CHANGING WHAT'S POSSIBLE

ARID Program Overview

B. PROGRAM OVERVIEW

The interdependency between water and energy, commonly known as the "water-energy nexus," has many facets, but perhaps none is so easily described as the use of water in the generation of electricity. The U.S. electric power industry has relied primarily on water cooling technologies to remove low grade heat from thermoelectric power plants. Of these technologies, cooling towers and spray ponds dissipate a substantial amount of water into the atmosphere via evaporation. It is anticipated that within a 20 year time horizon a combination of environmental concerns, increased water demand due to population growth, and the impact of climate change will significantly constrain the available water supply that can be allocated to power plant cooling. It is also anticipated that smaller scale distributed electric power generation will continue to penetrate the market, including in regions where water cooling for low-grade heat removal is not feasible.[1]

This program seeks to fund transformative new power plant cooling technologies that enable high thermal-to-electric energy conversion efficiency with zero net water dissipation to the atmosphere. Of particular interest to this program are technologies that incorporate air cooling, sorption-based cooling, multimode (convection/radiant) cooling, large capacity cool storage, or any other innovative heat rejection technology that addresses the programmatic goals. Successful technologies emerging from this program will enable continued reliable and efficient domestic electric power production, independent of population growth and climatic variations and with minimal impact on the aquatic environment. Market penetration of these technologies will significantly reduce the risk of lost thermoelectric power production. This program aims to bridge the gap between fundamental scientific advances, such as those arising from the NSF Thermal Transport Processes Program[2], ONR Ship Systems and Engineering Research Program (Thermal Energy Management)[3], and the NSF/EPRI Advanced Dry Cooling for Power Plants program[4], and technology that will have a transformative impact in dry-cooling of power plants.

1. Wet Cooling

Fresh water withdrawal for thermoelectric power generation in the U.S. is approximately 139 billion gallons per day (BGD), or 41% of all fresh water withdrawal, making it the largest single use of fresh water in the U.S.[5,6] For perspective, this is equivalent to filling 10,000 Olympic sized swimming pools every hour. Of the fresh water withdrawn for the thermoelectric sector, 4.3 BGD was dissipated to the atmosphere by cooling towers and spray ponds.[5] This consumed water is then unavailable to the local environment for other important uses[6]; for example, this amount of water could be used to produce 17.4 million tons of potatoes[7], approximately the annual U.S. potato yield[8] (the potato is a staple crop grown worldwide, thus motivating the comparison).

The average energy conversion efficiency of a power plant ranges from about 35–55%[9] using water cooling strategies. Plants that produce hundreds of megawatts of electricity must also dissipate hundreds of megawatts of low-grade waste heat. The temperature at which this heat is rejected to the environment directly impacts energy conversion efficiency; heat rejection at a lower temperature increases the net power production and energy efficiency. A lower cooling water temperature allows for a lower steam condensation pressure in a steam Rankine cycle[10], reducing the backpressure on the turbine outlet and allowing for more power to be extracted by the turbine. A 3°C rise in the steam condensation temperature is estimated to result in about a 1% reduction in power production from the turbine.[11]

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[1] Owens, Brandon. "The Rise of Distributed Power". General Electric, 2014
[2] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13367
[3] http://www.onr.navy.mil/Science-Technology/Departments/Code-33/All-Programs/331-ship-systems-engineering.aspx
[4] NSF/EPRI Collaboration on "Water for Energy - Advanced Dry Cooling for Power Plants". Program Solicitation NSF 13-564, 2013
[5] U.S. Department of Energy. "The Water-Energy Nexus: Challenges and Opportunities". Jun 2014
[6] Williams E. D. and Simmons J. E. "Water in the energy industry". BP, 2013
[7] Assumes 287 m^3 water required per metric ton of potatoes produced.
[8] USDA National Agricultural Statistics Service. "National Statistics for Potatoes". USDA, 2013
[9] Calculated from heat rate values in Table 8.2 of "Assumptions to the Annual Energy Outlook 2014", U.S. Energy Information Administration. June 2014. [Available from: http://www.eia.gov/forecasts/aeo/assumptions/pdf/electricity.pdf]
[10] Moran, Michael J., et al. "Fundamentals of engineering thermodynamics". John Wiley & Sons, 2010.
[11] Stephens, Mark. "Keeping Customers Competitive & Productive with Energy Efficiency & Power Quality Solutions". EPRI, 2012

To adequately reject megawatts of low-grade heat from low pressure condensing steam, a massive cold sink is required. The two principle heat sinks historically used for heat rejection are large water bodies and atmospheric air. Water is favored because rivers, lakes, and oceans tend to be cooler than ambient air (resulting in higher energy conversion efficiency), have more uniform temperatures, and water enables higher heat flow rates through a given surface. Water-cooled condensers are considerably less expensive than air-cooled units owing to the high rate of convective heat transfer afforded by water flow. This is fundamentally due to the fact that the thermal conductivity of water is approximately twenty-fold that of air. The economic and energy conversion efficiency advantages afforded by water cooling have led to the current U.S. paradigm where 99% of base-load thermoelectric power plants are water cooled, while only 1% of power plants are air cooled. Wet-cooling systems include once-through configurations (43%), cooling towers (42%), and cooling ponds (14%).[12]

Once-through cooling systems are the most basic, but environmental regulations have made them increasingly less viable. The Clean Water Act[13] and its implementing regulations require limits on the effluent temperature discharged to local water bodies and require the "best available technology" be used to limit fish impingement at water intakes of power plant cooling systems.[14] Some states, like California, have decided to try phasing out once-through cooling altogether.[15] Similarly, in anticipation of recent updates to the Clean Water Act implementing regulations, recently proposed new power plants have focused on closed-cycle cooling rather than once-through cooling systems.[5, 16]

Cooling towers and spray ponds currently seem best equipped to address the effluent temperature limits set by environmental laws and regulations. As a result, many once-through cooling systems employ a cooling tower or spray pond on the backend to perform additional cooling before the effluent is released back to the initial source. Many cooling tower systems are also part of recirculating cooling systems in which the cooling water is continuously recirculated through a closed-loop cooling system. Both cooling towers and spray ponds take advantage of latent heat transport due to water evaporation and convective heat exchange with air. However, a significant amount of water consumption results through evaporation from cooling towers and cooling ponds.

