THERMODYNAMIC AND ELECTRIC BEHAVIOUR OF A MONOCRYSTALLINE PHOTOVOLTAIC MODULE UNDER NATURAL WEATHER CONDITIONS

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ABSTRACT

In this work a complete thermal and electrical study is conducted for a commercial photovoltaic module of 34 monocrystalline silicon cells each of 10 cm. diameter. The output power, current, fill factor, plate temperature, and the module electrical resistance, were taken as dependent variables, whilst the solar intensity, light intensity, ambient temperature and wind speed were taken as independent variables. Several day-long experiments were conducted. It was found that the atmospheric effect of absorbing solar rays at different wavelengths, at different times, created variation in light intensity while solar intensity is constant. Thus, at constant solar intensity the module output is proportional to light intensity (lux) and inversely proportional to the plate temperature. The fill factor was found to be inversely proportional to the plate temperature, and the plate temperature was inversely proportional to the wind speed. The mathematical model was found to be suitable for describing the results to a high degree of accuracy.

INTRODUCTION

The public use of the photovoltaic electrical generators began to be feasible, specially in places where arrangements of infra-structure facilities are lacking. More use is expected in the future if prices continue to drop [1,2,3]. However even at today prices Wolf [4] states that for power generation of peak loads in the range (1-10) kWs the photovoltaic generators are cheaper than Deisel generators. In the cell, energy conservation occurs via light induced transition of the current carriers from ground state (neutral) to excited state. This produces a transport mechanism which conveys away the resulting excited electrons and holes and as they are unable to flow backwards and mix again to neutralize, they need an external path to do so. This produces the current [5].

Current flow and solar input, both cause an increase in the cell temperature. For any kind of cell the solar energy is divided into two parts: usable energy and unusable energy: According to the frequency the unusable energy increases the cell temperature. As the cell temperature increases, the output power decreases, and inlet electrical Resistance increases. Cooling the cell by increased wind speed is a powerful tool for keeping the cell cold, [6]. This work was carried out to bridge the gap between the thermal input-output balance and the electrical output of a model consisting of 34 monocrystalline photovoltaic cells, each of 10 cm. diameter. And to build a mathematical model which can symulate the arrangement properly and accurately.

THE EXPERIMENTAL ARRANGEMENT

The flat plate module of 34 cells each of 10 cm. diameters was erected at an angle of 45 degrees to a horizontal. The output terminals were connected in a way to measure both the voltage and the current. The output was fed to a rheostat in order to simulate a changing external loads. Several points for plate face and plat back temperatures were terminals for a cupper-constant thermocouple, a digital signal processor was used to read the temperatures. A pyranometer (kipp and Zonen solar integrator was used to measure the solar intensity. Light intensity in lux was measured using Wilh. Lambret GmbH model. Also wilhelm Lambrecht wind velocity indicator was used. At each quarter an hour the variables were recorded, at different rheostat settings from zero to maximum. The following parameters were recorded:

Plate face temperature, Tp.c
Plate back temperature, Tb.c
Ambient temperature, Ta.c.
Open circuit voltage, Voc v.
Short circuit current, Isc amp.
Load voltage and current, V,I.
Solar intensity normal to the module, Is W/m^2
Light intensity, Lux, lux.
Wind speed, V m/s.
Time, t,h.

The cell temperature differs from the plate temperature by a value of less than 2 °c.

MATHEMATICAL ANALYSIS

In this section the physical and mathematical relations of the energy conversion by the module are stated. An energy balance of heat in-heat out, and electrical output indicated. All this together formulate what is known as mathematical model.

The solar intensity vertical to the Plate and absorbed by the module is

$$Qs = Is\ A\ \beta\ E \qquad (1)$$

Where β is glass transmittance, Is is the solar intensity normal to the plate, E is the plate absorptivity and A is the module area.
The solar intensity absorbed by the glass is given by,

$$Qg = Is\ A\ E_g \qquad (2)$$

The heat transferred to the environment by convection is determined from,

$$Qc = h\ A\ (Tp - Ta) \qquad (3)$$

Where h is the convection heat transfer coeficient which can be found from the following equation, [8].

