HEATS Program Overview

B. PROGRAM OVERVIEW

Thermal energy transport and conversion play a very significant role in more than 90% of energy technologies. More than 60% of all primary energy consumption in the United States is currently wasted in the form of thermal energy. Thermal energy storage can significantly enable reuse of wasted energy and enhance the efficiency of energy delivery and consumption. Thermal storage - both hot and cold - can be employed for a variety of critical energy applications. This ARPA-E Funding Opportunity aims to support the development of novel, advanced thermal energy storage technologies to enable the following transformative energy solutions:

- Next generation non-intermittent and cost-competitive solar thermal power plants.
- Advanced nuclear power plants which can supply peaking power capability on the grid
- Production of fuel using thermochemical reactions to store solar energy in chemical form
- Novel Electric Vehicle HVAC systems with dramatic improvements in driving range.

POTENTIAL NEW MATERIALS AND SYSTEMS FOR THERMAL STORAGE INNOVATIONS

ARPA-E is interested in all forms of thermal storage such as sensible heating, phase change, super-critical systems and thermochemical storage. With significant advancements in new materials in the past such as metal-organic-frameworks (MOFs)[1], ionic liquids[2], catalyzed decomposition reactions, high temperature composites and system design, it may be possible to develop highly efficient high temperature thermal storage system.

ARPA-E has significant interest in advancing the state of the art in thermophysical thermal storage technology. There have been significant advances in the field of material science with impacts on applications ranging from carbon capture[3] to high temperature rocket engines[4]. Some of these advances may be applied to thermal energy storage either in the direct thermophysical storage material or in the balance of systems. Examples include new developments in the properties of ionic liquids or molten salts, which can be designed to be used as high energy density thermal storage material for both sensible or phase change storage[5]. Nanotechnology can also potentially enable advanced thermal energy storage. For example some recent results suggest that mixing nanoparticles in liquids can anomalously enhance specific heat[6]. Alternative thermal storage mechanisms also merit renewed exploration with recent materials advances. For instance, adsorption/absorption based thermal storage may benefit from developments in ionic liquids, new sobents and MOFs, whose binding energy with a gas can be tuned based on recent advances in synthetic chemistry. Beyond the active thermal storage medium, recent developments may present an opportunity for relaxed constraints in system design. Supercritical fluidic system have the potential to be cheap storage materials due to their higher energy density, but the pressure vessel required for the supercritical system represents a significant added cost. Advancement in cheaper materials to be used as pressure vessels may thus enable supercritical thermophysical systems. Finally, cost

[1] O. Yaghi et al. Science, 2008, 319, 939-943
[2] J. Brennecke et al. J. Am. Chem. Soc., 2010, 132, 2116–2117
[3] J. Anthony et al., Int. Journal of Environmental Technology and Management, 2004, 4, 105 - 115
[4] D. Marshall, and Brian Cox, Annual Rev. of Materials Research, 2008, 38, 425- 443
[5] B. Wu et al, Proceedings of Solar Forum 2001, Solar Energy: The Power to Choose, April 21-25, 2001, Washington, DC
[6] D. Shin and D. Banerjee, J. of Heat Transfer, 2011, 133, 24501

effective thermal storage can also be enabled by better system design, for instance by eliminating heat exchangers between the storage medium and charging systems.

ARPA-E also has significant interest in developing insulation free thermal storage which can be enabled by thermochemical storage. Although there have been some investigations in the literature on thermochemical systems, several issues have limited the technological applications. The potential benefits of these thermochemical storage technologies include the ability to store heat for a variable, controllable period of time and to control the rate of charging or discharging reactions using catalysts. Some thermochemical storage systems have been proposed in the past using endothermic decomposition reactions such as[7] $CaCO_3 \Leftrightarrow CaO + CO_2$. However, the volumetric energy densities of these thermochemical storage systems are low because at least one component in the reaction, in this case CO_2, is a gaseous state. The energy density of these systems can be increased by storing the gases at a higher density using new materials such as ionic liquids of metal-organic-frameworks (MOFs). Additionally, to maintain an acceptable energy density per unit mass (MJ/kg), the storage materials must have a moderate molecular weight.