The U.S. has had abundant fresh water resources and throughout the twentieth century evaporative cooling for thermoelectric power plants has been an acceptable practice. However, with growing population, industry, farming, aquaculture, drought, and changing precipitation patterns, several regions within the U.S. are beginning to experience fresh water as a limited resource. As the demand for fresh water approaches or exceeds supply, regions are becoming water stressed. States that have recently experienced significant water stress include California, Texas, and Florida. As a result, these regions have employed water conservation measures and have incorporated alternative water sources (reclaimed, treated, desalinated) into their supply. A study by the Electric Power Research Institute (EPRI) examined the impact of projected population growth on water availability across the United States and projected the water sustainability by county in 2030.[17] ARPA-E examined a list of water-cooled thermoelectric power production by county and cross-referenced it to the EPRI study. Assuming the status quo is maintained, it appears that by 2030, more than 3 Quads out of the 13 Quads (delivered) of U.S. electrical power production could be generated in counties that are at moderate to severe risk of water stress. This analysis did not include impacts of climate variability on water availability.

Uncertainty in future water supply and quality due to climate change adds further complexity in understanding the sustainability of water cooling thermoelectric power plants in many regions of the country. Northeastern University recently studied the impact of different climate change scenarios in combination with population growth on future water supply and demand. Details of this study can be found in the report made available as a supporting document to this FOA.[18] These results quantify the amount of future power production at risk due to water stress. The study found that with expected population growth (as set by projections from the U.S. Census Bureau) and the median result of an ensemble of climate change and environmental model combinations, about 4.5 Quads are currently produced in regions

[12] Report of Department of Energy, National Energy Technology Laboratory, "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements", DOE/NETL-400/2008/1339, 2008
[13] 33 U.S.C. § 1251, et. seq.
[14] e.g. 33 U.S.C. § 1326; See also, Environmental Protection Agency, *EPA Finalizes Standards to Protect Fish, Aquatic Life from Cooling Water Intakes* (News Release, May 2014).
[15] "Tracking Progress: Once-Through Cooling Phase-Out". California Energy Commission. August 2014. [http://www.energy.ca.gov/renewables/tracking_progress/documents/once_through_cooling.pdf]
[16] Office of Nuclear Energy, U.S. DOE, "Cooling water issues and opportunities at U.S. Nuclear Power Plants". at pg. ES-2, December 2010. pg. 70; [get second support citation from James]
[17] "Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005-2030)", EPRI Report 1023676
[18] Ganguli, P., Kumar, D., and Ganguly, A. R. "Water Stress on U.S. Power Production at Decadal Time Horizons". Sept. 2014

that will be water stressed in 2040. The most extreme scenario suggests that number could be as high as 9 Quads. Additionally, the results of this analysis suggest that there will be multiple regions where maximum stream temperatures approach the limits established as a result of the Clean Water Act regardless of the scenario considered. The combination of water stress and increasing water temperatures will likely interrupt power production, as it has before.[19,20]

Whether or not sufficient water resources will be widely available for continued cooling of future thermoelectric power production is uncertain at best. It is clear that development of cost competitive power plant cooling systems that do not rely on a continuous water supply will significantly add reliability to the U.S. thermoelectric power production infrastructure, as well as free up precious fresh water resources that can be utilized for other important uses. Moreover, distributed power generation deployment can be further enhanced since large bodies of water would not be required for cooling.

2. Dry Cooling

Dry-cooling systems installed at thermoelectric power plants are commonly classified as direct or indirect. Direct dry cooling utilizes a large standalone air-cooled condenser and is used as far north as Alaska and as far south as Southern California. Approximately 1% of thermoelectric power plants in the U.S. utilize air-cooled condensers.[4] Indirect dry cooling combines a water-cooled condenser with a convective air-cooled heat exchanger and water is continuously recirculated between the two in a closed loop. Indirect dry cooling is not common and there are no units in operation within the U.S.[21] In regions of the U.S. where water scarcity and environmental concerns make permitting for wet-cooled systems difficult there has been a recent trend toward dry-cooling systems.

With current technology, power producers are reluctant to use dry-cooling systems for two principle reasons: (1) the low air-side heat transfer coefficient necessitates massive heat exchangers that are costly and occupy a large land footprint and (2) air cooling imposes a performance penalty when ambient temperatures are high, as detailed below.

Challenge 1: Air-side heat transfer coefficient

The air-side convective heat transfer coefficient (10–100 W/m^2K) is roughly two orders of magnitude lower than that for water (1,000–10,000 W/m^2K), depending on the operating regime (laminar or turbulent). Therefore, an air-cooled system requires significantly more surface area and higher fan power compared to a wet-cooled system with the same heat rejection requirements. Both the capital and operating costs for an air-cooled condenser can each be 3.5 times of a comparable wet-cooled system carrying the same heat load.[22]

Challenge 2: Ambient dry bulb temperature and second law limitation

The dry bulb ambient air temperature and the second law of thermodynamics set the lower limit steam condensation temperature within an air-cooled condenser. In contrast, evaporative water cooling within a cooling tower utilizes latent heat transport (due to evaporation) to drop below the ambient air dry bulb temperature. The lower limit for evaporative cooling is the wet bulb temperature, which equals the dry bulb temperature only at 100% relative humidity (i.e. when the ambient air is fully saturated). Under all other conditions, water can evaporate into the ambient air and the wet bulb temperature is lower than the dry bulb temperature, by an average of 3–5°C.[23]

As a result of this fundamental thermodynamic limitation, the use of air-cooled condensers result in an average 2% loss of power output from the steam turbine compared to water-cooled operation.[22] Periodically, there are ambient temperature excursions that result in large differences between the wet and dry bulb temperatures. For such temperature excursions, there can be upwards of 10% reduced power production when using dry cooling.[4]

In addition to the two principle challenges with dry cooling cited above, there are other considerations such as wind loading, fan failure, fan noise, and leakage that impede adoption of dry-cooling systems. Due to increased capital and

[19] U.S. Department of Energy. "The Water-Energy Nexus: Challenges and Opportunities". pg. 1. Jun 2014
[20] US Department of Energy, "U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather", July 2013.
[21] "Assessment of Indirect Dry Cooling Systems". EPRI, July 2008.
[22] "Comparison of Alternate Cooling Technologies for U. S. Power Plants: Economic, Environmental, and Other Tradeoffs", EPRI, 2004.
[23] U.S. Environmental Protection Agency. "Technical Development Document for the Final Regulations Addressing Cooling Water Intake Structures for New Facilities". Docket No. EPA-821-R-01-036, Nov 2001

operating costs and lost power production, the utilization of air-cooled condensers for thermoelectric power plants increases the levelized cost of electricity (LCOE) by approximately 5-9% relative to wet cooling.[24,25,26]

3. Summary

The United States is heavily reliant on water to cool its thermoelectric power plants, yet the future promises both reduced water availability and more stringent requirements to maintain water quality. Continued dominant reliance on water for cooling is therefore risky and undesirable. Moreover, making thermoelectric power plants more independent from the nation's water supply infrastructure, while operating with high efficiency, can yield significant benefits to agricultural, municipal, and industrial sectors. Principle challenges with currently available dry-cooling systems highlight several needs and point to some possible solutions, such as (1) significant cost reduction (via significant air-side heat transfer enhancement to reduce size and/or low cost materials and manufacturing) and (2) the ability to cool below the dry bulb temperature limit and address temperature excursions with supplemental cooling systems and/or cool storage. The development of transformative cooling technologies to address future challenges of thermoelectric power production (fossil, solar, and nuclear) is the focus of the ARID FOA.

