DISTRIBUTED ENERGY PROGRAM REPORT

Review of Thermally Activated Technologies

July 2004

By

TIAX LLC

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Abstract for TIAX Report, "Review of Thermally Activated Technologies"

At the request of the U.S. Department of Energy, the Distributed Energy Program, and Oak Ridge National Laboratory, TIAX reviewed the status of various Thermally Activated Technologies (TATs). We assessed each TAT based on its potential for further significant energy savings and cost reductions. The review included both fuel-fired and waste-heat-fired applications of thermally-driven cooling systems, thermally-driven heat pumps, and thermally-driven bottoming cycles, primarily for use in commercial buildings. Technology attributes assessed include current technical and market status, energy savings potential, end-user economic attractiveness, and opportunities for improvement.

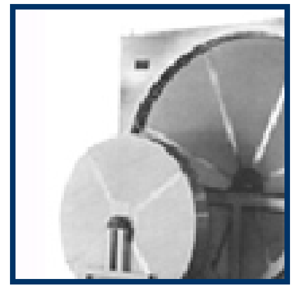
TAT sales for U.S. commercial building applications are small due to poor economics in much of the country. While TAT sales are robust in other parts of the world (such as Japan and China), the factors contributing to those high sales (such as favorable utility rate structures, government policies, and grid reliability concerns) generally do not exist in the U.S. TATs are used in the U.S. where electric demand charges are particularly high, where other incentives for peak-load reduction are offered, or where end users have very long-term investment horizons.

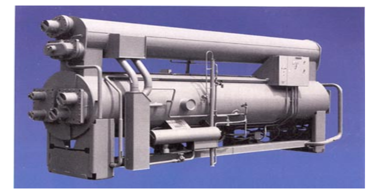
TATs can provide significant energy savings in waste-heat-fired applications, as part of Combined Heat and Power (CHP) systems. For example, TATs can increase the energy savings associated with commercial building CHP systems by 10 to 25 percent in southern climates while improving economics. Development needs to further tailor TATs for CHP applications including optimization for use with CHP, integration into CHP systems, packaged air-cooled CHP systems, Organic Rankine Cycle (ORC) generator system improvement, and optimization of desiccant wheels for post-processing system configurations.

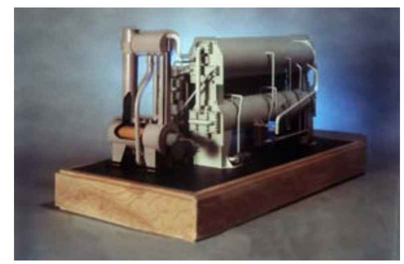
TATs generally offer limited national energy-savings benefits in fuel-fired applications, with one important exception. DOE-sponsored development efforts have advanced reversible (heating and cooling) absorption heat-pump technology to the point where it can achieve significant energy savings in the heating mode, but with some compromise on energy efficiency in the cooling mode relative to electric alternatives. A heating-only absorption heat pump could be significantly less expensive relative to a reversible heat pump, with even greater energy efficiency and energy cost savings.

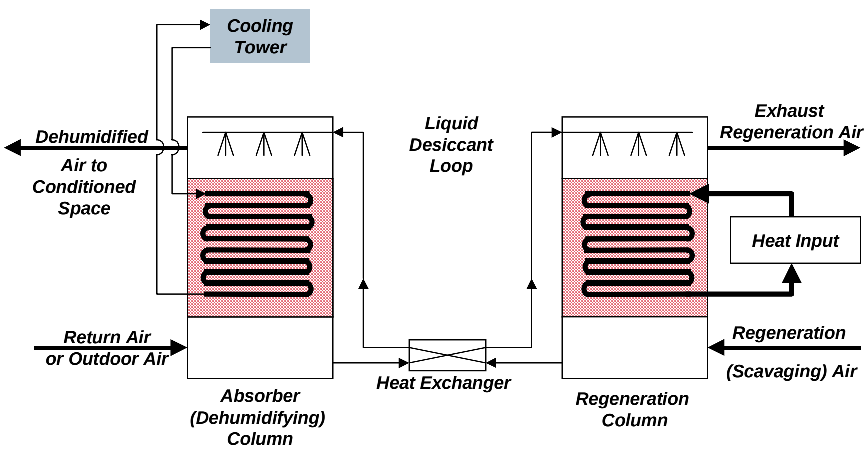
Although not yet properly evaluated, there are novel applications of waste heat that may have merit, including desalination, wastewater treatment, hazardous waste concentration, water purification, and fuel conversion to hydrogen. Further investigation of the impacts of thermal storage on waste-heat utilization is also warranted.

DOE/ORNL asked TIAX to review Thermally Activated Technologies (TATs) to highlight potential for improvement.









DOE has contributed significantly to the development of TAT.

- DOE has supported development of TAT since the 1970's:
  - LiBr chillers: double-effect, triple-effect, air-cooled, solar-heated
  - GAX
  - Desiccant systems
- In FY03 the DOE TAT Program funded development of a specific group of TATs: GAX, Chemisorption, Liquid Desiccant, Solid Desiccant
- Development of other TATs (i.e., ORC, Waste-heat-fired LiBr-Water absorption) has been funded through other DOE initiatives
- Recent History
  - Shift in focus from fuel-fired to waste-heat fired
  - TIAX TAT R&D Needs Study (Late 2002)
  - TAT Roadmap Process (Nov 2002 -- May 2003)

We reviewed a range of Thermally Activated Technologies (TATs).

Thermally Driven Cooling**:** Technologies that use heat to provide cooling/dehumidification functions:

- Absorption
  - LiBr-Water
  - Ammonia-Water
- Desiccants
  - Solid
  - Liquid

Thermally Driven Heat Pumps**:** Technologies that use heat to drive heat-pump thermodynamic cycles for both cooling and heating functions:

- GAX

Thermally Driven Bottoming Cycles**:** Technologies that use low-grade heat to generate shaft power (or electricity):

- Steam cycles
- Organic Rankine Cycle Engines

Our investigation focussed primarily (but not exclusively) on commercial building applications.

There are two fundamental sources of heat for TAT.

- Fuel Firing:
  - The heat is supplied by a dedicated burner usually using natural gas, whether the TAT is fired directly or indirectly
- Recycled Heat:
  - Utilizes reject heat from on-site power systems (I.C. Engines, Microturbines, Fuel Cells, etc) - such systems are a focus of the ongoing DOE/ORNL BCHP projects for commercial buildings

We addressed the following technology attributes focussing on the potential for further significant energy savings and cost reductions.

- Current technical and market status
- Energy savings potential
- End-User Economic Attractiveness
- Opportunities for Improvement.

The DOE is now addressing several issues that will impact the future direction of the TAT program.

- What is the current technology and market status of the various TAT options?
- What are benefits of TAT, such as energy savings potential and electric grid support in both the fuel-fired and waste-heat-fired operating modes?
- What are the opportunities for performance or capital cost improvements that could lead to larger markets, increased national benefits, and increased industry participation?

Currently, the sales of TAT for commercial building applications in the United States are low.

TAT Option	Typical Capacity	US Sales (Units/Year)	Technical Potential[1] (Units/Year)	Notes
LiBr-Water Absorption	200 - 2,000 tons	200	2,000 - 3,000	
Ammonia - Water Absorption	3 to 5 tons, multi-ple up to 25 tons	~2,000	2,000,000+	
Desiccants	5,000 to 10,000 cfm	~3,000	N/A	Primarily niche markets with premium on humidity control
Rankine Engines	100's of kW	<100	N/A	Current market represents primarily industrial installations.

The sales of LiBr-Water absorption units has dropped dramaticaly over the last decade due at least in part to gas industry deregulation (i.e., fewer incentive/rebate programs).

[1]Number of electric units that would be displaced if the TAT were used in all technically feasible installations.

Large interest in TAT in other parts of the world are due to different utility rate structures, government policies, and/or grid reliability concerns.

- Total worldwide production of LiBr-water chillers is on the order of 5,000 units annually
- Sales of absorption equipment are high in Asia, particularly Japan and China
- Japan: Utility rate structures established to limit electric demand growth, favor use of gas-fired equipment
- China: Grid reliability concerns makes electric-powered equipment less attractive

The factors favoring high sales levels in Japan and China do not exist in U.S. markets. All US manufacture of LiBr chillers has moved off shore to be closer to markets and to benefit from lower manufacturing cost structures.

The current limited status of TAT in the U.S. reflects the marginal economics in most applications.

- Most US sales of TAT are currently in fuel-fired applications using natural gas
- In such applications the payback periods are usually longer than acceptable for most building operators
- Current sales are usually in selected areas with very high demand charges or other peak-load-reduction incentives, or for end users having long-term investment horizons (such as universities)

The national benefits of TAT depend significantly on the source of heat used to drive the processes.

National Benefits - Impact on Primary Energy Use:

Fuel-Fired:

- There are limited opportunities for primary energy savings as compared to conventional electric vapor-compression equipment
- If compared to new central power generation being installed (increasingly GTCC), the primary energy use comparison becomes even more difficult

Waste-Heat Driven (in CHP systems):

- TAT will increase energy savings of CHP systems by 10-25% in southern climates having large, long-duration, air-conditioning loads (due to the effective use of waste heat that would otherwise be "dumped")

The economics of TAT depend significantly on utility rate structures.

National Benefits - Impact on Energy Infrastructure;

- TAT technologies provide their output (air conditioning) preferentially during utility peak periods
- TAT technologies therefore, can significantly reduce peak-load requirements (by about 0.6 kW per ton) for commercial buildings with associated benefits for the electric utility infrastructure
- The direct benefits provided by TAT (and DG) in electric infrastructure support (such as deferred T&D investment) are not yet recognized in commercial practice and, therefore, have minimal impact on sales
- A primary motivation for current sales of TAT (particularly absorption) is to reduce high electric demand charges associated with peak air-conditioning loads (an indirect recognition of the value of infrastructure support)

Further development of fuel-fired LiBr absorption is unlikely to provide significant primary energy savings.

Technology Status:

- Over the last decade the performance of LiBr chillers has improved due to DOE- and industry-sponsored efforts (for example, the COP of double-effect absorption has increased from 1.0 to 1.3)
- Even triple-effect LiBr absorption will not contribute significantly to energy savings relative to best available electric chillers
- Due to these prior efforts, LiBr chillers are now approaching their potential limits in performance (COP, capacity, etc) based on thermodynamic and material compatibility considerations
- Advanced heat-exchanger concepts offer some potential for cost reductions due, in large part, to the large heat-transfer areas required (up to 3 times as much as in vapor-compression equipment)

Development of a heating-only GAX heat pump may provide significant national benefits.

- DOE support of the GAX program over nearly two decades has resulted in technology on the verge of production, with significantly better cost and performance characteristics relative to previous ammonia-water systems
- While the potential exists for significant heating-season energy savings with a GAX heat pump, cooling-season energy use will likely increase, and market acceptance must still be tested
- A heating-only GAX heat pump could be significantly less expensive relative to heating/cooling GAX[1], with greater energy efficiency and energy-cost savings (about 40% energy savings or more for heating). Economics may, however, limit the market to applications having high capacity factors.

1) Of course, in many applications, a conventional electric cooling system will still be needed, but the combined cost of a heating-only GAX and a conventional electric cooling system could be roughly the same as the cost of a heating and cooling GAX system alone.

Desiccants may have a role in educational, supermarket, and other commercial applications requiring improved humidity control.

- The market viability of fuel-fired desiccant systems depends on taking advantage of these systems' dehumidification benefits where careful humidity control is needed
- Solid desiccant post-processing designs, which are currently being commercialized, make these systems more energy efficient relative to previous generations of solid-desiccant systems, but even these improvements may not achieve original energy-saving goals in mainstream HVAC applications.
- Liquid-desiccant systems can save energy (~5%) in dedicated outdoor air systems (DOAS), but their market potential uncertain.

Effective integration of TAT with CHP systems can improve the energy savings and economics of CHP.

- The largest national benefits of TAT derive from their integration with DG technologies in CHP architectures
- Use of TAT with DG can improve economics, particularly for microturbines
- Most TATs have been developed for direct-fired applications that allow for flexible control of temperatures/flow rates and associated interface heat-exchanger designs
- The temperature levels, flow rates, and form (gases, or liquids) of waste-heat streams from DG vary widely and are different than those available from direct-fired equipment
- Organic Rankine Cycles (ORC) may have similar economics to LiBr chillers, and (since electricity is produced) they can serve non-cooling loads as well

TAT options exist for use with current and future DG technologies.

	DG Technology	Waste-Heat Medium	Typical Waste-Heat Temp.		TAT
			Liquid	Gases	
Current	Combustion Turbines	Flue Gas	NA	800 to 1,100	LiBr Absorption (1E, 2E, 3E), Steam Rankine
Current	Diesel Engines	Flue Gas, Coolant	200	700 to 1,000	LiBr Absorption (primarily 1E), Organic Rankine
Current	Natural Gas Engines	Flue Gas, Coolant	200	700 to 1,000	LiBr Absorption (primarily 1E), Organic Rankine
Current	Microturbine (recuperated)	Flue Gas	NA	450 to 600	LiBr Absorption (1E, 2E), Ammonia-water Absorption, Desiccants, Organic Rankine
Emerging	Current Pem Fuel Cells	Coolant	160	120 to 170	Perhaps Desiccants
Emerging	Phosphoric Acid Fuel Cells	Flue Gas, Coolant		350 to 400	LiBr Absorption (1E), Ammonia-Water Absorption, Desiccants, Organic Rankine
Future	Molten Carbonate Fuel Cells	Flue Gas	NA	700 to 800	LiBr Absorption (1E, 2E, 3E), Steam Rankine
Future	High Temp. PEM Fuel Cells	Primarily Coolant	280	230 to 300	Ammonia-water Absorption, Desiccants, Organic Rankine
Future	Solid Oxide Fuel Cells	Flue Gas	NA	350 to 400	LiBr Absorption (1E), Ammonia-Water Absorption, Desiccants, Organic Rankine

There are several developments needed to tailor TAT for CHP.

- Optimization of TAT for CHP (including heat exchangers)
- CHP system integration
- Air-cooled TAT to improve market acceptance: air-cooled LiBr-Water chiller for medium-sized buildings, larger capacity low inventory ammonia-water air-cooled absorption, air-cooled liquid desiccant technology
- ORC system improvement potential through more aggressive system design: water cooling, interchangers
- Optimization of desiccant wheels for “post-processing” system configuration[1]

1) There are also development needs for fuel-fired modes to reach full potential.

While not yet properly evaluated, use of waste heat for alternative applications may have merit.

- Alternative uses of waste heat:
  - Fuel conversion to hydrogen
  - Desalination[1]
  - Waste water treatment[1]
  - Hazardous waste concentration[1]
  - Water purification[1]
- Impact of thermal storage on utilization of heat in building and/or industry applications

1) The various water treatment alternatives may have more application in industrial buildings than in commercial buildings.

