AB-10-XXX

Solar Cooling with Concentrators

Sargon Ishaya, PE
Member ASHRAE

ABSTRACT

The aim of this report is to introduce the concept of cooling with concentrating solar panels (CSP) and compare solar cooling via CSP with photo-voltaic (PV) systems.

CSP harnesses a much larger portion of the sun's energy than PV systems do; however, CSP drives the absorption refrigeration cycle while PV can drive vapor compression cycles with a higher coefficient of performance (COP). Comparing the combined efficiencies of solar harnessing and coefficient of performance, both CSP and PV become virtually equivalent from a solar cooling perspective. The balance tips in favor of CSP systems due to its many advantages over PV systems such as cost per ton, energy payback time, and recyclability at the end of panel life. PV systems have the advantage of an essentially free storage system (the public utility grid); however, solar cooling systems' economics dictate that they only be sized for transient peak loads and storage is not a significant advantage when that factor is taken into account.

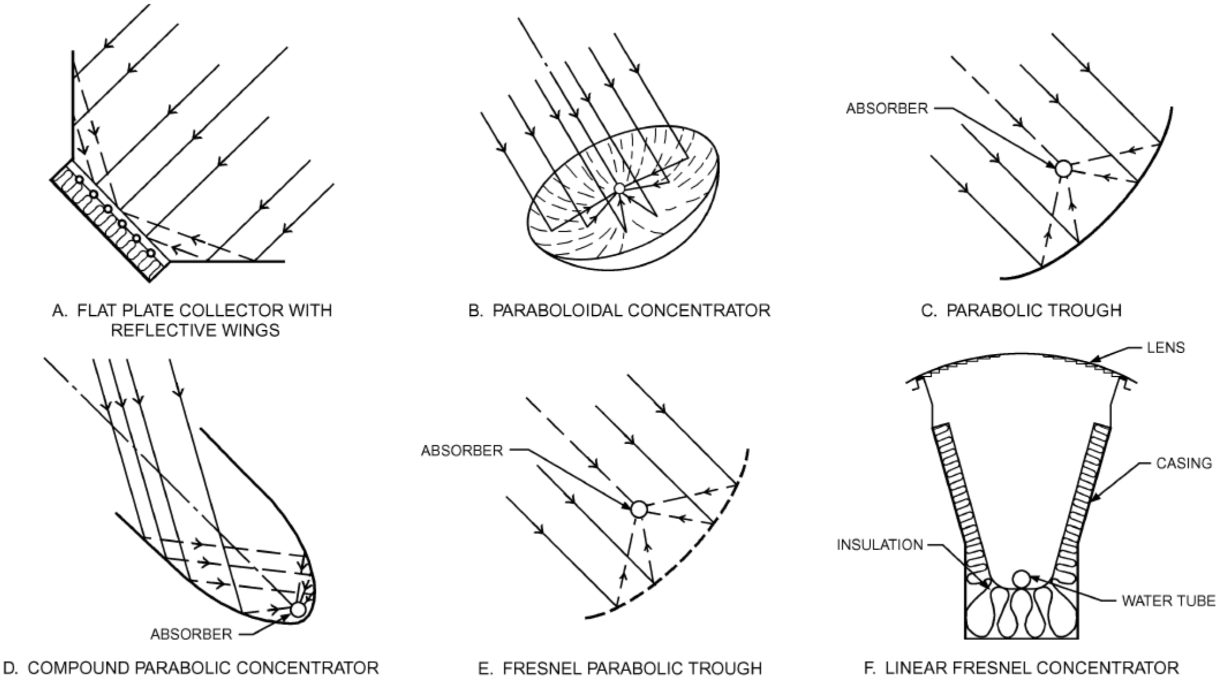
INTRODUCTION

The ASHRAE handbooks have included descriptions on various concentrating solar collectors for many years[i]. Concentrating solar collectors take sunlight and focus it by ways of mirrors or lenses on to a receiver as shown in Figure 1 below. Concentrating sunlight in this manner helps solar-thermal systems reach much higher temperatures or, in the case of photo-voltaic systems, harness the same amount of solar energy with much less silicon.

When sunlight is harnessed and converted to heat by way of a concentrator it can provide the thermal energy necessary to drive absorption chillers. Recall that the absorption refrigeration cycle is driven by heat rather than an electrical compressor as in the vapor-compression cycle. When the heat comes from the sun by means of a solar concentrator, then the cooling effect is essentially a free commodity that comes from the environment just like an airside economizer.