Alternatively, the energy density of thermochemical storage systems can be increased by using reactions of the form $AB \Leftrightarrow A+B$ that are exclusively in the condensed phase. Like the storage technologies discussed above, the molecular weight of these components should be low enough to maintain an acceptable energy density per unit mass. Some reactions that could be used to meet these metrics include organic reverse Diels-Alder[8]/sigmatropic[9], disproportionation[10] and depolymerization[11] reactions. These are common reactions in synthetic organic chemistry, but have never been applied to thermal storage technologies. For any of these reactions, and others, energy costs associated with separating the two product components (A and B) must be accounted for. Additionally, there is interest in developing catalysts that can be used to control the rate of the charging and discharging thermal storage reactions.

THERMAL STORAGE FOR NEXT-GENERATION NON-INTERMITTENT AND COST-COMPETITIVE SOLAR THERMAL POWER PLANTS

Thermal energy storage (TES) can significantly increase the capacity factor of concentrated solar thermal power plants, from ~30% to greater than 60% which in turn can reduce the levelized cost of electricity (LCOE) produced. The concentrated solar power (CSP) program in DOE's EERE program has significantly advanced the technology of thermal storage for CSP by funding multiple programs on a variety of materials and systems, most notably molten salts. These programs have established a critical base of knowledge and significantly increased the understanding of solar thermal storage; but, nearly all work to date has focused on storage compatible with traditional parabolic trough systems, which operate at temperatures less than 500 ^{o}C. The Sunshot program that leverages the technical expertise across DOE has now established an aggressive target LCOE for solar-based electricity of 5-6 cents/kWh by 2017 so that solar electricity can scale without subsidies, while making US globally competitive. It is increasingly clear that traditional parabolic trough systems will struggle to reach these aggressive targets due to efficiency limits at low temperatures. As such, a new generation of solar thermal technologies is in development, providing higher efficiency by greater concentration and higher operating temperatures. To accommodate this next generation of technology, and achieve the goal of low cost, dispatchable solar energy, there is a strong need for novel thermal storage solutions operating at much higher temperatures than previously investigated.

[7] G. Ervin, Journal of Solid State Chemistry, 1977, 22, 51-61
[8] H. Kwart et al. Chem. Rev., 1968, 68 (4), pp 415–447
[9] Hoffmann R. Acc. Chem. Res., 1968, 1 (1), pp 17–22
[10] Swain et al., J.Am Chem. Soc., 1979, 101,3576-3583
[11] Duda and Penczek, Macromolecules 1990, 23, 1636-1639

THERMAL STORAGE FOR ADVANCED NUCLEAR POWER PLANTS THAT CAN SUPPLY PEAKING POWER CAPABILITY ON THE GRID

Existing nuclear power plants operate free of greenhouse gas emissions, but are used exclusively for providing base load power. In contrast, peaking plants, primarily based on fossil fuels, are responsible for significant CO_2 emissions due to their poor efficiency. As sources of clean electricity generation (based on various technologies such as solar, wind, hydro, and nuclear) become more prevalent, there is a strong need for emission-free on-demand peaking capability to ensure a clean, efficient, and secure power grid. Thermal storage can enable the use of nuclear power plants for providing peaking power by storing part of the thermal energy from the nuclear reactor to subsequently run a thermodynamic cycle, such as the Brayton cycle, for power generation. While current generation light water nuclear reactors work at temperatures less than 300 ^oC, Gen IV advanced reactors[12] are being planned for temperatures higher than 700 ^oC. Given similar output temperatures, there are significant synergies in developing high temperature thermal storage for enhanced dispatchability of both CSP and nuclear power. The nuclear industry is exploring various power generation technology such as those based on He and supercritical CO_2 cycles[13] for high temperature generation. If CSP is pushed to high temperatures the power generation technologies being developed for nuclear industry can also be used for CSP. Some discussions on this already exist in the literature[14].

PRODUCTION OF FUEL USING THERMOCHEMICAL REACTIONS THAT STORE SOLAR ENERGY IN CHEMICAL FORM

Production of fuel from sunlight is also a form of energy storage. In this case, thermal energy is stored in the form of chemical bonds. ARPA-E, other parts of DOE and other Federal funding agencies have significantly funded research and development of a wide range of methods for producing fuel from sunlight including traditional approaches to biofuel and biomass production and the direct fuel production by chemical and biological catalysts [15]. On the other hand thermochemical production of fuel from sunlight, where solar energy is used to produce heat to break chemical bonds, has not been investigated to the same extent. The theoretical efficiency of thermochemical production of fuel from sunlight is very high and limited primarily by the collector efficiency[16]. Recent reports[16] suggest that due to significant improvement in a two-step solid-state catalytic process it's possible to generate syngas by thermolysis of CO_2 and H_2O with high efficiency. The efficiency of this process can be further increased by improved reactor design and heat harvesting and recycling. This discovery and other recent developments suggest that there is a renewed opportunity to develop high efficiency thermochemical routes to solar fuels. Moreover, because thermolysis requires very high temperatures, the development of high temperature thermal storage systems can benefit from the significant synergies between thermochemical production of fuel and thermoelectrical systems for production of electricity.