C. PROGRAM OBJECTIVES

The ARID program seeks to enable the development of transformational power plant cooling technologies that:

1. Dissipate no net water to the atmosphere (note that in cases where water vapor is dissipated to the atmosphere, not including surface water evaporation, an equal or greater amount of water vapor must be captured);
2. Result in no loss of efficiency for the power plant (note that while any single technology may not be able to accomplish this goal in standalone operation, ARPA-E seeks to fund a suite of technologies that when operating synchronously or asynchronously within a cooling system can meet the objective); and
3. Result in less than 5% increase in the levelized cost of electricity.

1. Program Vision

In order to meet the programmatic objectives outlined above, ARPA-E seeks to develop transformational cooling technologies including, but not limited to, ultra-high-performance air-cooled heat exchangers, supplemental cooling systems, and cool storage systems. As previously discussed, the limiting cool-side temperature for an air-cooled heat exchanger is dictated by the ambient dry bulb temperature that is subject to large temperature excursions. The development of transformational supplemental cooling and cool storage technologies are needed to work synchronously with air-cooled units in order to cool below the dry bulb temperature and preserve the power plant energy conversion efficiency, especially during large ambient temperature excursions. Supplemental cooling and cool storage systems are most easily integrated within an indirect dry cooling system configuration as shown schematically in Figure 1. This representative indirect dry-cooling system includes a water-cooled condenser, where the discharge cooling water is recirculated and cooled through an air-cooled heat exchanger and a supplementary cooling or cool storage system. For the sake of convenience, the indirect dry-cooling architecture will henceforth be used for outlining the ARID program vision. However, *all transformative* technologies being proposed for other system cooling architectures will be considered *as long as the system performance and cost are able to satisfy the program objectives* and are justified using sound technical and economic analysis. Applicants proposing alternate cooling system architectures are required to clearly explain and illustrate the entire cooling system design.

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[24] Ku, A. Y.; Shapiro, A. P. "The Energy−Water Nexus: Water Use Trends in Sustainable Energy and Opportunities for Materials Research and Development". MRS Bull. 2012, 37 (4), 439−447.

[25] Turchi, C. S., M. J. Wagner, and C. F. Kutscher. "Water Use in Parabolic Trough Power Plants: Summary Results from Worley Parsons' Analyses." Contract 303: 275-3000, 2010

[26] The potential cost savings associated with easier permitting is not considered in the 9% LCOE increase.

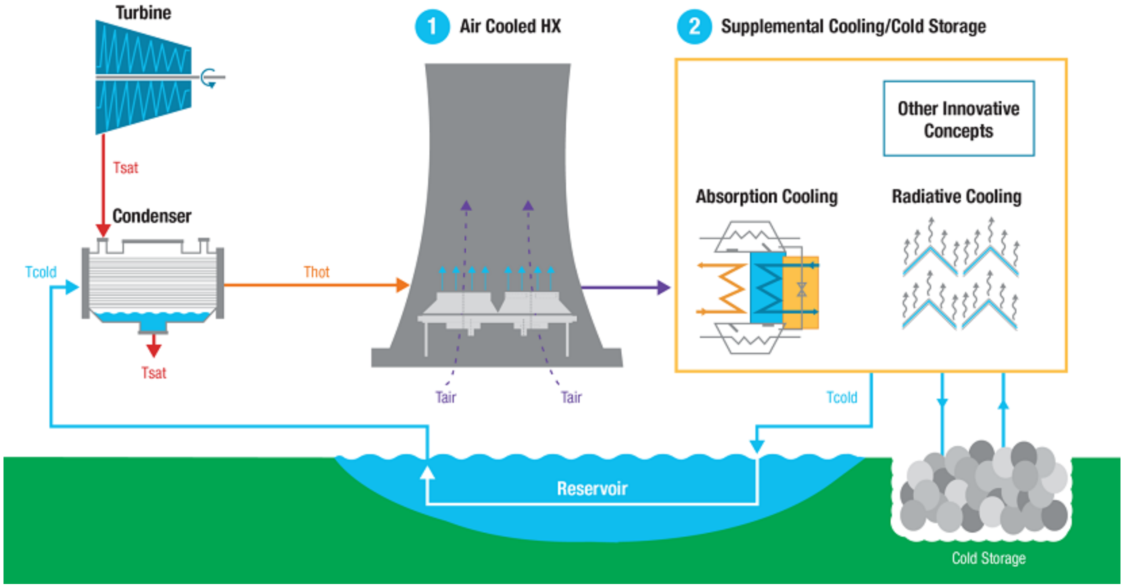

Figure 1: Schematic of representative indirect dry-cooling system that satisfies ARID program objectives.

2. Techno-economic Analysis for Indirect Dry-cooling System

ARPA-E has created a techno-economic model to study the economic feasibility of installing the indirect dry-cooling system, shown in Figure 1, within a Greenfield natural gas combined-cycle (NGCC) power plant. The 550 MW NGCC power plant model, DOE Office of Fossil Energy National Technology Laboratory (NETL) Case 13 described in *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity*[27], was used as the base case. The NETL report and reference cases contained within are well-regarded standards in the power generation community and have sufficient transparency and level of detail in plant design, operating conditions, costs, and accounting methodology to be useful for the present analysis. The ARPA-E cost model was used to compute the LCOE for NETL Case 13 parameters (including the original wet-evaporative cooling system) and it was confirmed that the ARPA-E model could reproduce the performance and cost parameters of the NETL plant.

The ARPA-E indirect dry-cooled NGCC plant model was then created by replacing the original open-loop evaporative cooling system (NETL Case 13) with the indirect dry cooling system shown in Figure 1. Detailed water-cooled condenser and air-cooled heat exchanger design modules were developed for the analysis that include associated pumps and fans. The baseline air-cooled heat exchanger design was based on heat transfer and pressure drop characteristics associated with high performance louver-finned tube heat exchangers.[28] An optimization algorithm was used to explore power plant cooling system configurations, resulting in designs with a global minimum LCOE. To help understand the performance necessary to achieve the program objectives, ARPA-E then incorporated modules of air-cooled heat exchangers with "aspirational" performance. Essentially, the air-side heat transfer coefficient was artificially increased beyond the baseline louver-finned tube heat exchanger (up to a factor of 5), while also increasing the pressure drop (up to a factor of 1.5). These aspirational target cases were then also run through the optimization algorithm.

