Solar Heat Recovery from Dynamic Building Envelopes

John Archibald

ABSTRACT

Heating for space heating, water heating, and clothes drying, is the largest site energy end use in many buildings. In residential buildings, it can be as high as 2/3rds of the total site energy need and similarly high in laboratory buildings and many commercial buildings with high ventilation requirements.

Traditionally the opaque portions of the building envelope have been treated only as a barrier to heat, air, and moisture flow and did not contribute to energy supply from the large surface subjected to daily solar heating. Heating and cooling energy had to be delivered from another energy source and the function of the opaque envelope was simply to prevent the loss of this valuable energy to the outdoors.

Over the past 18 years American Solar, Inc. has used heated air recovered from the solar heating of 'conventional' metal walls and roofs to deliver heat energy to over 30 buildings. These have included all the largest solar air heating roofs in North America, with one solar air heating roof over 200,000 square feet. The buildings have spanned from industrial to agricultural, laboratory, office, and residential. The uses of solar heat have included; direct space heat, air-to-water preheat for domestic hot water, heat pump preheat, air conditioning reheat, radiant floor heating, clothes dryer preheat, and equipment heating. Almost all of the installed systems have been monitored, including 3 that have been monitored under DOD ESTPC and USDA contracts for up to one year. Analysis of the data collected from those systems has generated performance algorithms that enable performance to be predicted in all US locations using available TMY and solar position data.

Varied approaches to solar heat recovery from walls and roofs are discussed. Typical performance metrics are given for different applications. Several case studies are described and national energy savings potential is estimated.

Heating Energy Use in Buildings

Heating for space heating, water heating, and clothes drying, is the largest site energy end use in many buildings. It can be as much as 70% of all the site energy used in residential buildings. Figure 1 (DOE) shows that space heating and water heating make up 63% of all residential site energy use. The other heating energy use is in the 'Wet Cleaning' category where the humble act of drying clothes, with a household average of 283 loads per year (Energy Star), makes up 2% of all energy use. So, a total of 65% of all the energy needed within the confines of an average home is for heating something.
When we consider the end use temperatures for those heating loads, we find that most of the heating takes place at fairly low temperatures: space heat- 75F, water heat- 120F, clothes drying- 140F. However, these end use

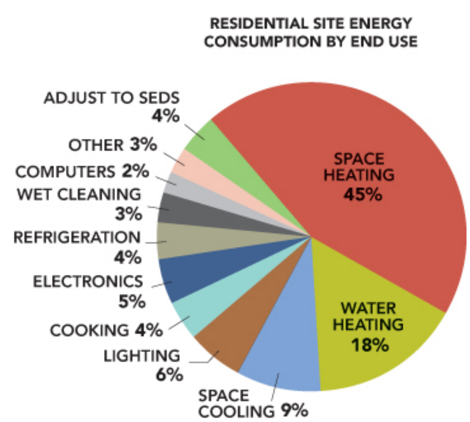

Figure 1 Residential Site Energy Use

John Archibald is President of American Solar, Inc. Annandale, VA 22003

temperatures are not the temperature where the heating need begins. For example, water heating begins when cold well or city water enters the house at a temperature somewhere between 40 & 80F. Space heating begins when cold outside air enters a house, between 0 and ~60F. Clothes drying begins when cold outside air enters the house to supply a source of air to replace the air drawn from the conditioned space around the dryer. So, clothes dryer heating takes place from 0 to 140F. When commercial and industrial buildings are considered, the heating energy percentage remains about the same. While the heating and drying functions vary widely across the commercial and industrial sectors, many heating and drying applications still start with either cold outdoor air or cold or room temperature materials. Considering all the buildings in the US including residential, commercial, and industrial, about 2/3rds of all energy used is for heating.

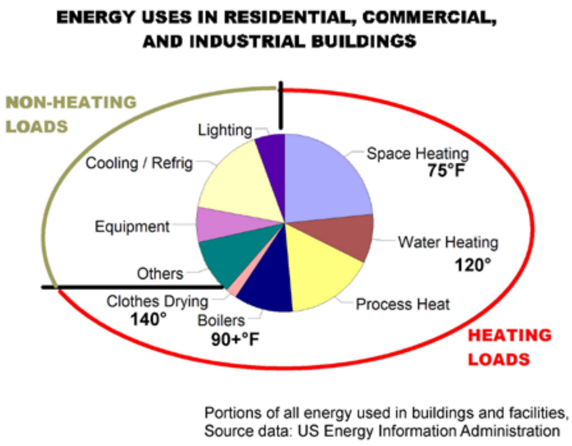

Figure 2 Energy Use in US Buildings

The building envelope has a role to play in reducing the heat energy required for many of the energy consuming applications. Certainly it can reduce the loss of heat and desirable humidity on cold days and nights. It can also control the infiltration of cold air and reduce energy robbing condensation. It can also reduce the air conditioning load on hot days.

Of the envelope components, only windows function as a 'dynamic' portion of the envelope, with their capacity to admit energy as light and heat, to help supply heat to the loads, while blocking unwanted heat flows,. The static, opaque envelope does not deliver much energy to the large heating loads such as; space heating, water heating, and clothes drying. Even an opaque envelope, which is a perfectly efficient, static barrier, will never replace the need for a supplemental energy source for heating, as cold air is drawn into the building to maintain air quality and cold water is drawn in for domestic and other uses.

The magnitude of the waste solar heat on our buildings in the US is measured in Quads. Table 1 shows an estimate of roofing and siding of residential and commercial buildings derived from EIA RECS and CBECs data. Many of those billions of square feet are solar heated each day. The table provides an estimate of the recoverable solar heat considering the performance of recent projects which have recovered solar heated air from opaque building envelopes.

