Design of PV Modules Including a Layer between Solar Cells and Glass Cover to Increase PV Module Lifetime

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ABSTRACT

Nowadays, design of the modules of the solar cells (PV modules) makes these cells completely attached to the coat of the glass. Therefore, damaging of the cover glass lead to replace the PV module totally. Furthermore, it is means loss in the solar cells despite being correct and does not damage. This paper proposed solution based on a lamination layer between solar cells and the tempered glass of the PV module to show the feasibility from these PV modules even after the cover glass damaging.

Keywords

Anti-Reflecting Coating Layer (ARC Layer), Photovoltaic modules (PV modules).

1. INTRODUCTION

This work studies the effect of the lamination layer between solar cells and the tempered glass of the PV module, such a layer enables one to replace only the tempered glass in case of its damage instead of replacing the PV module totally. Thus, the cost of replacement of PV modules at the end of its lifetime is drastically reduced. As a result, a significant reduction in PV systems cost may be achieved.

ZHU, in [1] presents the effects of lamination condition on durability of PV module packaging and performance.
Laminating PV modules with EVA using solar ovens is presented in [2] by Richard Komp.
In [3], Kamal Alameh discusses the solar energy harvesting clear glass for building-integrated photovoltaics.

The paper is organized as follows. Section 2 shows the analysis of incident light on solar cell. Section 3 introduces the results of the system. Finally, the paper is concluded in section 4.

2. ANALYSIS OF INCIDENT LIGHT ON SOLAR CELL

In this paper, the proposed design is classified into two sections: calculating the reflected power (*r*) from a silicon solar cell at normal incidence case and in the proposed design case.
Some parameters played an important role in the results of calculating the reflected power (*r*) such as the refractive index of anti-reflecting coating (n_{ARC}), incidence angle from the sun (θ_{inc}), refractive index of lamination (n_{lam}) and the incidence wavelength (λ_{air}).

2.1 Normal Incidence

The equations used at normal incidence are:
Snell's law is depicted in equation (1) [4].

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i} \tag{1}$$

Under normal incidence conditions: $\theta_i \to 0$ and $\theta_r \to 0$, then

$$\sin(\theta_i - \theta_r) \approx \tan(\theta_i - \theta_r) \approx \theta_i - \theta_r \tag{2}$$

$$\sin(\theta_i + \theta_r) \approx \tan(\theta_i + \theta_r) \approx \theta_i + \theta_r \tag{3}$$

Then from Fresnel's equation the reflected power (*r*) is given in equation (4).

$$\mathbf{r} = \frac{1}{2}\left[\frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)}\right] \tag{4}$$

Combining equation (4) through equations (2, 3) then one finds equation (5).

$$\mathbf{r} = \left(\frac{n_r - n_i}{n_r + n_i}\right)^2 \tag{5}$$

Note that normal incidence case always measured in case of two axis tracking system.

2.2 The Proposed Design

The proposed design depends on some important factors such as:

a) Incidence angle from the sun (θ_{inc})
b) Input wave length from the air (λ_{air})
c) Refractive index of lamination (n_{lam})
d) Refractive index of anti-reflecting coating (n_{ARC})

All these parameters used in Snell's law and substituted in equation (4). So, the reflected power (*r*) is calculated and the absorption coefficient in silicon solar cell in the two cases of equations (4, 5) can be calculated from equation (6).

$$\alpha_{\text{abs in Si}} = 1 - r \tag{6}$$

The proposed design works under some conditions:

Table 1. Constant parameters in the proposed module

Parameter	Value
I_{sco} (G=1Kw/m^2)	8.27 A
V_{oc}	33 V
I_{mp}	8 A
V_{mp}	25 A
V_T	2.34 V
I_o	6.126 μ A

Finally, all the equations used in the proposed system to get the energy and the power for the designed module are.

