Driving Innovation in Dry-Cooling at ARPA-E

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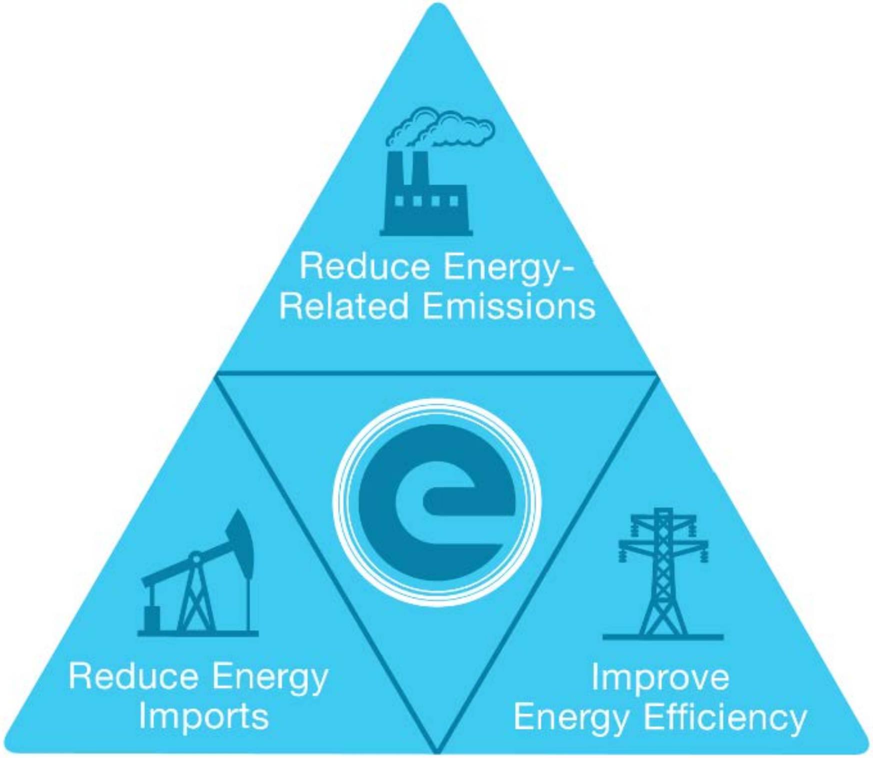
ACC Users Group Annual Meeting
Dallas, TX