Table 1. Recoverable Solar Heat From Dynamic Building Envelopes[1]

Building Type	# of Buildings (Millions)	Sqft Siding (Billions)	'Recoverable' Siding Solar Heat (Quads)	Sqft Roofing (Billions)	'Recoverable' Roof Solar Heat (Quads)
Commercial Buildings	5.5	27	0.33	56	0.70
Residential Homes	~88 buildings 115 homes	164	2.05	148	1.85
Total			2.38		2.55

[1] Heating is calculated by the air mass flow x temperature rise x specific heat. Moving 1 cubic foot per minute, with at 40F delta T, in one square foot of solar surface, generates 42 BTU/hr. American Solar has tested the energy delivery in the majority of our solar air heating roof installations for weeks or months. The best documented case is for a DOD ESTCP project at Fort Meade, mentioned below (Archibald). For the tested system, the energy delivery is ~34,000BTU/sqft/yr. 25,000 is used above as a conservative value. Heat recovery assumed from ½ of all roofing and siding on buildings, using EIA building area characteristics data reduced by ½ for north side surfaces, windows, doors, etc. Note the total solar heat 'hitting' all walls and roofs is roughly 4-5 times larger than the recovered heat, ...roughly 20-30 Quads per year.

There have been several attempts over the years to use the building envelope to collect solar energy as that supplemental energy source. Numerous projects have simply added glazing over a south wall or added more windows to increase the amount of solar heat to reduce space heating loads. Jones described a conventional metal roofing panel as an air heating collector in 1987. Hollick patented exterior metal building panels, one with perforations that allow air to be heated as it passed from the exterior to the interior of the solar heated panel. The air is collected and often used as a source of preheated outdoor air in commercial buildings. It is marketed along with other variations by a variety of companies. One company (Dawn) used a conventional metal roof that covered over a liquid filled PEX tubing. The water or water/glycol in the tubing would be heated in the hot air space beneath the solar heated metal roof panel. Attempts have been made (ASI, Solex, Soltech) to use clear glazing tiles that resemble conventional roofing tiles to shed precipitation and collect higher temperature heated air from the space between the tile and dark sheathing below. While technically successful, there has been minimal market penetration and the ASI system was abandoned in favor a simpler less expensive system.

That system recovers solar heated air directly from beneath the conventional metal roof or from behind the metal wall panel. The solar air heating metal roof or wall uses conventional metal roofing and siding installed in a manner that is code approved and carries a manufacturer's warranty for weather tightness. It uses almost any profile or color that is available in the market place. In many cases, it has been installed as a retrofit roofing or siding system over an existing roof or wall. In other cases the existing metal roofing and siding have been used and only the air heat recovery fan, ductwork, and controls have been installed to recover solar heated air. In each case, the metal roofing or siding is considered the weathertight envelope and the solar collector surface.

Solar Thermal Lessons Learned

After 6 decades of commercial solar thermal developments, with dozens of different technologies and systems, there are a few lessons to be learned. Some are negative and some are positive.

On the negative side, many attempts to provide solar heat were hampered by trying to achieve 100% of the heating load, with either high temperature, or multi-day storage. Another negative was the desire to serve each hot water load as it occurred, each day throughout the year, in order to maximize the delivered solar heat and cost savings. However, this required; complex plumbing, storage, and often freeze protection systems. From a business perspective this required code approval, a specially trained workforce, a marketing effort to reach, train, and sell customers to install an add-on appliance. All of this added costs to the end product, which many customers also considered unsightly and too complex. The high cost reduced the return on investment. Eventually, Federal support for these water based systems and market support mechanisms ended, leaving local installers and trade associations to continue to promote market support with reduced budgets.

On the positive side, the low temperature of many of the heating loads can be met substantially with low temperature solar heat. The low temperature of the incoming outdoor air and water make them candidates for low cost, low temperature air preheating. After 6 decades of research and development, there is significant data available about the solar energy engineering and local weather files that make accurate prediction of solar heating and cost savings very precise. Solar heating performance of various materials and paint colors enables accurate temperature prediction of solar heated envelopes. Aerial photos of building and energy consumption data for various building types make solar energy estimation possible with minimal time and cost. Proven examples of the dual use of conventional metal roofing and siding as weather protection and solar collection surfaces, eliminates the large cost of dedicated, add-on solar panels. Because all buildings need a new roof eventually, there is an opportunity to sell a conventional looking solar air heating roof, where there might not have been an opportunity to sell an add-on solar panel which had to be fastened through the otherwise weathertight roof.

One positive lesson on the envelope front, is that envelopes are now tighter, reducing infiltration. However, the tightness of the envelope may actually result in a need for more dedicated mechanical ventilation at added expense and fan energy use for air-to –air heat exchangers. Envelopes are now better insulated, reducing the heating load in the building and reducing the 'back loss' for solar heated envelope surfaces, which contributes to higher solar air temperatures to be recovered from solar envelopes. While buildings are getting larger every year, the envelope also gets larger, including the portion that is available for solar heat recovery.

Solar Heat Recovery from Roofs and Walls

The alternative to previous 'black box' solar heating panels is to use the conventional building envelope to harvest solar heated air. The heat harvested from the envelope can be applied to various loads within the building. Even the cooling load can be reduced with a well designed solar air heating roof.

The biggest difference in this approach is the application of solar heat to the lowest temperature loads. In many cases this is preheating the incoming air, water, or material instead of trying to deliver solar heat at the higher delivered temperature of the conventional heating systems. Preheating incoming air from 30 to 60F delivers ¾ of the heating when 70F is the required delivered temperature.

Other differences are that; 1) this approach use the conventional weathertight surface as a solar air collector and 2) this approach does not try to use high capacity heat storage, except for short term smoothing of relatively small demands by the loads.

By using the conventional weathertight surface (roof or wall) as a solar collector, no added cost is required to install a collector surface outside the weathertight roof or wall. The use of relatively harmless free flowing air instead of liquids with complex plumbing, and the 40 year life of the metal panels, and available tax credits, together significantly reduce the installed cost and life cycle cost of large envelope solar heating systems.