THERMAL STORAGE FOR NOVEL ELECTRIC VEHICLE HVAC SYSTEMS WITH DRAMATIC IMPROVEMENTS IN DRIVING RANGE

While the above applications relate to large scale, high temperature thermal energy storage systems, there is separately a strong need for advances in modular, high energy density thermal energy storage. Such systems could have a dramatic impact in next-generation HVAC (Heating Ventilation Air Conditioning) systems for plug in hybrid electric vehicles (PHEV)

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[12] C. Oh et al, Development of a Supercritical Carbon Dioxide Brayton Cycle: Improving PBR Efficiency and Testing Material Compatibility Project Number: 02-190Nuclear Energy Research Initiative
for October 2004 to September 2004, Idaho National Lab, INEEL/EXT-04-02437
[13] V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, March 10, 2004
[14] C. Turchi, Proceedings of SCCO2 Power Cycle Symposium 2009, RPI, Troy, NY, April 29-30, 2009
[15] http://www.science.doe.gov/bes/Hubs/JCAP_Tech_Summary.pdf
[16] T. Kodama and N. Gokon, Chemical Review, 2007, 107, 4048 - 4077

and electric vehicles (EV). In today's electric vehicles both cabin cooling and heating loads must be provided by the electrical energy stored in a battery whose capacity determines the range of the vehicle. These cabin HVAC loads can be significant relative to the powertrain load, and in some cases can cause reduction in EV range by as much as 40%[17]. An advanced Thermal Energy Storage system that provides heating and cooling to the vehicle cabin can reduce or eliminate the added load on the electrical storage system, and thereby significantly increase the range of next generation EVs with little or no added cost or packaging. The TES solution will ideally be a single system that can provide both cooling and heating at minimal cost, weight and volume when compared with the vapor compression based air conditioners and resistive heaters currently in use. If successfully developed modular thermal-storage based HVAC systems could have a broad energy impact beyond the automotive sector. For instance, coupled to combined heat and power systems or as a novel solution for distributed, location-specific building HVAC that can rely on off-peak power while delivering heating and cooling during peak hours.

1. PROGRAM OBJECTIVES

The focus of this FOA is to develop revolutionary, cost effective thermal storage systems for:

1) Large scale, high temperature systems for high efficiency, non-intermittent CSP and zero-emission peaking power from nuclear energy
2) Thermochemical production of fuel from sunlight
3) Small scale, high-density thermal storage based HVAC systems for range-enhanced Electric Vehicles

2. AREAS OF INTEREST

Areas of Particular Interest:

Area of Interest 1: Utility scale thermal storage for next-generation CSP and Nuclear power generation with storage temperatures greater than 600^{o}C

ARPA-E seeks innovative applications in the area of high-temperature storage for both CSP and nuclear applications. As described above, advanced CSP and Nuclear reactor designs suggest a strong and urgent need to develop thermal storage at higher temperatures than previously investigated. Internal research by ARPA-E and the CSP program of EERE, along with information gathered through focused workshops, suggests that in order to achieve an LCOE of ≤ 6 cents/kWh for CSP electricity generation, systems must be operated at temperatures higher than roughly 600 °C. Storage at similar temperatures would also open an entirely new opportunity to extract green house gas emission-free peak power capabilities from next-generation nuclear plants.

In developing thermal storage technologies, round-trip energy efficiency is often cited as a key metric of performance; however, it is in fact most critical that *exergetic* efficiency be very high to ensure that heat quality is maintained after storage. Therefore the primary technology target specification for this focus area is based on round-trip exergetic efficiency. Figure (1) shows for sake of illustration a generic sensible heating thermal storage system – note that other systems are possible and applicants are highly encouraged to look into alternative approaches including chemical and physio-chemical means of storage.
Exergy transfer is given by:

