U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0001607
on
Lower Grade Waste Heat Recovery

Objective:

ARPA-E seeks input from the waste heat recovery, materials development, and novel solid-state materials technology communities (emerging compositions, materials synthesis/processing, combinatorial screening/optimization, robust module designs, *etc.*) regarding the development of next-generation waste heat recovery systems. This request includes input from the researchers, developers and end-users of waste heat recovery technologies, such as power plants, factories, utilities, manufacturers, data centers, and the like. Consistent with the agency's mission, ARPA-E is seeking clearly disruptive, novel technologies, early in their R&D cycle, and not integration strategies for existing technologies.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below, and note, in particular, 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. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

Background:

Waste heat recovery is a significant opportunity – in 2015, 59.2 quadrillion BTU of energy was wasted mainly in the form of heat[1]. Much of the waste heat has been characterized by its source and its temperature, particularly in the transportation and power generation sectors[2], as well as in the industrial sector[3]; only very limited waste heat characterization has been applied to the buildings sector. In total, approximately 71% of all waste heat sources have been well characterized, as shown in Table 1.

Through aggregated analysis of waste heat data from the literature, ARPA-E found that most waste heat (~75%) is low-grade (≤230°C). This temperature regime is not easily converted to usable work as its exergy is roughly a third of the total heat generated (Figure 2); a Carnot analysis yields a maximum efficiency of only ~40% (*e.g.* 25°C cold-side). A majority of the higher grade waste heat resides in the 230°C to 400°C range. This can be seen in Figure 2, which shows the cumulative percentage of total waste heat as a function of temperature differential. Figure 2 also illustrates the cumulative percent of the total maximum work potential at each temperature difference. The maximum work potential is defined here as the amount of waste heat available at any temperature multiplied by the Carnot

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[1] Lawrence Livermore National Laboratory. Estimated U.S. Energy Consumption in 2015. https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2015.png

[2] Rattner, Alexander S., and Srinivas Garimella. "Energy harvesting, reuse and upgrade to reduce primary energy usage in the USA." Energy 36.10 (2011): 6172-6183.

[3] Johnson, Ilona, William T. Choate, and Amber Davidson. Waste Heat Recovery. Technology and Opportunities in US Industry. BCS, Inc., Laurel, MD (United States), 2008.

efficiency at that temperature. From Figure 2, it can be seen that approximately 85% of work potential from waste heat sources across all sectors in the United States comes from waste heat sources at or below 400°C. Thus, ARPA-E is keenly interested in waste heat conversion in this temperature range.

Table 1: The amount of waste heat in Quadrillion Btu's (Quad), that has been well characterized (source, temperature) in the open literature.

Sector	Characterized waste heat [Q]	Total waste heat [Q]	% Characterized	Estimated Work Potential* [Q]
Power Generation	23.1	25.4	91%	3.2
Industrial	1.6	4.9	33%	2.1
Transportation	17.2	21.9	78%	6.7
Buildings	0.0	7.0	0%	Unknown**
TOTAL	41.9	59.2	71%	12.0

*Work potential estimates were calculated using the characterized waste heat data and then scaled up to project the work potential for the entire sector. The implicit assumption is that the distribution of waste heat in the characterized subset is representative of the full sector; this is likely to give an over estimate of the work potential in each sector.

**Because the building sector waste heat sector has not been well characterized in the literature, it is not possible to estimate its work potential accurately. However, most waste heat is likely to come from lower temperature sources like exhaust streams from HVAC and dryer systems, mechanical systems and lighting,

Figure 1: Unrecovered Waste heat in different hot side temperature ranges (Industrial Sector)[3]