Operations are simplified. For example, if there is no heating demand, the solar thermostat simply shuts off the solar fan. When the demand picks up, the fan turns on. For intermittent water heating loads, a small (10 to 40 gallon) storage tank, circulating cold incoming water through a solar air-to-water heat exchanger will deliver adequate preheated water to the conventional hot water heater. For commercial buildings with daytime loads, this approach is well timed for loads such as domestic or process water preheating when buildings are occupied. For residential buildings, when water heating loads may be early morning and evening, a second 40 gallon tank will hold heat for several hours, and even through the night, to serve the evening and partially serve the morning load.

One goal in implementing these systems is to maximize BTU delivery and dollar savings, not to achieve high peak temperature of the delivered solar air or water. A second goal is to minimize aesthetic impacts by using traditional envelope materials, installed at any conventional orientation on the building façade which can produce useful heat. A third goal is to minimize complexity with simple mechanical systems that are well understood in design, fabrication, operation, and maintenance by existing building professionals and trades.

Applications of Solar Air Heating Walls and Roofs

Since 2005, over 47 solar air heating roof and siding systems have been installed using conventional metal roofing and siding construction. The systems consist of installations with new metal roofs or siding (25) and installations where existing roofing or siding was used (22) and only required the installation of solar air ducts, fans, and controls to recover solar heated air. A partial list of projects and end use applications is shown in Table 2.

The applications include;

Outdoor air preheat, where the solar heated air is pulled from the solar air space and delivered to the outdoor air intake when preheating is desirable for space heat, dryer air preheat, combustion air preheat.

Direct Space Heat, where solar heated air is pulled from the solar air space and delivered directly to the occupied space for space heating.

Indirect Space Heat, where solar heated air is pulled from the solar air space and delivered to the back side of the finished interior sheathing (behind drywall or below floorboards) for space heating using an 'air-radiant' heating approach.

Equipment Heat, where solar heated air is pulled from the solar air space and delivered directly to the equipment or surrounding space, e.g. standby heating of emergency diesel generators, freeze protection, air source heat pump evaporator, etc.

Hot Water Preheat, where solar heated air is pulled from the solar air space and delivered to an air-to-water heat exchanger (e.g., copper fin tube coil). Water is continuously circulated through a small tank and the heat exchanger as long as the solar air temperature is ~10F above the circulating water temperature. With any hot water use, make up cold incoming water to the building enters this preheat tank and preheated water exits to the conventional water heater/boiler to be heated, as necessary, to the final delivered temperature.

Heat Pump Hot Water Heater Preheat, where solar heated air preheats the evaporator coil of an air-to-water heat pump water heater. This approach provides a continuous source of hot water even when solar heating is not available. However, when solar heated air is available to preheat the evaporator air stream, the heat pump heating performance (COP) can increase by as much as 50%.

Heat Pump Preheat, where solar heated air preheats the evaporator coil of an air-to-air heat pump for space heat. This approach provides a continuous source of warm air even when solar heating is not available. However, when solar heated air is available to preheat the evaporator air stream, the heat pump heating performance (COP) can increase by as much as 50%.

Combi Systems, where solar heated air; preheats the evaporator coil of an air-to-water heat pump water heater and preheats the outdoor air supply when solar air temperatures are too low for economical heat pump use, ~30F outside air temperatures. The heat pump water heater provides: a) consistent high temperature (120F+) hot water at high COP with solar assist, and b) cooler, dryer exhaust air (~15-35F lower than solar supply air), which is useful at reducing the latent and sensible cooling load in the building.

Performance Metrics

Most of the 47 systems have been designed with an air flow of 1 cfm/sqft of solar area. At this air flow rate, the systems will typically deliver a temperature rise of 30-40F above outdoor air temperatures during peak midday hours. At this flow and temperature rise, the systems will add about 30-40 BTU/sqft solar/hr to the outside air. At zero flow, typical stagnation temperatures at midday can reach 60-80F above outdoor air temperatures. See Figure 3. If higher solar air temperature is desired, the air flow can be slowed, but with a slight energy loss as the higher roof/siding temperature causes more heat loss from conduction, convection, and radiation from the exterior of the metal panel to the atmosphere.

Figure 3 65F Delta T, Vinyl Siding in Full Sun and Shade on a 57F Day

Figure 4 Light Colored Siding on an 80F Degree Day

Darker colors achieve higher temperature rise, but even light colored exterior surfaces (Figure 4) often reach 40-50F above outside air temperatures under bright sun conditions. For darker colored materials, air flow path lengths of about 15 feet are usually sufficient to fully heat the moving air. Extending path lengths will not increase air temperature. Designing and installing ideal path lengths from large areas over 30 feet long is often not worth the expense compared to simply gathering less than the maximum heat available from fewer outlets, at lower installed cost.

Figure 5 Re-roof Solar Air Space and Outlet

The depth of the air flow space within the envelope has varied from less than one inch to over a foot depending on the building construction. Typical retrofit or re-cover of a roof with new metal panels will result in a depth of 3 inches (Figure 5). Air flow paths within the roof or wall, from inlets to outlets, are either through the support structure, or over the structure by moving air within the corrugations of the metal panels, shakes, or tiles.

With minimal design effort, the pressure drop through the solar air flow space is typically ½ inch of water from inlet to outlet. Fan energy required under these conditions is typically 1 watt per square foot. Under these conditions, the energy delivered to the outdoor air (~40 BTU/sqft) is roughly 12 times that required by the fan at 1 watt/sqft (3.412 BTUeq/sqft). This is a COP of 12 or an EER of 41. However, there have been many monitored cases where temperature rise of 60F and fan energy of less than 1 watt/sqft have resulted in higher COPs over short time periods. During the course of a day, variations in solar heating from varying sun angles, wind, and overcast skies will change the instantaneous solar heating performance. Comparing envelope solar heat recovery to the use of the envelope as strictly a barrier to heat, air, and moisture flow, shows a large difference in energy savings. If we consider a simplified example of a typical south facing wall of a home, with R-20 total insulation, on a day with a 30F temperature difference across the wall (70F inside, 40F outside), the heat loss through the opaque envelope is 1.5 BTU/sqft/hr. For about 8 hours of a winter day, there would be no heat loss as the exterior of the opaque wall is solar heated to ~70F. For the other 16 hours, the heat loss would total ~24 BTU/sqft. In contrast, solar siding heat recovery would provide about 160 BTU/sqft in the same 8 hour daytime period. At night, with the solar fan turned off, the R-20 wall with solar siding would see the same heat loss as the non-solar wall, ~24 BTU/sqft. So, the total daily heating benefit from the solar siding to various loads could be as much as 160 BTU/sqft compared to the opaque wall.

