U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Solar-thermal Fuels and Thermal Energy Storage via Concentrating Solar-thermal Energy

DATE:	March 8, 2023
SUBJECT:	Request for Information (RFI)

Description

This request for information (RFI) is intended to inform the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) on the specific research, development, and demonstration opportunities to enable cost-effective production of hydrogen, ammonia, liquid fuels—such as gasoline, diesel, jet fuel—and solid fuels using concentrating solar-thermal energy.

In addition, SETO seeks information on thermal energy storage (TES) for concentrating solar power and concentrating solar-thermal (industrial) applications. While TES is an integral feature of concentrating solar-thermal power (CSP) generation, other applications of TES include energy supply for industrial process heat. Multiple modes of TES include sensible heat, latent heat, and thermochemical energy storage. Sensible heat TES using molten nitrate salt is currently used in commercial CSP plants. High temperature sensible heat storage in tanks of large size have had inconsistent operational success. Future generation CSP plants may make use of particles or rock to store thermal energy as they do not suffer from temperature limitations. This RFI will focus on improvements to various TES technologies appropriate for CSP integration for both power and industrial decarbonization applications.

Background

To build a clean and equitable energy economy and address the climate crisis, SETO invests in innovative research, development, and demonstration (RD&D) projects that work to drive down costs of solar technologies and develop next-generation products ready for commercialization. This RFI seeks information to help advance the goals of achieving carbon pollution-free electricity by 2035 and to "deliver an equitable, clean energy future, and put the United States on a path to achieve net-zero emissions, economy-wide, by no later than 2050."[1] DOE is committed to pushing the frontiers of science and engineering, catalyzing clean energy jobs through research, development, demonstration, and deployment (RDD&D), and ensuring environmental justice and inclusion of underserved communities.

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[1] Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," January 27, 2021.

This is a Request for Information (RFI) only. EERE will not pay for information provided under this RFI and no project will be supported as a result of this RFI. This RFI is not accepting applications for financial assistance or financial incentives. EERE may or may not issue a Funding Opportunity Announcement (FOA) based on consideration of the input received from this RFI.

Achieving a net-zero carbon economy by 2050 will require the adoption of clean energy technologies in sectors beyond electricity generation. Currently, CSP is primarily commercially deployed to produce electricity in the form of CSP plants. There are nearly 100 CSP plants producing electricity in commercial operation worldwide, representing almost 7 gigawatts (GW) of capacity. Many CSP plants in operation today utilize TES systems, which store solar energy as heat for use when it is needed. Long-term storage (greater than 10 hours) can help alleviate the impact of longer periods of cloudy weather, for example, or even seasonal variations of solar energy production. Existing CSP plants have already demonstrated long durations of daily storage, up to 17 hours, which increases their value to the grid. With integrated TES, CSP plants can dispatch electricity or heat on demand, regardless of the time of day or amount of cloud cover. TES may help enable the generation of solar-thermal chemicals/fuel but requires further research.

CST technologies can directly produce steam or high-temperature fluids by concentrating sunlight. Solar-thermal processes could also generate energy-dense chemicals or fuels that could deliver stored solar energy throughout the country and the world. Developing pathways for solar-derived chemicals or fuels can help reduce the carbon intensities of numerous industries. In another sense, both approaches to energy storage in CSP systems are considered here: thermochemical storage via solar fuel production and TES. Together these approaches will support the government-wide approach to address the climate crisis by driving innovation to deploy clean energy technologies, which are critical for meeting climate targets. However, significant technological challenges remain, including the design of equipment and systems for integrated solar-thermal processes that can address the variability challenges inherent in using sunlight as an energy source.

To achieve more efficient and lower cost CSP systems, SETO R&D efforts have primarily focused on increasing the operating temperature and stability of heat transfer media and components, including receivers. This has been realized through the Generation 3 (Gen3) CSP funding program,[2] which aims to develop a fully integrated thermal transport system, including a receiver and TES, able to deliver heat to an advanced power cycle based on supercritical CO_2 (sCO_2) at approximately 720 °C. The Gen3 CSP program identified several heat transfer media (HTM) that showed promise in meeting SETO's goals, organized by phase of matter – gas, liquid, or solid. Recently, SETO announced the down-selection[3] of just a single pathway, based on solid

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[2] U.S. Department of Energy Solar Energy Technologies Office. FOA: https://www.energy.gov/eere/solar/funding-opportunity-announcement-generation-3-concentrating-solar-power-systems-gen3csp. Selections: https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp.

