Thin- Film Photovoltaics and Their Impact on a Commercial Building's Cooling Load

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Abstract

A white reflective roof can significantly reduce the cooling load placed on a commercial building by reducing the solar heat gain. When a thin-film amorphous silicon photovoltaic system is installed on such a roof, 85% or more of the roof surface may be covered with a product that can have a lower solar reflectance than the roof surface. Using United Solar Ovonics' *UNI-SOLAR*® product as an example, the rated solar reflectance coefficient is 0.26. The lower reflectance value results in a higher solar heat gain, and creates a "penalty" in the cooling load of an otherwise cooler roof. However, the photovoltaic system is itself converting solar energy into electricity.

Using the DOE Low Slope Roof Calculator, and the PV Watts calculator from the National Renewable Energy Laboratory, several scenarios were used to calculate the cooling load penalty.

Calculations performed on buildings in other cities with 2006 IECC insulation levels and realistic air conditioner COP values, showed that the thermal cooling energy penalty is less than 2.5%. This suggests that a building-integrated thin film photovoltaic system can generate a significant net gain of electricity, even while powering air conditioners and other energy loads in new commercial low slope roofed buildings without a significant penalty to the cool roofing performance.

Background

The Energy Independence and Security Act of 2007 authorized the formation of the Zero Net Energy Commercial Buildings Initiative. The Initiative is an alliance of industrial, academic and government representatives working to transform energy performance in commercial buildings. Sponsors include DOE, ASHRAE, AIA, USGBC, The World Business Council for Sustainable Development, LBNL, and the Alliance to Save Energy.

The California Public Utility Commission recently announced a challenge to builders to construct all new commercial structures to be net zero energy by 2030. For such a challenge to be met, significant conservation of energy and improvements to energy efficiency will be required. But also, renewable energy sources like thin-film photovoltaic (PV) systems will be necessary to generate on-site electricity.

In the 2008 California Building Energy Efficiency Standards, building-integrated photovoltaic panels are exempt from the minimum prescriptive requirements for solar reflectance and thermal emittance. This is a sensible exception to the cool roof provisions. Similarly, in the draft language of ASHRAE 189.p.1 Standard for the Design of High Performance Green Buildings Except Low-Rise Residential Buildings, the area of a roof covered by a PV system is exempt from the SRI criteria for the roof. These are positive developments for the use of PV systems.

Other states such as MA, NV, NJ and NM have passed legislation or are seriously considering legislation that would require the construction of net-zero energy buildings. The use of building-integrated thin film PV modules will play an integral role in any zero energy building initiative.

Introduction

Photovoltaic roof systems are a passive renewable energy source for converting sunlight into electricity. The generation of electricity from photovoltaic effect based technology is possible through the interaction of sunlight with certain “doped” semi-conductor materials. Electrons are released from these materials resulting in a current. That direct current is then converted to alternating current with an inverter, and provides electricity to power the building. The most prevalent material used in the production of photovoltaic arrays is silicon. The basic building block of PV technology is called the “solar cell”. (1)

There are two primary types of cells within silicon based PV systems: Crystalline (mono and poly) and Amorphous. Crystalline PV systems currently represent 80% of the market. The crystalline PV wafers are typically 0.2-0.4 millimeters thick. However, once packaged in metal and glass they are approximately 0.25-1 inches in total thickness, and require 20 kg of silicon per 1 kW of PV. An electricity conversion efficiency of 15-20% is typical. (2) Crystalline PV is rigid and brittle and must be housed sufficiently to maintain its single crystal nature or simply not shatter.

Conventional crystalline silicon PV cells are connected to form a PV module and many modules are linked together to form a PV array. The modules consist of an assembly of silicon wafers sandwiched between two layers of glass in a metallic frame. These panels are relatively heavy but can be mounted to metal roofing with a special fastening device that does not penetrate the roof surface, while other fastening devices do. A typical four-inch silicon solar cell can produce about one watt of direct current electricity. (3)

An alternative to crystalline silicon PV modules is thin-film amorphous silicon products. The thin-film PV layers are less than 2 microns thick (0.12 inches thick with a fully encapsulated module), and are flexible and semi-transparent. These systems *use 0.067 kg of silicon per kW.* Amorphous silicon is deposited from silane gas, SiH_4; therefore it is not subject to the polysilicon shortage in the crystalline PV industry. Amorphous silicon products with multi-junction cells are the typical composition of thin film PV products. They are produced by depositing films of doped silicon-germanium alloys to a thin sheet of stainless steel and then encapsulating them with a flexible but highly light transmissive top-layer. The PV material is then laminated to the flat pan section of a standing seam metal roof surface. One such product is produced by United Solar Ovonics and sold under the trademark UNI-SOLAR®. (2)

In general, thin-film amorphous silicon laminated PV modules reflect about 26% of incoming solar energy (i.e. solar reflectance [SR] = 0.26). Only about 6.5% of total solar energy that strikes the surface is converted into electricity. Since the converted energy is not absorbed, but photo-electrically converted, it can be considered (in a thermal sense) part of an “effective solar reflectance” of 32.5% (SRe 0.325). In other words, from a thermal perspective, a thin film PV system is similar to a cool roof surface with solar reflectance of approximately 0.30.

