Power, Voltage, and Current Characteristics of Photovoltaic Modules in Saudi Arabian Cities

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***Abstract*—Solar energy projects have been mushrooming in the Middle East where sun light is abundant and PV economics are attractive. Using the mathematical PV model introduced in [3], this paper presents the I-V and P-V plots for the cities of Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait, for various temperatures, and for a single PV string and for 2 PV strings connected in parallel, using the measured mean irradiances for these cities. The maximum powers, along with corresponding operational voltage and current values, are also presented for the maximum and mean air temperature values and mean irradiances for these cities. Such results help in proper economic solar power project valuation and in accurate forecasting of solar power.**

Keywords-PV module modeling; power characteristics; Saudi Arabian solar energy; optimal operational voltage and current

I. INTRODUCTION

Solar power is growing in the Middle East given the abundance of sun light. Fields of PV panels can be deployed near load zones to provide electricity during peak hours. Each PV panel has usually 36 or 72 solar cells connected in series. Because power is lost when solar PV panels are shaded, bypass diodes are commonly connected in parallel to the tandem of 36/72 solar cells, to make the current avoid the shaded cells and flow through the low-resistance bypass diodes. Several solar photovoltaic (PV) panel projects were introduced in Saudi Arabia such as the mega sun farm in Riyadh and the 300MW project in Sakaka which launched in 2019, in addition to tens of solar projects in progress in cities such as Medina, Rafha, Qurayyat, Al-Faisaliah, Rabigh, Jeddah, and Mahd alDahab [1]. A recent study by KAPSARC estimated the upper rooftop solar PV capacity for the city of Riyadh to be 4.3 GW, sufficient to meet 9% of the energy demands of Saudi Arabia's Central Region [2]. However, the abundance of dust and the high cost of fresh water in the region keep solar panel cleaning a remaining challenge to solve. Despite the cleaning challenges which reduce the panel efficiencies and generated power, the solar energy economics, population growth leading to rising energy demands, and global warming policies are keeping renewable energy viable in the region. Solar energy also allows more hydrocarbons to be exported by the Kingdom while reducing CO2 and CO emissions. A climate-based study for Saudi Arabia was conducted in [4]. A renewable hybrid energy study comparing the costs of three systems, PV and PV-Wind and PV-Wind-Fuel cell, can be found in [5]. The future of solar energy in the Kingdom of Saudi Arabia was presented in [6] and reports that the Kingdom ranked 14 in the World in CO2 emissions, and that the Kingdom's solar energy cost falls below the conventional generation (diesel) energy costs if the latter's indirect health and environmental costs are factored in. The optimal PV, inverter and PV/inverter sizes were investigated in [7].

Accurate modeling or simulation of the solar PV panel output helps in accurate economic solar project valuation and solar power forecasting in various regions and over the various seasons. A mathematic model of series-parallel PV modules was introduced in [3]. This model can handle a variety of solar cells connected in series and/or in parallel. In this paper, we use this mathematical model to generate the I-V (PV panel Current-Voltage) and P-V (PV panel Power-Voltage) plots for the Saudi Arabian cities of Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait for a variety of temperatures.

The mathematical PV model is reviewed in Section II. In Section III, the results of evaluating this model for the cities of Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait, are presented. The paper concludes in Section IV.

II. MATHEMATICAL PV PANEL MODEL

Various studies [11] have modeled PV cells and modules, often as diode-based electric circuits. Maximum power tracking methods [8] were also introduced to identify the best operating parameters for PV modules for generating the maximum power. Simulations of PV modules have been presented in [9-10]. A piecewise linear model with three diodes was presented in [12].

The mathematical PV panel model [3] used by this work allows the I-V and P-V plot generation for various PV panels with any number of solar cells connected in series or in parallel. It generates the photo current, series resistance, voltages and expresses the current equations in the form f(I)= 0 and solves that equation iteratively using the Newton-Raphson method. Given input values of the module voltage V, the temperature in degrees Celsius, the solar irradiance in KW/m^2, the number of solar cells in series, and the number of solar series-connected cell tandems connected in parallel, the model solves for the current I, and generates the current and power plots versus the voltage V.

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The mean solar irradiances and temperatures, and maximum temperatures for the cities of Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait are obtained from [4] and are given in Table I, where 1 Sun is 1 KW/m^2.

