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Performance examination of CIGS thin-film photovoltaic system: a case study

Badanie wydajności cienkowarstwowego systemu fotowoltaicznego CIGS: studium przypadku

Abstract: This work conducts performance analysis on a thin-film based photovoltaic (PV) solar system located on the Middle East University (MEU) campus in Jordan. The analysis includes gauging the performance of the PV system using established industry performance parameters, and studying the energy production trends. After investigating different aspects affecting the PV solar system such as the PV modules temperature losses and component availability, several causes of low energy output are hypothesized and discussed. Afterwards, a new PV system that relies on crystalline silicon technology was proposed and designed with proper system components along with an economic feasibility study. The new system is designed to provide a comparison to the currently installed system under the same site conditions and to be presented as a future project proposal for the university to pursue. As a result, we have found that the performance ratio of the new proposed PV solar system is five times higher in comparison with the currently installed system.

Streszczenie: W tej pracy przeprowadzono analizę wydajności cienkowarstwowego systemu fotowoltaicznego (PV) zlokalizowanego na terenie kampusu Middle East University (MEU) w Jordanii. Analiza obejmuje pomiar wydajności systemu PV przy użyciu ustalonych parametrów wydajnościowych branży oraz badanie trendów produkcji energii. Po zbadaniu różnych aspektów wpływających na system PV, takich jak straty temperatury modułów PV i dostępność komponentów, wysunięto hipotezę i omówiono kilka przyczyn niskiej wydajności energetycznej. Następnie zaproponowano i zaprojektowano nowy system PV, który opiera się na technologii krzemu krystalicznego, z odpowiednimi komponentami systemu wraz ze studium wykonalności ekonomicznej. Nowy system ma zapewnić porównanie z obecnie zainstalowanym systemem w tych samych warunkach na miejscu i zostać przedstawiony jako przyszła propozycja projektu, którą uniwersytet będzie mógł realizować. W rezultacie odkryliśmy, że współczynnik wydajności nowego proponowanego systemu PV jest pięć razy wyższy w porównaniu z obecnie zainstalowanym systemem.

Keywords: PV, solar energy, c-Si, CIGS, performance analysis
Słowa kluczowe: PV, energia słoneczna, c-Si, CIGS, analiza wydajności

Introduction

Due to the increasing demand for electrical energy production, countries over the world are witnessing higher levels of integration of renewable energy systems into their electrical grids. Such measures are inevitable to overcome the dependency on fossil fuels, and its negative impact on every aspect of life including increasing level of greenhouse gases which in return raise overall temperature of earth surface. Therefore, the renewable sources such as wind and solar are the main driving force to provide clean energy for many generations ahead.

One of the most prevalent technologies employed in such systems is photovoltaic solar energy (PV), having the second highest absolute generation growth after wind in 2021 and accounting for 3.6% of global electricity generation [1]. Analyzing the actual performance of existing PV systems, and comparing their output and behavior to what is expected in the design phase and in software modeling plays a crucial part in the continual development of the solar PV industry. Manufacturers, researchers, and consumers are relying on the accurate evaluation of existing systems to aid them in benchmarking existing products, predict future trends and guide in decision making [2].

Since PV systems are lightweight, modular and easy to install, they are often employed on rooftops in urban areas as well as in large remote power plants. Such flexibility allows for both small households and large establishments to set up their own grid connected systems to reduce electrical operating costs. Educational institutions like the Middle East University (MEU), which is addressed in this work are examples of such suitable establishments for PV system installation. In addition to the previous advantages, an academic campus will benefit from the silent operation, low operating costs, low maintenance costs and the lack of moving parts of such systems. More importantly, help with world efforts to decrease the reliance on conventional power generations, and in reducing electricity bills.

Many international and regional higher educational institutions conduct case studies for campus PV systems. These studies are either based on real-world cases of installed and operating PV systems, or on theoretically modeled designs. Literature regarding proposed PV designs is concerned with system modeling through software, like PVsyst [3], PVGIS [4], or theoretical studies based on analytical models [5, 6]. In addition, economic feasibility studies of such systems are also performed. On the other hand, real-world case studies usually focus on analyzing the performance [7], economics [8, 9] and/or comparing different aspects of PV systems [10].