Sargon Ishaya, PE, LEED AP is Vice-President of HVAC Applications for Chromasun and an assistant professor in the Department of Mechanical Engineering, San Jose State University, San Jose, California.

A photo-voltaic panel generates electricity from sunlight; therefore, the cooling effect from a vapor-compression chiller driven by PV panels is also a free commodity. Is there an advantage on a building rooftop to using solar-thermal flat panels in lieu of photo-voltaic panels to get free cooling? This report will answer that question through a comparison describing the advantages and disadvantages of each approach.



A. FLAT PLATE COLLECTOR WITH REFLECTIVE WINGS

B. PARABOLOIDAL CONCENTRATOR

C. PARABOLIC TROUGH

D. COMPOUND PARABOLIC CONCENTRATOR

E. FRESNEL PARABOLIC TROUGH

F. LINEAR FRESNEL CONCENTRATOR

Figure 1: Samples of Solar Concentrators (2007 ASHRAE Applications, page 33.9)

RULES OF THUMB ON APPLYING GREEN TECHNOLOGIES

Designing and applying green technologies to building systems is different than engineering a conventional system. Comparing rooftop solar cooling methods requires a familiarity with how to evaluate and implement green technologies. The following sections describe some of the general concepts that will be used later in the report to evaluate solar cooling methods.

Base Loads and Transient Building Loads

When applying a green technology it is important to understand whether the load that it satisfies is a base load or a transient load. A base load of a building is a load that is relatively constant over time. The lobby and corridor lighting in a large hotel is a good example of a base load because these areas must always be lit without respect to the time of day or season of the year.

A transient load of a building is a load that varies based on the time of day or season of the year. The utilities required to operate the primary restaurant in a large hotel vary based on transient loads. For example, the restaurant probably closes at or around midnight and doesn’t open until morning. When the restaurant is closed it will not require any water, lighting, natural gas, or electricity.

Base and Transient Commodities

It is possible to harness commodities like electricity, cooling, heating, and water (to name a few) through green technologies without any variance based on the time of day or seasons of the year. A green commodity that is harnessed continuously is defined as a base commodity in this report. An excellent example of a base commodity is electricity generated from a fuel cell. Fuel cells for buildings typically use natural gas in a low emission, non combustion process to produce electricity. The natural gas from the public utility is always available; therefore, the electricity generated from a fuel cell is a base commodity.

When harnessing a green commodity is a function of the time of day or seasons of the year, then it is defined as a transient commodity in this report. An example of a transient commodity is rainwater harvested for reuse in a building or on site. Obviously rainwater is not continually available so it is a transient commodity.

Correlation, Utilization, and Payback

Unfortunately for sales engineers in the air-conditioning industry a majority of projects are analyzed using simple payback periods rather than net present values. While the author prefers net present values, payback will be referred to when discussing financial analyses in order to avoid any contention regarding the discount rates associated with net present value calculations. In order to minimize the payback period of any green building technology it is vital to take two factors into account: correlation and utilization.

Correlation. In this report correlation refers to how closely the availability of a green commodity tracks the building load that it satisfies. For base commodities satisfying base loads the correlation is 100%. It is rare to find this kind of correlation with transient commodities satisfying transient loads. One uncommon case where this could occur is waste heat (green commodity) from restaurant cooking equipment used to temper the makeup air (building load) for the grease hoods in a ski lodge. This assumes that the ski lodge is located in a cold environment and the makeup air will therefore always require heating.

Utilization. In this report utilization refers to how much a piece of equipment within a system is actually used to satisfy a building load. This is a much more important number when analyzing transient commodities and loads because it drives system sizing.

Payback Periods. There are two important design strategies to achieving the most attractive payback periods when applying green technologies to building systems. The first is to identify which building loads and green commodities are closely correlated. The ramification of this strategy is to use base commodities for base loads and transient commodities for transient loads.

Let’s look at an elementary school classroom as an example of how correlation can minimize payback. Assuming that the elementary school is only open during the day it makes sense to install windows, sidelights and skylights with daylighting controls. The room lighting is a transient load, sunlight is a transient commodity, and the correlation is nearly 100% since the school is only open during the day. Due to the high correlation the electrical infrastructure for lighting this room can be decreased in size to account for the daylighting component. Note how the correlation strategy minimizes the payback for the added glazing.

