한국신·재생에너지학회 2005년도 춘계학술대회논문집 pp.397~402

SWPV 태양 열-전기 복합생산 모듈 성능 평가 연구

아메드 나비드[1), 강 은철[2), 이 의준[3)

Performance Evaluation Study of Solarwall-Photovoltaic Module to Generate Solar Electric Power

Ahmed T Naveed, RETCan, Ottawa, Canada

E. C. Kang, and E.J .Lee, Korea Institute of Energy Research(KIER),71-2 Jang-Dong Yusong-Gu, Daejeon 305-343, South Korea

Key words: Photovoltaic(태양전지), Solarwall(공기식집열외벽체), Building integrated PV(건물일체형 태양전지), PV efficiency(태양전지 효율)

Abstract: Photovoltaic (PV) module can generate electricity using sunlight without causing any environmental degradation. Due to higher fossil fuel prices and environmental awareness, PV applications are becoming more popular as clean source of electricity generation. PV output is sensitive to the operating temperature and can be drastically affected in Building Integrated PV (BIPV) systems. PV Solarwall (SWPV) combination and PV systems have been evaluated in this study for improvement in electrical output and system costs. PV modules under forced ventilation. A 75W polycrystalline silicon PV module was fixed on SW in front of the ventilation fan as it was indicated to be the coolest position on the SW in phoenix simulations. The effectiveness of cooling by means of the forced ventilating air stream has been studied experimentally. The results indicate that there appears to be significant difference in temperature as well as electricity output comparing the SWPV and BIPV options. Electrical output power recovered is about 4% during the typical day of the month of February. RETScreen® analysis of a 3kW PV system hypothetically located at Taegu has shown that with typical temperature reduction of 15°C, it is possible to reduce the simple payback periods by one year. The work described in this paper may be viewed as an appraisal of a SWPV system based on its improved electrical and financial performances due to its ability to operate at relatively lower temperatures.

Nomenclature

V_{oc} Open circuit voltage (at reference values, V).
I_{sc} Short circuit current (at reference values, amps).
V_{mp} Voltage at maximum power point (at reference values, V).
I_{mp} Current at maximum power point (at reference values, amps).
Q Incident solar radiations (W/m^2).
Q_{ref} Reference solar radiations (usually 1000 W/m^2).
T_{ref} Reference temperature (usually 298K).
n, m Number of series/parallel connected cells (-).
N_{pnnl} Number of modules (-).
DF Diode factor.
I_o Diode current (amps).
I_L Light generated current (amps).
V_{mpp} Voltage at maximum power point
P Panel power output (W).
e Charge on electron (1.60×10^{-19}C).
K Boltzmann, s constant (1.380×10^{-23} J/K.mole).
T Panel temperature.
SWPV Solarwall Photovoltaic
$\eta(T)$ efficiency of the solar cell at temperature T,
$\eta(T_{ref})$ efficiency of the cell at temperature T_{ref},
T operating temperature of the module °C,
T_{ref} reference temperature.

1. Introduction

Building integrated photovoltaic (BIPV) has many significant advantages as it is an option for urban areas which do not have enough separate space for the installation of photovoltaic (PV) modules.

However, the main drawback of such designing is that temperature of photovoltaic modules is much higher than the ambient temperature because of the absence of natural ventilation mechanism for excessive heat removal. The output power of the module is sensitive to the operating temperatures and power reduction of 0.4-0.65% per K increase in temperature is observed [1]. The results of the theoretical and experimental analysis has shown that a temperature drop of 15°C for the roof surface could be