The baseline louver-finned tube air-side heat transfer coefficient (h_{air}) and pressure gradient (dP/dL) for the air-cooled heat exchanger operating at different Reynolds numbers (Re) is shown in Figure 2. Also shown are the most aggressive ARPA-E targets. For the baseline heat exchanger performance, the increase in LCOE at the global minimum using the indirect dry-cooling system is 2.3% operating at the steady-state design condition. When the air-cooled heat exchanger

[27] DOE/NETL, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity", Rev. 2, DOE/NETL-2010/1397, Nov 2010.
[28] Achaichia and Cowell, "Heat Transfer and Pressure Drop Characteristics of Flat Tube and Louvered Plate Fin Surfaces", Experimental and Thermal Fluid Science 1 (1988) 147-157.

operates at the aspirational target performance, its size and cost is significantly reduced and the increase in LCOE is only 1.6%.

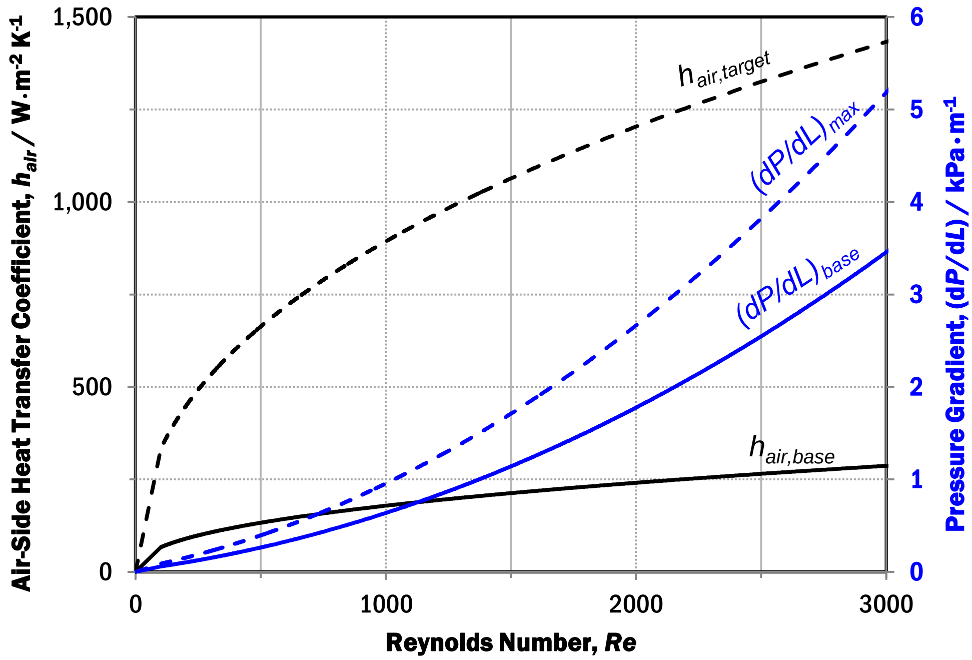

Figure 2: Air-side heat transfer coefficient and pressure gradient as a function of Reynolds number for the baseline and target finned-tube heat exchanger designs.

The required cooling water temperature into the condenser used in the model was 29°C. When the dry bulb ambient air temperature is 15°C the entire 318 MW heat load can be carried by the air-cooled heat exchanger without the need for supplemental cooling. When the ambient air temperature increases, the power plant energy conversion efficiency drops off rapidly with a corresponding increase in LCOE, as shown in Figure 3. Such ambient air temperature excursions can be mitigated by integrating supplemental cooling into an indirect dry-cooling system, as shown in Figure 1. However, the challenge with supplemental cooling is that it will almost always cost more than the approximate $50/kW for air-cooling systems. The estimated allowable costs for 1-4°C of supplemental cooling that result in no more than a 4% increase in LCOE (over the wet-cooled base case) for the aspirational air-cooled heat exchanger is shown in Figure 4. At 3°C of supplemental cooling, which accounts for 90 MW of the 318 MW load, the allowable cost for supplemental cooling is approximately $150/kW with a 4% increase in LCOE. Since this level of supplemental cooling is sufficient to maintain power plant energy conversion efficiency, the indirect dry-cooling system shown in Figure 1 with the target air-cooled heat exchanger and supplemental cooling described above would be a transformational cooling system that meets the ARID program goals. Accordingly, this analysis was used to guide the establishment of the technical targets for heat exchangers and supplemental cooling in Section I.E.

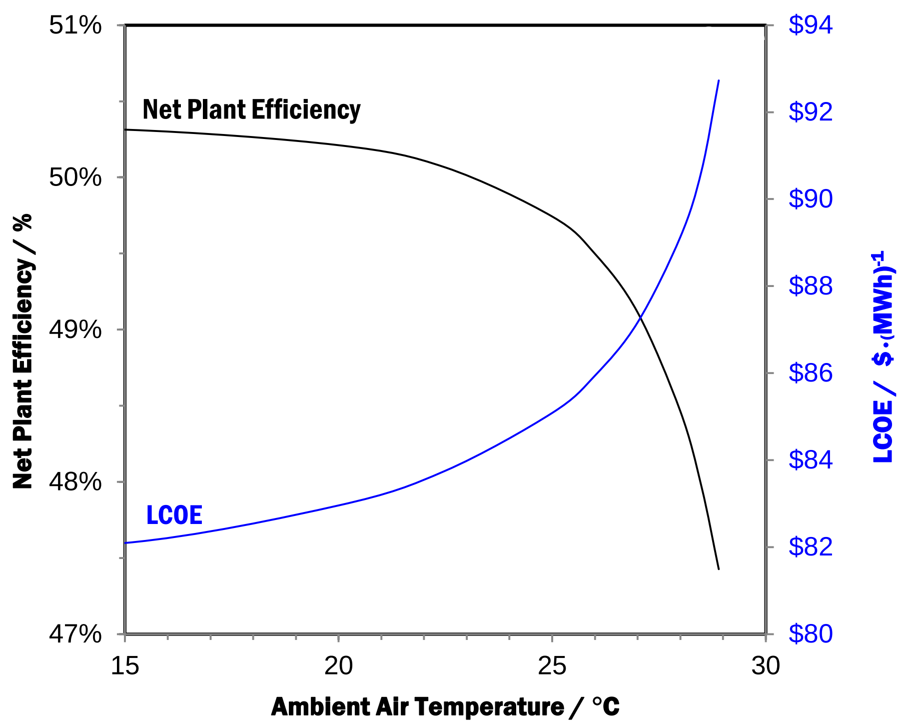

Figure 3: Variation in power plant energy conversion efficiency and LCOE as a function of increasing ambient air temperature for an aspirational target air cooled heat exchanger).

