Solar Thermal System for Industrial Dehumidification and Steam Generation

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ABSTRACT

This paper introduces a solar thermal system that powers an absorption chiller, generates low pressure steam, or does both simultaneously. The project is only the fourth known solar thermal-driven double-effect (2E) absorption chiller project installed in the United States. It is the largest rooftop system of its kind, is the only industrial project installation with this type of system to date, and is the only one to produce both cooling and process steam.

Steinway & Sons in New York City is installing tracking parabolic trough solar energy collectors to generate 340°F hot water. In summer months, the hot water will drive a 99-ton double-effect absorption chiller to provide dehumidification and cooling. The dual-fuel chiller will use natural gas to supplement the solar resources when necessary. When dehumidification is not needed and the collectors can generate hot water above 275°F, the hot water will circulate through a steam generator and produce 15-psig steam to offset a portion of the plant's 1,200 kBtu/hr load.

After federal tax benefits and a NYSERDA grant, quality and productivity gains will result in cumulative net positive cash flow in less than 5 years. The incremental cost over that of a conventional packaged rooftop cooling system will pay for itself in less than 2 years.

The Application

Steinway & Sons manufactures their legendary pianos in the Queens borough of New York City. Their manufacturing facility was built in the 1870s and is not air conditioned. In their second-floor Action Department, employees build the hammer assemblies that strike the piano strings. The department's heating system consists of two 600-hp dual fueled boilers that inject low pressure steam into the space as needed to manage humidity in the winter but has no means of dehumidifying or otherwise conditioning the space in the summer. Maintaining consistent humidity is important in order to control moisture content of the wood components in the assembly.

Steinway has embarked on a dehumidification project factory wide to ensure product quality and decided to begin with the Action department. Installing a conventional packaged rooftop system was an option, but ultimately they decided to install a solar-powered system instead.

The project team consists of the following companies:

- Steinway & Sons: Project manager, owner and operator.
- ERS: Project management support, system performance analysis, instrumentation, system commissioning, NYSERDA grant administration, and reporting.
- Sustainable Energy Consulting: Solar 2E absorption system concept design, collector performance predictions.
- Abengoa IST: Solar trough supplier, trough installation and commissioning supervision.
- Sunshine Plus Solar: Collector field installation.
- Broad USA: 2E absorption chiller supplier, chiller commissioning.
- Schuyler Engineering: Engineering design.
- GCF-Inc.: Control system design.

The History of Solar Thermal Cooling in the United States

Sufficient numbers of solar thermal single-effect (1E) absorption chiller HVAC systems have been installed worldwide over the past 30 years to show that this is a technically feasible solar thermal application. These systems supply space heating and cooling, and service hot water. One of the earliest projects in the US was at Wagner College in New York City in the early 1980s which was primarily funded by NYSERDA. These systems generally utilize flat plate or evacuated tube collectors which supply upwards of 200ºF hot water to the single-stage absorption chiller with a design COP of around 0.7. With a relatively low solar collection efficiency of about 20% at this temperature, the overall solar to cooling conversion efficiency is around 15%.

