ERDC/CERL TR-21-18

Construction Engineering Research Laboratory

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Installation Technology Transition Program (ITTP)

Performance Testing and Modeling of a Transpired Ventilation Preheat Solar Wall

Performance Evaluation of Facilities at Fort Drum, NY, and Kansas Air National Guard, Topeka, KS

Sean M. Wallace, Scott M. Lux, Constandinos M. Mitsingas, Irene A. Andsager, and Tapan C. Patel

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U.S. Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)
2902 Newmark Dr.
Champaign, IL 61824

Technical Report

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600 Army Pentagon, Washington, DC 20314-1000

Under MIPR 10956020

Abstract

This work performed measurement and verification of installed, operational solar wall systems at Fort Drum, NY, and Forbes Field, Air National Guard, Topeka, KS. Actual annual savings were compared estimated savings generated by a solar wall modeling tool (RETScreen). A comparison with the RETScreen modeling tool shows that the measured actively heated air provided by the solar wall provides 57% more heat than the RETScreen tool predicted, after accounting for boiler efficiency. The solar wall at Fort Drum yields a net savings of $851/yr, for a simple payback of 146 years and a SIR of 0.16. RETScreen models indicate that the solar wall system at Forbes Field, Kansas Air National Guard, Topeka, KS saves $9,350/yr, for a simple payback of 58.8 years and a SIR of 0.34. Although results showed that, due to low natural gas prices, the Fort Drum system was not economically viable, it was recommended that the system still be used to meet renewable energy and fossil fuel reduction goals. The current system becomes economical (SIR 1.00) at a natural gas rate of $16.00/MMBTU *or* $1.60 /therm.

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Preface

This study was funded by and conducted for the Installation Technology Transfer Program (ITTP) and sponsored by the Office of the Assistant Chief of Staff, Installation Management (OACSIM) under MIPR 10956020.

The work was performed by the Energy Branch (CFE) of the Facilities Division (CF), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Mr. Jedediah B. Alvey was Branch Chief, CEERD-CFE; Ms. Giselle Rodriguez was Division Chief, CEERD-CF; and Mr. Kurt Kinnevan, CEERD-CV-T was the Technical Director for Environmental Quality and Installations. The Deputy Director of ERDC-CERL was Ms. Michelle Hanson, and the Director was Dr. Andrew J. Nelson.

The Commander of ERDC was COL Teresa A. Schlosser, and Dr. David W. Pittman was the Director.

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1 Introduction

1.1 Background

Of all renewable energy technologies, solar thermal systems are among the most adopted because they are simple, effective, and require very little maintenance. Since solar thermal systems convert solar radiation directly into heat, they can significantly offset the fossil fuel use requirements of traditional heating systems in many applications (NRG 2009), such as heating swimming pools, providing domestic hot water, meeting or supplementing the demand for space heating, etc. (Kaltschmitt, Streicher, and Weise 2007). Solar thermal collection systems can potentially yield significant energy savings especially in northern climates where the demand for building space heating is relatively high.

The transpired ventilation preheat "solar wall," which has been commercially available since the 1990s, is a simple solar thermal system that uses the energy of solar radiation to preheat ventilation air and dramatically reduce utility bills. The technology is based on the principle of a transpired collector. It consists of perforated metal siding, typically painted a dark color that is installed on a building facade to create an air cavity. During the day, incident solar radiation heats air in the cavity, which is then drawn through ventilation ducts (via an Air Handling Unit [AHU]) and supplied to the facility. Other than the ventilation fan, the technology has no moving parts. The solar wall's simple design results in applications that last for decades and minimize maintenance requirements (WBDG 2016).

Solar walls are particularly effective in facilities with high ventilation requirements (e.g., Hazardous Materials [HAZMAT] and vehicle maintenance facilities). Such facilities require high rates of fresh air ventilation; the solar wall meets this need by providing a method to heat outside air using renewable energy. Where high fresh air ventilation is not required, the solar wall can also heat indoor air circulated through the solar wall.

Solar walls offer significant secondary benefits as well. They increase the overall R-value of the facade on which the wall is installed. The (hot) air cavity created by the solar wall reduces heat losses through the envelope during the heating season. Heat loss through the building wall is captured and sent back into the building. Solar walls also provide air destratification within the facility. For facilities with high ceilings, destratification fans are typically installed to drive the warm air down towards the occupied space. Note that destratification fans can be installed independently of the solar wall to provide additional savings.

This work was undertaken to perform measurement and verification (M&V) of installed, operational solar wall systems at two U.S. Department of Defense (DoD) installations: Fort Drum, NY, and Forbes Field, Air National Guard, Topeka, KS). M&V of solar walls is necessary because: (1) DoD reporting requirements for renewable energy systems include the requirements to accurately report the energy consumption/savings of these systems, and (2) monitoring and tracking the performance of these systems over time can identify issues with system operation and assist others in making decisions about installing such systems.

1.2 Objectives

The objective of this project was to validate the performances of solar walls at Fort Drum, NY, and to model the system at Forbes Field, Air National Guard, Topeka, KS. Specific objectives were to:

1. Evaluate energy savings and system economics, i.e., determine energy savings and system economics including simple payback and Savings to Investment Ratio (SIR).
2. Determine the economic viability of the solar walls using the "RetScreen Energy Modeling" tool to compare actual vs. estimated savings.

1.3 Approach

1.3.1 General approach

1.3.1.1 Energy savings

Monitoring equipment was installed at both sites (May 2016 at Fort Drum and September 2016 at the Kansas Air National Guard). This equipment consisted of weather stations, flow rate measurement devices, and temperature sensors. The solar wall at Fort Drum heats fresh ventilation air, whereas the solar wall at the Kansas Air National Guard heats indoor air via recirculation. In both cases, the energy savings were calculated as follows:

1. The amount of heated air supplied by each AHU was determined using air flow monitoring stations.
2. The change in air temperature due to the solar wall was determined. At Fort Drum, this was calculated by comparing outdoor ambient temperature and temperature in the duct after the solar wall. At the National Guard site, this was calculated by comparing indoor air temperature (before the solar wall) and temperature in the duct after the solar wall. Using the relative humidity, the enthalpy of the air before and after the solar wall was calculated. Appendix A provides additional information on heat energy calculation.
3. Heat delivered ($\dot{Q}$) was calculated by:

$$\dot{Q} = \dot{m} * (h_{out} - h_{in}) \tag{1}$$

   where $\dot{m}$ is the mass flow rate of the air, and h_{in}, h_{out}, respectively, are the enthalpy of air before and after the solar wall.

4. In many cases, the energy consumed by the AHU fans should be subtracted. However, at Fort Drum, the facility requires constant ventilation. The solar wall fans are dual purpose; they provide heating and constant ventilation. There is no additional energy consumption above what is required for the baseline facility. Therefore, fan energy consumption was not considered in these calculations.

   Note that solar walls also provide savings due to recaptured building heat and destratification. These savings were obtained from the RETScreen modeling tool. Evaluating the actual savings from recaptured heat and destratification was outside the scope of this project.

1.3.1.2 System economics

To accurately calculate the system economics, it was important to collect 12 months of data:

1. During the hours of solar wall operation, a correlation was developed between incident solar radiation (American Society of Heating 2001) and the change in temperature (ΔT) across the solar wall.

2. The ΔT was estimated using historical solar radiation and ambient temperature data from a nearby weather station.
3. The mass flow rate was determine using known ΔT – mass flow relationships.

Any heat provided by the solar wall supplements the existing heating system within the facility. At Fort Drum and the Kansas Air National Guard, natural gas is the primary source for heating. The system economics were determined as follows:

1. Using published rates of natural gas ($/MMBTU) and the total heat provided (MMBTU) by the solar walls, the annual heat savings were calculated ($/yr). The cost of operating the fans ($/yr) was calculated by multiplying the published electric rates ($/kWh) by the energy consumption of the fans (kWh). Since the power consumption of the fans is relatively low, no demand charges were considered. The total annual savings ($/yr) were calculated by subtracting the cost of operating the fans from the annual heat savings.
2. The annual savings and the cost of the installed system were entered in the Federal Energy Management Program (FEMP) Building Life Cycle Cost (BLCC) analysis tool. The Military Construction (MILCON) Energy Conservation Investment Program module was used to determine the simple payback and SIR. A 30-year lifetime was assumed for the system economic calculations.

1.3.1.3 Accuracy of solar wall modeling tools

RETScreen is a computer software package used to predict the performance metrics of the solar wall system based on a variety of inputs including weather data, building design, and energy costs. This tool is used to evaluate sites for solar wall feasibility. A model was created for each site. The savings from actual performance data were used to compare against modeled data to determine the accuracy of the models.

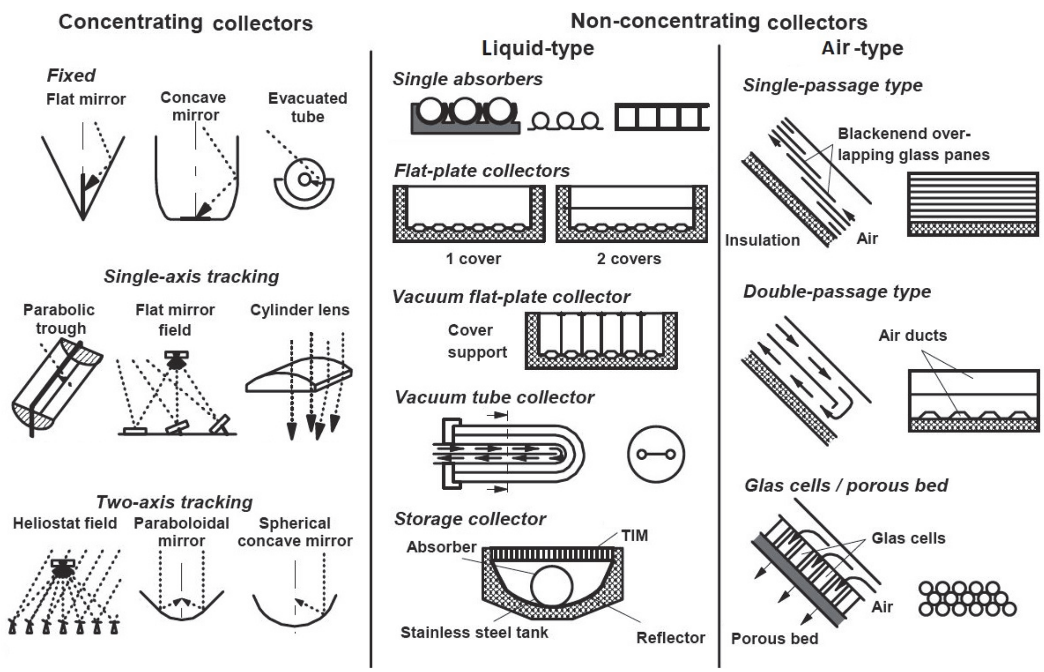
1.4 Mode of technology transfer

It is anticipated that the information in this report may be used by energy managers across the DoD to determine the economic viability of solar walls in similar cases.

2 Technology Description

All solar energy systems for space heating perform three principal functions: (1) collection of solar energy, (2) storage, and (3) distribution of the energy (heat) from storage to living space (Hami, Draoui, and Hami 2012). Figure 1 shows the broad range of solar collectors, each with different applications.