2.2.1 Declination angle (δ)

Declination angle is described into equation (7) [5, 6].

$$\boldsymbol{\delta = 23.45\sin\left[\left(\frac{284+d}{365}\right) * 360^{o}\right]} \qquad (7)$$

The monthly average values of declination angle (δ) and the corresponding average day every month is indicated in table (2).

Table 2. Monthly average declination angles

Month	Date	Day of year (*d*)	Declination angle (δ°)
January	17th Jan.	17	-20.9
February	16th Feb.	47	-13.8
Marth	16th Mar.	75	-2.4
April	15th Apr.	105	+9.4
May	15th May	135	+18.8
June	11th June	162	+23.1
July	17th July	198	+21.2
August	16th Aug.	228	+13.5
September	15th Sep.	258	+2.2
October	15th Oct.	288	-9.6
November	14th Nov.	318	-18.9
December	10th Dec.	344	-23.0

2.2.2 Hour angle (ω)

Hour angle is described into equation (8).

$$\omega = \frac{\pi}{12}(t-12) \qquad (8)$$

2.2.3 Incidence angle (Θ_T)

Incidence angle is described into equation (9) [13].

$$\boldsymbol{cos\theta_T = \cos(\Phi-\beta)\cos\delta\cos\omega + \sin\delta\sin(\Phi-\beta)} \quad (9)$$

Equation (9) is valid for any tilted surface facing the equator.

If such condition (of facing equator) is not fulfilled, then one has to consider the general case considered in the next section.

Let us now consider on interesting special case where the tilt angle (β) is equal to the latitude angle (Φ) under this condition equation (9) becomes equation (10).

$$\cos\Theta_T = \cos\delta\cos\omega \qquad (10)$$

$$\boldsymbol{\Theta_T = \cos^{-1}[\cos\delta\cos\omega]} \qquad (11)$$

The angle of incidence of solar beams on a horizontal surface in a place having latitude (Φ) is given from equation (12).

$$\boldsymbol{\cos\Theta_h = \cos\Phi\cos\delta\cos\omega + \sin\delta\sin\Phi} \qquad (12)$$

2.2.4 Sunset Hours (ω_s)

From equation (12), at sunset $\Theta_h = \pi/2$ when $\omega = \omega_s$ yields, equation (13) [7]-[9].

$$\boldsymbol{\omega_s = \cos^{-1}[-\tan\delta\tan\Phi]} \qquad (13)$$

Now let us determine the sunshine duration on a surface tilted by an angle (β), where equation (9) is applicable.

The sun beams are tangent to the tilted surface when $\omega = \omega_s''$ and $\Theta_T = \pi/2$, using equation (9) yields to equation (14) [8, 9].

$$\boldsymbol{\omega_s'' = \cos^{-1}[-\tan\delta\tan(\Phi-\beta)]} \qquad (14)$$

In the proposed design the tilt angle (β) equals to the latitude angle (Φ) under this condition ($\Phi = \beta$) equation (14) becomes

$$\boldsymbol{\omega_s'' = \frac{\pi}{2}}$$

The sunset hour angle on tilted surface (ω_s') is always less than or equal to sunset hour angle on horizontal surface thus one can write the following formula represented in equation (15) [7].

$$\boldsymbol{\omega_s' = \mathrm{Min}(\omega_s \text{ and } \omega_s'') = \mathrm{Min}(\omega_s \text{ and } \frac{\pi}{2})} \qquad (15)$$

Which mean that (ω_s') is the minimum value of either (ω_s) given by equation (13) and (ω_s'') given by equation (14).

2.2.5 Clearness Index (K_T)

Clearness index (K_T) which is defined in [10].

$$\boldsymbol{K_T = \frac{H_B}{H_{ext.}}} \qquad (16)$$

Where (H_B) is the global solar radiation on a horizontal surface and its value is given from table (3) [11].