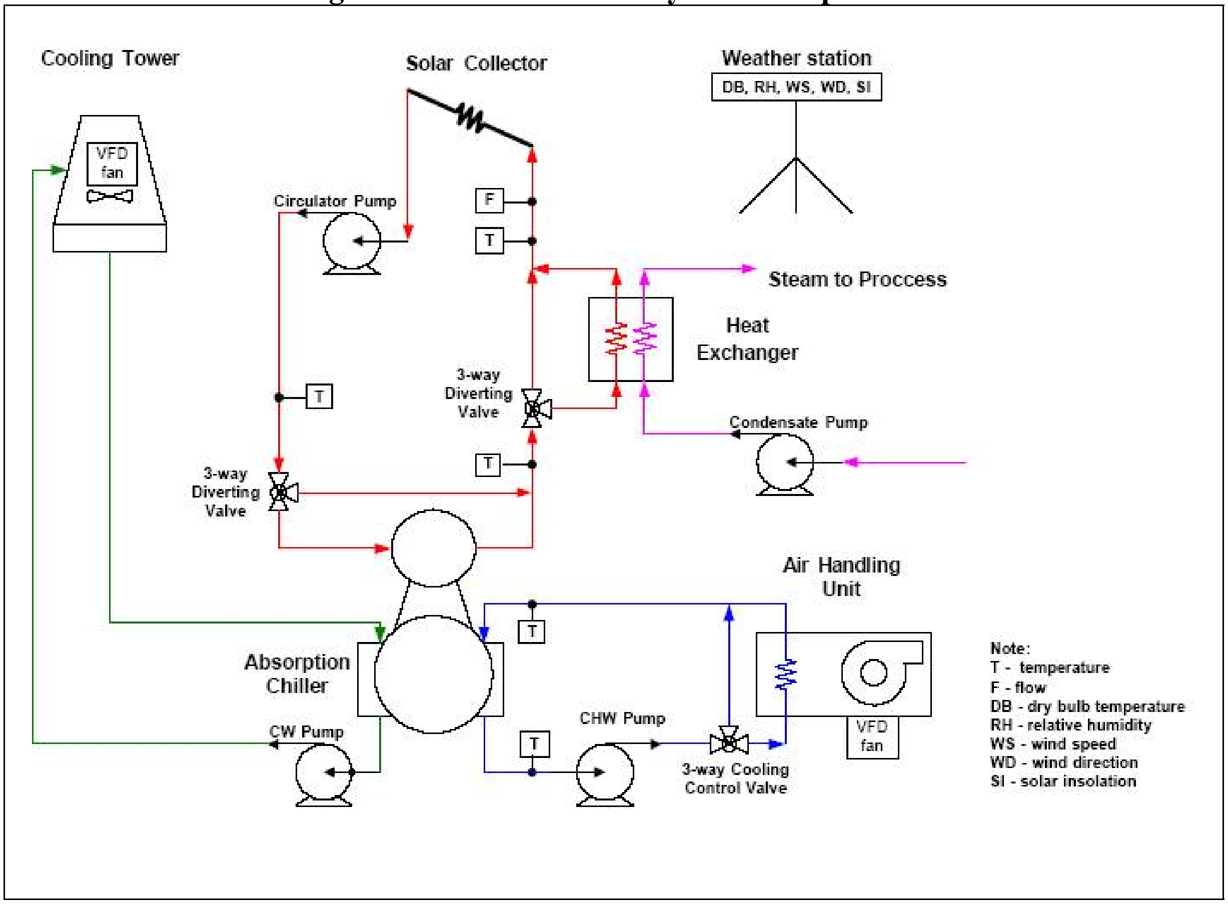
With the advent of two-stage (2E) absorption chillers in the late 1980s, R. Winston and his associates at the University of Chicago undertook the development of a concentrating evacuated tube collector that could produce sufficiently high temperature heat to drive these more efficient chillers. This work culminated in a 20-ton commercial demonstration project in Sacramento CA in 1997 with Integrated Compound Parabolic Concentrating (ICPC) non-tracking evacuated tube solar collectors driving a 20-ton Sanyo-McQuay direct-fired 2E absorption chiller that was modified to run on 330ºF hot water at full load. With a collection efficiency of approximately 50% at this temperature and the chiller COP of at least 1.2, the overall solar to cooling conversion efficiency was demonstrated to be approximately 60%, roughly four times that of a solar-driven 1E absorption chiller.

The second US solar-driven 2E absorption HVAC system was a commercial 50-ton Broad hot water fired 2E absorption chiller driven by the Solargenix tracking Power Roof™ solar collection system installed in Raleigh, NC in 2002. The third US system is a 4.6-ton Broad dual energy source (hot water and natural gas) 2E absorption chiller and four tracking parabolic trough collectors installed at Carnegie Mellon University in Pittsburgh PA in 2006.

The Solar Thermal System

Figure 1 illustrates key components of the proposed system. All the components shown in the diagram are new.

Figure 1: Solar Thermal System Components



Thirty-eight Abengoa Model PT-1 solar collectors mounted on the roof concentrate heat onto evacuated glass tubes, heating a pressurized water and glycol mixture from nominally 320ºF to 340ºF (the red loop in diagram). Photographs of the collectors are shown in Figure 2. The actual temperature varies with solar availability but is limited to 350ºF maximum. When cooling is needed the diverting valve directs this hot water to a 99-ton double-effect absorption chiller. The chiller has a rated coefficient of performance (COP) of 1.39 and integrated part load value (IPLV) of 1.586. The dual-fuel chiller uses natural gas when solar is not available and cooling is needed. It can use gas to supplement solar-sourced energy or run entirely on gas. The Broad dual fuel design (fossil fuel or hot water-fired) is relatively new, having been introduced in this country in 2005.