$$h = 5.6 + 18.6\ v \qquad (4)$$

Where v is the wind speed Ta is the ambient temperature and Tp is the plate temperature.
The rate of heat absorbed by the module and the cover is given by,

$$Hc = (m_C\ Cp_C + m_G\ Cp_g)\ dT/dt \qquad (5)$$

Where m is mass; Cp_c is specific heat of the m[...] Cp_g is the specific heat of the glass; and [...] temperature T is,

$$T = (Tp + Tb)/2$$

and t is time Tb is the module back temperature.
The rate of hear transferred to the back insulati[...] the module is given by,

$$Qb = (k/L)A\ (Tp-Tb) + m_b\ Cp_b\ (dTb/dt)$$

Where K is the insulation thermal conductivity; [...] insulation thickness; m_b is the insulation mass; C[...] the insulation specific heat capacity.
The maximum power output of the module ca[...] expressed by, [2].

$$Qo = Isc\ Voc\ Ff$$

Where Isc is the short circuit current; Voc the [...] circuit voltage and Ff the fill factor.
The heat produced inside the module due to cu[...] flow is calculated from,

$$H = (Voc - V)\ I = I^2\ R$$

Where V and I are load voltage and current.
The energy balance for the module is demonstrate[...] the equation,

$$Qs + Qg = Qc + Qb + Qo + Hc$$

A computer programme fed with module param[...] and solar data designed to evaluated the maxi[...] output power was introduced to an amstrad PC. [...] Basic language. Results were compared to experim[...] ones and exhibited in the results of this work.

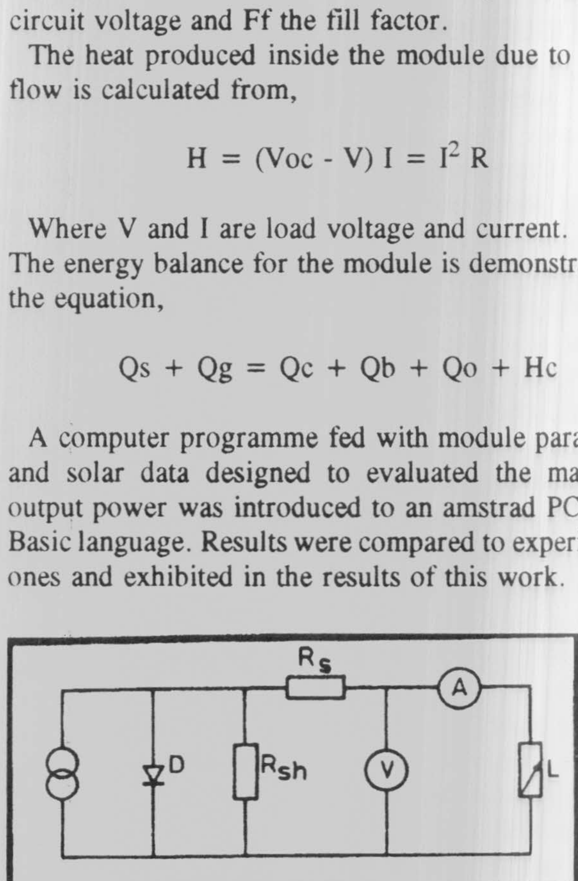

Figure 1. Equivalent circuit of the test arrangement.

DISCUSSION

The results of the different experiments of this work are illustrated in the figures shown at the end of this paper. Figure (1) shows the electrical equivalent circuit used in the experiment with the module as the source of power with diode (semiconductor) (D), and enternal resistance, on series (Rs) and on parallel (Rsh).

The voltage and the current are measured at different load settings by a rheostat. Weather parameters are shown in Figures (2,3,4) and (5), all of them included daily distribution values, these values included solar intensity (I) W/m^2, and wind velocity (v) in m/s, light intensity in (lux), and ambient temperature (Ta) in C. The solar intensity normal to the module surface for the three different experiments shown reached a maximum value of 460 W/m^2, local wind velocity ranged from 0-3 m/s, while the local light intensity reached a maximum value of about 109 lux. In the same time the ambient temperature varied within the range of 20 - 32 C.

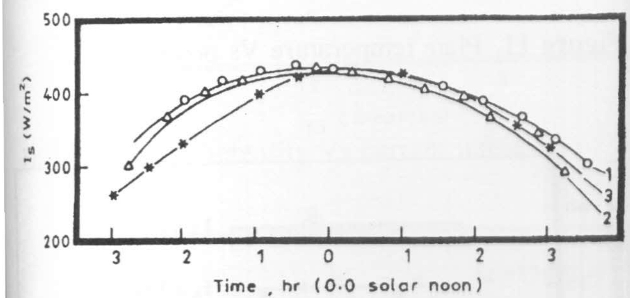

Figure 2. Daily distribution of solar intensity normal to the module.