The second strategy to minimizing payback involves sizing the most expensive components of a green technology system such that the utilization is as high as possible (preferably 100%). For example, the most expensive component of a ground-source heat pump system is typically the underground piping which can greatly increase the cost compared to a conventional heat pump system. Adding a thermal storage component can potentially decrease the amount of underground piping and in turn drive up the utilization. If the thermal storage component is a minimal cost increase compared to the savings realized by making the underground piping network smaller, then this utilization strategy will help minimize the payback.

HARNESSING THE SUN FOR BUILDING LOADS

What is the best use of the sun for green technologies? Recalling the definitions and concepts described above, first note that the sun is a transient commodity. Transient commodities correlate closely with transient loads and minimizing payback stipulates a close correlation between commodities and loads. The next question is which building loads track most closely with sunlight? Fortunately for air conditioning engineers most buildings across the globe have one particular load that has a very close correlation with sunlight - the cooling load.

Solar Cooling

There are many ways to implement solar cooling for buildings, but for the purposes of this discussion the methods will be limited to rooftop panels that harness sunlight for use with water-cooled chiller systems. The rooftop panel constraint makes sense because typical buildings do not have other large areas freely available for panels. The water-cooled chiller constraint is reasonable because they constitute one of the most common energy efficient refrigeration systems used for cooling buildings. It is economically advantageous to limit the size of a solar cooling system by coupling it with an efficient refrigeration system. Another reason to consider only water-cooled chiller plants is that they usually implement multiple chillers and this is almost always a requirement for a solar cooling system because something has to cool the building when the sun is not available. The two solar cooling methods for comparison in this report are via photo-voltaic panels (PV) and concentrating solar-thermal panels (CSP). The major system components of a PV solar cooling system are shown in Figure 2 below and Figure 3 shows the components of a CSP solar cooling system.

