BIPV PERFORMANCE LOSSES DUE TO HIGHER TEMPERATURES: POSSIBLE SOLUTIONS FROM EVAPORATION

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ABSTRACT

Building integrated photovoltaics modules (BIPV) heat up more than rack mounted ground arrays, and thus have power performance losses due to elevated temperatures. Airflow is restricted in BIPV or low profile, aesthetically pleasing, building applied photovoltaic (PV) arrays. The electrical production losses are significant.

This paper investigates the electrical loses, and proposes forced air, using waste cooling from the first stage of two stage evaporative coolers as a source of increased electrical production for BIPV.

Modern two stage evaporative coolers have less water consumption than markets perceive. Water usage for a PV powered two-stage evaporative cooler is compared to central station electrical plant powering direct expansion air conditioning for the western region of the United States. By comparison, the evaporative cooler is shown to be very conservative in water consumption.

As PV module efficiencies approach 20 percent, forced air-cooling becomes more attractive for peak power production. Photovoltaic / Thermal (PV/T) collectors harvest waste heat from the backs of PV arrays during the winter when low-grade heat is desirable. The same mechanical system used to harvest heat from a PV/T in the winter can be used to cool the modules in the summer.

1. TEMPERATURE EFFECTS ON PV

If a PV panel is hot, it doesn't put out as much electricity as when it is cold. Increased cell temperature leads to decreased open circuit voltage and slightly increased shore circuit current. [1]. An easier, less accurate approach, is to use temperature correction factors for power production; 0.005/ °C for crystal silicon, and 0.002/ °C for amorphous, varying slightly between manufacturers. Various nomenclature exists for dealing with actual performance of PV systems: Standard Test Conditions (STC; 1,000 W/m^2 and 25 °C), PVUSA Test Conditions (PTC; a better STC for alternating current), American Society for Testing and Materials [2] nominal operating cell temperature (NOCT; 800 W/m^2, 1 m/s wind speed and 20 °C ambient temperature with no load). Ideally, designers will know the installation parameters for accurate hour-by-hour analysis. This paper will not address the inadequacies of the industry standards, but hopes to present a scenario for optimal utilization of power from BIPV for hot dry climates where conditioned air is desired.

1.1 PV Temperature Corrections

When designing a photovoltaic system it is important to know the installed weighted average cell temperature at which most of the power will be produced. This temperature is typically called the installed nominal operating cell temperature (NOCT in °C). NOCT is obtained at reference conditions and in a specific mounting configuration. It is used to estimate the temperature at which PV cells will operate, T_c (°C), using the ratio of actual irradiance on the array, E (W/m^2), to the reference standard 1,000 W/m^2, E_o, plus the ambient temperature, T_a (°C), conditions:

$$T_c = (NOCT * E / E_o) + T_a \qquad (1)$$

The actual operating efficiency, $\eta_{(pv)}$ is obtained by using the cell technology correction factor per °C, α, STC efficiency, η_{stc} obtained at 25 °C but corrected for the actual cell temperature, T_c (°C)[3]:

$$\eta_{(pv)} = \eta_{pv\ stc} * \ (1+ [\alpha * (25^{o}C - T_c)]) \qquad (2)$$

Recent studies funded by the California Energy Commission have evaluated various installed power-weighted average module temperatures as shown in Table 1. These are based on May 1, 2004 conditions average ambient temperature of 23 °C, average wind speed of 1.5 m/s, 7.5 peak sun hours or between 750 and 950 W/m^2 for the majority of the hours in the day; not exact, but very close to ASTM conditions [4].

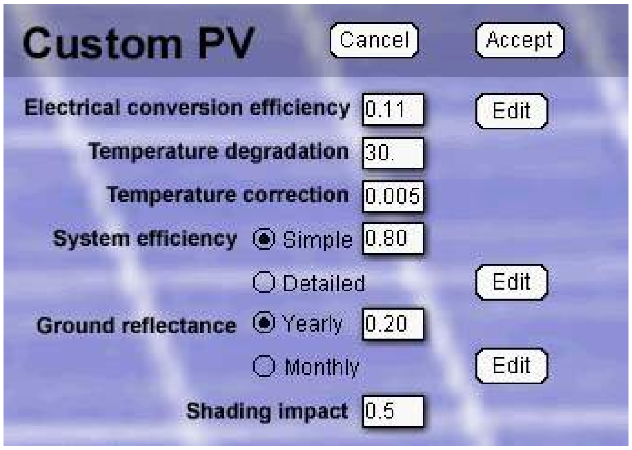
Installations that restrict airflow have higher installed NOCT than open rack installations; Table 1 represents open rack and restricted air flow installations. BIPV that emulate roofing will have higher losses due to elevated temperatures than rack mounted modules. As shown in Graph 1, crystalline have dramatic disadvantage with the higher temperature correction; higher installed NOCT exacerbate the problem. For example, a 1 kW STC crystalline BIPV with an installed NOCT of 65 °C will produce only 600 watts DC at 40 °C (104 °F) ambient temperature in 1,000 W/m^2 sunlight; a $\eta_{(pv)}$ which is only 60% of the $\eta_{pv\ stc}$.