[17] R. Barnitt, A. Brooker, L. Ramroth, J. Rugh, and K. Smith, "Analysis of Off-Board Powered Thermal Preconditioning in Electric Drive Vehicles," Presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition Shenzhen, China November 5 – 9, 2010, NREL/CP-5400-49252 ,December 2010

$$\Delta G = \Delta H - T_{amb}\Delta s \quad (1)$$

Where ΔG is the exergy transfer, ΔH the change in enthalpy, Δs the change in entropy and T_{amb} is the ambient temperature. T_{amb} should be assumed to be 300 K (27 ^{o}C) in evaluating the roundtrip efficiency. Round trip exergetic efficiency (ε) of the storage is defined by:

$$\varepsilon = \left|\frac{\Delta G_d}{\Delta G_c}\right| = \left|\frac{(\Delta H - T_{amb}\Delta s)_d}{(\Delta H - T_{amb}\Delta s)_c}\right| \quad (2)$$

Where subscripts *c* and *d* refer to charging and discharging of thermal storage respectively. For example for the system shown in Figure (1), Eq. (2) for incompressible substance reduces to

$$\varepsilon = \left|\frac{\Delta G_d}{\Delta G_c}\right| = \left|\frac{(\Delta H - T_{amb}\Delta s)_d}{(\Delta H - T_{amb}\Delta s)_c}\right| = \left|\frac{\int_{T_{di}}^{T_{do}} c_p(T)dT - T_{amb}\int_{T_{di}}^{T_{do}} \frac{c_p(T)dT}{T}}{\int_{T_{ci}}^{T_{co}} c_p(T)dT - T_{amb}\int_{T_{ci}}^{T_{co}} \frac{c_p(T)dT}{T}}\right| \quad (3)$$

where c_p is the specific heat. Note that absolute value is used in Eq. (3) because exergy transfer from the charging fluid is negative in the charging stage and positive in the discharging stage.

It is to be noted that Figure (1) is one possible embodiment of thermal storage based on sensible heating concept, however it is expected that there are multiple other schemes possible where charging/discharging of the storage may take place at constant temperature. Therefore, applicants are expected to use the generic Eq. (2) for deriving the exergetic efficiency of their system. In the application, applicants are required to clearly show the exergy formula based on Eq. (2) for their system to evaluate the exergetic efficiency of the storage systems. The main area of interest is for storage systems that can enable the downstream power plant to operate at temperatures greater than 600 ^{o}C. Therefore, for this area of interest only solutions that can accommodate downstream operating temperature greater than 600 ^{o}C will be entertained.

