Laboratory Building Envelopes That Solar Heat And Cool

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Abstract

Laboratory buildings are recognized as one of the most energy intensive building types. Government organizations with a high proportion of laboratories typically have the highest energy intensity.

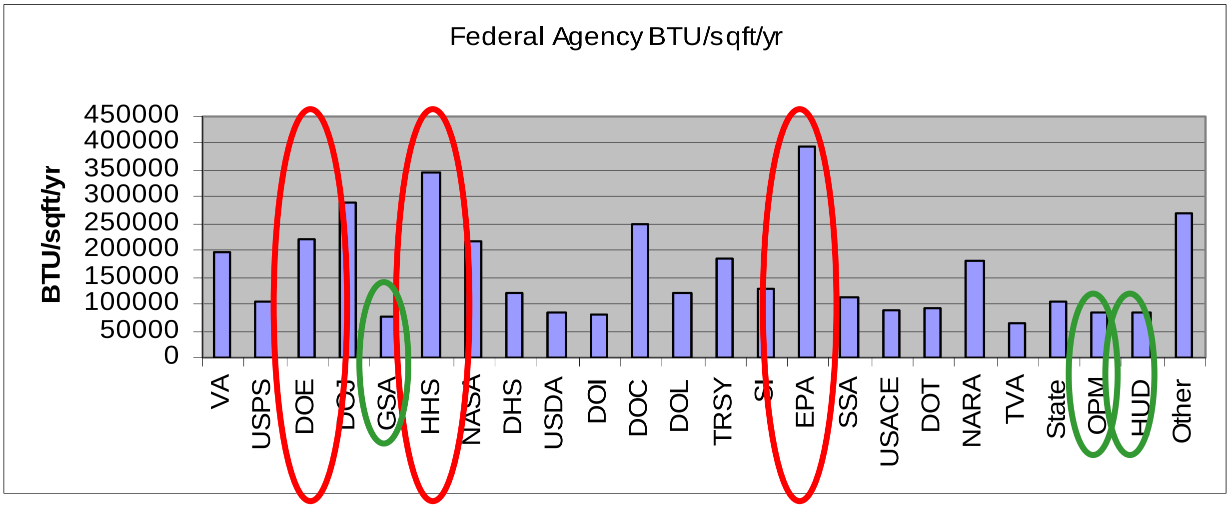
A significant portion of the laboratory energy use is for space heating and cooling due to high ventilation requirements. In the past several years, technologies have been developed that use the building envelope itself to intercept solar energy and generate useful heat and reduce the cooling load on the building. These solar building envelopes (roofs and walls) represent a largely untapped source of energy to reduce operating costs in laboratories.

This paper will; review the energy needs in laboratories, present several solar building envelope technologies that have been applied, and provide performance indicators of the most common technologies, and recommend principles for applying these technologies in new and existing laboratories.

Background

Energy use in buildings depends largely on the type of activity in the building. Across all common commercial and institutional building types, healthcare and food service tend to be high energy users, consuming roughly 200,000 BTU/sqft/yr with an energy cost of about $2/sqft/yr. However, many laboratory buildings have higher energy use than most common building types.

One indication of that is the average energy use in Federal agencies that are lab focused. This includes agencies such as the Department of Energy, Health and Human Services, and the Environmental Protection Agency. These agencies average about 300,000 Btu/sqft/year across their entire building stock. This is about 3 times higher than agencies such as the General Services Administration and Housing and Urban Development, which are predominantly housed in office buildings.



A closer look at particular agencies shows that the energy use across different lab complexes varies greatly. Within the Environmental Protection Agency, most complexes are above 200,000 BTU/sqft and several are between 300,000 and 650,000 BTU/sqft/yr. The USDA has several buildings above 400,000 BTU/sqft/yr and Health and Human Services has 4 buildings, which each have energy use between 1,200,000 and 1,500,000 BTU/sqft/yr.