TABLE 1: INSTALLED WEIGHTED NOCT (°C) FOR VARIOUS SYSTEMS

Company System	Weighted NOCT °C
PowerLight	50
RWE Schott SunRoof FS	47
United Solar US-116	61
United Solar PVL-128	57
Shell ST 40	51
First Solar FS50	52
Solar Quilt Astropower Apx-130	65
Evergreen	48
BP Solar	50
RWE Shott SAPC-123	48
Shell SP-140	50
AstroPower AP-100	48
Minimum	47
Maximum	65

2. COOLING PV

Force air can cool PV arrays; previous analysis indicated the fan horsepower required did not justify increased electrical performance. We suggest, that with an air stream cooler than ambient temperatures from a two stage evaporative cooler, a forced air-cooling system for high efficiency BIPV modules might be justified. Initial study based on calculations from BIPV Designer shareware (Google "BIPV" for software [5]) for May through October for various southwest cities are shown in Graph 2. Design parameters are a 4-meter by 4 meter PV array, tilted at 20 degrees (higher tilts have less thermal energy in summer), ground reflectivity is 20%. Other parameters that vary are system efficiency; 80% for normal AC power, 88% for a directly coupled commutated DC motor on the evaporative cooler, module efficiency at 11% and 20% and temperature correction at 0.005/ °C and 0.004/ °C for typical crystal and high efficiency SunPower cells, respectively. Figure 1 shows available variables in BIPV Designer. The legend of Graph 2 indicates coefficient of energy loss per °C, with or without cooling, system efficiency, module efficiency, and NOCT; the first item is 0.005, w/o, 80%, 11%, 45.


Custom PV

Electrical conversion efficiency 0.11
Temperature degradation 30.
Temperature correction 0.005
System efficiency ● Simple 0.80
○ Detailed
Ground reflectance ● Yearly 0.20
○ Monthly
Shading impact 0.5

Fig. 1: Interactive variables available in BIPV Designer.

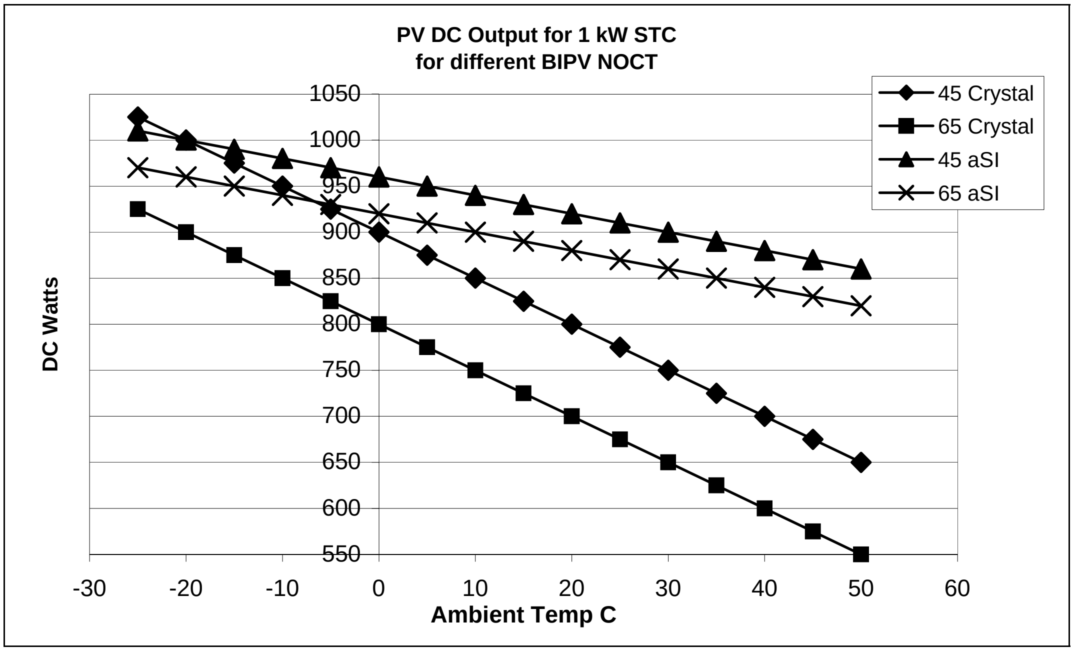
Untested assumptions used in the simulations are that the first stage waste-coolth from an indirect / direct evaporative coolers (IDEC) is able to cool the array down to ambient temperature (exhaust 1st stage dry bulb typically 13 °C cooler), and ¼ horsepower, or 186 watts of additional fan power is needed to compensate for PV array static pressure drop for plenum on back of PV. Cooling was simulated when module temperatures reached 30 °C (98.6 °F). Performance and hours of two-stage evaporative cooler operation are shown in Table 2. For the various cities, cooling and elimination of the inverter provides 13% to 15% more DC electricity.