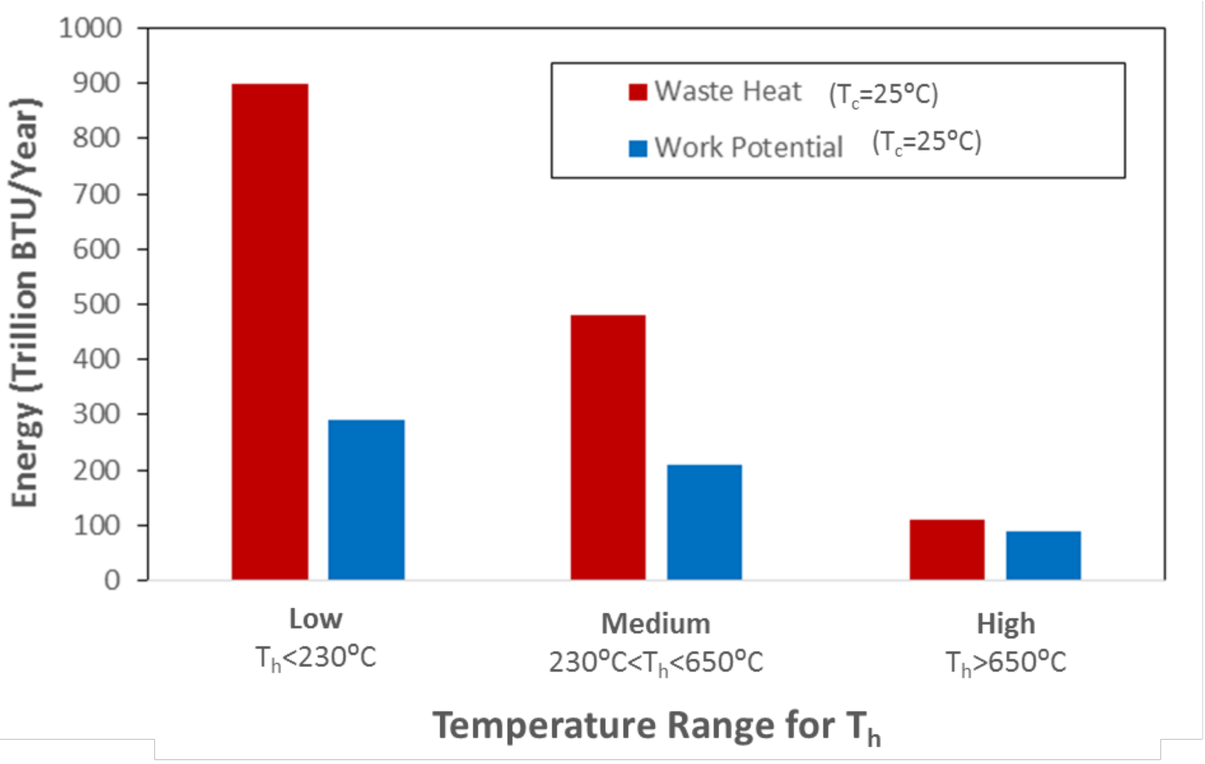
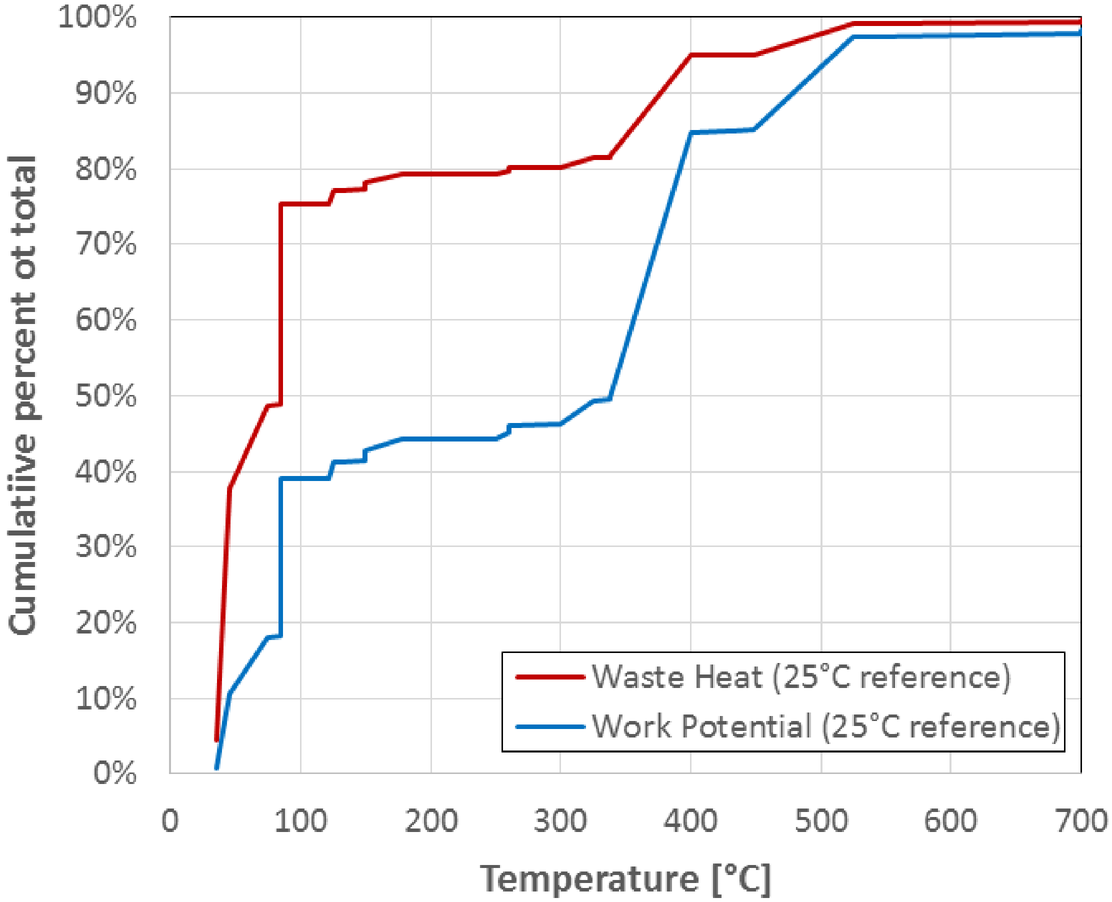