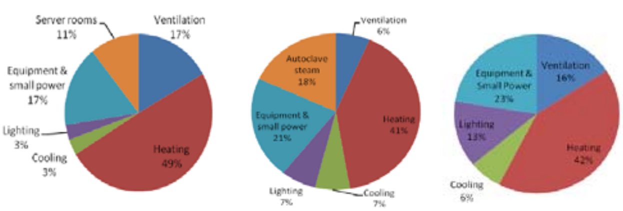
There are two common functions in these labs that drive high energy use. One is biological research, which includes: animal buildings (vivariums), plant buildings, and microbiology spaces. The second is inorganic research activities. In these spaces, the toxicology of the materials is a hazard to the researchers and occupants. While the materials being researched may not be toxic, the materials that support the research may introduce toxins. In many cases, the materials being assayed are unknown and levels of protection must be provided, to minimize the potential of toxicity.

Across both of these functions, and across different lab types, the solutions to minimize hazards are typically the same and rely on standard equipment that drives high energy use, particularly in HVAC and water heating. These high energy solutions include:

- Removing or diluting the hazardous vapors, dusts, or odors [HVAC]
- Maintaining comfortable temperatures and humidity for people [HVAC]
- Maintaining optimal temperatures and humidity for animals, plants, microbes and experiments [HVAC].
- Cleaning and Sanitizing [Hot water/Steam]

A study was recently completed of university biology and chemistry labs in Britain. The climate of those labs had between 5,000 and 6,000 heating degree days (65F base), which is roughly equivalent to US climate zone 4, for Boston, DC, and St. Louis. The labs had energy use between 200,000 and 310,000 BTU/sqft/yr and spent between $1.70 and $4.05/sqft/yr on energy.

The study found the between 54 and 69% of the energy consumed was for HVAC. The chart below shows the energy use for each of the 3 labs. In each lab, the largest individual component of energy use is the heating energy use.



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Heating, including space heating and hot water/steam heating, dominates laboratory energy use because:

1. There is a high outside air flow,
2. There are many hours of the year when outside air is below the temperatures required for proper HVAC,
3. Humidity, is often outside the comfort range and needs to be controlled, and
4. Water heating is required for sanitizing and cleaning

High outside air flow is required to carry away and dilute contaminants in the air. A typical lab may require about 6 air changes per hour, varying from 2.6 to 12. Building codes tend to drive outside air supply of 0.43 to 1.0 cubic foot per minute for every square foot of space. In comparison, an office might be 1/6th of that outside airflow.

With all that outdoor air moving into the lab, the temperature of the air drives heating or cooling energy use. In the ‘lower 48’ states in the US, the average outdoor air temperature is below 53 degrees F (53F). This is about 20F below comfort temperatures. In one specific city, Washington, DC, there are 4,700 hours below 55F and the weighted average temperature during the heating season is 37F. So, for labs in DC, a large volume of outdoor air, that is well below the comfort level for the occupants, is moved into the lab during the year. For labs requiring higher temperatures than are needed just for the comfort of the occupants, such as animal or plant labs, the outdoor air temperatures have an even greater effect on heating energy.

Humidity is another large driver in laboratories. In most labs the humidity issue is driven by a difference between the humidity of the outside air and the desired interior humidity level. In the winter the humidity is typically lower than desired, and in the summer it may be higher than required.

In winter, energy is required to evaporate water into the interior air to raise humidity levels. In summer, energy is required to condense excess humidity from the outside air entering the lab. In many locations in the eastern half of the US, the excess humidity in the outside air requires 5-6 times the energy to condense than the energy required to simply cool the dry air down to a target temperature. A typical air conditioning system will cool air down to ~55F in order to condense out excess humidity. However, the 55F air leaving the cooling coil will be too cold to introduce directly into the occupied spaces. One strategy used in many buildings is to mix the cold outdoor air with returning air from the occupied spaces to warm the cold dry air. However, in labs with a high percentage of outside air flow, the mixing strategy may not be sufficient to warm the cold dry air. In many labs, a reheat strategy is used, where boilers are used during the summer to supply heat to a reheat coil in the air handler to warm the cold, dry dehumidified air. Recent building design standards have eliminated many of the reheat practices that were allowed in the past but there are still some exceptions, including allowing reheat where the energy is from on-site solar heat.