A predictive algorithm has been developed (Archibald) for the solar roof installed at the Gaffney Gym at Fort Meade, MD (Figures 6 and 7). The formula for solar air temperature accounts for solar insolation, outdoor air temperature, wind speed, and solar elevation. It has also been validated against a second installation of a northwest facing solar reroof of the Gaffney Pool.

Roof Solar Air Temp = -5.82363 + 1.15796 * Outdoor air temp (Deg F) + 0.333505 * Wind Speed (MPH) + 0.045709 * Solar Insolation (W/m^2) + 0.081632 * Solar elevation (Deg)

A sample chart, Figure 8, shows the predicted and measured solar air temperatures for a 4 day period. Of these days, the solar fans ran whenever the roof air was above the outside air temperature.

Economics

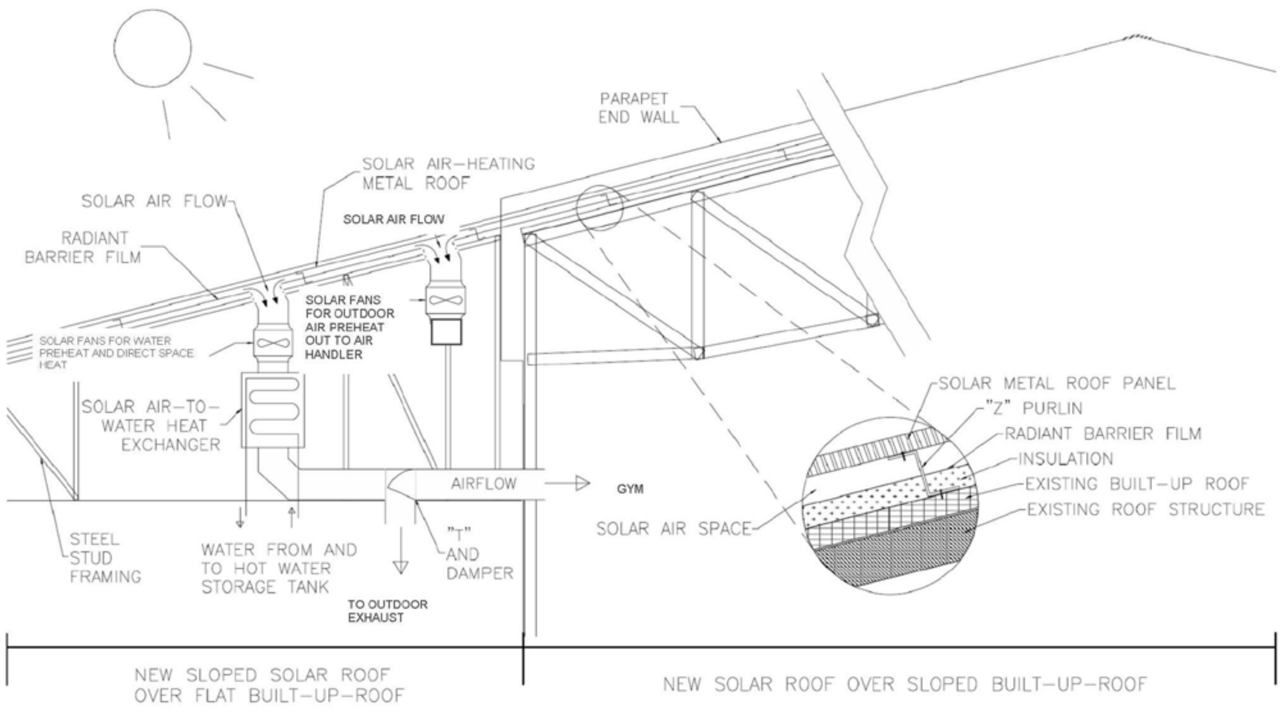

Figure 6 Gaffney Gym Solar Air Re-Roof Schematic

Using the solar COP of 12, and an electricity price of $0.1255/kwhr (EIA$), the cost of solar heat delivered to the outside air is $2.44/MMBTU. In comparison, heat delivered from electric resistance heat would be $36.52/MMBTU. With natural gas at an average US residential price of $10.05/MMBTU and burned at 95% efficiency the cost of heat delivered would be $10.58/MMBTU. So, building envelope solar heat recovery can deliver heat at 3-25% of the cost of conventional heating sources. Installed costs of these dynamic solar heat recovery systems vary depending on the type of building and the loads to be served. If a solar roof is to be installed in new construction, it can and should be assessed against the cost of the building and not against the cost of the solar heating systems. The cost of the solar 'roofing' components (metal panels, sub-structure, inlets and outlets, and trim) can be insignificant compared to the same roof installed without the solar heat recovery features. Typical 'non-solar' metal roof costs for larger commercial buildings range from $11-15/sqft foot installed. Added solar features for air inlets and outlets, solar air space zoning partitions, radiant barrier insulation, and sensors installed during construction add about $1 sqft for a roof larger than 4,000 sqft.

Figure 7 Gaffney Gym Solar Air Re-Roof

With a 40 year life of the metal roof and 15 year life of the fan, the life cycle cost of heat can be under $3/MMBTU. The mechanical and electrical systems (fan, ducts, power, and controls,) add about $3 per square foot for a simple system sending air to a nearby outdoor air intake using simple thermostatic control. The cost can be as high as $6/sqft for more complicated systems with;

a) long insulated duct or plumbing runs,
b) air-to-water heat exchangers,
c) heat pumps with higher electric power needs, plumbing connections, and separate controls, or
d) very complex controls to 'optimize' solar recovery or centralized control from a building automation system.

