospheric methane concentration.

The 2018 EPA's Greenhouse Gas Inventory (GHGI) shows methane accounts for 23% of US anthropogenic greenhouse gas emissions, using a 20 year life in the atmosphere (greenhouse gas warming potential 86), and amounts to ~1.83 Gt CO_2^e per year[4]. Other studies show methane emissions from oil and gas operations may be underestimated, particularly for abnormal operations such as malfunctioning of liquid storage tanks, vents, dehydrators, separators and flares.[5,6,7]. **Figure 1** shows US methane emissions based on the EPA data and estimates by Alvarez for some of these under-estimated sources.

Figure 1: 2015 US Methane Sources EPA and Alvarez, et al



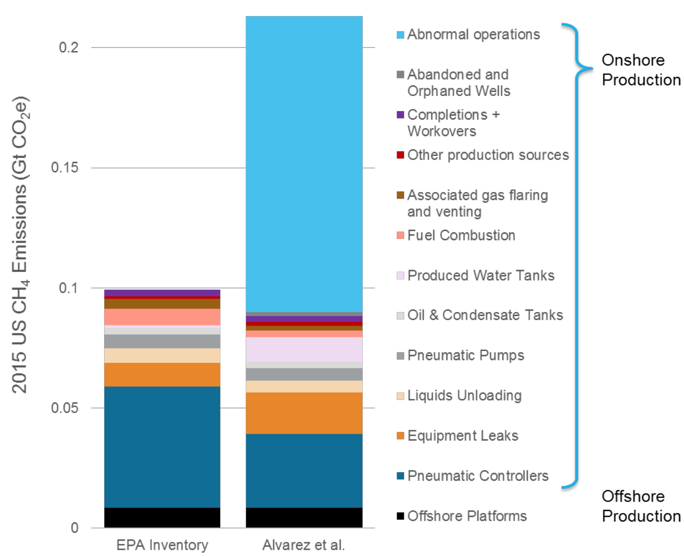
The EPA numbers show agricultural activities are the largest single source, accounting for ~35% of US

[3] Saunois, *et al*., Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.
[4] United States Environmental Protection Agency (US EPA) Green House Gas Inventory, 2018.
[5] Alvarez *et al*.., *Science*, 361, 186-188, 2018.
[6] Pandey *et al*., *Proceedings of the National Academy of Sciences*, 116(52), 26376-26381, 2019.
[7] Duren et al, Nature, 575(7781), 180-184, 2019.

anthropogenic methane emissions[8]. As shown in Figure 1, ruminants account for the majority of agriculture sector emissions. Yu *et al*. show good agreement between bottom up and top down methane emissions for beef, but more discrepancy with dairy[9].

Oil and gas industry sector accounts for the majority of US methane emissions, 203 MMT CO_2^e, which occur across the supply chain[10]. **Figure 2** provides details on methane emission sources from the oil and gas production segment. Normally operating vents from pneumatic controllers are recognized as a major source of emissions[11]. However, Alvarez concluded that super-emitters and abnormal operations, causing highly variable methane emissions, may be the dominant source. Negron, et al, also found that super-emitters accounted for a majority of emissions for offshore platforms in the Gulf of Mexico[12].

Figure 2: Stacked bar chart comparing the contributing factors from O&G production segment to methane emissions, EPA and Alvarez, et al



Figures 1 and 2 suggest many methane emission sources may be debated. Other reports estimate methane emissions could range up to ~2.2 Gt CO_2^e per year[5]. In addition to super-emitters discussed above, under-estimated sources may include:

- "Orphan" wells, plugged wells that subsequently develop leaks, and landfills[13,14,15].
- Flares, which are assumed to have >95% combustion efficiencies based on EPA emission