One final driver of the heating load in laboratories is the water heating load. In addition to the normal domestic hot water load in all buildings, laboratories tend to have high cleaning and sanitizing hot water and steam loads. Simply supplying hot water for conventional cleaning of lab surfaces and experiments substantially raises the hot water demand compared to most commercial buildings. In large animal labs, hot washdown of the spaces is a significant hot water load. In small animal labs, cage washing can be a large energy expense.

In the British lab study mentioned above, the Edinburgh example is a cancer research lab. In that lab, 18% of the energy was for autoclave steam. For labs with a high sterilization need, including; heating the incoming water from city water temperature, boiling the water, raising the steam temperatures to 250-270F, and ultimately discharging the exhaust steam, often without heat recovery, is an energy intensive process.

How 'Hot' Are Lab Heating Needs?

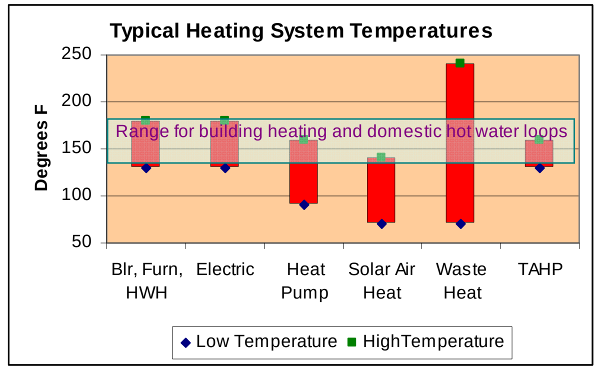
Lab heating needs are not as 'hot' as the common heating systems typically deliver. These common, primary heating systems, which include; boilers, water heaters, heat pumps and furnaces, typically deliver heat at ~90-180F, with steam boilers operating at ~250F. They deliver their heated air or water to serve space heating loads that require a finished temperature of about 75F and water heating loads that typically require about 140F.

Space heating air is typically no warmer than 75F. In large animal buildings, target temperatures are about 65F. If only freeze protection is required, then target temperatures are about 40F.

For water heating, 140F is typically required for domestic service and many hydronic heating services. Radiant floor heating only requires 80-90F. Hot water for HVAC reheat can be about 100F. The higher temperatures delivered from the heating equipment enables those systems to meet peak heating loads, (coldest day, highest hot water demand) with smaller components and to achieve high heat transfer rates across heat exchange surfaces with high temperature differences. However, the high temperatures require high energy fuels (natural gas, fuel oil, propane) or electric power and the expense that comes with using these energy sources.

Yet, for most hours of the year, the heating loads are far from the peak loads. Typical space heating loads on any given day are driven by the coldest air temperature for that day, that may be only 20-40 degrees colder than the ~75F desired, as opposed to 75-80 degrees colder on a peak heating day.

In reality, the heating loads occur across a range of temperatures, from the coldest temperatures of the air or water, to the target temperature of the end use (~75F space temp, ~140F water temp). For example, if 60F dry outdoor air is entering the HVAC system targeting 75F as a finished temperature, then heating the air starts with a heat source that can be anything warmer than about 65F and



stops at 75F. In another example, if 40F cold city water enters a domestic hot water system targeting 140F, the heating starts with any heat source warmer than about 45F. If that heat source takes the water up to a temperature of 120F, is will have done 80% of the heating required on the lowest temperature portion of the load. The finish heating to the target temperature can be done by another heating source (gas fired boiler, electric water heater, thermally assisted heat pump (TAHP), etc.), but only requiring 20% of the total heating energy.