Table 3. Monthly average global solar radiation on horizontal surface

Month	H_B (KWh/m^2/day)
January	3.3
February	4.5
Marth	5.7
April	6.6
May	7.5
June	7.8
July	7.7
August	7.2
September	6.2
October	5.0
November	3.5
December	3

And (H_{ext}) is the monthly average daily extraterrestrial solar insolation (KWh/m^2/day) on horizontal surface at the same latitude (Φ) of the site under consideration and can be calculated from equation (17) [10, 11].

$$\boldsymbol{H_{ext} = \frac{24}{\pi} G_{sc}[\cos\delta\cos\Phi\sin\omega_s + \omega_s\sin\delta\sin\Phi]} \qquad (17)$$

Note that the extraterrestrial solar irradiance (KW/m^2) on a surface normal to solar beams is constant and equal to the solar constant (G_{SC} =1.35KW/m^2) [12].

In the proposed design the latitude angle (Φ =30 ^{o} north) in Cairo.

2.2.6 The factor (R_b)

The ratio between direct solar radiations on tilted surface to that on a horizontal surface (R_b) is described into equation (18).

$$R_b = \frac{\cos\delta\cos(\Phi-\beta)\sin\omega_s' + \omega_s'\sin(\Phi-\beta)\sin\delta}{\cos\delta\cos\Phi\sin\omega_s + \omega_s\sin\Phi\sin\delta} \qquad (18)$$

2.2.7 The global radiation (H_T)

The global radiation (direct plus diffused) on a tilted surface can be obtained from equation (19).

$$H_T = H_B[1.13K_T R_b + 0.5(1+\cos\beta)(1-1.13K_T) + 0.5\rho 1{-}\cos\beta \qquad (19)$$

Where (ρ) is the reflectivity of ground ($\rho = 0.2$ for normal ground and 0.7 for snow).

2.2.8 The instantaneous solar irradiance (G_T)

$$G_T = \frac{\pi}{24} H_T \frac{\cos\omega - \cos\omega_s''}{\sin\omega_s' - \omega_s'\cos\omega_s''} \qquad (20)$$

Equation (20) gives the instantaneous solar irradiance on tilted surface if the solar radiation on horizontal surface (H_B) is known; table (3) gives Monthly average global solar radiation on horizontal surface (H_B).

2.2.9 The array current (I_A)

From equations (4, 6 and 20) and from the constant parameters of the proposed design from table (1).The current of the array can be calculated from equation (21).

$$I_A = \alpha I_{sco} G_T - I_0 e^{\frac{V}{V_T}} \qquad (21)$$

2.2.10 The generated electric power and energy

$$P = I_A * V_B \qquad (22)$$

$$E_n = V_B I_A \Delta t + E_{n-1} \qquad (23)$$

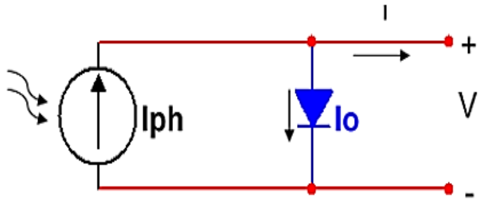

Fig 1: Equivalent circuit of ideal solar cell

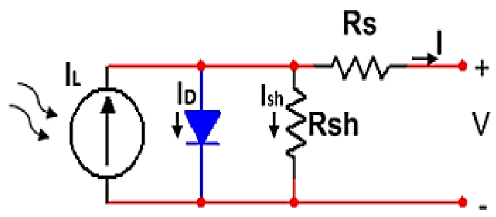

Fig 2: Equivalent circuit of real solar cell

3. RESULTS FROM MATLAB AND EXCELL SHEET CALACULATIONS

3.1 Normal Incidence

In this case we discuss the effect of Refractive index of anti-reflecting Coating (n_{ARC}) and incidence angle from the sun (Θ_{inc}) on the absorption Coefficient of silicon solar cell (α_{abs}).