Figure 2: Cumulative percent of waste heat and maximum energy generation potential as functions of hot side temperature. Maximum energy generation potential is the amount of waste heat that can be converted to electricity, assuming conversion occurs at the Carnot efficiency limit.



Several technologies exist to realize the opportunity of lower-grade waste heat recovery, and are typically either mechanical, solid state, or hybrid systems. Examples of mechanical systems include the Organic Rankine cycle, and Kalina cycle, while examples of solid-state devices include thermoelectric generators, piezoelectrics, and multiferroics among others. Mechanical systems are often limited by their complexity, large footprint (*e.g.* size/mass), and parasitic power requirements. These are particularly challenging limitations for waste heat recovery in the transportation or mobile sectors, where a majority of the opportunity lies (Table 2). Solid-state devices have advantages in mobile applications due to their small footprint and lack of complexity and parasitic power requirement. Unfortunately, existing solid-state technologies have low efficiency and high cost. However, there may exist an opportunity to greatly improve most solid-state technologies.

Table 2: Total waste heat and maximum work potential for stationary and mobile sources.

Source type	Waste heat [Q]	Estimated Work Potential [Q]
Stationary	37.3	5.3
Mobile	21.9	6.7

For example, one might seek to improve the performance per unit cost of a thermoelectric generator (TEG). To date, TEG devices remain very inefficient (<6%) and costly. If their figure of merit for TEGs (ZT, a surrogate for device efficiency), were to be improved from current state-of-the-art values of around 0.8 – 1.4 up to 3, device efficiencies could reach approximately 20%. With that level of performance, if device costs could also drop to $1/W, TEGs could significantly penetrate the waste heat recovery market[4]; this would include a significant portion of the work potential in Table 2. Similar transformative performance and cost goals can be envisioned for the other solid-state waste heat recovery systems.

Thus, ARPA-E is seeking input from the broader research and development community regarding lower grade waste heat recovery systems and, in particular, solid-state recovery opportunities. Since preparing technologies for an eventual transfer from lab to market is a key element of ARPA-E's mission, concepts should eventually be commercializable with reasonable operational systems costs (*e.g*. $1/watt).[4]

Purpose and Need for Information:

The purpose of this RFI is solely to solicit input for ARPA-E’s consideration to inform the possible formulation of future programs intended to help create transformative waste heat recovery systems. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use the information submitted to this RFI on a non-attribution basis. This RFI provides the broader research community with an opportunity to contribute their views and opinions regarding the needed development path for waste heat recovery technologies, including energy use and adoption consideration in relevant end-use applications. Based on the input provided to this RFI and other considerations, ARPA-E may decide to issue a Funding Opportunity Agreement (FOA). If a FOA is published, it will be issued under a new FOA number. No FOA exists at this time. Additionally, ARPA-E reserves the right to not issue a FOA in this area.

[4] Quadrennial Technology Review 2015. Department of Energy. Chapter 6: Direct Thermal Energy Conversion Materials, Devices, and Systems – Technology Assessments. 2015.

REQUEST FOR INFORMATION GUIDELINES:

ARPA-E is not accepting applications for financial assistance or financial incentives under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop or pursue the project or ideas discussed. ARPA-E may decide at a later date to issue a FOA based on consideration of the input received from this RFI. 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 reserves the right to contact a respondent to request clarification or other information relevant to this RFI. All responses provided will be taken into consideration, 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 might 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 September 30, 2016.** ARPA-E will not review or consider comments submitted by other means. All emails should conform to the following guidelines:

- Please insert "Responses for RFI for FOA DE-FOA-0001607" 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 methodologies. However, do **not include any information in a response to this RFI that might be considered proprietary or confidential.**

- **Questions:** ARPA-E encourages responses that address any subset of the following questions of relevance to the respondent and encourages the inclusion of references to important supplementary information.