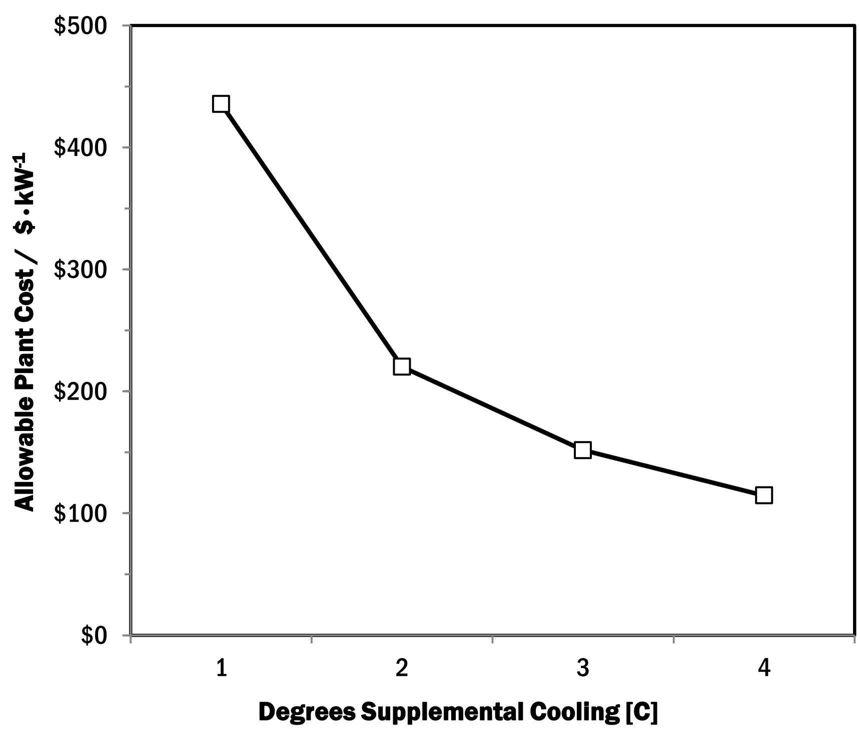

Figure 4: Projected allowable supplemental cooling cost for a 4% increase in LCOE when operating with an aspirational target air-cooled heat exchanger.

3. Air-cooled Heat Exchanger

The development of low cost and durable heat exchangers that can dissipate heat with minimal pumping power is central to the success of the ARID program. With the advent of novel manufacturing techniques and capabilities, as well as advancements in material science, the design space for heat exchangers has been widely expanded in recent years. The ARID program will enable the exploration of this exciting new heat exchanger design space to identify and realize technological innovations that address the program goals.

Due to its relative simplicity and lower cost compared to supplemental cooling and cool storage systems, air cooling is expected to handle at least 70% of the power plant heat load. One intriguing technology path that supports the program goals is the development of ultra-high performance, finned-tube metallic heat exchangers that meet the target heat transfer and pressure drop performance shown in Figure 2. A high rate of heat transfer significantly reduces the heat exchanger size, resulting in reduced capital cost and lower pumping load, provided the accompanying increase in pressure drop is limited.

Many different air-cooled heat exchanger operating conditions were considered in the ARPA-E techno-economic model, but under all cases studied the global minimum LCOE corresponded to *laminar* flow regime operation, with Reynolds number ranging from 1000–2000 Thus, a transformative metallic heat exchanger design that can achieve a five-fold increase in air-side heat transfer coefficient (operating in the 1000-2000 Reynolds number regime) must be capable of introducing flow disturbances to generate significant vorticity without large frictional losses as air flows across the heat transfer surfaces.

Another possible transformative route to achieving a low cost heat exchanger that supports the program goals is to use very inexpensive materials of construction, such as polymers. The inevitable decrease in overall heat transfer coefficient due to low thermal conductivity polymers will result in a much larger heat exchanger to handle the heat load. But, as long as the capital, installation, and operating costs are low enough and the lifetime of the unit is sufficient, such a solution could meet the program goals. Care must be taken to consider the increase in pumping load that will result with a larger heat exchanger and could negatively impact both the operating cost and power plant energy conversion efficiency.

Due to large heat loads and inherently small temperature differences, an air-cooled heat exchanger for power plant applications will be massive no matter what technical path is pursued. Therefore, a desired outcome from the ARID program is that the emerging transformative heat exchanger designs can be applied to not only power plants, but to also much smaller applications, such as residential and commercial heat pumps. Thus, a preferred design will be highly scalable and modular. The low cost, high throughput manufacturability of the heat exchanger design must be considered as part of the program. As such, collaboration with the advanced manufacturing community is encouraged.

The metallic finned-tube and polymeric heat exchangers mentioned are merely examples, and are not intended to be exclusive. All transformative air-cooled heat exchanger technologies that address the program goals will be considered by ARPA-E.

4. Supplemental Cooling and Cool Storage

A major drawback to managing the entire power plant heat rejection load solely with air cooling is that temperature excursions on hot days can lead to dramatically reduced energy conversion efficiency, as shown in Figure 3. To overcome this limitation, supplemental cooling is required. The need for supplemental cooling varies regionally, seasonally, and daily. An EPRI study considered power plant cooling in five locations across the U.S. that represent a range of major climate types (humid/dry, hot/temperate/cold, etc.).[22,29] For each of these locations, a wet-cooled system was modeled and an optimal cool water temperature feeding the condenser was identified. To study the need for supplemental cooling using the indirect dry cooling system in Figure 1, ARPA-E compiled hourly temperature data across one full year for each of these five locations from the EPRI data set.[30] The hourly ambient temperatures were compared to the required cool water design temperatures established in the EPRI study, factoring in a typical 7°C approach

[29] The locations chosen were El Paso, TX; Portland, OR; Jacksonville, FL; Pittsburgh, PA; and Bismarck, ND.
[30] National Solar Radiation Data Base. 1991- 2005 Update: Typical Meteorological Year 3. Available from: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html [accessed may 2014]

temperature for air-cooled systems.[22] This comparison was used to compute, for each hour, the amount of supplemental cooling required to lower the exit cool water temperature from the air-cooled heat exchanger to the required cool water inlet temperature to the condenser. The analysis revealed that supplemental cooling is required for 10–40% of the year, depending on the region, and 90 MW of supplemental cooling is sufficient to meet the required load for all regions considered. Different options for meeting the supplemental cooling load are described next.

Sorption/Desorption Supplemental Cooling

One intriguing option for supplemental cooling is sorption/desorption cooling technology driven by waste heat from a fossil-fired or solar thermal power plant. For example, the model 550 MW NGCC plant (NETL, Case 13)[27] has 150 MW of waste sensible heat that could be extracted from exhaust stack gasses, assuming a temperature drop of 106 to 60 °C. The condenser component of a fluid absorption cooling system typically rejects heat at relatively high temperature and can be transferred to liquid condensate discharged from the power plant steam condenser. Putting this waste heat back into the power block can boost the power plant energy conversion efficiency. In this way, sorption cooling systems and power plants have the potential to be highly complementary.