3. IDEC WATER USAGE

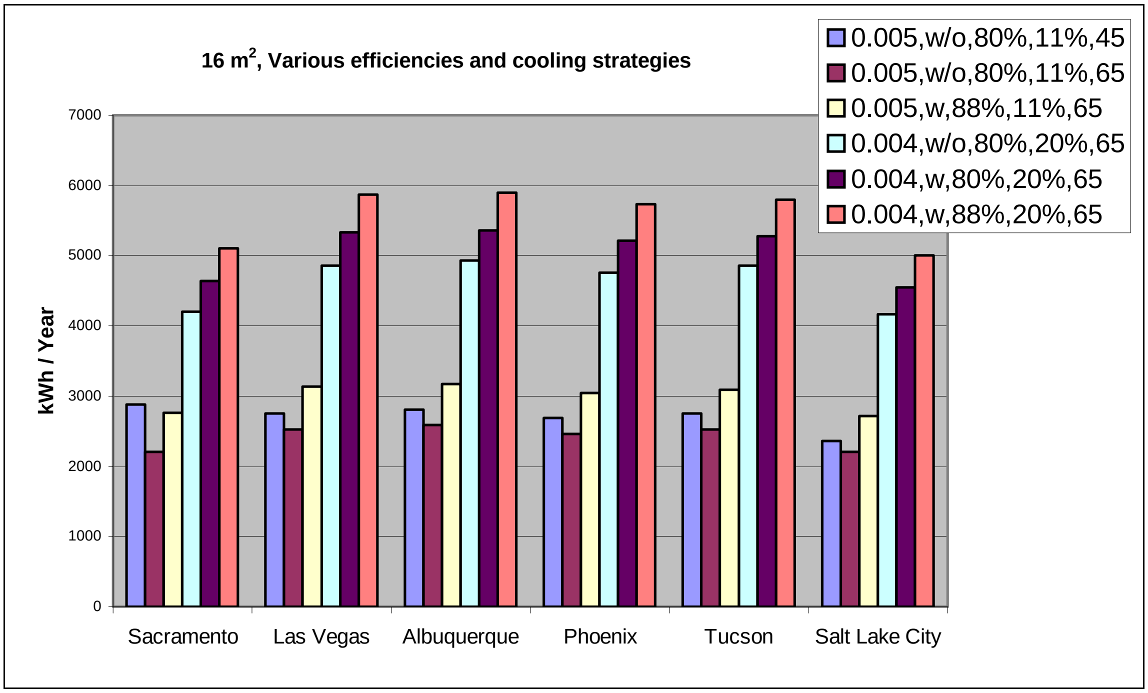
The base-case home with a conventional DX air conditioning system rated at 12 SEER uses 1,886 kWh/yr with a peak of 3 kW, while the two-stage evaporative cooler uses 135 kWh/yr with a peak of 0.52 kW. [6]

According to Larry Kinney, generating a kWh of electricity with a new coal plant in the Southwest uses about 0.67 gallons of water, while a new natural-gas- fired plant consumes about 0.33 gallons of water per kWh generated, for an average 0.5 gal / kWh for new plants [7].
According to Torcellini, the national weighted average for thermoelectric and hydroelectric water use is 2.0 gal / kWh of evaporated water for electricity consumed at the point of end use. It is an average 4.42 gal / kWh for the western region, 4.64 gal / kWh for California and 7.85 gal / kWh for

Arizona when including water usage for electricity from older coal, older natural gas, and evaporative water losses from hydro-electricity [7]. These varying perspectives are shown in Table 3.