    1) **Mechanical systems** (*e.g.* Organic Rankine cycle and Kalina cycle)
        - Are there any novel technological pathways that would enable these systems to be viable in mobile applications? What might the energy balance look like, considering the waste heat conversion, parasitic requirement, and increase in weight from the system?

    2) Solid-state devices

        a) Thermoelectric Generators
        - A number of theories exist about how to achieve higher figure-of-merit for module (ZT) and material (zT). These include nanostructuring (superlattice) and big atom substitution, among others. Please comment on the degree to which these various theories have been proven or disproven with experimental data on materials and devices. Information regarding emerging potential mechanisms for thermoelectric enhancement may also be of interest.

        - To what extent have high performing semiconductor, narrow bandgap compositions, and semi-metal material classes been explored and characterized as potential thermoelectric materials?

- Are there emerging thermoelectric material classes that show promise towards reaching very high module performance ($ZT \geq 3$) at low/medium grade temperatures (<400°C)? For each proposed technology, please address not only the issue of conversion efficiency in the targeted temperature ranges, but also the holistic properties needed for manufacturability, and functional performance in application (*e.g*. cost, material compatibility), including the potential to meet the $1/W goal.

- Band-structure engineering is constrained by trade-offs between thermal and electrical properties. The Lorenz ratio between electrical and thermal conductivity is one such constraint and, in existing thermoelectric materials, varies only over a factor of two range. Are there any material classes or materials engineering strategies which can exhibit a Lorenz number significantly below 2.44×10^{-8} W/(Ohm-K)?

- Canonically and empirically, reduction in thermal conductivity by scattering is limited to the reduction of the phonon mean-free-path to one half the phonon wavelength. Are there strategies that can decrease the thermal conductivity beyond the minimum value this constraint implies?

- Are there emerging computational methodologies that might give significant predictive or directional insight?

- To what extent has combinatorial scouting been used to discover promising, new classes of thermoelectric materials versus merely optimizing existing classes? Can existing combinatorial methods be predictive, or give directional insight? Are there any emerging combinatorial technology approaches that might be more effectively leveraged (*e.g*. aerosol spray deposition)?

- Please comment on the role that novel module design and form factors (*e.g*. wires, thin films, heat pipes, *etc*.) may play in driving down the cost per Watt.

b) Thermionics

- Can thermionics ever be made suitable for lower grade waste heat harvesting (see #4 below)? Please comment on materials issues, performance at the indicated temperature ranges, as well as any other factors that should be considered?

- Are there emerging computational methodologies that might give significant predictive or directional insight? For example, systems where lower emission barriers via design (*e.g*. novel metamaterials), compositions or both allow a higher efficiency at lower temperatures (<<900^{o}C).

- To what extent has combinatorial scouting been used to discover promising, new classes of thermionic materials versus merely optimizing existing classes? Can existing combinatorial methods be predictive, or give directional insight? Are there any emerging combinatorial technology approaches that might be more effective at producing new alloys or lower temperature emitters?

c) Multiferroic Thermoelectrics

- Can multiferroic thermoelectrics ever be a suitable solution for low grade waste heat harvesting? Please comment on materials issues, performance at the indicated temperature ranges, as well as any additional factors that should be considered?

- Are there emerging computational methodologies that might give significant predictive or directional insight? For example, systems where reversible, phase change compositions might show low barriers to rapid, interconversion.

- To what extent has combinatorial scouting been used to discover promising, new classes of multiferroic materials versus merely optimizing existing classes? Can existing combinatorial methods be predictive, or give directional insight? Are there any emerging combinatorial technology approaches that might be more effectively leveraged (*e.g*. aerosol spray deposition)?

3) Electrochemical approaches

- Are there hybrid thermochemical methodologies that would be amenable to waste heat utilization?

4) Up-conversion of waste heat (low grade to higher grade conversion)

- Are there novel approaches to up-convert low temperature heat to high temperature heat? For example:
  - Through the use of photonics;
  - Through the use of acoustics;
  - Through the use of phonon-phonon coupling or pumping?

- For each proposed technology, please address not only the issue of conversion, but also the holistic properties needed for design, manufacturability, and functional performance in application.

5) Other

- Are there any other inherently transformative technology concepts for waste heat recovery that ARPA-E should consider?

- What are the challenges to developing a ubiquitous low-grade waste heat recovery technology? For example, there are significant variations in form factor requirements, such as between a vehicle circular exhaust tailpipe, a flat panel PV panel to a large cylindrical/conical blast furnace. Are there technological solutions that can be more universally applicable given this, and other, application specific requirements?