Despite the potential synergy between sorption-based cooling systems and power plant cooling, many challenges still remain. For example, the coefficient of performance (COP) for state-of-the-art sorption-based cooling systems remains low, limiting the amount of cooling that can be achieved with available waste heat. Single-effect absorption cooling systems have a COP of about 0.7[31] and multi-effect units can achieve a COP just above 1, but are complex and expensive. The range of COP for various sorption cooling technologies over a range of regeneration temperatures and sorption media is shown in Figure 5.

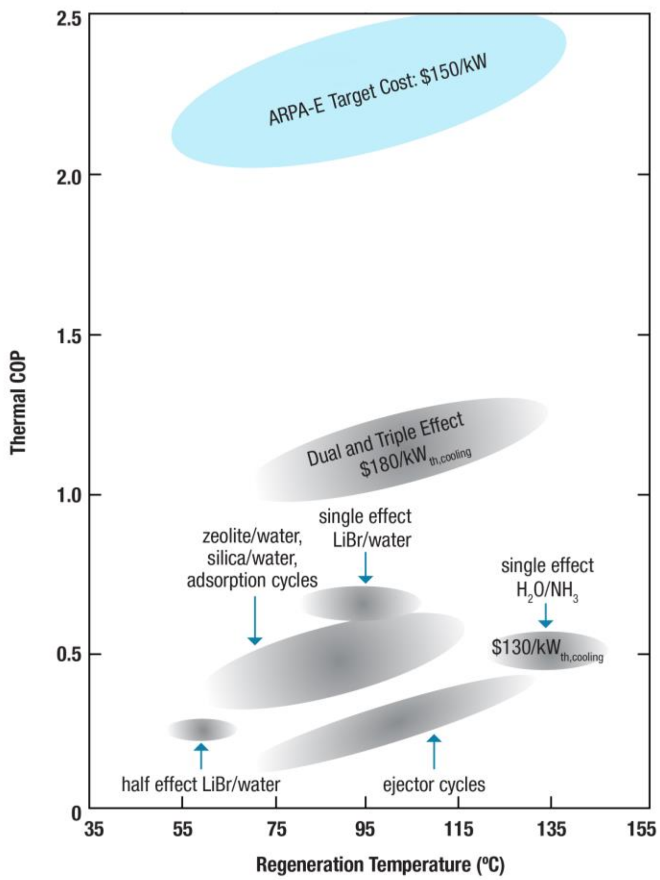

Figure 5: Coefficient of performance (COP) as a function of regeneration temperature for various sorption-based cooling media.[31]

[31] Beith, Robert, ed. “Small and micro combined heat and power (CHP) systems: Advanced design, performance, materials and applications”. Elsevier, 2011. [Figure adapted].

Recent proprietary advancements with sorption media suggest that a COP of 2 may be possible with single-effect sorption cooling systems, motivating ARPA-E to target a high COP with a low enough cost to be economically attractive to dry power plant cooling. High COP and low cost sorption cooling technologies will be disruptive to the market, however achieving this aim will require transformative ideas. ARPA-E is interested in all innovative sorption/desorption cooling concepts that have the potential to reach a high COP at low cost.

Cool Storage

Cool storage during nighttime hours could be an attractive option to mitigate daily ambient air temperature excursions. In order to determine the usefulness and appropriate size of a cool storage system, the hourly temperature profiles of the five representative locations were considered. Since a cool storage system could be charged 10 h per day or more when the cool water condenser temperature (T_{cool}) is below its design temperature, any day that the ambient air temperature exceeded the cool water condenser design temperature ($T_{ambient} > T_{cool}$) for less than 14 h was assumed to be a feasible day for using cool storage. The distribution of daily cool storage and the annual number of days of needed storage in the five U.S. regions is shown in Figure 6. As indicated in Figure 6, 80 MW of cool storage charged for 10 h/day or more (800 MWh/day) could mitigate the majority of temperature excursions across all five U.S. regions considered.

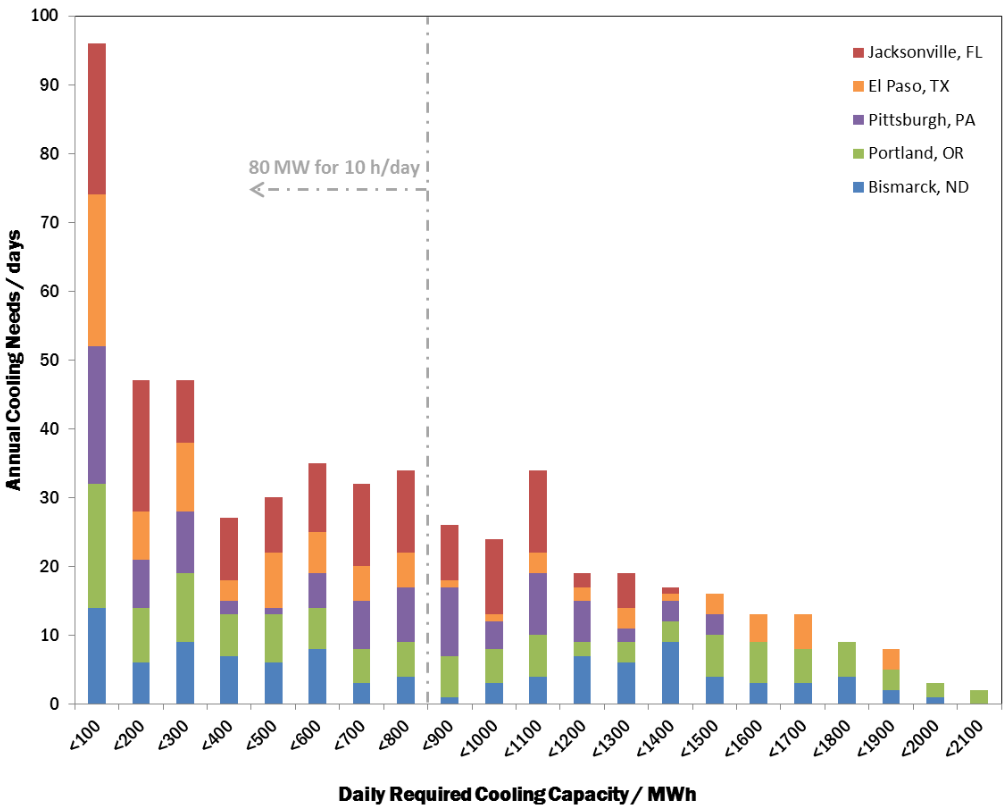

Figure 6: Amount of daily cool storage (MWh/day) and number of days needed for five U.S. regions.[30]

Many different schemes could be employed to charge a cool storage system. One intriguing approach is to use radiative cooling to the sky during nighttime hours. Nighttime radiative cooling takes advantage of the sky as a cold sink, which has not traditionally been considered for dumping a large waste heat load. A radiative cooling system could be envisioned, in which heat is dissipated by long-wavelength infrared radiation emitted within a narrow 8–13 μm wavelength band, assuming 30°C water exiting a heat exchanger.[32] On a clear arid night, this radiative emission would be absorbed in the

[32] Catalanotti, S., et al. "The radiative cooling of selective surfaces". Solar Energy 17.2 (1975): 83-89.

atmosphere at a height of approximately 25 km above the earth's surface.[33] The sky temperature is approximately -50°C at this altitude and assuming ideal emission and absorption over this spectral band, the maximum theoretical heat flux is approximately 120 W/m^2.[34] This relatively low heat flux may not be practical to dissipate large heat loads in a standalone solution; however, the implementation of a heat exchanger that includes multimode heat transfer (both radiation and convection) may provide an interesting solution for charging a cool storage system.