In heating-dominated climates a thin film PV system is well suited for integration into a metal roof design. (4) However, in cooling dominated climates, building owners sometimes question the thin-film PV product’s ability to generate enough power to compensate for the added air conditioning load resulting from a higher solar heat gain into the building. That higher solar heat gain is due to a relatively dark colored PV surface with a lower solar reflectance value.

This paper looks at new commercial roofing applications for thin-film PV systems and evaluates the energy generated by the PV modules in contrast to the additional cooling load that the entire PV system thermally imparts to the roof. Research on this specific topic appears to be limited. Using available tools, calculators, and data, we have determined that any penalty resulting from the UNI-SOLAR laminated PV system is minimal.

Photovoltaic Power Generation

The actual net power balance generated by an installed PV system is affected by the overall integrity of the roof, the size and efficiency of the PV system, the local climate conditions (driving total solar irradiance), and the wind conditions. When a thin-film PV system is installed over a very light colored roof (higher SR), there will be an added cooling load due the darker color of the PV surface and lower solar reflectance compared to the high-reflectance roof. However, when installed over a dark colored roof, the PV system will actually improve the thermal performance of the roof by providing a higher solar reflectance over the PV system's covered area. When installing a thin-film PV product over a painted metal roof surface, the thermal emittance (TE) of both surfaces may be similar. A palette of colors such as Champagne, Brown, Dark Bronze, Green, Blue, Terra Cotta, and Charcoal Gray are available as "cool" paint systems commonly used for steep slope metal roofing. [(5)]

Thin-film amorphous silicon PV cells offer outstanding power generation characteristics at higher temperatures. Multi-junction amorphous silicon PV cells collect more efficiently during low-light (diffuse) conditions. Each amorphous silicon layer in a multi-junction cell is "doped" to absorb red, green, or blue light and layered accordingly within the cell. The nature of this thin-film PV structure means their specific angle of inclination has much less effect on the generated output than crystalline PV. As a result, amorphous silicon PV modules can generate more power per annum than crystalline PV modules of identical rated output [(6, 7)].

In addition, the content of the solar spectrum can change continuously as the climate conditions change. Since amorphous silicon thin-film PV systems produce more energy under low light levels (compared to crystalline silicon modules) and are more efficient for greater amounts of time under variable spectrums of light, they generate more actual power per (installed) watt. They also retain their efficiency twice as well as crystalline silicon PV modules at elevated temperatures. This means more actual power is being generated during peak sun hours when the surface temperature is above ambient.

The Energie Centrum Nederland (ECN) laboratory in Europe has found that some amorphous silicon thin film cells can be up to 40% more efficient than other crystalline silicon PV products when light levels are less than ¼ suns. Since amorphous silicon thin-film PV products lose half as much voltage, per degree of temperature increase, as compared to a crystalline silicon solar cell[(8)] , this means electricity is being generated for more hours per day than crystalline silicon technologies allow. The UNI-SOLAR thin-film PV product uses a proprietary Triple Junction color cell technology. Each cell is composed of three semiconductor junctions, connecting different doped amorphous silicon-germanium alloys, stacked on top of each other to match the colors of light and their indexes of refraction. Each doped amorphous silicon junction preferentially absorbs different colors of the visible light spectrum. The bottom cell absorbs red light, the middle cell absorbs green/yellow light and the top cell absorbs the blue light. The ability to wavelength-tune photovoltaic layers, essentially multiplexing, in the sun's spectrum is one of the keys to the improved efficiencies and higher energy output, for more hours of the day (even during low or diffuse light conditions), of amorphous silicon thin-film PV products. In the future, micro and nanocrystalline silicon will be merged with amorphous thin films at UNI-SOLAR, promising a wider photo-conversion spectrum and even higher efficiencies.

