Post-Installation Performance Characteristics of a Solar-Driven System for Industrial Dehumidification and Steam Generation

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ABSTRACT

At the 2009 ACEEE Summer Study, the author presented a paper on a unique cutting-edge solar thermal dehumidification and steam generation project proposed for the Steinway & Sons US piano manufacturing facility located in New York City. As a result, the authors received requests to publish performance data once available. This follow-on paper will present available post-installation performance data and characterization of the system, as well as installation challenges, operational considerations, overall lessons learned, and the applicability of this technology in industry. Additionally, a synopsis of the feasibility analysis, system configuration, design parameters, and funding sources will be discussed. It is the largest industrial double-effect solar application to date to use the heat for both steam generation and cooling.

Steinway installed thirty-eight rooftop tracking parabolic trough solar energy collectors that generate 340°F pressurized hot water. In the summer months, this solar fluid drives a 100-ton double-effect absorption chiller enabling humidity management in a moisture sensitive assembly area that had previously encountered high scrap and rework rates. When solar resources are not available, the dual-fuel chiller uses natural gas for the same effect. If dehumidification is not needed and the collectors can generate hot water above 275°F, a steam generator is used to develop 15-psig steam to offset a portion of the plant's minimum 1,200 kBtu/h load. Simultaneous dehumidification and steam generation is also supported.

The project was completed in the summer of 2010 and was partially funded by the New York State Energy Research and Development Authority (NYSERDA) and federal tax benefits.

Project Background

Over the past several years, Steinway & Sons has been aggressively addressing productivity and energy issues at their 150-year-old manufacturing facility in New York City (Astoria Queens). As part of this effort, improvements in environmental control in specific manufacturing areas were targeted to enhance product quality and reduce rework.

As a result, Steinway installed rooftop tracking parabolic trough solar collectors in conjunction with a dual-fuel (solar input or natural gas) absorption chiller for cooling/dehumidification and a steam generator for process heating purposes. In the summer months, this solar fluid drives a 100-ton double-effect absorption chiller enabling humidity management in the Action Department where the intricate keyboard mechanism of the piano is manufactured. If dehumidification is not needed and the collectors can generate hot water above 275°F, a steam generator is used to develop 15-psig steam to offset a portion of the plant's continuous steam load. Simultaneous dehumidification and steam generation is also supported with this system. The system became operational and was partially commissioned in the late summer/fall of 2010 and will be fully commissioned during the early cooling season of 2011.

Feasibility Study

The project originated with a grant from the New York State Energy & Research Development Authority (NYSERDA) to do a proof of concept analysis of the system given the solar resources in New York. ERS, and its partner Sustainable Energy Consulting, conducted this initial phase of the feasibility, which proved favorable and encouraged NYSERDA to release additional funds to perform a feasibility study at a specific facility in New York State. ERS had conducted a comprehensive energy study at the Steinway facility in New York City and thus was familiar with the plant and the goals of management. Steinway expressed interest, and an in-depth feasibility study on the cost-effectiveness of solar thermal cooling/dehumidification was conducted. The project team performed intensive energy analysis, building modeling, and economic evaluation of the system. The study concluded that with NYSERDA incentives for implementation, a solar thermal dehumidification/cooling system with steam generation could deliver a 4.8-year payback compared to no space conditioning (existing scenario) due to productivity enhancements at the plant and a 1.1-year payback compared to installing a traditional packaged air-cooled system.

Based on the results of the feasibility, Steinway decided to move forward with the installation of the system and commenced the design phase of the project.

System Configuration

Figure 1 illustrates key components of the proposed system. All the components shown in the diagram are new. Thirty-eight Abengoa Model PT-1 solar collectors mounted on the roof concentrate heat onto evacuated glass tubes, heating a pressurized (115 psig) water and glycol mixture from nominally 320ºF to 340ºF. 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 100-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 chiller otherwise operates like other conventional chillers, supplying chilled water for the air handling unit and rejecting heat through a condenser to a cooling tower.

