A Novel Technique for PV Panel Performance Prediction

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ABSTRACT
Today majority of the methods used to measure the performance of a Photo-Voltaic panel are based on conversion efficiency; they do not take into consideration factors such as temperature and internal resistance variations on which output power of Photo-voltaic (PV) panels depends thus leading to an incomplete measure of real time performance. Also most of the methods require isolating panels from the grid, which makes it a cumbersome and expensive practice. To monitor real time performance of PV panels on the field an accurate and robust technique is essential which overcomes above deficits. In this paper such a simple and novel technique is proposed to accurately predict the PV module performance based on a key measure known as Fill Factor. This technique is implemented by means of a cost effective prototype. This prototype device continuously monitors the PV panel taking into consideration the effect of varying meteorological parameters and warns the user if it is not performing as per operational standards. The device functions while the panel is connected in a power grid without the need to disconnect and requires human intervention only after a fault is detected.

General Terms
Renewable Energy, Embedded Systems, Measurement, Design, Performance, Experimentation.

Keywords
PV panels; grid-connect; I–V curve; Short-circuit current; Open-circuit voltage; Fill factor; Maximum power Output; Solar panel health ; monitoring systems; renewable energy.

1. INTRODUCTION
Renewable energy can play an important role in meeting the ultimate goal of replacing large parts of fossil fuels. One of the promising applications of renewable energy technology is the installation of PV systems to generate power without emitting pollutants while requiring no fuel. Despite relatively low power density of solar energy, this resource could potentially satisfy the global energy demand on its own[6].

In recent years, there has been a sharp decline in capital costs for solar PV plants. PV module prices have fallen a sharp 80% in the last five years and 30% during last year alone. A very long life of around 20-30 years and negligible maintenance is guaranteed by most of the manufacturers of the solar PV modules [6]. Thus, once installed consumers don't bother to check if the panels are performing up to the standards. But it is important to note that reduction in performance of a single PV panel can hamper the overall efficiency of both on-grid and off-grid systems. If care is taken to check its health status and provide it with the necessary treatment then the solar PV systems will last long while generating maximum power.

The performance of a PV module strongly depends on the availability of solar irradiance at the required location and the PV-module temperature. A lot of work has been done on analysis of the environmental factors that influence PV module performance [1–4]. Kerr and Cuevas [2] presented a new technique, which can determine the current–voltage (I–V) characteristics of PV modules based on simultaneouslymeasuring the open-circuit voltage V_{oc} as a function of a slowly varying light intensity [1].

The objective of this paper is to describe a new approach to performance measurement of a PV panel based on Fill Factor. A prototype is developed based on it, which estimates the actual performance of the PV panels under varying operating conditions, with acceptable precision and no complex iteration involved in the calculation. It allows one to find out the performance of a PV module at any time in the field requiring human intervention in case of some fault at a very cost-effective rate. The equations that we have employed to calculate these parameters are in accordance with a simple model [1] with acceptable precision.

In this paper, first we establish the requirement of a solar panel health monitor by briefly listing the most likely causes of solar panel degradation and describe their impact on conversion efficiency. Second, we introduce Fill-Factor as a reliable measure of real-time performance of solar panel and thus as an indicator of its health. Third, we illustrate the calculation of Fill-Factor by defining the electrical parameters involved along with their equations. Finally, we present the design and implementation of our device and the results of the performance evaluation of our panel under test.

2. NEED FOR A SOLAR PV PANEL MONITOR
A reliable PV module should perform its intended purpose adequately under all operating conditions encountered. Nevertheless, there are several degradation mechanisms which may reduce the power output or cause the module to fail. Degradation in module performance is mainly caused by

- Increases in series resistance(R_S) due to decreased adherence of contacts or corrosion (usually caused by water vapor);
- Decreases in shunt resistance(R_{SH}) due to metal migration through the p-n junction; or
- Anti-reflection coating deterioration.
- Ageing
- Cell breakage

These become major issue while installing megawatt PV farms where it is important tokeep the rate of production steady.

2.1 Effect of shading

PV modules are very sensitive to shading; unlike a solar thermal panel which can tolerate some shading; many brands of PV modules cannot even be shaded by the branch of a leafless tree. Even thick or thin coat of dust and bird droppings on the panels causes shading. Partial-shading even of one cell of a 36-cell module reduces its power output. Because all cells are connected in a series string, the weakest cell will bring the others down to reduced power level. Therefore, whether ½ of one cell is shaded, or ½ a row of cells is shaded, the power decrease will be the same and proportional to the percentage of area shaded.