- Executive Summary
- **Background**
- LiBr-Water Absorption
- Ammonia-Water Absorption
- Desiccant Technologies
- Rankine Cycles
- Other

We performed this assignment through five tasks.

- Task 1: Summarize Current Industry and Technology Status for Selected TATs
- Task 2: Summarize the Economic Attractiveness and Energy Savings Potential for Selected TATs
- Task 3: Outline Improvement Opportunities for TATs
- Task 4: Identify Options for DOE Actions
- Task 5: Reporting/Deliverables

We reviewed both fuel-fired and waste-heat-driven TATs.

Fuel-Fired	Waste-Heat Fired
◆ LiBr-Water Absorption ◆ Ammonia-Water Absorption ◆ Solid Desiccants ◆ Liquid Desiccants	◆ LiBr-Water Absorption ◆ Ammonia-Water Absorption ◆ Solid Desiccants ◆ Liquid Desiccants ◆ Steam Rankine ◆ Organic Rankine

Note: TATs activated with a heat transfer medium (i.e. single-effect absorption) are considered fuel-fired if fuel is burned in another system component such as a boiler for the purpose of creating the heat for the TAT.

Task 1 addressed the current status of key TAT technologies.

- Brief description of applicable TATs.
  - Technical Status
  - Major Equipment Manufacturers (or developers)
  - Typical performance characteristics
  - Typical cost characteristics
  - Current markets
- Results based on use of existing, readily available sources.
  - Draft 2 of the TAT Technology Roadmap (March 2003);
  - TIAX's draft report on TAT R&D needs (December 2002);
  - TIAX's (ADL's) BCHP report (April 2002)
  - Interviews with key stakeholders (ORNL, NREL, equipment manufacturers and developers, utilities, ESCO's)
- TAT Technologies
  - LiBr-Water and Ammonia-Water Absorption (Fuel-Fired & Waste-Heat Driven).
  - Solid and Liquid Desiccant Technology (Fuel-Fired & Waste-Heat Driven).
  - Steam and Organic Rankine Cycles (Waste-Heat Driven).

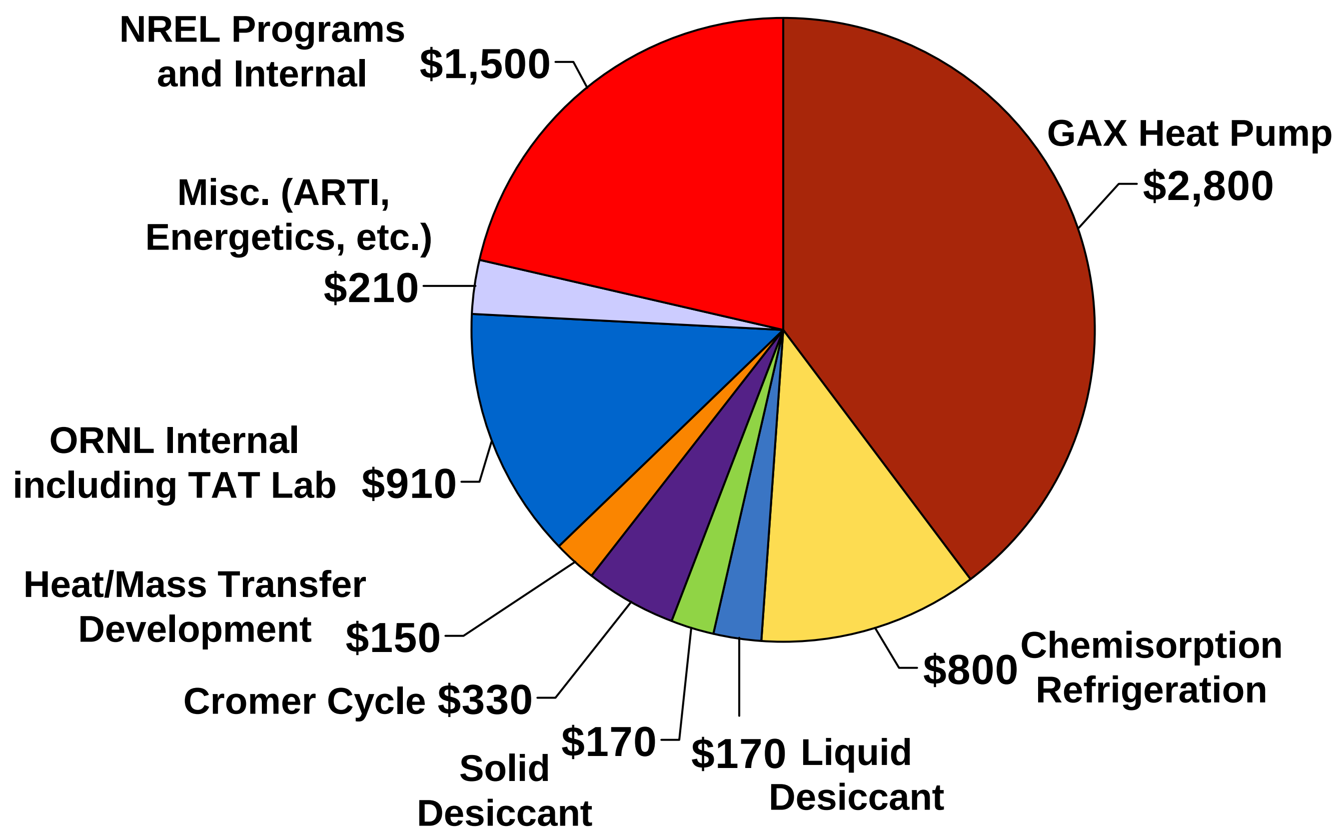
Task 2 addressed energy savings and economic attractiveness of key TAT technologies.

- Is the TAT likely to provide significant primary energy savings?
- Can the TAT address DOE's emerging role in energy infrastructure?
- Can the TAT provide attractive economics in broad commercial building applications?
- What are the major deficiencies of the TAT that limit its commercial applications?

Tasks 3 & 4 outlined technical improvement opportunities and options for DOE action.

- Technology improvements to improve economics and energy savings potential.
- Addressed by the current TAT program?
- Addressed in the draft TAT Technology Roadmap?
- How do the likely R&D costs and risks compare to the targeted benefits?
- Options for DOE Action?

The Thermally Activated Technology Program Budget in FY2003 was roughly $7 Million.

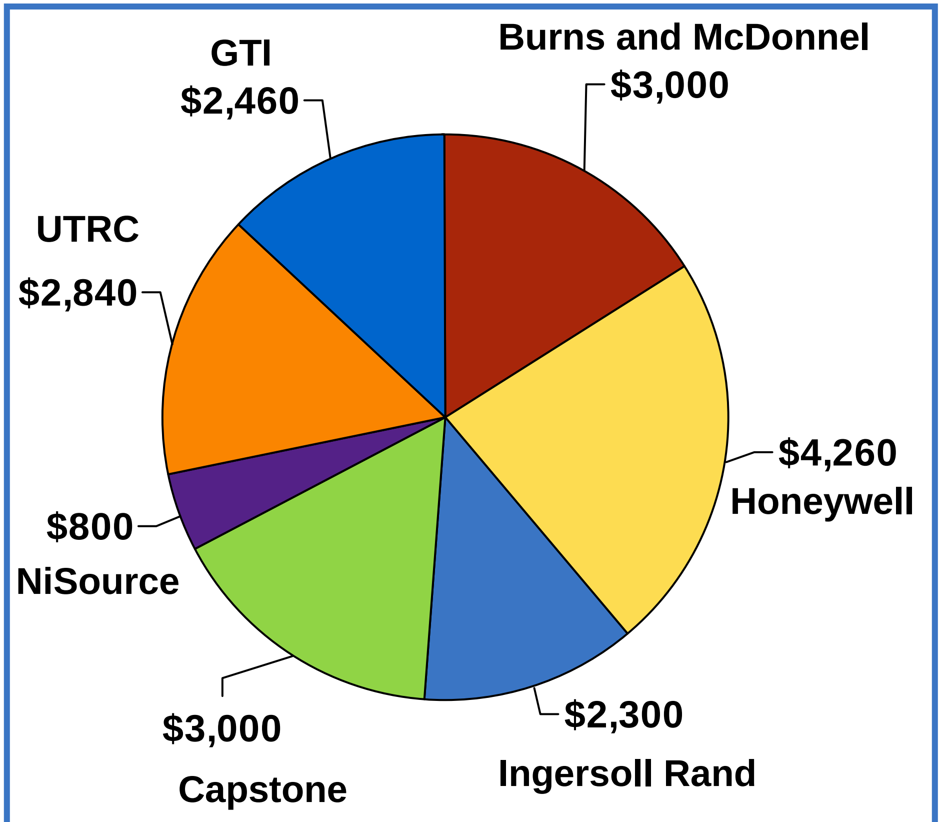


$1,000's
Total $7.04 Million

DOE FY2003 funding for TAT development was about $7 Million.

Development	Companies	FY2003 Funding ($1,000's)
GAX Heat Pump	Rocky Research, Ambian, ITT	$2,800
Chemisorption Refrigeration	Mississippi Energies, Rocky Research	$800
ADM, IADM Desiccant Dehumidification	SEMCO	$170
Liquid Desiccant Outdoor Air Pretreatment Unit	Kathabar, AIL Research	$170
Cromer Cycle	University of Central Florida	$330
Heat and Mass Transfer Technology Improvement	PROJECT NOT YET IDENTIFIED	$150
ORNL internal, including TAT Lab	ORNL	$910
Miscellaneous: ARTI Absorption Pgm, TAT Roadmap, Desiccant Van	ARTI, Energetics, UIC, TBD	$210
NREL Programs	Solid and liquid desiccants, NREL internal, including labs	~$1,500
TAT TOTAL		**~$7,040**

The CHP Program has contributed to development of Thermally Activated Technologies for use in CHP systems.



$1,000's Total $18.7 Million over 3 years

TAT Technology	No. of CHP Programs Using this Technology
1-Effect Absorption	1
2-Effect Absorption	5
NH_3-H_2O Absorption	1
Desiccants	1

The DOE-cofunded Packaged CHP projects also incorporate TAT hardware development oriented towards CHP.

Technologies	Capacity	Prime Contractor	Partners	DOE Award ($ million)
Gas turbine and **LiBr Absorption chillers**	5.2MW; 20,000 RT	Burns & McDonnell, Kansas City, MO	Solar Turbine and Broad USA	$3
Gas turbine and **LiBr Absorption chiller**	2-5 MW; 500-2000 RT	Honeywell, Minneapolis, MN		$4.26
Microturbine and **Ammonia-Water Absorption Refrigeration**	70 kW	Ingersoll Rand, Portsmouth, NH		$2.3
Microturbine, **Absorption chiller and Desiccant system**	60kW	Capstone Turbine Corp., Woodland Hills, CA		$3
Microturbine, heat recovery, **Absorption chiller and desiccant system**	Not available	NiSource, Merrillville, IN		$0.8
Microturbine and **Absorption chillers**	400 kW	United Technologies Research Center, East Hartford, CT	DTE Energy Technologies and Carrier Corp.	$2.84
Gas engines and **Absorption chiller**	290 kW - 770 kW	Gas Technology Institute, Des Plaines IL	Waukesha and The Trane Company	$2.46

These multi-year programs were awarded in 2001.

Other DOE funding of TAT includes Organic Rankine Cycle (ORC).

- Funding of ORC as part of UTRC’s high-efficiency microturbine program.
- No other known significant developments.

The May 2003 DOE TAT Technology Roadmap recommends several TAT hardware development actions[1].

- Develop Advanced Control Systems
- Develop Packaged CHP Rooftop Systems
- Develop Competitive, Compact, Quiet, and Clean Advanced Residential/Commercial (3 to 500 kW) Energy System
- Integrate TAT with Wastewater Treatment, Desalination, and Aquaculture Applications

1) The Roadmap also includes two non-hardware-related actions: 1) Create Linkage and Standards between CHP System Integrators and TAT Manufacturers, and 2) Improve Design and Modeling Tools for Core Systems.

Fuel-fired TAT generally do not save energy in cooling mode, but would save energy in heating mode.

	Conventional	TAT (not including electric power input)
Chiller	0.5 to 0.65 kW/ton Current Grid ~11,000Btu/kWh **Fuel COP 1.7 to 2.2**	Double-Effect: COP 1.2 Triple-Effect: COP 2 (?)
Unitary	EER 10 to 11 Net COP 3.3 to 3.6[1] Current Grid ~11,000Btu/kWh **Fuel COP 1.0 to 1.1**	GAX COP 0.7 (Design) COP 0.84 (Seasonal)
Refrigeration (Low Temperature)	Compressor COP 1 to 1.3 Current Grid ~11,000Btu/kWh **Fuel COP 0.3 to 0.4**	Chemisorption COP 0.25 to 0.3
Heating	Condensing Furnace **COP 0.9** Electric Heat Pump COP 3.1 (@47°F) **Fuel COP ~1**	GAX COP 1.5

[1]Not including 0.12kW/ton blower power

Use of TAT in CHP installations can provide energy savings.

- Distributed generation facilities provide heat that cannot always be used for space, water, and process heating
- TATs provide a way to utilize DG waste heat to displace electric power supplied by the grid
- The magnitude of the energy savings associated with TAT can be up to 20% of primary energy use of a building. This level of savings requires use of waste heat in TAT for upwards of 3,000 hours per year
- There is a good range of TAT technology options which can be integrated with the key current and future DG technologies
- However, optimization of DG/TAT interface and integration will improve CHP system performance, cost, and market acceptance

- Executive Summary
- Background
- **LiBr-Water Absorption**
- Ammonia-Water Absorption
- Desiccant Technologies
- Rankine Cycles
- Other

LiBr-Water absorption systems status summary.

Absorption Technology	LiBr Single-Effect	LiBr Double-Effect	LiBr Triple-Effect
Key Manufacturers and Developers	Trane, McQuay, York, Carrier Broad, Thermax, Yazaki, Kawasaki, Daikin, Sanyo		Recent Past: York, Trane, Currently: Japanese Manufacturers
Capacity Range (tons)[1]	100 - 2,500[4]		>100
Typical COP (Fuel-fired, HHV)[2]	0.7	Up to 1.2 (some claim 1.3)	1.4 (current) 1.8 to 2.0 (projected)
Generator Solution T (°F)[3]	180	320	400 - 500
Installed Cost ($/ton)	$450	$600	Not yet known perhaps $800 to $900
Technical Status	Fully Developed and Commercialized		York work ended with Demo unit operating in Las Vegas. Japanese Companies actively developing.
	Heat input steam or hot water	Heat input steam, hot water, direct-firing.	
Current Markets (includes CHP)	U.S.: Less than 200 units per Worldwide: 3,000 to 5,000 per year, mostly in Asia		Not yet commercialized

1. One ton equals 12,000 Btu/hr.
2. Heat rejection using a cooling tower.
3. Heat Input is at the generator. The reported temperatures represent the highest solution temperature within the generator.
4. Products are available with capacity down to 5 tons, but sales are limited in capacities under 100 tons.