Heat pump systems can add $5-6/sqft of solar for the installation of a new heat pump. However, if the heat pump is the primary water heating/space heating system, its cost can be assessed as part of the building cost. In that case, only the cost of the other solar features (duct, fan, power, and controls), which are about $2-3/sqft of solar are the appropriate costs to assess against the solar systems.

Tax benefits are available for certain solar air heating roofs and walls that meet the definition of solar thermal systems. These include a 30% first year tax credit and accelerated depreciation. The benefits of using these tax incentives are the installed cost, after taxes, of a solar roof can be 68% of the installed cost of the exact same non-solar roof. In addition, the annual energy savings can result in payback periods of less than 10 years. In contrast, the same non-solar roof is merely an expense, which will never repay the cost of the installation.

For many solar air heating roofs or walls, only a portion of the solar roof/siding area is required to meet the most economical heating loads. This is often due to the high heating capacity of the large solar area presented by the roof or wall, compared to loads, or the timing of the loads within the building. As an example, buildings with low daytime occupancy (movie theaters, religious buildings, etc.) will often have minimal outside air requirements and low heating loads during the daytime when

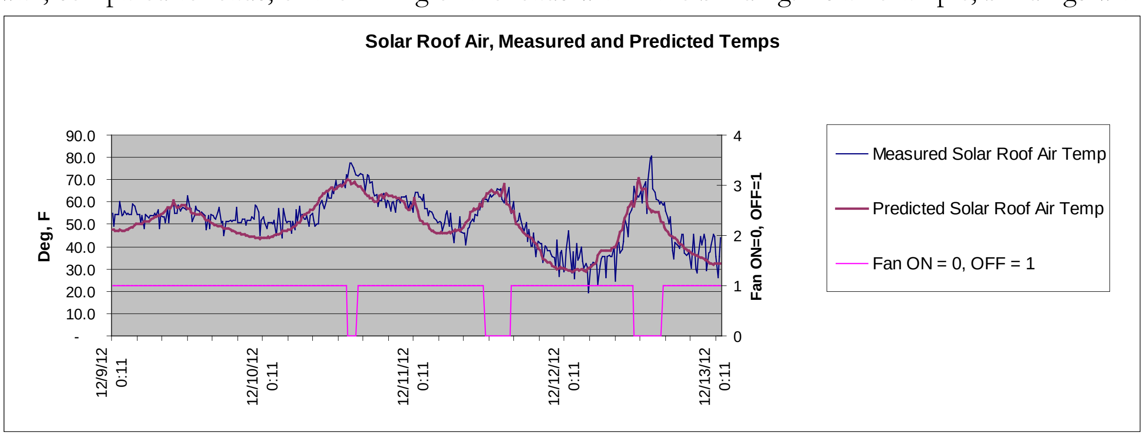

Figure 8 Measured and Predicted Solar Air Temperatures

solar heat is available. For these buildings, the roof covering can be of consistent appearance over the entire roof surface, but the solar air components need only cover the area and capacity to meet the economical heating needs in the building.

In one example, the gymnasium of the Gaffney Fitness Center at Fort Meade, MD, Figures 6 and 7, needed to be re-roofed. The solar re-roof covered the entire southwest facing slope and a lower flat roof area. The solar heated air was delivered to; a) the outdoor air intake of an air handler, b) an air-to-water heat exchanger for domestic water preheat, and c) directly to the gymnasium for direct space heat. The combined loads did not require all the solar heat available from the solar roof area, but the southwest slope of the roof needed to be completely re-roofed. The solar roof was installed consistently across the roof and solar heated air was drawn from each of four 2,400 sqft sections of the solar roof, as required by the heating loads. Air flow was less than 1 cfm/sqft.

Another example is a building at Aberdeen Proving Ground in Aberdeen, MD (Figure 9). The solar air heating roof replaced a corrugated concrete roof that had degraded and was failing. Only the south, east, and west facing sides of the roof were adapted for solar heat recovery. The north facing roof had an identical metal roof covering, but had no solar air handling equipment installed. This is the largest solar air heating roof in North America with over 106,000 sqft of solar air heating surface out of the 210,000 sqft of roofing and siding surface installed. Air is drawn from the solar air space beneath the south, east, and west facing roofs and blown directly down to the shop floor below. This not only recovers solar heat from the envelope but destratifies the air in the shop to bring down warmer interior air from below the underside of the roof.

A similar project at Hill Air Force Base, UT, Figure 10, used the solar heated air collected from the existing southeast and southwest facing metal siding and delivered the air to the hangar floor below the southeast and southwest walls.

Applications

A few of the many applications of solar heated air recovered from building envelopes are described below.

Outdoor air preheat - The most common application of solar heated air from the building envelope is for outdoor air preheating. It has the advantage of working with a load that starts at lower temperatures than the solar air temperature for many hours of the year. Solar heated air that is warmer than outdoor air is either sent into the outdoor air intake of the ventilation systems or directly into the space, if it is above the required indoor air temperature. Hard ducting to the outdoor air intake is not required or the most economical solution. If the solar air flow is equal to or less than the minimum outdoor air required at the inlet, then merely blowing the solar heated air at the air intake from a short distance away will flood the inlet with warm air. That warm air will be pulled into the outdoor air intake. When no solar air is available or required, 100% of the outdoor air supply will be met by outdoor air with unobstructed access to the outdoor air intake. This approach eliminates the need for additional expensive ductwork, motorized dampers, and controls, while delivering the same amount of solar heat as a hard ducted system.

For matched flow rates of solar air and outdoor air, all the solar air at the intake will be taken in by the outdoor air intake. When solar air flow is lower than outdoor air flow, all the solar air will be pulled into the outdoor air intake and will blend with the additional outdoor air also pulled in to satisfy the higher total outdoor air required. All the energy in the solar air will be delivered to the total higher volume of outdoor air and solar air.