However, since it is impossible to prevent occasional shading, almost all panels of the solar panels that are offered come with by-pass diodes integrated right into the module itself [7]. In spite of the protective diodes, hot spot heating is likely to take place due to large currents flowing through them when a large number of solar panels are connected in a network. If this problem is not detected early, it may ultimately result in the failure of the whole PV system.

Moreover, power output of even a healthy PV panel is dependent on varying atmospheric conditions which deviates from the output rating quoted by the manufacturer, which is measured in the laboratory at Standard Test Conditions (STC, i.e. the solar spectrum AM1.5, 1000 W/m^2 solar radiation intensity, 25°C module temperature and 2 mph wind speed). Therefore there is a need of parameter to evaluate the actual performance of PV panel, which is able to map the panel output with the varying atmospheric conditions; Fill factor satisfies these requirements (neglecting wind speed and spectrum effects).

2.3 Fill-Factor

The Fill Factor (FF) is essentially a measure of quality of the solar cell. It is a measure of the deviation of the real I-V characteristic from the ideal one. FF can be interpreted graphically as the ratio of the rectangular areas depicted in Figure 1.

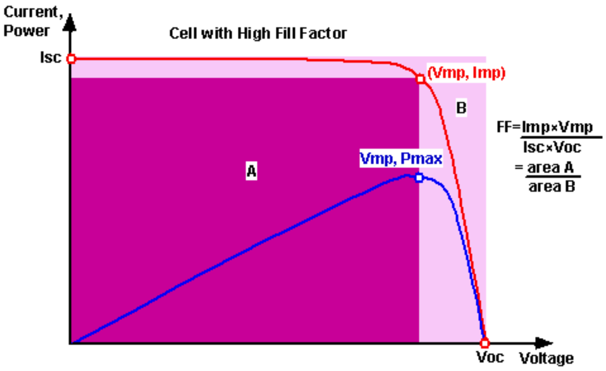

Figure 1: A typical current-voltage I-V and maximum power curve[10].

This is a dimensionless quantity; it is calculated by comparing the maximum actual power (P_{max}) that can be delivered to the load to the maximum theoretical power (P_T). At P_{max}, the output voltage of the solar cell is called V_{mpp} and the output current is called I_{mpp}. P_T is the power when the output voltage is equal to open circuit voltage (V_{oc}) and output current is equal to the short circuit current (I_{sc}) [1].

It is defined as ratio of the product of V_{mpp} and I_{mpp} and the product of I_{sc} and V_{oc} as in (1) [8].

$$FF = \frac{P_{max}}{V_{oc}\ I_{sc}} = \frac{I_{mpp} V_{mpp}}{V_{oc} I_{sc}} \quad (1)$$

The Fill Factoris a key parameter in evaluating the performance of solar cells. It remains constant for a set of operating temperature and irradiation, provided the Solar Cells of a Panel are working normally.

A reduction in the value of Fill Factor of a particular panel below its optimum value indicates degradation of the Panel. PV cells with a high fill factor have a low equivalent series resistance anda high equivalent shunt resistancethus thecurrent dissipation losses in the PV cell are reduced.

3. CALCULATION OF FILL-FACTOR

To calculate the value of FF, we require values of output electrical parameters I_{mpp}, V_{mpp} , I_{sc} and V_{oc} ; I_{mpp} and V_{mpp} are the current and voltage output of a solar panel operating at maximum power point, these can be measured directly with the help of meters. However, direct measurement of Isc and V_{oc} is not possible. To measure I_{sc}, it is required to short circuit the panel terminals and for V_{oc} the panel is required to be disconnected from load each time; which are not practical for both on grid and off-grid PV systems. Thus, they are modeled as a function of temperature and irradiance.