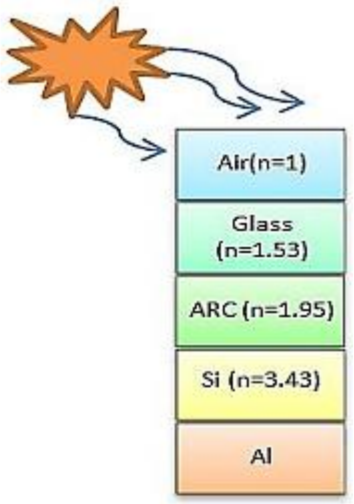

Fig 3: Layers of ideal solar cell at normal incidence

Table 4. Relation between the refractive index of antireflecting coating and the absorption coefficient of silicon solar cell

n_{ARC}	α abs in Si
1.5	0.847
2	0.931
2.5	0.975
3	0.996
3.5	0.99989797
4	0.994
4.5	0.982
5	0.965

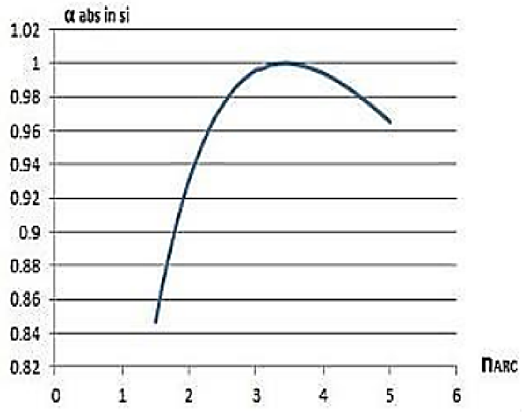

Fig 4: Relation between the refractive index of antireflecting coating and the absorption coefficient of silicon solar cell

Table 5. Relation between the incidence angles from the sun and the absorption coefficient of silicon solar cell

Θ_{inc}	$\alpha_{\text{abs in Si}}$
10	0.924323876
20	0.924303705
30	0.924227208
40	0.924043271
50	0.923718489
60	0.923267873
70	0.922776515
80	0.922386424
90	0.922236845

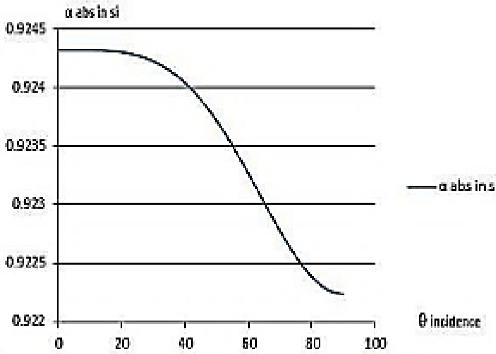

Fig 5: Relation between the incidence angles from the sun and the absorption coefficient of silicon solar cell

Table 6. Some results of the energy and the generated power from the proposed design at normal incidence

T (hour)	Θ_T (degree)	α (rad)	G_T (Kw/m^2)	I_A (A)	E_n (Whr)	P (W)
7	74.96	0.9225	0.221	1.36	13.855	34
7.5	67.47	0.9229	0.326	2.14	31.7	53.5
8	59.97	0.9233	0.426	2.88	64	71.9
8.5	52.47	0.9236	0.518	3.56	105.16	89
9	44.98	0.9239	0.602	4.18	154.37	104
9.5	37.48	0.9241	0.675	4.73	210.76	118
10	29.98	0.9242	0.737	5.18	273.3	129
10.5	22.49	0.9243	0.786	5.54	340.86	138
11	14.99	0.9243	0.824	5.81	412.22	145
11.5	7.49	0.9243	0.843	5.97	486.12	149
12	0	0.9243	0.85	6.02	561.22	150