Oct 5, 2016

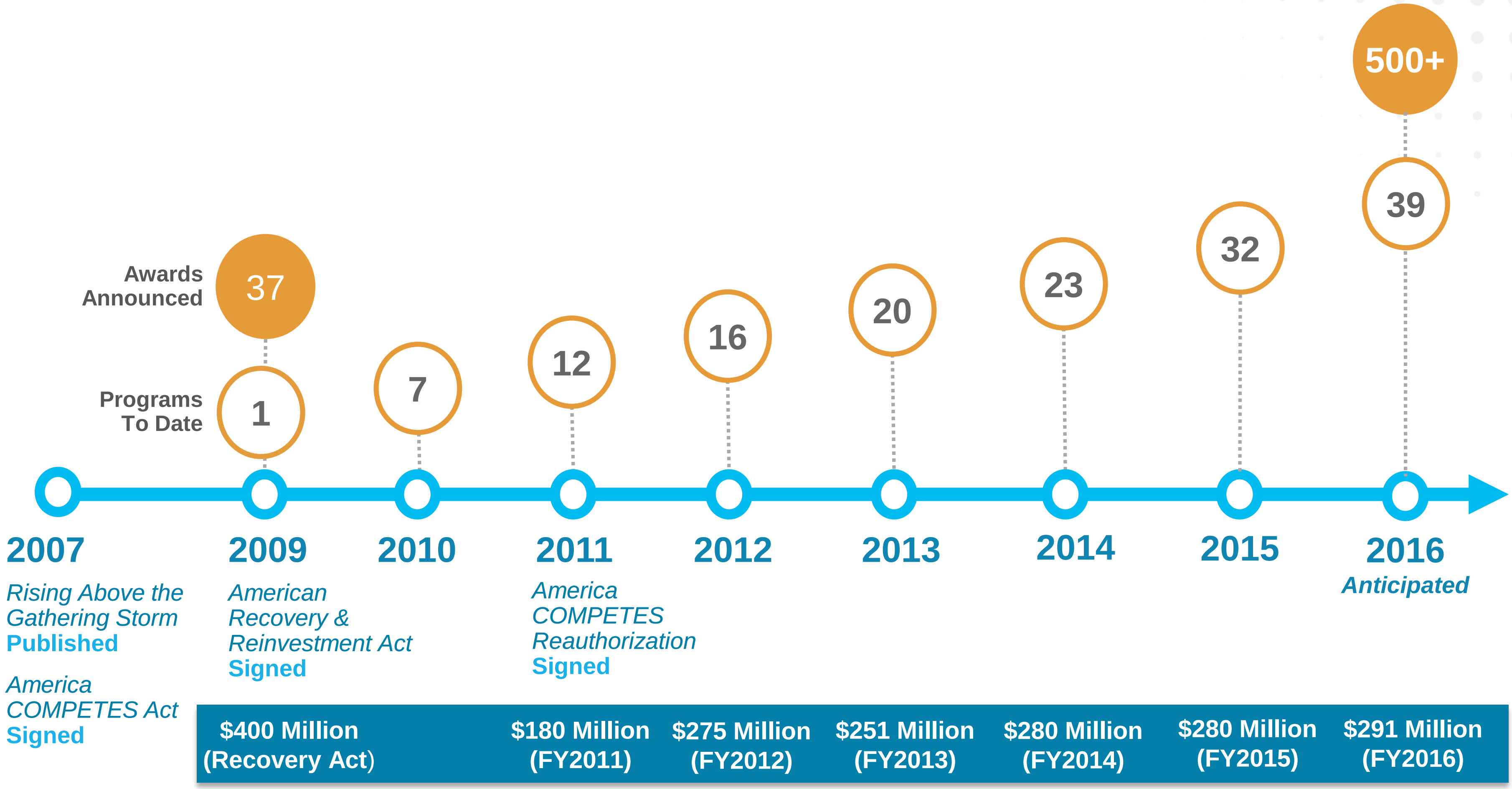
ARPA-E Mission

Catalyze the development of transformational, high-impact energy technologies

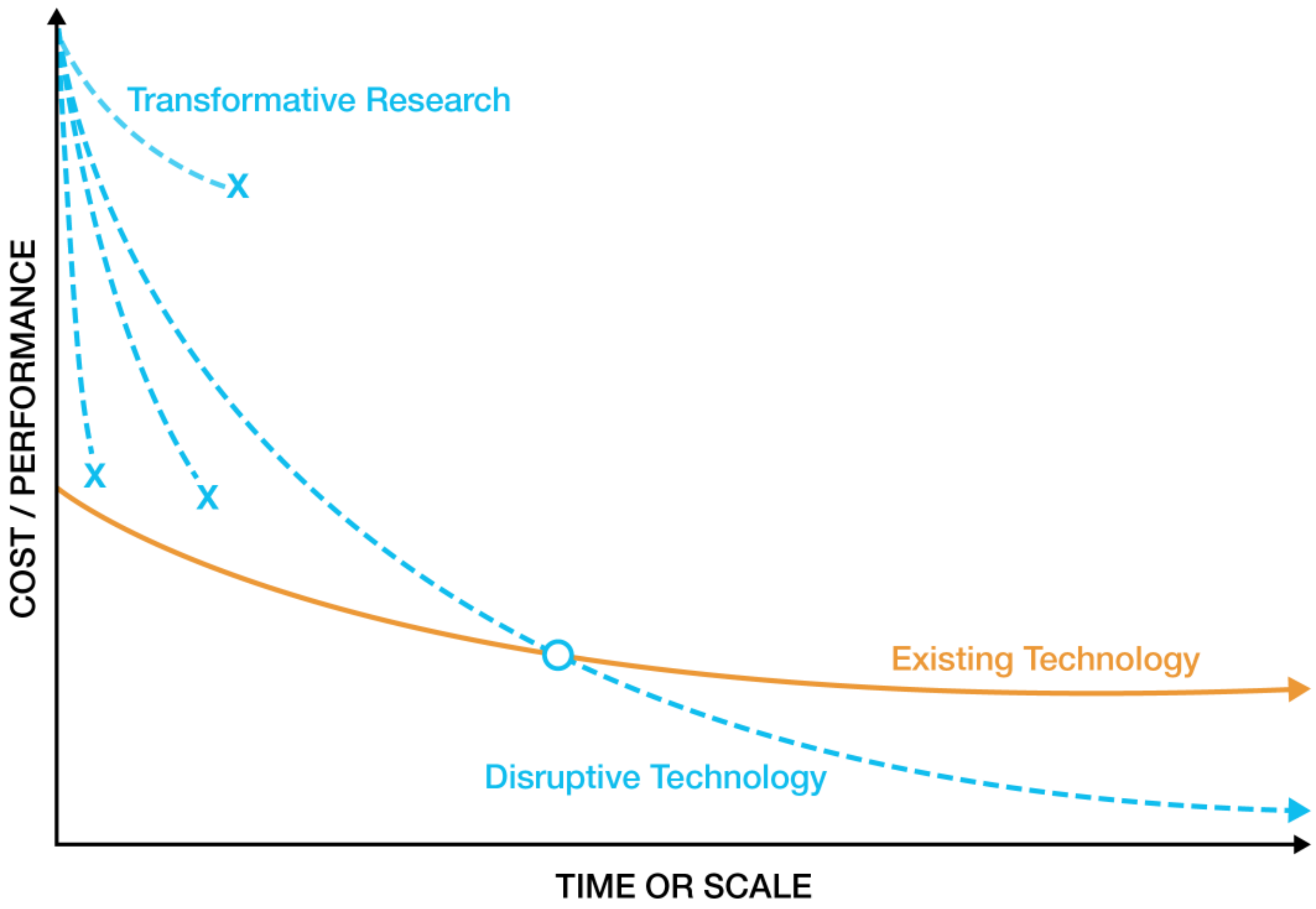


Ensure the U.S. maintains a lead in the development and deployment of advanced technologies

Evolution of ARPA-E



Creating New Learning Curves



What Makes an ARPA-E Project?

IMPACT

- High impact on ARPA-E mission areas
- Credible path to market
- Large commercial application

TRANSFORM

- Challenges what is possible
- Disrupts existing learning curves
- Leaps beyond today's technologies

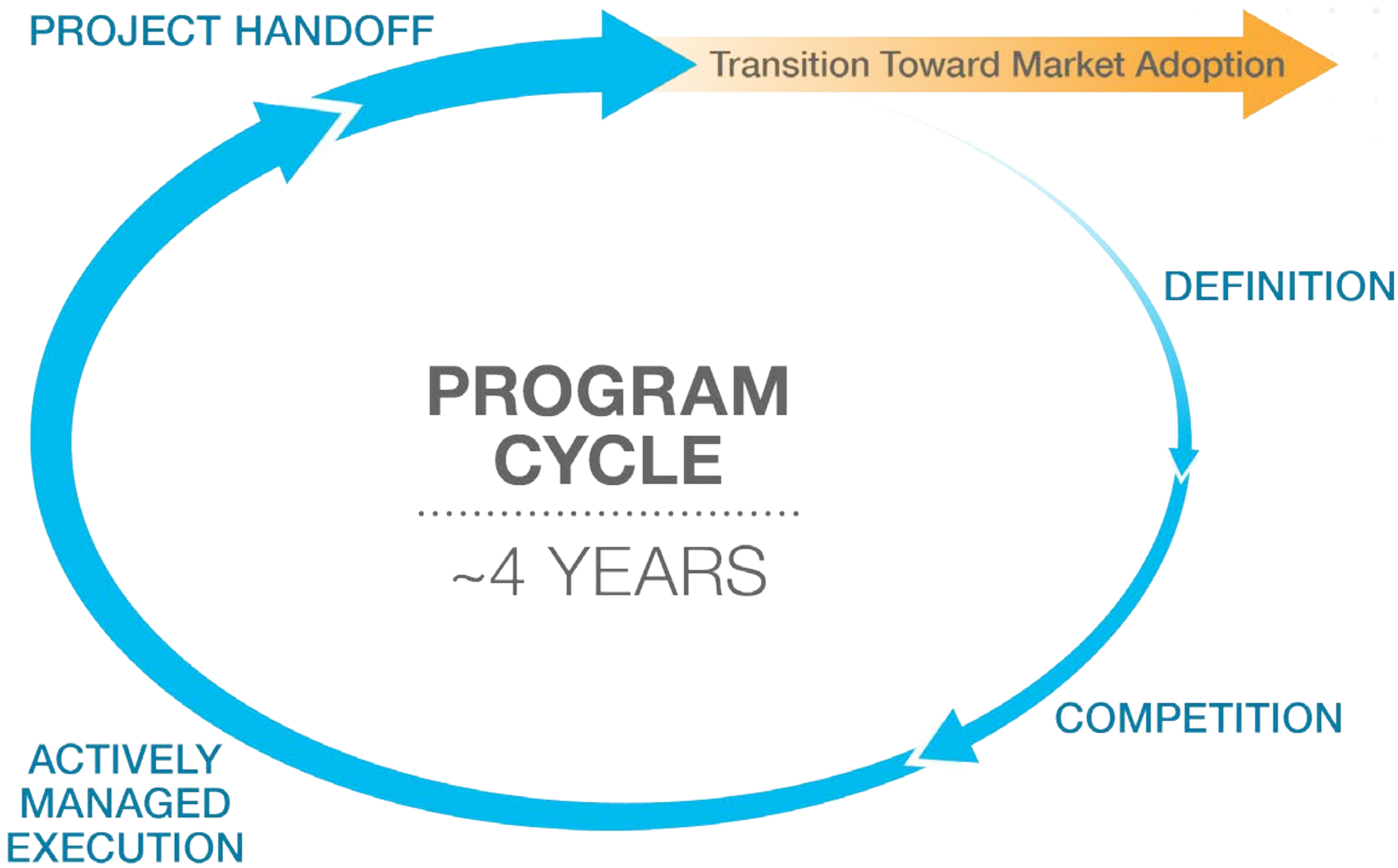
BRIDGE

- Translates science into breakthrough technology
- Not researched or funded elsewhere
- Catalyzes new interest and investment