3.1 Short-circuit current I_{sc}:

It is the largest value of the current generated by a cell. At normal levels of solar irradiance, the short-circuit current can be considered equivalent to the photocurrent which is proportional to the solar irradiance, G(W/m^2). But this may result in some deviation from the experimental result, so a power law having exponent α is introduced in this paper to account for the non-linear effect that the photocurrent depends on. The short circuit current Isc of the PV modules is not strongly temperature dependent. It tends to increase slightly with increase of the module temperature. For the purposes of PV module performance, modeling this variation can be considered negligible. Then theshort-circuit current I_{sc} can be simply calculated by the following equation,

$$I_{sc} = I_{sc0}\left(\frac{G}{G_0}\right)^{\alpha} \quad (2)$$

where I_{sc0} is the short-circuit current of the PV module under the standard solar irradiance G_0; while Isc is the short-circuit current of the PV module under the solar irradiance G; α is the exponent responsible for all the non-linear effects on which the photocurrent depends [1].

3.2 Open-circuit voltage V_{oc}

It corresponds to the voltage drop across the diode (p-n junction), when it is transversed by the photocurrent only. It reflects the voltage of the cell at night. The relationship of the open-circuit voltage to irradiance is known to follow a logarithmic function based on an ideal diode equation, and the effect of temperature is due to the exponential increase in the saturation current with an increase in temperature. This conclusion causes some difficulties in replicating the observed behaviors of the tested PV modules. Additional terms or some amendatory parameters must be introduced to account for the shunt resistance, series resistance and the non-ideality of the diode. Taking into account the effect of temperature, the open-circuit voltage V_{oc} at any given conditions can be expressed by the following equation,

$$V_{oc} = \left(\frac{T_0}{T}\right)^{\gamma} \frac{V_{oc0}}{1+\beta \ln\frac{G0}{G}} \quad (3)$$

Where,V_{oc} and Voc_0 are the open-circuit voltage of the PV module under the normal solar irradiance G and the standard solar irradiance G_0, respectively; β is a PV module technology specific related dimensionless coefficient; and γ is the exponent considering all the non-linear effects of temperature on voltage [1].

3.3 Model parameter estimation

To carry out the simulation, the three parameters (α, β, γ) in the model need to be determined first. Beside the data from the specification sheet, a limited number of basic test data are needed, i.e. I_{sc},V_{oc} of the PV module under two different solar irradiance intensities (G_0,G_1) and two PV module temperatures (T_0,T_1) must be used to find the three parameters as follows.

$$\alpha = \frac{ln\left(\frac{I_{sc0}}{I_{sc1}}\right)}{ln\left(\frac{G_0}{G_1}\right)} \quad (4)$$

In (4) I_{sc} and I_{sc1} are the short-circuit currents of the PV module under radiation intensity G_0 and G_1, respectively.

In order to calculate the parameter β, the PV module temperature is assumed to be constant,and the solar irradiance changes from G_0 to G_1,and then the parameter β can be calculated as given in the following equation,

$$\beta = \frac{\left(\frac{V_{oc0}}{V_{oc1}}\right)-1}{ln\left(\frac{G_0}{G_1}\right)} \quad (5)$$

where,Voc0 and Voc1 are the open-circuit voltage of the PV module under the solar irradiance of G_0 and G_1 while the PV module temperature remains to be T_0.
Similar to the method used in the parameter calculation, the solar irradiance remains stable, while the PV module temperature changes from T_0 to T_1, and then the parameter γ can be estimated according to as given by the following equation,

$$\gamma = \frac{ln\left(\frac{V_{oc0}}{V_{oc1}}\right)}{ln\left(\frac{T_1}{T_0}\right)} \quad (6)$$

where,V_{oc0} and V_{oc1} are the open-circuit voltages of the PV module under two different temperatures T_0 and T_1, respectively, when the solar irradiance is at G_0[1].

4. SYSTEM DESIGN

The prototype is designed for monitoring health of 75W PV panel with V_{mpp}= 17.3V and I_{mpp} =4.3A under STC. It is designed around a microcontroller to sense current and voltage output of the PV system under test and two meteorological parameters i.e., irradiance and temperature. The change in temperature and irradiance causes change in the operating point of the PV panel considerably. Therefore, MPPT (maximum power point tracker) is connected to the panel terminals, before the load which maintains the output at maximum power point. In this case MPPT is emulated by a variable resistance of high power rating which can be manually changed to match the internal resistance of panel for maximum power transfer; this provides low cost solution for prototyping. Once the resistor is adjusted manually microcontroller sense Voltage V_{mpp} and Current at I_{mpp} as well as temperature and irradiance at the same instant of time. The available data are used to calculate fill factor. And thus, the health of PV panel is determined. Assumption made here are temperature and irradiance do not change during the measurement interval, thus making manual adjustment of resistor valid. The block diagram is illustrated in figure 2.