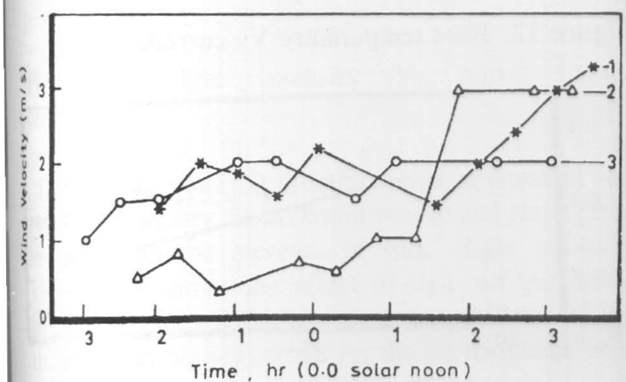

Figure 3. Wind velocity daily distribution.

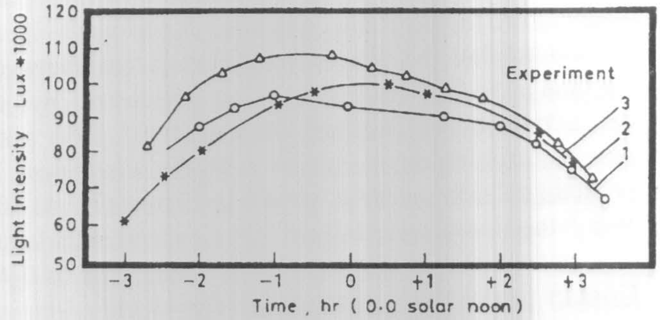

Figure 4. Light intensity, daily distribution.

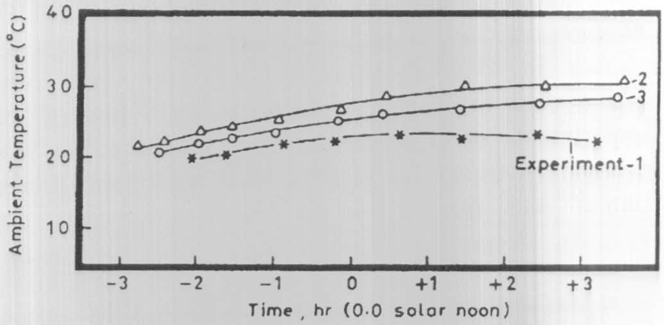

Figure 5. Ambient temperature, daily distribution.

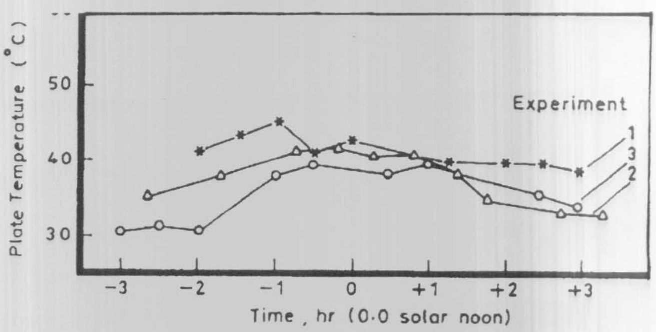

Figure 6. Plate temperature, daily distribution.

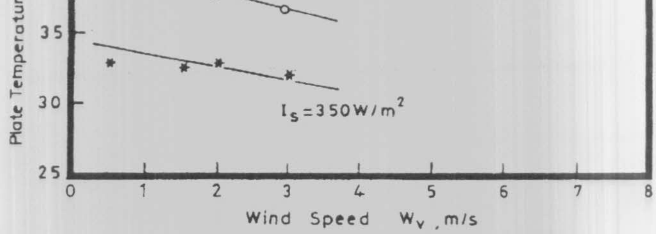

Figure 7. Wind speed Vs plate temperature.