Although a multimode radiative and convection heat exchanger is highlighted here as a possible cool storage charging technology, it is recognized that many other solutions exist. For example, transformative heat pipe or thermosyphon technology could provide a solution for passively charging the cool storage medium. ARPA-E is interested in all cool storage system concepts that meet the programmatic objectives and specified technical targets.

5. Scalability and Modularity for Commercialization

Since 2002, an average of 15-20 thermoelectric power plants of at least 50MW nameplate capacity have been built each year in the U.S.[35] A business model that relies on low sales volume of high capital cost units is very challenging to sustain. As such, it is important to develop highly scalable thermal management solutions that meet the needs for large-scale power plant cooling, as well as small and intermediate-scale emerging applications in order to cultivate and sustain business opportunities. Another consideration is the recent trend towards distributed power generation solutions with larger sales volumes of smaller capacity power plants. It is conceivable that future power production will be significantly more distributed than today with unit level power production capacity as small as the kilowatt-scale.[1] These considerations suggest that next-generation power plant cooling technologies developed through the ARID program need to be highly scalable. Here scalable implies that sound engineering principles can be used to design a transformative cooling concept to operate with equally high performance at the kilowatt and megawatt-scales. In addition, modular systems lend themselves to low-cost mass-manufacturing. As the final task for each of the projects funded through the ARID program, ARPA-E will require prototype testing of the cooling technologies at a scale of 20–100 kW, depending on the testing capabilities available to the research teams. Prototype cooling technologies will be expected to scale-up to megawatt-cooling capacity without a loss in performance. Research teams are encouraged to plan for offsite testing if internal testing capabilities at the 20–100 kW scale are not available.

D. TECHNICAL CATEGORIES OF INTEREST

ARPA-E seeks to develop transformational power plant dry cooling technologies, including: (1) ultra-high performance air-cooled heat exchangers, (2) supplemental cooling/cool storage systems, and (3) other transformative power plant dry cooling technologies that meet all of the programmatic objectives. To accommodate the synchronous operation of different cooling technologies that meet the ARID program objectives, ARPA-E has envisioned an indirect dry-cooling architecture; however, technologies that are better-suited for other power plant system architectures, such as direct dry cooling, may be proposed *so long as such a system is capable of meeting the program objectives and technical targets.* In cases where supplemental cooling and/or cool storage systems are required for these alternative architectures, applicants will need to clearly explain and illustrate the design of the entire cooling system and demonstrate that system level operation can meet the objectives and relevant targets of the program.

Regardless of the system architecture, it is recommended that applicants focus on developing a single cooling technology as opposed to dispersing the team effort by trying to advance multiple technologies. For all cooling concepts proposed, it is acceptable to propose the development of only the enabling technology, provided the remainder of the system is already commercially available. Applicants are expected to clearly explain the cooling technology concept being offered, how it fits into a power plant cooling system architecture, the technical risks and challenges to be addressed through transformative research, and the supporting analysis to justify a development path to meet the performance and cost requirements.

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[33] Determined from data from NOAA Satellite and Information Services. National Environmental Satellite, Data, and Information Service. IGRA Interface, Station Selection. Sept 2013. Available from: http://nomads.ncdc.noaa.gov/cgi-bin/ncdc-ui/igra/main-station.cgi [accessed May 2014].
[34] Assumes a water temperature of 28 C, a sky temperature of -50 C, and no convection at the radiative surface.
[35] Calculated from data from U.S. Energy Information Administration. Form EIA-860 detailed data. Dec 2013. Available from: http://www.eia.gov/electricity/data/eia860/ [Accessed May 2014]

Category 1: Air-Cooling Systems

Transformative air cooling technologies of interest include, but are not limited to, one or more of the following elements:

(1) Ultra-high performance air-side heat transfer with low pressure drop;
(2) Flow path features that induce vorticity and disrupt the development of a laminar boundary layer;
(3) Concepts incorporating phase change materials (non-volatile in cases where the PCM will be directly exposed to the environment);
(4) Construction with low-cost and durable materials;
(5) Concepts that incorporate large throughput advanced manufacturing methods;
(6) Concepts that are highly scalable and/or modular.

Category 2: Supplemental Cooling/Cool Storage

Transformative supplemental cooling and cool storage technologies of interest may include, but are not limited to, one or more of the following:

(1) Low-cost, high-COP sorption/desorption cooling systems driven by captured waste heat from stack gases, solar thermal energy, or other sources;
(2) Systems where rejected heat is reused in the power cycle;
(3) Multimode convective/radiative cooling systems with tuned spectral properties for night time operation;
(4) Advanced heat pipes coupled with a large-capacity heat sink;
(5) Novel cool storage media with high capacity.

Category 3: Other Transformational Cooling Concepts

The indirect dry cooling system described above is only one possible approach to achieve the program objectives and is not intended to be prescriptive. Other transformative power plant cooling technologies are of interest, so long as they meet the programmatic objectives.

E. TECHNICAL PERFORMANCE TARGETS

It is customary for ARPA-E to set aggressive technical and economic targets in order to encourage applicants to propose transformative solutions and creative alternatives to existing solutions. Only those technologies that have a well-justified potential to approach, meet, or exceed the technical and economic performance targets will be considered for funding. It is recognized that prototype technologies may not meet the cost targets without projection to full-production manufacturing. For such cases, a well-justified cost analysis is necessary. The analysis presented in Section I.C.2 above served as a guide in setting some of the technical performance targets. In addition, assumptions regarding other key working parameters used to arrive at the performance targets are listed in Table 1.