This paper analyses the performance of a multiple part grid-connected PV system installed on the campus of the MEU in the MENA region and discusses proposing a new system that would substitute for the old existing system. While most regional case studies are based on designs and models [11-14], few papers like this one and [15] study and analyze the performance of regional installed PV systems. This paper also discusses the design and performance analysis of a theoretically modeled system for comparison with the existing one.

This work is divided to several sections as follows: Section two provides PV system overview and describes the existing system location, components and structure. Section three contains the PV system performance analysis in terms of its performance parameters and production trends, and investigates issues regarding system power production. Section four contains the design, modeling, performance analysis and economics of a new solar PV system. The work is concluded in section five.

Overview of the Currently Installed Thin-film CIGS PV System

The PV system of MEU is located at 31°48'33.5" north and 35°55'12.7" east in the southern part of the capital city of Amman, Jordan. The PV system starts to operate in November 2018 as part of the university plan to adopt clean energy solutions and green campus measures. The PV system is in a region of the solar belt that is well known for its semi-arid desert climate and high solar insolation. Typical solar irradiance values normally range between 4-8 kW/m^2 and the region experiences more than 300 sunny days per year [16].

The MEU is one of the leading universities in Jordan that rely on thin-film PV solar module technology. The PV system is composed of 6960 copper indium gallium selenide (CIGS) solar modules, where each module produces 140 W_p. More details regarding the installed PV modules are listed in Table 1. The PV system is spread on 5 campus building rooftops and surrounding structures as shown in Figure 1. The area of a single module is around 1.05 m^2, resulting in a total system area of 7334.23 m^2 and a total DC power capacity of 974.4 kWp. All system arrays have a tilt angle of around 10 degrees to the horizontal and oriented to the south-west. Table 3 shows the number of the PV modules, total DC capacity, total module area and inverter configuration for each location where the panels are mounted.

The PV system uses both 20 kW and 40 kW Refusol inverters depending on the number of modules and the string configuration of the different arrays in each system location. A total of 21 Refusol inverters are installed for a total AC output power capacity of 780 kW_p. The electric specifications of the inverters are shown in table 2. All inverters output ~415V (phase to phase voltage) three-phase electricity to multiple junction boxes across campus that recombine into a main junction box. The AC energy output of the PV system is then injected into the utility electrical grid through a net metering tariff system. It is worth mentioning that the electric utility company in Amman has an agreement with the university to set the power factor of the PV system output to 0.8 leading (capacitive).

Due to the nature of the metering system imposed from the utility company, the university electric system is separated into a generation part and a production part, where each one is individually measured and connected to the main three-phase grid. At the end of each month, the value of consumed energy is subtracted from the generated energy. The surplus energy produced is kept in a balance at the utility company to be deducted from the consumption of the following months.

Fig. 1: Top satellite view of MEU campus showing the main five locations where the solar modules are mounted. The “new” box represents the proposed new PV system location.

Table 1: The electrical specifications of the CIGS Thin-film module.

PV Module Name and model	Avancis Powermax 3.5
Max. Power (W)	140
Module Efficiency (%)	13.3
Open-Circuit Voltage (V)	59.8
Short-Circuit Current (A)	3.36
Max. Power Point Voltage (V)	46.1
Max. Power Point Current (A)	3.04
Nominal Operating Cell Temperature (°C)	40
Temp power coefficient (%/°C)	-0.39

Table 2: Electrical specifications of the inverters used in the thin-film solar system

Inverter Name and Module	Refusol 20K	Refusol 40K
Max. DC input power (kW)	26.2	60
Max. DC input voltage (V)	1000	1000
Operating DC input voltage range (V)	230-960	490-850
No. of independent MPPTs	2	1
No. of DC inputs per MPPT	2	1
Max. MPPT input current (A)	24	84
Max. input short-circuit current per MPPT (A)	30	160
Rated AC power (kW)	20	40
Max. efficiency (%)	98.2	98.2