Figure 1. Summary of the primary types of solar thermal collectors.



Drawing adapted from (Kaltschmitt, Streicher and Weise 2007).

The technology studied in this project is an Unglazed Transpired Solar Collector (UTSC). In general, a UTSC is made of metal cladding with perforations, installed a specified distance from a building wall, creating a cavity through which the air can circulate. The metal cladding is heated by the solar radiation from the sun, and ventilation fans create negative pressure in the cavity, extracting the solar-heated air through the perforated panel. The heated air is generally withdrawn at the top of the wall (due to air temperature gradients in the cavity), ensuring that all the produced solar heat is collected and distributed in the building via the ventilation system. Flow characteristics and other external system parameters can intensify the heat transfer between the air and the metal.

The specific technology used at Fort Drum uses a two-stage heating process. With the heating system shown in Figure 2, in the first stage, the sun heats the collector, and fresh air is heated as it passes through the surface. In the second stage, the air is heated a second time, which boosts the temperature rise as it passes behind the glazing. The solar-heated air is then directed either into the building's ventilation system or through a dedicated fan and ducting system, which distributed the air throughout the building (Figure 3). Figure 4 shows the two-stage solar wall installed at Fort Drum, NY.

Figure 2. Two-stage air heating process.

Figure 3. SolarWall® fan and ducting system attached to a building.

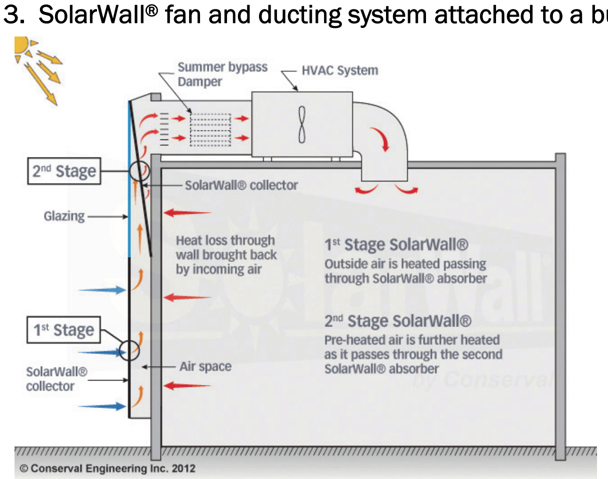


Figure 4. Installed two-stage solar wall installed at Building P-1660 in Fort Drum, NY.

The Kansas Air National Guard uses a single stage system, which is more cost effective when a lower temperature rise (ΔT) is suitable. In contrast with the Fort Drum system, the Kansas Air National Guard solar wall is installed on the facility's roof (Figure 5). The facility, a helicopter storage/maintenance hangar, does not require high levels of fresh ventilation air. Therefore, the system was set up to heat indoor air via recirculation through the solar wall.

Figure 5. Solar wall installation on facility at Topeka, Kansas Air National Guard.

3 Facility/Site Description

3.1 Fort Drum, NY

A two-stage collector was designed and installed on the south elevation of Building P-1660 in December 2011. The collector is ~18 ft high and 181 ft, 5 in. long, and covers a total area of about 3,265 sq ft. The panels are (color) profile SW150 and SW6068, black in color. The top 10 ft, 0 in. of the two-stage collector is covered with SW150G polycarbonate panels, which are 1.5 mm (0.059 in.) thick.

The ventilation design of the two-stage system uses two Model EJ24D fan units that each supply 3,500 cubic feet per minute (CFM) of air through perforated metal ducting. Thus, the system is designed to supply 7,000 CFM. Insulated round ducting is used to connect the air plenum of the two-stage collector to the outdoor air intake of the EJ24D fan units. A recirculation damper is located on the top of the EJ24D fan unit to mix warm, ceiling air with the outdoor air when the outdoor air is too cold. A Johnson Control C450CPN-1 temperature controller is used to modulate the outdoor air damper and recirculation dampers of the EJ24D fan unit. The dampers modulate in opposition to each other based on the outdoor air temperature sensor located at the transition duct between the two-stage air intake and the insulated ducting. Figures 6 and 7 show schematics of the West and East AHUs, respectively, and Fort Drum. A Trane Building Automation System (BAS) is used to activate the solar wall controls in the morning and shut it down at night.

Figure 8 shows a diagram of the damper controls for the Fort Drum facility. The Outside Air (OA) damper is linked with the Return Air (RA) damper to provide a constant volume system. The position of the damper is controlled through a BAS and is based on the temperature of the heated air, as follows:

Intake Air < 55 F → = 5%
55F <Intake Air < 75F → Damper = 5%-100% linearly
75F<Intake Air → Damper = 100%.

Figure 6. Schematic of West AHU at Fort Drum.

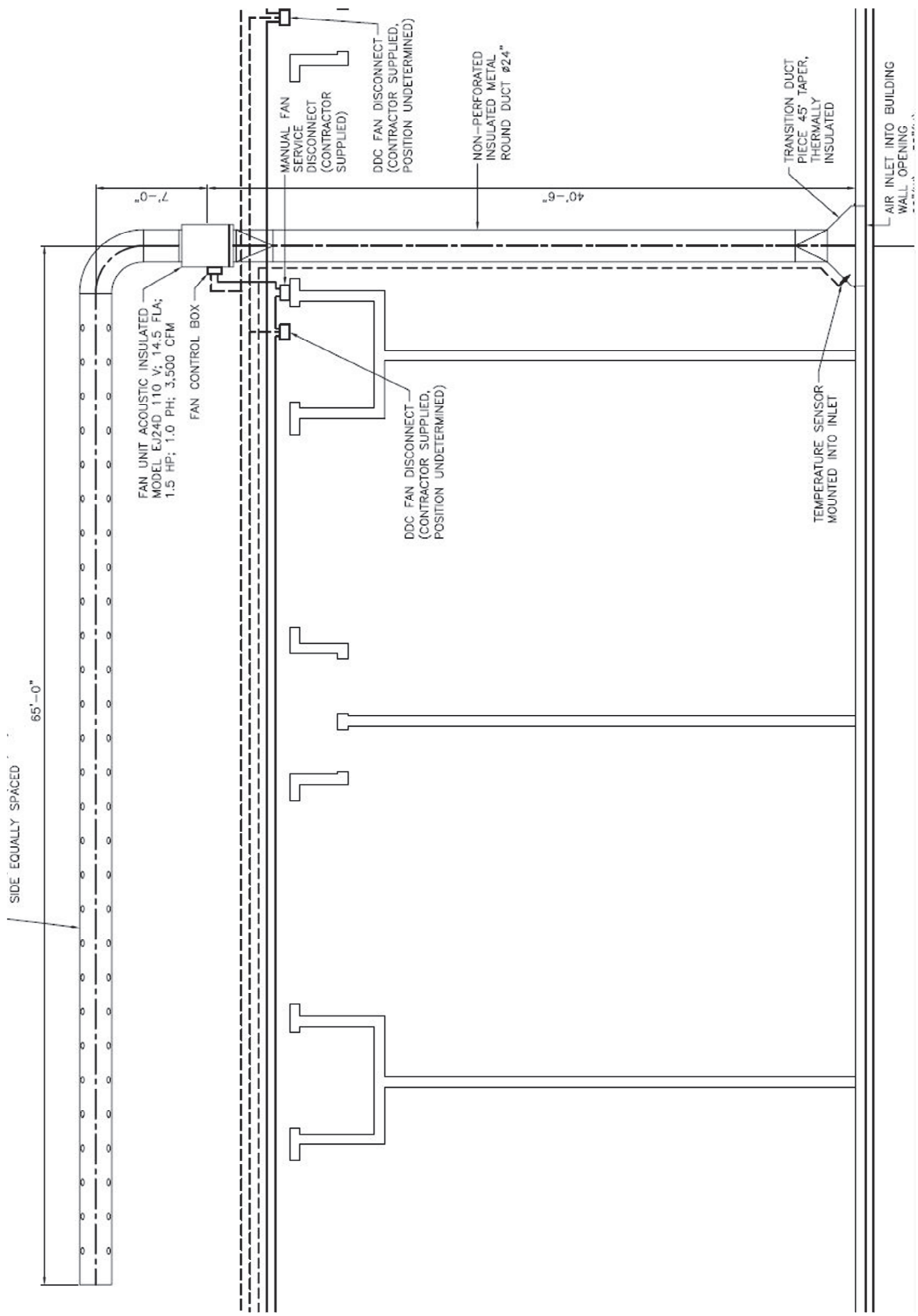


Figure 7. Schematic of East AHU at Fort Drum.

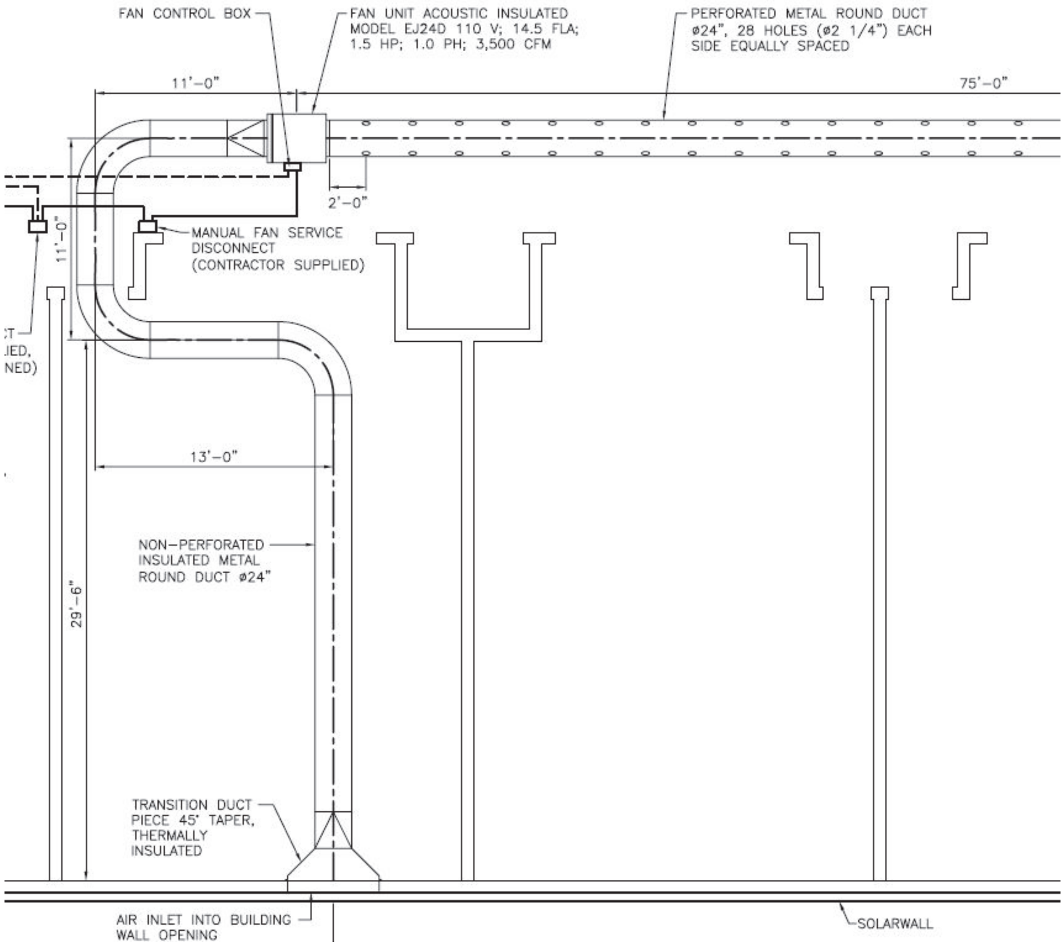
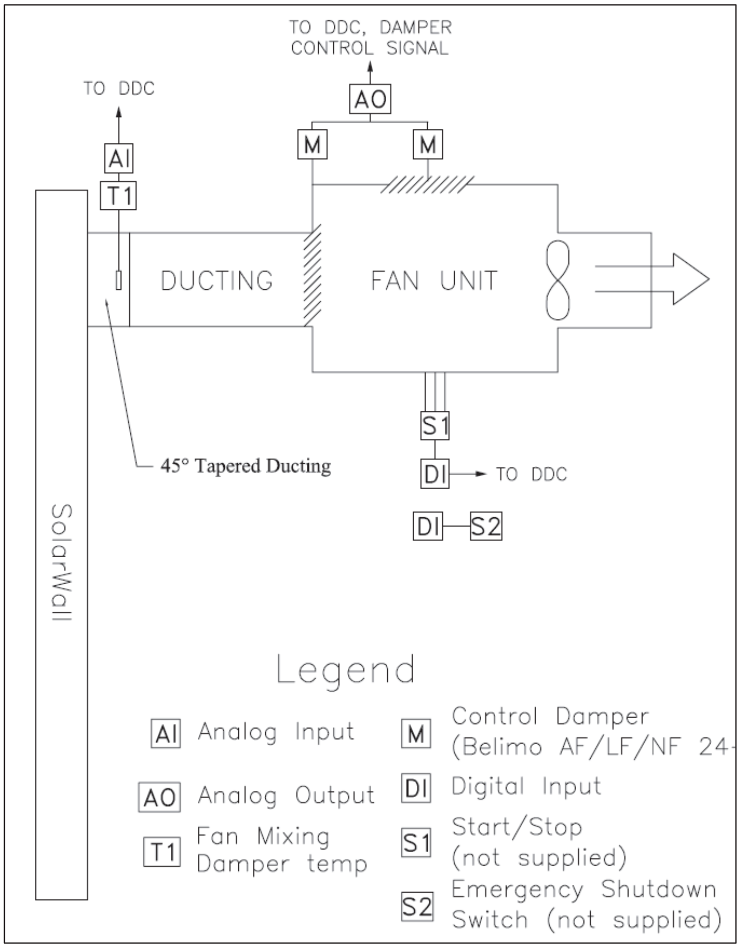