TABLE I. MEAN SOLAR IRRADIANCES IN SAUDI ARABIAN CITIES

City	Mean Irradiance (W/m^2)	# Suns	Mean Temp. (deg. C)	Max Temp. (deg. C)
Dhahran	195	0.195	25.8	45.7
Guriat	235	0.235	19.8	43.9
Riyadh	252	0.252	25.1	43.7
Jeddah	257	0.257	27.9	41.7
K. Mushait	289	0.289	18.9	34.3

III. RESULTS

Various In this work and as in [3], the electrical characteristics of the MSX-60 PV module were employed: maximum power of Pmax=17.1V x 3.5A=60W, short circuit current Isc=3.8A, open-circuit voltage Voc=21.1V, temperature (temp) coefficient of Voc=-(80+/-10)mV/deg. Celsius, and temp coefficient of Isc=(0.0065+/-0.015)%/deg. Celsius, and n=diode ideality factor between 1(ideal diode) and 2. From these values, we derive:

- Reference start temp (in deg. K) T1=25 deg. C,
- Reference end temp (in deg. K) T2=75 deg. C,
- Open-circuit voltage at temp T1 Voc_T1=21.06volt/Ns,
- Open-circuit voltage at temp T2 Voc_T2=17.05volt/Ns,
- Short-circuit current at temp T1 Isc_T1=3.8A,
- Short-circuit current at temp T2 Isc_T2=3.92A,
- Series resistance Rs=0.0078556 ohms, depends mainly on Ns which is held constant at 36
- Number of solar cells in series Ns=36
- Number of solar PV module strings (each string with 36 cells in series) in parallel Np=1 (1 PV string only; none in parallel) or 2 (2 PV strings in parallel)

Figures 1-10 show the I-V and P-V plots for the considered cities for a string of 36 PV cells in series, assuming Ns=36, Np=1, and n=1.2 for temperatures between 10-80 degrees Celsius, and using the Sun values of Table I.