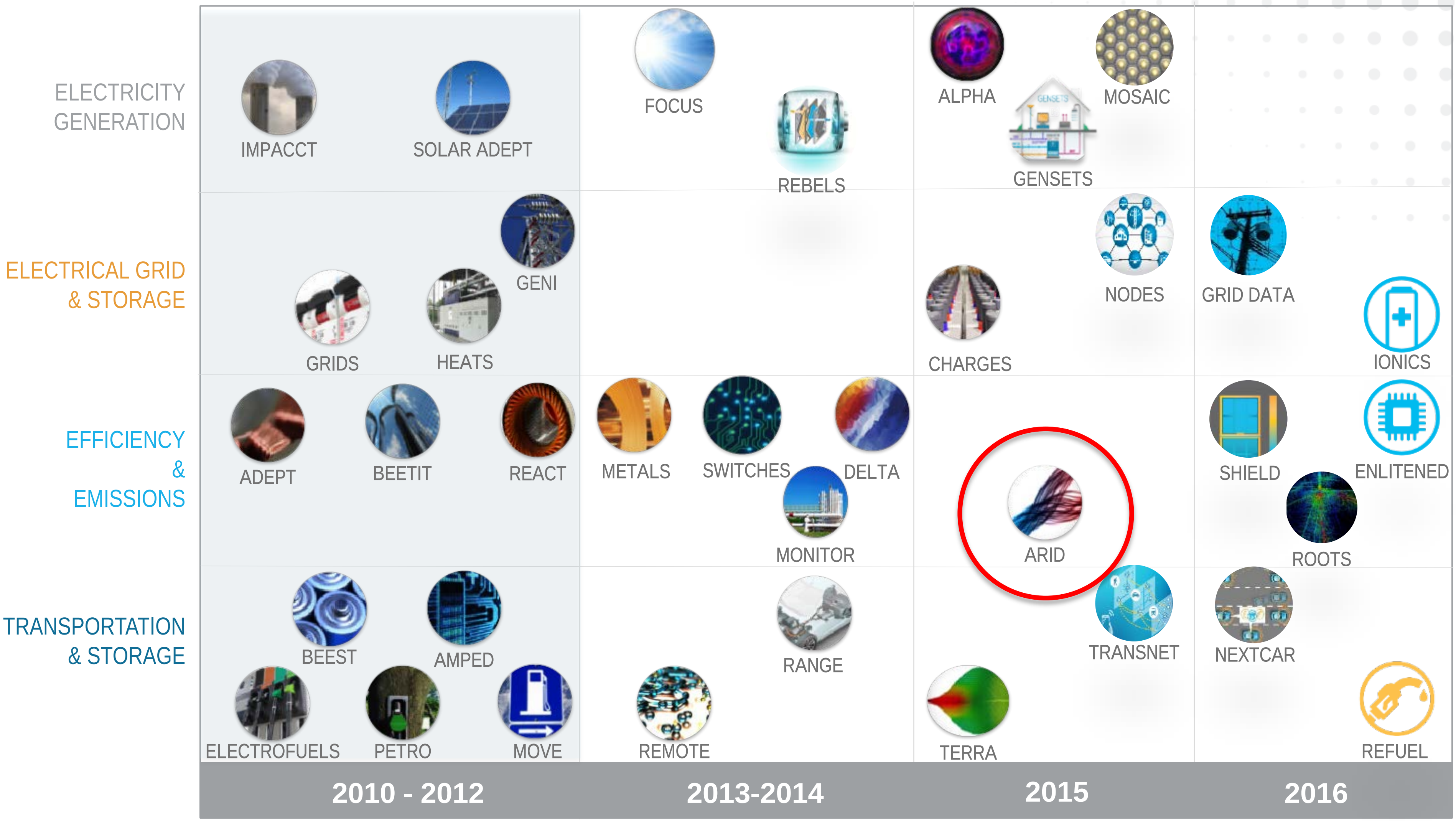
TEAM

- Comprised of best-in-class people
- Cross-disciplinary skill sets
- Translation oriented

Technology Acceleration Model



Focused Program Portfolio



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Measuring ARPA-E's Success

MOVING TECHNOLOGY TOWARD MARKET

- Private-Sector Funding
- Partnerships with Other Government Agencies
- Licensing/Acquisition by an Established Firm
- Licensing/Acquisition Resulting in a Spinoff
- Growth of Existing Company (e.g., Organic Growth)

BREAKTHROUGH ACHIEVEMENTS

- Patents
- Publications

OPERATIONAL EXCELLENCE

- Expedited program development and project selection
- Aggressive performance metrics

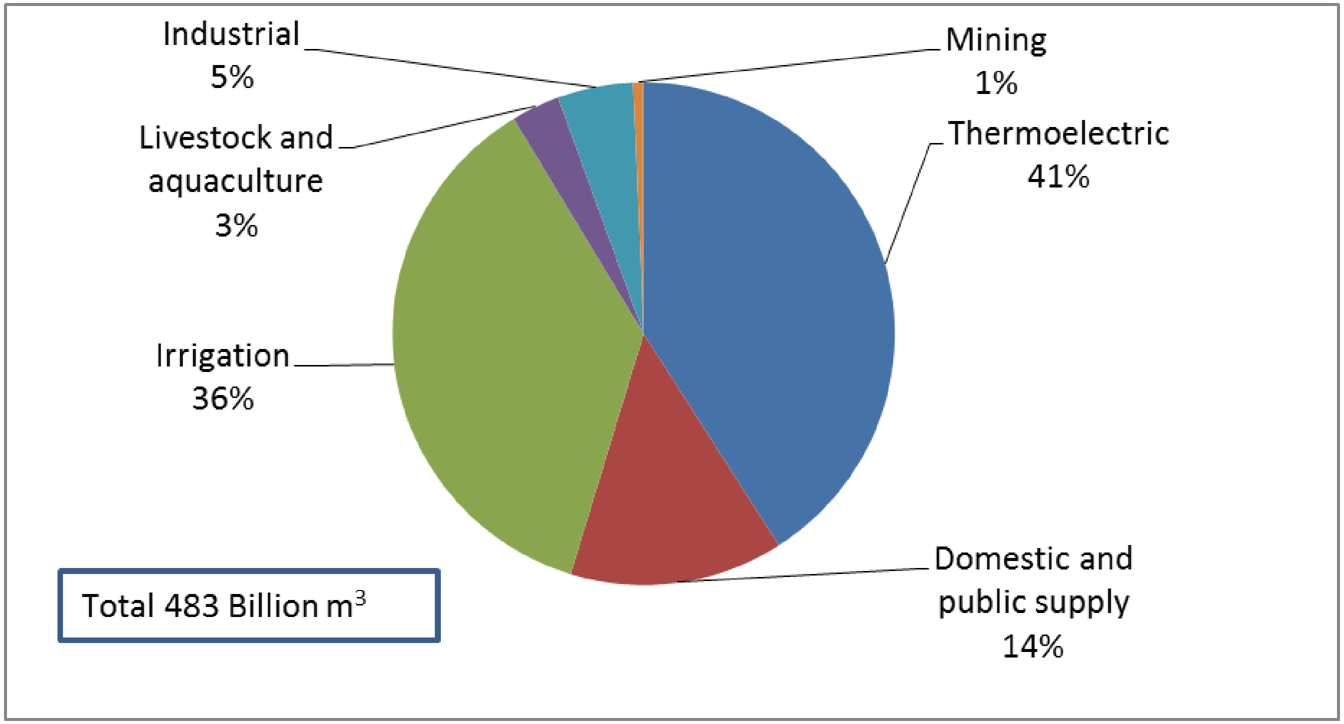
Energy as a Water Problem

Energy/Water as a U.S. Problem

- 41% of freshwater drawn in the U.S. is for thermoelectric power plant cooling
- 3% of cooling tower water load is evaporated and dissipated (energy/agriculture competing for same fresh water resource)
- Approximately 2.1 billion fish, crabs, and shrimp killed per year due to power plant intake on once through cooling
- Warming trend and over-pumping of natural water bodies puts water cooling for thermoelectric power at risk
- Water demand for fossil energy exploration and production is increasing
- Agricultural runoff water is damaging eco systems and is increasingly regulated

Plurality of U.S. Fresh Water Withdrawal is for Cooling Thermoelectric Power Plants

Withdrawal (2005, US)



197 billion m^3 annual withdrawal for thermoelectric power

*22 billion m^3 withdrawn for cooling towers, **5 billion m^3 dissipated***
287 m^3 water required per metric ton of potatoes produced
***17.4 Mtons of potential food production dissipated** (more than 5 times world annual yield of potatoes)*

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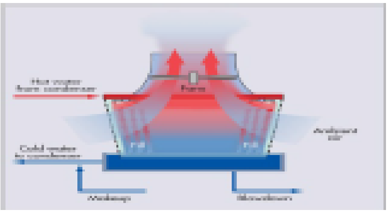
U.S. Power Plant Infrastructure is Heavily Reliant on Water Cooling

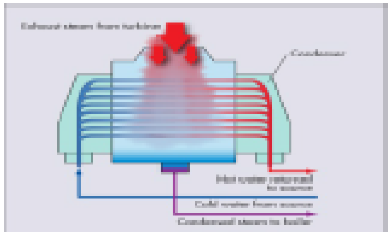
99%	1%	<1%

Water Cooling

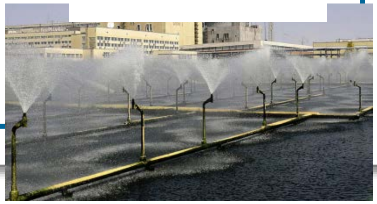
Cooling Tower[1] (42% in US)[2]



Once Through Cooling[1] (43% in US)[2]

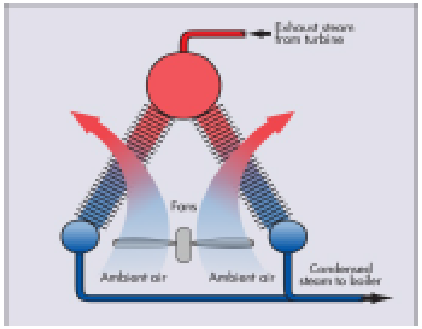


Cooling Pond (14% in US)[2]