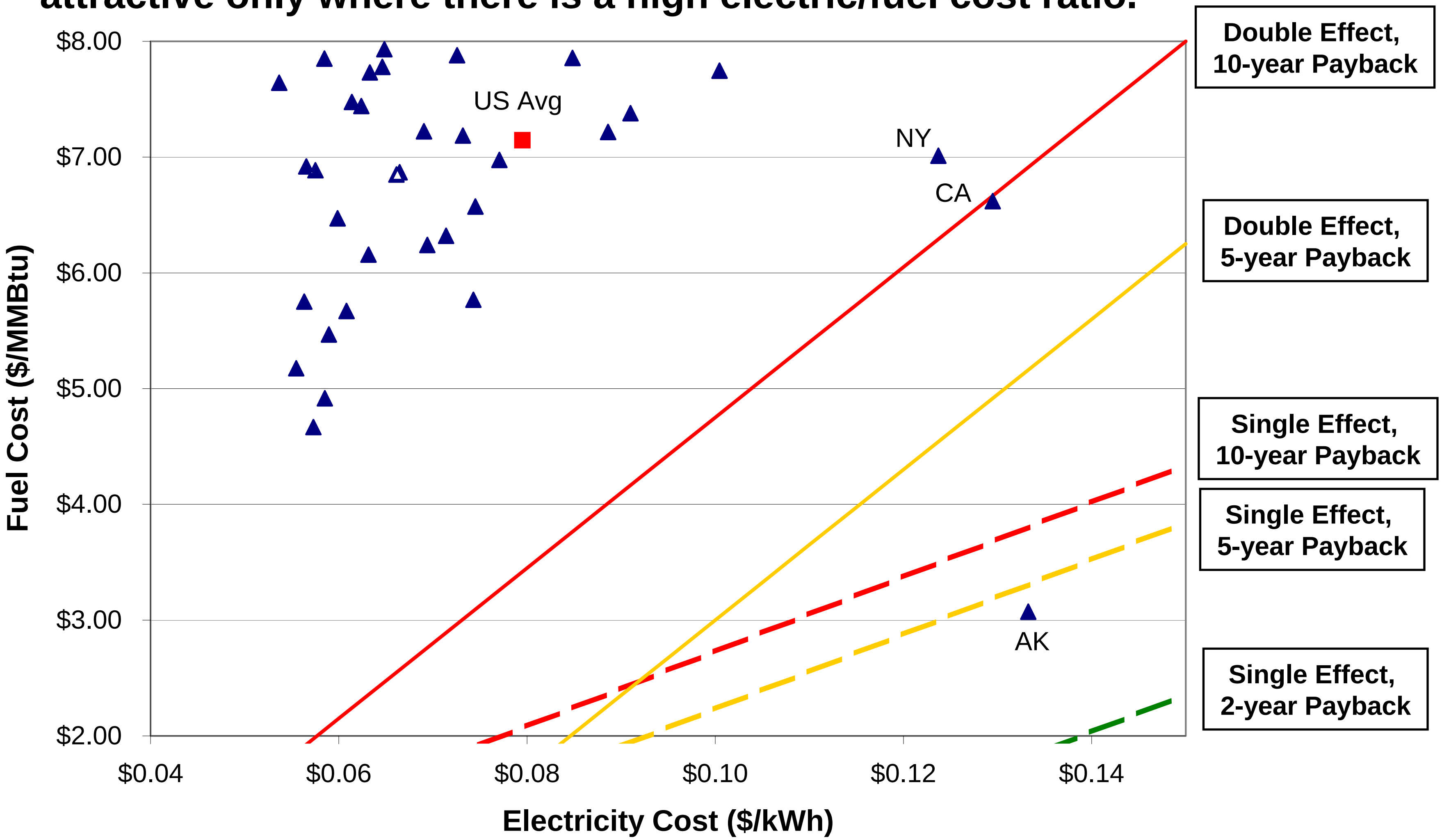
There is limited potential to address DOE's objectives through further development of fuel-fired LiBr-Water Absorption systems.

- **Energy Savings:**
  - Projected triple-effect performance (COP about 2.0) will not reduce energy use as compared with electric-powered equipment in most cases.
  - If compared to marginal power installations (increasingly GTCC) the primary energy use comparison becomes even more difficult.
- **Electric Grid Relief:**
  - The economics of fuel-fired double-effect absorption chillers is not good enough for most U.S. applications to expect significant contributions from additional absorption chiller installations.
  - The economics for triple-effect absorption chillers is not likely to represent enough improvement to change this.
- Much research has already investigated the potential of alternative design approaches for cost reduction or performance improvement
  - Alternative fluids
  - Alternative cycle configurations
  - Solution additives for reduction of crystallization tendency and/or corrosion inhibition
  - Material coatings to reduce corrosion of lower-cost materials

LiBr-Water absorption systems--fuel-fired.

Energy Savings	◆ HHV COP of 1.8 required for parity with 0.6kW/ton electric equipment and average 11,000Btu/kWh grid (not considering electric power for pumps, tower fan). ◆ Current equipment (double-effect) COP is 1.2. ◆ Triple-effect could potentially reach 1.8 to 2.0. ◆ The grid in future and on the margin have better performance.
Electric Grid Relief	◆ All fuel-fired absorption equipment can reduce peak summer electric loads.
Economics	◆ Trends over the last two decades show that interest in absorption is primarily restricted to areas with very favorable utility cost structures and/or utility incentive programs. ◆ Simple calculations show that acceptable economics are achieved only for areas with large electric/fuel utility cost ratios.
Deficiencies for Broad Commercial Markets	◆ High first cost ◆ Slow payback through operating cost savings ◆ Not compatible for buildings which would conventionally be using unitary AC (water-cooled, cost even higher for low capacities, perception of maintenance issues)

Fueled-fired LiBr-Water absorption systems are economically attractive only where there is a high electric/fuel cost ratio.



Assumptions: 2,000 hours/year useful cooling; 0.5kW/ton electric cooling; absorption COP's of 0.7 (1-effect), 1.2 (2-effect); Installed costs $300/ton electric, $450/ton 1-effect, $600/ton 2-effect, added cooling tower premium of $50/ton for absorption systems; absorption system electric power input ignored.

Development to optimize LiBr-Water absorption systems for waste-heat-activation has started.

- Notable CHP-oriented developments
  - UTC Power/Carrier
  - Broad, Thermax: Designs for flue-gas firing with co-firing
  - Trane: Development of absorber designed for low-temp input (engine waste heat) as part of GTI CHP Project
- Technical Approaches
  - Flue-gas firing (with or without cofiring)
  - Intermediate heat transfer medium: steam, water, glycol; can be used with off-the-shelf designs.
- Issues
  - Benefits of double or triple effect? Depends on temperature of waste heat source.
  - Design for dual-use fuel-fired and waste-heat-fired?
  - COP depends on waste heat temperature and integration design, but can be as good or better than fuel-fired COP.
  - Heat exchanger redesign, particularly for generator, to maximize heat input from lower-temperature heat source
- Sales for CHP significant but in the minority.

WASTE-HEAT-FIRED

Improved LiBr-Water absorption system designs for CHP applications will enhance DG technologies by increasing energy savings and improving economics.

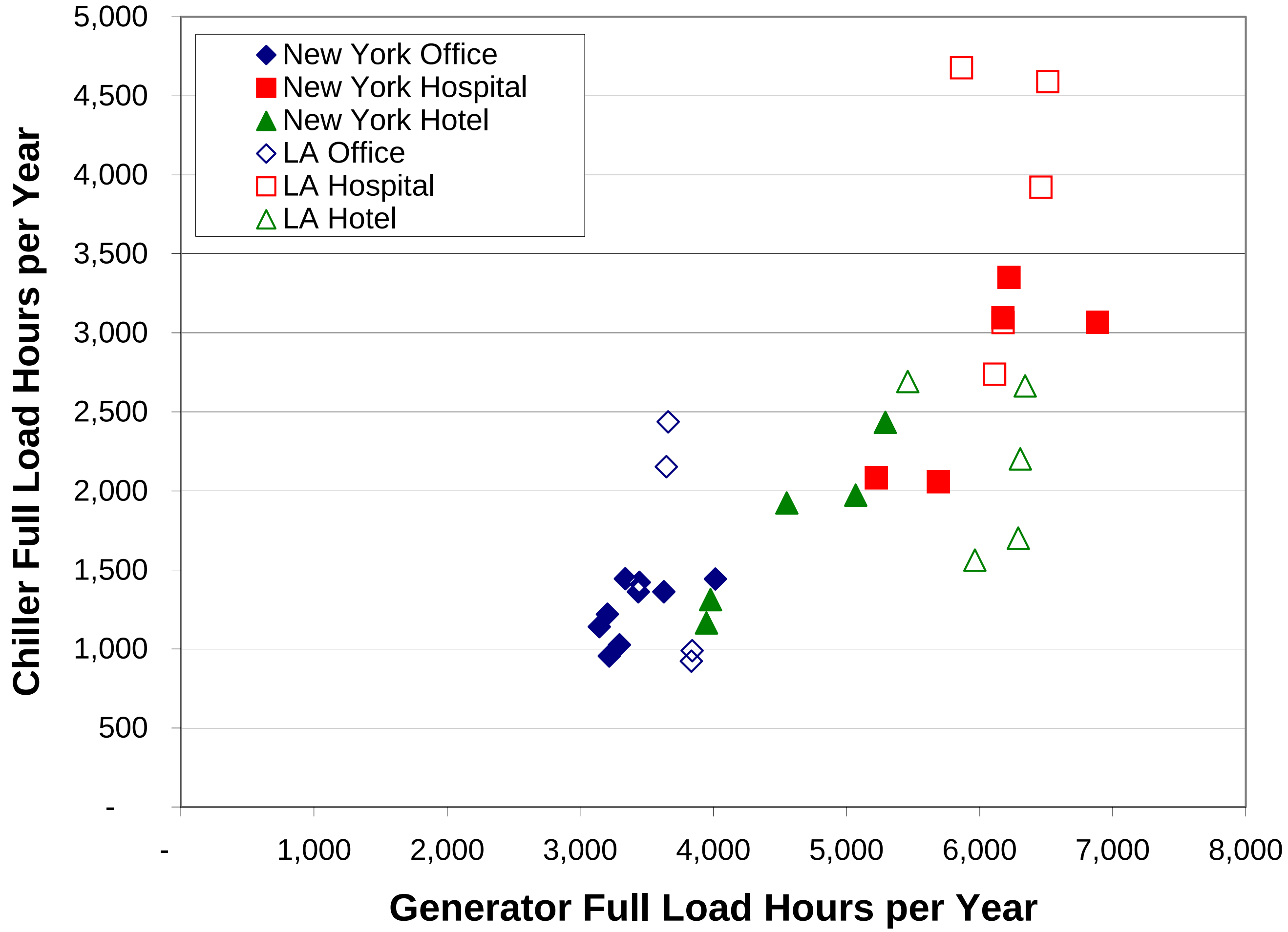
- LiBr-Water absorption technology is well suited for interface with current and future DG technologies
  - Sufficient waste heat at required temperature levels can be recovered from DG power technologies (IC Engines, mircoturbines, combustion turbines, and in future, SOFC) to generate significant cooling capacity with appropriate LiBr-Water absorption systems.
  - The primary interface issues are associated with modifying heat exchangers to transfer the needed heat flows when using waste heat flows from DG power units.
- The limited need for heating in many U.S. commercial buildings makes heat use for absorption chillers the only way to maximize use of CHP energy input.
  - In southern climates absorption technology can increase the effective utilization of waste heat by 30% to 40% (of fuel input) in many building types (office, retail, etc).
  - The associated decreases in primary energy utilization (as compared to DG with heat recovery for space or water heating needs alone) can be on the order of 10% to 20%.
  - The associated energy cost reduction in many cases has a better payback rate than DG alone, thus improving overall economics of the CHP installation.
- However, the market for CHP-oriented LiBr-Water absorption will be determined primarily by the market for building based DG, which adds risks and business uncertainties.

LiBr-Water absorption systems--waste-heat-fired.

Energy Savings	◆ Energy saved through use of waste heat which would otherwise not be utilized. ◆ However, use of waste heat for space/water heating (if needed) saves more. ➢ 1 Btu of waste heat used in a double effect absorber would create ~1.4Btu of cooling, which displaces **~0.64Btu of primary energy**. ➢ 1 Btu of waste heat used for heating displaces **~1.2 Btu primary energy**. ◆ Importance of level of absorber technology depends on generator technology ➢ Triple effect would potentially save the most primary energy when used with Combustion Turbines (~900F exhaust temperature) ➢ Single effect saves the most when used with Engines
Electric Grid Relief	◆ All waste-heat-fired absorption equipment can reduce peak summer electric loads.
Economics	◆ Most studies show that adding CHP to DG installations improves economics.[1] ◆ Economics can be good for specific applications and regions, but are not consistently good. ◆ Economics strongly dependent on the generator technology (generator economics dominate, type and quality of available waste heat).
Deficiencies for Broad Commercial Markets	◆ High first cost. ◆ Complicated economic story and utility rate uncertainty increases risk. ◆ Not compatible for buildings which would conventionally be using unitary AC (water-cooled, cost higher for low capacities, perception of maintenance issues)