United Solar Ovonics states that most (66%) of the heat that builds up at the surface of their thin-film PV modules can be dissipated through convective cooling from wind. The high thermal emissive surface (0.87) of the PV modules allows for radiative losses to the night sky which can account for another 33% of the heat loss. [9]

The best markets for thin-film PV include well insulated buildings and new buildings that are already energy efficient. In those types of structures PV laminates would have the least thermal impact. A building-integrated PV system would also be beneficial for re-roofing projects where insulation is brought up to or in excess of code, HVAC equipment is improved, and/or lighting efficiencies were increased.

Power Ratings

The actual energy yields of PV systems can not be determined strictly on the nominal rated power of a module. The peak power performance labels on PV modules are based on controlled testing that is done under standard testing conditions (STC). These conditions include holding the module temperature constant at 25º C, irradiating the surface with one type of solar spectrum, and then irradiating the surface directly at 1000 W/m^2. However, in actual installations, PV module temperatures can be much higher (in the range of 40-60º C), and receive solar irradiance of 1000 W/m^2 less than 1% of the time. [7]

The PVUSA Test Conditions (PTC) represent more realistic conditions. PTC are defined as 45°C (113°F) cell temperature, 1000 W/m^2 solar irradiance, and 1 m/s wind speed. This test was developed in an attempt to simulate what happens in a real-world outdoor installation. Usually, the PTC rating for a PV panel is between 70% and 85% of the STC rating. The reason that the PV panels produce less power under these conditions has to do with the material properties of the PV modules. As stated previously, amorphous silicon PV have about half the power loss per degree of temperature increase, as compared to crystalline silicon PV technology. On a hot sunny day with a 40^o above ambient surface temperature, this translates into more power for the amorphous thin film customer.

DOE Low Slope Roof Calculator

The DOE Low Slope Cool Roof Calculator was used to evaluate the impact of the "darker" thin-film amorphous silicon photovoltaic systems on the heat gain into a building. The calculator allows one to compare the cooling energy and cooling loads of a building with a roof of interest to that of a building with a black roof as the reference in any location. [10]

To determine a worst case condition, or the greatest anticipated cooling load encountered, we chose Phoenix as the location because of the high solar radiance levels. We also used an R-5 level of roof insulation, recognizing that this level is well below code for the required R-value. Another assumption for the worst case calculation was that the air conditioner unit has a COP of 2.0. Again, this is lower than what is commonly installed as new air conditioning units [12, 13].

Starting with a low-slope white roof as the ideal case for a cool roof (i.e. lowest cooling load to the building) compared to a black roof, we input the initial solar reflectance of 0.70 and initial thermal emittance of 0.90 into the calculations. We also calculate the cooling load for a roof that is covered 100% with a thin-film PV, using an effective solar reflectance of 0.30 and thermal emittance of 0.90.

The results from the DOE calculator compare both types of roofs to a black roof. The values below indicate the effect of the different solar reflectance values on the cooling load.

	Cooling Load (BTU/ft²/yr)		
	black reference	Thin Film PV [(1)]	White roof[(2)]
Phoenix	35,801	27,477	13,919

[(1)] assuming 100% coverage, TSR 0.30, TE 0.90

[(2)] TSR 0.70, TE 0.90

In reality, a roof with laminated thin film PV modules is never fully covered. For example, the size of an individual UNI-SOLAR panel is 18' long x 15.5" wide, each rated a 136 Watts. If we use a 100,000 ft^2 roof, measuring 80' x 1250', it would allow for 937 rows of PV panels laminated within the 16" width of a standing seam metal roof pan. Four panels would run from the eave to ridge and down again to the other eave (72' in total length). With that layout, a total of 3,748 panels would be installed, each 23.25 ft^2 in area, and generating 510 kW. (3,748 panels X 136 watts/panel). That would yield a total PV surface area of 87,141 ft^2 compared to the total roof surface area of 100,000 ft^2 or an 87% coverage factor.

The calculation must be modified to take into account the fact that the thin-film PV cooling load applies to only 87% of the roof surface, and the cool white roof's effect applies to the remaining 13% of the surface. That calculation is shown below:

Thin-film PV at 87% coverage (with white roof at 13%)			
Thin-film PV load x 87%	23,905	BTU/ft²/yr	
White load x 13%	1,809	BTU/ft²/yr	
Effective Cooling Load	25,714	BTU/ft²/yr	

To determine the extra cooling load that the thin-film PV laminated roof creates, as compared to a white cool roof, we must subtract the effective cooling load of the roof from the fully covered white roof.