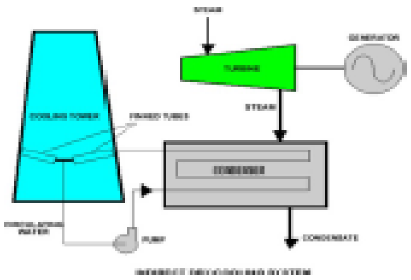


Dry Cooling

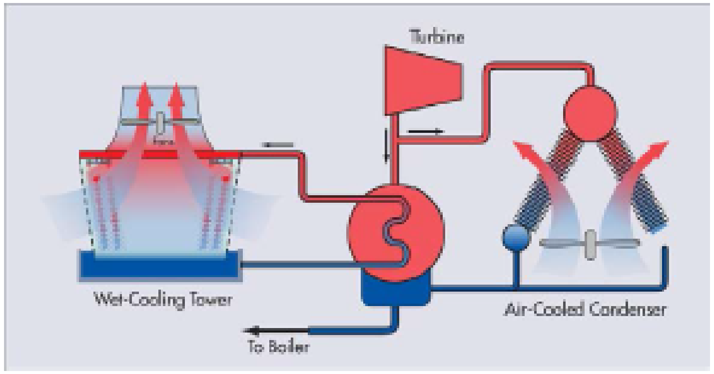
Direct Dry Cooling[1]:
Air Cooled Condenser (1%Usage in US)[2]



Indirect Dry Cooling[3]



Hybrid Cooling[1]

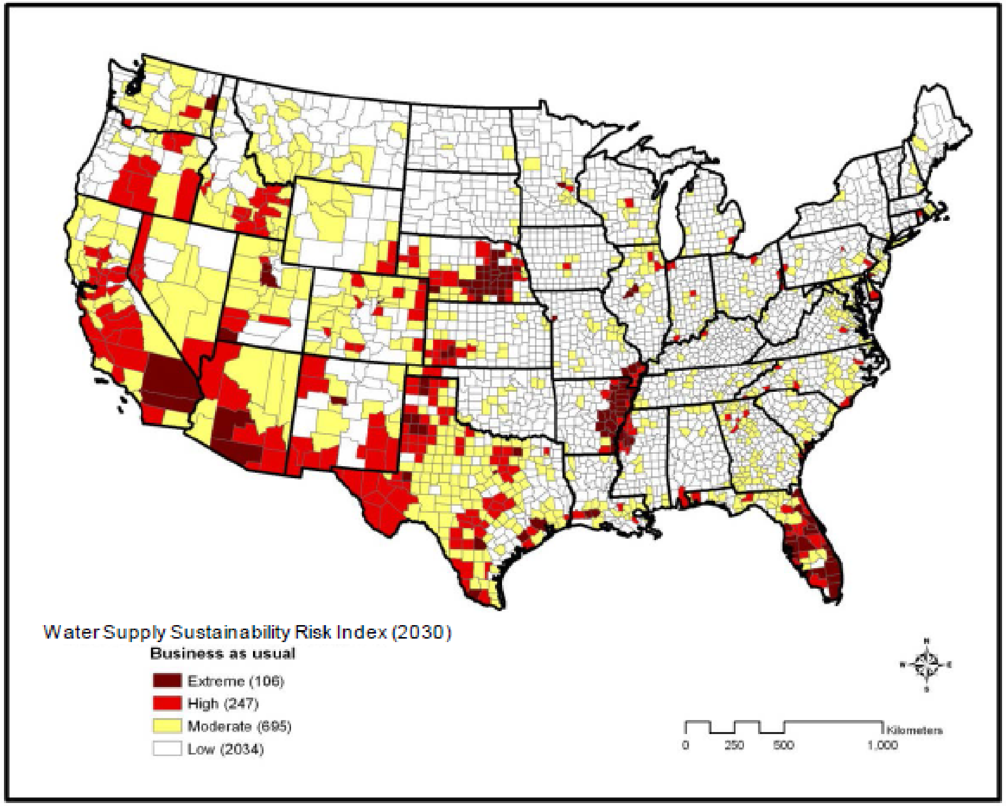


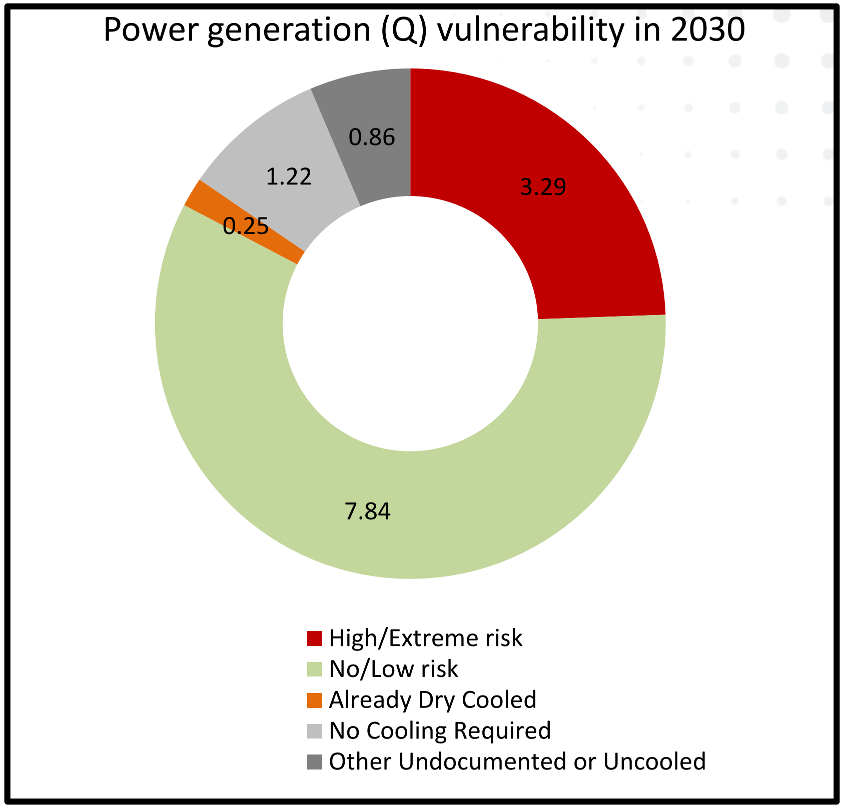
Increasing demand for dry cooling in water scarcity regions.

1. EPRI Report, "Water Use for Electric Power generation", No. 1014026, 2008.
2. Report of Department of Energy, National Energy Technology Laboratory, "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements", DOE/NETL-400/2008/1339, 2008
3. http://www.globalccsinstitute.com/publications/evaluation-and-analysis-water-usage-power-plants-co2-capture/online/101181

EPRI Study Suggests that Water Availability in 2030 puts >3 Quads Electricity Generation at Risk

3.29 of 13.5Q electricity generation at risk due to population growth alone





Notes/Assumptions
- Only considers existing production
- Water use *per capita* remain at 2005 levels
- Population growth ~1%/yr (US Census Bureau)
- Water supply/trends at 2005 levels, *No climate change*

How will climate change impact water availability? ARPA-E contract with Northeastern University addresses issue