Figure 2: Abengoa IST Parabolic Solar Collectors (stowed position)

The chiller otherwise operates like other conventional chillers, cooling chilled water for the air handling unit (the blue loop in Figure 1.) and rejecting heat through a condenser to a cooling tower (the green loop in Figure 1).

When dehumidification is not needed and the collectors can generate hot water above 275°F, the hot water circulates through a vertical helical tube and shell steam generator heat exchanger and produces 15-psig process steam to offset a portion of the plant's constant 1,200 kBtu/hr load (the magenta loop in Figure 1).

A control system integrates the collector field and field circulator pump controls, chiller controls, and the steam generator diverting valve. The system is fully instrumented with flow-meters, temperature sensors, a pyronometer and weather station to monitor and record the system performance. If there is a loss of power or load during daylight operation, the controls will instruct an emergency power pack to place the collector field in the stow position.

Single Effect versus Double Effect Solar Thermal Cooling

Single-effect absorption chillers are more common and less expensive than double-effect chillers. This project captures the benefits of the double-effect design.

A double-effect (2E) absorption chiller driven by steam or hot water has a coefficient of performance (COP) of 1.1 to 1.6 depending on design and operating conditions, almost twice the efficiency of a single-effect unit. However it requires a heating fluid supply temperature of over 300˚F. Single-effect chillers can operate effectively with water at or below 200˚F. Concentrating solar thermal collectors can consistently provide such high operating temperatures[1] and operate with a collection efficiency more than double that of other collectors. Therefore the conversion efficiency for space cooling is four times better than non-concentrating solar thermal systems with single-effect chillers. The benefits of the system compared to a flat plate and single effect system include:

- Four times the efficiency (tons of cooling per square foot of collector area)
- Less than half the roof space required per ton of cooling
- Can generate low pressure steam when cooling is not needed

Siting

When roof-mounted, solar collectors also significantly reduce solar gain to the building, thus reducing the building A/C load. In this particular application, a top-floor space covered by an uninsulated concrete deck with a near-black cover, the reduction in solar heat gain reduced the cooling load by almost 10 percent.

The downstate New York market is a good market for such a system because absorption cooling is a relatively familiar technology to engineers and operators there, which is not true in all parts of the country. Furthermore, certain parts of New York City are capacity strained in mid-summer, precisely when this system most relieves the electrical distribution system of load. Also, electric rates are significantly higher than the national average. These advantages were found to outweigh the disadvantage of having lower direct solar resources there than in some other regions of the world.

Performance

ERS analysts measured internal loads, computed the hourly building envelope cooling loads and compared them with the solar availability to estimate the amount of useful heat that

[1] The world's first solar-driven 2E absorption chiller was installed in Sacramento, CA in 1997 by the Solargenix Energy-affiliated company, Solar Enterprises International. This solar HVAC project featured a 20-ton chiller and non-tracking Integrated Compound Parabolic Concentrating (ICPC) evacuated tube solar thermal collectors. Solargenix installed a hot-water fired 50-ton Broad 2E absorption chiller with a tracking solar thermal collection system in Raleigh in 2002. These two demonstration projects verify that building-integrated concentrating solar thermal collectors can consistently deliver the required high temperature solar hot water to load and confirm that solar-driven 2E absorption chiller is a viable solar application.

delivered to the cooling and steam generation systems. Figures 3 and 4 illustrate hourly building cooling load and solar availability in the summer, as modeled by Sustainable Energy Consulting. Note that the solar curve does not correspond exactly to usable cooling capacity because the system cannot effectively use the solar heat until the system hot water loop warms up in the morning to the chiller's minimum operating temperature. It is anticipated that solar driven cooling for this application will begin between 9 and 10 a.m.