Extra cooling load from Thin-Film Pv_{87} vs. white Roof		
Effective Roof Load minus White Roof Load		
25,714 - 13,919 =	11,795	BTU/ft²/yr

To convert this value into energy expressed as kWh/ft^2/year we must use a conversion factor. The traditional conversion factor between these two units would be 3413 BTU per kWh. However in the case of air conditioning energy, that conversion applies only when the COP is 1.0. For the worst case scenario we are assuming an air conditioning unit COP of 2.0, which changes the conversion factor to 6826 BTU/kWh.

Converted to kWh/ft^2/yr [3] =	**1.73 kWh/ft^2/yr**

[3] with COP=2.0, conversion factor of 6826 BTU/kWh

This then becomes our cooling load penalty resulting from the thin-film PV laminated product on the white roof.

Since the energy yield from a PV system can not be determined on the basis of labeled nominal power of the module, another way to evaluate the energy was necessary. Under outdoor conditions the irradiance and ambient temperatures are constantly changing. [7] At these non-standard conditions the characteristics of the modules are often unknown.

A calculator developed by the National Renewable Energy Laboratory allows one to calculate the energy produced by a PV system in any location on a monthly basis. The input parameters include the DC rating, the DC to AC derate factor, the type of array, the array tilt and the array azimuth. Using Version 1 of this calculator allowed us to determine the monthly and annual energy generated by a thin-film PV system in select cities. [11]

To calculate the actual energy generated by the PV module, we assume a 100,000 ft^2 roof area. With the assumptions and values used for our worst case scenario, the Version 1 calculator yielded the following energy for a PV installed on this type of building in Phoenix:

Energy Generation from Thin-Film PV Array on 100,000 ft^2 roof	
(based on calculation according to www.pvwatts.org)	
Assumptions:	DC rating 510 kW [4]
	DC to AC de-rate factor 0.770
	AC Rating 3.85 kW
	Array Tilt 10^o (2:12 low slope)
	Array Azimuth 180^o (facing south)
	775,105 kWhr / yr
[4] DC rating of 5.1 kW/ 1000 ft^2 for UNI-SOLAR	

Now the calculated annual energy generated from a PV unit in Phoenix is known. To compare this energy generated against the added cooling energy resulting from the PV surface itself, we use the 100,000 ft^2 roof surface area assumption and apply the extra cooling load of 1.73 kWh/ft^2/yr to yield 173,000 kWh/year. The ratio of the extra cooling load to the energy generated give us the cool roof penalty as expressed in a percentage of the total energy generated.

ENERGY REQUIRED TO COMPENSATE FOR COOLING LOAD PENALTY		
100,000 ft^2 roof		
Extra cooling load from UNI-SOLAR vs. white = 100,000 X 1.73 =		**173,000** kWh/yr
PV energy generated:	**775,105** kWhr/yr	Ratio : 173,000/775,105 =
		22 % of PV Energy

From this example in Phoenix, we used specific conditions that were representative of an older building (a reproofing project where PV is installed) with insulation levels below the 2006 International Energy Conservation Code (IECC) levels and inefficient air conditioning units. **The calculations suggest that at most, about 20% of the energy generated by the thin-film PV modules would be required to compensate for the added cooling load from the penalty of the dark surface of the PV product.**

To look at a more practical comparison, other calculations were performed using different cities, levels of insulation based on the 2006 IECC, and an average commercial air conditioner COP of 3.0, as indicated in the DOE Buildings Energy Data Book of 2007 [12,13]. For the "white" roof in these more practical calculations, we used an aged SR of 0.55 and an aged TE of 0.75, to be consistent with the proposed 2008 California Building Energy Efficiency Standards in Title 24, Part 6.

New construction would comply with the 2006 IECC code with higher R-values of roof insulation entirely above deck, and higher efficiency of new air conditioning units. Since the radiant properties of a roof can change over time, a more realistic approach to calculating the long-term cooling loads would be to use aged values of solar reflectance and thermal emittance.

By increasing insulation and the COP as well as using aged values of the radiative properties of the cool roof, a significant reduction in the penalty was achieved. **In all of the practical cases, the calculators suggest that less than 2.5% of the energy generated by the thin-film PV modules were needed to compensate for the added cooling load.** Thus, the thin-film PV system can generate more than enough energy to offset any additional cooling load caused by the darker colored PV product.