Figure 8. Damper control sequence Fort Drum.



This sequence of operations is used to limit the amount of cool air that is introduced during the heating seasons. Although this operational detail is outside the scope of this project, it is interesting to note that Fort Drum runs the solar wall ventilation during the night in the summer to passively cool the building.

For the purposes of this project, a weather station, an air flow measurement system, and temperature sensors were installed in each of the two ducts. A HOBO* weather station (Figure 9) was installed near the solar wall to collect weather data including ambient temperature, relative humidity, and broadband solar irradiation (using a pyranometer).

*For further information on HOBO Weather Stations, see the Onsite® products web site at: http://www.onsetcomp.com/products/data-loggers/weather-stations?gclid=CKjkjLnh4NQCFRW4wAodIM8C6A

Figure 9. Photo of weather station at Fort Drum.

A Paragon Controls Incorporated Model FE1500 circular Air Flow Measurement Station, with a 24-in. diameter (Figure 10), was installed in line with each of the two ducts. A 0-10 Volt DC (VDC) linearly scaled output was used for data logging purposes.

Figure 10. Air flow monitoring stations.

A Johnson Controls Model TE-631JM-1, 18 in. long, temperature sensor (Figure 11) was installed at the intake of each duct. The resistance on the 1k ohm nickel averaging sensor was used to determine the temperature. The resistance increases by 3 ohms/°F. All data were logged on a HOBO data logger (Figure 12).

Figure 11. Temperature sensor.

Figure 12. Installed data logger at Fort Drum.

3.2 Kansas Air National Guard, Topeka, KS

Solar walls were installed on two hanger facilities at the Kansas Air National Guard in Topeka, KS (Figure 13). The system was installed on the roof of the facilities at an angle of 45 degrees, with an azimuth of 180 (facing south).

Figure 13. Solar thermal installation at Kansas Air National Guard facility in Topeka, KS.

The air handling system consists of three ducts (and fans) that draw air from a common plenum. The negative pressure from the fans causes air to be drawn from the facility through dampers, routed through the solar wall and into plenum (Figure 14). As Figure 14 shows, the damper only controls the amount of heated air, in contrast with the linked damper system at Fort Drum. In other words, the Kansas Air National Guard facilities use a variable air volume system, but the Fort Drum facility uses a constant volume system. A similar HOBO weather station was installed close to the facility (Figure 15).

Due to ducting limitations, fan inlet mount flow sensors (with temperature capabilities) were installed. Three Ebtron Model HTx104-F (Figure 16) units were installed, one on the inlet of each fan in the three ducts. The transducer unit provided with the sensors can provide both 0-10V and 4-20mA outputs. The system was connected to the existing BAS rather than data loggers. Existing indoor temperature sensors were used for the analysis.

Figure 14. Schematic of solar wall and AHUs at Topeka, KS.

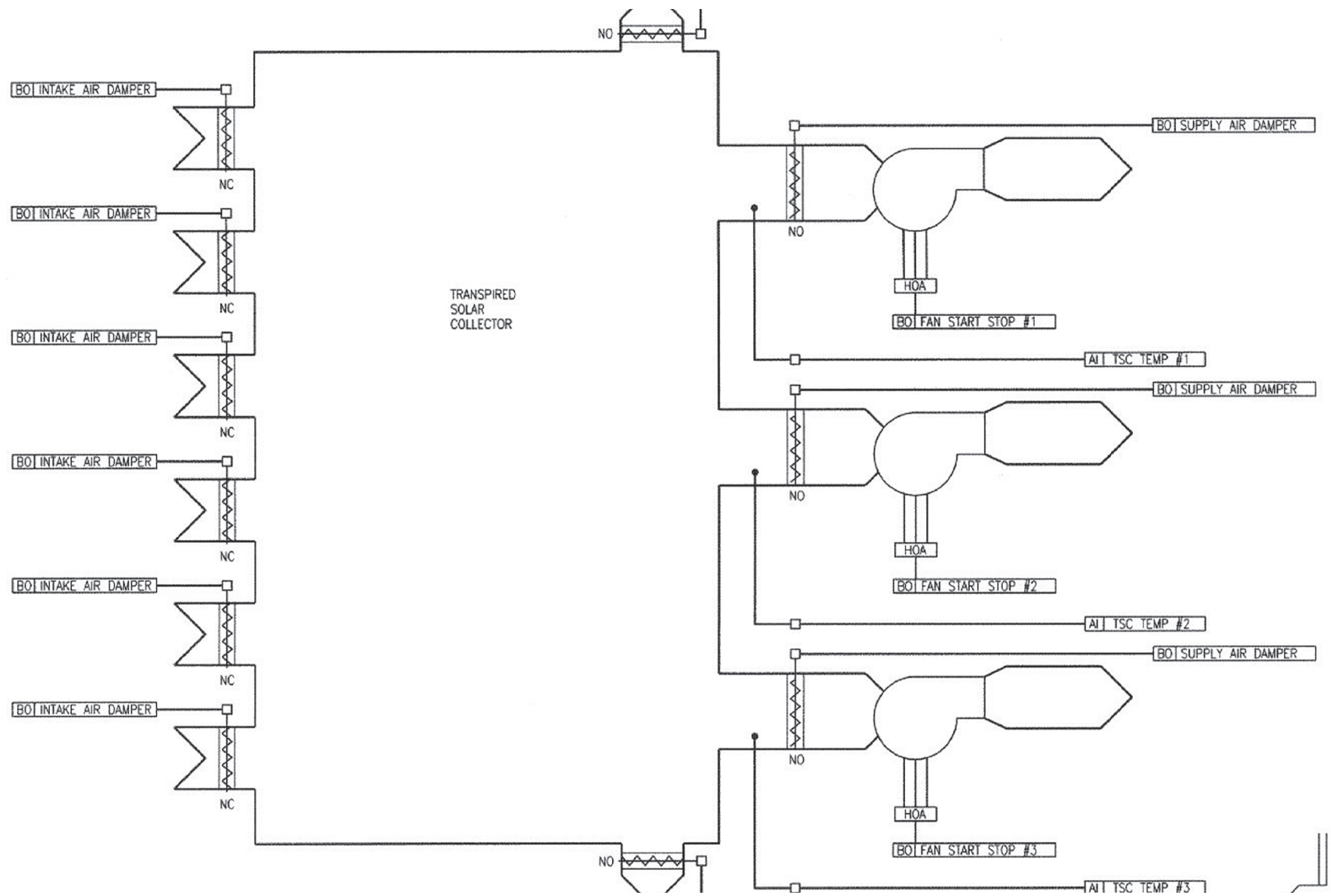


Figure 15. Installed weather station at Topeka, KS.

Figure 16. Ebtron flow/temperature sensors.

4 Performance Results

4.1 Fort Drum solar wall performance

4.1.1 Flow rate vs. temperature

Usable data from 26 September 2016 through 23 April 2017 were analyzed to develop trends and estimate energy savings. In general, both AHUs showed similar trends for flow rate and temperature. For simplicity, only the East AHU is discussed here. Appendix B provides data for the West AHU. Figure 17 shows a scatter plot of the flow rate for the East AHU as a function of temperature.

Three important conclusions can be drawn from this data:

1. Between intake temperatures of 55-75 °F, the flow rate increases linearly. This is expected due to the damper modulation sequence. Figure 18 shows a bin analysis of the flow rate vs. intake temperature (55-75 °F). The high R^2 value shows that the correlation is indeed linear.
2. The maximum flow rate for temperatures above ~75 °F is ~2800 CFM. This maximum flow rate is below the 3500 CFM design. Further review revealed additional bends in the ductwork not indicated in the original design. The increased pressure drop created by these bends caused the maximum flow rate to decrease. A partial correction to the increased pressure drop was done by adding additional 1-in. diameter holes in the supply ducts and ends. This increased the flow rate (to the final 2800 CFM) but still resulted in lower-than-expected savings.
3. At temperatures above ~75 °F, there are three distinct flow rate bands. In Figure 17, these are seen at ~2800 CFM, ~2300 CFM, and ~1700 CFM. In an ideal system, there should only be one band at ~2800 CFM. Potential causes for this include loose damper linkages, faulty temperature sensors, or localized cloud cover causing temporary dips in flow rate. These potential causes were investigated without significant results. The cause of these distinct bands remains unknown. Since the system is not operating as designed, there is a detrimental impact to the overall savings. These same trends were seen in the West AHU.

Figure 19 shows the temperature rise for the East intake on a sunny day.

Figure 17. East intake flow rate vs. temperature.