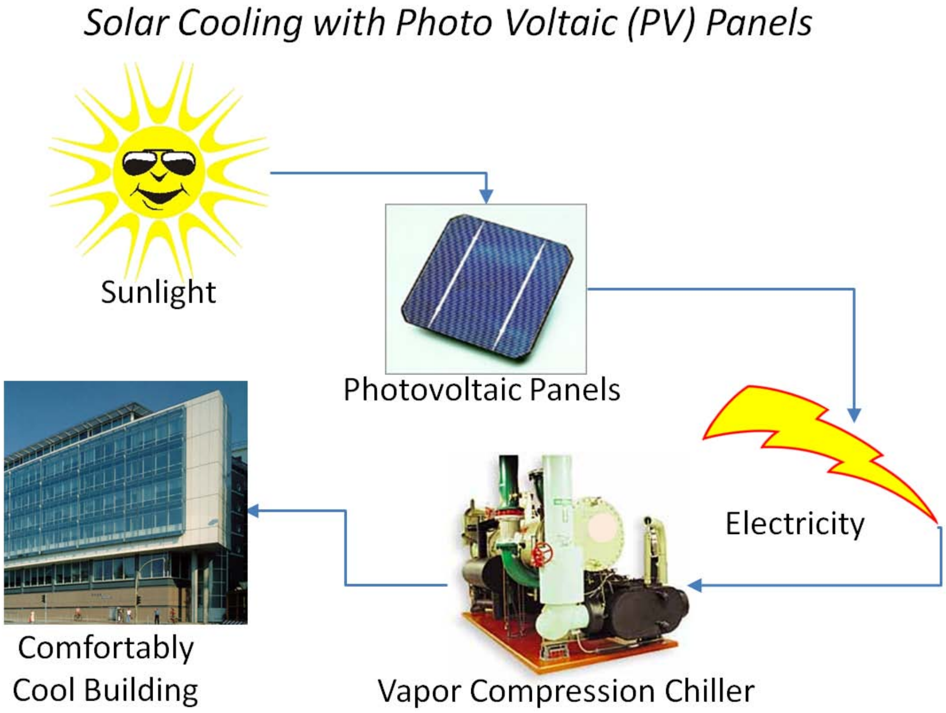


Figure 2: Photo Voltaic Solar Cooling Schematic

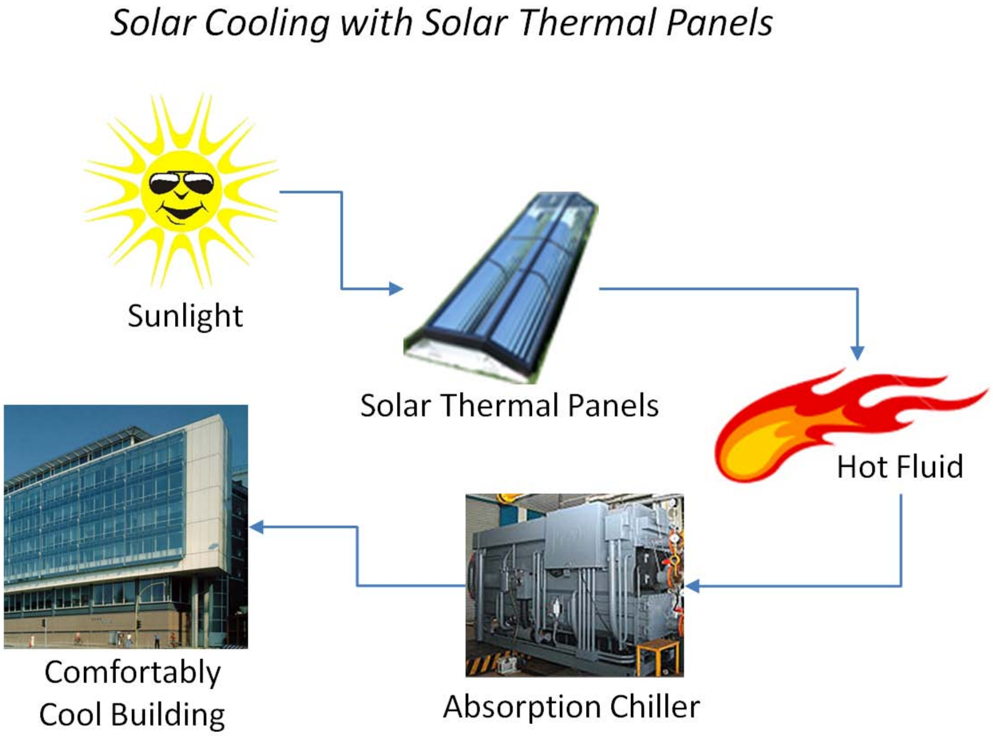


Figure 3: Concentrating Panel Solar Cooling Schematic

Panel Utilization

One of the first apparent problems with solar cooling is the fact that it only works when the sun is out. Most buildings still have cooling loads at night or on cloudy days. Note that solar panels, whether PV or CSP, are by far the most expensive components in solar cooling systems. In order to maintain high utilization, the solar cooling system should generally be sized only for the solar component of the building cooling load. The other loads will need to be satisfied by conventional systems or airside economizers.

Sometimes the panels will harness sunlight when there is no cooling load (airside economizing). This does not adversely affect panel utilization. In a PV system the electricity generated will be used to offset other building electrical loads. In a CSP system the heat generated will be used to offset building heating loads during these periods.

COMPARISON BETWEEN PV AND CSP SOLAR COOLING

In comparing PV and CSP solar cooling systems it is important to note that every building, installation, and locale will have its own set of challenges and costs. The comparison below is robust, but it needs to be analyzed and repeated on a case-by-case basis before making a decision regarding any specific projects.

Solar Cooling Efficiency

To help compare the two methods from an efficiency standpoint it is necessary to define one more term called the solar cooling efficiency (SCE).

$$\mathrm{SCE} = \text{Solar Panel Efficiency} * \text{Chiller COP} \qquad (1)$$

The solar panel efficiency for a decent PV system is 15%. For a flat-plate solar-thermal collector the efficiency rises to 50% and for a Frensel concentrating flat-plate collector the efficiency is upwards of 65%. Assuming that COP= 5 for vapor-compression, COP=0.7 for single-effect absorption, and COP=1.3 for double-effect absorption, the Solar Cooling Efficiencies become:

1. SCE_{PV} = 75%
2. $\mathrm{SCE}_{\text{Flat Plate}}$ = 35%
3. $\mathrm{SCE}_{\text{Fresnel Concentrator}}$ = 85%

The flat plate collectors perform so poorly due to the single-effect absorption chillers that they will no longer be considered in this discussion as a viable alternative. What remains are PV panels and flat plate Fresnel CSP systems

Roof Area

The roof area required for PV solar cooling including service access requirements is 66 square feet (6.1 square meters) per ton and CSP requires 62 square feet (5.75 square meters) per ton. The slight difference is due to the small discrepancy between the SCE of each system, but for the purposes of this discussion they are equivalent. The important point to note is that a solar cooling system has the potential to satisfy several floors of a building even if the available roof area is significantly less than the total roof area.