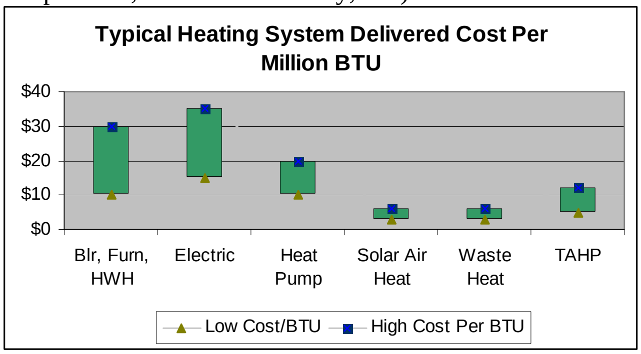
The objective is to do the heating for the lowest cost. That includes the capital cost of the heating systems, the operating cost for fuels and supplies, and the maintenance and repair cost.

What does all that heating and cooling energy use cost?

Consider, for a typical office building, that energy use for all needs would cost about $1-2/square foot per year. In contrast, energy use in a lab would cost about $3-6 per square foot per year. That energy expense is driven by the cost of the energy sources used to serve those loads. In general, the cost of those energy sources can range from $10 to $29 per million BTU of heating energy purchased from natural gas or electricity. The conversion of that raw energy source to delivered heat to the load is never 100% efficient. As a result, the heat delivered to the loads can be anywhere from about $12-40 per million BTU. The chart below shows some typical costs for heat from various energy sources.

There are some heating sources, such as solar and waste heat that can be delivered at much lower cost than heating by conventional fuels. The solar heat from building envelope systems (not PV or hot water panels, but air from walls and roofs) can be delivered at $3-$8 per million

BTU. Waste heat from equipment (boiler condensate, compressors, elevator machinery, etc.) or even waste heat from exhaust HVAC air on a cold day can also be very low cost to gather and deliver to a colder heating load. The thermally assisted heat pump (TAHP) supplied with solar heat from the building envelope can provide consistently high temperature heat at high efficiency and lower cost than conventional fossil and electric systems.



When these low cost sources are applied, even to the low temperature parts of the heating needs, they can reduce the heating required by the more expensive fossil fuel fired and electric heating sources. However, these sources are often overlooked because they add another heating system to the mix in the building. This adds more hours and dollars spent on the design and on the hardware than if a single fossil fuel or electric heating source were installed. In years past, when operating staffs needed more “hands on” participation to start and stop equipment, this added to the operating costs. However, with modern sensors and controls allowing ‘hands off’, automatic operation, the operating costs are minimal with only small power loads for fans or pumps. As a result, these low cost, building envelope heating sources can more than compensate for the up front capital or added operating expenses by cutting energy costs.

Building envelopes for heating and cooling

Traditional thinking about building envelopes is that they are there to provide weather protection and enclose a comfortable climate indoors despite uncomfortable weather outdoors. The envelope also provides structure to support the building against gravity, wind, snow, etc. It provides security and privacy for what’s inside. When done well, it adds to the appearance and value of the building. Lastly, it provides an enclosure to support the heating, cooling, lighting, and mechanical equipment that keeps the interior comfortable, safe, and productive. Traditionally, once the building envelope was designed, the mechanical systems would be designed inside the envelope to support the heating, cooling, etc.

That was the Traditional Concept, which was very utilitarian, where each piece was built for a separate purpose.

The Current Building Envelope Concept includes all of the traditional purposes, but includes several more recent goals, such as daylighting, solar harvesting and control, rainwater management, sustainability, energy and cost efficiency, and compliance with an abundance of new and evolving codes and ‘standards’.

With the roof as an envelope component, the durability of the material often influences the owner’s life cycle cost. For example, an asphalt roof, either shingles or built up roof, may have the lowest first cost, but 2 or more tear-offs and replacements during the comparable life of a metal roof will often make the metal roof less expensive for the owner. When energy, tax credits, and appearance benefits of the metal roof are considered, the metal roof may more than pay for itself over its life.