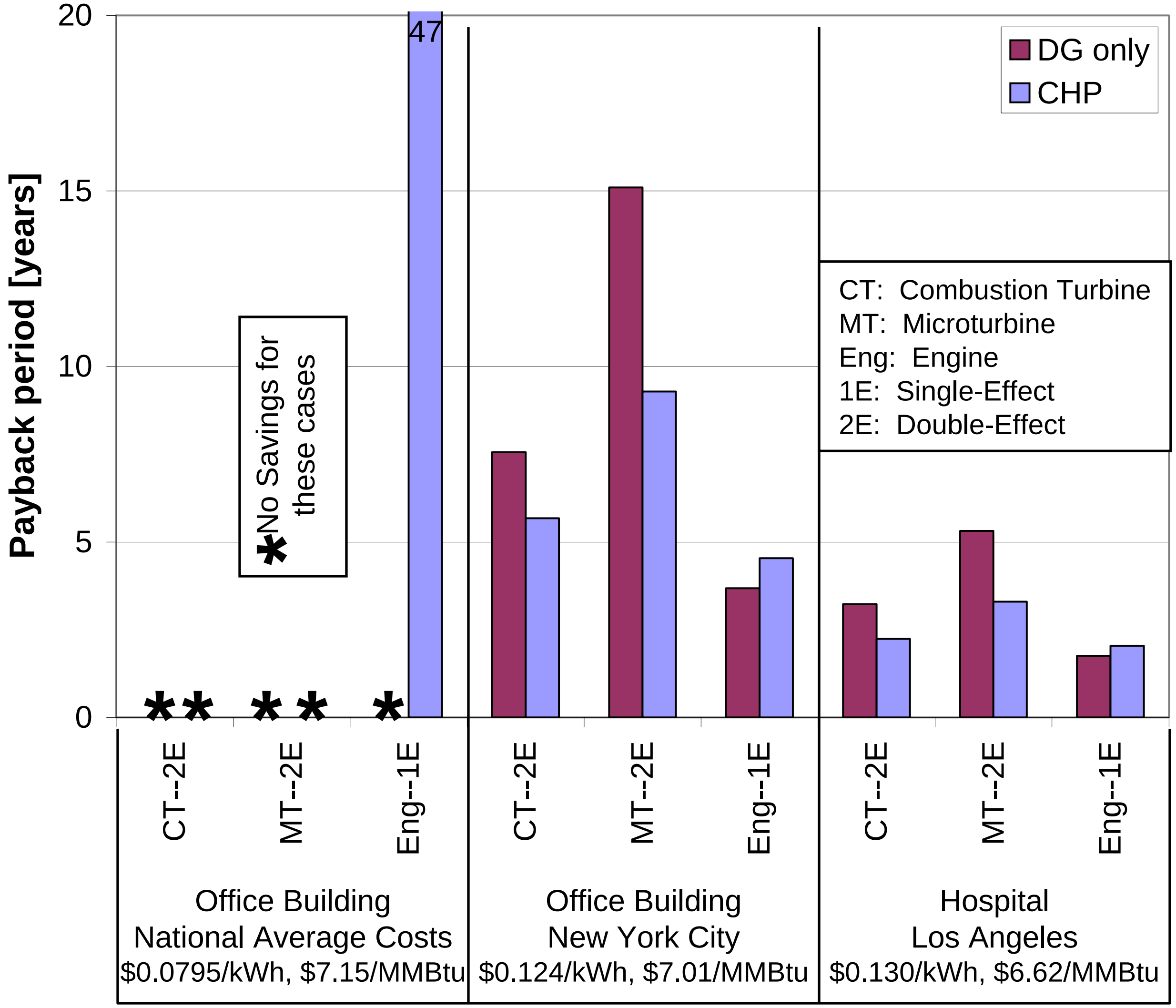
[1]UIC Study (part of GTI Packaged CHP Project); UTRC Packaged CHP Project

Hours of operation estimates developed during our BCHP study[1] were used to develop simplified illustrations of CHP system economics and energy savings potential.



1) "Cooling, Heating, and Power (CHP) for Commercial Buildings Benefits Analysis"; prepared for DOE/OPT under ORNL Subcontract 4000008858; prepared by Arthur D. Little, Inc.; April 12, 2002.

Waste-heat fired LiBr-Water absorption can improve DG economics, especially when DG electric efficiency is marginal.



<u>Key Assumptions</u>

DG Installed Costs: CT--$780/kW, MT--$880/kW, Eng--$570/kW.

DG HHV Electric Efficiencies: CT--27.1%, MT--26%, Eng--34%.

DG O&M costs: CT--0.6¢/kWh, MT--1.5 ¢/kWh, Eng--0.9¢/kWh.

Chiller Costs: Electric--$300/ton; Single-Effect--$500/ton; Double-Effect--$650/ton. Additional Cooling Tower Cost for Absorption $50/ton. Additional cost for waste heat recovery only for engine: $220/kW.

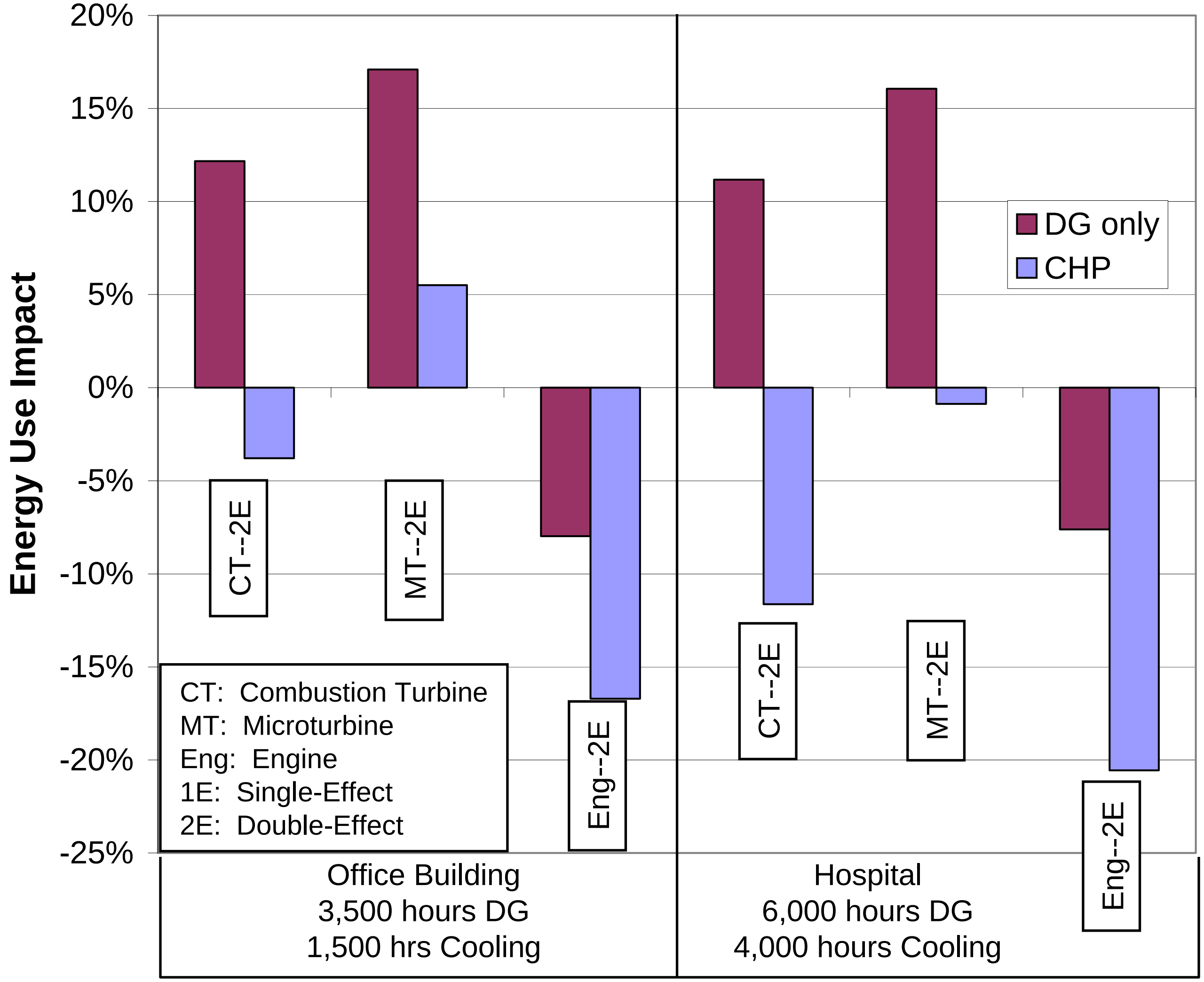
Absorption Chillers sized to utilize max possible amount of DG heat: 5,800Btu/kW for CT, 4,000Btu/kW for MT, 5,000Btu/kW for Eng.

Absorption chiller generator-heat-based efficiencies equal to 0.7 (1E) and 1.4 (2E). No absorber parasitic loads considered. Electric chiller avg. 0.65kW/ton.

DG utilization 3500 full load hours for office, 6000 for hospital. Chiller utilization 1500 full load hours for office, 4000 for hospital.

Grid net efficiency 11,000Btu/kWh.

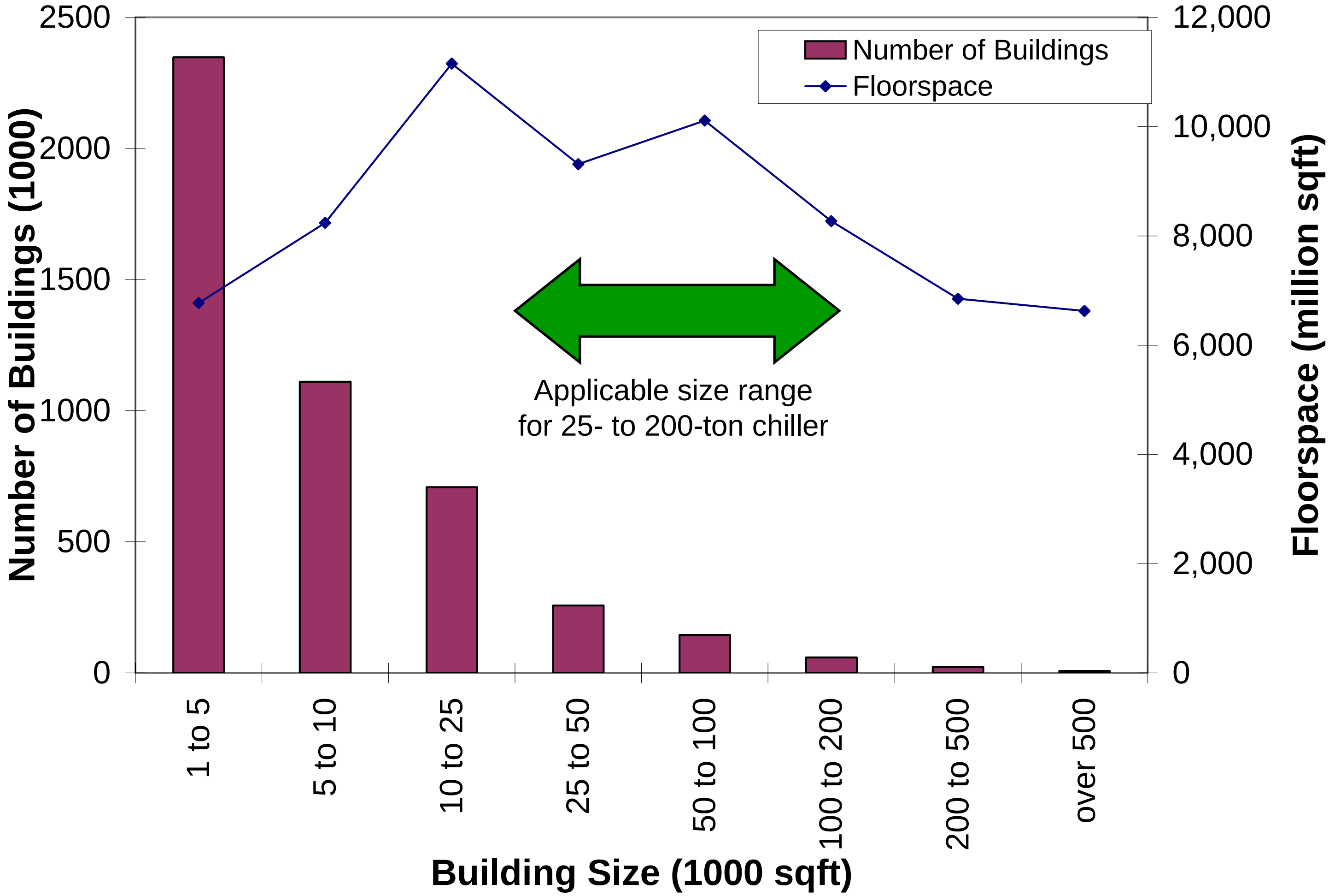
Waste-heat-fired LiBr-Water absorption will reduce energy use in DG installations.



LiBr-Water absorption systems.

Technology Improvement Options	♦ CHP-focussed developments can improve economics and energy savings: better integration in CHP system, heat exchanger designs, multi-level input.	♦ Market acceptance would be enhanced by development of lower-capacity air-cooled chillers.
Addressed by Current TAT Program	♦ No LiBr-Water absorption technology currently under development ♦ Triple-effect program ended recently.	
	♦ The CHP programs address design of LiBr-water chillers for CHP	♦ No
Addressed in TAT Roadmap	♦ TAT Roadmap is strongly focussed on CHP.	♦ TAT Roadmap mentions air-cooled absorption chillers in the 10RT to 150RT range.
Costs and Risks vs. Benefits	♦ Moderate changes in chiller design should provide significant CHP system performance benefits at modest cost.	♦ Ability of air-cooling to break the medium-sized building barrier for CHP is uncertain. Market study of this issue may be warranted prior to program launch.
Opportunity for DOE Action?	●	◒

Air-cooled chillers would address moderate building sizes, which make up a larger percentage of commercial floorspace.



Building data from CBECS99

- Executive Summary
- Background
- LiBr-Water Absorption
- **Ammonia-Water Absorption**
- Desiccant Technologies
- Rankine Cycles
- Other

Ammonia-Water Absorption Heat Pump

Efficiency/Energy Savings Potential

- GAX prototype HHV COP is ~0.7 in cooling mode and ~1.5 in heating mode with a heat input temperature range of 250F to 350F. Further increases in efficiency will likely be modest.
- With the above performance, GAX has negative primary energy use implications in the cooling mode, BUT significant energy savings (40%+) in space and water heating modes
- GAX technology is, therefore, of primary interest in northern areas where heating loads dominate - or as a dedicated water heater in commercial applications where the high heating mode COP would have particular value.
- Northern residential applications, which have greater heating/cooling load ratios, are of more interest for GAX than commercial applications.

Capital Cost and Economics:

- The target factory price for a GAX heat pump is ~$700/ton. End-user installed cost will be at least 2 times higher. This estimate is for commercial production volumes of 50,000 units per year and higher.
- With these costs, the economics of GAX shows reasonably good but not compelling potential (payback period under 3 years) in some northern areas with high energy costs.
- Preliminary estimates indicate that equipment costs could be reduced by 25% to 35% for a heating-only version of GAX. Such a product might have quite attractive economics in areas with long heating seasons (or for water heating)
- At production levels associated with market entry (under 5,000/yr) the costs would be much higher, and economics would be poor to marginal at best.

Ammonia-Water Absorption Heat Pump

Industry Structure:

- The current ammonia-water absorption system manufacturers are small companies or have a small U.S. presence.
- None of the large U.S. HVAC industry companies are involved in ammonia-water absorption system development or manufacture (since Carrier dropped out).

Waste-Heat-Fired Ammonia-Water Heat Pumps (using waste heat in CHP systems):

- The heating capability of GAX does not add appreciable value in commercial applications, since there would be ample waste heat for space/water heating functions without the added efficiencies resulting from GAX technology.
- A universally accepted approach has not emerged for interface of absorption systems with unitary equipment (which is used in most buildings in the ammonia-water absorption capacity range).