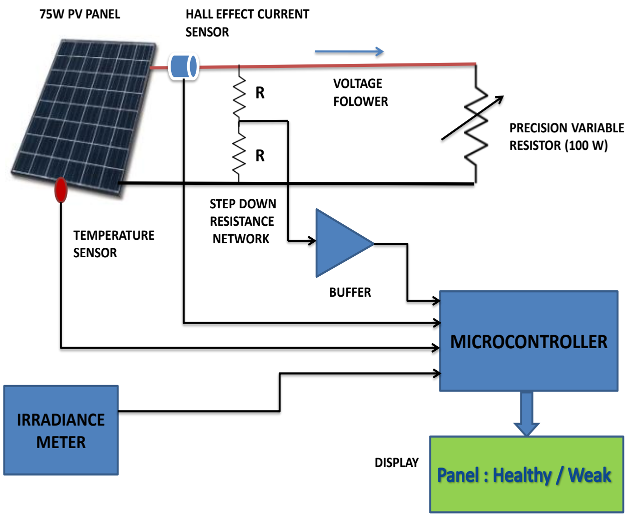

Figure 2: Block diagram of PV panel monitoring system

The ADC of microcontroller receives temperature and irradiation from the temperature sensor and irradiance meter. The output voltage of the temperature sensor is directly proportional to the cell temperature (T) and is calibrated in degree Celsius (°C).

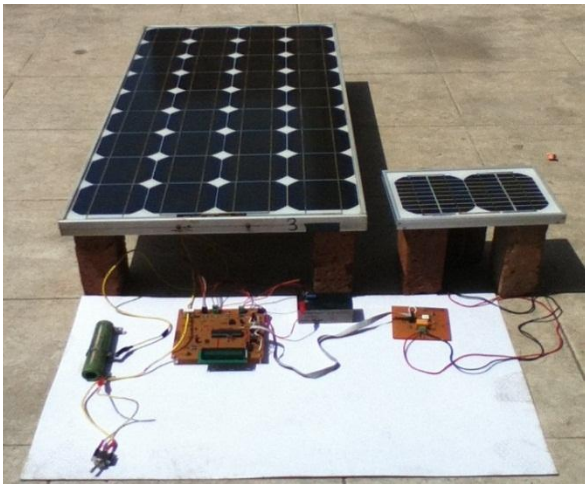

Figure 3: Experimental setup of PV panel monitor

In the figure 3, the complete PV monitoring system is shown. The picture is taken during demonstration of the device with 75W solar PV panel under test.It can be seen that the irradiance meter used is an assembly of a 5W solar panel and its short circuit current sensing circuit.The output of the irradiance meter is the voltage equivalent of the short circuit current across the 5W PV panel. As it is proportional to the solar irradiation (G),it is calibrated in W/m2with respect to a standard pyranometer.Thus, the measured quantities Impp, Vmpp, G, and T serve as input to microcontroller which are then processed them according to the programming done. Finally, it calculates Isc, Voc, Fill factor and Pmax and displays

these parameters on the LCD.The figure 4 shows the printed circuit board fabricated for constructing the device.

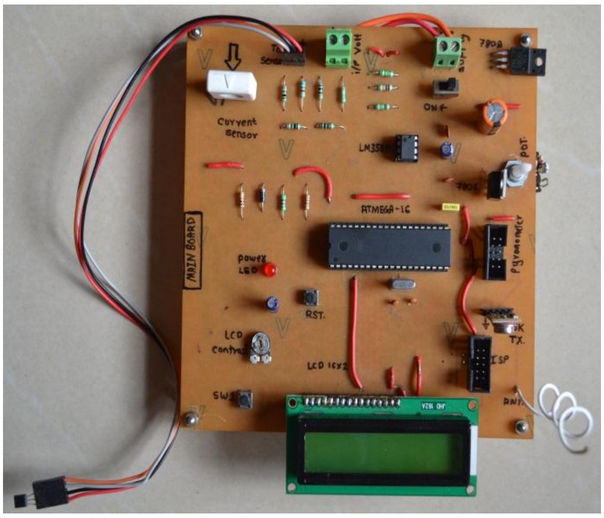

Figure 4: Main circuit board of PV panel Monitor.