Graph 1: DC Output based on Ambient Temperature for various NOCT.



Graph 2: Performance of various BIPV systems, with and without cooling.

TABLE 2. HOURS OF COOLING PV AND ENERGY BALANCE FOR 20% EFFICIENT PV

City	Hours IDEC Operation	kWh cooling gains	1/4 HP Motor kWh	Net kWh	Saving kWh DC Operation	Total Increased Performance kWh	1 HP IDEC Yearly kWh
Sacramento	1,342	435	250	185	465	650	1,000
Las Vegas	1,587	471	295	176	533	709	1,182
Albuquerque	1,404	436	261	175	536	711	1,046
Phoenix	1,648	454	307	148	521	669	1,228
Tucson	1,587	414	295	119	527	646	1,182
Salt Lake City	1,375	383	256	127	454	581	1,024

TABLE 3. VARIOUS ELECTRICAL PLANT WATER USAGE

Location	Kinney gal/kWh	Torcellini gal/kWh
California	0.5	4.64
Arizona	0.5	7.85
West	0.5	4.42

Water usage rates for an IDEC on a typical day when the evaporative unit operates for 5 hours should vary from a minimum of approximately 6 gallons per hour at 750 cfm to a maximum of 11 gallons per hour at 1,550 cfm, or 30 4. to 55 gallons per cooling day [8].

Single stage, high-efficiency residential evaporative coolers use an average of 5,100 gallons of water per year in the Southwest, about 3% of the average annual residential water use. This amount of water costs $5 to $20 per cooling season. Evaporative coolers save on the order of 3,200 kWh per year. This equates to a net water use of 3,500 gallons if using new central station power plant water consumption rates [6]. However, if using average water usage for states including older fossil and hydro-electric facilities, net water savings is an average 16,354 gal/kWh for the selected locations and 37,048 gal/kWh for Phoenix as shown in Table 4.

4. COMBINING PV AND IDEC

A direct current (DC) motor on an IDEC using waste coolth to cool PV modules can be sized to use the additional electrical production of summer months directly from PV system. This corresponds to when building cooling is needed, and when a PV array can use waste coolth from an IDEC. 8% PV system gains can be achieved by eliminating the inverter for powering such a DC system. As seen in Table 2, 1.0 kWh/yr to 1.2 kWh/yr is all the power needed for a two stage evaporative cooler with a 1 H.P. DC motor. This can be supplied from a modest PV system, providing additional water savings. Directly coupling the DC output from a PV system can eliminate the need for inefficiencies of DC to AC inverters.

Cooling high efficiency modules can potentially have a net positive energy balance when considering additional horsepower required due to additional static pressure of the needed plenum. In winter months, when buildings can use low-grade heat from the zero-glazed-collectors, the plenum used for cooling the modules in the summer can harvest available waste heat; commonly described as a photovoltaic / thermal PV/T collector. Again, even in the winter, harvest of heat, thus cooling of the modules, will increase electrical production from a PV/T collector [9]. Figure 2 illustrates airflow, DC and AC power for an IDEC in a net metered PV system. 1st stage air cools the PV, 2nd stage air is for space conditioning. Note that the above simulation assumes when an inverter is not used, all power is DC.

A more detailed drawing of the IDEC is shown in Figure 3, exhaust air is the 1st stage waste coolth, and conditioned air is the second stage cooling air.