Ammonia-Water absorption systems--fuel-fired.

Key Manufacturers and Developers	Robur, Rocky Research (Ambian), Energy Concepts Company, Cooling Technologies
Capacity Range (tons)[1]	5 to 30
Typical COP (Fuel-fired, HHV)[2]	COOLING: 0.62 to 0.68 (current) 0.7+ (next generation) HEATING: 1.5 (at 47F ambient---next generation)
Generator Solution T (^oF)[3]	340
Cost ($/ton)[4]	Current (Robur): $900 Target (Ambian): $500 cooling/conventional heating $700 cooling/heat pump
Technical Status	Robur product has been on the market for many years.Cooling Technologies' product commercialized about a year ago. Ambian (heat pump) projected commercialization within a year. Targeted improvements over current technology include GAX cooling/heat pump design, 30% performance improvement, 35% cost reduction, 25% size/weight reduction.
Current Markets	U.S.: Perhaps 1,000 units per, much of it replacements. Worldwide: 2,000 to 5,000 per year.

1. One ton equals 12,000 Btu/hr.
2. Heat rejection using air-cooled condensers and absorbers.
3. Heat Input is at the generator. The reported temperatures represent the highest solution temperature within the generator.
4. Factory Price. End-use cost likely to be 2 or more times higher.

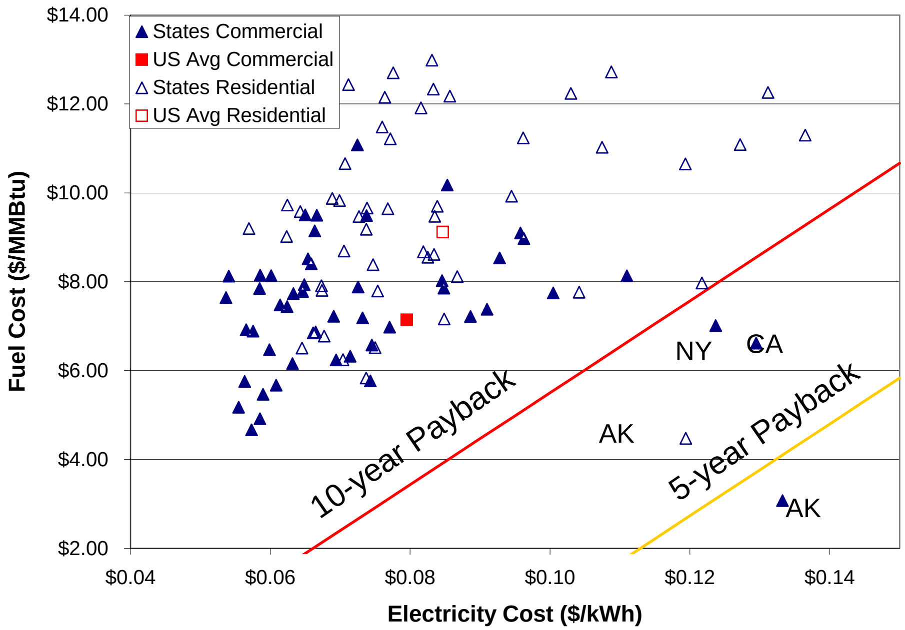
Ammonia-Water absorption systems--CHP.

- Notable developments:
  - Energy Concepts Company team with IR Powerworks--Supermarket liquid subcooling and refrigeration.
  - Cooling Technologies demonstration site using microturbine exhaust heat.
  - Ambian: Consideration of Capstone performance characteristics in design, but primary commercialization focus is fuel-fired.
- Issues
  - Design for dual-use fuel-fired and waste-heat-fired?
  - Capacity derating for waste-heat-firing vs. redesign with larger generator heat exchanger

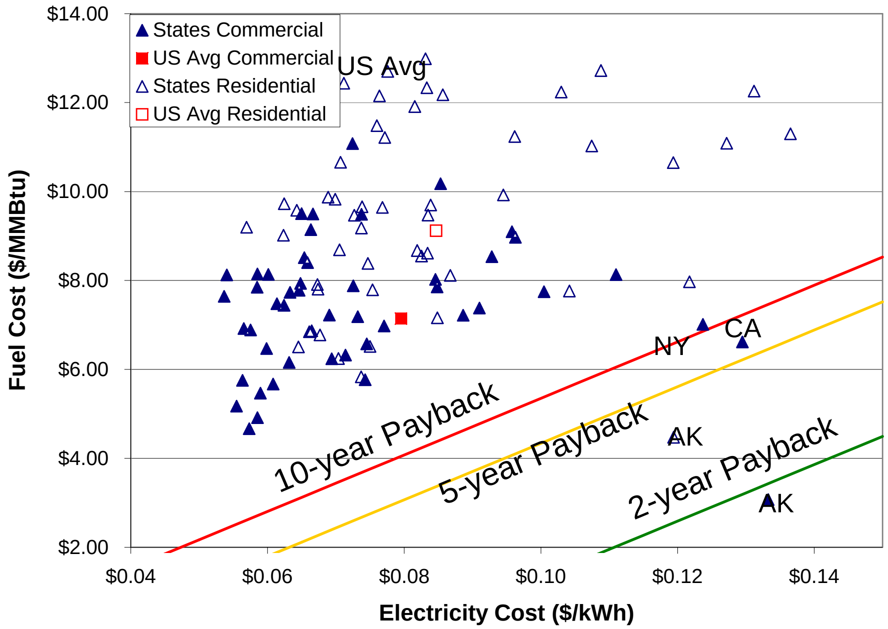
Ammonia-Water absorption systems--fuel-fired.

Energy Savings	♦ Cooling COP of 0.7 at ARI rating conditions will generate no savings: ⇒ASHRAE 90.1-1999 10.1 EER for the smallest-size "commercial" unitary air-conditioners. ⇒COP 0.9 required for parity with 10.1EER (if ignoring abs. electric input) ♦ Heating COP of 1.5 at 47F ambient, 1.3 at 17F ambient will generate savings: ⇒Condensing Gas Furnace effective HHV COP of 0.9---44%+ improvement ⇒90.1-1999 commercial air-cooled heat pump COP 3.1, effective primary energy COP 1.0, 30% improvement. ♦ Net savings depends on application (ratio of annual heating and cooling loads)
Electric Grid Relief	♦ All fuel-fired absorption equipment can reduce peak summer electric loads.
Economics	♦ Reasonable economics only in areas with favorable utility cost structures. ♦ Economics is better for applications using GAX heat pumping.
Deficiencies for Broad Commercial Markets	♦ High first cost ♦ Reality or Perception of flammability/toxicity issues with ammonia systems. ♦ Interface with AC systems with chilled water or heating water, incompatible with current unitary AC system practice.

The economic attractiveness of fuel-fired GAX absorption systems is good where there is a high electric/fuel cost ratio.



Chiller/Heat Pump
2,000 Full-Load Hours Cooling; 1,200 Full-Load Hours Heating



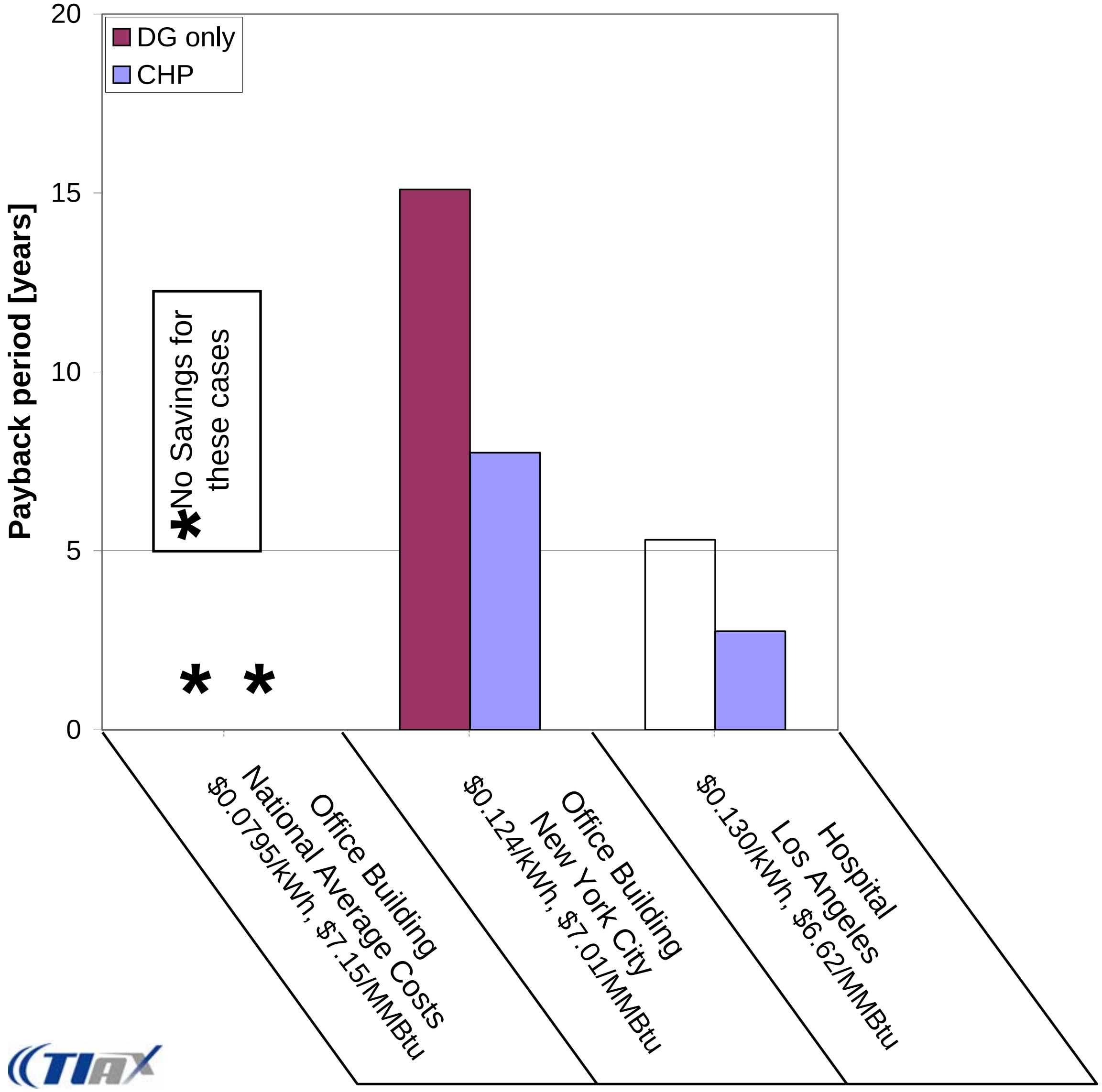
Chiller
2,500 Full-Load Hours Cooling, no Heating

Assumptions: 10.1 EER electric cooling; 120W/ton indoor blower, indoor blower power equal for GAX and conventional systems; GAX HHV seasonal COP's of 0.84 (cooling), 1.4 (heating), electric parasitics of 160W per delivered ton for GAX unit (ignores glycol pump); Distributor cost $320/ton electric, $500/ton GAX chiller, $700/ton GAX chiller/heater; 100% markup to end-user; Utility costs from EIA for 12-month period ending April 2003.

Ammonia-Water absorption systems--waste-heat-fired.

Energy Savings	♦ Energy saved through use of waste heat that would otherwise not be utilized. ♦ Energy savings per waste heat Btu is better than for LiBr-Water absorption due to the narrower efficiency gap with respect to displaced electric equipment. ⇒1 Btu of waste heat used for cooling would create ~0.8Btu of cooling, which displaces **~0.9Btu of primary energy**. ⇒1 Btu of waste heat used for heating would create ~1.6Btu of heating, which displaces **~1.9Btu of primary energy**. ⇒1 Btu of waste heat used for refrigeration system liquid subcooling (i.e. PowerWorks/Energy Concepts) would create ~0.6Btu of liquid subcooling or refrigeration, which displaces **~1.5Btu of primary energy** (low-temperature)
Electric Grid Relief	♦ Waste-heat driven absorption equipment can reduce both peak summer and peak winter electric loads.
Economics	♦ Some improvement in DG economics through the utilization of the waste heat for cooling.
Deficiencies for Broad Commercial Markets	♦ High first cost ♦ Reality or Perception of flammability/toxicity issues with ammonia systems. ♦ Interface with AC systems with chilled water or heating water, incompatible with current unitary AC system practice.

Waste-heat fired Ammonia-Water absorption can improve microturbine DG economics.



Key Assumptions

DG Installed Costs: MT--$880/kW.

DG HHV Electric Efficiency: MT--26%.

DG O&M costs: MT--1.5 ¢/kWh.

AC System Distributor Costs: Electric--$320/ton; GAX Chiller--$500/ton; GAX Chiller/Heat Pump--$700/ton.

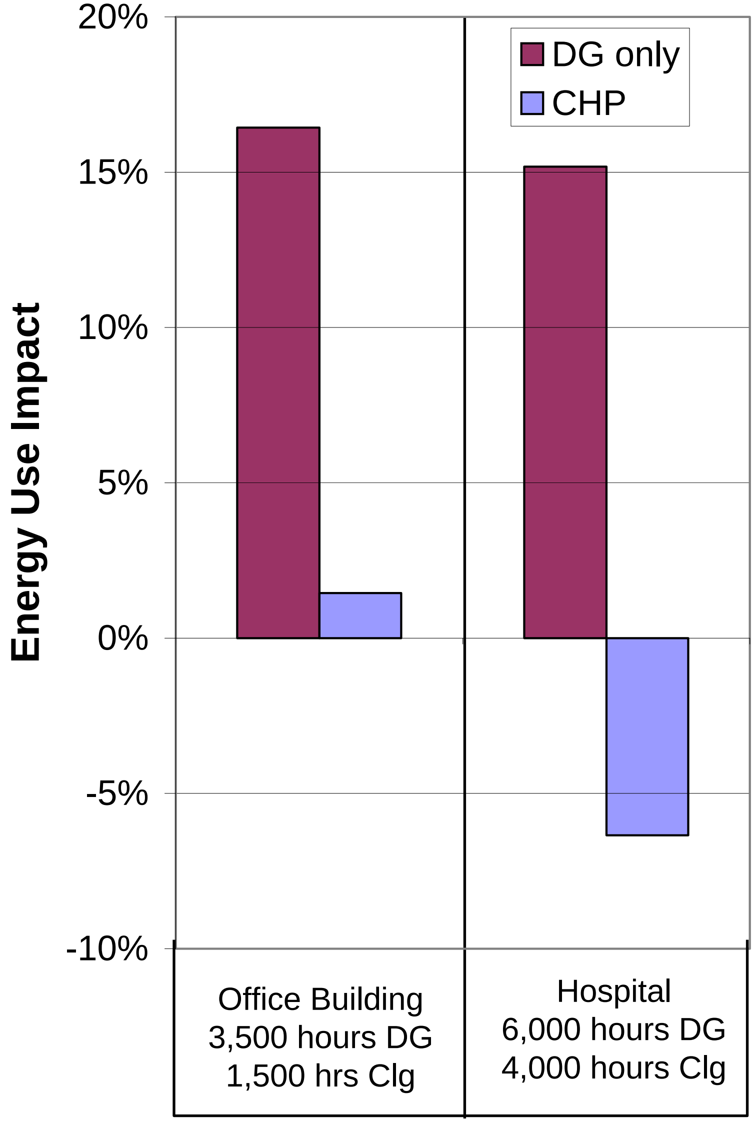
Absorption Chillers sized to utilize max possible amount of DG heat: 5,500Btu/kW for MT.