First Cost

First costs are high for each system and vary considerably depending on the type of building. The author has analyzed and estimated several systems in the San Francisco Bay Area and a 100-ton system will cost approximately $6,300 per ton for PV and $5,200 per ton for CSP. These costs do not include the chiller or tower infrastructure because the assumption is that the same quantity and size of chiller plant components will be installed regardless of whether or not a solar cooling system is implemented for the building. In plants of 200-tons and less this assumption should not be made; rather, the entire cooling plant needs to be priced up and compared for each option.

Most people will balk at these numbers; however, they do not include any federal or state incentives and they do not take into account the energy savings over the life of the system. In an optimal correlation scenario (high outside air loads) the simple payback can drop to below four years in Northern California once the incentives are taken into account.

Energy Payback Time (EPBT)

The EPBT is the energy required to manufacture a panel divided by it’s annual output. This is not related to cost in dollars; rather, it is a measure of the cost on the environment to build the panel. The EPBT for a PV panel is very high due to the manufacturing processes involving silicon. One detailed study puts this figure at about 7 years[ii]. CSP panels are mainly glass, aluminum, and stainless steel which put their EPBT about one order of magnitude lower at 0.7 years.

Recyclability

This is another measure of environmental cost only it deals with the end of a panel’s useful life rather than its beginning. In 2009 the Silicon Valley Toxics Coalition published ***Toward a Just and Sustainable Solar Energy Industry*** which states that “the most widely used solar PV panels...have the potential to create a huge new wave of electronic waste (e-waste) at the end of their useful lives...new solar PV technologies are increasing cell efficiency and lowering costs, but many of these use extremely toxic materials or materials with unknown health and environmental risks.” The only portions of a CSP panel that are not 100% recyclable are the sealing gaskets at the glass and metal interfaces as well as some black paint used on the 5/8” diameter receiver pipe to increase emissivity. This represents less than 1% of a CSP panel’s total mass.

Storage

The distinct advantage that a PV system has over a CSP system is the fact that storage is free if the public utility allows feed-in tariffs. Most public utilities have feed-in tariffs and this is essentially a free storage system for PV systems that maintains their utilization at 100%. CSP systems do not have free storage systems unless they are implemented in large campuses where they could potentially feed the loop to other buildings with any excess chilled water.

This point is somewhat moot for solar panel arrays sized for the solar component of the building cooling load as advocated above. A system sized for the solar load will have minimal excess that can be used for storage.

PROS AND CONS OF SOLAR COOLING

Advantages

Real Estate. From the window seat on a plane flying in or out of any metropolitan airport one can see the vast expanse of open roof areas on buildings. Since real estate is indeed a commodity anywhere in the world, then why waste so much of the rooftop of a building? Rooftop solar cooling will not only alleviate a significant portion of the cooling load, but the panels also serve to insulate the roof from sunlight that leads to building heat gain and faster deterioration of the roof envelope.

Sustainability. The environment is capable of fully satisfying the cooling load of a building in many climates around the world. When the ambient air is cold enough, then an airside economizer is the typical strategy by which a building is cooled by the environment. What happens when the outside air is not cold enough? Fortunately for the case of solar cooling, the outside air is often too warm to cool a building at the same time that the sun is shining. Coupling airside economizers with solar cooling can lead to offsetting 100% of the refrigeration load by the environment.

An hourly analysis of annual weather data from San Jose, California is shown in Figure 4 below. The green line charts the hours per year that the outside air is cool enough to satisfy the entire cooling load. The blue line depicts the added hours achieved when the outside air is cool enough or there is direct normal insolation available. Direct normal insolation (DNI) refers to direct sunlight as opposed to diffuse sunlight that reaches the earth on a cloudy day. Note how a building with a supply air temperature setpoint of 60°F (15°C) will be cooled by airside economizers for almost 45% of the entire year. Adding the DNI component (solar cooling) to the system has the potential to cool the building for almost 95% of the year. A sustainable building engineer should implement solar cooling in many climates to remove the refrigeration load from the air conditioning system.