5. FLOWCHART

The flow of the software program is shown in the figure 5.The program is executed as an infinite loop. The first four blocks denotes sampling of T, G, V_{mpp}, and I_{mpp} from the respective sensors, which are this information is processed according to standard equations (2), (3), (1) to find out I_{sc}, V_{oc} and FF respectively. The condition block compares the obtained FF with its optimum value (F_{opt}). If FF is greater than FF_{opt} then the LCD is triggered to display the output as 'panel healthy', otherwise if FF is greater than FF_{min} then LCD displays 'Panel weak' else 'panel failure'. After this, the processor waits for a finite sampling period to again start from the beginning. The value of F_{opt} and F_{min} are specific to the type and grade of the solar PV panel.

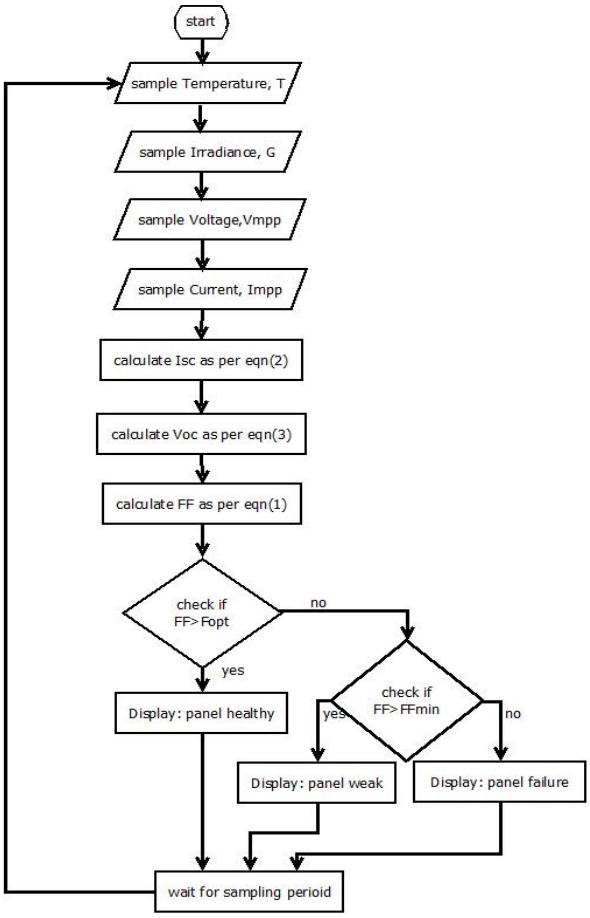

Figure 5: Program Flow chart

6. RESULTS

The following are the observations and results are of our Solar Panel (TATA BP SOLAR 375 mono-crystalline 75W).

Table 1. Observations on 31st March 2012

No.	Time	Irradiance (G)	Temperature (°C)	I (A)	V (V)	I_{sc} (A)	V_{oc} (V)
1.	12.47	809	45.4	3.25	14.05	3.81	18.96
2.	3.15	500	38	2.96	13.11	3.13	19.45
3.	3.23	567	39.5	2.84	12.83	3.01	19.33
4.	3.37	527	39	2.67	11.72	3.37	19.38
5.	3.53	451	40.5	2.49	11.22	2.55	19.14
6.	4.10	372	40.5	2.15	9.39	2.22	19.90
7.	4.25	305	41.5	1.90	8.23	1.93	18.90
8.	4.40	236	39	1.66	7.3	1.69	18.90
9.	5.00	184	38.5	1.33	5.73	1.34	18.81

Table 2. Observations on 2nd April 2012

No.	Time	Irradiance (G)	Temperature (°C)	I (A)	V (V)	I_{sc} (A)	V_{oc} (V)
1.	12.05	708	54.1	2.47	15.16	3.61	18.24
2.	12.15	734	59.0	2.54	15.40	3.69	18.40
3.	12.28	773	59.5	2.61	15.82	3.80	18.82
4.	12.37	734	52.7	2.63	16.02	3.79	19.09
5.	12.45	699	49.8	2.63	15.98	3.70	19.09
6.	12.56	751	51.2	2.64	16.13	3.71	19.24
7.	2.37	567	40.5	2.40	15.79	3.10	19.07
8.	2.50	543	37.5	2.38	15.70	2.98	19.29
9.	3.00	519	38.0	2.35	15.33	2.88	19.33
10.	3.10	477	39.0	2.27	15.31	2.74	19.20
11.	3.20	411	37.5	2.28	15.36	2.68	19.35

Table1 comprises of readings taken on 31st March 2012, with load=6.3Ω and Table 2 contains readings taken on 2nd April 2012, with load=6.4Ω at Mumbai.