Figure (6) shows daily distribution of the plate temperature for the three conducted experiments, it can be noticed that the plate temperature ranged between 30 and 45 C. This range is considered by all researchers as the normal working band. The plate temperature decreases linearly with the wind speed at constant solar intensity as shown in Figure (7). At 400 W/m^2 the line shows a slope of 1 C/ (m/s). this value can be compared with Servants value [9] of-0.48 C/(m/s) which was formulated for double glazing modules while this work modules a single glazing one, this caused the difference in the values, also it is comparable to Birgess et al results [6]. The I-V characteristic or the module for different readings are shown in Figures (8), (9) and (10) each was constructed for different readings from one of the experiments on a sequence form. These curves are commonly used to calculate the maximum power output and the fill factor, both parameters are considered essential for the performance of the module.

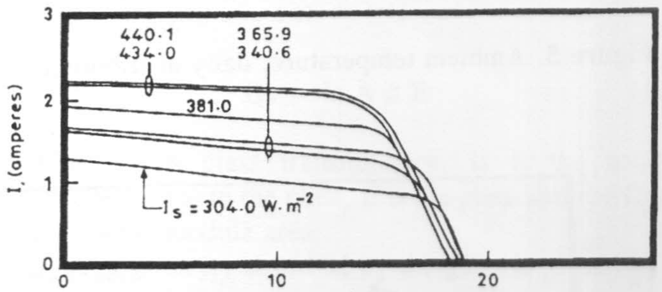

Figure 8. I-V curves, experiment No1 at differnt times.

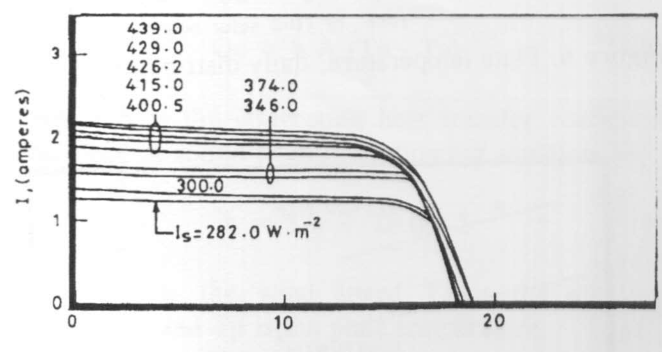

Figure 9. I-V curves, experiment No2 at differnt times.

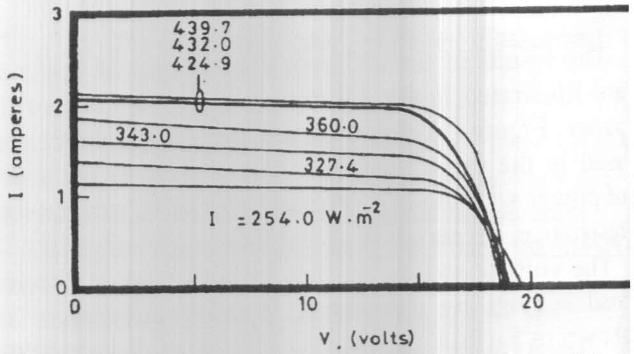

Figure 10. I-V curves, experiment No3 at differen times.

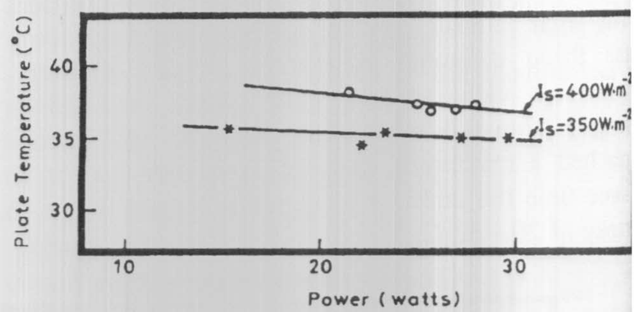

Figure 11. Plate temperature Vs power output.

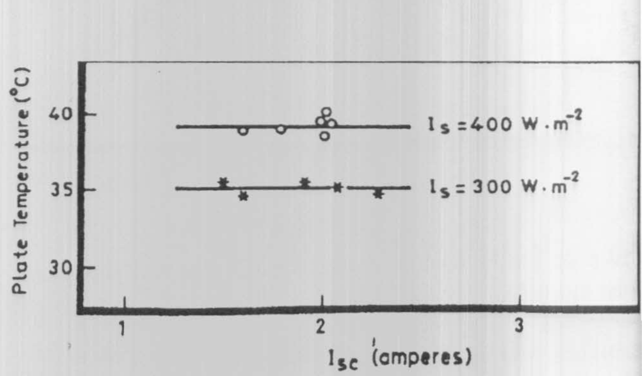

Figure 12. Plate temperature Vs current intensity.