Note the priority for cooling in Figure 4 is via the airside economizers. For this reason there are hours when DNI is available, but it is not needed for cooling. During these hours the CSP system has the potential to alleviate the heating load of the building. These hours are depicted by the red line on the graph and note that for the case where the supply air temperature setpoint is 60°F (15°C), the heating load of the building is offset for almost 25% of the year.

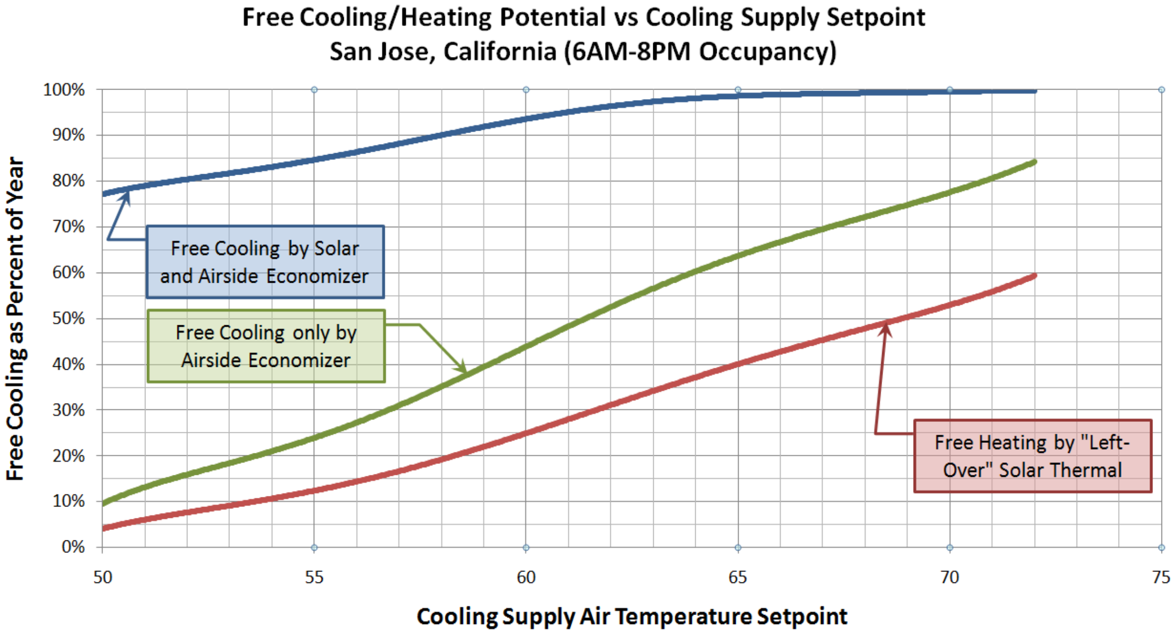


Figure 4: Sample of Environmental Refrigeration Offset Potential

Disadvantages

Cost. For many applications both CSP and PV solar cooling technologies do not have favorable payback or net present values without government incentives. Whether it is good for government to subsidize these technologies in lieu of something else or alternatively not spend taxpayer money at all is a question that is beyond the reach of this paper. It is at least fair to say it is a challenge in many applications for solar cooling to "stand on its own two feet" at the present time.

Unproven Reliability = Added Risk. Solar concentrating is not a new concept nor is double-effect absorption refrigeration. Despite these facts, there are no installed systems around the world where the two technologies have complemented each other over a long period of time. In most cases the economics of double-effect absorption chillers dictate that the system be larger than 100-tons. For many prospective developers who would like to try this system the risk associated with these larger sizes is an additional obstacle to overcome.

CONCLUSIONS

Solar cooling literally has a bright future and the good news for air conditioning engineers is that CSP systems have many advantages over PV systems. The growing popularity of sustainable building design behooves engineers to explore solar cooling because it is a very viable and robust option in most climates across the world. As with any green technology applied to a building, it is vital to understand and design solar cooling to optimize payback in order to help bring the system to market.

REFERENCES

---

[i] ASHRAE. 2007. ASHRAE Handbook-Applications. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Chapter 33.

[ii] Blakers, A., and K. Weber. 2000. The Energy Intensity of Photo-voltaic Systems. Engineering Department, Australian National University.