Table 3: Details of the PV system sub-locations

System No.	System Location on Campus	No. of PV Modules	Total Module Area (m^2)	System Nameplate DC Capacity (kWp)	Inverter Number x Inverter AC Rating (kW)
1	Building A	810	853.55	113.4	2x40 1x20
2	Building B	1050	1106.46	147	2x40 2x20
3	Building F	2340	2465.82	327.6	6x40
4	Car Park	720	758.71	100.8	2x40
5	Bus Park structure	2040	2149.69	285.6	6x40

Performance of the Currently installed Thin-film CIGS PV System

The thin-film PV system was analyzed using data collected for the years 2019 and 2020. Monthly consumption and production values for the MEU campus were obtained from the electricity bills and are represented in Figure 2. Starting from January 2019 to December 2020, energy consumption and generation values were 1,553,840 kWh and 779,340 kWh, respectively. This means that the thin-film based solar system covers only 50.2% of the university consumption rather than the whole demand. Such findings accompanied with known prior design system capacity indicate that the installed PV system is not meeting its intended performance level and requires investigation. Solar irradiance and temperature values for the calculation hereafter were taken from the NASA POWER Data Access Viewer portal [17]. These values are used with some of the data available through the on-site monitoring system on campus.

Several performance parameters can be extracted from the current PV system such as the final system yield, the reference yield and the performance ratio [2]. These performance parameters were standardized by the International Energy Agency (IEA) Photovoltaic Power Systems Program in IEC standard 61724 [18] and are used to define the whole system performance with respect to the energy production, solar resource and overall system losses. These parameters are discussed herein below and are summarized in table 4.

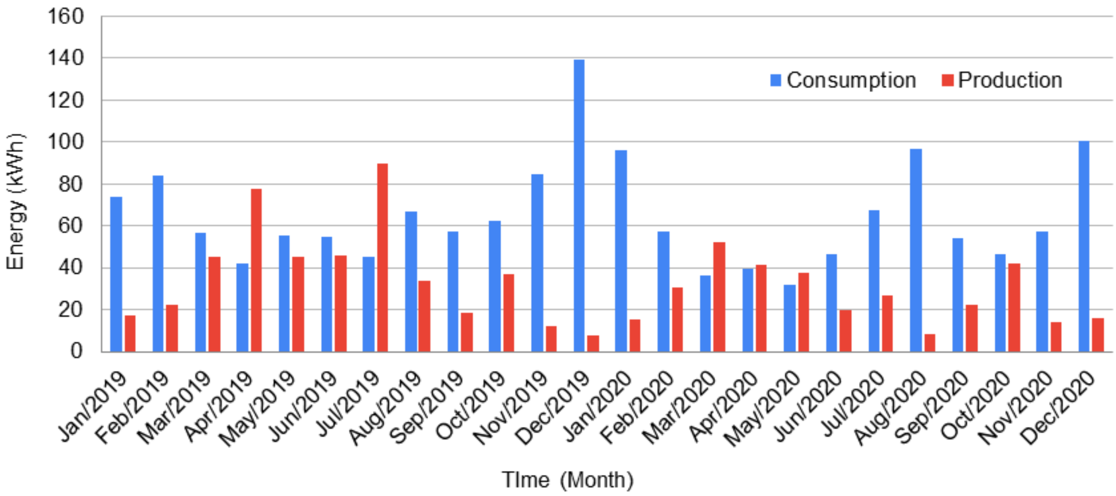

Fig. 2: Monthly university consumption and production energy figures for 2019 and 2020.