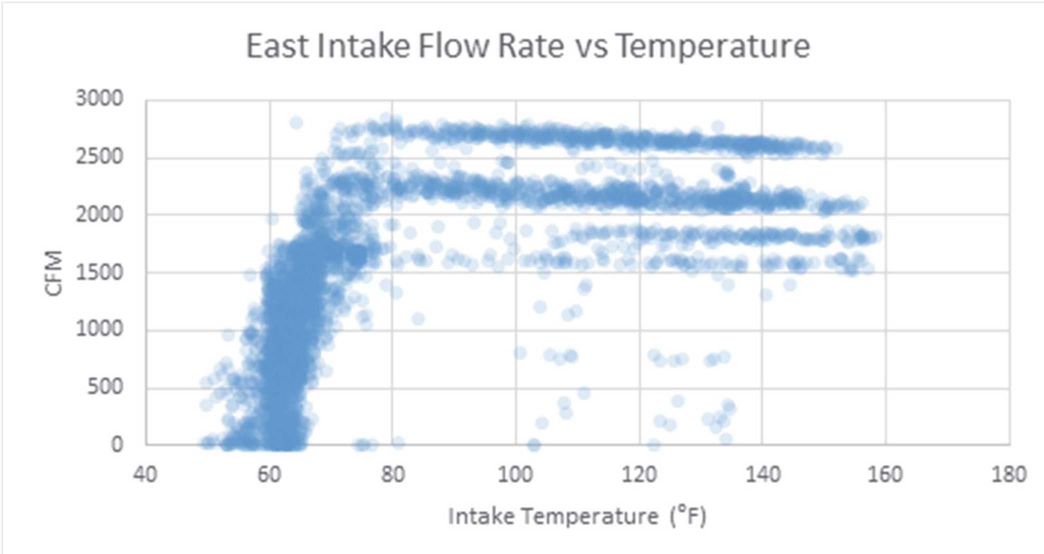


Figure 18. East intake flow rate vs. temperature.

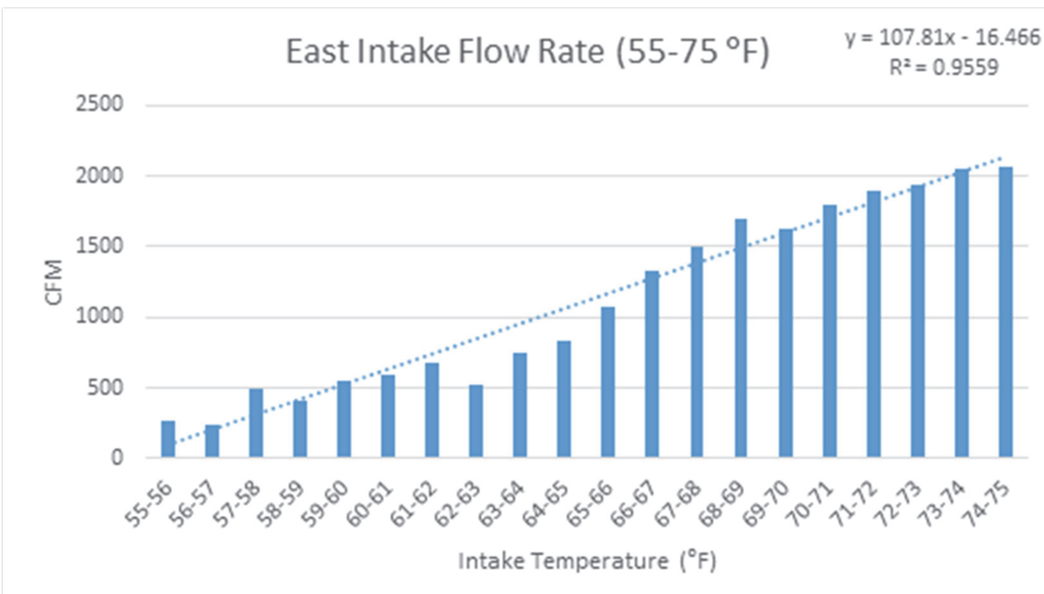
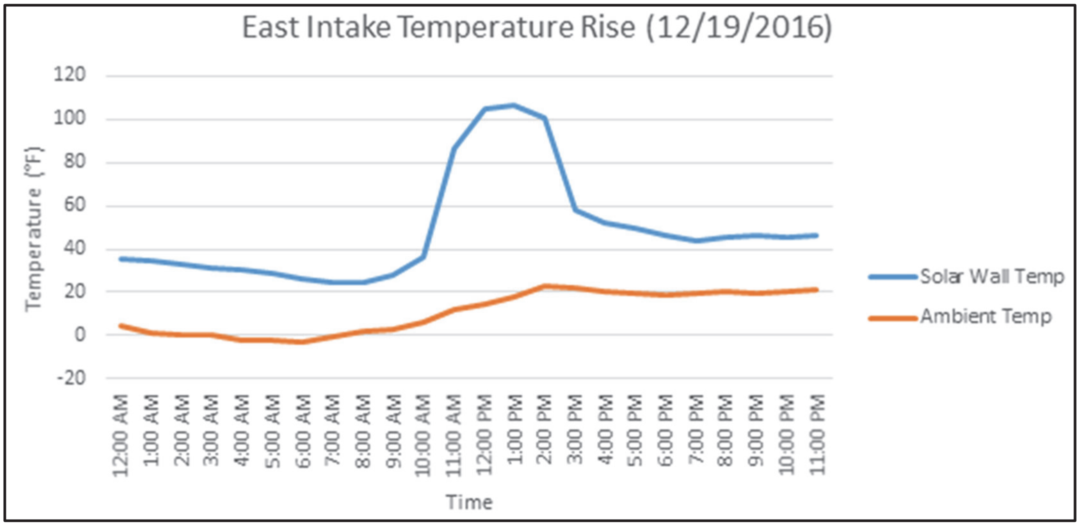


Figure 19. East intake temperature rise.



4.1.2 Solar radiation vs. ΔT

A correlation between incident solar radiation (insolation) and change in temperature, ΔT, across the solar wall was developed using bin analysis (Figures 20-22). Three different increments were chosen for the insolation (10 W/m^2, 25 W/m^2, and 50 W/m^2). As expected, these data show a linear correlation between ΔT and insolation.

Figure 20. East intake average ΔT vs. insolation (10 W/m^2 bin).

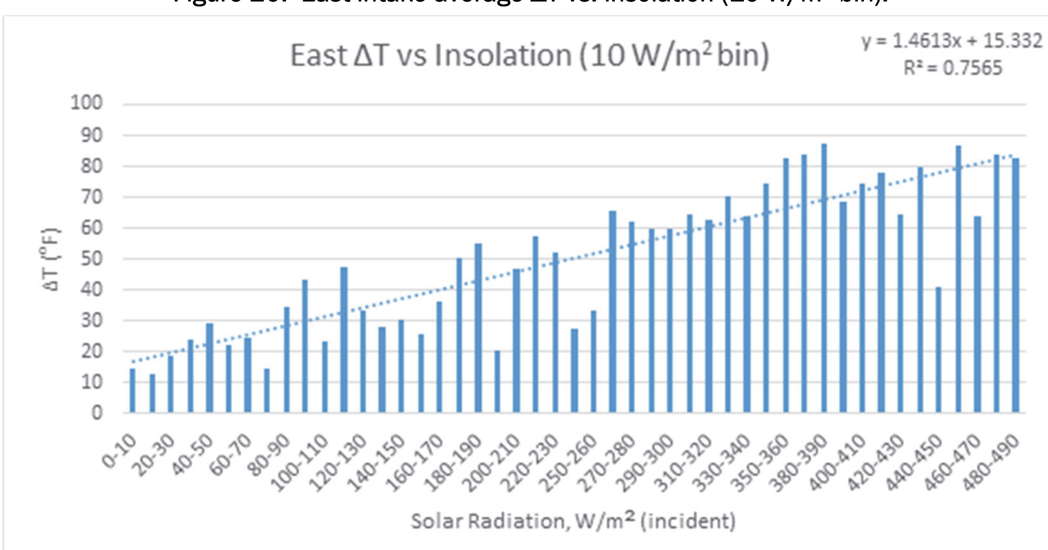


Figure 21. East intake average ΔT vs. insolation (25 W/m² bin).

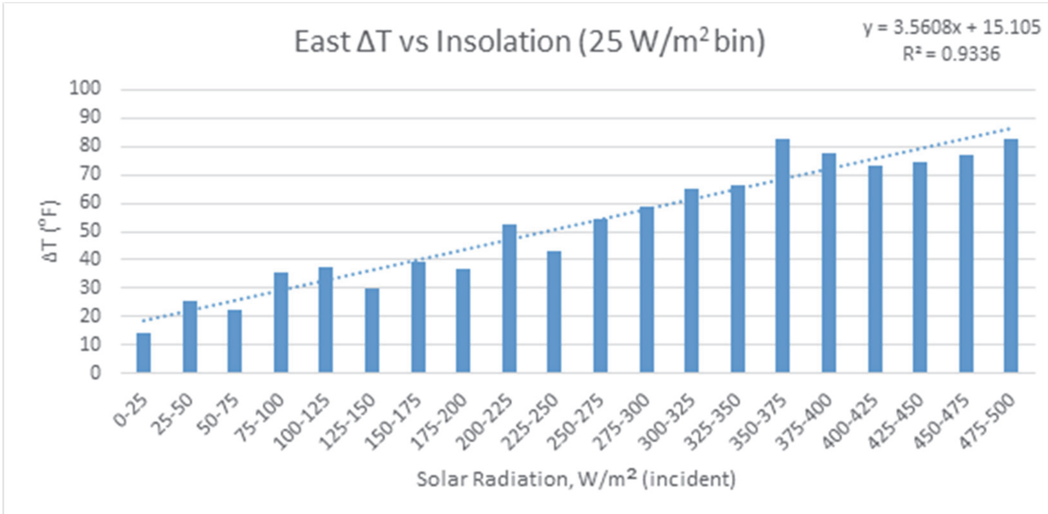
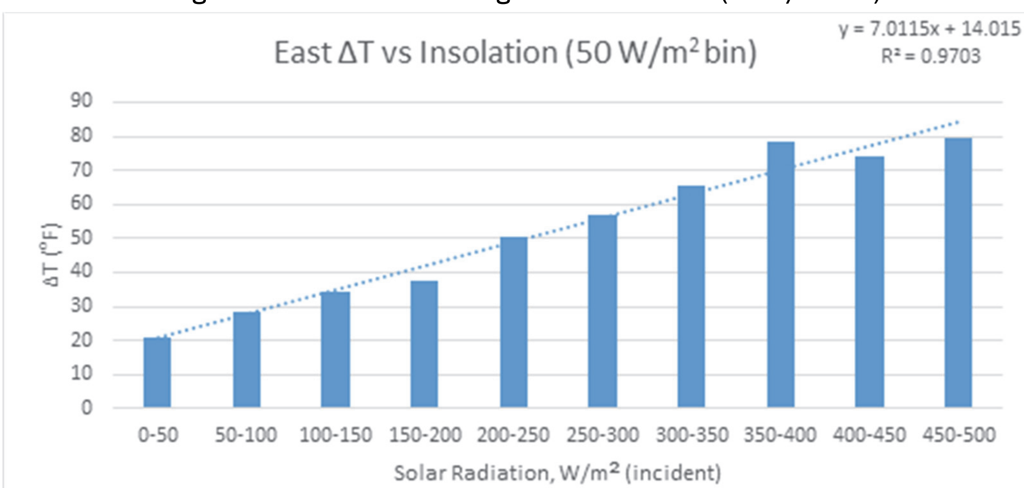


Figure 22. East intake average ΔT vs. insolation (50 W/m² bin).