---

[8] Turner, A. J.,(2015). Atmos Chem and Physics, 15(12), 7049–7069. https://doi.org/10.5194/acp-15-7049-2015
[9] Yu, X., *et al*. (2020). J of Geophys Res: Biogeosciences, 125, e2019JG005429. https://doi.org/10.1029/2019JG005429
[10] United States Energy Information Administration (US-EIA), 2017. www.eia.gov
[11] EPA Natural Gas START program, https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-sector-united-states
[12] A. Gorchov Negron, et al, Environmental Science & Technology 2020 54 (8), 5112-5120 DOI: 10.1021/acs.est.0c00179
[13] Schout, *et al.* Science Total Environment, (659), 773, 2019.
[14] Kang, *et al.*, *Proceedings of the National Academy of Sciences*, 118(48), 136373, 2016.
[15] Duren *et al*., Nature, 575(7781), 180-184, 2019.

factors[16]. However, Leahey et al showed theoretically and experimentally that flare combustion efficiency is sensitive to wind speed. Efficiencies ranged from 62-84% in the field, with methane having lower combustion efficiency than higher hydrocarbons[17]. Johnson et al also discuss operating conditions that can reduce flare efficiency[18]. Gvakharia conducted field tests in the Bakken and found that median flare efficiency was 98%. However, the measured efficiencies followed a log-normal distribution, leading them to estimate flares could account for ~20% of Bakken methane emissions[19]. Aerial surveys of the Permian have shown some flares are not operating, leading to large emissions[20].

- Methane slip from gas-fired internal combustion engines can be 1% of fuel input and higher[21]. Gas turbines have low methane emissions during operation, but can have spikes during start-up[22,23].

Example Prevention and Abatement Approaches

Recent improvements in methane detection and sensing technologies facilitate identification and quantification of methane emissions[24]. This potential program is intended to leverage these advances, and develop processes that prevent or abate methane emissions. The process should have a system-level approach, which includes means for assessing source and exhaust methane flows and concentrations, a control or feedback mechanism, and the prevention/abatement process. Systems which are robust with respect to variable flow rates and methane concentrations are preferred.

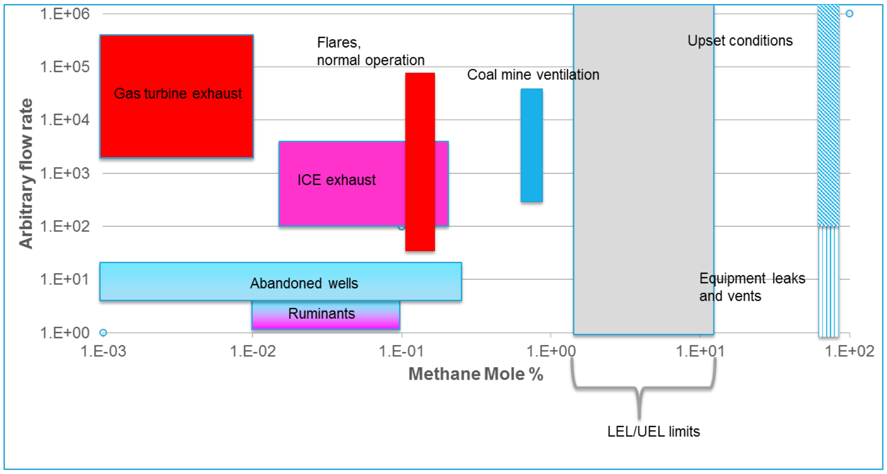
Reacting methane is challenging: methane is a very stable molecule, with an activation energy of 359 kJ/mol, approximately 40% of its heat of combustion (889 kJ/mol). Methane's autoignition temperature is theoretically calculated to be 540 °C, but experimentally observed is higher at ~600 °C[25]. Its autoignition temperature is relatively insensitive to pressure, dropping to 390 °C at 1100 bar[26]. It flammability range is 4.4-17%.

Figure 3 shows that methane sources have a wide range of flow rates and concentrations. As noted above, many sources have variable flow rates and/or methane concentration, particularly those from abnormal oil and gas operations. Most sources are "cold"; i.e. below the autoignition temperature, with the exception of flares and gas turbine exhaust streams. All sources are outside the flammability range (~4-17%), and a significant number are lean or ultra-lean with regard to methane concentration.