Figure 3: Building Cooling Load

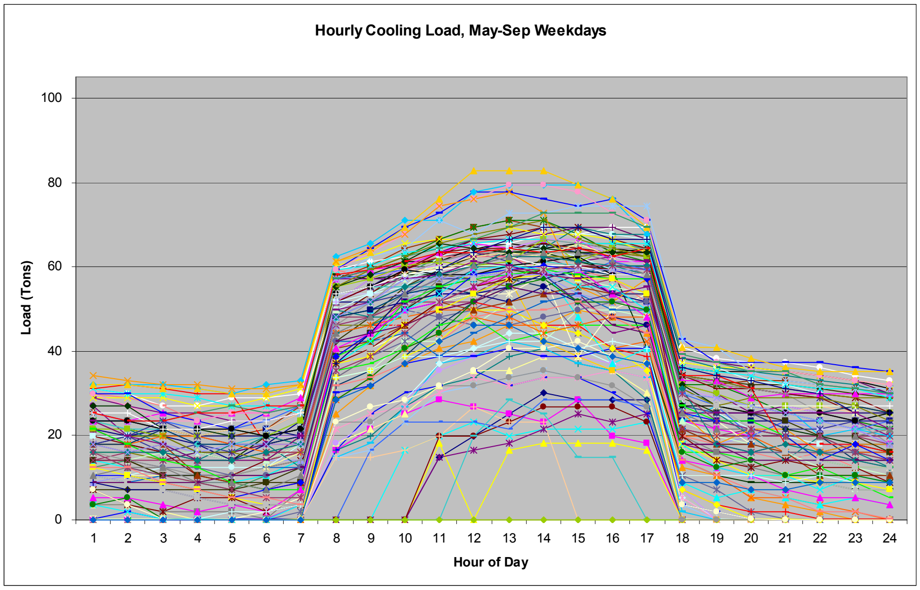
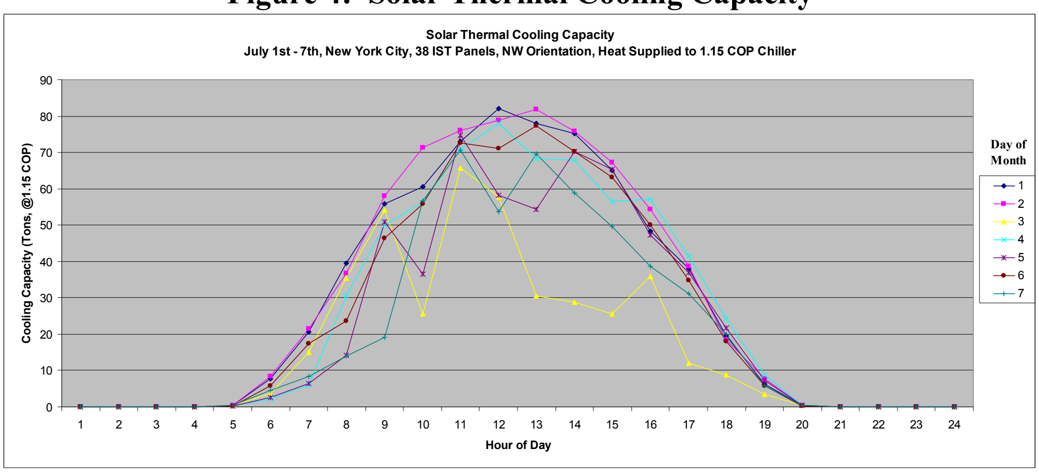


Figure 4: Solar Thermal Cooling Capacity



The lowest curve in Figure 4 illustrates the lesser production on a cloudy day.