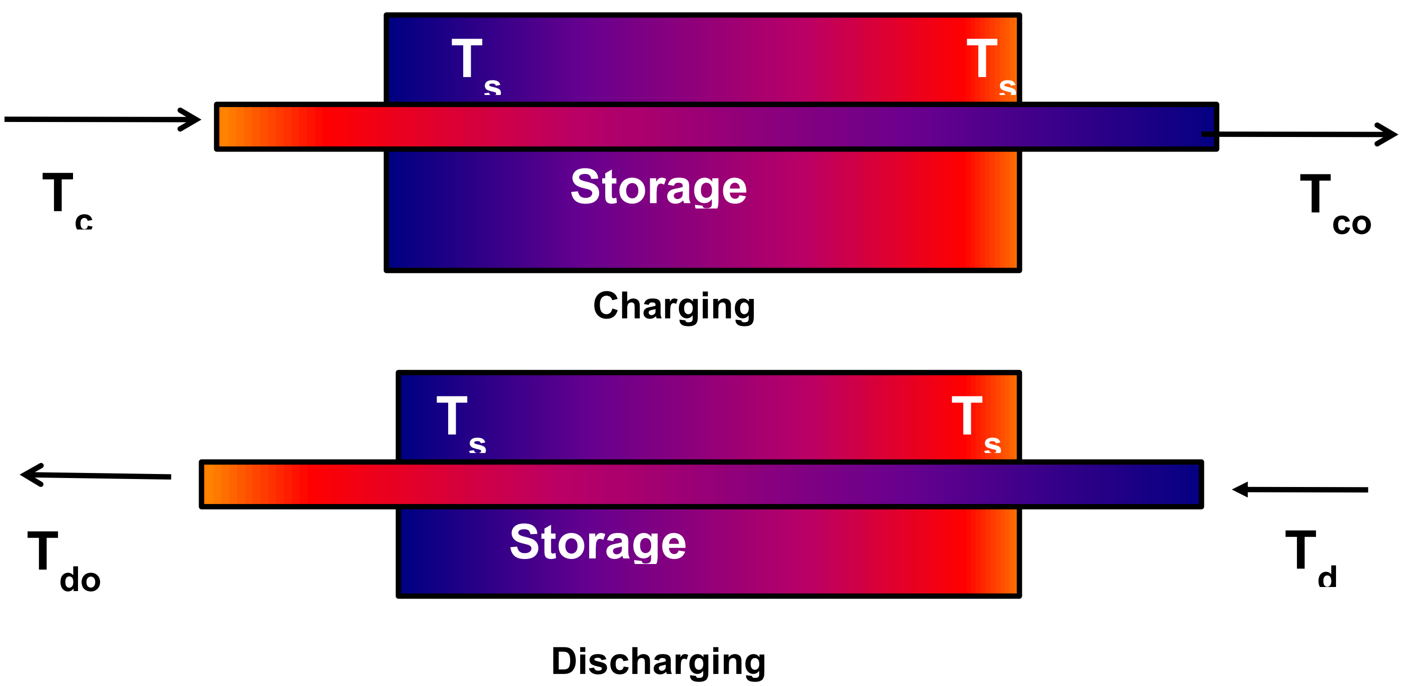

Figure 1: *A schematic demonstrating the charging and discharging of thermal storage system. Note that this is for illustration purposes only. Other embodiments of thermal storage are also possible and the general Eq. (2) should be used for other embodiments to evaluate the exergetic efficiency. It is expected that applicants will provide the right equation based on Eq. (2) for their specific idea. In this figure T denotes the temperature, i, o, c, and d in the subscript denote inlet, outlet, charging and discharging respectively, sl and sh in the subscript denote lower and higher temperature of the storage media respectively.*

An ideal team for addressing this area of interest would comprise of materials, chemical, thermal, and/or mechanical engineers/scientists as well as individuals or organizations with expert knowledge of CSP or Nuclear power plant design and operation. It's important that the team should have expertise in every aspect of the system including a solid understanding of CSP and/or nuclear systems.

The technology target specification for this area of interest is given in Section I.B.4 a and b. Proposed technology development plans must have well justified, realistic potential to meet or exceed the stated "Primary Technology Target Specification" by the end of the period of performance of the proposed project in order to be considered for award. Proposed technologies will secondarily be evaluated against their well-justified, realistic potential to approach the "Secondary Technology Target Specification" by the end of the period of performance of the proposed project. Proposed technologies will still be considered for award if they fall short of one or more of the Secondary Technical Targets below, but will be evaluated and compared to one another according to their strengths and weaknesses in addressing these targets. For purpose of target evaluation, the storage system is intended to describe the full system i.e. it includes all components such as charging and discharging devices, pumps, storage containers, insulation, and storage material. While the application should focus on the thermal storage solution, applicants are expected to understand and describe the imagined use-case for thermal storage in CSP and/or Nuclear applications, and should consider integration with both the heat source and down-stream power generation mechanism. For example, applications should indicate the type of power block system that would be expected to be used for the CSP or the nuclear system (e.g. supercritical steam plant vs. supercritical CO_2 cycle, etc.). *Any parasitic load in the system such as the power consumed by the pumps should be clearly stated in the application.*

Area of Interest 2: Thermochemical production of fuel from sunlight

Thermochemical production of fuel provides a possible pathway to produce fuel from solar energy. However, demonstrated efficiency is less than 1 %[18] whereas theoretical efficiency can be significantly higher than 10%[16]. ARPA-E is interested in developing thermochemical method to produce chemical fuels from sunlight. The solar-to-fuel conversion efficiency is given by

$$\eta = \frac{r_{fuel}\Delta H_{fuel}}{p_{solar}+p_{parasitic}} \qquad (4)$$

where r_{fuel} is the molar fuel production rate, ΔH_{fuel} is the higher heating value of the fuel, p_{solar} is the incident solar radiation power and $p_{parasitic}$ is any parasitic power used in the system. The technology target specification for this area of interest is given in Section I.B.4 c. It is expected that for this area of interest applicants will develop a prototype reactor which can reach the high temperature needed for thermochemical production of fuel.

Ideal team for this area of interest should comprise of materials, chemical, thermal, mechanical engineers/scientists. It's important that the team should have expertise in every aspect of the system and good understanding of solar energy collection, and reactor design. Teams should demonstrate and articulate a strong understanding of the practical use-case for the proposed fuel cycle, including both commercial and operational merits and limitations.