Working Parameters	Units	Value
Depreciation period	y	20
Plant operating period	y	30
Estimated fraction of LCOE due to cooling	%	1.2%
Estimated cooling CapEx	$/kW	50
Max increase in LCOE	%	5%
Max increase in CapEx	$/kW	215
Max cooling CapEx	$/kW	265

Table 1: Working parameters used in the derivation of technical performance targets

Category 1: Air-Cooling Systems

Category 1 contains two subcategories: (A) metallic air-cooling heat exchangers and (B) all other air-cooling heat exchangers. The primary heat transfer surface material determines the appropriate subcategory. In the case(s) where the heat exchanger will incorporate more than one heat transfer surface material (e.g. metal/polymer hybrid), the concept should go to subcategory (B). Metallic heat exchangers are most common in practice today. The cost of materials for metallic heat exchangers is inherently high. As such, the primary goal for the metallic heat exchangers subcategory is to dramatically improve heat transfer performance to meet the cooling load with a smaller volume, lower cost, and without an excessive fan load. Also of interest are polymeric air-cooled heat exchangers. Here, the material costs are cheaper, so larger systems might be acceptable, so long as the parasitic load, especially that of the fans, is not excessive. Polymeric heat exchangers are not expected to achieve the dramatic heat transfer performance enhancement that is needed for metallic heat exchangers. Another example of a non-metallic heat exchanger is one that incorporates phas example of a non-metallic heat exchanger is one that incorporates phase change materials as the primary heat transfer surface. Other innovative material solutions to advanced heat exchangers can also be envisioned.

For concepts that fall within Category 1, the size of the final prototype should be at the 20–100 kW scale. Since air-cooled heat exchangers for power plant application are typically driven by small temperature differences, all concepts in Category 1 must assume that the ambient air temperature is no greater than 20°C below the working fluid entering the air-cooled system ($T_{work,inlet} – T_{air,inlet} < 20°C$) as part of any relevant analysis.

Subcategory 1A: Metallic Air-Cooling Heat Exchanger

ID	Description	Target
1A.1	Air-side heat transfer coefficient (h_{air})	$h_{air} \geq 5\ h_{air,base}$
1A.2	Pressure gradient	$\Delta P/\Delta L \leq 1.5\ (\Delta P/\Delta L)_{base}$
1A.3	Capital cost of heat exchanger	Cost ≤ $50/kW$_{th}$

Explanations:

The baseline heat transfer coefficient and pressure gradient are taken to be those shown in Figure 2 for Reynolds number between 1000 and 2000.

Subcategory 1B: Other Air-Cooling Heat Exchangers

ID	Description	Target
1B.1	Heat exchanger coefficient of performance COP_{HX},	$COP_{HX} \geq 200$
1B.2	Heat exchanger effectiveness ε	$\varepsilon > 0.6$
1B.3	Capital cost of heat exchanger	Cost ≤ $50/kW$_{th}$

Explanations:

When determining COP_{HX}, all parasitic power requirements need to be accounted for, such as pumping power and other auxiliary loads. Here COP_{HX} is defined as $\frac{\dot{Q}_{transferred}}{\dot{P}_{parasitic}}$.

Applicants should use the following formula for calculating the capital cost of the heat exchanger:

$$Cost = \frac{\text{Cost}\left(\frac{\$}{\text{kW}_{\text{th}}}\right)\text{x life(yrs)}}{30\ \text{(yrs)}}.$$

Category 2: Supplemental Cooling and Cold Storage

Category 2 is organized into three subcategories: (A) sorption/desorption cooling systems, (B) multimode (convective/radiative) cool storage systems, and (C) standalone cool storage systems. For all concepts that fall within Category 2, the size of the final prototype should be at the 20–50 kW scale.

Subcategory 2A: Sorption/Desorption Cooling System

ID	Description	Target
2A.1	Cooling system coefficient of performance COP_{cool}	$COP_{cool} \geq 2$
2A.2	Capital cost of system	Cost ≤ \$150/kW$_{th}$
2A.3	Regeneration temperature, T_{regen}	T_{regen} = 60–80°C

Explanations:

In COP_{cool}, all parasitic power requirements need to be accounted for, such as pumping power and other auxiliary loads. Here COP_{cool} is defined as $\frac{\dot{Q}_{cool}}{\dot{Q}_{heat,in} + \dot{P}_{parasitic}}$. Note that the Qheat,in term includes all external heat input to the sorption cooling system, excluding that input to the evaporator.

The regeneration temperature assumes ambient temperature, $T_{ambient}$ ~ 20°C.

Subcategory 2B: Multimode (Convection/Radiative) Cooling Plus Storage

ID	Description	Target
2B.1	Radiative heat flux $q''_{radiant}$	$q''_{radiant} \geq 100$ W/m^2
2B.2	Capital cost of system	Cost ≤ \$150/kW$_{th}$

Explanations:

The radiative heat flux is during night time operation. The cost includes the cost of the full system. If a proposed concept will use a commercially available storage unit or a storage media that does not require development, it should not be included in the development plan, but should be specified and factored into the cost analysis.

Subcategory 2C: Cool Storage System

ID	Description	Target
2C.1	Prototype storage capacity P_{cool}	P_{cool} = 200–500 kWh
2C.2	Time to fully charge t_{charge}	$t_{charge} \leq 10$ h
2C.3	Capital cost of system	Cost ≤ \$150/kW$_{th}$

Explanations:

The cost includes the cost of the full system, including heat exchangers for charging. If a proposed concept will use commercially available heat exchangers that do not require development, they should not be included in the development plan, but should be specified and factored into the cost analysis.

Category 3: Other Innovative Concepts

ARPA-E is interested in other innovative power plant cooling technologies that can meet the programmatic objectives, even if they do not fall into one of the subcategories above. These technologies must enable a cooling system to meet the following metrics:

ID	Description	Target
3.1	Capital cost of system	Cost ≤ $200/kW_{th}$
3.2	Temperature difference between steam inlet temperature $T_{steam,in}$ and air inlet temperature $T_{air,in}$	$T_{steam,in} - T_{air,in} < 25°C$
3.3	Prototype cooling capacity size Q_{cool}	Q_{cool} = 20–100 kW_{th}

Explanations:

The cost includes the cost of the full cooling system architecture, including any supplementary cooling systems that might be required. Only the proposed transformative technology should be included in the development plan, but other components and subsystems should be factored into the cost analysis. In addition to an illustration of the technology concept proposed for the development plan, all Category 3 concepts *must* also provide an illustration of the full cooling system enabled by the proposed technology.

F. Applications Specifically Not of Interest

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.E of the FOA.
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed solely at discovery and/or fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).
- Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.
- Applications that propose the following technologies:
  - Improvements in condensation heat transfer that do not also: (1) incorporate both air cooling <u>and a means for supplemental cooling and/or cool storage</u> and (2) achieve the targeted increase in air side heat transfer coefficient.
  - Technologies with <u>net</u> dissipation of water vapor (e.g. when water vapor is dissipated to the atmosphere, not including surface water evaporation, and an equal or greater amount of water vapor is not captured);
  - Once-through cooling systems.