Figure 1: Solar Thermal System Components

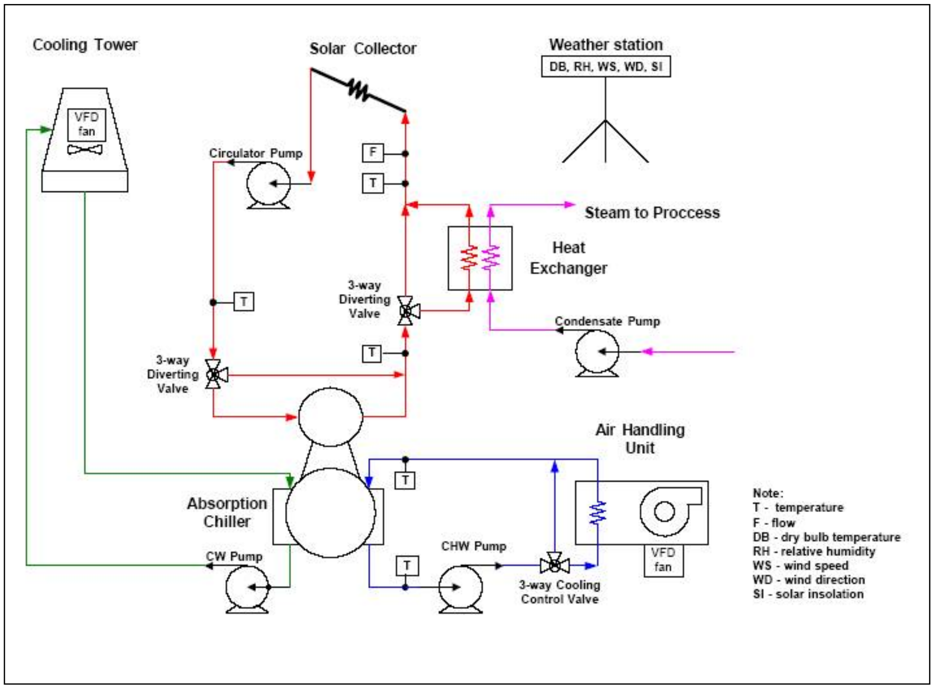
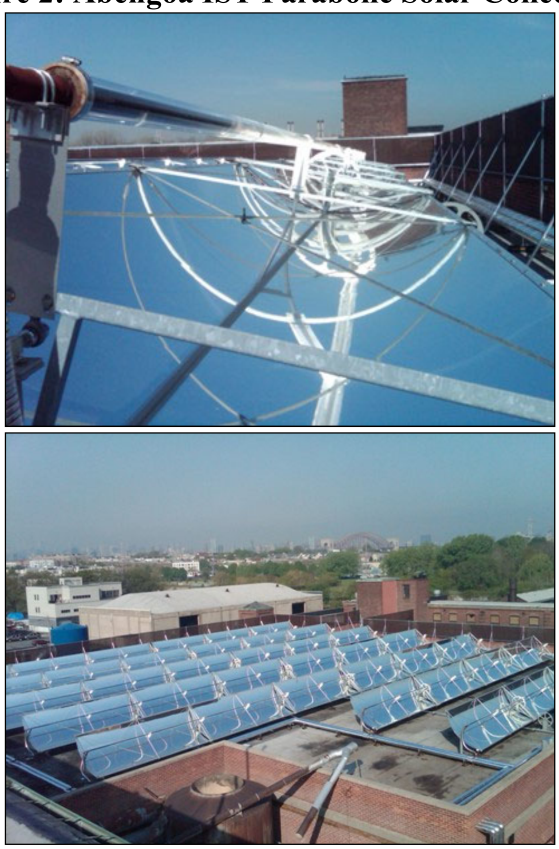


Figure 2: Abengoa IST Parabolic Solar Collectors



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/h load.

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, 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.

Cost

The project's final costs increased approximately 20% over the estimated costs developed during the feasibility study and totaled approximately $1.2M. Most of this increase can be attributed to contractors being unfamiliar with installing high temperature/high pressure piping systems. The installing contractors, many of which were selected based on existing relationships, were instrumental in developing construction costs for the feasibility study. Unfortunately, neither the mechanical/HVAC contractor nor the solar array installation contractor had direct experience with the equipment they were installing. The HVAC contractor failed to consider all components required for a complete system and failed to realize that ASME pressure-rated materials such as valves, fittings, and heat exchangers would cost significantly more than the materials that they typically install in HVAC projects. The contractor installing the array failed to include costs for a wind fence rated for hurricane conditions. Neither the array contractor nor the solar array supplier properly accounted for the extra cost associated with anchoring and support of the arrays on a concrete slab roof as opposed to the ground. The result was that feasibility costs were estimated to be significantly lower than actual bid costs.