Figure 3: Schematic showing the range of concentrations and flow rates of methane from various

[16] U.S. EPA Office of Air Quality Planning and Standards (OAQPS). Parameters for Properly Designed and Operated Flares. https://www3.epa.gov/airtoxics/flare/2012flaretechreport.pdf (accessed on 4/13/2016)
[17] D.Leahey, et al, (2001), Journal of the Air & Waste Management Association, 51:12, 1610-1616
[18] Johnson, M. & Kostiuk, L. (2002). Proc. Combustion Institute. 29. 1943-1950. 10.1016/S1540-7489(02)80236-X.
[19] Alexander Gvakharia, *et al*, Environ. Sci. Technol. 2017, 51, 5317−5325
[20] https://www.edf.org/media/initial-data-showing-permian-flaring-rise-again-new-survey-finds-1-10-flares-malfunctioning
[21] Korakianitis, et al Progress Energy Combustion Science, 37 (1) p.89 (2011)
[22] Rokke *et al*., International Gas Turbine and Areoengine Congress, May 24-27, 1993
[23] Hajny, et al, Environ. Sci. Technol. 2019, 53, 8976−8984
[24] ARPA-E MONITOR Program, https://arpa-e.energy.gov/?q=arpa-e-programs/monitor
[25] Robinson *et al., Journal of Hazardous Materials*, 8(3), 199-203. 1984.
[26] Stein *et al.,* Ber. Bunsenges. Phys. Chem., 99 (1), 66-73, 1995.

anthropogenic sources



Given the challenges of reacting methane, prevention is one area of focus. As noted above, the agricultural sector is a major source. Prevention and/or reduction strategies for enteric methane production include genetics[27], modifying ruminant biota and feeds, and combination of approaches[28]. Ruminants, manure and wastewater digesters, and landfills have similar biological processes, suggesting that advances in one area could be broadly applicable across a range of sources. Other biological approaches, focused on methanotropes, have been proposed to reduce methane emission from point sources such a as coal mines[29] and dispersed sources such as swine farms[30] and landfills[31]. Blanchette et al demonstrated that printing methanotropes' methane monooxygenases (MMOs) enzyme on a silicone lattice is an option to convert methane to methanol[32]. These biological approached may also be applicable for methane removal from oil and gas wells and scrubbing methane from air.

New approaches for abandoned and leaking oil and gas wells are needed to prevent methane emissions and reduce future costs[33]. A 2011 report from the National Petroleum Council noted the technology has not changed substantially for more than 100 years, and listed R&D as the first barrier to progress[34].

Known abatement technologies include palladium and other platinum group metal catalysts, which are also used to control emissions of volatile organic compounds, and non-noble metals, which have the potential to reduce costs[35]. Variations to enhance catalyst activity include photo-catalyst oxidation[36]

---

[27] Pickering, *et al*., Animal (2015), 9:9, pp 1431–1440
[28] B.M. Buddle *et al*., The Veterinary Journal 188 (2011) 11–17
[29] Apel, W., et al, Fuel, Volume 70, Issue 8, August 1991, Pages 1001-1003
[30] Girard, M., et al, Chem Eng J, 168 (1) p. 151, 2011
[31] Abichou, T., et al, (2015). *Journal of Water Resource and Protection*, *7*, 1087-1097
[32] NATURE COMMUNICATIONS | DOI: 10.1038/ncomms11900
[33] D. Raimi, Resources for the Future, accessed at https://www.rff.org/publications/testimony-and-public-comments/virtual-forum-reclaiming-orphaned-oil-and-gas-wells/
[34] Paper #2-25, National Petroleum Council, September 15, 2011
[35] Li He, et al, Renewable and Sustainable Energy Reviews 119 (2020) 109589
[36] C. Taylor, Catalysis Today 84 (2003) 9–15

(preferred for oxidation at ambient temperature) and NEMCA (non-faradaic electrochemical modification of catalytic activity)[37]. Plasma and additives (*i.e*. hydroxyl radicals, ethane, etc.) can promote catalytic and non-catalytic methane oxidation[38,39,40]. Plasma and additives may be useful for removing methane from air.