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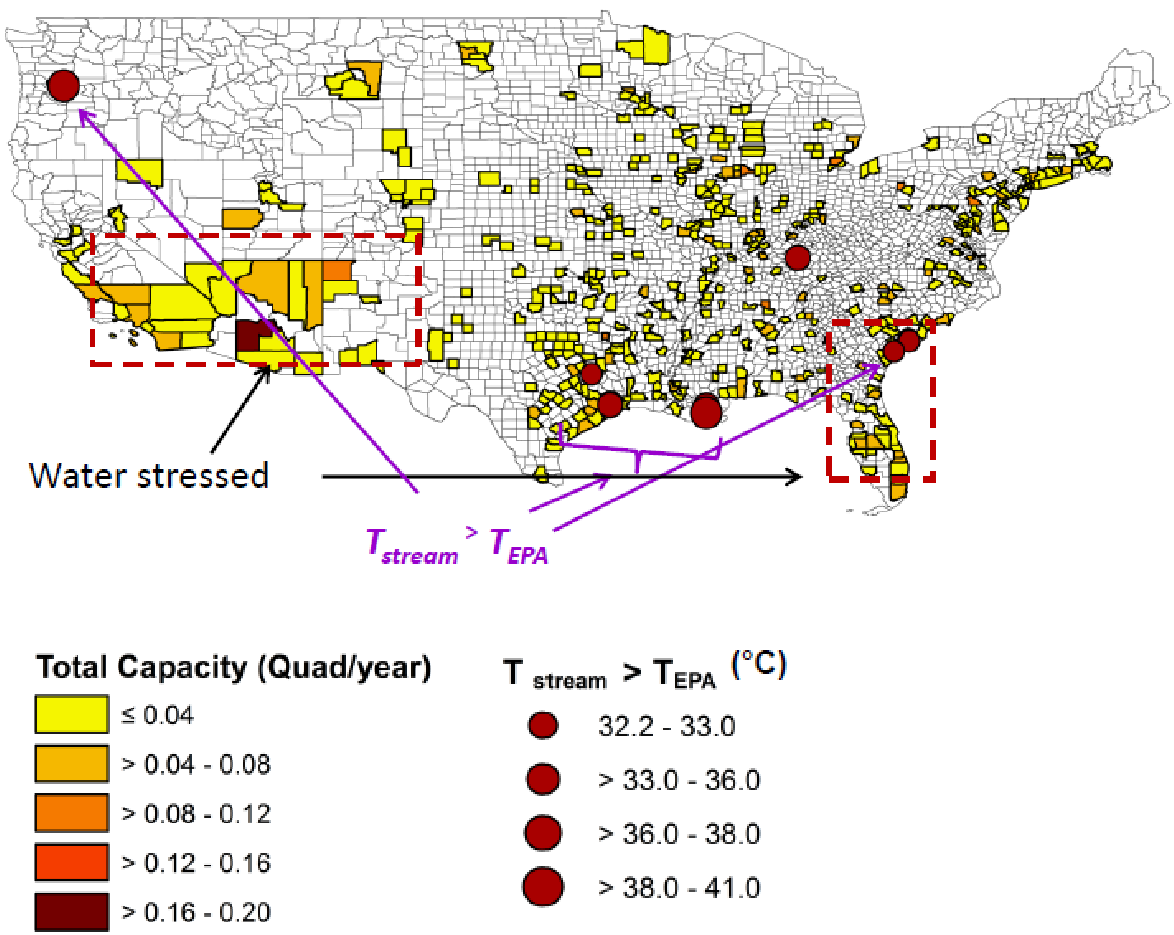
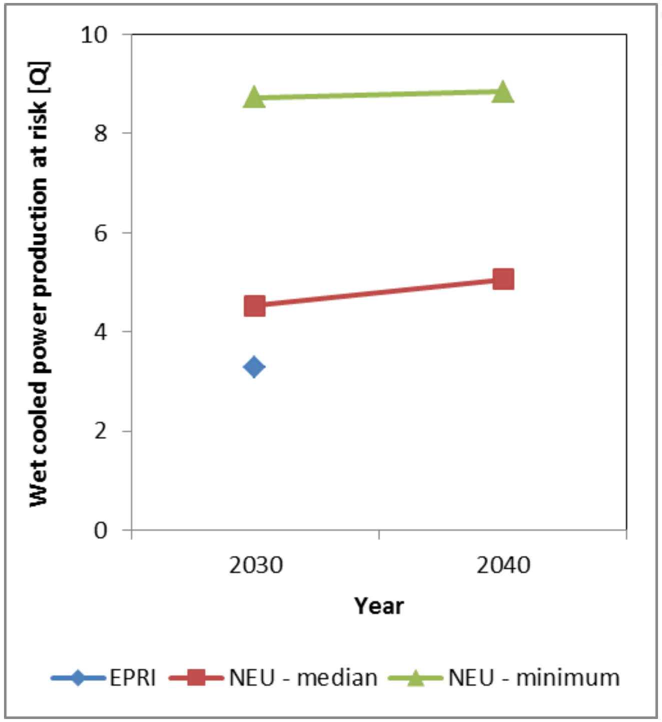
Between 4.5 and 9 Quads of power production could be at risk between 2030 and 2040



Aggregate wet cooled power production in counties at risk



Based only on water availability

(does not account for power at risk from rising water temperatures)

Conclusion: Continued Reliance on Water Cooling for Thermoelectric Power Plants is Risky

- Negative water recharge expected to grow significantly over next 15 years

- More stringent EPA regulations on water intake and thermal discharge will render once-through cooling obsolete

- Rising water temperatures adversely impact power production and efficiency
  - Potential for more frequent curtailment events
  - **EPRI study: 3° C rise in condenser temperature results in 1% reduction in power production**

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State of the Art:
Air Cooling vs Water Cooling

…

you guys know this already

The ARID Program Vision
and
Transformative Technology Solutions

Program Approach

ARID Program	
Kickoff Year	2015
Projects	14
Investment	$30 Million

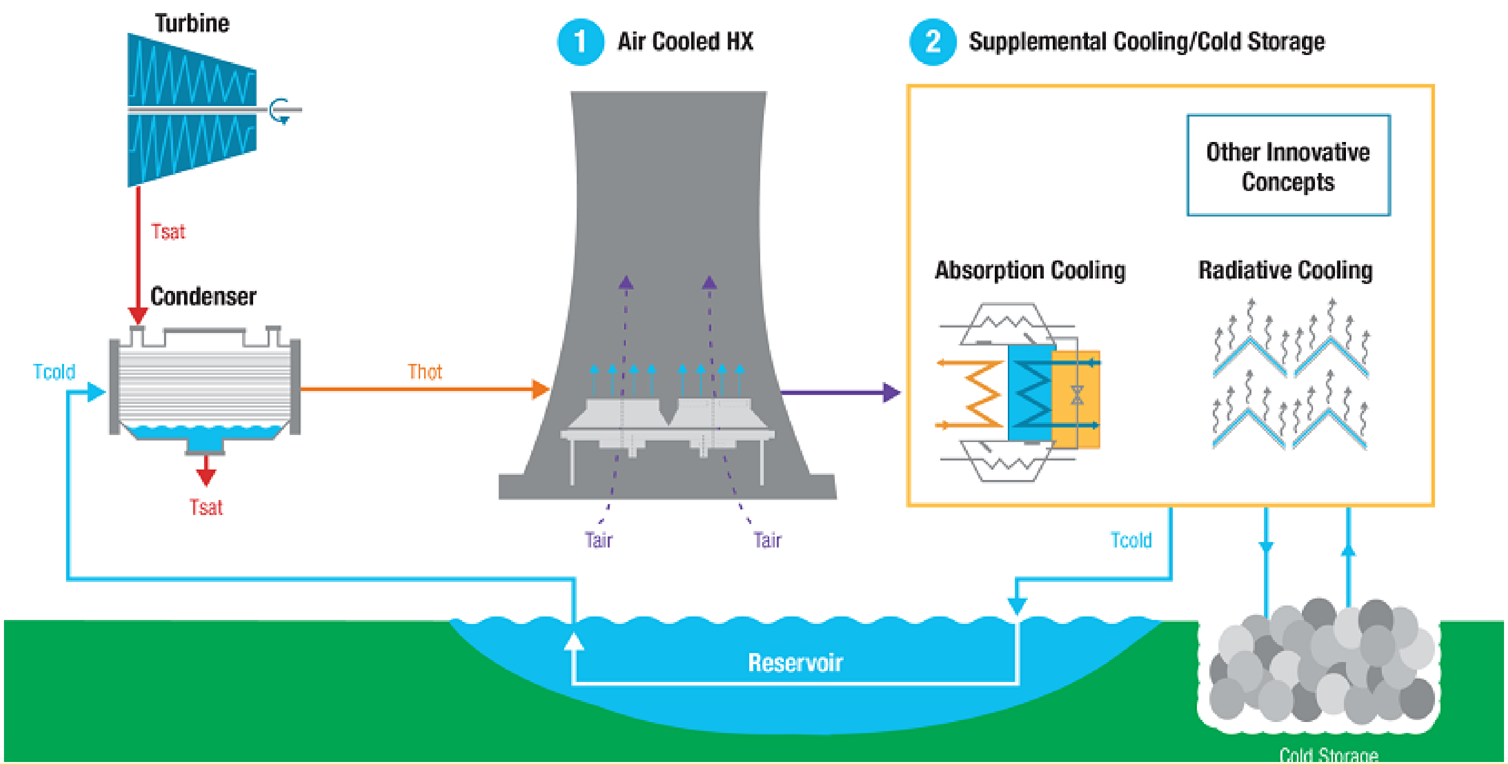
Approach:

- Combine expertise from thermal engineering and manufacturing community to realize new indirect dry-cooling concepts at low cost
- Drastically enhance air side heat transfer coefficient with minimal pressure drop increase
- Sorption cooling systems with COP >2
- Integration of cool storage systems to mitigate temperature excursions
- Radiative supplemental cooling

Program Technologies (14 total)

- Air-cooling heat exchangers (3 projects)
- Sorption & other supplemental cooling (4 projects)
- Radiative cooling and cool storage (3 projects)
- Flue gas H_2O recovery & cool storage (2 projects)
- Combined ACC & cool storage (2 projects)

Sample Indirect Dry-Cooling System that Satisfies ARID Program Objectives



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Category 1: Air cooling systems

Subcategory 1A: Metallic Air-Cooling HX

Description	Target
Air-side heat transfer coefficient (h_{air})	$h_{air} \geq 5\ h_{air,base}$
Pressure gradient	$\Delta P/\Delta L \leq 1.5\ (\Delta P/\Delta L)_{base}$
Capital cost of HX	Cost ≤ \$50/kW_{th}

Explanations:

The baseline heat transfer coefficient and pressure gradient are taken to be those shown in Figure 3 for Reynolds number between 1000 and 2000.