Another significant cost increase can be attributed to the relative locations of the major system components. Initial estimates in the feasibility study were based on the chiller being installed almost directly below the solar array. This would have kept high temperature and chilled water piping to a minimum. The final design placed the chiller a considerable distance from the array.

The final chiller plant costs were less than budgeted, and the distribution system costs were greater. Table 1 normalizes the costs for the project in dollars per ton based on the typical summer afternoon cooling capacity, using a double-effect absorption chiller with a 1.2 average coefficient of performance, for a 75- to 100-ton system. The normalized cost in dollars per kBtu/h of collector thermal output is the cost per ton divided by 10.

Table 1 - Solar Thermal Normalized System Cost,
Air Conditioning/Dehumidification and Low Pressure Steam Generation Configuration

System Component	Description	Cost per Ton
Hot water production	Parabolic collectors, shipping, and collector controls	$3,000
	Structural engineering, special purpose hot water pumps with VFDs, rigging, roof installation, fencing, piping to chiller and steam generator, insulation, and glycol	$3,700
Steam generator	Material and installation, connection to low pressure steam line, condensate return, and make-up water line	$700
Chiller plant	Double-effect dual-fuel absorption chiller	$1,400
	Cooling tower, condenser water pumps, piping, wiring, connections,VFDs, chiller installation, controls, related engineering	$2,600
Cool side distribution	Single zone AHU with VFD, chilled-water pump and piping, short duct runs or tie-in to existing distribution system, related engineering	$3,200
Project oversight	System design engineering, project oversight	$1,200
TOTAL		**$15,800**

For comparison, a packaged air-cooled rooftop system with similar requirements might cost $3,000 per ton in New York City, installed. Many of the costs cited above will be greatly influenced by the specific installation. Large variations in piping costs are to be expected based on the relationship among the locations of the solar array field, chiller, steam generator, and chilled-water connection. The pilot site had long pipe runs between the array and chiller, and between the chiller and the cooling air handler. Costs can be reduced significantly by co-locating equipment to the maximum extent.

System Performance

The system became operable late in the cooling season of 2010 and thus complete performance data is not yet available. The system was well instrumented to characterize performance and will provide continuous data collection through a server-based data acquisition system. This data acquisition system is still being finalized and commissioned at the time of this writing, but some performance data for the collector array was available and is presented.

Projected System Performance

The project team computed the hourly building envelope cooling/dehumidification loads and compared them with the solar availability to estimate the amount of useful heat that was delivered to the cooling and steam generation systems. Figures 3 and 4 illustrate hourly building cooling load and solar availability in the summer. 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 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