1) E-mail : naveed@kier.re.kr
Tel : (042)860-3275 Fax : (042)860-3739
2) E-mail : kec8008@kier.re.kr
Tel : (042)860-3511 Fax : (042)860-3739
3) E-mail : ejlee@kier.re.kr
Tel : (042)860-3514 Fax : (042)860-3739

achieved with a duct behind the PV modules and, hence, increasing power output of the modules by 8.8% [2]. One added benefit of removing the thermal energy from the back of the solar modules in a BIPV system is the reduction in the cooling load of the building during the summer and thermal energy recovered can be utilized to meet the heating load of the building in winter. Thus, PV and thermal collector combination (PVT) has substantial advantages over its components as it produces more energy per unit area than that obtained with separate use of a PV module and a solar thermal collector. Zakharchenko R. et al [3] studied PV and solar thermal collector cooled by water and found that the presence of a PV above the solar heat collector reduces the heat flux to the latter, correspondingly reducing the thermal efficiency of the collector. On the other hand, the collector ability to extract heat from PV is reduced when the water inside it is heated. Therefore, the optimal case proposed was to make the PV of smaller area than that of the heat collector, and to place it above the initial part of the latter near the cooling fluid entrance, to provide a more efficient cooling of the PV and a higher thermal efficiency of the heat collector.

Unglazed Transpired solar collectors [4] are being successfully used in many parts of the world for air heating and are commercially available. The structural strength of transpired solar collectors allows the installation of PV modules on it. However, only proper thermal contact will enable the thermal heat extraction from the PV modules. Thus, combination of PV and transpired solar collectors will not only assist in PV module operation at relatively lower temperature but also provides warm air for the building simultaneously. Installation of PV modules on the transpired solar collector has miner effect on the solar thermal efficiency of the solar collectors [5]. However, combined energy conversion efficiency is dependent on many factors such as thermal contact between PV and transpired collector, position of the PV module, incident solar radiation, wind speed, and forced air ventilation rate. In this study, the temperatures of PV module in a Solarwall®-PV (SWPV) and a typical BIPV application have been monitored to evaluate its impact on the PV electrical output. Also, the impact of recovered electrical output on the simple payback period of a PV system has been studied using RETScreen® to demonstrate the possible financial savings of SWPV system over the BIPV.

2. Temperature dependence of PV output

Photovoltaic modules consist of solar cells connected in a combination of series and parallel connections to generate the desired output current and voltage. A solar cell is basically a p-n junction diode which also generates electric current through photo-generated carriers under illumination. The power output of a single crystalline PV module with n cells in series and m cells in parallel connection can be represented with the following sets of equations [6]

$$\mathrm{DF} = \frac{e}{kT_{ref}} \frac{V_{mp} - V_{oc}}{n} \left[\ln\left(\frac{I_{sc} - I_{mp}}{I_{sc}} \right) \right]^{-1}$$

$$I_L = \frac{Q}{Q_{ref}} \frac{I_{sc}}{m}$$

$$I_o = 2^{\frac{T_c - T_{ref}}{c_T}} \frac{I_{sc}}{m} \left[1 - \exp\left(\frac{e \frac{V_{oc}}{n}}{kT_{ref} \mathrm{DF}} \right) \right]^{-1}$$

$$P = \left[V_{mpp} I_L - V_{mpp} I_o \exp\left(\frac{e V_{mpp}}{kT_c \cdot \mathrm{DF}} - 1 \right) \right] n \cdot m$$

If Q is the incident solar insolation, then the corresponding electricity generating efficiency given by,

$$\eta_e = \frac{P}{Q} \cdot 100\%$$

These expressions can be used to predict electrical output of PV module and required inputs are the short-circuit current, the open circuit voltage, the voltage and current at the maximum power point, the reference values at which these are measured (usually 1000 W/m^2 and 25°C), and the number of series and parallel connected cells in each module. It is evident from the mathematical expressions that the output power is dependent on temperature. Also, another important characteristic of the solar cell material is energy band gap on which the penetration depth of the incident solar energy is dependent. The energy band gap dependence of silicon on temperature can be expressed as [7]:

$$E_g(T) = 1.12 - 0.00028(T - 300K)$$

At higher temperatures, smaller energy band gap will reduce the penetration of incident sun light, consequently, reducing the output of solar cell. Thus, the operating temperature of PV module must be kept as low as possible for the optimum electrical output.