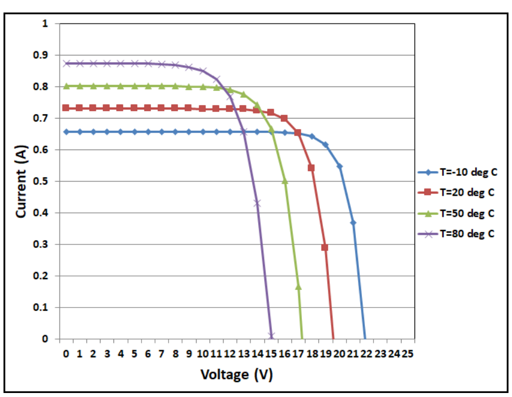

Figure 1. I-V Plot for Dhahran for Various Temperatures, Ns = 36, Np= 1

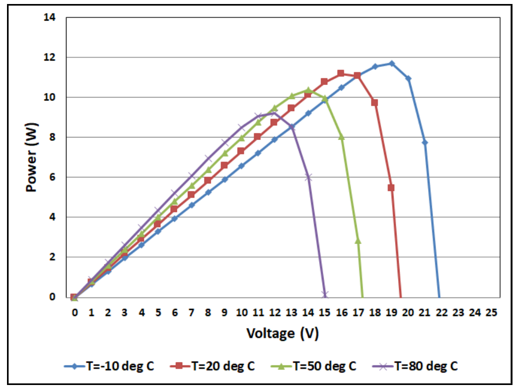

Figure 2. P-V Plot for Dhahran for Various Temperatures, Ns = 36, Np = 1

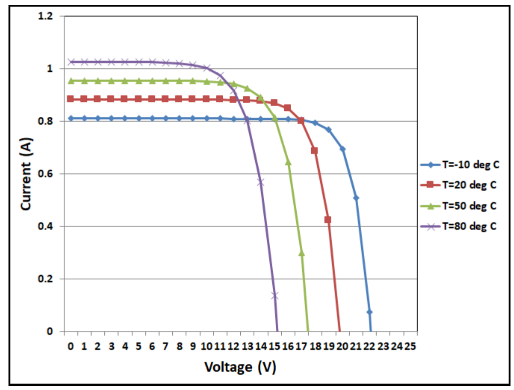

Figure 3. I-V Plot for Guriat for Various Temperatures, Ns = 36, Np = 1

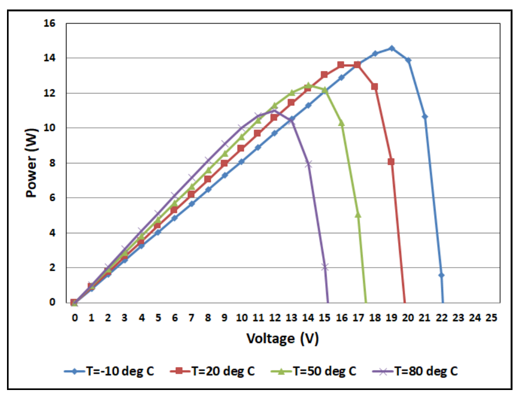

Figure 4. P-V Plot for Guriat for Various Temperatures, Ns = 36, Np = 1

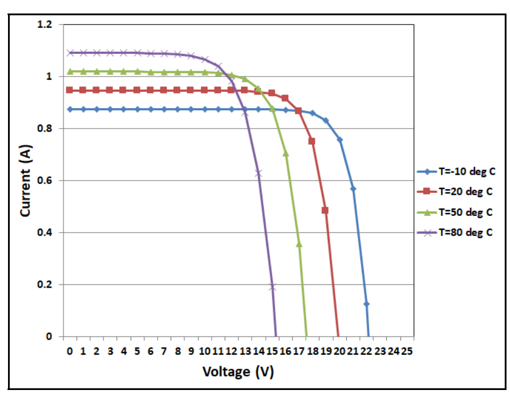

Figure 5. I-V Plot for Riyadh for Various Temperatures, Ns = 36, Np = 1

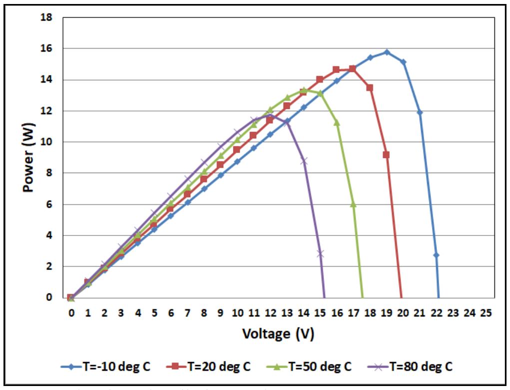

Figure 6. P-V Plot for Riyadh for Various Temperatures, Ns = 36, Np = 1

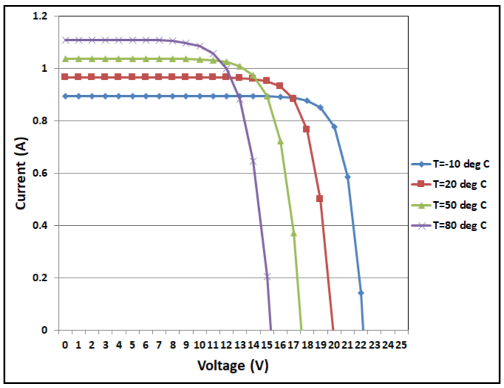

Figure 7. I-V Plot for Jeddah for Various Temperatures, Ns = 36, Np = 1

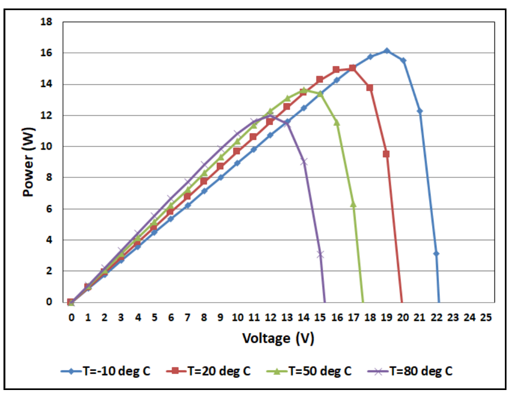