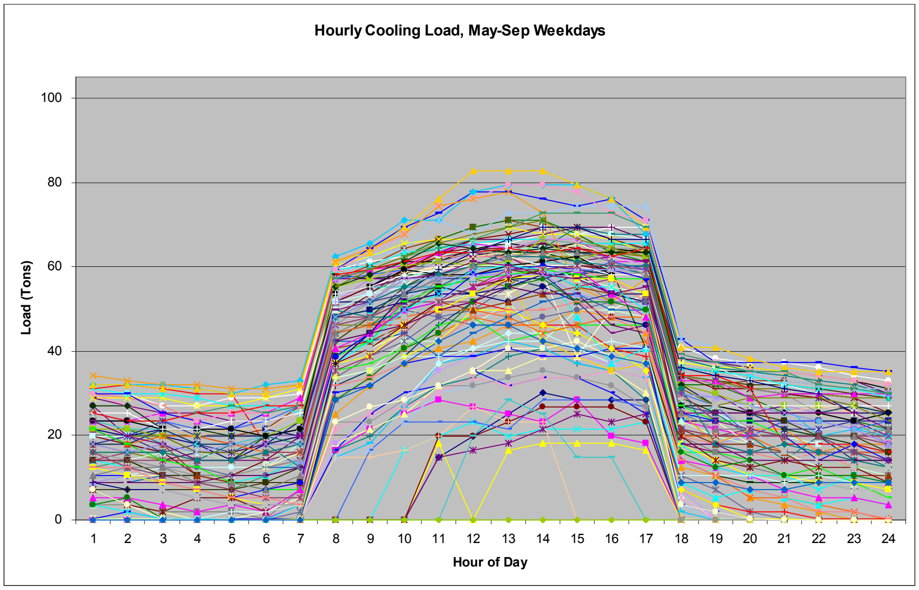
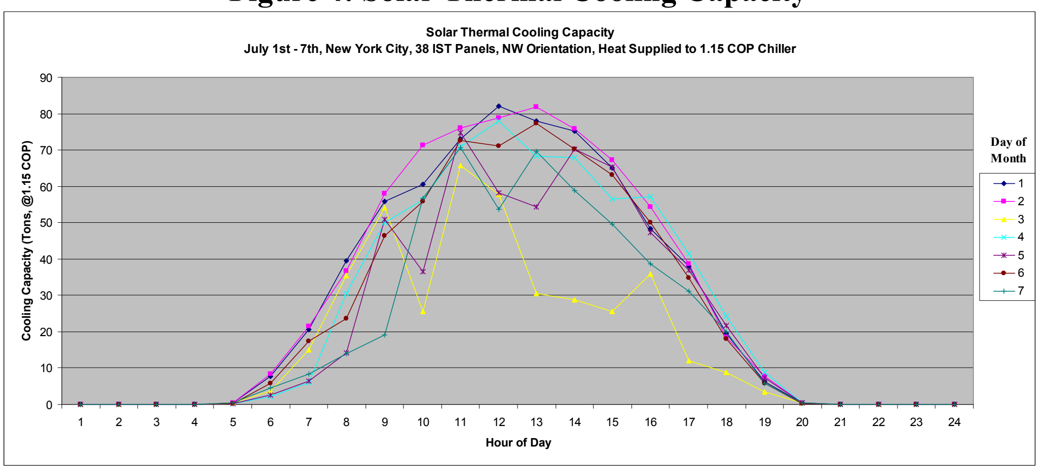


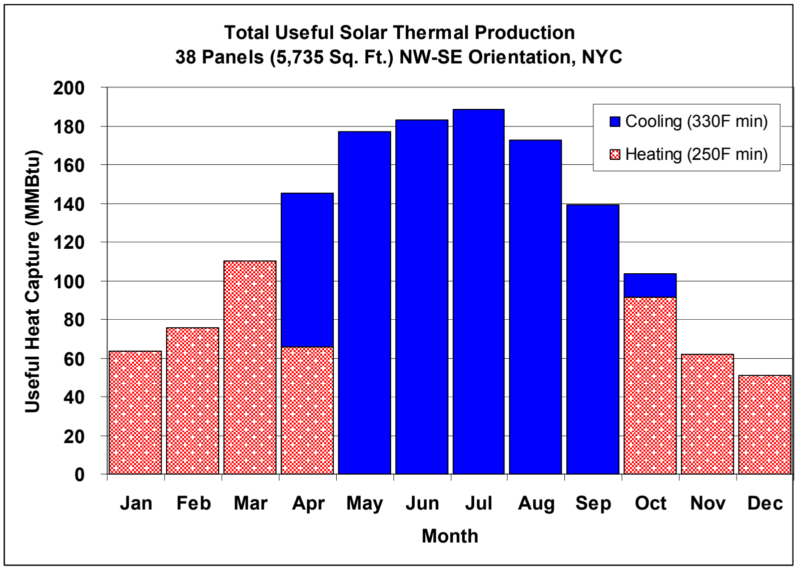
Figure 4: Solar Thermal Cooling Capacity



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. 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. The minimum facility load exceeds the 800 kBtu/h 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. Figure 5 summarizes the projected production rate for the collector system.