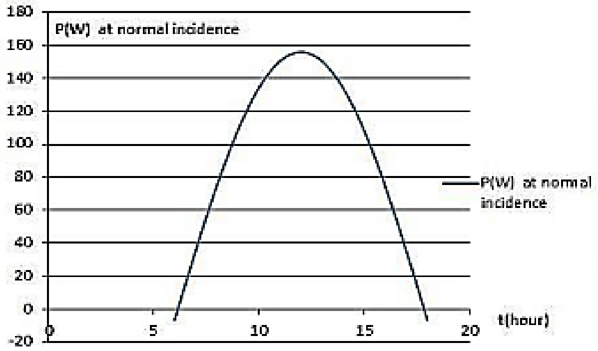

Fig 6: Generated power from the proposed design at normal incidence

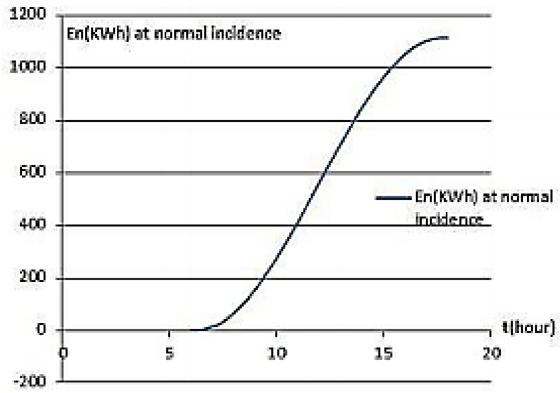

Fig. 7: Generated energy from the proposed design at normal incidence

3.2 The Proposed Design

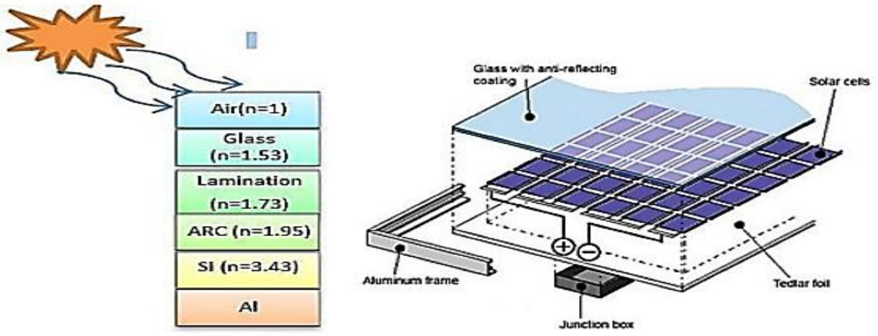

Fig 8: Layers of real solar cell in the proposed design

Table 7. Some results of the generated energy and power from the proposed design at 15th September

T (hour)	Θ_T (degree)	α (rad)	G_T (Kw/m^2)	I_A (A)	E_n (Whr)	P (W)
7	74.97	0.9226	0.228	1.42	15.99	35.4
7.5	67.48	0.9229	0.337	2.22	39.78	55.5
8	59.99	0.9233	0.440	2.98	73.32	74.6
8.5	52.51	0.9236	0.536	3.69	115.99	92.3
9	45.02	0.9239	0.622	4.33	167.01	108.3
9.5	37.54	0.9241	0.698	4.89	225.46	122.3
10	30.06	0.9242	0.762	5.37	290.27	134.2
10.5	22.6	0.9243	0.813	5.74	360.27	143.6
11	15.15	0.9243	0.850	6.02	434.21	150.4
11.5	7.82	0.9243	0.872	6.18	510.77	154.6
12	2.22	0.9243	0.880	6.24	588.58	155.9

Table 8. Some results of the generated energy and power from the proposed module at 16th Marth

T (hour)	Θ_T (degree)	α (rad)	G_T (Kw/m^2)	I_A (A)	E_n (Whr)	P (W)
7	74.97	0.9226	0.228	1.37	15.35	34.26
7.5	67.48	0.9229	0.327	2.15	38.38	53.82
8	59.99	0.9233	0.428	2.89	70.89	72.35
8.5	52.51	0.9236	0.521	3.58	112.29	89.55
9	45.02	0.9239	0.605	4.20	161.80	105.11
9.5	37.54	0.9241	0.679	4.75	218.54	118.76
10	30.06	0.9242	0.741	5.21	281.45	130.25
10.5	22.6	0.9243	0.790	5.58	349.42	139.4
11	15.15	0.9243	0.826	5.84	421.22	146.05
11.5	7.82	0.9243	0.848	6.00	495.56	150.08
12	2.22	0.9243	0.855	6.06	571.12	151.43

Note that all the results after time (t=12 hour) repeated it self.