Figure 8. P-V Plot for Jeddah for Various Temperatures, Ns = 36, Np = 1

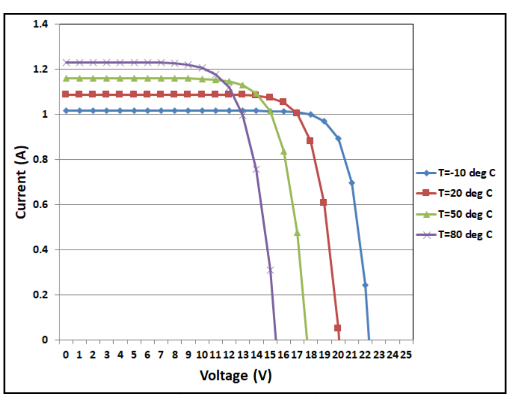

Figure 9. I-V Plot for Khamis Mushait, Ns = 36, Np = 1

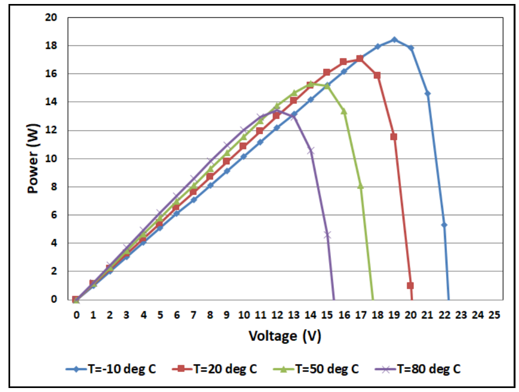

Figure 10. P-V Plot for Khamis Mushait, Ns = 36, Np = 1

As the cities are sorted in Table I from lowest to highest mean irradiance, the model confirms the following:

- Higher generated currents and powers at the same voltage for the cities with higher irradiances, and
- Lower currents and powers at lower temperatures and lower voltages
- Higher currents and power at lower temperatures and higher voltages

Figure 11 displays the I-V plots for Riyadh for the diode ideality factor, n, varying between 1.2 and 1.8. We observe that varying n has little effect on the I-V curve. When two 36-cell strings are connected in parallel, the I-V and P-V plots are displayed in Figures 12-21.