Figure 5: Projected Annual Solar Thermal Production



If all available cooling/dehumidification is used for production and a relatively modest annual average COP of 1.15 is assumed, the total cooling effect would be about 80,000 ton-hours per year.

Actual Collector Performance

In the late summer of 2010, solar insolation and array temperatures were captured and assessed. Figures 6 through 9 present temperature and power data captured on two different days in August and September. Temperatures achieved in the collector field approached 320°F and were sufficient to drive the system and develop cooling or steam resources. Full system performance data will be collected and analyzed in the summer of 2011.

Figure 6: August 31, 2010 Collector Temperature Output
Max Temp = 150°C (302°F)

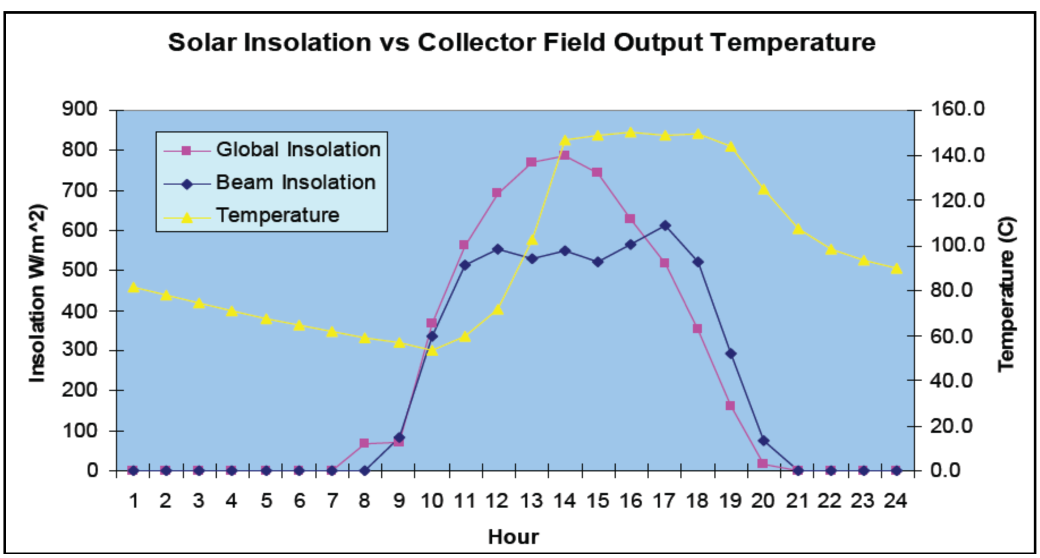


Figure 7: August 31, 2010 Collector Power Output
Power = 922 kWh

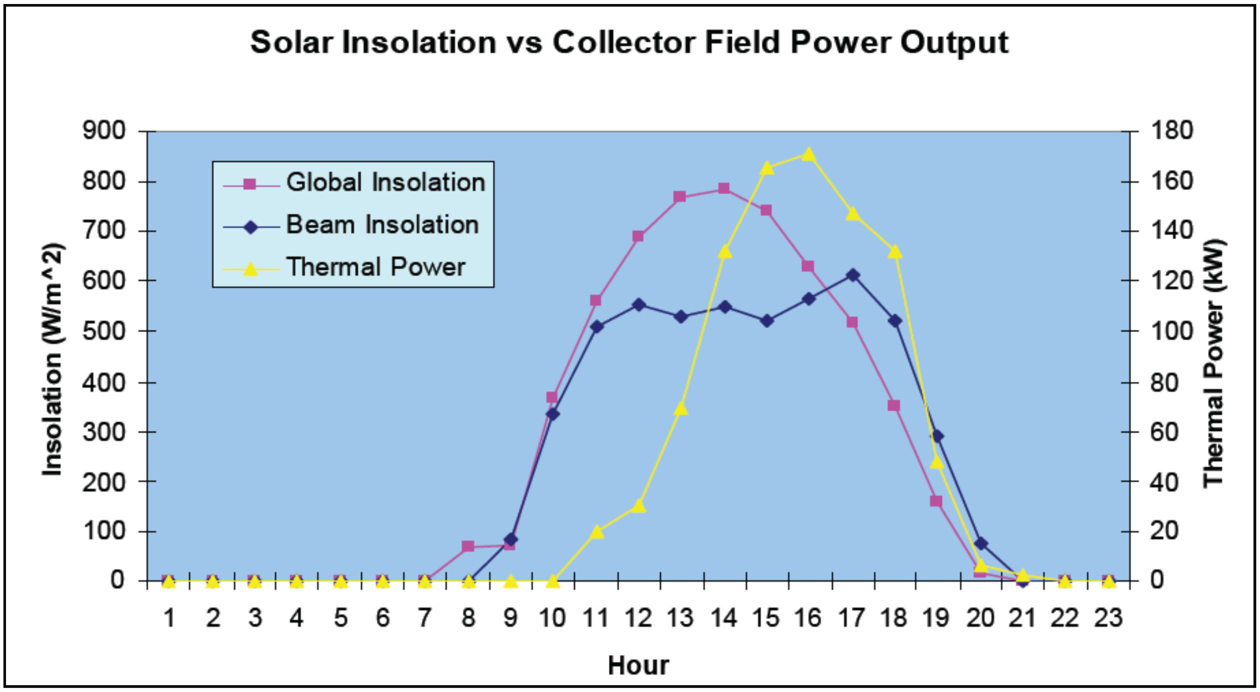


Figure 8: September 7, 2010 Collector Array Temperature Output
Max Temp = 159°C (318°F)

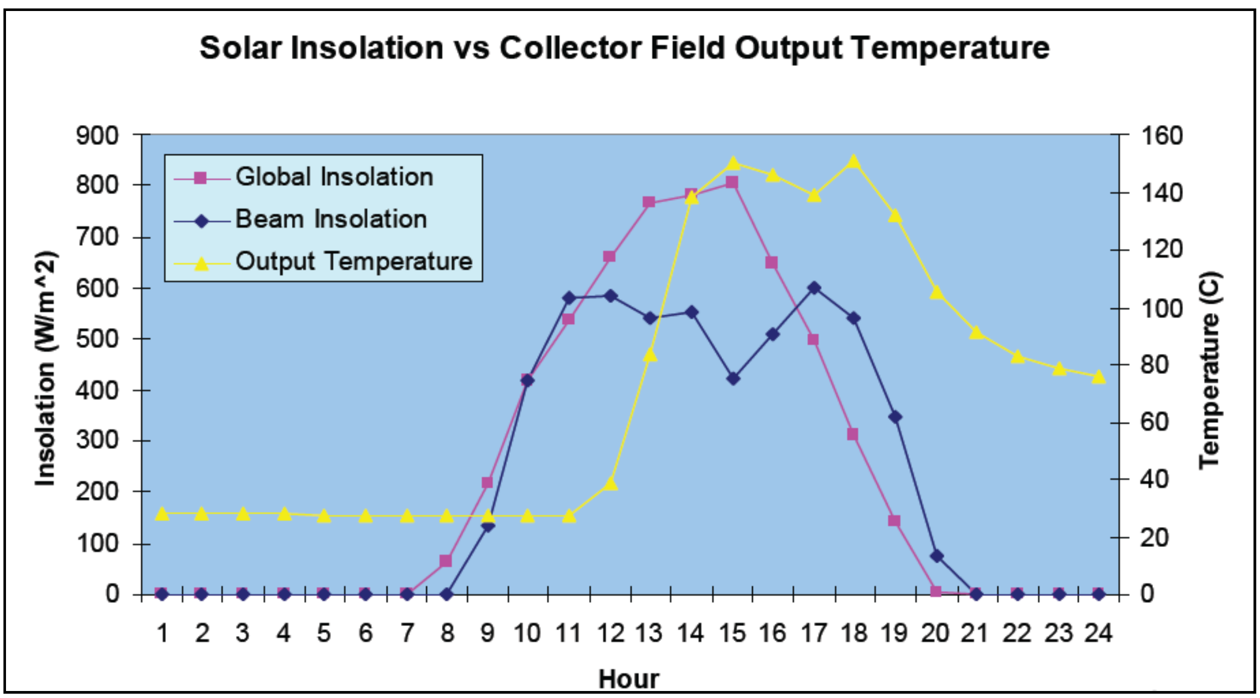
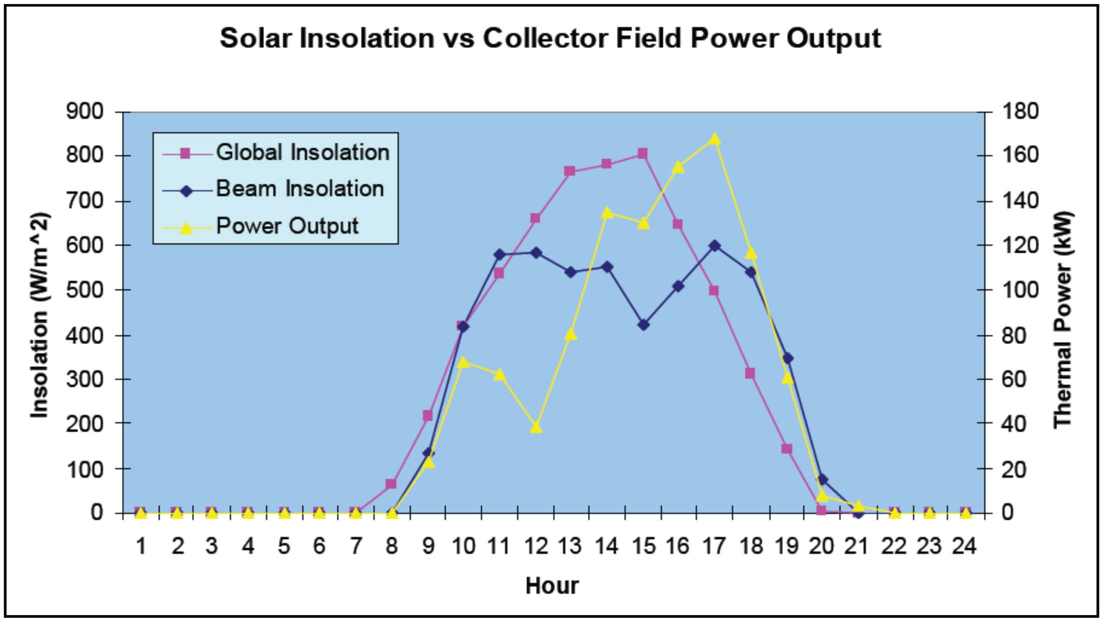