Parameter estimation of the panel under test, using Table I and Table II:

Calculating $\boldsymbol{\alpha}$:

As per Table 2.Observations on 2nd April 2012, reading no 7

$$\boldsymbol{\alpha}= \frac{ln\left(\frac{I_{sc0}}{I_{sc1}}\right)}{ln\left(\frac{G_0}{G_1}\right)} =\frac{ln\left(\frac{4.7}{3.10}\right)}{ln\left(\frac{1000}{567}\right)}= 0.733$$

Calculating $\boldsymbol{\beta}$:

As per Table 2.Observations on 31st March 2012, reading no 3

$$\boldsymbol{\beta}= \frac{\left(\frac{V_{oc0}}{V_{oc1}}\right)-1}{ln\left(\frac{G_0}{G_1}\right)} =\frac{\left(\frac{21.8}{19.33}\right)-1}{ln\left(\frac{1000}{567}\right)}= 0.223$$

Calculating $\boldsymbol{\gamma}$:

As per Table 3.Observations on 31st March 2012, reading no 2 and 4

$$\boldsymbol{\gamma}=\frac{ln\left(\frac{V_{oc0}}{V_{oc1}}\right)}{ln\left(\frac{T_1}{T_0}\right)} =\frac{ln\left(\frac{19.38}{19.45}\right)}{ln\left(\frac{38}{39}\right)} = 0.0138$$

Thus, the average value of α = 0.74, the average value of β = 0.22, andthe average value of γ = 0.013.
During, demonstration, the Fill Factor of the panel under test is calculated to be 0.5 implying that it has weak performance.

7. CONCLUSION

The motivation of this project is to allow one to know the health of the PV module in field by monitoring its performance over extended period of time. To achieve this objective, an automatic health monitoring system which tests PV Panels is described. This automated tool allows evaluating, analyzing, and testing PV modules under actual operating conditions in the field itself. It shows the interdependence between the electrical parameters of a PV module and the environmental parameters and calculates the Fill Factor of the solar panels in the operating condition. If its value is less than the prescribed standard for the type of panel, it indicates that the health of the panel is deteriorated. Thus, panels can be attended to quickly by either cleaning off the dust, clearing off any physical body causing shade or by replacing as per the reasons detected by the technician.

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9. REFERENCES
[1] Zhaohong Fang Wei Zhou, Hongxing Yang., 2007. A novel model for photovoltaic array performance prediction. *Elsevier Applied Energy* 2007; 84:1187–1198.

[2] Kerr M.J. , Cuevas A. ,2003. Generalized analysis of the illumination intensity vs. open-circuit voltage of PV modules. Sol Energy 2003;76:263–7.

[3] http://articles.timesofindia.indiatimes.com/2012-06-25/india-business/32408484_1_solar-power-jnnsm-940mw

[4] http://www.renewableenergyworld.com

[5] http://ecocentric.blogs.time.com/2012/02/13/bright-days-how-india-is-reinventing-solar/#ixzz1zAOnFm21

[6] A.Maheshwari, C.S. Solanki and V. Agarwal, 2006. Field Measurements Of Pv Module Performance Using A handy Tool. *Advances in Energy Research (AER – 2006)222-227*.

[7] G. N. Tiwari, Swapnil Dubey,2009. Fundamentals of Photovoltaic Modules and Their Applications, RSC publishing.

[8] National Instruments, 2012. TUTORIAL :Part II – Photovoltaic Cell I-V Characterization Theory and LabVIEW Analysis Code, May 10 ,2012.

[9] T.Bazouni, 2009. SolarOne “What is the Fill Factor of a Solar Panel". Mar 02, 2009. http://www.solarfreaks.com/what-is-the-fill-factor-of-a-solar-panel-t138.html.

[10] http://pveducation.org/pvcdrom