[3] https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp-phase-3-project-selection

particle HTM[4] to develop an integrated, megawatt-scale Gen3 CSP test facility, led by Sandia National Laboratories.[5] Unlike the other pathways, ceramic, sand-like particles can readily withstand temperatures greater than 800 °C, making them promising for both electricity production as well as high-temperature industrial applications. This pathway also matches well with processes where solid media are an essential component, like refining iron ore for steel production or cement production from limestone. It is also worth noting that temperatures in Gen3 CSP are consistent with those needed for thermal neutral operations of solid oxide electrolysis cells.[6] These systems are known to have relatively high electrical efficiency producing hydrogen, relative to other electrolysis technologies.[7]

This RFI is focused on the application of CST for production of solar fuels such as hydrogen, ammonia, liquid, and solid fuels. In parallel, to enable long and diurnal TES integrated with power generation and for industrial applications, select questions on TES are included.

To limit the scope of the RFI, questions focus on the following fuels: hydrogen, ammonia, and liquid fuels, as representative of high fuel consumption, high emission applications. However, conversion of non-fossil fuel inputs such as hydrogen and carbon dioxide into various chemicals using solar energy is of interest. The following gives a summary of the current state of technology of each of these processes:

- *Hydrogen (and fuel reforming processes)*
    - Although most hydrogen is currently produced by steam methane reforming, using natural gas as a feedstock, there is significant R&D in electrolytic methods. Clean hydrogen can by produced by electrolysis using high or low temperature electrolyzers utilizing electricity from renewable sources. Heat from CST supplied to highly efficient solid-oxide electrolyzers may be an attractive pathway toward carbon-free hydrogen production. With further R&D, high temperature thermochemical splitting may be a promising hydrogen production pathway.
- *Liquid fuels*
    - The present generation of liquid fuels (e.g., aviation jet fuel, kerosene, gasoline, diesel) are produced with crude oil as input. Biobased fuels such as ethanol are

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[4] Ho, Clifford, Albrecht, Kevin, Yue, Lindsey, Mills, Brantley, Sment, Jeremy Niko Iversen, Christian, Joshua Mark, and Carlson, Matthew David. "Overview and Design Basis for the Gen 3 Particle Pilot Plant (G3P3) (paper).". United States. https://www.osti.gov/servlets/purl/1642710.

[5] Sment, Jeremy Niko Iversen, and Ho, Clifford K. Fri . "G3P3 Phase 3 Project Execution Plan.". United States. https://www.osti.gov/servlets/purl/1761300

Consider cross referencing the H2insteel 101 White Paper Authored for HFTO.

[7] See Table 2 on page 6 of DOE Hydrogen and Fuel Cells Program Record #20006 (2020) Accessed August 2021. Note the 98% Stack Conversion Efficiency (% Lower Heating Value H2) under Stack Electrical Usage (kWh/kg). See also Table 2 on page 5 of Hydrogen Production Cost From PEM Electrolysis Program Record # 19009 (2019) Accesses August 2021. Note the <70% Stack Conversion Efficiency (% Lower Heating Value H2) under Stack Electrical Usage (kWh/kg).

    also commercially produced. However, the focus of this RFI is the use of non-fossil and non-bio-based precursors such as water, steam, hydrogen, and carbon dioxide. The goal is to transform water and carbon dioxide to hydrogen and carbon, and then to liquid fuel. Alternative chemical production such as propylene and ethylene from non-fossil fuel is encouraged. Bio-based liquid fuels are part of the DOE Bioenergy Technologies Office scope.