3. Position of PV on the SW

The effectiveness of heat extraction from the back of the PV module will dependent on the position of the PV module on the SW. It is desired to place the PV module at a position where the temperature is the lowest so that maximum heat could be removed from the PV module. The SWPV system was simulated using Phoenix simulation software. The simulation results indicate that the temperature is lowest at the position of the ventilation fan as shown in figure 1. Based on these simulations, PV module has been fixed in front of the ventilation fan (figure 2b).

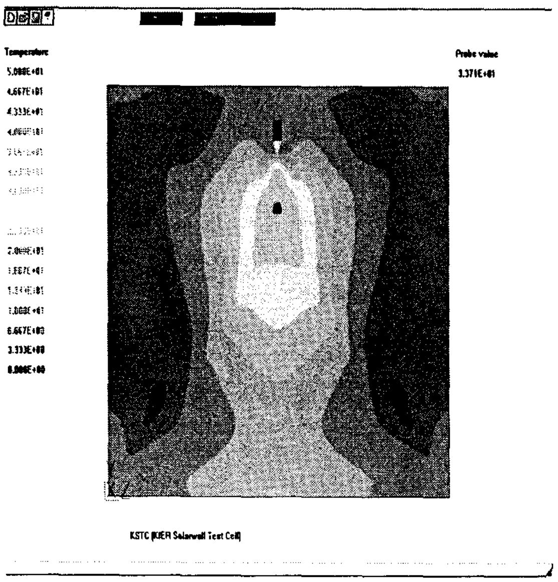


Figure 1. Phoenix simulation of SW system with 2% porosity.

4. Experimental Setup

Two PV modules of 75W output power each with 36 poly-crystalline silicon solar cells in series have been used in two different configurations. The first one is a typical BIPV configuration in which PV module is mounted directly on the south facing wall of a room as shown in figure 2a.

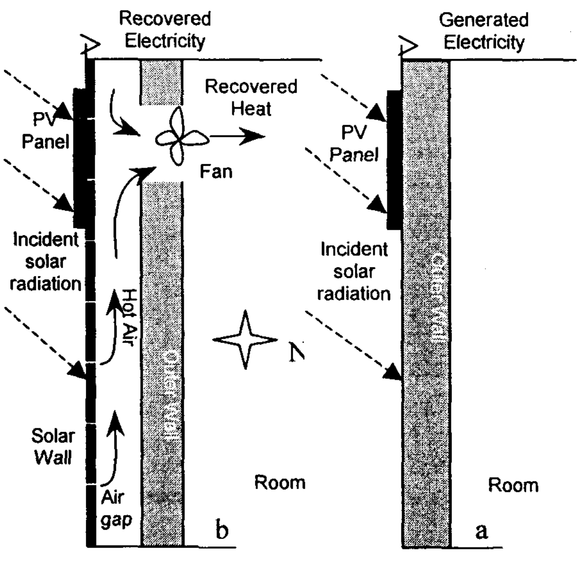


Figure 2. Experimental arrangements a) BIPV and b) SWPV

In the second configuration, commercially available unglazed transpired solar collector known as Solarwall® made of corrugated steel absorber sheet with perforations covering 1% of its surface area was fixed to the south-facing wall of the room. The area of the Solarwall® was $6.48m^2$ with a 0.1m plenum connected by a fan inside the room for heated air circulation or ventilation purposes. The gap between the solarwall and wall was covered on all sides. PV module was mounted on a 1.2 m wide and 0.54m high steel structure to obtain good thermal contact between Solarwall® and the PV module. The steel structure frame and the junction box behind the PV modules might have caused some air flow disturbances and make the ventilating airflow at the gap turbulent in nature. The SWPV setup is shown schematically in figure 2b.