Figure 9: September 7, 2010 Collector Power Output
Power = 1047 kWh



Installation Challenges

There were several challenges over the course of the installation that impacted the project schedule. The installation took considerably longer than anticipated due to equipment shipment delays, contractor inexperience with the types of equipment being installed, coordination of system controls integration, and structural mounting issues. Each of these is discussed further below.

System Integration & Contractor Inexperience

One of the biggest challenges of the project was the overall coordination of contractors and the respective integration of system components. Although each of the technology components was relatively mature, the integration into this type of system was cutting edge and had not been done on this scale before. The lack of a single turnkey design-build entity complicated the project and in the end caused many delays and integration issues.

Equipment Delays

The two primary components of the system - the solar array and the absorption chiller - were both delayed in shipment due to longer manufacturing times than promised. The chiller was ordered in September of 2008. Manufacturing time was stated as 13 weeks with an additional 2 weeks for delivery from China. The manufacturing time slipped to 24 weeks and the chiller did not arrive to the site until March of 2009, well behind schedule. Additionally, several months after delivery, but prior to system startup, the manufacturer realized that field modifications were necessary for proper chiller operation. These chiller issues alone would have caused a project delay, but the major problems in the delivery and installation of the solar array caused a much greater delay - almost one year. The solar troughs were ordered in August of 2008 for delivery in November to facilitate installation prior to the winter season. Delays occurred in the manufacture of the panels and the array was not delivered until well into December. Installation issues described below further delayed the operational startup of the array.