Advanced combustion devices have been proposed that do not require catalysts. Burners have been tested at lean[41] and ultra-lean conditions[42]. There are also developments in reactor configurations to manage heat and extend operating ranges[43].

As noted in the Introduction, this potential program prioritizes prevention or oxidation of methane to CO_2. However, other approaches with recover or beneficially use methane acceptable, provided they address at least 1 billion standard cubic feet/yr economically. Potential approaches include methane capture/recovery from air[44], power generation from coal mine vents,[45] and production of bioproducts from methane[46].

These examples are illustrative, and not intended to be limiting. ARPA-E is seeking information on approaches that can meet the performance metrics.

Approaches Not of Interest

This potential program is focused on systems to prevent or abate methane emissions. Approaches not of interest include:

- Work focused on basic research aimed at discovery and fundamental knowledge generation.
- Concepts that focus on methane detection and/or quantification without addressing prevention and/or abatement.
- Solutions that focus on incremental improvements in commercial technologies, incremental improvements in control systems for commercial technologies, or incremental improvements in operation or maintenance procedures.
- Large-scale demonstration projects of existing technologies.

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.**

[37] A. Katsaounis, J Appl Electrochem (2010) 40:885–902
[38] Huu, T, et al, Catalysis TodayVolume 257, Part 1, 15 November 2015, Pages 86-92
[39] Nath,M, et al, J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 760–763
[40] Mohammadi, A., et al SAE Technical Paper 2006-01-0419
[41] H. Dai, et al., Applied Thermal Engineering, Volume 90, 3 August 2015, Pages 489-498
[42] S. Wood and A.T. Harris, Progress Energy Combustion Science, Volume 34, Issue 5, October 2008, p. 667-684
[43] Kucharczyk, B., et al, Fuel Processing Technology, Volume 166, November 2017, Pages 8-16
[44] Jackson, R.B., et al, Nat Sustain 2, 436–438 (2019)
[45] NadF., et al, Energy and Fuels, Volume 32, Issue 4, 19 April 2018, Pages 4579-4585
[46] Cantera, S., et al, Current Opinion in Biotechnology 2018, 50:128–135

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 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 should clearly mark any information in the response to this RFI that might be considered proprietary or confidential. Information marked proprietary or confidential will protected from public release by DOE to the maximum extent permitted by law, such as Exemptions under the Freedom of Information Act.**

Depending on the responses to this RFI, ARPA-E may consider the rapid initiation of one or more funded collaborative projects to accelerate along the path towards commercial deployment of the energy technologies described generally above.

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 October 15, 2020**. Emails should conform to the following guidelines:

- Please insert "Responses for Methane Prevention and Abatement RFI" in the subject line of your email, and 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 in the body of your email.
- 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

ARPA-E is interested in surveying stakeholders interested in methane emission prevention and abatement within the scope of approaches outlined above. The questions posed in this section are classified into several different groups as appropriate. Please provide responses and information about any of the following. We do 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.

<u>Emission prevention from underground sources</u>

1. The time horizon for sealing subsurface methane sources such as coal mines and oil and gas wells is hundreds to thousands of years.
    a. Similar timelines are anticipated for carbon sequestration wells and nuclear waste