Subcategory 1B: Other Air-Cooling HX

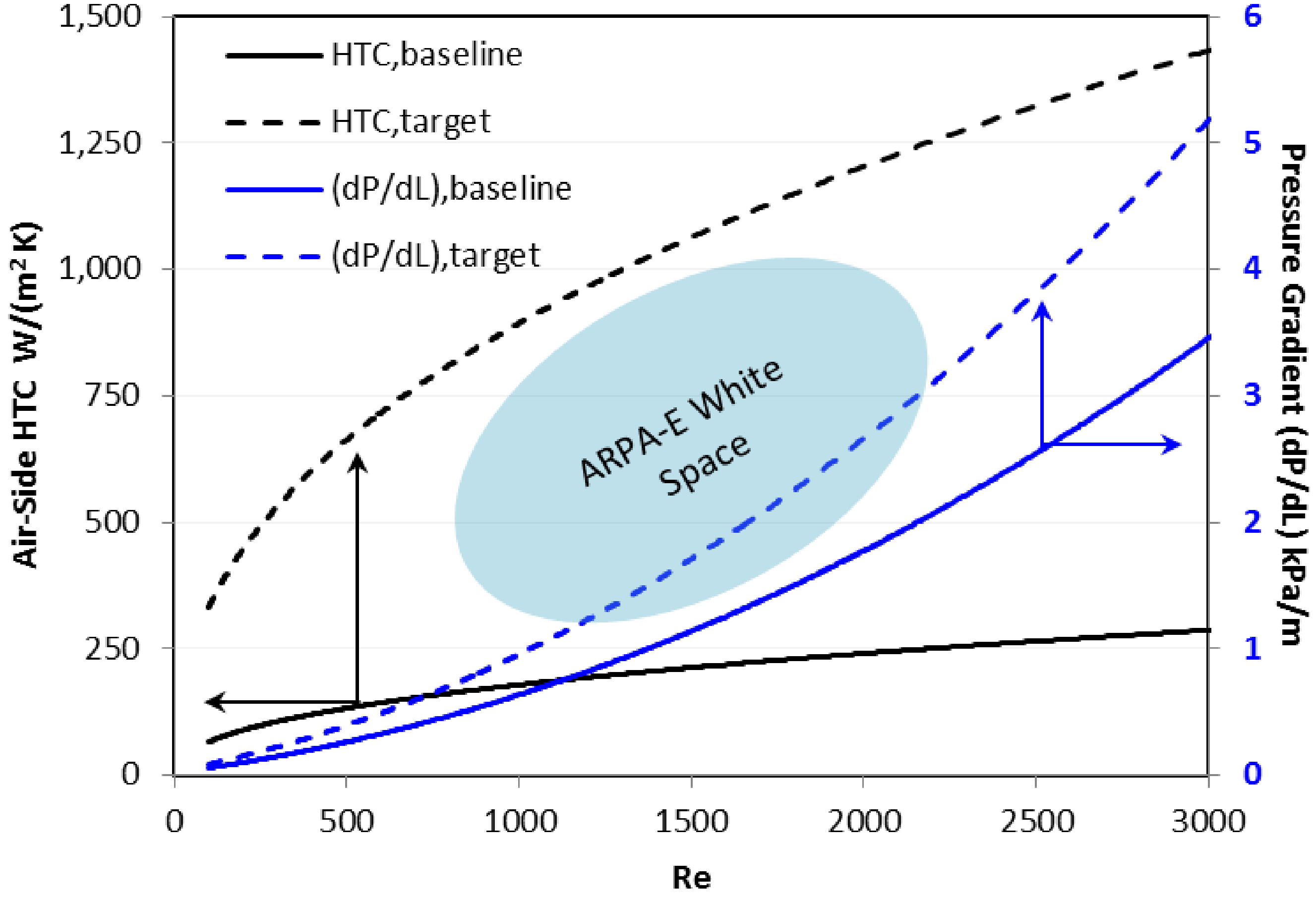
Description	Target
Heat exchanger coefficient of performance COP_{HX},	$COP_{HX} \geq 200$
Heat exchanger effectiveness ε	$\varepsilon > 0.6$
Capital cost of HX	Cost ≤ \$50/kW_{th}

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

Transformative Advancement in Air Side Convection



Category 1 technologies - themes

Category 1B: Low Cost Air-cooled Heat Exchangers

Low cost polymer HXs enabled by AM

Low cost PCM-based rotary HX

ACHX and Cool Storage

HX w/ surface features to promote vorticity for HTC enhancement + cool storage

Category 1A: High Performance Metallic Heat Exchangers

High performance metallic HXs enabled by AM

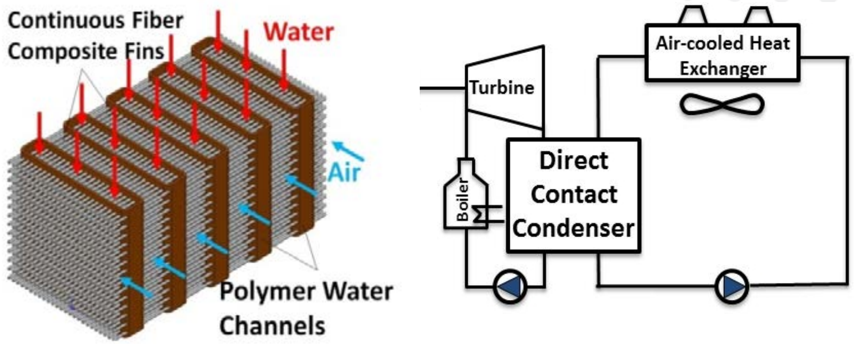
ARID Project – University of Maryland

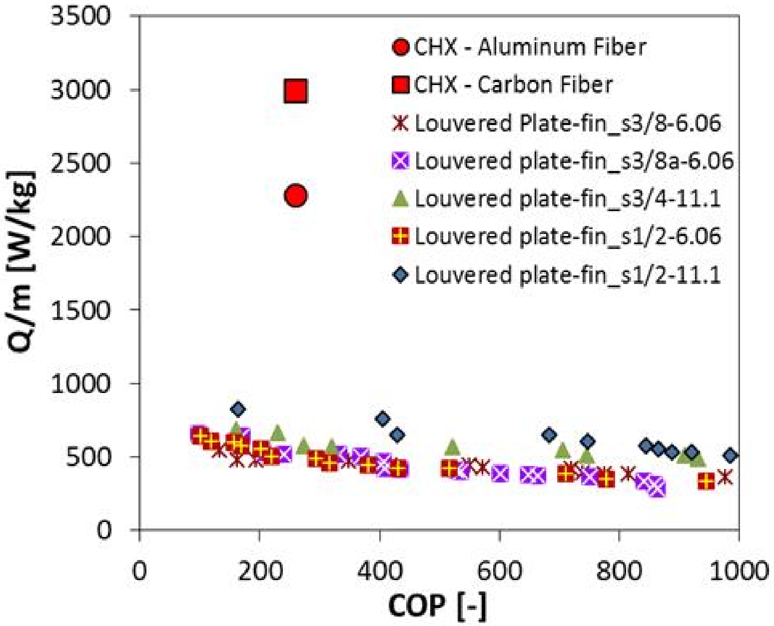
Novel Polymer Composite Heat Exchanger for Dry Cooling of Power Plants

Funding:	$1.9 million
Tech Area:	Air-cooled Heat Exchangers
Location:	College Park, MD