When we think about the nation wide building envelope market, we can think of $20-$30 billion spent on roofing alone with nearly $5 billion spent on 300 to 400 million square feet of metal roofing and siding. Compare that to the market of purchased energy which is $1.4 trillion per year in the US.

So how can we use the billions of square feet of installed roofing and siding to address the trillion dollar US energy expenses. One of the best uses of the building envelope is “Solar Heat Recovery”, which is the process of collecting solar heated air (or water) from the roof or walls of the building. Once the heat is collected, it is used for a variety of different air, water, and equipment heating purposes.

The primary reason to use solar heat recovery is simple, … the solar heat collected from the envelope can be the lowest cost source of heat available to the building and it targets the largest energy need in labs, which is heating. In addition, the solar heat collected, actively manages the roof temperature against the conditioned space. It also passively boosts the R-value of the roof, with both the solar air space and any added insulation increasing the insulating value of the solar roof. It also improves the humidity control in the roof air space by actively ventilating the space whenever it is warm and dry.

For building cooling, there are three ways to use the envelope. One method that is popularly described in many articles and voluntary design guides is to use “cool” roofing colors. These colors use special pigments that reflect some of the incoming solar radiation back into the atmosphere, reducing the solar energy absorbed and keeping the roof surface cooler. A second method is to move air under a roof, as is done with the solar air heat recovery system. This lowers the peak temperature below the roof surface by about 40F in the case of an air heating roof, reducing the cooling load on the building. A third method uses a combination of reflective insulation, thermal insulation, and air flow, all as parts of a solar air heating roof. This reduces the peak temperature below the roof surface by about 65F compared to a black membrane. This final approach actually results in a peak temperature below the solar roof being 10-20F cooler than the peak temperature experienced by a 'cool roof' membrane.

Solar Building Envelope Construction

Solar building envelopes are constructed the same way traditional building envelopes are constructed. In fact, they are the code approved, building envelope, constructed by the same roofing and siding contractors that install the hundreds of millions of square feet of metal roofing and siding, every year. There are no solar panels involved or covering the roof when the project is complete. There is no electricity produced from PV panels, or utility permission for interconnection to the electrical grid. Just solar heated air (or water) is produced, by the metal roof or wall and captured from the space below, or behind, the metal surface. The solar heated air is delivered by HVAC ducts and fans to the load.

The solar building envelope can be deployed in either new construction or retrofit. Since the majority of roofing done every year is retrofit of worn out roofing, the solar building envelope is more often installed in retrofit construction, where the need for a re-roof gives the building owner the opportunity to both improve the roofing and realize energy savings compared to other roofing options.

The figures below show three roofing retrofits.

One is a metal re-roof over a worn out metal roof, to provide heated air to an animal laboratory building. The second is new construction using a metal shake that has a less industrial appearance, which may be appropriate for buildings in a mixed use environment such as a college campus. The third shows a low slope metal roof on a building with mixed office and laboratory space. In all cases, the metal roof is attached to the existing roof or roof deck using manufacturer and code approved construction. Solar heated air is gathered from the air space below the metal roof panel, shake. The solar air is delivered to the outdoor air intakes of the building or used for air-to-water pre-heating or for equipment pre-heating.

Envelope and Mechanical System Integration

Of all the ways to collect solar energy, air heat recovery is usually the simplest and least expensive. There are no extensive piping systems, large tanks, high voltage wiring, utility interconnections, roofing penetrations for solar panel mounts, etc. The solar air heat recovery involves the collection of solar heated air from one or more locations. Where the air is collected, ... how much and where it is delivered, … and what it heats, are all routine mechanical design questions that are easily determined using standard HVAC engineering methods.