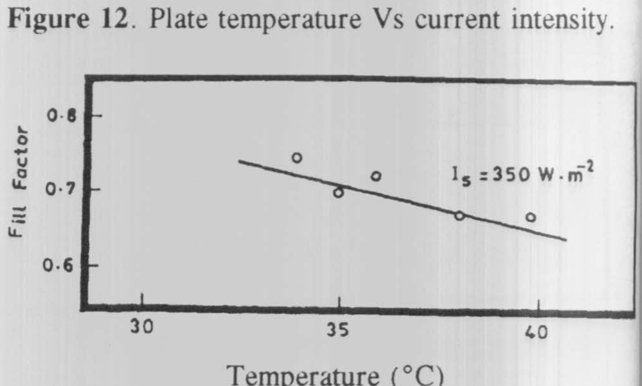

Figure 13. Fill factor Vs plate temperature.

The effect of the temperature on its performance is shown in Figures (11), (12) and (13) the maximum power output and the fill factor show a linear degradation of their values with the temperature increase in rates of -10 W/C and 0.01 C^{-1} respectively, while the short circuit current stays approximately constant. These results compares with literature results [5-10], while ref. [2] noticed a slight increases in the short circuit value of such cells with temperature increase which is not supported by this work. Degradation of both the maximum power and the fill factor supports the idea of keeping the plate temperature within the workable range, the generators design must take into consideration temperature effect on output specially in hot climatical and local conditions.

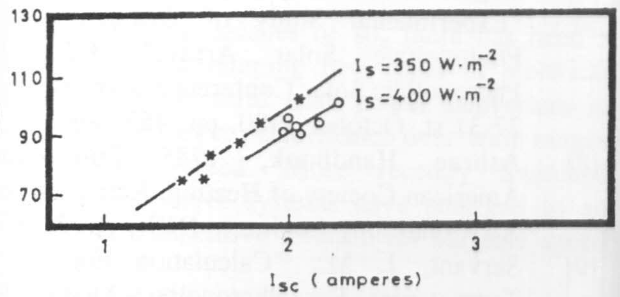

Figure 14. Light intensity Vs current intensity.

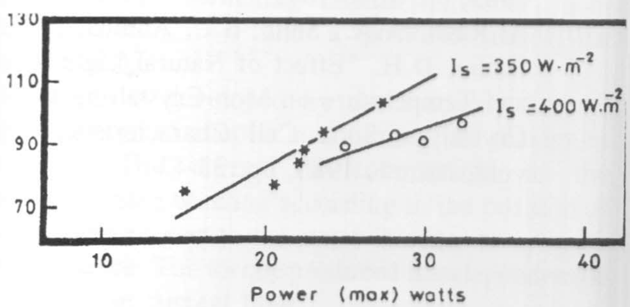

Figure 15. Light intensity Vs power output. (maximum).

Figure (14) and (15) illustrates that at constant solar radiation intensity, both output power and short circuit increase with the increase of flux. (light intensity). This clearly shows the effect of light on the module output, and shows that the wave length band of light radiation has higher, effect on the performance of the photovoltaic modules than other wave lengths.

Figures (16) and (17) illustrates the influence of the load values on the output current and voltage quantities, such curves must be consulted in any design attempt of generators, knowledge of the load and modules behaviour are essential. Results of Rogers et al work [6] agrees with these results. Computer simulation program results using the mentioned mathematical analysis are shown in Figure (18). Experimental results are shown on the same figure, a good agreement is exhibited with slight differences attributed to common experimental errors. Computer simulation programmes can also be a suitable tool for the design of photovoltaic generators.

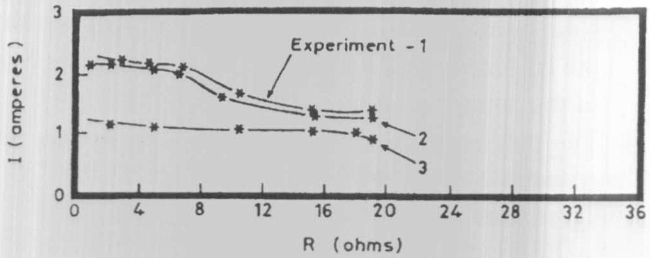

Figure 16. Load resistance (R) Vs output current.