<u>Technology & Impact</u>

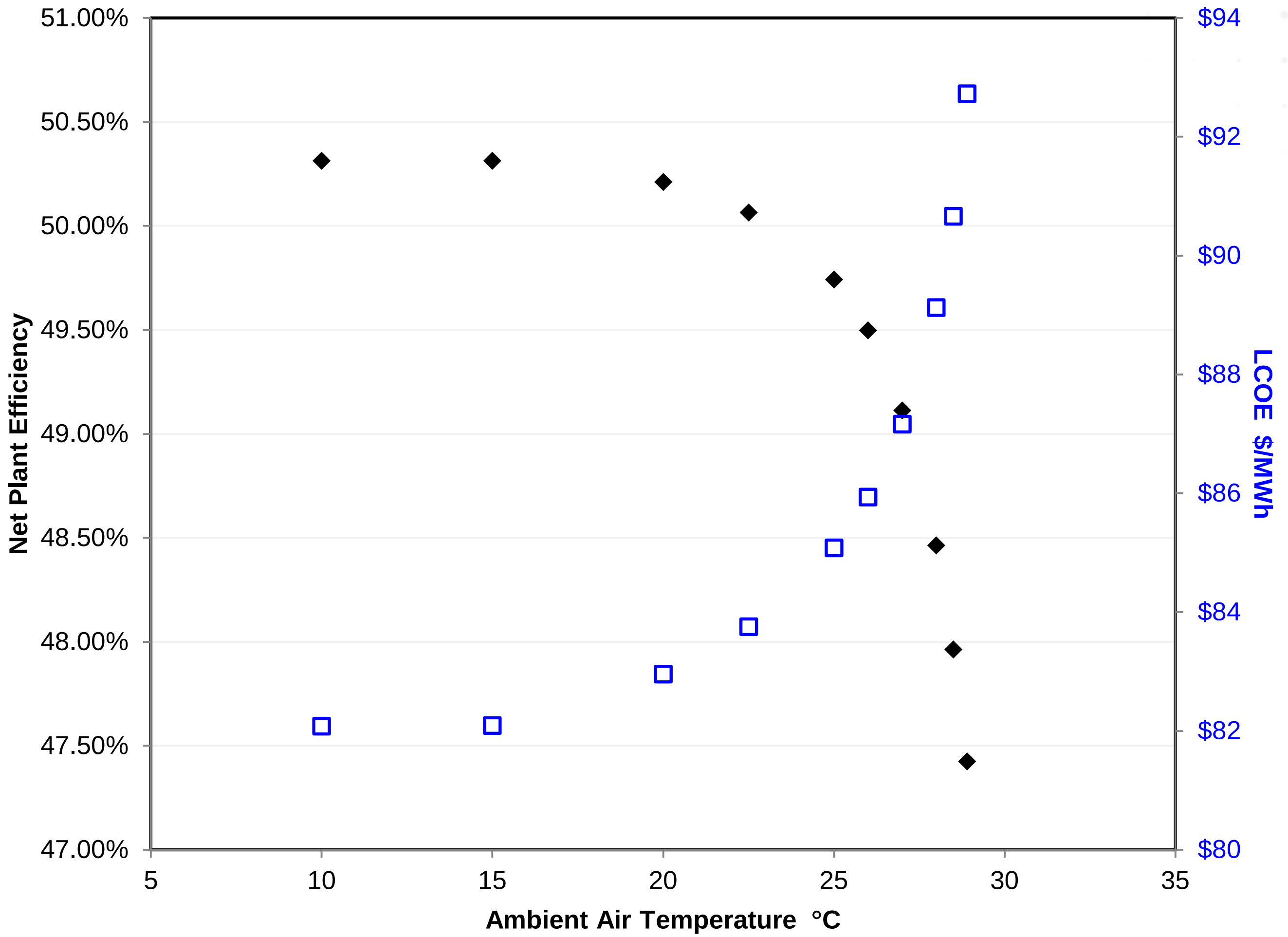
- Polymer based composite heat exchanger manufactured via advanced additive manufacturing.
- Potential for very low-cost and high COP (>200)
- High air-side heat transfer coefficient enhancement
- Potential for on site additive manufacturing





Category 2: Supplemental Cooling & Cold Storage

Need for Supplemental Cooling—Plant Efficiency Falloff with Increasing Air Temperature



Sub-category 2a: Sorption/Desorption Cooling System

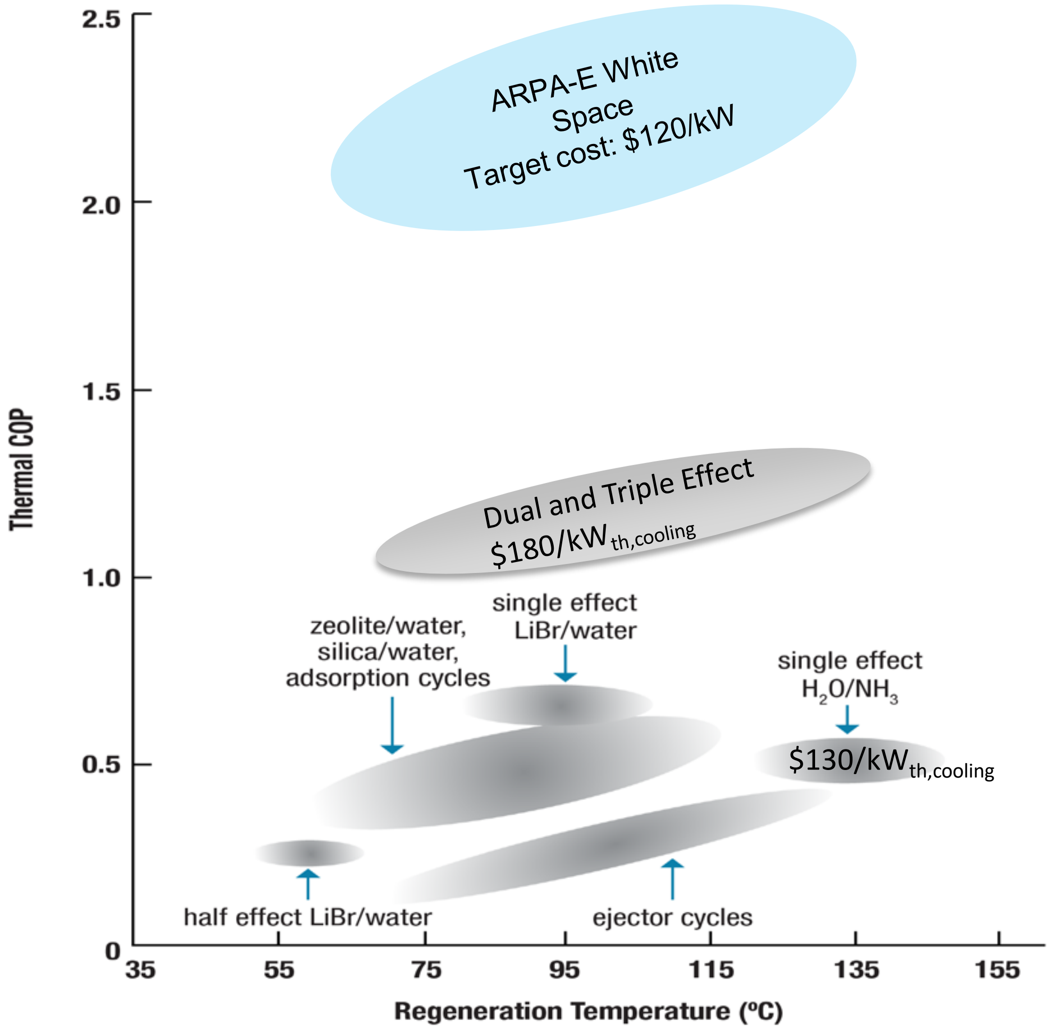
Description	Target
Cooling system coefficient of performance COP_{cool}	$COP_{cool} \geq 2$
Capital cost of system	Cost ≤ $150/$kW_{th}$
Regeneration temperature, T_{regen}	T_{regen} = 60–80°C

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.