- *Chemicals*
    - Several chemicals are added to liquid petroleum products for octane enhancement and other considerations. Some of the fuel additives can be directly produced from non-fossil precursors. Fossil fuel additions that can be produced from non-fossil input using solar energy are another focus of the topic.
- *Ammonia*
    - Ammonia is considered separately as a fuel for marine and other applications. Present generation ammonia plants have evolved over 100 years and use a combination of natural gas reforming, the water gas shift reaction, methanation and ammonia conversion, a process with significant CO_2 emissions. Aside from renewable pathways toward producing the necessary hydrogen precursor for clean ammonia production, CST may be an attractive choice to provide heat for driving the endothermic ammonia synthesis reaction.
- *Other industrial sectors*
    - Although the focus of this RFI is on the above, responses that describe opportunities for significant greenhouse gas emissions reduction in other industrial sectors is also welcome.

SETO aims to use the responses of this RFI to help develop promising pathways to incorporate CST into the production of solar-thermal fuel, both to accelerate decarbonization of the industrial sector and as long-term TES. This work complements existing efforts from the DOE Industrial Energy Decarbonization Office and Office of Electricity in the area of storage; and in concert with the Hydrogen and Fuel Cell Technologies Office on the recently announced Hydrogen Energy Earthshot.[8] Specifically, SETO is interested in the use of CST as both heat and electricity inputs to produce and replace fuels, with the aim of full decarbonization by 2050.

Purpose

This RFI solicits feedback from industry, academia, research laboratories, government agencies, and other stakeholders on two separate topic areas:

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[8] https://www.energy.gov/eere/fuelcells/hydrogen-shot

- Solar fuels production using non-fossil fuel input and concentrating solar-thermal energy. (Categories 1, 2, and 3)
- TES for integration with and production of power in CSP; and for use in industrial decarbonization applications. (Category 4)

This RFI is focused on solar heat at temperatures above 400°C and excludes low temperature industrial processes and TES. Lower temperature processes are being explored in other DOE initiatives, like the American-Made Challenges: Solar Desalination Prize.[9]

This is solely a request for information and not a Funding Opportunity Announcement (FOA). EERE is not accepting applications.

Disclaimer and Important Notes

This RFI is not a Funding Opportunity Announcement (FOA); therefore, EERE is not accepting applications at this time. EERE may issue a FOA in the future based on or related to the content and responses to this RFI; however, EERE may also elect not to issue a FOA. There is no guarantee that a FOA will be issued as a result of this RFI. Responding to this RFI does not provide any advantage or disadvantage to potential applicants if EERE chooses to issue a FOA regarding the subject matter. Final details, including the anticipated award size, quantity, and timing of EERE funded awards, will be subject to Congressional appropriations and direction.

Any information obtained as a result of this RFI is intended to be used by the Government on a non-attribution basis for planning and strategy development; this RFI does not constitute a formal solicitation for proposals or abstracts. Your response to this notice will be treated as information only. EERE will review and consider all responses in its formulation of program strategies for the identified materials of interest that are the subject of this request. EERE will not provide reimbursement for costs incurred in responding to this RFI. Respondents are advised that EERE is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI. Responses to this RFI do not bind EERE to any further actions related to this topic.

Confidential Business Information

Pursuant to 10 CFR 1004.11, any person submitting information that he or she believes to be confidential and exempt by law from public disclosure should submit via email, postal mail, or hand delivery two well-marked copies: one copy of the document marked "confidential" including all the information believed to be confidential, and one copy of the document marked

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[9] https://americanmadechallenges.org/solardesalination/

"non-confidential" with the information believed to be confidential deleted. Submit these documents via email or on a CD, if feasible. DOE will make its own determination about the confidential status of the information and treat it according to its determination.

Evaluation and Administration by Federal and Non-Federal Personnel

Federal employees are subject to the non-disclosure requirements of a criminal statute, the Trade Secrets Act, 18 USC 1905. The Government may seek the advice of qualified non-Federal personnel. The Government may also use non-Federal personnel to conduct routine, nondiscretionary administrative activities. The respondents, by submitting their response, consent to EERE providing their response to non-Federal parties. Non-Federal parties given access to responses must be subject to an appropriate obligation of confidentiality prior to being given the access. Submissions may be reviewed by support contractors and private consultants.