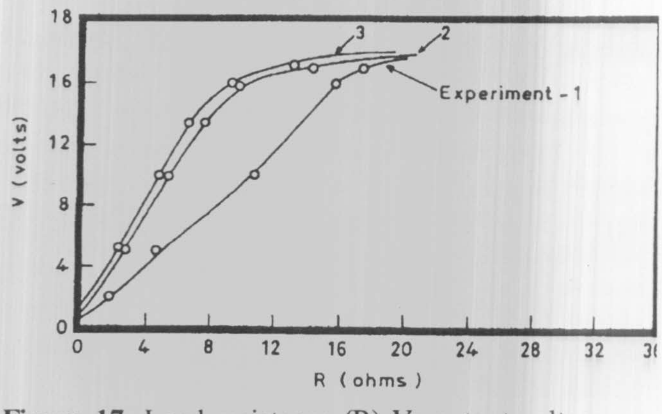

Figure 17. Load resistance (R) Vs output voltage.

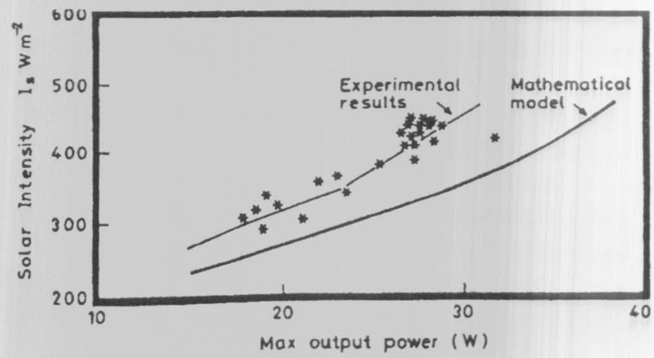

Figure 18. Solar intensity Vs power output.

CONCLUSION

As a result of this study fixed conclusions are reached for the photovoltaic systems:

1- Plate temperature decreases when wind speed increase and a linear relation exists. The single glazing is better for cell cooling.
2- Plate temperature increase has the following effects: Module resistance increases; short circuit current keeps constant; output power decreases and fill factor decreases.
3- Light intensity increases the output power even if solar intensity is kept constant. This suggests that the frequency range of light is he most useable band of the solar radiation.
4- The mathematical analysis which uses thermal and electrical power equilibrium gave results in a good agreement with the experimental results.

REFERENCES

[1] Mahmoud. M., Nabhan, I. and Daoud, K. "Photovoltaic Activities of Jordanian Royal Scientific Society". Proceedings of the International Conference of Energy Systems, Amman, May 15-17 th., 1989, pp. 121-141.

[2] Green. M.A. "Solar Cells, Operating Principles, Technology and System Applications". Printice hall, Englewood, Cliffs, New Jersey, 1982.

[3] Sartawy, M. "Plate Voltaic System F Electrical Peak Shaving, Kuwait Case Proceedings of the International Conference Energy Systems Amman, May 15-17 th. 198 pp. 279-288.

[4] Wolf. P.R, "Photovoltaic Power For T People" Solar World Forum, Pergamon pres 1981, pp. 2743-2749.

[5] Fonash. S.J. "Solar Cell Device Physics Academic press, 1981, pp. 1-4.

[6] Birgess E.L. and Shafer, B.O. "Operatio Reliability and Maintenance Experience W Photovoltaic Concentrator Arrays". The 3 r E.E.C. Photovoltaic Solar Energy Conferenc Cannes, France, 27-31 st. October 1980, p 360-367.

[7] Roger. J.A., Fayolle, P. and Pivot, "Experimental Study of Disequilibriums Photovoltaic Solar Arrays" 3rd E.E.C Photovoltaic Solar Conference, Cannes, Franc 27-31 st. October 1980, pp. 485-489.

[8] Ashrae Handbook, 1985 Fundamental American Cociety of Heating, Refrigeration ar Air-Conditiong Engineers INC., pp. 3.16-3.2

[9] Servant, J. M., "Calculation For the Ce Temperature For Photovoltaic Module Fro Climatic Data", Intersol- 85, Pergamon pres 1985, pp. 1640-1642.

[10] Al-Rawi. N.A., Salih, S.I., Ahmed, M.F. ar Hamo, D.H. "Effect of Natural Light Intensi and Temperature on Mon-Crystalline and Pol Crystalline Solar Cell Characteristics" JSE vol3, No., 1, 1985, pp. 33-43.