Absorption Cooling



Sub-category 2A technologies

Liquid desiccant sorption cooling w/ liquid desorption

High speed turbo-compressor for vapor compression

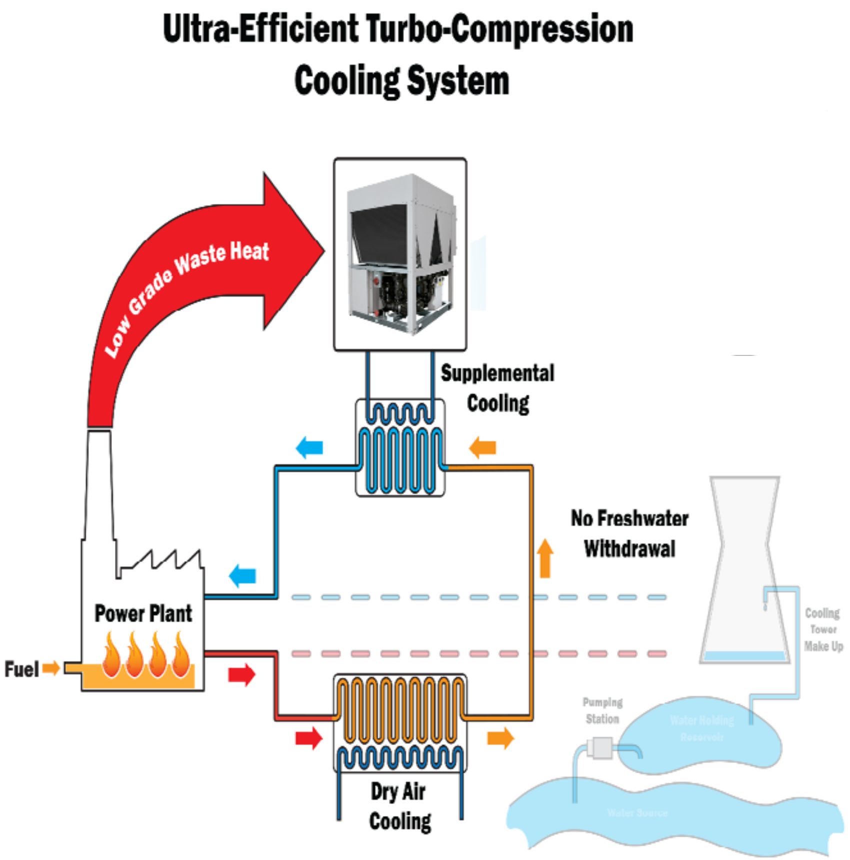
ARID Project – Colorado State University

Ultra-efficient Turbo-Compression Cooling

Funding:	$1.9 million
Tech Area:	Supplemental Cooling
Location:	Fort Collins, CO

Technology & Impact:

- Dry cooling driven by flue gas waste heat
- Optimal working fluids used in separate power and cooling cycles
- Highly efficient turbo-compressor enables transformational thermally activated cooling COP under realistic conditions.
- Heat exchanger technology developed for HVAC and large vehicle industries enables modularity and low system capital cost.
- MW-scale, domestically fueled power plants are made feasible in arid regions



Sub-category 2B: Multimode (Convection/Radiative) Cooling

Description	Target
Radiative heat flux $q''_{radiant}$	$q''_{radiant} \geq 100\ W/m^2$
Capital cost of system	Cost $\leq \$150/kW_{th}$

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.

Sub-category 2B technologies

Low cost R2R manufacturing of radiative cooling modules

Low cost polymer radiative “surface blanket”

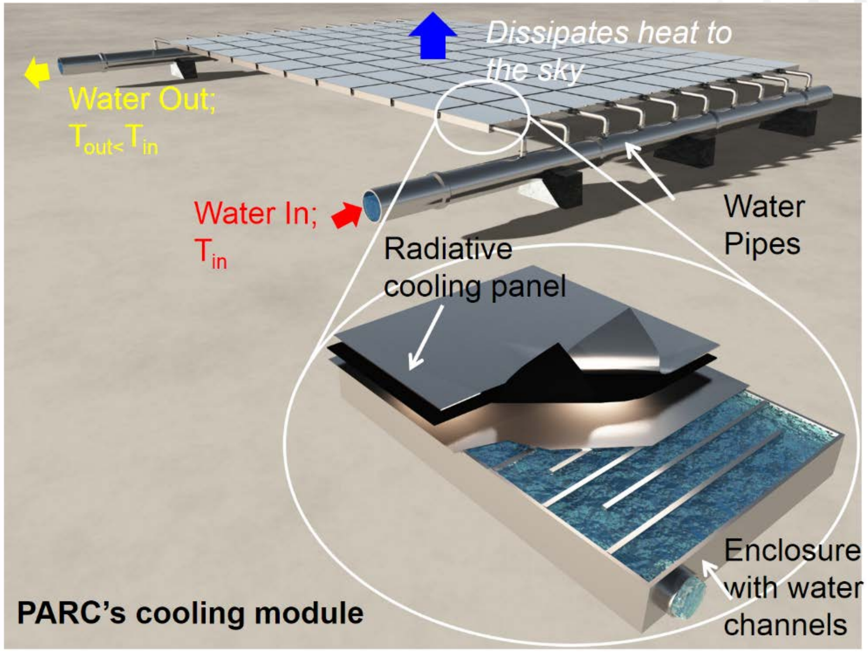
ARID Project – Palo Alto Research Center

Metamaterials-Enhanced Passive Radiative Cooling Panels

Funding:	$1 million
Tech Area:	Radiative Cooling
Location:	Palo Alto, CA

Technology & Impact

- Scalable and low-cost passive radiative cooling architecture, capable of "self-cooling" water temperatures 8^{o}C below ambient temperatures
- Novel metamaterial surface consists of engineered nanostructures tailored to exhibit an emissivity close to unity, emitting heat in the atmospheric transparency window (8-13 μm)
- Key innovation is a simple photonic design that is scalable to a large-are roll-to-roll process that does not require expensive photolithographic patterning



Sub-category 2C: Cool Storage System

Description	Target
Prototype storage capacity P_{cool}	P_{cool} = 200–500 kWh
Time to fully charge t_{charge}	$t_{charge} \leq 10$ h
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.

Sub-category 2C Technologies

Polymerization/Depolymerization thermochemical cycle w/ cool storage

Advanced passive thermosyphon for stack gas water extraction

Heat pipe w/ self-agitated fins & PCM bath

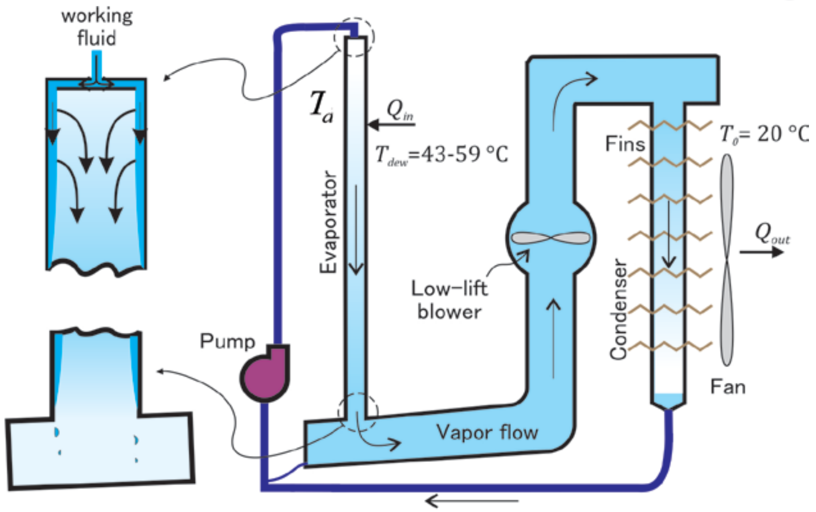
ARID Project – Stony Brook University

Condensing Flue Gas Water Vapor for Cool Storage

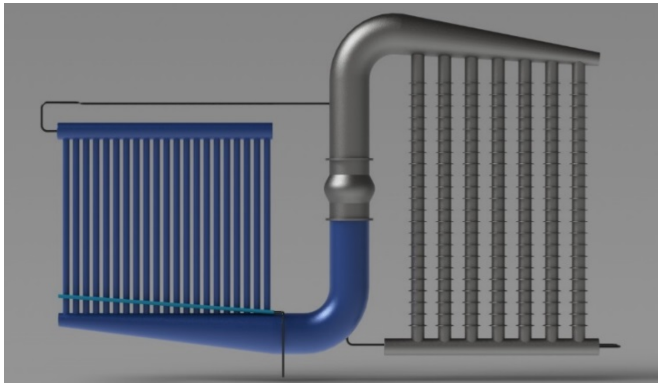
Funding:	$2.5 million
Tech Area:	H_2O Recovery
Location:	Stony Brook, NY

<u>Technology & Impact</u>

- Use advanced, high-performance two-phase thermosyphon to condense flue gas using ambient temperatures only
- Develop high-thermal-conductivity polymer heat exchanger components for flue-gas HX
- Optional blower to increase performance on demand
- Captures 320,000 gallons /day for evaporative cooling that would otherwise be lost to atmosphere



Loop Thermosyphon with Active Fluid Management and Blower



Thermosyphon Module Concept

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- Technical marketing
- Techno-economic analyses
- Stakeholder outreach

Fellow

- Independent energy technology development
- Program Director support
- Organizational support

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