[18] W. Chueh, Science, 330, 2010, 1797

Area of Interest 3: High density thermal storage to provide heating and cooling for Electric Vehicles

Electric battery capacity and cost represent the highest barriers to wide scale adoption of electric vehicles as the large and expensive batteries needed to provide significant driving range can result in unattractive vehicle design and price-points. A key drain on the electrical battery system of an Electric Vehicle is the need to serve cabin heating and cooling loads. To make matters worse, today's EVs generally use electric battery capacity for highly inefficient resistive heating as opposed to internal-combustion vehicles, which simply route waste engine heat to the cabin. In general, Cabin Climate conditioning can significantly reduce the electric range of plug-in and full Electric Vehicles, by as much as 40% in extreme cases[20], or inversely can increase the battery size and cost by a comparable amount for the same range.

Significant reduction in size/cost of EV batteries or significant increase in driving range can be enabled by eliminating the need for cabin climate load to draw on the electrical battery system. ARPA-E has significant interest in developing thermal battery technology that can provide both cooling and heating to the vehicle cabin, freeing critical electrical battery capacity for driving loads. Today's thermal storage solutions are already lower cost than electrical energy storage systems, at comparable energy densities. If the design and energy density of thermal battery systems can be improved, then an ancillary thermal battery could supply cabin climate loads without introducing significant additional space or volume to the vehicle. In today's vehicles, heating and cooling systems must be sized to meet peak demand while most normal operation is to serve a much lower steady state load. In the ideal case, the space occupied by thermal battery for partial heating and cooling would be equivalent to the total space saved by downsizing or eliminating the existing vapor compression cooling system and the existing heating system in PHEVs and EVs. In that case, cost effective climate control can be achieved with no tradeoff in vehicle design performance. In the typical use case, such a thermal battery would simply be charged upon plug-in, in tandem with the electrical battery being charged.

Most vehicles will require some level of heating/cooling capabilities once the thermal battery is depleted. As such, we envision hybrid HVAC solutions in which a thermal battery can deliver some portion of the peak cooling/heating power, but a minimal level of active HVAC is available on demand from the electrical battery. Various hybrid systems are possible. For example, intelligent systems can be designed where in case of emergency the on-board charging system for the thermal battery can be directly used for cooling/heating by deriving energy from the electrical battery. Figure 2 shows one particular embodiment of this concept however applicants are highly encouraged to provide other system designs and concepts. Furthermore, this system can also provide thermal management of the electrical battery pack which is very important for reliable operation of the electrical battery[20].

Although preference will be given to systems that can provide both heating and cooling, new concepts that represent significant energy density advances in either cold or hot storage materials will be also entertained. It is expected that the proposed solution will be a self-contained system which includes both on-board charging and discharging devices for the thermal battery as well as mechanism for deploying the thermal energy (e.g. fans, etc.). ARPA-E seeks highly innovative applications in this area.

The technology target specification for this area of interest is given in Section I.B.4 d and e. Proposed technology development plans must have well justified, realistic potential to meet or exceed the stated "Primary Technology Target Specification" by the end of the period of performance of the proposed project in order to be considered for award. Proposed technologies will secondarily be evaluated against their well-justified, realistic potential to approach the "Secondary Technology Target Specification" by the end of the period of performance of the proposed project. Proposed technologies will still be considered for award if they fall short of one or more of the Secondary Technical Targets below, but will be evaluated and compared to one another according to their ability to address these targets. For purpose of target evaluation, the storage system is intended to describe the full system i.e. it includes all components such as charging and discharging devices, pumps, storage container, insulation, and storage material.

An ideal team for this area of interest should comprise materials, thermal, mechanical and automotive engineers/scientists. It's important that the team should include expertise in every aspect of the system and good understanding of automotive HVAC systems. Space is a big constraint in automobile, and while total volume of the system is specified in the specifications it is expected that different components will be distributed throughout the vehicle as is the practice today. Therefore it is important to have an automotive expert in the team who is familiar with integration and space challenges in automobiles.