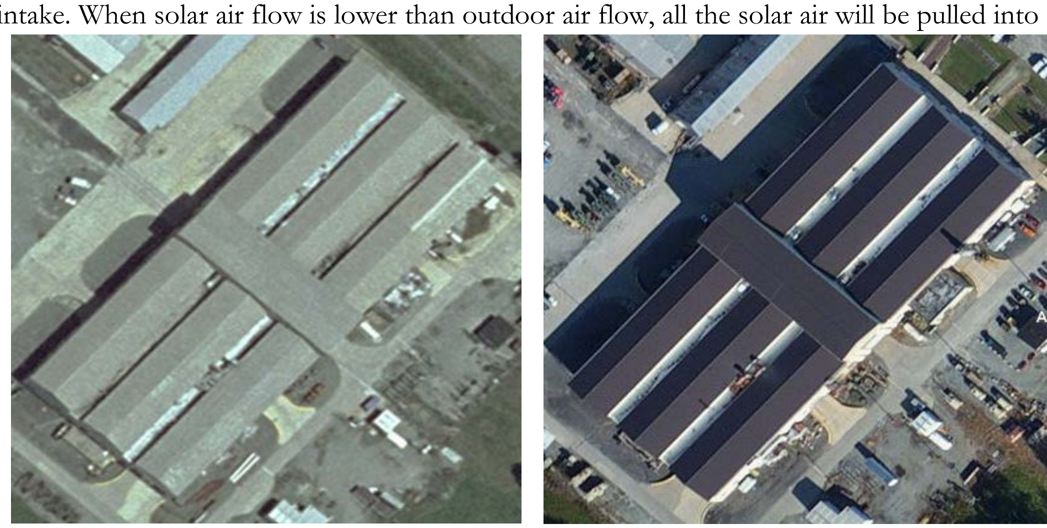

Figure 9 Solar Air Heating Re-roof, Before and After, Aberdeen Proving Ground, MD

Direct Space Heat – Direct space heat is available when the solar air temperature is above the required indoor air temperature. In that case the solar air is delivered directly into the space. The disadvantage of this approach is that there are far fewer hours when the solar air provides useful heat compared to the outdoor air preheat approach, when cooler solar air can deliver useful heat to the outdoor air even when it is below

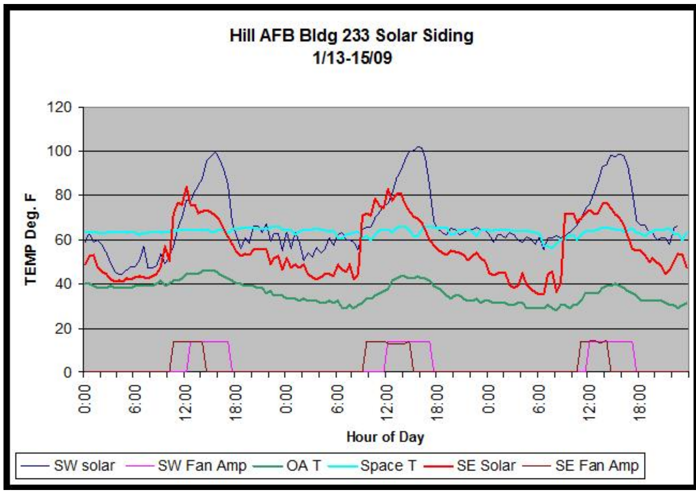

Figure 10 Solar Temperatures for Existing Siding Adapted for Solar Heat Recovery - Building 233, Hill AFB, Utah

the required indoor temperature.

An example of the benefit of outdoor air preheat vs. direct space heat is shown in Figure 11 from Hill AFB. The graph on the left shows the solar air temperature of a solar roof in the white area. The indoor temperature is shown in the blue area. The outdoor air temperature is shown in the purple area. In the graph on the left, the height of the white area is the solar air temperature above the indoor air temperature. In the graph on the right, the height of the white area is the solar air temperature above the outside air temperature. Since the energy delivered is a function of the delta T from solar to load, the higher the delta T (height of the white area), the greater the heat energy delivered from the roof. In addition, heating outside air continues for many more hours before and after the solar air is cooler than the indoor air, when direct space heating would cease. Another way to view the difference is that the large white area of the graph for outdoor air preheat is representative of the large solar energy delivered compared to the smaller white area for direct space heat.

One final consideration is the fact that the air in the solar roof stays warmer than the outside air during cold nights. This higher temperature is up to 20F above the outdoor air temperature on the coldest nights in the Hill AFB example. While the roof panel itself may be colder than the outside air due to night time radiative cooling, in the solar roof there is an insulating air layer below the roof layer and above the warmer old roof and main insulation layer. The