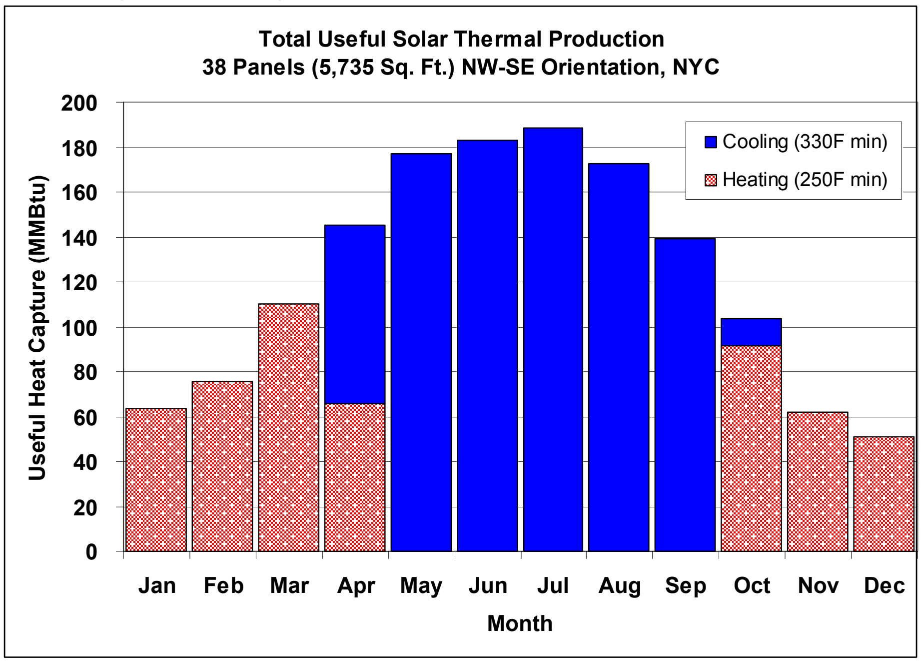
About half of the annual necessary energy is expected to be provided by solar, with the remainder by gas.

The current gas and electric tariffs for Steinway are such that the energy cost of cooling with a gas-fired double-effect chiller is less than cooling with a packaged air-cooled electric system. This means the double-effect absorption system is less expensive to operate than a packaged air-cooled system even when no solar resources are available.

The building low pressure steam system provides process and space heating and humidification. In the summer the load is relatively constant and a minimum of about 50 boiler horsepower. Load increases in the winter. The minimum facility load exceeds the 800 kBtu/hr maximum production capacity of the solar thermal system by about 50%. This means that all solar energy captured by the collectors is usable by the system at all times. There is never a time when thermal production exceeds demand.

Figure 5 summarizes the projected production rate for the collector system.

Figure 5: Projected Annual Solar Thermal Production



If all available cooling is useful production and assuming a relatively modest annual average COP of 1.15, the total cooling effect would be about 80,000 ton-hours per year. Because there are periods when some of the cooling is not needed, the building model assumed a lesser amount of cooling production, about 50,000 ton-hours per year, and correspondingly higher steam generation.

Design Issues

Steinway has managed the installation with the assistance of ERS, and has acted as their own general contractor. This has saved significant cost. While the installation generally has proceeded as planned there have been three challenges for which future designers will want to give due consideration.

First, the heat transfer fluid selection process was not easy. Water performs more efficiently than other fluids, but the system will operate in the winter in a climate that requires freeze protection. A drain-back system that empties the pipes whenever the water is not circulating was not feasible for this application. Using the steam generator system in reverse mode to maintain a minimum loop temperature was an option but would have been contrary to the energy saving goals and hurt the economics. Thermal oils met the temperature requirement, but they have relatively poor heat transfer properties at the system's design temperatures, so the heat recovery rate and chiller capacity would have had to be substantially derated with oils, again hurting the economics. Water with antifreeze that was capable of 0ºF freeze protection and also resistant to breakdown at up to 350ºF was the best solution. The system's piping layout was designed to minimize stagnant flow regions. The team ultimately selected an ethylene glycol-based fluid, DowTherm 4000, which is rated to 350ºF. Controls will be added to avoid operational temperatures in excess of 350ºF and fluid sample testing will be conducted with accelerated intervals because the system will operate so near the design limits of the glycol. Such issues will not be a concern for applications with summer-only operation or in warmer climates.

Second, collector mounting was more difficult than expected. The collectors must be mounted securely enough to sustain hurricane-force winds, and while the collectors can be placed in low-drag stowing position, the requisite holding force is high. The vintage building on which the collectors are mounted is four stories high, was built to bear additional floors that never were added, and consequently has an 8-inch reinforced concrete deck. Sunshine Plus Solar performed the installation. Mounting the collectors required specialized anchors and structurally supporting highly loaded mounting pylons. In addition, a wind fence was installed to reduce loads acting on the collectors.

Third, plumbing costs were extremely high. Copper prices are at historic highs and New York City labor costs are never low. Close coupling the system—keeping the collectors, chiller, AHU, cooling tower, and heat exchanger within a few dozen feet of each together—would have saved considerable funding but was not practically prudent given the facility layout.

Economics

The total project capital cost is about $1,050,000. The air-cooled system option would have cost about $250,000.