A summary of those calculations for practical cases is shown below:

			For 100,000 ft^2 roof surface		
City	ASHRAE Climate Zone	2006 IECC above deck Insulation	Extra Annual Cooling Load from thin-film PV (kWh)	Annual PV Energy Generated (kWh)	***% of PV energy used to compensate for cooling load penalty***
Miami	1	R-15	16,600	664,716	***2.5%***
Houston	2	R-15	13,100	603,038	***2.2%***
Phoenix	2	R-15	18,000	775,105	***2.3%***
Charleston	3	R-15	11,500	644,200	***1.8%***
Los Angeles	3	R-15	4,300	709,351	***0.6%***
San Francisco	3	R-15	700	693,585	***0.1%***
St. Louis	4	R-15	9,000	604,301	***1.5%***
Chicago	5	R-20	3,800	564,717	***0.7%***
Minneapolis	6	R-20	3,400	587,153	***0.6%***

The level of roof insulation has a significant impact on the cooling load penalty. Using aged solar reflectance and emittance values for a white roof in the DOE low slope roof calculator, we can compare an R-5 scenario against a code compliant R-15 scenario in Phoenix, for example (see below). The calculations are made using a 100,000 ft^2 roof as the example. As expected, the roof systems with lower insulation values result in higher cooling loads. The effect of increasing the insulation from R-5 to R-15 in that location is a 65% reduction in the extra cooling load caused by the thin-film PV system (52,600 kWh vs. 18,000kWh).

		100,000 ft^2 roof			
	Insulation	Effective Annual Roof Cooling Load (BTU)	Extra Cooling load from thin-film PV (kWh)	Annual AC Energy Generated by PV (kWh)	*% of PV energy to compensate for cooling load penalty*
Phoenix	**5**	2,667,300,000	**52,600**	775,105	***6.8%***
Phoenix	**15**	918,300,000	**18,000**	775,105	***2.3%***

Similarly, the solar reflectance and thermal emittance of the reference roof surface has an impact on the cooling load penalty. Using a 100,000 ft^2 roof in Phoenix again for the example, we can compare the results from a cool roof where the aged properties are used in the calculation versus results from a cool roof where the initial values are used. The DOE low slope roof calculator was used for this comparison, using R-15 insulation levels for both cases. A white roof was assumed as the reference, with an initial TSR of 0.70 and initial TE of 0.90. In comparison, a white roof with an aged TSR of 0.55 and aged TE of 0.75 was used, as more of a practical scenario. The impact on the extra cooling load was not as dramatic as that seen with different insulation levels. The calculations show that using the lower TSR/TE values for an aged surface resulted in a 55% reduction in the extra cooling load caused by the thin-film PV system (40,300 kWh vs. 18,000 kWh).

			100,000 ft^2 roof			
	TSR	TE	Effective Annual Roof Cooling Load (BTU)	Extra Annual Cooling load from thin-film PV (kWh)	Annual AC Energy Generated by PV (kWh)	*% of PV energy to compensate for cooling load penalty*
Phoenix	**0.55**	**0.75**	918,300,000	**18,000**	775,105	***2.3%***
Phoenix	**0.70**	**0.90**	884,100,000	**40,300**	775,105	***5.2%***

It is important to note, that the calculations that were performed in this study focused only on the annual cooling loads determined by the DOE Low Slope Roof Calculator. In colder climates, the darker surface of the thin film laminates may be beneficial in lowering the overall annual combined cooling/heating energy savings.

Conclusions and Comments

- Variables such as insulation, wind speed and direction, and solar irradiance can complicate the evaluation of a cooling load penalty.
- A thin-film amorphous silicon PV system installed on a new low-slope cool metal roof causes less than a 2.5% penalty to the electricity generated by the PV system, despite causing a slightly higher cooling load.
- A worst case scenario with low insulation, a poor conditioning COP and high solar radiance causes a 22% cooling load penalty. An example of this would be a case where re-roofing or adding PV to an existing older building takes place. In that case, insulation levels would be relatively lower and air conditioning equipment efficiencies would be much lower than that of new equipment.
- The level of roof insulation has a significant impact on the effective roof cooling load and cooling load penalty from the thin-film PV system.
- Calculations suggest that for new construction the energy generated by thin-film PV modules far exceeds the energy required for extra cooling that is caused by higher solar heat gain from the darker PV surface.
- The SR/TE values of today's thin-film PV modules are similar to other steep slope cool metal roof surfaces, as defined by ENERGY STAR roof products program. As thin-film PV modules' photoelectric conversion efficiencies rise, so will the effective SR, improving the thermal footprint (cooling load penalty).
- Installing thin-film PV modules on a <u>cool</u> metal roof is prudent to capitalize on those areas of the roof that are not covered with PV modules.

Further Study

- Verification comparison via FLIR camera and quantitative heat study with modeling of UNISOLAR and Competitor panels on various roof tops under various light and temperature conditions.
- Refinement of model using NREL's Solar Advisor Model for equipment specific I-V and Power-Efficiency curves designed into PV array scenario with higher precision, location specific, climate modeling.

Appendix A

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