Absorption chiller seasonal generator-heat-based efficiency equal to fuel-fired HHV seasonal efficiency. Absorber parasitic loads 160W per delivered ton. Electric AC 10.1 EER (includes indoor blower). Indoor blower load 120W per design load ton.

DG utilization 3500 full load hours for office, 6000 for hospital. Chiller utilization 1500 full load hours for office, 4000 for hospital.

Grid net efficiency 11,000Btu/kWh.

Waste-heat fired Ammonia-Water absorption will reduce energy use in microturbine DG installations.



Ammonia-Water absorption systems.

Technology Improvement Options	♦ Developments more directly focussed on specific market segments may improve performance/cost tradeoff: heating-only, water heating.	♦ Use of dual-wall vented evaporator rather than chilled water for applications in which unitary HVAC equipment is generally used.
Addressed by Current TAT Program	♦ Little focus on heating-only in the current TAT GAX program. ♦ No consideration of water heating based on claims of poor economics.	♦ No
Addressed in TAT Roadmap	♦ Not directly.	♦ No
Costs and Risks vs. Benefits	♦ Economic assessment to characterize potential is warranted.	♦ A track record with current GAX technology should be in place prior to launching a unitary-focussed absorption development.
Opportunity for DOE Action?	◒	◒

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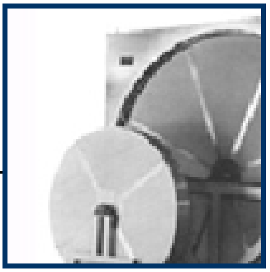
- Other



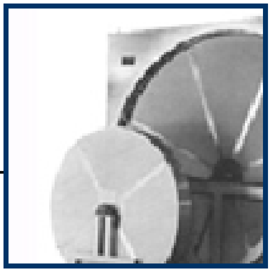
Desiccant Technology

Efficiency/Energy Savings Potential

- Energy use of HVAC systems using fuel-fired desiccant technology is likely to be at best equal to that of conventional systems and/or other developmental technology.
- Greater ability to treat more of the HVAC load and high parasitic power tend to increase energy use in many installations.
- The move to post-processing for solid desiccant systems has improved energy use.
- Opportunities for significant improvement to desiccant wheel efficiency (latent load vs. heat input ratio) of solid desiccant systems have not been identified.
- HVAC-market oriented liquid desiccant system developments may achieve energy savings as compared with available desiccant systems.

Capital Cost and Economics:

- The cost of currently-available HVAC systems utilizing desiccant technology is in the $3 to $6/cfm range, significantly higher than that of conventional equipment (roughly $1/cfm).
- The cost of such systems has been a barrier to sales in most commercial HVAC applications, limiting their use to niche applications with high latent load ratio.
- Evaporative cooling of liquid desiccant developments is an issue for many buildings.



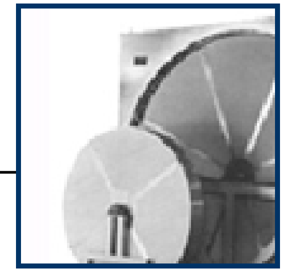
Desiccant Technology

Market and Industry Structure:

- Sales of desiccant systems are in the low 1000's in the U.S. Perhaps 1,000 sales are in the commercial building sector (the rest industrial).
- The low sales level reflects the poor economics. Applications with unusual latent load needs (supermarkets, ice rinks, etc.) represent a small proportion of the building stock.
- The large U.S. HVAC industry companies are getting involved in desiccant system development (i.e. Trane working with Semco) to address problem humidity applications.

Waste-Heat-Activated Desiccant Technology

- HVAC systems with desiccant wheels provide quantitatively much less opportunity for waste heat utilization and benefit than absorption.
- Desiccant wheels provide a technically plausible way to integrate DG and TAT with unitary air-conditioning.
- There is very limited use of waste-heat-activated desiccant systems to date.

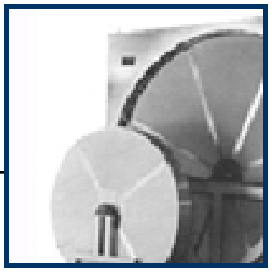


Desiccant technologies.

Technology	Solid Desiccants	Liquid Desiccants
Key Manufacturers and Developers	Munters, Novelair, Rotorsource, SEMCO	Munters, Kathabar, Niagara Blower, DryKor, AIL Research
Capacity Range (cfm)[1]	1,000 - 25,000	2,000 - 70,000
Typical COP (Fuel-fired, HHV)[2]	0.3 typical up to ~0.7 possible	Current Technology ~0.5 Up to 1.2 projected (AIL) with advanced cycles.
Heat Source Temp Range (ºF)	120 to 200	160 to 320
Installed Cost ($/cfm)	$3 to $6/cfm	Industrial systems $3 to $10/cfm Commercial systems competitive with solid desiccants.
Technical Status	Systems treating outdoor air have been available for many years. Systems for treatment of supply air soon to be available.	Industrial drying systems have been available for many years. Kathabar/AIL has shifted focus from "rooftop" total cooling unit to outdoor air pretreatment, development is ongoing, a few years from commercialization.
Current Markets	~3,000 units/year, about one third in commercial applications. Solid desiccants more prevalent in commercial applications, Liquid desiccants more in industrial.	
	Key commercial applications are primarily supermarkets and ice rinks which have unusual dehumidification challenges; schools also represent an important market.	

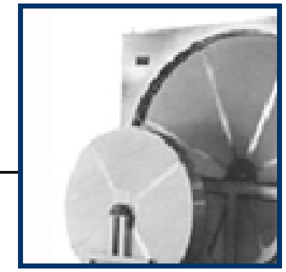
1. Capacities based on volume of air the system can treat.
2. COP is based on latent cooling (dehumidification) of air. For solid desiccant systems total net cooling is zero or negative.

- Related technology such as the Cromer cycle, passive energy recovery for outdoor air treatment, etc. are not addressed by this review.

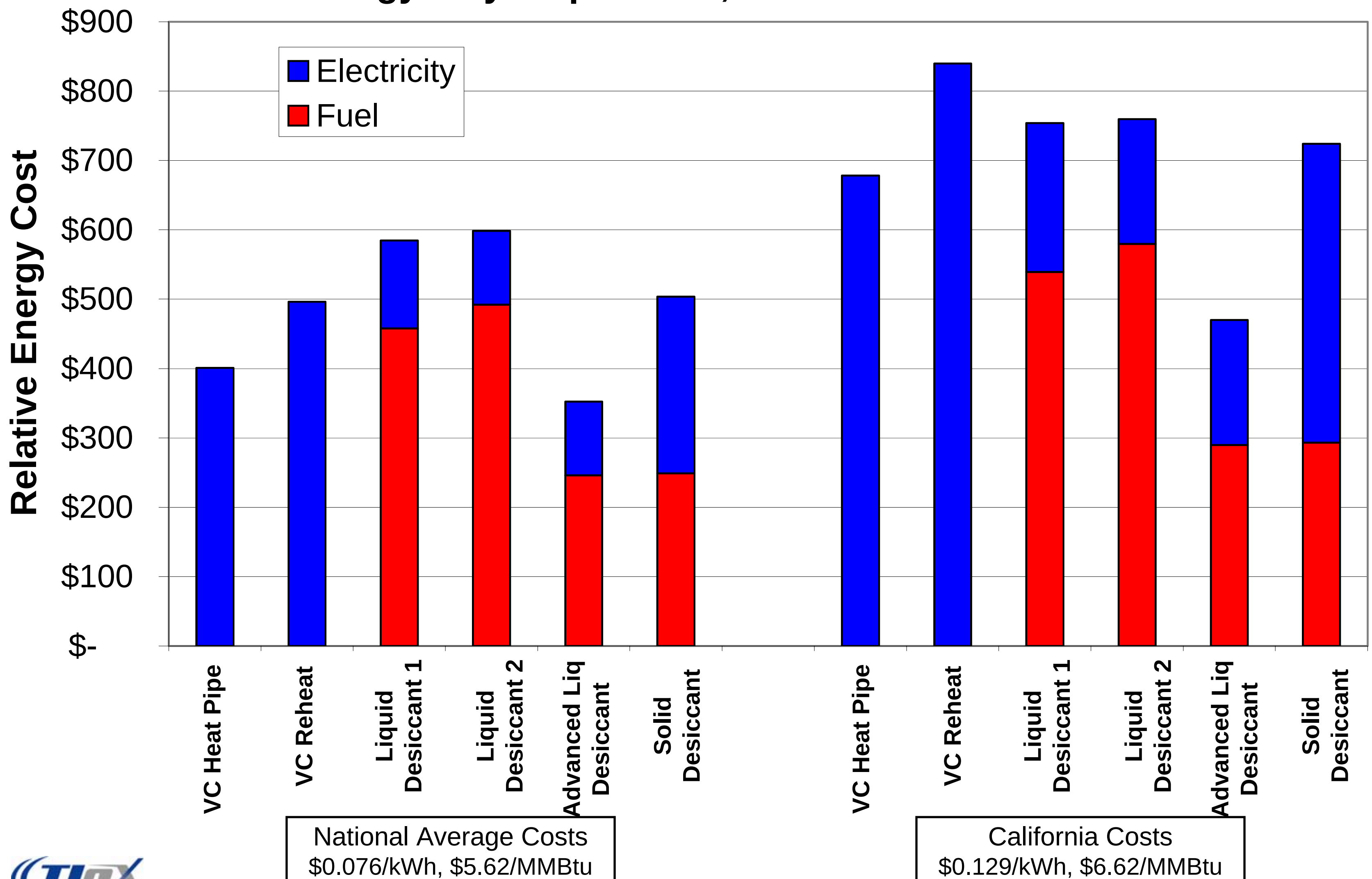


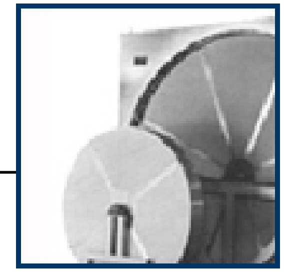
Desiccant systems--CHP.

- Limited focus on CHP
  - Munters recently installed their first CHP desiccant system at a Long Island A&P Supermarket. However, Munters interest in CHP is not high.
  - Semco has designed in flexibility for use of waste heat using a hot water coil.
- Issues
  - Turbine (microturbine) exhaust is too hot for direct use without dilution
  - Limited practical use of waste heat as compared with absorption, which can provide total cooling.
  - Other approaches are available for dealing with humidity issues in more mainstream HVAC applications: Hot Liquid Reheat (Carrier MoistureMi$er™), Hot Gas Reheat, Evaporator Bypass, Heat Pipes, Total Enthalpy Recovery, etc.



The following example for pretreatment of 86DB/78WB outdoor air shows that, while operating cost savings for fuel-fired Desiccant Technology may be possible, the case is not clear.





Key assumptions for the previous example are:

Outdoor Air Pretreatment unit based on 1,000scfm flow.

Outdoor air conditions: 86DB/78WB (1% WB Cooling Condition for Dover AFB, Delaware).

Air exit conditions: 75DB/45%RH/Humidity Ratio 0.0085 (neutral sensible cooling) all units but heat pipe unit, for which exit condition is 70DB/54% RH/Humidity Ratio 0.0085.

Heat Pipe Unit: Three-row heat pipe unit, providing 17°F reheat, precooling with pre-dehumidification, 4sqft coil face area, 5-row deep coil, total pressure drop coil and heat pipe 0.45 in wc.

Hot Gas Reheat Unit: 4sqft coil face area, 5-row deep coil, single row reheat, pressure drop 0.32 in wc.

Liquid Desiccant 1: Modulated to provide only as much dehumidification as required, cooling coils in space cooling units provide additional needed sensible cooling, no pressure drop penalty for additional cooling, total conditioner pressure drop 0.2 in wc. Fuel input assuming COP of 0.6. Power for pumps, cooling tower fan, and regenerator air fan 510W (scaled from data for existing AILR product).

Liquid Desiccant 2: Provide maximum possible dehumidification (based on AILR data), subsequent evaporative cooling to readjust for desired dehumidification, some additional cooling delivered by space cooling units, total conditioner pressure drop 0.2 in wc. Fuel input assuming COP of 0.6. Electric input same as for Liquid Desiccant 1.

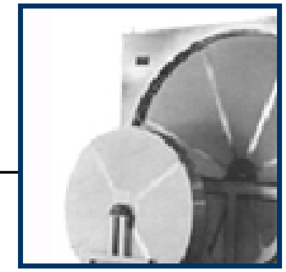
Advanced Desiccant Unit: Assumptions identical to Liquid Desiccant 2, except for COP of 1.2.

Solid Desiccant: Post-processing unit with 40% of process air passing through desiccant unit. Assumed desiccant wheel process air path optimistically assumed to be isenthalpic. Wheel pressure drop 0.2 in wc, Cooling coil 2.8sqft face area, 3-row, coil pressure drop 0.25 in wc. Fuel input three times latent load of desiccant wheel.