Request for Information Categories and Questions

Category A: Hydrogen and Ammonia

1. What are the most promising opportunities to integrate solar-thermal energy into the commercial production of hydrogen? As discussed above, high-temperature processes are of particular interest. Please include discussion of integration opportunities that are not yet currently cost-effective but may be in the future. Hydrogen may be used as a fuel and as a precursor to other fuels.
2. What opportunities, if any, exist for solar thermochemical water splitting to produce hydrogen? What should be DOE's role in enabling research in solar thermochemical hydrogen generation? The focus in this RFI in solar thermochemical hydrogen (STCH) is on the following four subtopics, but comments in other areas are welcome:
   2.1. Solar thermochemical integration with concentrated solar thermal plant
   2.2. Materials development for STCH catalysts
   2.3. Recuperation of energy for better solar thermal efficiency
   2.4. Improved component design for solar reactors
3. What aspects of ammonia production can be supported by CST? What research areas in ammonia manufacture using concentrated solar thermal require further investigation and technology development?

Category B: Liquid Fuels and Plastic Precursors

Solar thermal energy can be used to produce synthesis gas (syngas) as a precursor for producing liquid fuels via Fischer-Tropsch (FT) reaction. Hydrogen production has been addressed in the earlier category. This category focuses on syngas production. Two routes to syngas production are addressed in this category, however, alternate methods may be feasible via research.

1. One known method to produce syngas is via reverse water gas synthesis (RWGS) reaction. What specific opportunities exist for advances in technologies relating to RWGS including catalysis, energy recuperation, integration with FT synthesis, solar thermal integration, and integration with hydrogen generation?
2. Alternative approaches to syngas generation includes carbon dioxide electrolysis and solar thermochemical splitting. How can carbon dioxide electrolysis or solar thermochemical splitting best integrate with CST? What research in catalysis and solar thermal integration is required to enable an alternate resource of carbon monoxide for syngas production?
3. What syngas technoeconomic goals should be targeted to enable competitive syngas prices for industrial decarbonization? Competitive with syngas production from natural gas?
4. FT synthesis is a mature technology. What advances in FT synthesis and integration of CST with methods of solar syngas generation are promising avenues for R&D?
5. What other methodologies can be used, and fuels can be produced using CST and non-fossil inputs?
6. Alternate routes to chemical production (for chemicals that can be used as additives and substitutes for fuels) such as CO_2 electrolysis have been investigated. What alternate methods for solar-thermal chemical production (focusing on fuels) are promising avenues for R&D? Please provide a detailed discussion of possible research that could be performed with SETO funding by partners from the private sector.

Category C: Solar thermal receivers, receiver-reactors, and heat exchangers

Solar thermal energy can be introduced into solar fuel production processes either directly or indirectly, via a receiver – or multiple receivers operating in concert – which absorb concentrated solar light and convert it into thermal energy which is delivered to a heat transfer medium. That medium may directly be an input into an industrial process, being heated before being introduced to the reactor. Or a chemical reaction may be performed directly in a receiver-reactor, in which case the thermodynamics and kinetics of a chemical reaction must be evaluated and co-optimized with the instantaneous input of solar energy.[10] Operations may be

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[10] Rosa, Luís Guerra. "Solar heat for materials processing: A review on recent achievements and a prospect on future trends." *ChemEngineering* 3, no. 4 (2019): 83.

supplemented with heating from electricity, hydrogen, or other fuels to enable on-sun reactions.

Solar heat can also be introduced to a process indirectly, using receivers designed for inert heat transfer media that are looped between the receiver and a heat exchanger that transfers the heat into an industrial reactor. While this strategy may be simpler and enable less modification to industrial processes, it may lower both energetic and exergetic efficiency and increase capital costs relative to direct receivers.[11] In this RFI, SETO is interested in all potential pathways for solar-thermal integration with fuel production.