Similar as the results before (t=12 hour) in table (6, 7 and 8).

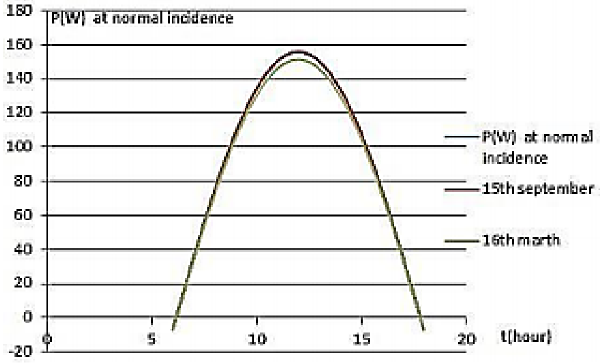

Fig 9: Generated power from the proposed design at normal incidence, 15th Sep and 16th Marth

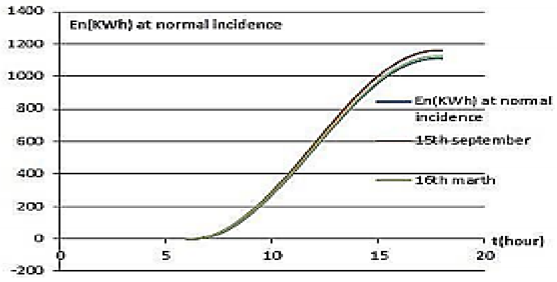

Fig 10: Generated energy from the proposed design at normal incidence, 15th Sep and 16th Marth

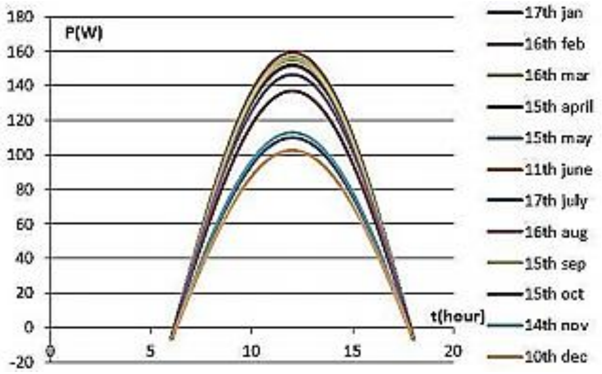

Fig 11: The monthly average daily generated power in the proposed design

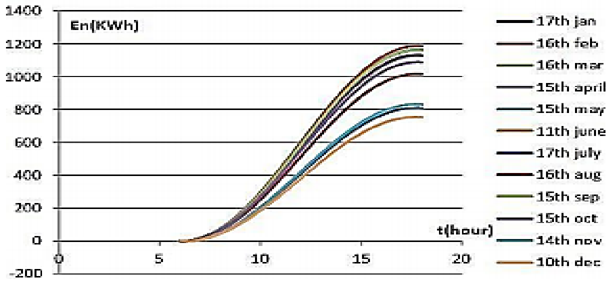

Fig 12: The monthly average daily generated energy in the proposed design

4. CONCLUSION

This paper introduces a full operational and low cost of the proposed system to preserve the solar cells from damage. It is done by placing a layer between the cells and the glass layer. In addition, the damaged glass is replaced only and not eliminates the solar cell completely. In the proposed system, the actual factors affecting on the solar cell are the angle of free fall and refractive index of the Anti-reflecting coating layer but the effect of the proposed layer was simple compared to them.

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