The dimensions and characteristics of both the south facing walls and the rooms are the same as listed in Table 1. The electric output power of the PV was recorded for both systems using a data logging system under the same measurement conditions such as solar radiation and ambient temperatures. For the present experimental work, the airflow rate was fixed at 160 CFM. The temperature conditions were measured with a Type 'T' thermocouple (Omega Co USA). Global irradiance was recorded using a calibrated pyranometer model M11 Kipp and Zonen (Holland) connected with a high-precision millivoltmeter and installed on the south facing wall of the SWPV. The fan in the SWPV system was turned on between 12:00noon and 5:00pm to study the effect of the forced air ventilation on the PV module temperature

Table 1. Characteristics of the two buildings used in the study

Building	Dimension	2.7 m × 2.8 m × 2.4 m	
	Volume	$18.14 m^3$	
	Wall area	$41.52 m^2$	
	Floor area	$7.56 m^2$	
Wall Material	Steel module	Conductivity (W/m-k)	194
		Thickness (m)	0.02
	Urethane foam	Conductivity (W/m-k)	0.047
		Thickness (m)	0.075
Thermal properties	U	1.65 kJ/hr °C	
	UA	$68.51 kJ/hr m^2 °C$	
	CAP	17039.18 kJ/ °C	

5 Experimental Results

5.1. Variation of Solar Module Temperature

The variations of the PV module temperature during the typical day of the month of February along with the irradiance are presented in figure 3. The temperature of SWPV is slightly higher than the BIPV for the first 90 minutes of the sunrise. During this period, the Solarwall will absorb solar energy due to absorber coating and will have higher temperature as compared to BIPV. However, the PV module temperature in the SWPV is lower after 9:30AM as the natural ventilation caused by the upward movement of warm air in the gap between SW and wall has initiated. However, the temperature difference is only 1°C which is increased as natural ventilation phenomenon is more effective at elevated temperatures. Once the ventilation fan is turned on at 12:00 noon, the cooling effect is become even more effective with PV module temperature 8°C lower than the PV module in BIPV configuration. . This is because the continuous ventilation of hot air behind the PV module becomes a cooling source of the PV module. The performance of the SWPV case becomes the best during this period.

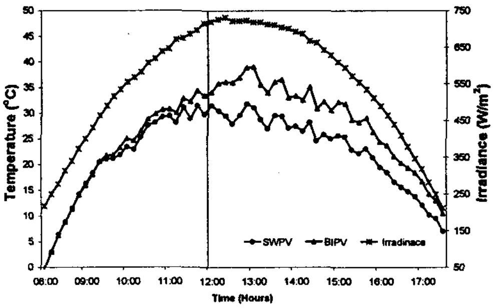


Figure 3. Variation of PV module temperature and irradiance during the day (02.26.2005)

5.2. PV Electrical Output Power

Results show that the PV output power between 12:00noon and 2:00PM is 54W for SWPV case which is about 4% higher as compared to the BIPV. This is because the continuous flow of warm air in solar wall plenum acts like a cooling source of the PV module resulting in increased output power of the module. The advantages of the SWPV option are more obvious during the forced ventilation period.

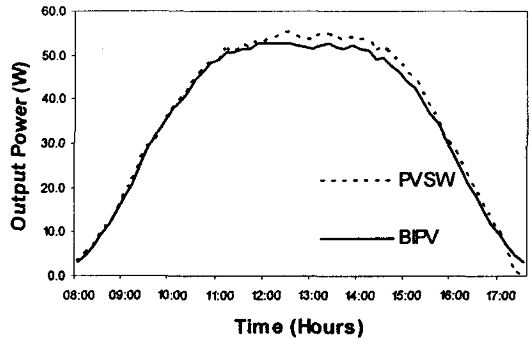


Figure 4. Variation in the electrical output of the PV module

6. Financial benefit of SWPV over BIPV

The experimental results of the SWPV system has been used to evaluate the financial benefits due to electrical output gain. RETScreen® [8]was used to calculate the simple payback period which is defined as the total time required for a project to recover its initial costs. A typical 3kW PV/battery system hypothetically located at Taegu, Korea has been considered for these calculations. The base case electricity generation is by a diesel generator.