The project made considerable use of external funding and tax benefits. NYSERDA provided a Research & Development grant that contributed funding for the initial feasibility study and project oversight by ERS as well as $300,000 towards the capital cost and advanced instrumentation. Federal tax credits pay for 30% of qualifying renewable system costs and is expected to be about $175,000. Federal accelerated depreciation improves the project economics further. The system is not only eligible for the federal 5-yr Modified Accelerated Cost Reduction System (MACRS) but also for a special 50% bonus depreciation, which applies to qualifying renewable systems. The MACRS plus the bonus depreciation means that equipment normally depreciated over 20 or 39 years can be depreciated over 75% for a tax deduction in just two years. The present value of accelerated depreciation is almost $200,000.

There are also New York-specific property tax advantages to the system and potential renewable energy credits. All of these elements are effectively external funding that improve the project cash flow and present value. The annual cash flow components include:

- Annual tax benefits during the first 5 years,
- Annual energy savings,
- Potential sale of renewable energy credits (the system is being heavily instrumented),
- Improved productivity and quality due to process changes the dehumidification allows,
- Elimination of costs associated with a dedicated wood conditioning room that no longer is necessary, and

- Increased maintenance costs.

Employee comfort and associated productivity are expected to increase but were not monetized. Sales increases due to higher quality also are possible.

These factors were incorporated into the economic analysis. The analysis was performed on an after-tax basis and has uneven cash flow streams because the MACRS is uneven.

Table 1 shows the detailed annual cost and benefit components for the incremental upgrade analysis. ERS prepared similar analysis to compare the economics of solar thermal cooling versus existing conditions.

Table 1: Annual Cash Flow, Solar Thermal versus RTUs

			Cash Flow by Year (in $1,000s)							
Item	**Simple Sum**	**NPV**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Capital Cost	($1,050)	($1,050)	($1,050)							
Research Costs	($100)	($100)	($100)							
Avoided Capital Cost of Air Cooled RTUs	$250	$250	$250							
NYSERDA Incentives	$400	$400	$400							
Federal Tax Credit*	$225	$210		$225						
MACRS Accelerated Federal Depreciation Tax Benefit	$312	$275		$187	$50	$30	$18	$18	$9	
Ordinary 20-Yr Straight Line Depreciation State+Local Tax Benefit	$172	$89		$9	$9	$9	$9	$9	$9	$9
Ordinary 20-Yr Straight Line Depr Fed+State+City Tax Benefit on RTUs	($128)	($42)		($3)	($3)	($3)	($3)	($3)	($3)	($3)
Property tax exemption, avoids tax on RTU system	$94	$60		$9	$9	$8	$8	$7	$7	$6
Net Annual Energy Savings	$835	$401		$30	$31	$32	$33	$34	$35	$36
Income Tax Expense Deduction Not Claimed Because of Energy Savings	($107)	($51)		($4)	($4)	($4)	($4)	($4)	($5)	($5)
Net Annual Renewable Energy Credit Sales	$41	$21		$2	$2	$2	$2	$2	$2	$2
Net Annual Increased O&M Costs Over RTUs	($112)	($54)		($4)	($4)	($4)	($4)	($5)	($5)	($5)
TOTAL	**$831**	**$408**	**($500)**	**$451**	**$89**	**$69**	**$57**	**$58**	**$49**	**$41**
Net Cumulative Cash Flow			**($500)**	**($49)**	**$40**	**$109**	**$166**	**$224**	**$273**	**$313**

**Assumes that the federal credit basis is the gross cost after deducting the NYSERDA grant. This avoids paying 35% income tax on the grant. If Steinway expects not to have to pay income tax in 2008 due to reinvestment of profits or other reason, SEIA documents suggest that the federal tax credit basis could be claimed on gross cost before deducting the NYSERDA grant. This would increase the value of the tax credit and the whole project by $90k.*

Figure 6 illustrates the cash flow compared to the alternative air-cooled system and to existing conditions. The system pays for the cost premium over air-cooled in less than 2 years.

Adding humidification control pays for itself in less than 7 years by improving productivity, reducing scrap and rework, and by allowing Steinway to remove a dedicated conditioning room. It may also improve the product quality. Figure 7 shows the cash flow for this comparison.