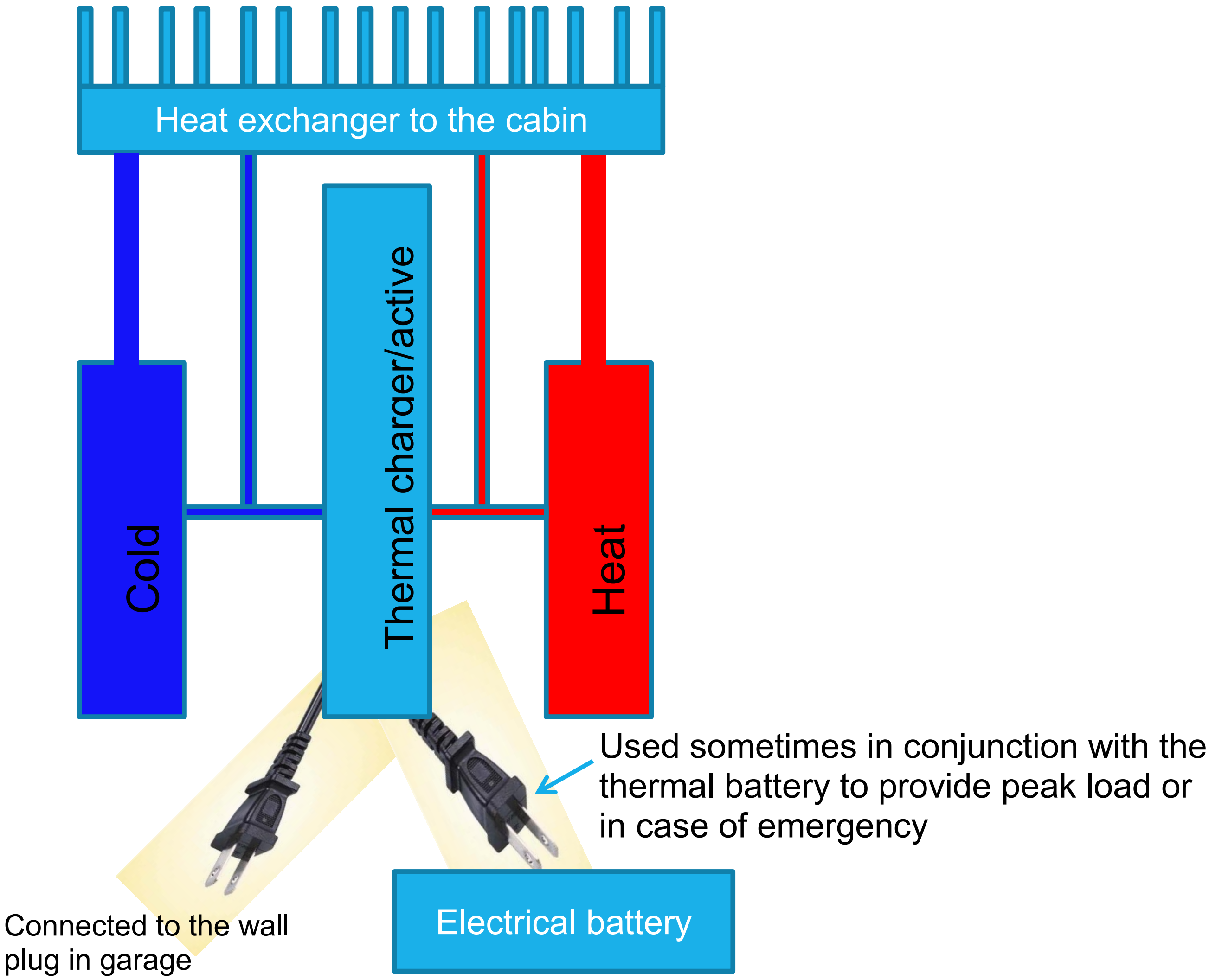

Figure 2: *A schematic demonstrating the concept of hybrid cabin climate control system*

Area of Interest 4 Seedling / Proof of concept for partial solutions or very novel, unexplored thermal storage concepts

ARPA-E recognizes that there may be new high-impact ideas related to the Areas of Interest above for which a novel thermal storage concept has been envisioned, but the concept has not yet been proven. In these cases, developing a system with the full specifications given in Areas of Interest 1 through 3 may not be realistic due to limitations in scale. For instance, a candidate may be interested in developing a very novel new material or approach for high-temperature CSP storage, but may not expect to be able to demonstrate that concept at >30kWh$_t$ scale. For such unproven and yet promising ideas, ARPA-E seeks small seedling applications to conduct experiments to achieve a proof of concept. In this case, the proof-of-concept experiments must be designed in a way that the results obtained suggest possible paths to approach the full system level specifications given in one of the areas discussed above.

- **Areas Specifically Not of Interest:**
  - Incremental improvements to, or combinations of, existing products and technologies, wherein no significant advances in understanding or reductions in technical uncertainty are achieved; and
  - Demonstration projects that do not involve a significant degree of technical risk.

Any Concept Papers or Full Applications that focus on "Areas Specifically Not of Interest" will be rejected as nonresponsive and will not be reviewed or considered.