The regression analysis (R^2 value) shows a best fit for the 50 W/m² bin, followed by 25 W/m² and 10 W/m², respectively. Local variations in temperature, insolation, and averaging functions from data logging can result in this trend. Similar trends were also seen in the West AHU.

4.1.3 Actual energy and cost savings

Using the procedure outlined in Section 1.3.1.1, the energy savings of the system (26 September 2016 through 23 April 2017) were calculated (Table 1). In fiscal year 2016 (FY16), Fort Drum's utility rates were \$0.0793/kWh for electricity and \$0.2544/therm or \$2.544/MMBTU. Table 2 lists the cost savings.

Note that the savings also include an estimated 18.75 MMBTU savings due to recaptured building heat and 75.75 MMBTU savings due to destratification. These savings were obtained from the RETScreen modeling tool. Evaluating the actual savings from recaptured heat and destratification was outside the scope of this project. These savings also assume an 80% boiler efficiency.

Table 1. Summary of actual net energy savings for Fort Drum solar wall.

AHU	Heat Savings (MMBTU)
East	102.63
West	137.25
Recapture	18.75
Destratification	75.75
Total	334.38

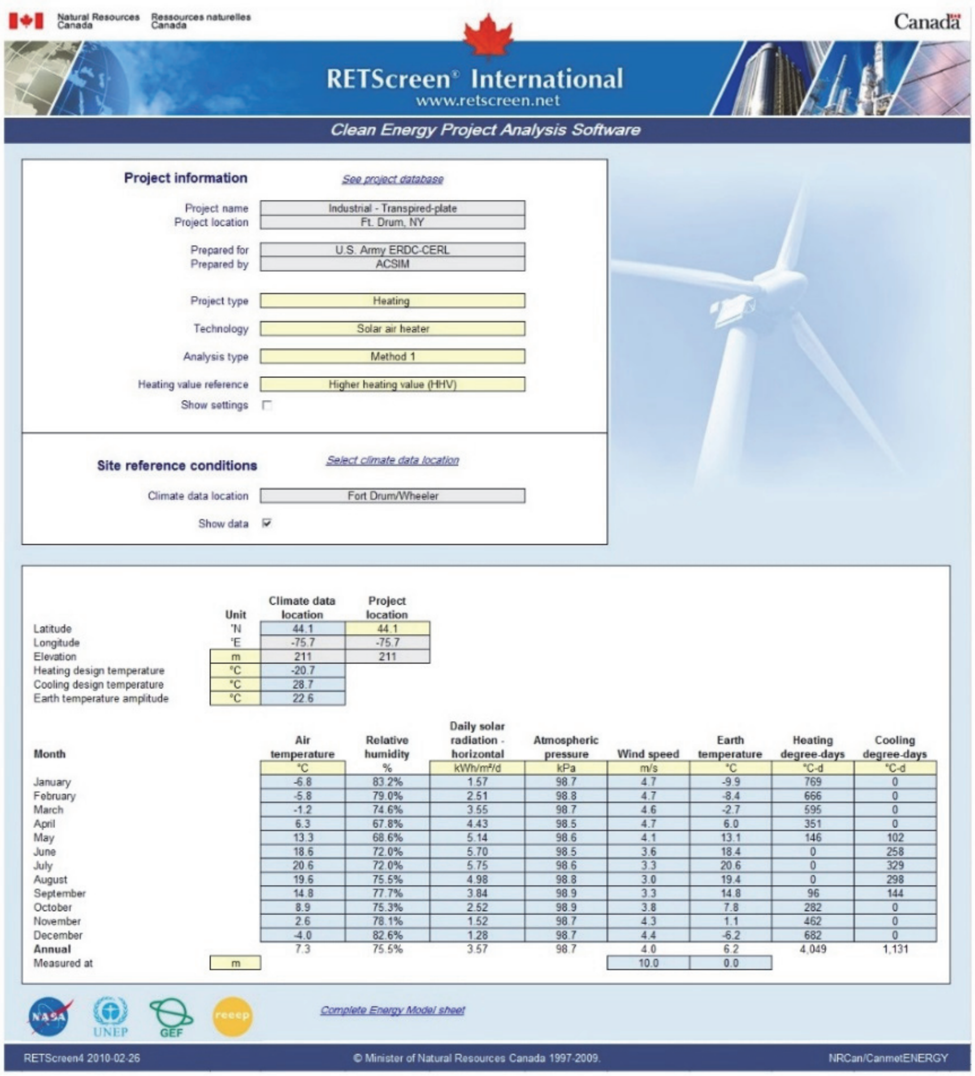
Table 2. Actual net cost savings for Fort Drum solar wall.

AHU	Heat Cost Savings ($)
East	261.08
West	349.16
Recapture	47.7
Destratification	192.71
Total	850.65

4.2 Computer simulation

RETScreen Version 4 was used to numerically calculate the energy and cost savings of the solar wall. This software is provided by Natural Resources Canada and is a system used for energy efficiency, renewable energy, and cogeneration project feasibility analysis, as well as ongoing energy performance analysis. Figure 23 shows the first tab in the RETScreen model for Fort Drum. The “Industrial – Transpired Plate” model was used with actual geographic weather data. Figure 24 shows the second tab of RETScreen where additional information, such as energy cost, solar wall size and orientation, are incorporated, along with the expected return on investment.

Figure 23. Screen shot of Tab 1 of RETScreen for model and location inputs.



Natural Resources Canada Ressources naturelles Canada

Canada

RETScreen® International

www.retscreen.net

Clean Energy Project Analysis Software

Project information

See project database

Project name: Industrial - Transpired-plate

Project location: Ft. Drum, NY

Prepared for: U.S. Army ERDC-CERL

Prepared by: ACSIM

Project type: Heating

Technology: Solar air heater

Analysis type: Method 1

Heating value reference: Higher heating value (HHV)

Show settings

Site reference conditions

Select climate data location

Climate data location: Fort Drum/Wheeler

Show data

	Unit	Climate data location	Project location
Latitude	°N	44.1	44.1
Longitude	°E	-75.7	-75.7
Elevation	m	211	211
Heating design temperature	°C	-20.7	
Cooling design temperature	°C	28.7	
Earth temperature amplitude	°C	22.6	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		-6.8	83.2%	1.57	98.7	4.7	-9.9	769	0
February		-5.8	79.0%	2.51	98.8	4.7	-8.4	666	0
March		-1.2	74.6%	3.55	98.7	4.6	-2.7	595	0
April		6.3	67.8%	4.43	98.5	4.7	6.0	351	0
May		13.3	68.6%	5.14	98.6	4.1	13.1	146	102
June		18.6	72.0%	5.70	98.5	3.6	18.4	0	258
July		20.6	72.0%	5.75	98.6	3.3	20.6	0	329
August		19.6	75.5%	4.98	98.8	3.0	19.4	0	298
September		14.8	77.7%	3.84	98.9	3.3	14.8	96	144
October		8.9	75.3%	2.52	98.9	3.8	7.8	282	0
November		2.6	78.1%	1.52	98.7	4.3	1.1	462	0
December		-4.0	82.6%	1.28	98.7	4.4	-6.2	682	0
Annual		7.3	75.5%	3.57	98.7	4.0	6.2	4,049	1,131
Measured at	m					10.0	0.0		

Complete Energy Model sheet

RETScreen4 2010-02-26 © Minister of Natural Resources Canada 1997-2009. NRCan/CanmetENERGY

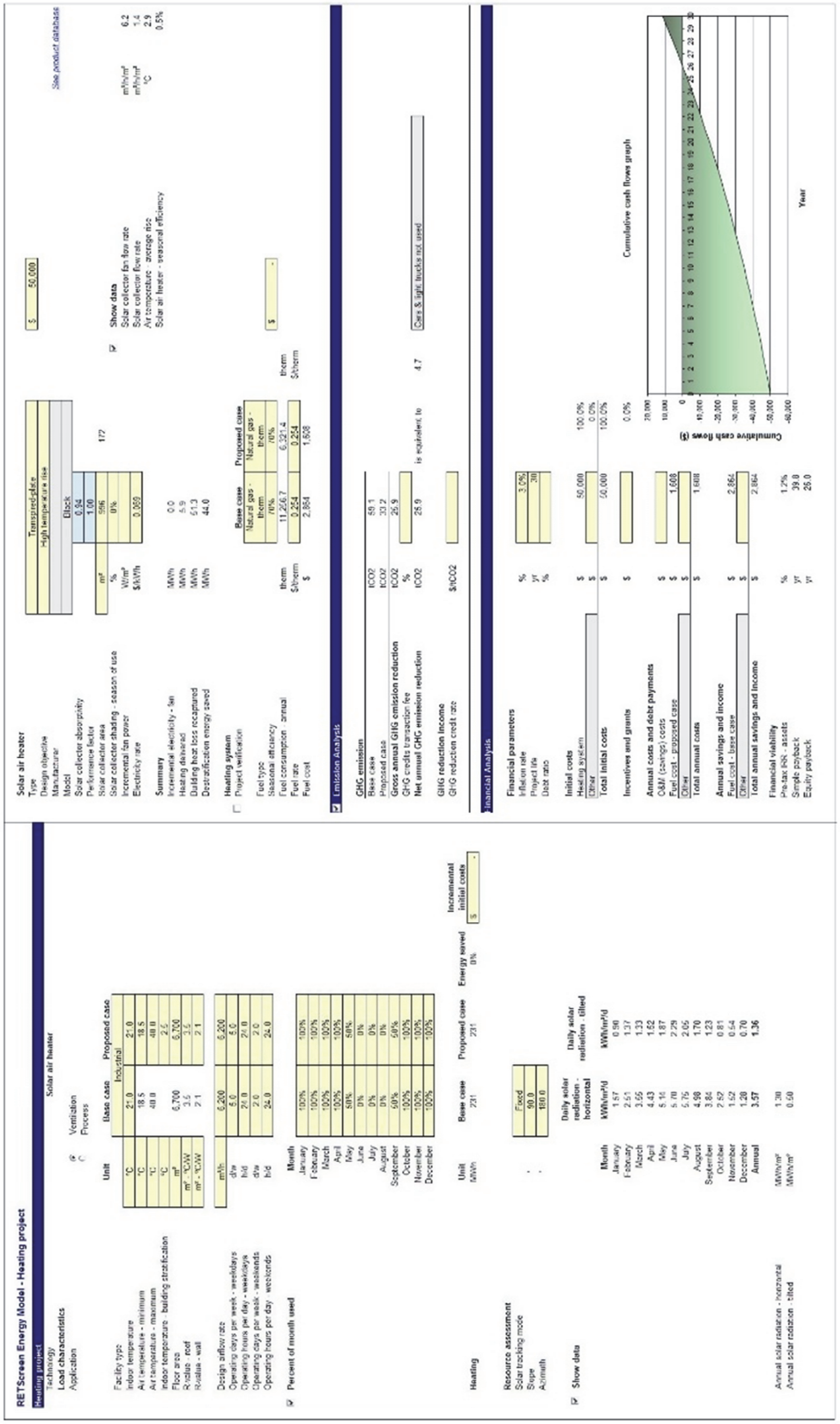


Figure 24. Screen shot of Tab 2 of RETScreen for energy inputs (shown horizontally for better readability).