The following mathematical expression has been used to calculate the efficiency at different temperatures [7]

$$\eta(T) = \eta(T_{ref})(1-\mu(T-T_{ref}))$$

Temperature coefficient μ is 0.4%/°C for the PV modules considered for the analysis.

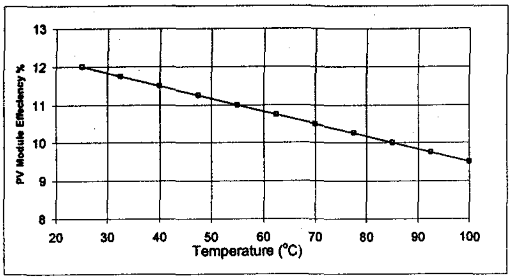
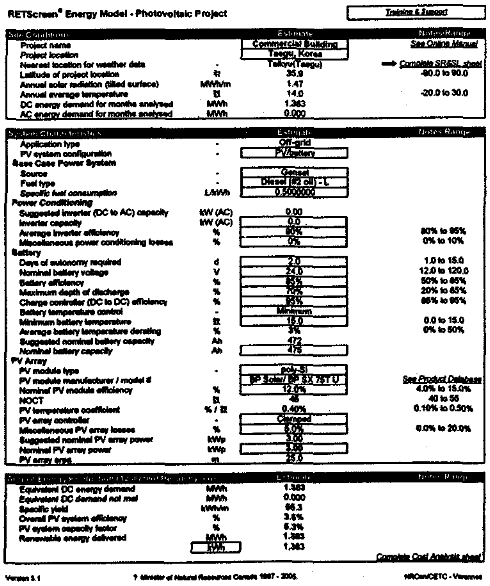


Figure 4. Temperature dependence of PV module efficiency

The calculated efficiency at various operating temperatures was used to estimate the number of PV modules required at lower temperature with higher electrical conversion efficiency. RETScreen® then iterated the simple payback periods of the PV system with varying PV efficiencies as operating temperature is raised. RETScrenn® worksheets for the PV system are presented in the following figures.



RETScreen® Energy Model - Photovoltaic Project — Training & Support

Site Conditions		Estimate	Notes/Range
Project name		Commercial Building	See Online Manual
Project location		Taegu, Korea	
Nearest location for weather data	-	Taikyu(Taegu)	Complete SR&SL sheet
Latitude of project location	°N	35.9	-90.0 to 90.0
Annual solar radiation (tilted surface)	MWh/m	1.47	
Annual average temperature	°C	14.0	-20.0 to 30.0
DC energy demand for months analysed	MWh	1.363	
AC energy demand for months analysed	MWh	0.000	

System Characteristics		Estimate	Notes/Range
Application type	-	Off-grid	
PV system configuration	-	PV/battery	
Base Case Power System			
Source	-	Genset	
Fuel type	-	Diesel (#2 oil) - L	
Specific fuel consumption	L/kWh	0.5000000	
Power Conditioning			
Suggested inverter (DC to AC) capacity	kW (AC)	0.00	
Inverter capacity	kW (AC)	0.0	
Average inverter efficiency	%	90%	80% to 95%
Miscellaneous power conditioning losses	%	0%	0% to 10%
Battery			
Days of autonomy required	d	2.0	1.0 to 15.0
Nominal battery voltage	V	24.0	12.0 to 120.0
Battery efficiency	%	85%	50% to 85%
Maximum depth of discharge	%	70%	20% to 85%
Charge controller (DC to DC) efficiency	%	95%	85% to 95%
Battery temperature control	-	Minimum	
Minimum battery temperature	°C	15.0	0.0 to 15.0
Average battery temperature derating	%	3%	0% to 50%
Suggested nominal battery capacity	Ah	472	
Nominal battery capacity	Ah	475	
PV Array			
PV module type	-	poly-Si	
PV module manufacturer / model #		BP Solar/ BP SX 75T U	See Product Database
Nominal PV module efficiency	%	12.0%	4.0% to 15.0%
NOCT	°C	45	40 to 55
PV temperature coefficient	% / °C	0.40%	0.10% to 0.50%
PV array controller	-	Clamped	
Miscellaneous PV array losses	%	5.0%	0.0% to 20.0%
Suggested nominal PV array power	kWp	3.00	
Nominal PV array power	kWp	3.00	
PV array area	m	25.0	