repositories. What information from these programs could be relevant to well abandonment? Please consider geomechanical, geochemical, materials development, sensors/leak detection, and related studies.
    b. Are there other programs/technical areas that have similar requirements or could inform on long-term well integrity issues?
2. The geology of subsurface sources and details of mine and well construction are diverse.
    a. Is there sufficient information to develop a range of solutions, or is there a need to focus on a narrow set of conditions due to lack of background science and/or specific site data?
    b. What databases/methodologies are available to assess current and future methane emissions? What strategies are available to prioritize sites for remediation?
3. What is the potential for approaches that use multiple technologies vs single technologies?
    a. Subsurface biological suppression of methane combined with sealing
    b. Surface abatement combined with sealing
    c. Sealing alone
    d. Biological treatment alone
    e. Surface abatement alone
    f. Other options
4. Well plugging and abandonment (P&A) is not generally an active area of research, and there are relatively few R&D programs focused P&A activities.
    a. Are there other research programs that could provide insights to P&A approaches? Who are the leading researchers in these fields?
    b. To what extent can current commercial practices be extended to meet the targets of this program, vs a need to seek entirely new approaches?
5. What other subsurface approaches should ARPA-E consider?

<u>Emission Abatement Approaches</u>

1. What are the practical ranges in methane concentration and flow rate for technologies today, and after a program, assuming success, for:
    a. Biological approaches, including mono-cultures, mixed cultures, cell-free/enzymatic reactors
    b. Advanced burners/combustion reactors, with and without additives such as H_2 to promote methane reactivity
    c. Catalytic reactors, with and without additives such as H_2 to promote methane reactivity
    d. Plasma reactors
    e. Methane adsorption systems
2. What is the potential for approaches that use multiple abatement technologies vs a single technology?
    a. Identify sources and conditions where multiple technologies preferred
    b. Identify sources and conditions where single technology preferred
3. Methane emission control is not generally required, and there are relatively few R&D programs focused on methane oxidation.
    a. Are there other research programs that could provide insights to methane abatement? Who are the leading researchers in these fields? For example, there have been many programs "C-1 chemistry" programs to convert methane to valuable products (vs CO_2 in this program).
    b. To what extent can commercial VOC control technologies be extended to methane emissions?
4. What other abatement approaches should ARPA-E consider?

System-level issues

1. ARPA-E is seeking systems which include monitoring/control hardware and software; ability to quantify emission reductions with sufficient precision to meet emission trading requirements; and the "core" prevention/abatement technology.
    a. What is the status/technology gaps for monitoring/control hardware for
        i. Subsurface installations
        ii. Surface installations
        iii. Widely deployed systems, for example, biological inoculation to promote methane mineralization in soil
    b. What is the status/technology gaps for emission quantification re: trading requirements
        i. Subsurface installations
        ii. Surface installations
        iii. Widely deployed systems, for example, biological inoculation to promote methane mineralization in soil
    c. What companies/organizations should ARPA-E contact to ensure system-level capabilities are available for project teams?
2. What system approach(es) do you see as most promising for which methane sources, and why?
    a. What will be the critical issues for demonstrating the approach(es)?
    b. What time and resources would be required to conduct a lab and field demonstration of the approach(es)?
    c. What entities are well-positioned to conduct the demonstration?
3. Which methane source(s) do you think will be most difficult to address, and why?
    a. What are the critical technical issue(s) that need to be resolved to develop a solution?
    b. What time and resources would be required to investigate the critical technical issue(s)?
    c. What entities have the capabilities to address the issue(s)?
4. What system-level issues have not been addressed in this RFI?

Metrics

1. The metrics implicitly assume carbon capture/sequestration (CCS) technologies set the marginal cost for greenhouse gas abatement, and that methane prevention/technologies will need to compete with CCS for credits.
    a. What are the best future projections for CCS costs and carbon credits?
    b. What greenhouse gas equivalent will be used for methane trading – i.e. 20, 80, another?
    c. Will "voluntary" trading programs recognize methane emission prevention/abatement projects? If yes, what certification/qualification processes will be required?
2. Methane abatement technologies have a different LCA and "environmental footprint" compared to CCS.
    a. What externalities should be considered for methane prevention/abatement projects?
    b. How should LCA be conducted when the time span is in centuries or longer?
    c. What risk factors and risk analysis (financial and technical) need to be considered in assessing methane prevention/abatement projects?