Table 3 lists the results of the RETScreen modeling. For Fort Drum, the model indicates a natural gas consumption from 405 to 158 MMBtu, which is a 61% reduction. The system installed at Topeka had expected fuel consumption from 1,754 to 185 MMBtu, an 89.4% decrease. The fuel cost is highly variable and depends on the current rate of natural gas. The values in the model were lower than the historic average ($2.54/MMBtu and $6.00/MMBtu at Fort Drum and Topeka, respectively).

The base RETScreen model was updated to include the TMY3 solar data and the two distinct air flow bands in each AHU at Fort Drum. Appendix C provides details on additional RETScreen inputs.

Table 3. RETScreen modeling results for Fort Drum and Topeka solar wall installations.

Parameter	Unit	Fort Drum		Topeka	
		Base Case	Proposed	Base Case	Proposed
Incremental Electricity – Fan	MMBtu	0		29.9	
Heating Delivered	MMBtu	122.0		778	
Building Heat Loss Recaptured	MMBtu	15.0		25.5	
Destratification Energy Saved	MMBtu	60.6		294	
Total Annual Fuel Consumption*	MMBtu	405	158	1,754	185
Fuel Cost*	$	1,031	403	10,454	1,104

*Total annual fuel consumption and Fuel cost include an 80% boiler efficiency factor.

5 Implementation

As described in Chapter 4, RETScreen modeling can be used to estimate the performance of a solar wall. The modeling results can be considered accurate and should be used to initially estimate the performance of the solar wall. Although this work did not measure the savings due to improved R-value of the wall and destratification, they should be considered in the total savings and system economics.

M&V of the installed systems is also important. For a minimal increment (~$7,000, or 5.6% of the total system cost at Fort Drum), airflow stations and temperature sensors can be installed. The M&V on the Fort Drum solar wall revealed inconsistencies between the design and actual implementation of the AHUs. The added pressure drops in the duct work resulted in a less efficient system. Using M&V data immediately after installation can help identify and correct any issues in the system.

For the system at Fort Drum, the system economics show that the system is not economically viable. (See Appendix D.) However, this is due to the very low natural gas rates. For similar site conditions (northeast United States), a natural gas rate of $16/MMBTU or higher would be required for this system to achieve economic viability.

The system at Forbes Field, Topeka KS, operates like the system at Fort Drum. However, one major difference is that, since the Forbes Field system has no ventilation requirement, the system heats indoor air (not outdoor air). Consequently, the solar wall system delivers higher temperatures. According to RETScreen models, the system at Topeka saves 1,569 MMBTU, or $9350 per year. At a rate of $6.00/MMBTU, the simple payback is 59 yrs and the SIR is 0.34.

6 Conclusion

This work monitored a solar wall system at Fort Drum, NY, to determine the energy and cost savings of using the solar wall relative to a traditional (natural gas fueled) heating technology. A review of the installed system revealed that the system was different from its original design, and the changed configuration was less efficient than originally designed.

Based on measured data, the solar wall at Fort Drum yields a net savings of $851/yr, which calculates as a simple payback of 146 years and a SIR of 0.16. A comparison with the RETScreen modeling tool shows the measured actively heated air provided by the solar wall provides 57% more heat than the RETScreen tool predicted, after accounting for boiler efficiency. The current system becomes economical (SIR 1.0) at a natural gas rate of $16/MMBTU. Although these calculations show that the system is not economical, it is recommended that the system still be used to meet renewable energy and fossil fuel reduction goals.

This work also modeled, but did not further analyze, a system at Forbes Field, Kansas Air National Guard, Topeka, KS. According to RETScreen models, the Forbes Field system saves $9,350/yr. The simple payback is 58.8 years, and the SIR is 0.34.

Appendix A: Heat Energy Calculation

To calculate the heating energy provided by the solar wall, the enthalpy (J/kg) of the air before and after passing through the solar wall is required. The enthalpies of each state are needed to determine the total energy provided from the solar wall to the air, as seen in Equation A-1. The known utility costs for gas ($/BTU) and electricity ($/kWh) are then used to determine the cost savings that the solar wall provides.

$$\dot{Q} = \dot{m} * (h_{out} - h_{in}) \tag{A-1}$$

The change in enthalpy is defined as the integral of the specific heat at constant pressure (C_p) over a temperature range. When C_p is relatively unchanged within that temperature range, enthalpy can be approximated as:

$$dH = \int_{T_1}^{T_2} C_p dt \xRightarrow{C_p = Constant} H = C_p(T_2 - T_1) \tag{A-2}$$

Additionally, the air under consideration is not dry but includes some water vapor. As a result, the enthalpy of each state (before and after the solar wall) will depend on both the temperature and the humidity ratio.

The enthalpy of humid air can be calculated by individually adding the enthalpy of dry air and the enthalpy of water vapor weighted by the humidity ratio (x), according to Equation A-3. It is assumed that the solar wall does not add or remove any moisture, and the water vapor in the air does not change state. Therefore, the humidity ratio, remains constant for both the outside air and solar wall air parameters.

$$h = h_{dry\ air} + x * h_{water\ vapor} \tag{A-3}$$

The variable x in Equation A-3 represents the humidity ratio in kg of wet air to kg of dry air. Table A-1 lists the properties for air and water.

Table A-1. Gaseous properties.

Unit	Air	Water (V)
Mw (g/mol)	28.97	18.02
R (J/K mol)	8.314	8.314
C_p	1.005	1.864

The enthalpy in the dry air can be determined using Equation A-4, which uses the direct relation between the specific heat of the air at constant pressure to the known dry bulb temperature of moist air.

$$h_{dry\ air} = C_{pa} * T \tag{A-4}$$

For the range of expected air temperatures, the specific heat of the air at constant pressure can be set to 1.005 $\frac{kJ}{kg*K}$. The enthalpy of the water vapor in the air can be determined using Equation A-5, which is shown as the product of the specific heat of the water vapor at constant pressure with the known dry bulb temperature of the moist air plus the evaporation heat of water at 0 °C (32 °F).

$$h_{water\ vapor} = C_{pw} * T + h_{we} \tag{A-5}$$

The specific heat of water vapor is known to be approximately 1.864 $\frac{kJ}{kg*K}$, and the evaporation heat of water at 0 °C is 2,500 $\frac{kJ}{kg}$. The known enthalpies can then be combined back into Equation A-3 to determine the total enthalpy of the air before and after it has passed through the solar wall.

The humidity ratio used to determine the total enthalpy in the air from Equation A-3 still must be determined. The available data will be in the form of temperature and relative humidity. Therefore, the humidity ratio can be calculated from the relative humidity and temperature, following the psychrometric relations shown in Table A-2.

Table A-2. Psychrometric relationships.

Term	Equation
Relative Humidity	$\varphi = {p_w}/{p_{ws}} * 100$
Humidity Ratio	$x = 0.62198 * \frac{p_w}{p_a - p_w}$

The atmospheric air pressure (p_a) must also be determined for input into the humidity ratio. Since atmospheric pressure is not constant at all elevations and can vary by ~20% between sea level and 6,000 ft, the geographical elevation must be known, and pressure is then calculated as:

$$P_a\ (Pa) = 101{,}325\ (1 - 2.25577 * 10^{-5} * h)^{5.25588} \tag{A-6}$$

However, to go from relative humidity to humidity ratio, the saturation pressure of water vapor is required (p_{ws}), from which the partial pressure of water vapor (p_w) (and thus the humidity ratio) can be calculated. Equation A-7 shows the polynomial fit for the saturation water vapor pressure.

$$\ln(p_{ws}) = \frac{g_0+(g_1+(g_2+g_7*\ln(T)+(g_3+(g_4+(g_5+g_6*T)*T)*T)*T)*T)*T}{T^2} \quad \text{(A-7)}$$

Table A-3 lists the saturation water vapor pressure polynomial constants.

Table A-3. Saturation water vapor pressure polynomial constants.

g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7
-2.99E3	-602E3	1.89E1	-2.84E-2	1.78E-5	-8.42E-10	4.44E-13	2.86

In the case of the solar wall where the relative humidity is not known and the temperature increases across the solar wall, the partial pressure of water vapor (p_w) cannot be immediately calculated using the equation for relative humidity. Since the atmospheric pressure (p_a) is known and the humidity ratio is assumed to remain constant across the wall, the partial pressure of water vapor can be determined by rearranging the humidity ratio equation in Equation A-8:

$$P_w\ (Pa) = \frac{(P_a*x)}{(0.62198-x)} \quad \text{(A-8)}$$

Now that the enthalpies of the outside air and solar wall air conditions are known, the total enthalpy difference between the two states (and the energy savings that the solar wall provides) can be calculated. The power used to reach the target state can be determined by:

$$Power = \rho * Q * \Delta h \quad \text{(A-9)}$$

where Δh = change in enthalpy to reach target state, Q = volumetric flow rate, and ρ = air density.

From the known power, the energy (BTU) used during the timestamp can be found from Equation A-10 (ASHRAE 2001) and ultimately the cost savings between the two states can be determined.

$$Energy\ (BTU) = Power\ \left(\frac{BTU}{hr}\right) * \Delta T\ (hr) \quad \text{(A-10)}$$

Appendix B: Trends for the West AHU

Figures B-1 to B-6 show trends for the West AHU.

Figure B-1. West intake flow rate vs. temperature.

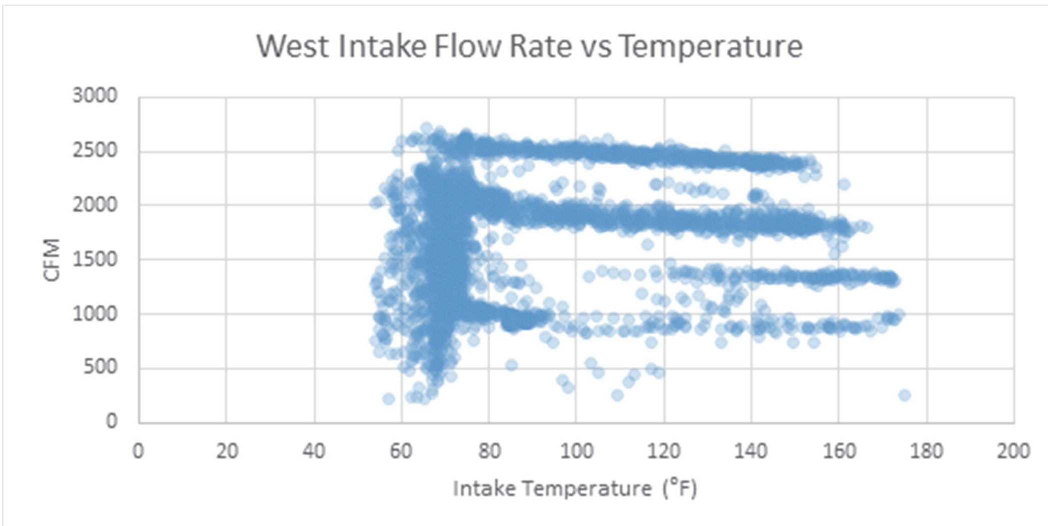


Figure B-2. West intake flow rate (55-75 °F).