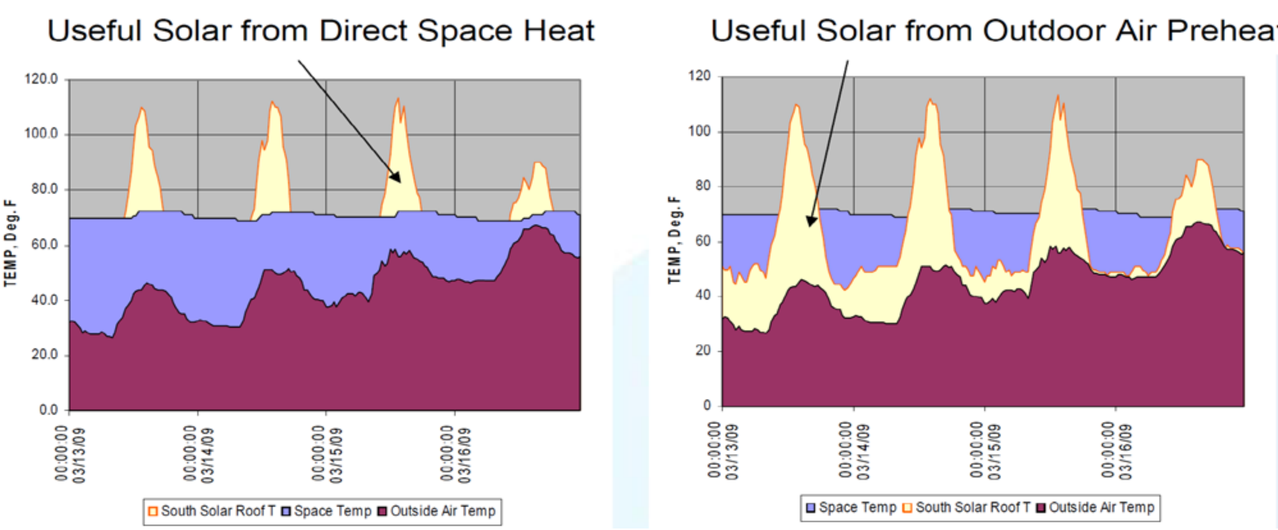

Figure 11 Solar Air Heat OA Preheat vs. Direct Space Heat

added layer helps capture heat lost from below, reducing overall heat lost from the roof.

Hot Water Preheat – Across most of the US water entering a building from a well or city main is typically at the local ground temperature, between 35 and 65F. It is most commonly heated for sanitary use. In homes this typically requires final temperatures of 120F. In commercial buildings, finish hot water temperatures for cleaning and sanitizing are often 140F to 165F. So hot water heating within a building may require raising the temperature of the incoming cold water by as much as 85 degrees in homes and 130F in many commercial buildings. Every degree (or BTU) of preheat from solar is a degree (or BTU) of heating not required by some purchased energy source (gas, fuel oil, electricity, etc.).

Air-to-water heating has been accomplished using several approaches. These include, solar air heating of water in a copper fin tube coil, solar air heating using a tank type hot water heater with heat exchange surface at the tank bottom and central flue (gas type hot water heater with no gas connection), and with solar assist to air-to-water heat pumps. In each system, the solar heated air was drawn from a solar roof and blown through the heat exchanger. With the copper coil and heat pump, the water was pumped through the heat exchanger. With the tank type hot water heater, no pump was needed, only solar air flow, and the tank was used as a combination preheater and supplemental storage. All these systems fed the preheated water to a conventional water heater that could handle the full peak load without any supplemental solar heating, when solar was not available.

A larger system at the Gaffney Fitness Center at Fort Meade delivered water as hot as 120F, when solar air temperature from the roof peaked at 132F. (Figure 12). Peak heat transfer was 45,000 BTU/hr just before noon. Total solar air flow from the roof was originally 3,025 cfm, but was reduced to 1,918 cfm in a final configuration, as the most economical air flow for the varied hourly demand.

In another, smaller residential scale, tank type preheat system, 85 cfm of solar air entering the tank at 105F on a 67F day exited the tank at 87F. The entering and exit temperature difference represented the heat transfer to the cold water in the tank. Over 3 sunny days in April, the heat transfer to the preheat tank averaged 1,300 BTU/hr and 9,200 BTU/day. This is equivalent to heating 40 gallons of water by 28F each day.

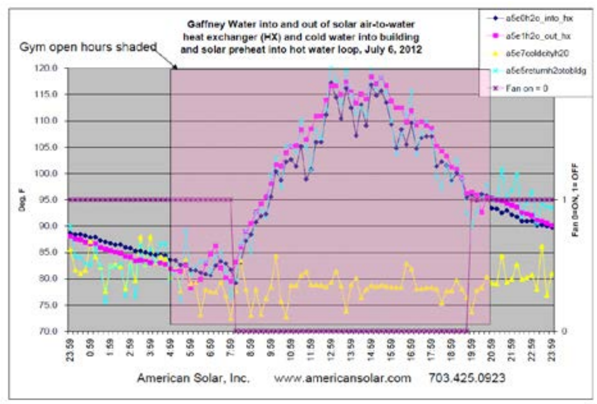

Figure 12 Gaffney air-to-water preheat

Heat from the exhaust air was used for dryer air preheat, boiler air preheat, and space heat that reduced electric heating of the dryer and the fuel oil heating of the space by the boiler.

A heat pump water preheat system operates with roof solar heated air supplying high temperature air to the evaporator of the heat pump. This boosts heat pump water heating performance (COP) by up to 50% for the same electric power use. One installed system at the Army Adelphi Garrison, MD heats hot water for an HVAC boiler reheat hot water loop. Another system at Fort Meade, MD draws solar heated attic air to heat domestic hot water for a barracks building. The hot attic air can also be used for outdoor air preheat in the winter when it is too cool to justify operation of the heat pump but the attic air is warmer than the outdoor air that is continuously brought into the building.

Combi Systems- Many of the systems described above use heat from the building envelope for multiple purposes either simultaneously or sequentially. The highest temperature solar air from the roof or wall is used to support the highest temperature heating load. The exhaust from that high temperature load is often still hotter than another heating load. This is true for heated exhaust air from a hot water preheat system, which is hotter than direct space heat, which is hotter then outdoor air preheat or heat pump preheat.

Of particular value is the solar assisted heat pump water heater. This Combi System uses solar heated air from the envelope to boost the performance of a heat pump water heater. The exhaust air from the heat pump is often cooler (<60F) and dryer than the indoor and/or outdoor air. In summer this exhaust air can be used for direct cooling or outdoor air pre-cooling. On cooler days, this cool air can be exhausted from the building.

Other uses -Another use of the solar heat from the envelope is to preheat the outdoor evaporator of an air-to-air heat pump used for space heating. As an example, a small 3-ton unit (York) which operates with 30F temperature boost from 20F outdoor air to 50F solar air, will increase heating capacity from 21,792 to 35,507 BTU/hr, a 68% increase for only 47% increase in total system electric power (2.950 to 4.335 kw). Even more important is the energy savings from keeping the heat pump evaporator above the temperature when electric resistance heating is required, generally below 30F. So, if 35,507 BTU are required at 20F and the heat pump only delivers 21,792, then 13,715 BTU (4.019 kw) must be provided by resistance heat. So, total system electric power without solar increases by 4.019 kw to 6.969 kw. In that case, the system energy use for the solar boost drops by 38% from 6.969 (HP and Resistance) to 4.335 (HP and solar fan).