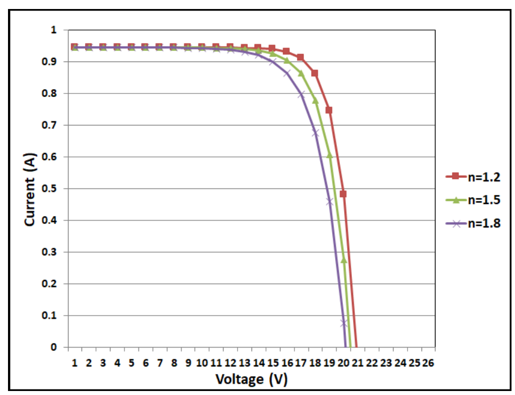

Figure 11. I-V Plot for Riyadh for n Varying Between 1.2 and 1.8

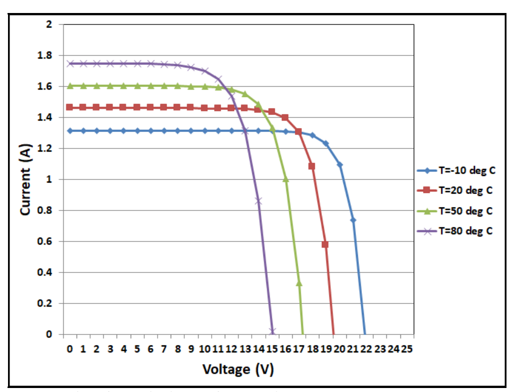

Figure 12. I-V Plot for Dhahran for Various Temperatures, Ns = 36, Np = 2

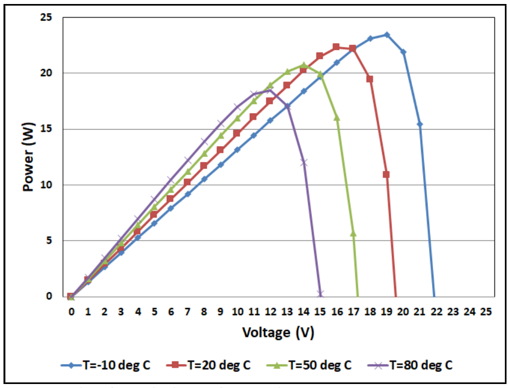

Figure 13. P-V Plot for Dhahran for Various Temperatures, Ns = 36, Np =2

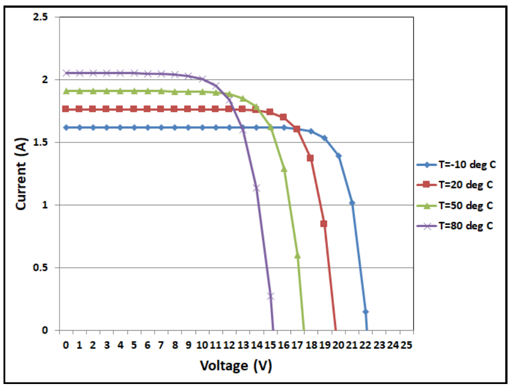

Figure 14. I-V Plot for Guriat for Various Temperatures, Ns = 36, Np=2

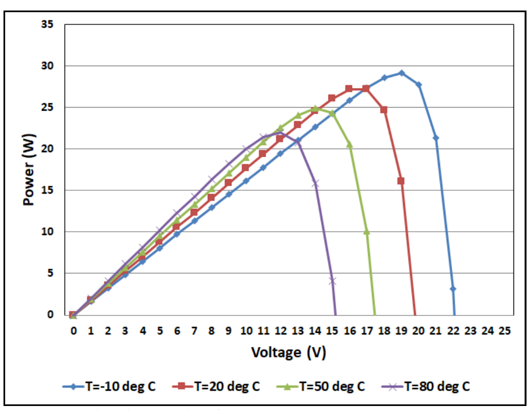

Figure 15. P-V Plot for Guriat for Various Temperatures, Ns = 36, Np = 2

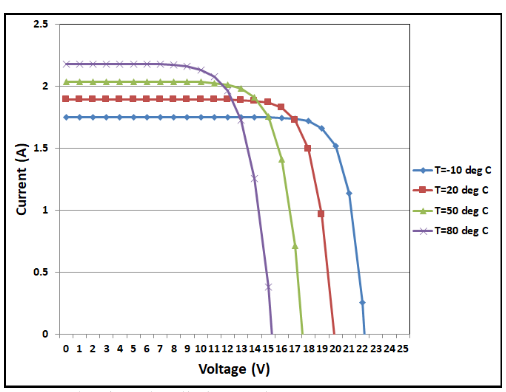

Figure 16. I-V Plot for Riyadh for Various Temperatures, Ns = 36, Np = 2

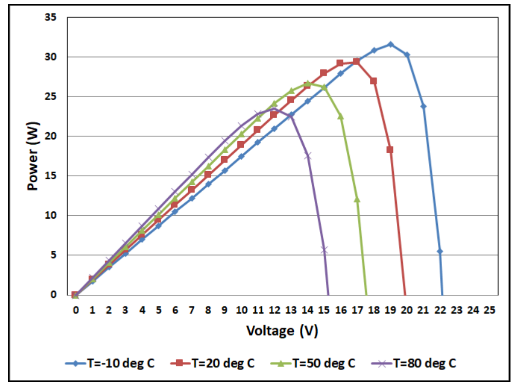

Figure 17. P-V Plot for Riyadh for Various Temperatures, Ns = 36, Np = 2

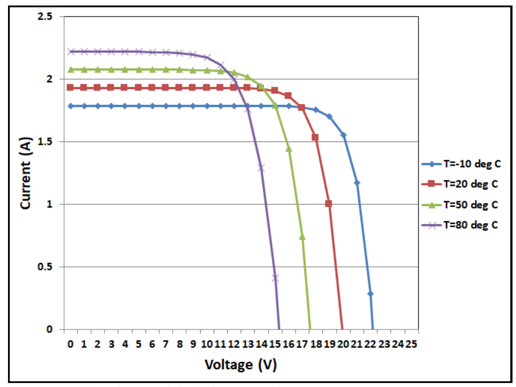

Figure 18. I-V Plot for Jeddah for Various Temperatures, Ns = 36, Np = 2

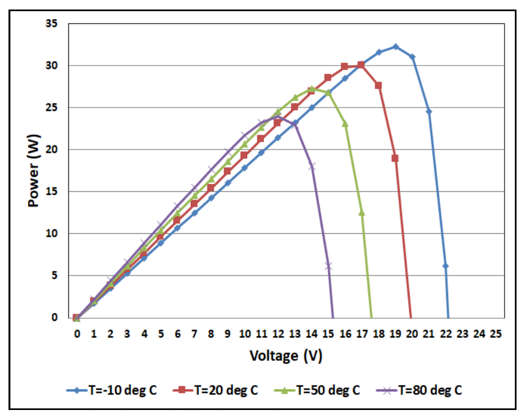

Figure 19. P-V Plot for Jeddah for Various Temperatures, Ns = 36, Np = 2

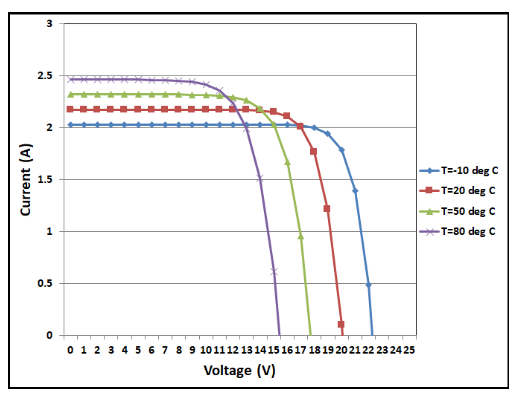

Figure 20. I-V Plot for Khamis Mushait, Ns = 36, Np = 2

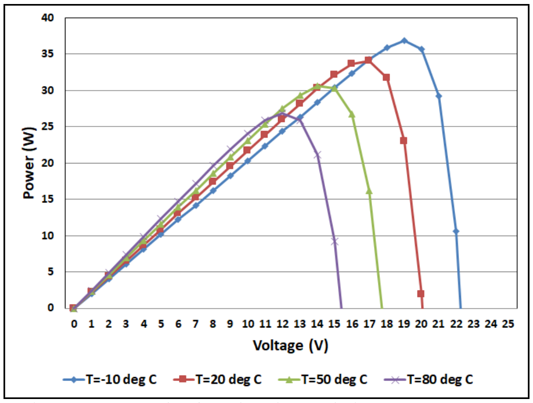

Figure 21. P-V Plot for Khamis Mushait, Ns = 36, Np = 2

When Np is doubled to 2, the current I and power P (=V I) are doubled for the same voltage.

The P-V plots can be examined to derive the maximum output power values (knee of curve) generated by the PV module, and the corresponding operational voltage Vopt. Afterwards the I-V plots are examined to mark the identified Vopt value which generates the maximum power, and determine the corresponding optimal I value, Iopt. Higher maximum output power values are achieved at lower temperatures, and for larger Vopt values. This procedure is employed next to find the maximum power and corresponding operational voltage and current.