[illegible]		Estimate	Notes/Range
Equivalent DC energy demand	MWh	1.363	
Equivalent DC demand not met	MWh	0.000	
Specific yield	kWh/m	55.3	
Overall PV system efficiency	%	3.8%	
PV system capacity factor	%	5.3%	
Renewable energy delivered	MWh	1.363	
	kWh	1,363	

Complete Cost Analysis sheet

Version 3.1 — © Minister of Natural Resources Canada 1997 - 2005. — NRCan/CETC - Varennes

Figure 5. Energy model of PV system

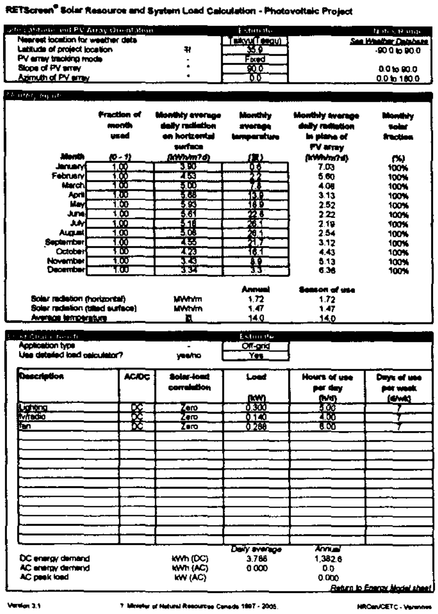


Figure 6. Solar resources and system load

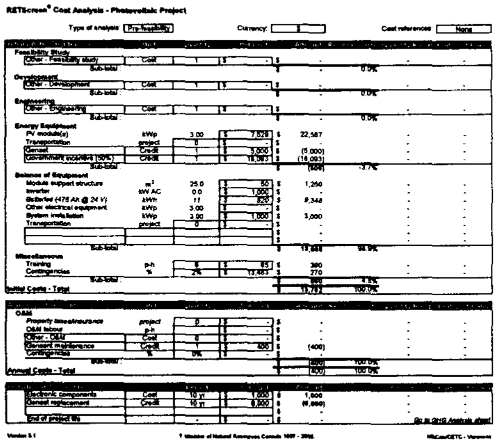


Figure 7. Cost analysis

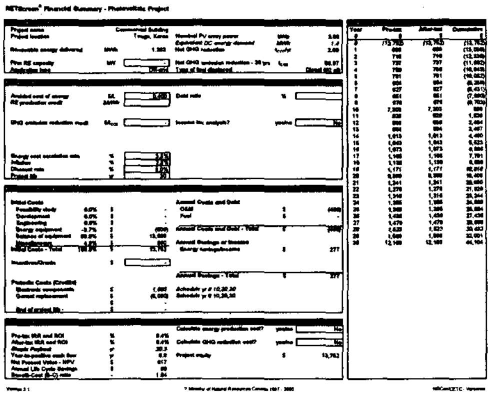


Figure 8. Financial summary

The figures present the analysis for the solar module efficiency of 12% only which is the maximum output of the PV modules under normal operating conditions. The cost of PV system per kW of power output used is KRW12.5M. The results are summarized in Table 2. It is evident from the results that end users will have cost benefits from the lower PV module temperatures. SWPV system can operate at a temperature which is 4-15°C lower than the BIPV system. The reduction in the temperature will trim down the size of the required PV system and related structure, however, the battery bank size will have no affect. Consequently, initial costs will also be lower which will reduce the simple payback period of the system. Figure 9 shows the variation of the PV system costs and corresponding payback period as a function of temperature. Higher PV module efficiency will lower the PV module and support structure costs but the battery costs will remain unchanged. Considering the typical temperature difference of 15°C for SWPV, the simple payback period will be about 1 year less than the BIPV system. However, this value will be much higher when the combine electrical and thermal output of the SWPV system is considered. The combined thermal and electrical efficiencies of SWPV systems are higher as compared the individual systems.