Direct Receivers and Receiver-Reactors

1. What strategies are available to design a direct receiver-reactor to operate both on-sun and off-sun, so that production can continue during times when the sun does not shine, either using stored thermal energy or alternative energy inputs?
2. What strategies and opportunities exist to optimize the controls and operation of a direct solar thermochemical receiver-reactor, considering the variability of the solar resource and the need to potentially control multiple inputs into the reactor, including solid or liquid reactant(s) and inert or reactive gases?
3. What are the limitations and availability of existing materials for use in high-temperature direct receiver-reactors? Limitations may include thermal, mechanical, and chemical (corrosion) risks, as well as cost, to the extent that it is known. Specifics regarding the relevant environmental conditions and process characteristics are pertinent.
4. What opportunities exist for using existing reactors and operational/development strategies in reactor design for use in receiver-reactors and indirectly heated reactors without the need for costly development and testing of solar-thermal reactors?
5. Direct concentrated solar heating of particle media can create uneven temperature distributions, which can cause some particles to sinter. Fluidized bed receivers and reactors have been proposed to assist with homogenous heat transfer. What design improvements are feasible and what challenges are expected in fluidized bed on-sun receiver-reactors and fluidized bed reactors heated by TES systems?

Category D: TES for CSP and solar-driven industrial processes.

1. The variability inherent in solar energy – on seasonal, diurnal, and shorter timescales – is at odds with the 24-hour operations typically required for power generation and commodity

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[11] Due to the fewer process steps that direct heating may enable.

production facilities. The current goal of DOE research is to enable TES for CSP plants to achieve 15 $/kWth-hr.[12]

2. Current power tower CSP facilities make use of nitrate salts for 550°C steam generation. Nitrate salt TES is held into two tanks, cold salt at 290°C and hot salt at 570°C. Stainless steel tanks holding hot nitrate salt have faced various structural issues. Do opportunities exist to redesign the hot tank which can significantly improve reliability?
3. Gen3 CSP facilities are likely to use particles as TES with bins for storage. The cost of particles and storage bins/elevators have a significant impact on total plant cost. What improvements in particle design and cost can make particle TES meet the DOE cost goals?
4. Sensible heat TES using two tank systems have been studied extensively. Do further development opportunities exist to enable sensible TES to achieve the DOE goals?
5. Latent heat thermal energy storage has been extensively studied. In embodiments where a phase change media is encapsulated, the cost of heat exchange integration prevents these systems from achieving DOE's cost goals. What innovations using latent heat thermal energy storage are feasible that will allow integration with solar energy and a power cycle? What options exist for scaleup to plant sizes? What methods exist for cost reduction? Do opportunities exist to integrate latent TES with sensible systems to improve temperature control?
6. Thermochemical energy storage (TCES) has been widely studied under DOE funding, but like latent heat storage, attaining cost targets have been difficult. In addition, scaleup to reasonable sizes have been difficult. Issues related to heat exchanger sizing, storage of products/reactants at temperatures lead to price escalation. What opportunities exist to improve CSP or CST systems with TCES? What existing TCES hold the most promise for further advancement? What challenges remain for any specified opportunities?
7. Rock bed thermal energy storage systems have the potential to attain the DOE cost goals. However, they suffer from thermocline issues and little control of outlet temperature during discharge has been difficult. DOE has funded methods of improvement including radial beds, thermosiphon control using withdrawal. What opportunities exist for thermosiphon control to regulate temperature output in rock beds?
8. What opportunities exist to cost effectively integrate thermal energy storage with industrial applications and with solar fuel production? What cost targets and technical targets are applicable for research into such an integration?

Request for Information Response Guidelines

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[12] The SunShot Initiative's 2030 Goal: 3¢ per Kilowatt Hour for Solar Electricity. United States: N. p., 2016. https://www.osti.gov/servlets/purl/1344203

Responses to this RFI must be submitted electronically to SETO.RFI.CSP@ee.doe.gov no later than 5:00pm (ET) on April 14, 2023. Responses must be provided as attachments to an email. It is recommended that attachments with file sizes exceeding 25MB be compressed (i.e., zipped) to ensure message delivery. Responses must be provided as a Microsoft Word (.docx) attachment to the email. Only electronic responses will be accepted.

Please identify your answers by responding to a specific question or topic if applicable. Respondents may answer as many or as few questions as they wish.

EERE will not respond to individual submissions or publish publicly a compendium of responses. A response to this RFI will not be viewed as a binding commitment to develop or pursue the project or ideas discussed.

Respondents are requested to provide the following information at the start of their response to this RFI:

- Company / institution name;
- Company / institution contact;
- Contact's address, phone number, and e-mail address.

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