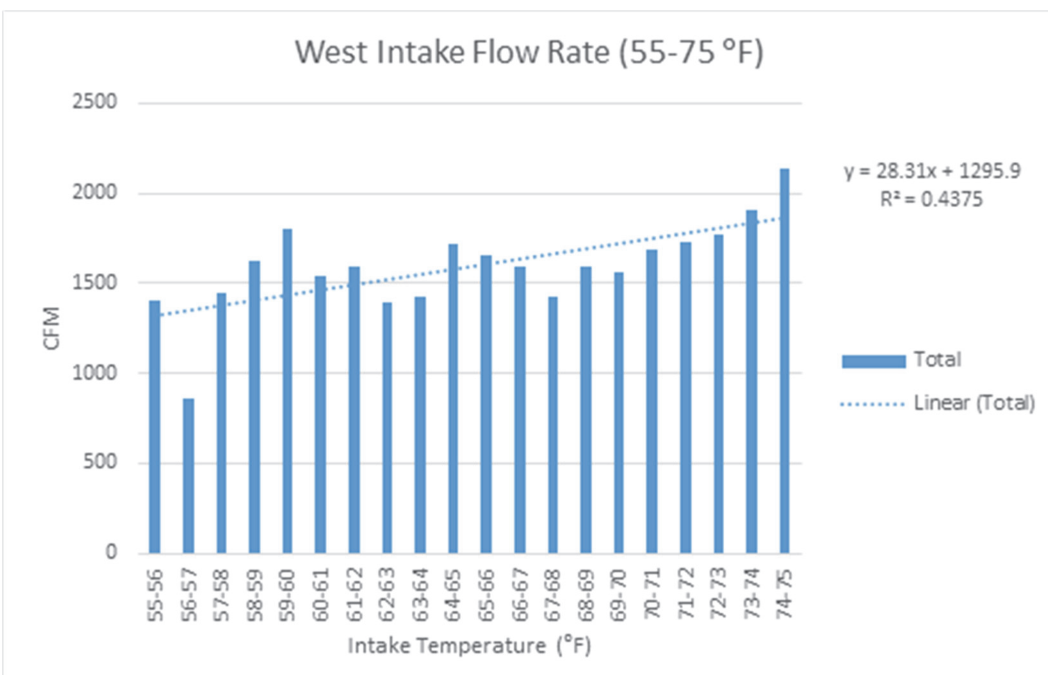


Figure B-3. West intake temperature rise.

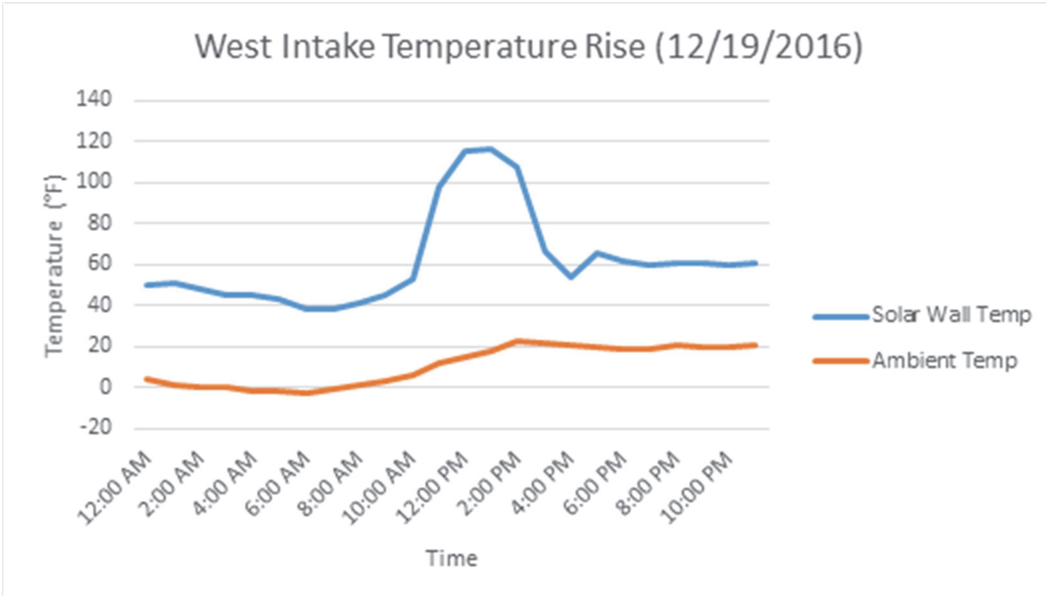


Figure B-4. West ΔT vs. insolation (10 W/m²).

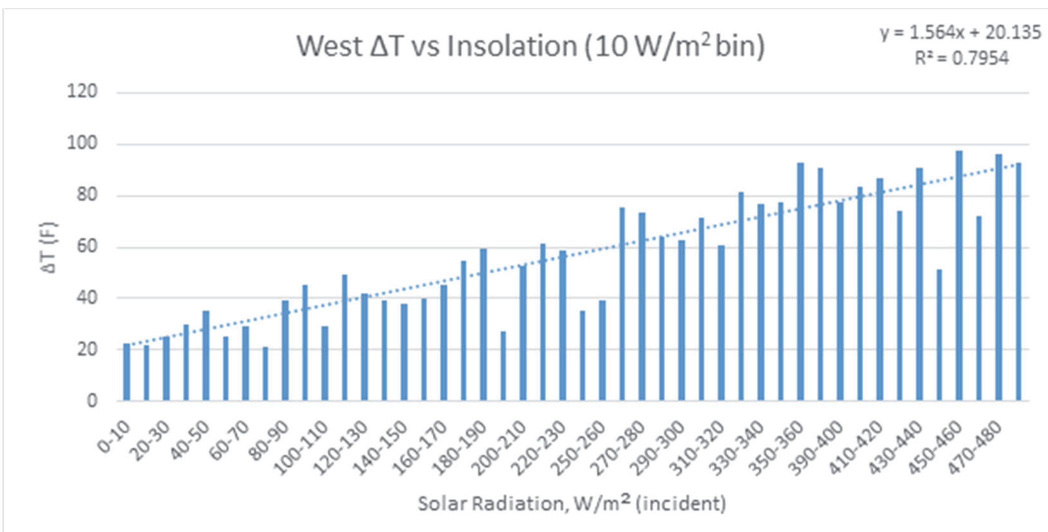


Figure B-5. West ΔT vs. insolation (25 W/m²).

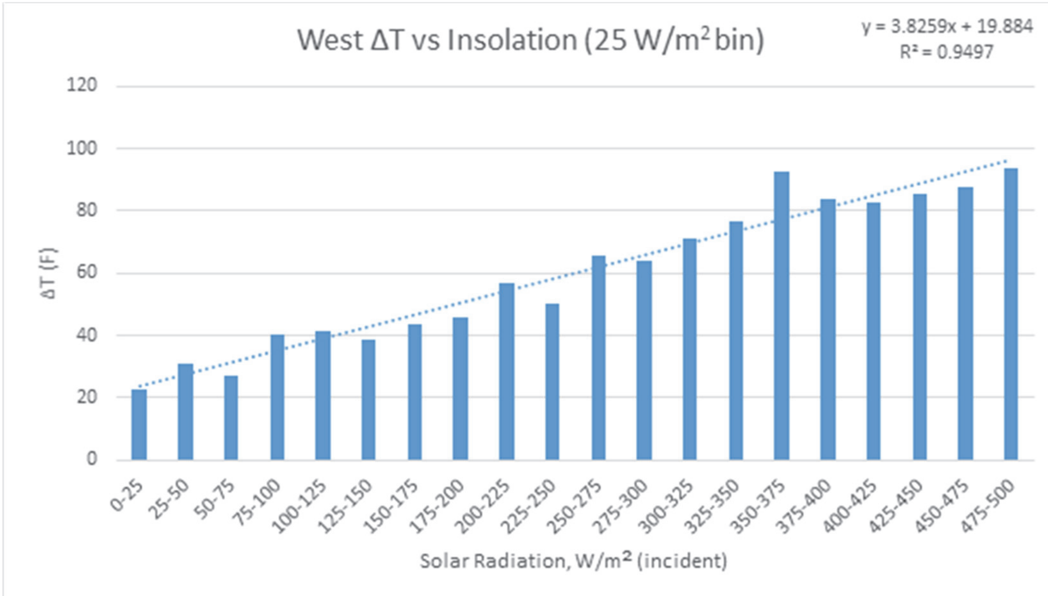
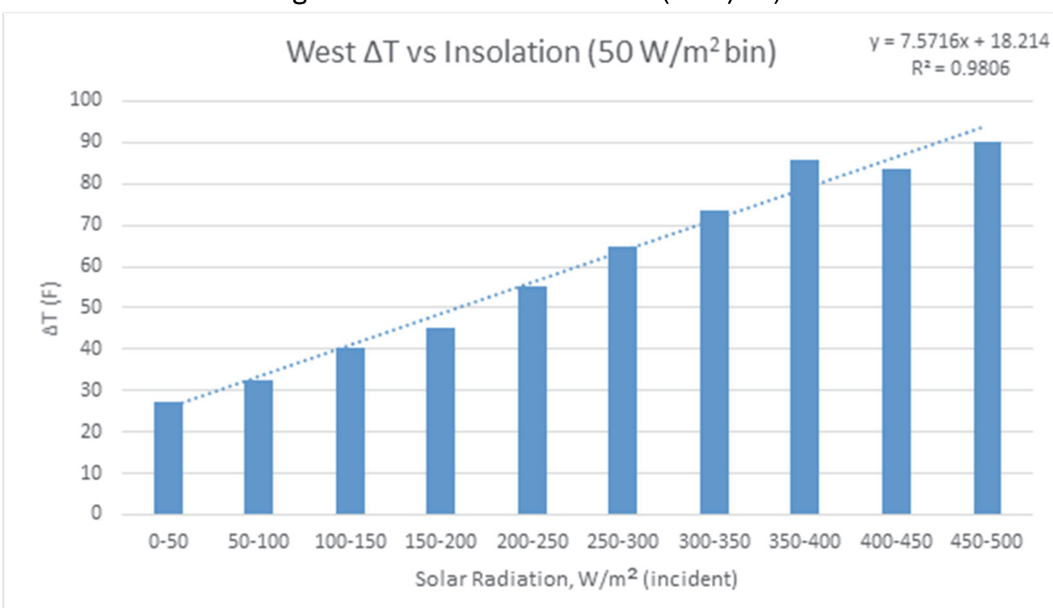


Figure B-6. West ΔT vs. insolation (50 W/m²).