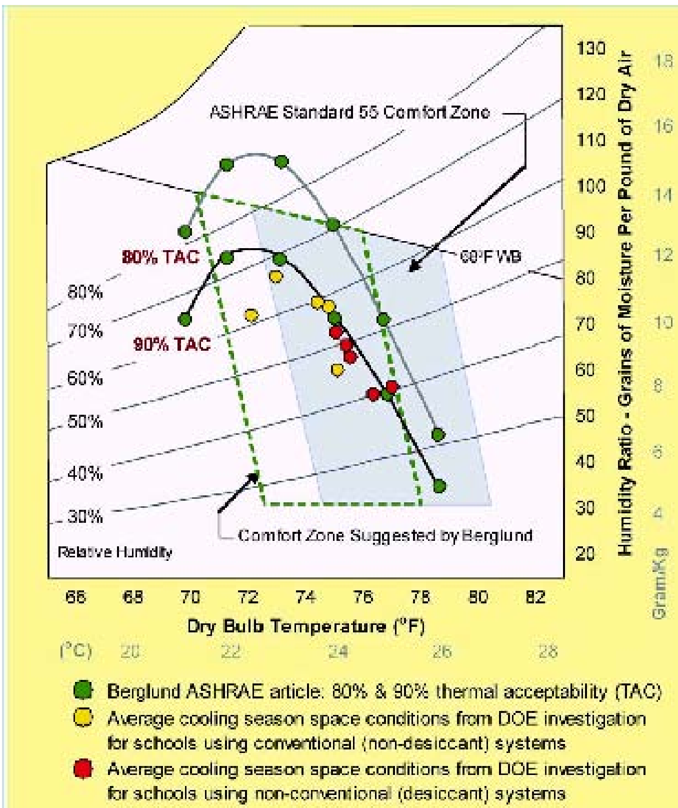
Power for cooling compressor based on Copeland ZR125KC.

Power for condenser fans 120W/ton of cooling.

Blower power included for internal pressure drop (coil, desiccant wheel, etc.) based on 50% efficient motor/drive/blower efficiency.

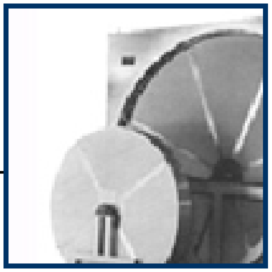


The key to energy savings with desiccant technologies is associated with shift of indoor conditions to higher temperature and lower humidity.

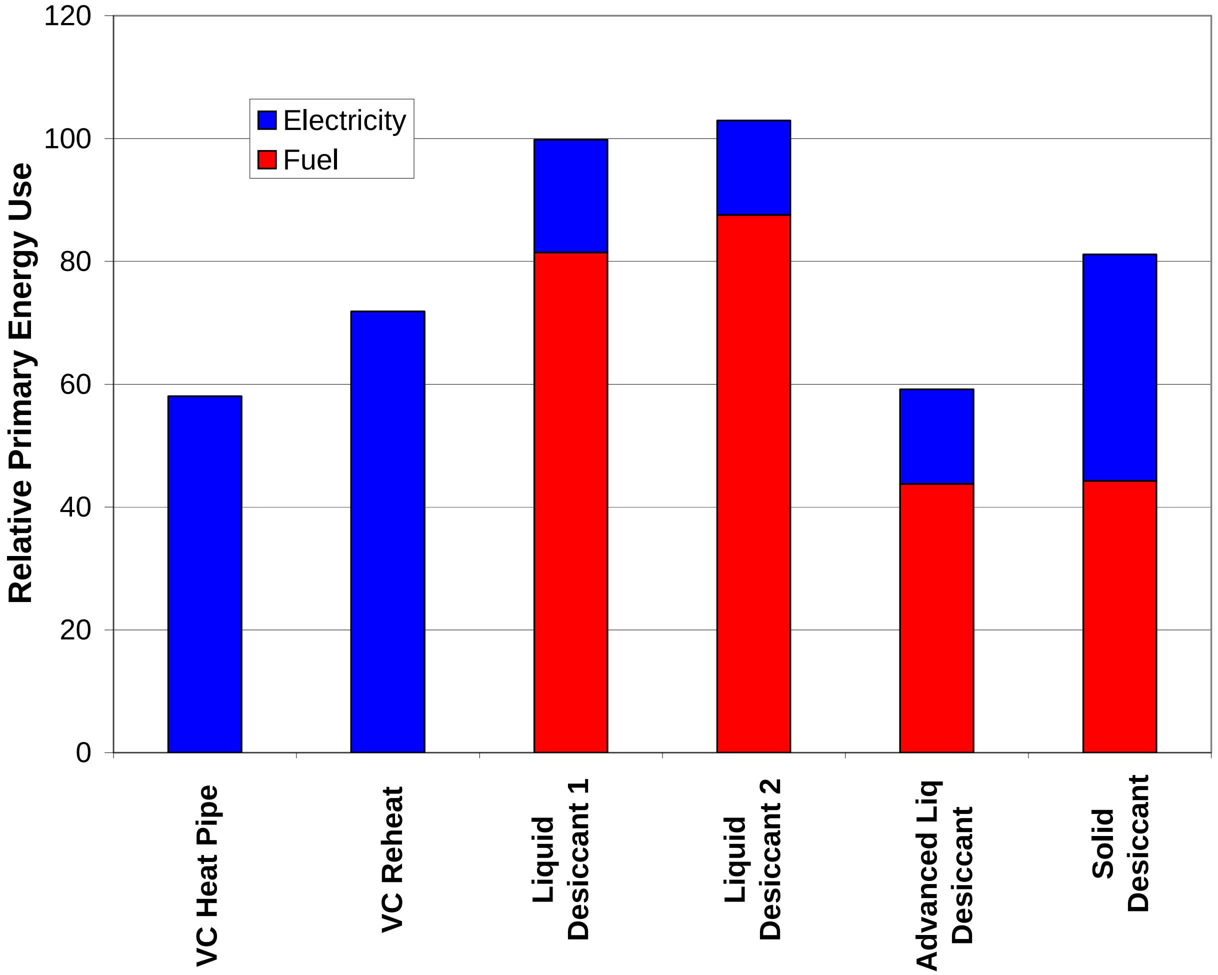


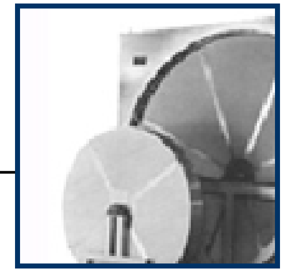
- Possible shift of indoor conditions is illustrated in the plot [Fischer, J.C. and C.W.Bayer, “Report Card on Humidity Control”, ASHRAE Journal, May 2003]
- Possible temperature increase of 2 to 5 degrees has been shown in the field.
- Energy savings result from reduced conditioning loads associated with the higher internal temperatures.

While conventional unitary air-conditioning equipment falls short of evolving performance requirements, advanced “conventional” equipment will be able to provide many of the same benefits claimed for desiccants.

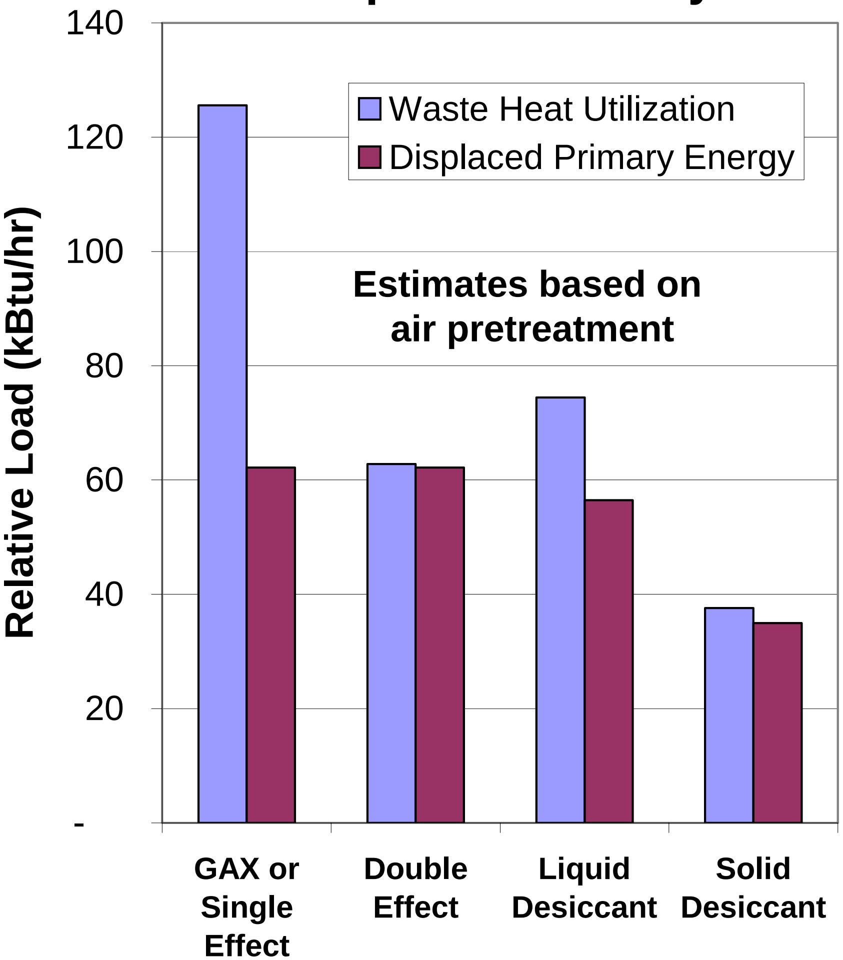


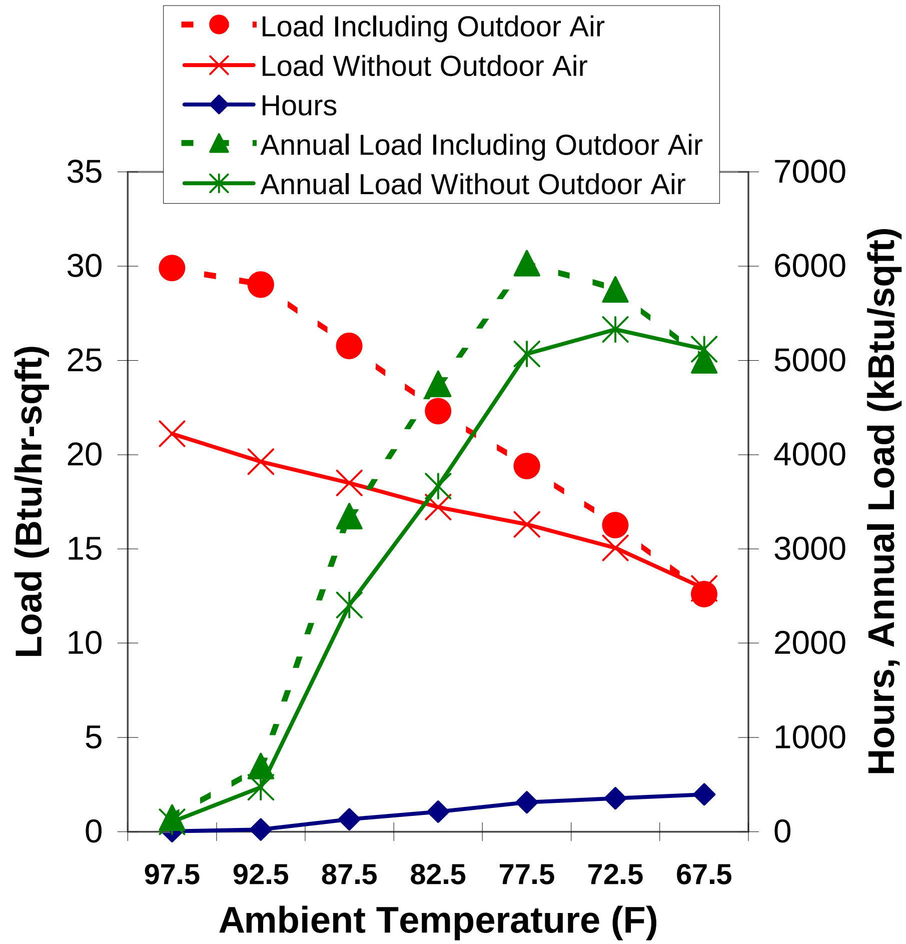
Energy use for outdoor air pretreatment is shown below.





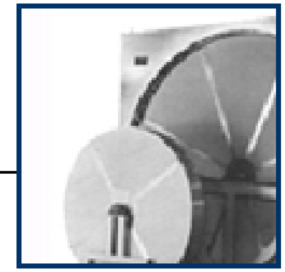
The market for Desiccants in CHP systems is likely to be limited to special humidity control applications.





Even absorption systems can make more impact for outdoor air pretreatment.

The importance of the outdoor air treatment load is modest on a seasonal basis



Desiccant technologies.

Technology Improvement Options	♦ Wheel optimization for "post-processing" approach.	♦ Air-cooled liquid desiccant systems.	♦ 1-1/2 effect liquid desiccant technology.
Addressed by Current TAT Program	♦ Limited focus on wheel improvement mentioned in project summaries.	♦ No	♦ Limited focus on 1-1/2 effect.
Addressed in TAT Roadmap	♦ Not directly.	♦ No	♦ Not directly.
Costs and Risks vs. Benefits	♦ Modest changes expected to be cost-effective.	♦ Low technical risk: Multiple approaches already available using technology developed in current program. ♦ Market impact uncertain.	♦ Moderate technical risk, since path to performance improvement has already been identified.
Opportunity for DOE Action?	◒	◒	◒

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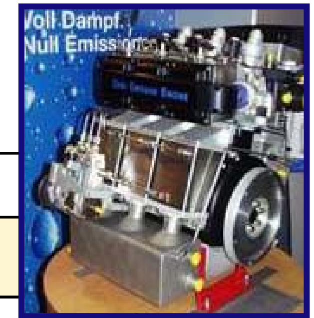
Rankine Bottoming Cycles

Steam

- Steam bottoming cycles have been around for about a century. Very little development need for this technology, except for small-capacity sizes.
- Sales are about 1,000/year, down from 10,000/year about 15 years ago.
- Each installation requires significant engineering for optimization.
- Most sales in commercial buildings involve special circumstances, such as availability of utility steam.
- Cost range $300/kW to $1,000/kW and higher, depending on application specifics.

Organic Rankine Cycles

- ORMAT has been in the business for 30 years, selling about 100/year to industrial customers.
- Potential for increase electric/thermal ratio for better fit with commercial building applications.
- Cost roughly $1,000/kW, competitive with steam Rankine requiring installation of all cycle components.
- Potential to improve DG economics.