Mechanical Issues

To compound the equipment delay, shortly after initial installation of the solar array to the concrete roof deck, the mounting system failed. All pylons had been installed with the specified anchors per the structural engineering design. The anchors had experienced a pull-out failure once the tracking system drive line cable was placed under operable tension. The quality of the anchor bolt installation on all 128 pylons became suspect. From that point, installation of the array stalled. Shortly thereafter, a moderate wind storm caused several pull-out failures and several bending failures in the anchors. It was clear that the anchor system design was inadequate and that the anchor installation was improper. A re-design of the anchor systems was completed and Steinway modified the system based on the new design.

Maintenance Considerations

The unique component of this system is the solar collector array. The chilled water system and steam generation components would require standard maintenance for those systems. The array however has some unique concerns. Maintaining a clean reflective surface is important and requires periodic washing – typically monthly. Additionally, snow maintenance was required during heavy winter snowfalls to provide clearance for the tracking collector movement to occur without impediment. Periodic assessment for system leaks, tracking focus, and smooth operation of the drive mechanism is also required. Finally, periodic monitoring of the array thermal fluid is required to check for degradation and mix.

Lessons Learned

Given that this is an early stage development project for this technology and contractors with limited experience with this type of system are available, a number of lessons were learned throughout the phases of the project. These lessons are presented in the section below.

Design & Development

1. Engineers experienced in high pressure steam or hot water systems should be included in the initial design development. Full plans and specifications are not needed to accurately estimate costs at the feasibility study phase, but competent design engineers should be tasked with creating preliminary designs, which would include a P&ID (process and instrumentation diagram) schematic, equipment sizing and selections, pipe sizing, and preliminary electrical and structural designs. This level of design gives the contractors information required to more accurately estimate costs.
2. If contractors are brought in to aid in design development and pricing during the feasibility study portion of the project, they should have specific experience in medium temperature water (MTW) or high pressure steam systems, controls integration, and installation of parabolic trough collector systems.

3. Competent design professionals should have no difficulty incorporating high temperature solar arrays and dual heat source chillers in future designs. Once design parameters and limitations are obtained from the manufacturer, the systems can be treated as any other system component.
4. Full plans and specifications are required before contractors are hired to do the work, and before major pieces of equipment are purchased. These plans and specifications completed in standard AIA master format clearly identify each contractor's scope of work and materials and equipment to be provided. Full plans were not developed until well into the project, which impacted the progression of the project.
5. An experienced turnkey solutions provider would have been preferable to a multi-contractor team and would have provided significant cost reductions and better quality control. Such providers are key to the commercialization of this technology.

Implementation

1. Construction of large complex projects must be planned and managed. Extra diligence is required when contractors are working outside of their typical project type. A thorough project plan with firm construction timeline commitments should be instituted with continuous monitoring in the form of periodic construction meetings.
2. Better solar array installation documentation is required, or a much closer working relationship between the array supplier and the installer must be fostered. Additionally, some of the solar array controls and drive components for this particular system (drive motors, controller) need to be more robust. Other drive styles exist and should be considered.
3. The solar array installation requires considerable expertise and should be done by experience installers. A customer cannot expect to order an array and install it like a packaged chiller or rooftop unit without substantial training, and optimization requires intricate knowledge.
4. The dual heat source chiller is an emerging technology. Significant field modifications were required after the chiller was delivered.
5. All parties must perform with competence. The design and installation errors surrounding the anchor system caused a long delay and numerous complications.

Applicability of the Technology

Based on the knowledge and experience gained from the development of this project as well as the preliminary performance observed for the system, the following general considerations can be stated about the applicability of this type of system for commercial or industrial applications.

1. Applications must have both sustained thermal and cooling/dehumidification loads year round. Industrial facilities with environmentally controlled manufacturing or commercial facilities with large reheat or hot water loads in the summer are examples of suitable operations.
2. The collector array (rooftop or ground mounted) requires considerable available real estate – approximately 2,000 sf/ton.

3. Given the emerging nature of this technology configuration and deployment, substantial incentives are required to make the economics and business case favorable. Non-energy benefits such as improved product quality, reduced scrap, or rework favorably impact the project economics. Further development of an integrated packaged system by turnkey providers could significantly reduce costs and improve the cost-effectiveness of these systems. Such providers improve the chance of viability in the marketplace.
4. The system is suitable for a variety of latitudes including one as northerly as NYC (40°47′).

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