1. TECHNICAL PERFORMANCE TARGETS

Applications will not be considered for funding unless they have a well-justified, realistic potential to meet or exceed all of the Primary Technical Targets by the end of the period of performance for the proposed project.

Applications will receive favorable consideration if they meet or exceed at least one of the Secondary Technical Targets. Preference will be given to applications that have a well-justified, realistic potential to meet or exceed most, if not all, of the Secondary Technical Targets.

The Primary Technical Targets and Secondary Technical Targets for **utility scale electricity generation from solar or nuclear source** are stated below:

A. PRIMARY TECHNICAL TARGETS FOR UTILITY SCALE ELECTRICTIY GENERATION FROM SOLAR OR NUCLEAR SOURCE

ID Number	Category	Value (Units)
1.1.1	Temperature for power generation in the down-stream power cycle	$\geq 600\ ^{o}$C
1.1.2	Exergetic efficiency (Eq. 2)	$\geq 95\%$
1.1.3	Charging time for storage	≤ 6 hours for full charge
1.1.4	Stored energy for Technology demonstration	≥ 30 kWh_t * (Minimum capacity to deliver 6 hours of stored energy at peak thermal power)
1.1.5	Technology demonstration	Peak delivered thermal power from storage ≥ 5 kW_t*

(See Section I.B.3 for details on Area of Interest 1 to which these Primary Targets apply)

* Note that subscript **t** denotes thermal.

B. SECONDARY TECHNICAL TARGETS FOR UTILITY SCALE ELECTRICITY GENERATION FROM SOLAR OR NUCLEAR SOURCE

ID Number	Category	Value (Units)
1.2.1	Cost of storage system including charging and discharging devices	$\leq \$15/\mathrm{kWh_t}$
1.2.2	Volumetric energy density	$\geq 25\ kWh_t/m^3$
1.2.3	Operational Lifetime	20+ years, 10,000+ cycles

(See Section I.B.3 for details on Area of Interest 1 to which these Secondary Targets apply)

The Primary Technical Targets for **solar thermochemical fuel generation** are stated below:

C. PRIMARY TECHNICAL TARGETS FOR SOLAR THERMOCHEMICAL FUEL GENERATION

ID Number	Category	Value (Units)
2.1.1	Solar-to-fuel efficiency (Eq. 4)	$\geq 10\%$
2.1.2	Highest temperature in the system	$\leq 1500\ ^{o}C$

(See Section I.B.3 for details on Area of Interest 2 to which these Primary Targets apply)

The Primary Technical Targets and Secondary Technical Targets for **climate control thermal battery for EVs and PHEVs** are stated below:

D. PRIMARY TECHNICAL TARGETS FOR CLIMATE CONTROL THERMAL BATTERY FOR EVS AND PHEVS

ID Number	Category	Value (Units)
3.1.1	Air temperature delivered to the cabin for heating	40 – 60 ^{o}C
3.1.2	Air temperature delivered to the cabin for cooling	3 – 10 ^{o}C
3.1.3	Maximum air delivery flow volume	675 m^3/hr
3.1.4	Minimum power capability of thermal battery (storage)	Cooling – 2.5 kW_t* Heating – 2.5 kW_t
3.1.5	Minimum capacity of thermal battery (storage)	Cooling – 2.5 kWh_t* Heating – 2.5 kWh_t
3.1.6	Minimum active power capability from electrical battery (must be available on demand at any time)	Cooling - 2.5 kW_t * Heating – 2.5 kW_t
3.1.7	Maximum System Volume (including active component(s), thermal charger, thermal batteries (storage)(s), blower(s), and any other components)	30 Liters
3.1.8	Charging time	<=4 hrs
3.1.9	Self discharge allowance	<10% per day

(See Section I.B.3 for details on Area of Interest 3 to which these Primary Targets apply)

* Note that subscript **t** denotes thermal.

E. SECONDARY TECHNICAL TARGETS FOR CLIMATE CONTROL THERMAL BATTERY FOR EVS AND PHEVS

ID Number	Category	Value (Units)
3.2.1	Coefficient of performance (COP)	>2 for **cooling** (assuming 38 ^{o}C ambient temperature and 10 ^{o}C delivered air temperature > 1.5 for **heating** (assuming 0 ^{o}C ambient temperature and 40 ^{o}C delivered air temperature)
3.2.2	Total weight of the system	< 35 kg
3.2.3	Manufacturing cost of the whole system	< $250/kW
3.2.4	Lifetime	10 years, 5000 on/off cycles

(See Section I.B.3 for details on Area of Interest 3 to which these Secondary Targets apply)