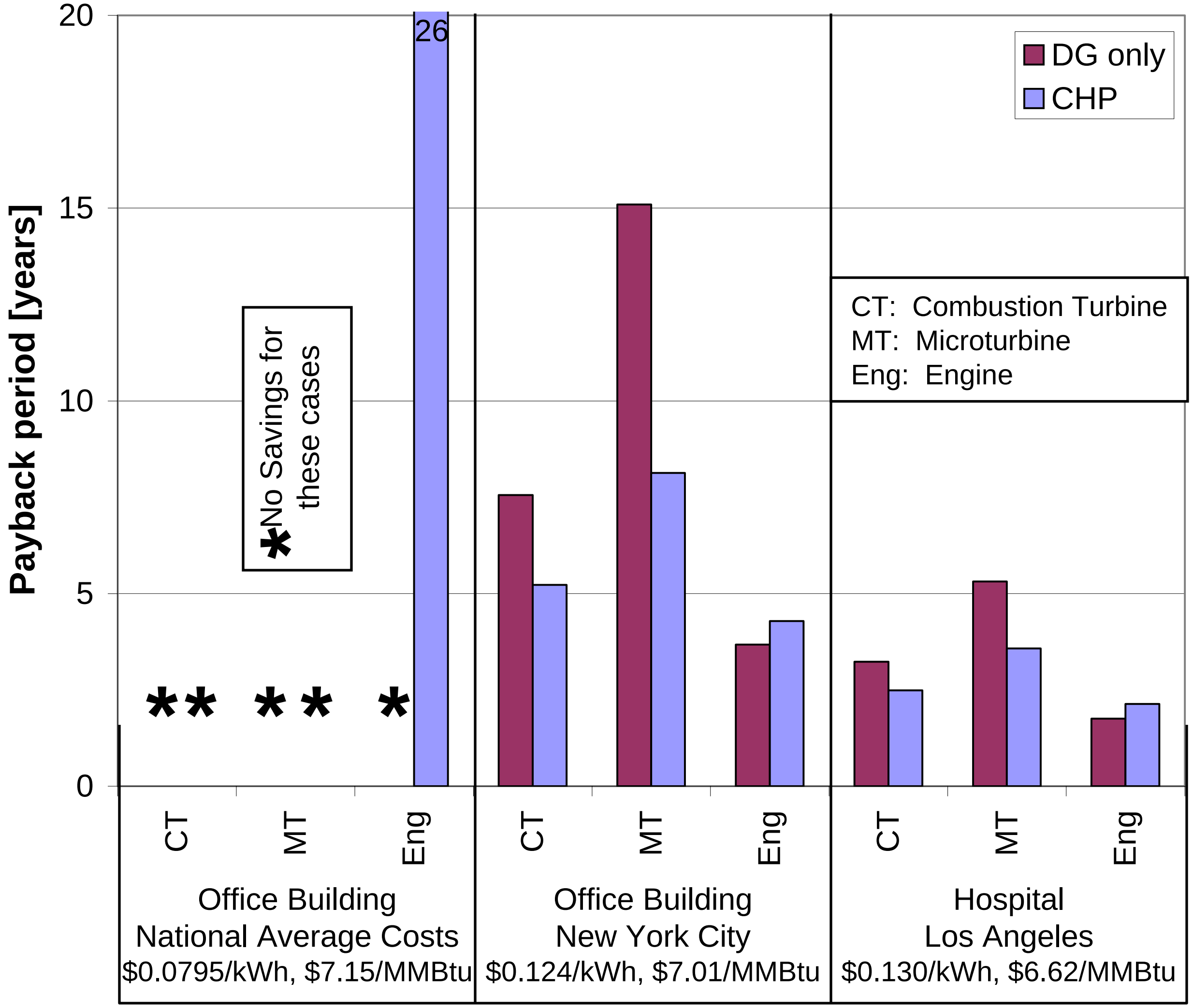
Rankine systems.

Technology	Steam Rankine	Organic Rankine
Key Manufacturers and Developers	Climate Energy LLC (Yankee Scientific and ECR International), Enginion (Germany), TurboSteam, others	UTC Power, ORMAT, Energetix MicroPower (Energetix Group and Battelle)
Capacity Range (kW)	10's to 1000's	UTC Power: 200; ORMAT: 6-130,000; Inergen: 2.5
Typical Heat Rate (Btu/kWh)	30,000+ (very high T/E ratios for Rankine cycles operating on typical building steam system pressures/temperatures)	34,000 (Typical thermal efficiency of 10%)
Heat Source Temp Range (°F)[3]	250 to 1000	300 to 800
Installed Cost ($/kW)	$300 to $1200 for MW-sized systems, range reflects need for ancillary equipment, level of engineering required for installation, etc.	UTC Power: $1000 (projected)
Technical Status	Conventional Steam Systems using HSRGs have been available for many years. Yankee Scientific has recently developed a scroll expansion system and is working on development towards commercialization.	UTC Power and Inergen using HFC245fa as working fluid. UTC Power 200kW system packaged on 40-foot flatbed. ORMAT technology unsuitable for commercial buildings due to use of hydrocarbons.
Current Markets	Large steam turbines ~1,000/year ~100/year of these with generators, the rest with mechanical drive. Most installations industrial and institutional campus applications. Most sales where steam is already available. Climate Energy LLC aiming for US microCHP market by integrating with furnace.	UTC Power just started marketing 200 kW ORC as ZeNOx 200, currently for use with flares and engines burning landfill gas. ORMAT primarily for industrial waste heat and geothermal. 3,000 units sold over 30 years. Inergen being commercialized by British company, Energetix LTD, for European microCHP market.

Rankine Systems--waste-heat-fired.

Energy Savings	♦ Energy savings will result from use of waste heat for added electricity generation.
Electric Grid Relief	♦ Added power generated in a distributed generation installation provides increased infrastructure support.
Economics	♦ Potential for some improvement to DG systems. ♦ Best economics in special cases (i.e. steam Rankine in locations with utility steam availability)
Deficiencies for Broad Commercial Markets	♦ Careful application engineering required for each installation. ♦ Added complexity for overall generation system.

Waste-heat fired ORC technology can improve DG economics, especially when DG electric efficiency is marginal.



<u>Key Assumptions</u>

DG Installed Costs: CT--$780/kW, MT--$880/kW, Eng--$570/kW.

DG HHV Electric Efficiencies: CT--27.1%, MT--26%, Eng--34%.

DG O&M costs: CT--0.6¢/kWh, MT--1.5 ¢/kWh, Eng--0.9¢/kWh.

ORC Costs: $1000/kW. Additional cost for waste heat recovery only for engine: $220/kW.

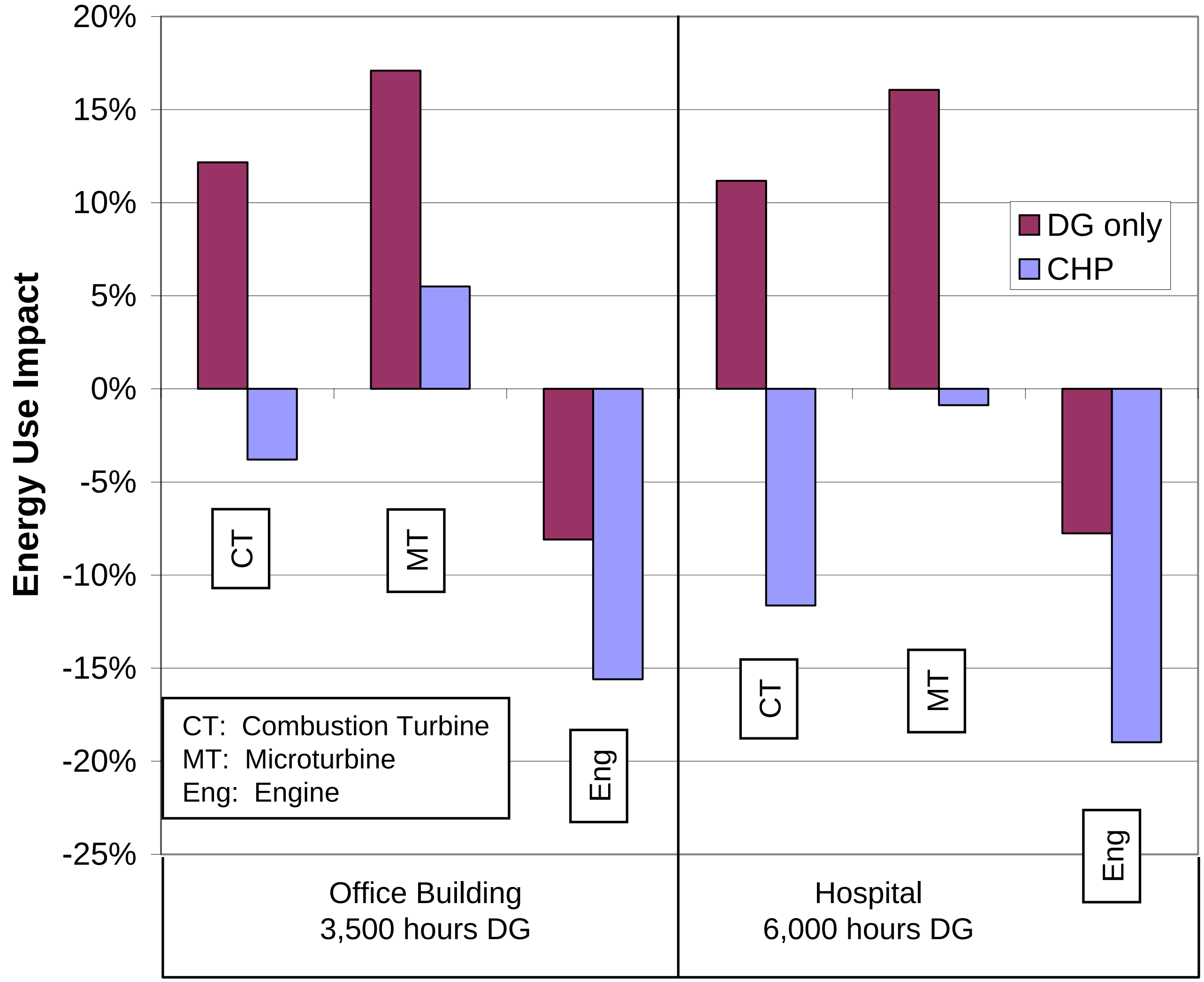
ORC Unit sized to utilize max possible amount of DG heat: 6,500Btu/kW for CT, 5,500Btu/kW for MT, 5,000Btu/kW for Eng.

ORC efficiency equal to 10% net.

DG and ORC utilization 3500 full load hours for office, 6000 for hospital.

Grid net efficiency 11,000Btu/kWh.

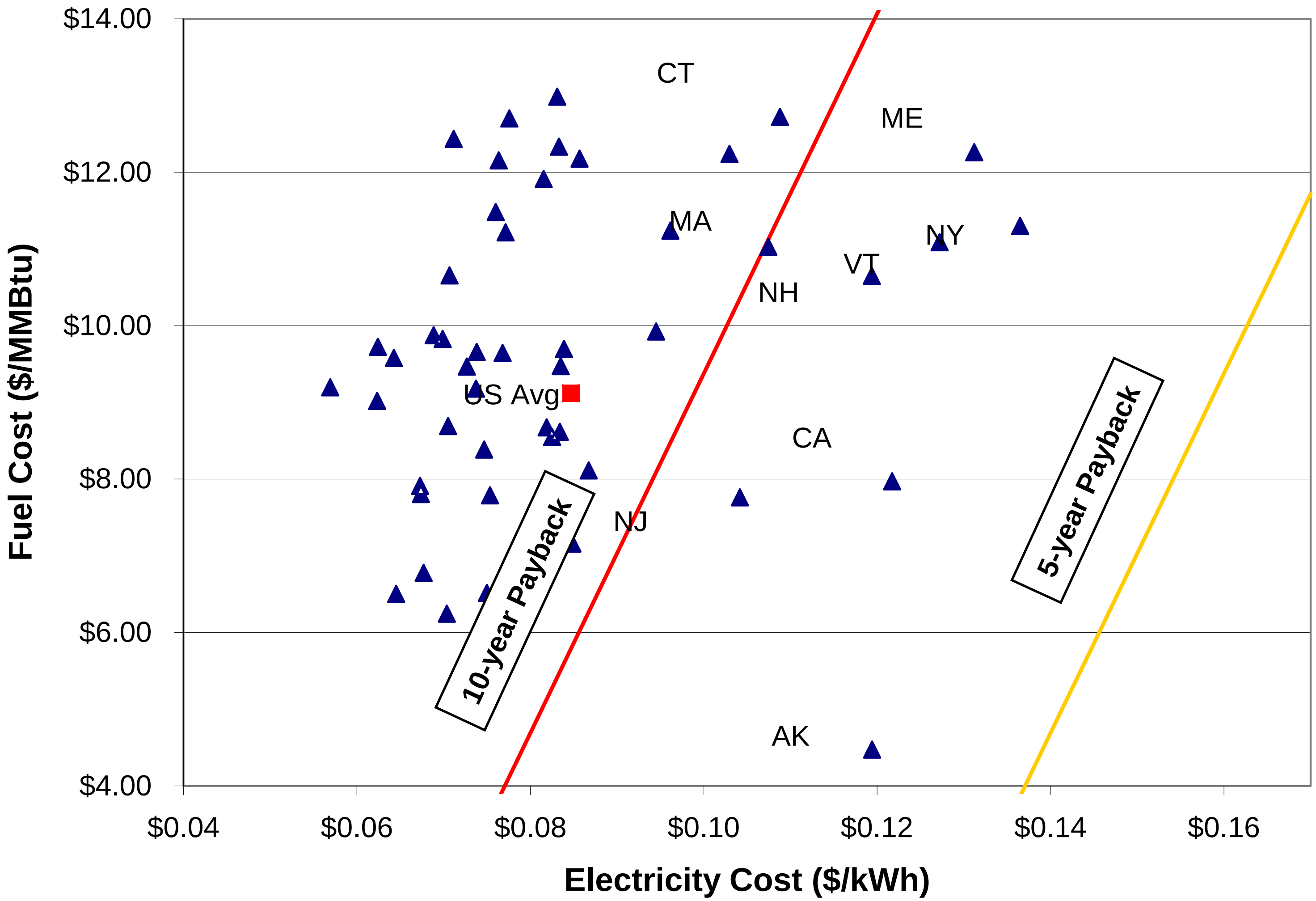
Waste-heat fired ORC will reduce energy use in DG installations.



Economics and Energy Savings are very similar to use of LiBr-Water chillers:

--Similar added cost
--Lower displaced kW
--Higher hours
--Similar displaced kWh

A residential ORC system that uses ORC waste heat for heating needs approaches reasonable economic attractiveness for a number of locations.



Assumptions: 2,500 hours/year full-load operation; 10% ORC Electric HHV Eficiciency, 80% Total HHV efficiency for ORC and conventional heating equipment; Installed costs adder for ORC $1,500 for a 1kW system.

Rankine Technologies.

Technology Improvement Options	♦ More aggressive large ORC design to enhance cycle efficiency (evaporative cooling, incorporate an interchanger).	♦ Development of viable residential systems.
Addressed by Current TAT Program	♦ No	♦ No, but likely to be a part of the current Micro-CHP solicitation.
Addressed in TAT Roadmap	♦ Not directly.	♦ Not directly.
Costs and Risks vs. Benefits	♦ Modest technical risk. Market acceptance of ORC remains to be seen, but this approach should improve economics and will increase energy savings.	♦ Significant energy benefit for viable system with broad market appeal.
Opportunity for DOE Action?	●	●

The Distributed Energy Program would like to acknowledge Oak Ridge National Laboratory for its Technical Project Input of this Report.

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