Table 2. Variation of simple payback period of PV system with operating temperature

Operating Temperature (°C)	PV efficiency (%)	Initial system cost* (M KRW)	Payback period (years)
25	12.0	13.752	20.3
40	11.5	14.282	21.1
55	11.0	14.858	22.0
70	10.5	15.490	22.9
85	10.0	16.184	23.9
100	9.5	16.952	25.1

* Initial costs are inclusive of 50% government incentive

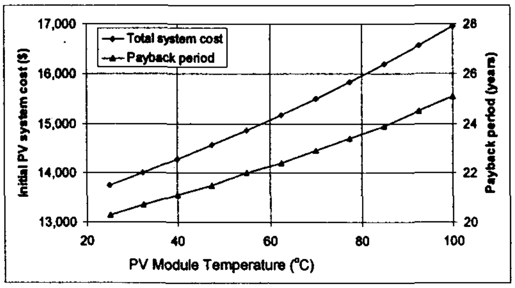


Figure 9. Impact of Solarwall on the payback periods and *initial system costs of PV system*

7. Conclusion

Photovoltaic module can generate electricity using sunlight without causing any environmental degradation. Due to higher fossil fuel prices and environmental awareness, PV applications are becoming more popular as clean source of electricity generation. PV output is sensitive to the operating temperature and can be drastically affected in Building Integrated PV systems. PV Solarwall combination has been studied to demonstrate the gain in the electrical output due to cooling of PV modules under forced ventilation. A 75W polycrystalline silicon PV module was fixed on SW in front of the ventilation fan as it was indicated to be the coolest position on the SW in phoenix simulations. The effectiveness of cooling by means of the forced ventilating air stream has been studied experimentally. The results indicate that there appears to be significant difference in temperature as well as electricity output comparing the SWPV and BIPV options. Electrical output power recovered is about 4% during the typical day of the month of February.

RETScreen® analysis of a 3kW PV system hypothetically located at Taegu has shown that with typical temperature reduction of 15°C, it is possible to reduce the simple payback periods by one year. However, the effect on the simple payback period will be more significant when both electrical and thermal outputs of the SWPV system are considered. The work is in progress for the evaluation of combined electrical and thermal performance of the SWPV system. The work described in this paper may be viewed as an appraisal of a SWPV system based on its improved electrical and financial performances due to its ability to operate at relatively lower temperatures.

References

[1] E. Radziemska, (2003), The effect of temperature on the power drop in crystalline silicon solar cells, Renewable Energy, 28(1), 1-12

[2] B.J. Brinkworth, B.M. Cross, R.H. Marshall and H. Yang. (1997), Thermal Regulations of Photovoltaic Claddings, *Solar Energy* **61** 3, p. 169-178

[3] R. Zakharchenko, L. Licea-Jiménez, S. A. Pérez-García, P. Vorobiev, U. Dehesa-Carrasco, J. F. Pérez-Robles, J. González-Hernández and Yu. Vorobiev (2004), Photovoltaic solar module for a hybrid PV/thermal system, Solar Energy Materials and Solar cells, 82(1-2), 253-261

[4] Hollick J. C. (1994), Unglazed solar wall air heaters, Renewable Energy, 5(1-4), 415-421

[5] Solar Cogeneration Panels, Renewable Energy, 15, 195-200

[6] J.A. Clarke, C. Johnstone, N. Kelly, P.A. Strachan, The simulation of photovoltaic-integrated building facades, in: Building Simulation '97, Prague, 1997, pp. 189–195

[7] Wolf HF, Semiconductors, New York, Wiley, 1971

[8] RETScreen International website: www.retscreen.net