TABLE 4: WATER USE / SAVINGS FOR DX AND EVAPORATIVE CONDITIONING, SELECT CITIES

Site (W-West, AZ-Arizona, Torcellini)	Cooling Energy DX kWh/yr	Cooling Energy Evap kWh/yr	Water Use Evap gal/yr	Elec. Water Savings New Plant gal/yr	Elec. Water Savings Including Old and Hydro gal/yr	Net Water Use (Savings) New Plant gal/yr	Net Water Use (Savings) Including Old and Hydro. Plant gal/yr
Albuquerque (W)	2,487	334	3,470	1,077	9,516	2,394	(6,046)
Las Vegas (W)	4,722	497	4,583	2,113	18,675	2,471	(14,092)
Phoenix (AZ)	6,043	574	5,884	2,735	42,932	3,150	(37,048)
Salt Lake City (W)	2,839	357	2,739	1,241	10,970	1,498	(8,231)
Table Average:	4,023	441	4,169	1,791	20,523	2,378	(16,354)

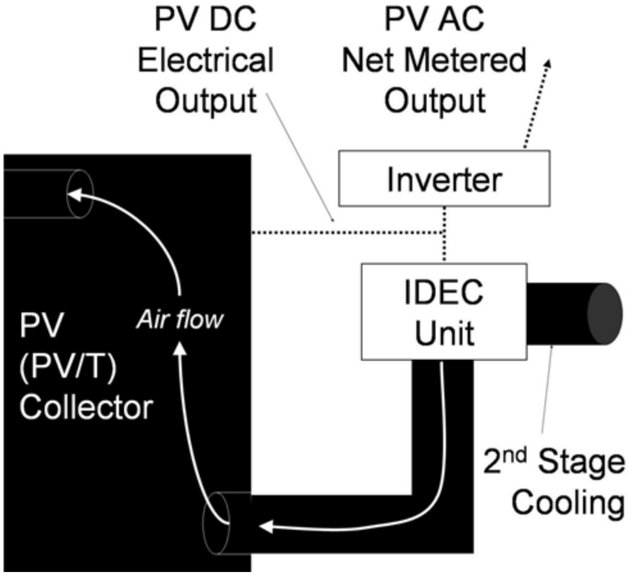
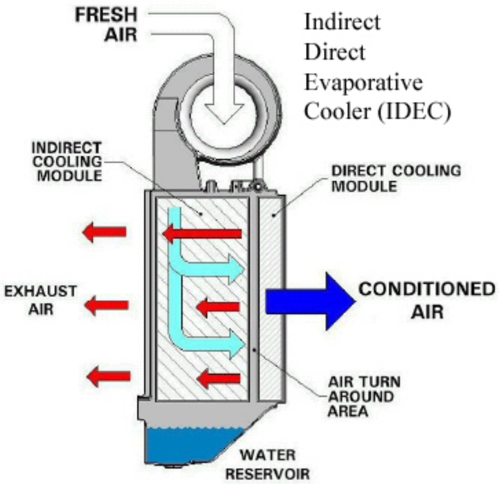


Fig. 2: Air flow and PV DC & AC Output.



Source: Davis Energy Group

Figure 3. IDEC

5. CONCLUSION

Substantial electrical losses occur from PV systems that have constrained airflow, as in BIPV. Opportunities to use waste coolth from two state evaporative coolers is show to be effective with low slope, high efficiency, crystalline silicon modules. A two stage evaporative cooled system run off grid power can provide a substantial monetary incentive to public goods programs that reward on the output from PV systems. For example, in Germany, systems are rewarded at $0.50 for each kWh produced. It will be interesting to see if this strategy is employed to cool down PV systems that have performance based incentives.

Water consumption for air-conditioning with DX units is compared to two stage evaporative coolers with varying assumptions for power plant water usage.

A two stage evaporative cooler directly using DC from PV, cooling the modules in summer months, harvesting heat in the winter, can add substantial value in southwest locations.

6. ACKNOWLEDGEMENT

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7. NOMENCLATURE

AC	Alternating Current
ASTM	American Society for Testing and Materials
BIPV	Building Integrated Photovoltaics (systems)
CFM	Cubic Feet per Minute
DC	Direct Current
Gal	Gallons
IDEC	Indirect / Direct Evaporative Coolers
kW	Kilowatts
kWh	Kilowatt hours
NOCT	Nominal Operating Cell Temperature
PCT	PVUSA Test Conditions
PV	Photovoltaic
PV/T	Photovoltaic / Thermal
PVUSA	Photovoltaics for Utility Scale Applications
SEER	Seasonal Energy Efficiency Ratio
STC	Standard Test Conditions
^{o}C	Degrees Celsius
W/m^2	Watts per squared meter
$\eta_{(pv)}$	Actual operating efficiency,
α	Cell technology correction factor per ^{o}C
η_{stc}	STC efficiency
T_c	Actual cell temperature (^{o}C)

8. REFERENCES

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