For a PV string of 36 cells in series, the maximum power, and corresponding operational voltage and current, Vopt and Iopt, for the various cities were obtained from the mathematical PV model using the mean irradiance values and mean and maximum temperatures of the cities given in Table I, and are displayed in Table II.

TABLE II. MAXIMUM POWER FOR SAUDI ARABIAN CITIES AT MAXIMUM AND MEAN AIR TEMPERATURES, NS=36, NP=1

City	Max Temp. Pmax (W)	Vopt (Volts)	Iopt (Amp.)	Mean Temp. Pmax (W)	Vopt (Volts)	Iopt (Amp.)
Dhahran	10.46	14	0.75	11.08	16	0.69
Guriat	12.72	15	0.85	13.62	17	0.80
Riyadh	13.68	15	0.91	14.52	16	0.91
Jeddah	14.08	15	0.94	14.72	16	0.92
K.Mushait	16.21	16	1.01	17.09	17	1.01

Percent changes in Pmax, Vopt, and Iopt, from maximum temperature to mean temperature, fall in these ranges 4.5%-7.1%, 6.2%-14.3%, and -8%-0%, respectively. Percentage-wise, the voltages resulting in maximum powers differ the most from maximum temperatures to mean temperatures, in comparison with powers and currents.

IV. CONCLUSION

Solar energy projects have been mushrooming in the Middle East where sun light is abundant. Using the mathematical PV model introduced in [3], this paper presented the I-V and P-V plots for the cities of Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait, for various temperatures, and for a single PV string and for 2 PV strings connected in parallel, using the measured mean irradiances for these cities. The maximum powers, along with corresponding operational voltage and current values, were also presented for the maximum and mean air temperature values and mean irradiances for these cities. Such results help in proper economic solar power project valuation and in accurate forecasting of solar power.

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