An additional use of solar heated air is for 'air radiant' heating. This approach uses the floors, walls, and ceilings of the interior space as air heated radiant panels. By moving heated air from the solar heated roof or wall, through the cavities of the structure surrounding the conditioned spaces, the floors, walls, and ceilings are heated above room temperature. This has the same effect as water based radiant heating, but with much less complexity, as water tubing installation is not required. The warm panels provide radiant heat to the occupants, and radiant floors help to destratify heated air within the space, providing greater overall comfort and lower energy use for the same temperature setting. Typical use is for daytime supplemental heating with nighttime and cloudy day heating by a conventional fuel fired or electric heating system.

Table 2 lists several examples of dynamic building envelopes with solar air heat recovery systems.

Table 2. Solar Heat Recovery from Building Envelopes, Examples

Building Type	Location	Envelope	Application
Office 20,000 sqft	Adelphi, MD	Re-roof	Outdoor Air Preheat, Domestic Water Preheat, HVAC Reheat
Maintenance Hangar	Aberdeen, MD	Re-roof	Direct Space Heat
Maintenance Depot	Hill AFB, UT	Existing Siding	Direct Space Heat
Agricultural Building	Beltsville, MD	Roof & Siding Re-cover	Outdoor Air Preheat
Boiler Plant	Reston, VA	Existing Siding	Boiler Air Preheat
Barracks	Ft Meade, MD	Attic Air	Domestic Water Preheat
Gymnasium	Ft. Meade, MD	Roof re-cover	Domestic Water Preheat, Outdoor Air Preheat, Direct Space Heat, Pool Heat Pump Preheat
Residential	Great Falls, VA	New roof	Outdoor Air Preheat, Pool Heat, Dryer Preheat, "Air-Radiant" Floor Heat

Summary

The opaque building envelope is the largest solar heated surface on most buildings. Traditionally it has been considered a barrier to unwanted heat, air, and moisture flows to and from the environment. However, that approach to energy control with the envelope leaves an enormous energy resource untapped. That resource is the solar heat available on the envelope surfaces.

That solar heat can be recovered economically and applied to the heating and cooling loads within the building. Many of those loads can not be affected by just considering the envelope as a static barrier to energy flow. For example, solar heated air recovered from the envelope can be used for necessary heating or preheating of cold outdoor air for; ventilation, combustion, or drying, or for direct space heating or water heating, which the barrier envelope can not do.

The simplest heat recovery approach from the opaque envelope is to recover heated air from behind the roof and wall surfaces. This is further simplified if conventional metal wall and roof panels are installed as the weathertight surface. The mechanical systems use relatively low powered fans and ducts. The low energy use by the fans compares favorably to the high energy delivered in the solar heated air. Systems routinely achieve COPs greater than 10.

Based on rough estimates of total envelope surface areas on US residential and commercial buildings and the potential heat recovery from those surface areas, nearly 5 quads of solar heat is available to eliminate current energy use supplied by conventional fuels.

Several examples of successful systems show a promising way forward to recover low cost solar heat from these dynamic uses of the building envelope.

ACKNOWLEDGMENTS
Research has been supported by the US Dept. of Defense Environmental Security Technology Certification Program, and the US Department of Agriculture.

NOMENCLATURE

BTU = British Thermal Unit
CBECS = Commercial Building Energy Consumption Survey
Combi System = Heating system serving combinations of loads
COP = Coefficient of Performance
DEG = Degrees
DOD = Department of Defense
F = Fahrenheit temperature
ER = Energy Efficient Ratio
EIA = Energy Information Administration
ESTCP = Environmental Security Technology Certification Program
HP = Heat Pump
Hr = hour
HVAC = Heating Ventilation and Air Conditioning System
M^2 = square meter
MMBTU = Millions of BTU
MPH = miles per hour
Quads = quadrillion BTU, 10^15 BTU
RECS = Residential Energy Consumption Survey
sqft = square foot
TMY = Typical Meteorological Year
USDA = US Department of Agriculture

REFERENCES

DOE, Dept. Of Energy, Office of Building Technologies, Building Energy Data Book, downloaded from http://buildingsdatabook.eren.doe.gov 4/7/14, expired website, data available from various commercial websites
Archibald, John, ESTCP Final Report, Energy and Water Project EW-201148 -Solar Air Heating Metal Roofing For Reroofing, New Construction, and Retrofit, May 2013
Jones, D. J. 1987 Unglazed Solar Air Heaters for Space-Heating In Cold Climates, Solar '87, Proceeding of the 1987 Annual Meeting, American Solar Energy Society and Solar Energy Society of Canada: 381-383
EIA, Residential Energy Consumption Survey, 2010, Commercial Builidng Energy Consumption Survey, 2010, and Manufacturing Energy Consumption Survey, 2013
EIA$, Annual US Residential Natural Gas Price 2016 and Electric Power Annual for 2016 posted 12/22/17 and https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm and https://www.eia.gov/electricity/annual/html/epa_02_10.html
ENERGY STAR Market & Industry Scoping Report, Residential Clothes Dryers, November 2011
Hollick, John US Patent 4,774,932 Oct. 4, 1988 and US Patent 4,899,728 Feb. 13, 1990 with Peter, R
Dawn Solar, Dawn Solar Systems, Inc. expired website, www.dawnsolar.com
ASI, American Solar, Inc., www.americansolar.com
Solex, http://www.solexenergy.co.uk/airheating.htm
Soltech Energy, www.soltechenergy.com/en/about-us
York Technical Guide Champion Series Single Package Heat Pumps 1HA036, 036-21311-001-A-1001, 2001