A few techniques and rules of thumb are helpful in the early stages of the assessment and design. As a starting point, determine if there is a sizeable "low temperature portion of the heating load" that can be served by solar heat. Determine if there is adequate solar resource at the site to provide a significant amount of solar heat. That includes a review of the timing of the solar heat delivery to the heating demand in the building. In general large heat storage systems are not as economical as simply using the heat when it is available and letting the traditional heating systems handle the load when solar heat is not available. One obvious energy demand in labs, that minimizes this timing concern by its nearly continuous demand, is the outdoor ventilation pre-heating load during the heating season. A third issue to evaluate is how difficult and expensive will it be to move the solar heated air to the heating load that will be served. A solar roof on a high rise building with a heating load in a distant, basement mechanical room will be more expensive to serve than a single story animal lab with outdoor ventilation intakes in the attic space under the solar roof. Finally, consider the temperatures of the solar heated air and the load. Solar air temperatures vary during the day and load temperatures vary, daily or seasonally. A simple 8,760 hours analysis using local weather files can indicate the hours when solar will contribute to the load. Such an analysis can be helpful, even as an early approximation of the expected solar energy delivery.

Economics of Lab Solar Building Envelopes

When considering a solar building envelope, the most important question to answer is, 'Do the solar roof/wall savings justify the added expense of the system?' As a rule of thumb consider $4-6 per square foot of roof as a starting point for solar heat recovery from an existing wall or roof. For a solar re-roof consider $12-20 depending on the complexity. However, when a re-roof is involved, the new roof value needs to be considered in the economic evaluation. The solar metal roof will last twice as long as a membrane, or asphalt roof. The life cycle 'roofing' savings of the solar roof are typically greater than the alternative roof systems, even when energy savings are not counted.

Energy cost savings vary depending on energy use and the cost of the energy source being displaced by solar heat. Electric resistance and fuel oil heating are often the most expensive source of heat. Natural gas and heat pumps are lower cost heating systems. With an 8,760 hour analysis and knowledge of energy cost and loads in the building, hourly savings can be estimated. The graph below shows projected savings from an 8,760 hour analysis for a thermally assisted heat pump drawing solar air from below the roof in the attic. The high temperature air-to-water heat pump provides domestic water heating to a 120F piping loop and pre-cooling outside air in the cooling season. The same solar ducts and fans deliver solar air to preheat outdoor air in the heating season. The hourly energy savings of each load (domestic hot water, air pre-cool, or pre-heat) times the utility costs for gas heat or electric cooling gives the cost savings for each hour.

During the earliest stages of a building assessment, where an 8,760 hour analysis is not appropriate, or energy costs are undefined, more generalized rules of thumb can be applied based on monthly or annual solar energy delivery. Solar savings can be as high as $4 per square foot of roof per year in the cases with the highest cost heating sources. However, in many buildings, the mismatch in timing of the solar availability and energy demand, or the fact that the large roof area my produce more heat than is needed by the building suggests that, about $0.30 to $1.00 per square foot roof per year in energy savings are reasonable numbers to estimate in the earliest stages of a building assessment. Cooling energy savings are slightly higher than that of a "cool" metal or membrane roof, which are estimated to save $0.005 square foot of roof per year in cold climates and $0.14 per square foot of roof per year in warm California climates. Roofing savings, where a retrofit solar roof is to be installed instead of a membrane or asphalt built up or shingle roof, can be estimated at about $0.05 to $0.25 per square foot of roof per year.

Summary

Laboratory energy use is higher than for most building types and is typically driven by the heating needs of the high outdoor air flow into the building. The solar heating and cooling envelope provides a source of low cost renewable heat to reduce the cost of fossil and electric heat. It can also reduce the cooling load in summer by reducing the heat transfer from the wall or roof to the building interior.

When the solar heating, cooling, and the roofing savings are combined, the system more than pays for the added capital and minor operating costs. In fact, the energy savings can more than pay for the cost of the re-roof, which can not be said for other long life roofing systems.

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