Figure 6: Project Cash Flow
Solar Thermal Versus RTUs

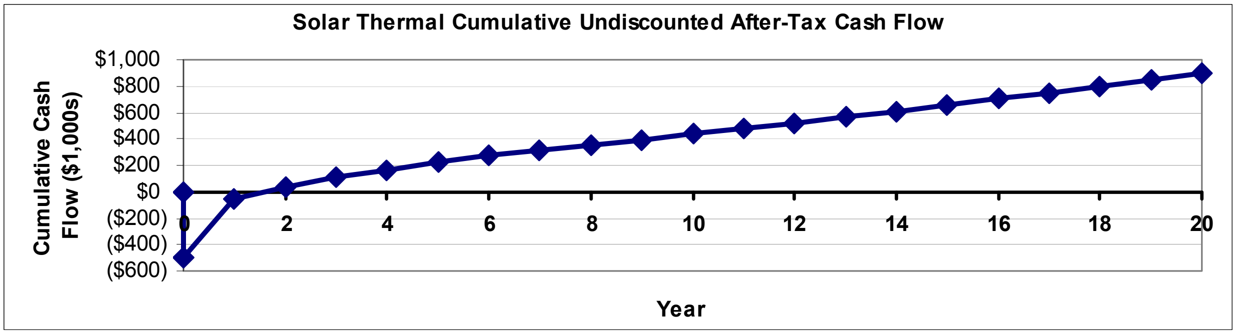
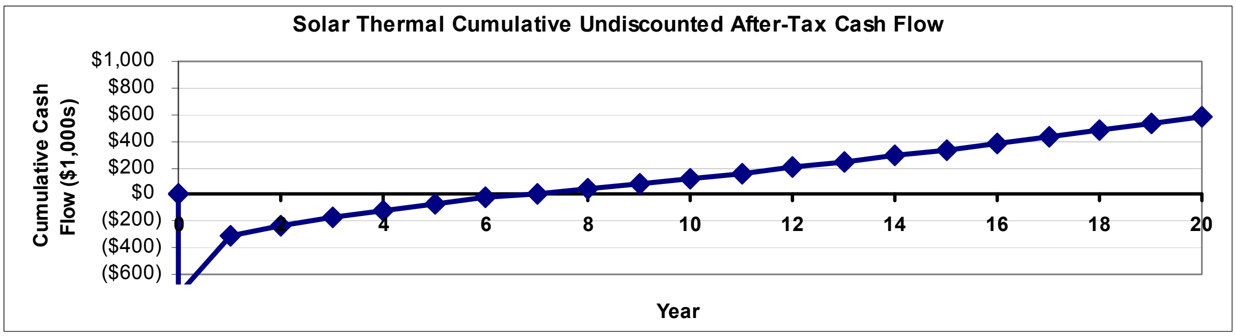


Figure 7: Project Cash Flow
Solar Thermal Versus Existing Conditions



Summary

Many observations and conclusions have been made over the duration of this project that are worthy of note. First and foremost is the conclusion that given the available grant funding in New York state and the federal tax credits, the economics of this system make sense from a business perspective. This is predicated on the ability of the facility to use the available energy streams from the system year-round. In this case, the facility operates a single shift, five days a week – but can use all of the energy generated by the system during the scheduled operations of the plant.

Concentrating solar thermal systems can generate higher temperatures (340ºF) than typical flat plate collectors (200 ºF), which enables them to be paired with a double-effect absorption chiller, which are up to twice as efficient as the single-effect chillers used with low temperature systems. Concentrating double-effect systems also require as little as 25% of collector area as flat plate systems per ton of cooling generated. An additional benefit of the system, if roof mounted, is to lower the incident radiation falling on the roof thus lowering the facility cooling load. In this application this benefit reduced the cooling load by about 10%.

Based on the projected results, these types of system are viable for northern latitudes. Additionally, this customer's gas and electric rates are such that even when the sun is not shining and the dual-fuel chiller heat source is natural gas, it will be less expensive to operate than an electric driven air-cooled system.

Finally, as additional manufacturers and system sizes become available, it is conceivable that packaged systems inclusive of all major components (solar array, chiller, steam generators, pumps, and integrated controls) will be developed which could reduce costs substantially - particularly if turnkey systems, inclusive of installation, are offered.

Over the next year, further data will be collected and analyzed to determine the annualized performance of this system. The results of this analysis will be publish when available.

Acknowledgements

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