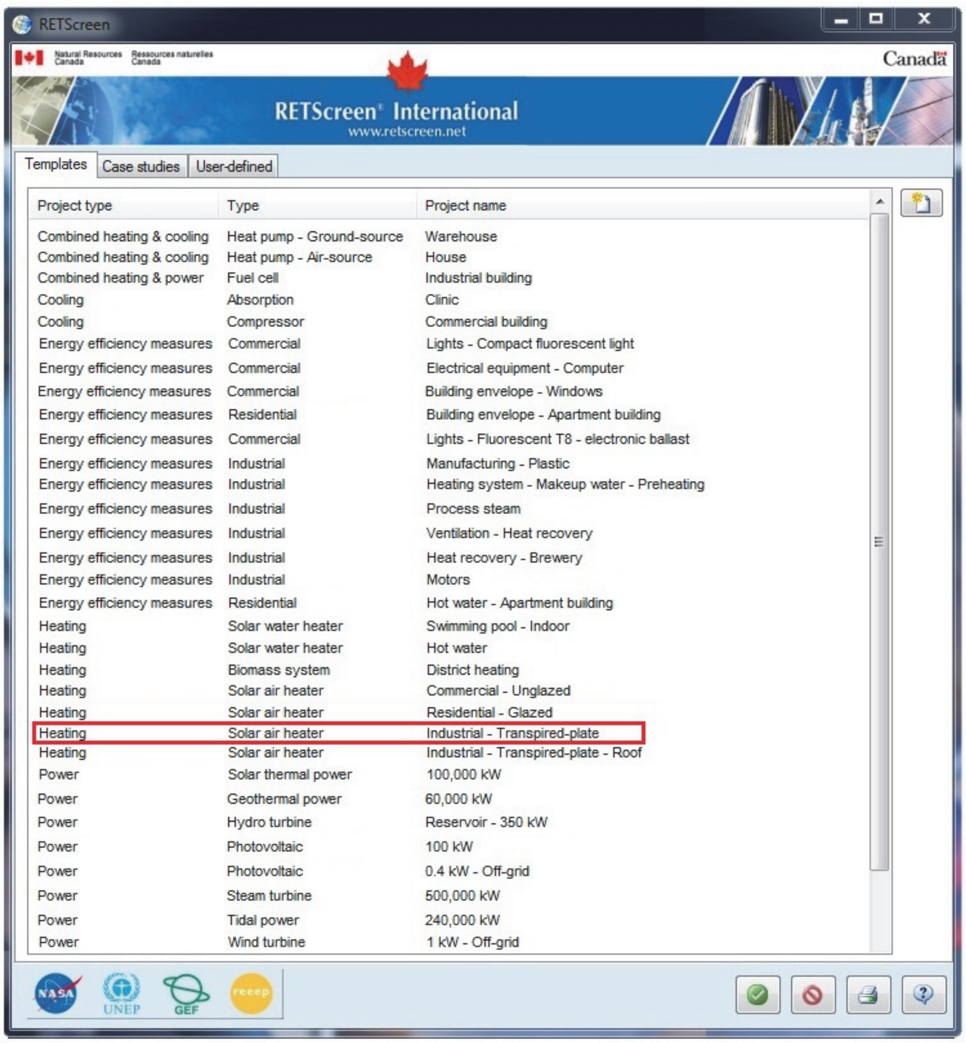


Appendix C: Details on RETScreen Settings

C.1 Start menu

Project Information: Once the user opens the model in the "Start" screen, shown earlier in Figure 23, the user can then use a pre-loaded template to help set up the analysis. Clicking on the hyperlink "Project Information" opens a separate menu that has a number of energy modeling templates (Figure C-1). The template "Industrial – Transpired plate" was selected for this project, and specific case studies are available to analyze for a comparative sample.

Figure C-1. Sampling of the 65 different templates currently available in RETScreen, with the Industrial – Transpired plate selected for the modeling in this project, highlighted with the red box.



Project Name, Project Location, Prepared for, Prepared by: General model information helpful to viewers but has no bearing on the results.

Project Type: This is a dropdown menu that the user can change, but the selection automatically changes when the user makes the template selection through the Project Database. In this project, the selection was "Heating."

Technology: This is similar to "Project Type." It is automatically updated through the selection in the Project Database. This project technology was "Solar Air Heater"

Analysis Type: The Excel-based RETScreen model allows the user two different settings to view the results. In Method 1, all of the results are on one single tab, where the user scrolls up and down to view the content. In Method 2, the results are separated into five different tabs,

Heating Value Reference: RETScreen automatically updates this metric as either higher heating value (HHV) or lower heating value (LHV). The current analysis used HHV.

Site Reference Conditions: Clicking on the hyperlink, "Select Climate Data Location," allows the user to input the climate data specific to the studied location. By selecting the "Show Data" box, the user can see the historical average data for several metrics, including temperature, solar radiation, wind speed, and heating and cooling degree days. For both models in this project, one parameter, the wind speed, was modified to account for a wind sheltering coefficient that was not incorporated into the model. Specifically, every monthly entry for wind speed was multiplied by 0.35, which was intended to account for a factor of 65% for wind sheltering.

C.2 Energy model

Table C-1 lists the settings used to model the performance of the transpired plate in both the Fort Drum and Topeka locations. This table differs from the screen shots shown in Chapter 4, in that it provides closer detail, commentary, and a comparison between the two sites.

Table C-1. Input settings and results of the RETScreen modeling for Fort Drum and Topeka locations.

Parameter	Unit	Fort Drum		Topeka		Comments
		Base Case	Proposed	Base Case	Proposed	
Load Characteristics	N/A	Ventilation		Ventilation		
Facility Type	N/A	Industrial		Industrial		
Indoor Temperature	°C	21.0	21.0	21.0	21.0	
Air Temperature - minimum	°C	18.5	18.5	18.5	18.5	
Air Temperature - maximum	°C	99.9	99.9	99.9	99.9	Ensures model will account for all heating
Temp - building stratification	°C		7.0		7.0	0.5-1.0 °F per foot of height
Floor area	sq ft	6,700	6,700	7,048	7,048	
R-value - roof	m^2-°C/W	4.0	4.0	4.0	4.0	
R-value - wall	m^2-°C/W	2.0	2.0	2.0	2.0	
Design airflow rate	m^3/h	6,200	6,200	22,936	22,936	
Operating days/week, weekday	d/w	5.0	5.0	5.0	5.0	
Operating hrs/day, weekday	h/d	24.0	24.0	16.0	16.0	
Operating days/week, weekend	d/w	2.0	2.0	2.0	2.0	
Operating hrs/day, weekend	h/d	24.0	24.0	8.0	8.0	
Percent of Month Used						
January	100%	100%	100%	100%	100%	
February	100%	100%	100%	100%	100%	
March	100%	100%	100%	100%	100%	
April	100%	100%	100%	100%	100%	
May	50%	50%	50%	50%	50%	

Parameter	Unit	Fort Drum		Topeka		Comments
		Base Case	Proposed	Base Case	Proposed	
June	0%	0%	0%	0%	0%	
July	0%	0%	0%	0%	0%	
August	0%	0%	0%	0%	0%	
September	50%	50%	50%	50%	50%	
October	100%	100%	100%	100%	100%	
November	100%	100%	100%	100%	100%	
December	100%	100%	100%	100%	100%	
Solar Tracking Mode	N/A	Fixed		Fixed		
Slope	N/A	90.0		45.0		Fort Drum (vertical), Topeka (45-degree angle from roof)
Azimuth	N/A	30.0		0		Direct south facing = 0.0. Fort Drum is set facing southwest
Solar Radiation Values	These are set amounts based on location and prior inputs, and are not adjustable					
Solar Air Heater Information						
Cost	$US	$124,132		$503,000		
Solar Collector Absorptivity	N/A	0.95		0.95		
Performance Factor	N/A	1.27		1.10		
Solar Collector Area	sq ft	3,265		5,292		
Incremental Fan Power	W/sq ft	0.5		0.5		
Electricity Rate	$/kWh	0.069		0.090		
Fuel Rate	$/therm	0.254		0.596		

Appendix D: Fort Drum Life Cycle Cost Details

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A, the Life Cycle Cost (LCC) calculations are based on the FEMP discount rates and energy price escalation rates updated on 1 April 2013.

Location:	New York	Discount Rate:	3%
Project Title:	Ft Drum Solar Wall_High_10	Analyst:	Sean Wallace
Base Date:	April 1, 2013	Preparation Date:	Thu Jun 08 12:03:47 CDT 2017
BOD:	April 1, 2013	Economic Life:	20 years, 0 months
File Name:	C:\Users\U4CFESMW\Documents\1 CERL - Projects\ITTP Solar Wall Demo\BLCC5 Models\NEW_Ft Drum_Real Data.xml		

1. Investment.

Construction Cost	$124,132
SIOH	$0
Design Cost	$0
Total Cost	$124,132
Salvage Value of Existing Equipment	$0
Public Utility Company	$0
Total Investment	$124,132

2. Energy and Water Savings (+) or Cost (-) (Base Date Savings, unit costs, & discounted savings).

Item	Unit Cost	Usage Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	$23.24054	-10.1 MBtu	-$234	14.729	-$3,448
Natural Gas	$2.54400	191.9 MBtu	$488	16.589	$8,098
Energy Subtotal		181.8 MBtu	$254		$4,650
Water Subtotal		0.0 Mgal	$0		$0
Total			$254		$4,650

3. Non-Energy Savings (+) or Cost (-).

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
Non-Annually Recurring Subtotal	$0			$0
Total	$0			$0

4.	First year savings	$254	
5.	Simple Payback Period (in years)	488.68	(total investment/first year savings)
6.	Total Discounted Operational Savings	$4,650	
7.	Savings to Investment Ratio (SIR)	0.04	(total discounted operational savings/total investment)
8.	Adjusted Internal Rate of Return (AIRR)	-12.60%	(1+d)*SIR^(1/n)-1; d=discount rate, n=years in study period

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Acronyms and Abbreviations

Term	Definition
AHU	Air Handling Unit
BAS	Building Automation System
BLCC	Building Life Cycle Cost
BTU	British Thermal Unit
CEERD	US Army Corps of Engineers, Engineer Research and Development Center
CERL	Construction Engineering Research Laboratory
CFM	Cubic Feet per Minute
DoD	U.S. Department of Defense
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
FEMP	Federal Energy Management Program
HAZMAT	Hazardous Materials
HHV	Higher Heating Value
ITTP	Installation Technology Transition Program
LCC	Life-cycle Cost
LHV	Lower Heating Value
M&V	Measurement and Verification
MILCON	Military Construction
MMBTU	million BTU
OA	Outside Air
OACSIM	Office of the Assistant Chief of Staff, Installation Management
RA	Return Air
SF	Standard Form
SIR	Savings to Investment Ratio
TR	Technical Report
UTSC	Unglazed Transpired Solar Collector
VDC	Volt DC

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14. ABSTRACT
This work performed measurement and verification of installed, operational solar wall systems at Fort Drum, NY, and Forbes Field, Air National Guard, Topeka, KS. Actual annual savings were compared estimated savings generated by a solar wall modeling tool (RETScreen). A comparison with the RETScreen modeling tool shows that the measured actively heated air provided by the solar wall provides 57% more heat than the RETScreen tool predicted, after accounting for boiler efficiency. The solar wall at Fort Drum yields a net savings of $851/yr, for a simple payback of 146 years and a SIR of 0.16. RETScreen models indicate that the solar wall system at Forbes Field, Kansas Air National Guard, Topeka, KS saves $9,350/yr, for a simple payback of 58.8 years and a SIR of 0.34. Although results showed that, due to low natural gas prices, the Fort Drum system was not economically viable, it was recommended that the system still be used to meet renewable energy and fossil fuel reduction goals. The current system becomes economical (SIR 1.00) at a natural gas rate of $16.00/MMBTU *or* $1.60 /therm.

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Solar heating--Passive systems, Solar heating—Evaluation, Cost effectiveness, Rate of return, Application software, Fort Drum (N.Y.), Forbes Air Force Base (Kans.)

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