Final PV System Yield

The final PV system yield (Y_f) represents the number of hours that the PV system would need to operate at its rated power to produce the same energy as it did in a year. The purpose of this parameter is to normalize the energy output of the system with respect to its size. Therefore, it can be used to compare the energy output of different systems with different sizes. It is calculated by dividing the total yearly energy output of a system (E) by the total nameplate DC power ($\mathrm{P_0}$) of the installed module array as shown in Eq. 1. This parameter is measured in hours or kWh/kW. For the current PV system at MEU, the final system yields for both 2019 and 2020 are 464.8 and 343.3 kWh/kW, respectively. Nominal values for the final system yield of PV systems are usually around 900-1825 hours [2]. We can conclude that the campus PV system does not meet the normal values of a typical PV solar system.

$$\boldsymbol{Y_f = \frac{E}{P_0}} \tag{1}$$

Reference Yield

The reference yield (Y_r) represents the equivalent number of hours of solar resource available at a location compared to a reference irradiance. It is simply the total horizontal irradiance (H) in kW/m^2 for a location divided by a reference irradiance (G) in kW/m^2, which is in this case 1000 kW/m^2. This is the most common reference irradiance used by manufacturers and defines the solar resource at a specific location including weather variability. The reference yield values for the MEU system location for 2019 and 2020 are 2130.2 and 2067.7 hours, respectively. Equation 2 for the reference yield is shown below:

$$\boldsymbol{Y_r = \frac{H}{G}} \tag{2}$$

Performance Ratio

The performance ratio (PR) is the final system yield divided by the reference yield, as shown in Eq. 3. The formula considers all losses affecting the energy output of a system and quantifies them using one parameter. The parameter is dimensionless.

$$\mathbf{PR} = \boldsymbol{\frac{Y_f}{Y_r}} \tag{3}$$

The system losses include component mismatch, inverter inefficiencies, wiring losses, system shutdowns, temperature losses, light-induced degradation, and weather conditions like soiling. In this case, the performance ratios for the same two consecutive years were 22.1% and 16.6%, respectively, signifying the poor and degrading performance of the system. Normal values of PR range from 0.6 to 0.8 depending on weather conditions throughout the year, with values being greater in winter than in summer due to less module temperature losses. The monthly MEU thin-film system PR values and typical PR values obtained from NREL performance data for PV systems in the USA [2] are presented in Figure 3 for comparison.

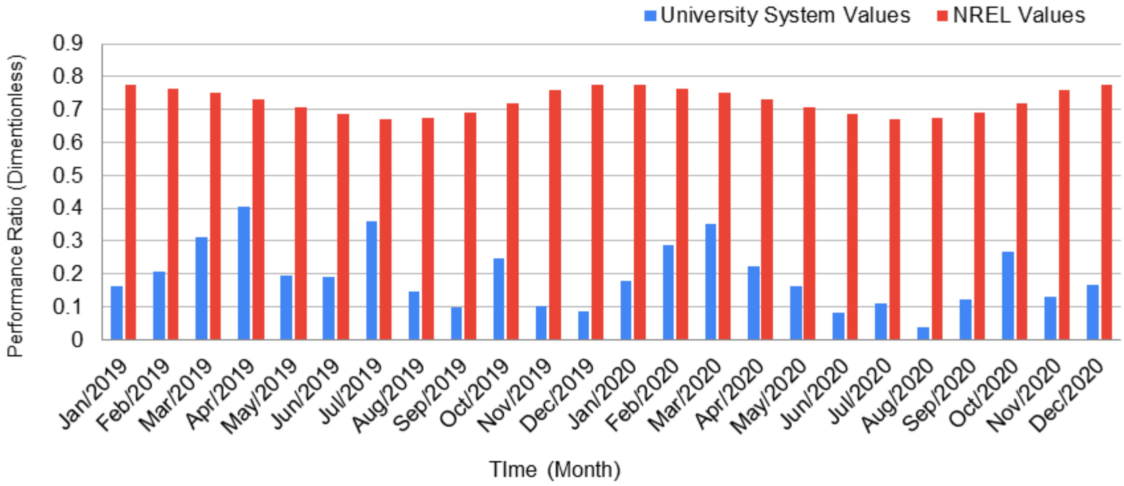

Fig. 3: Monthly typical NREL and university system PR values.

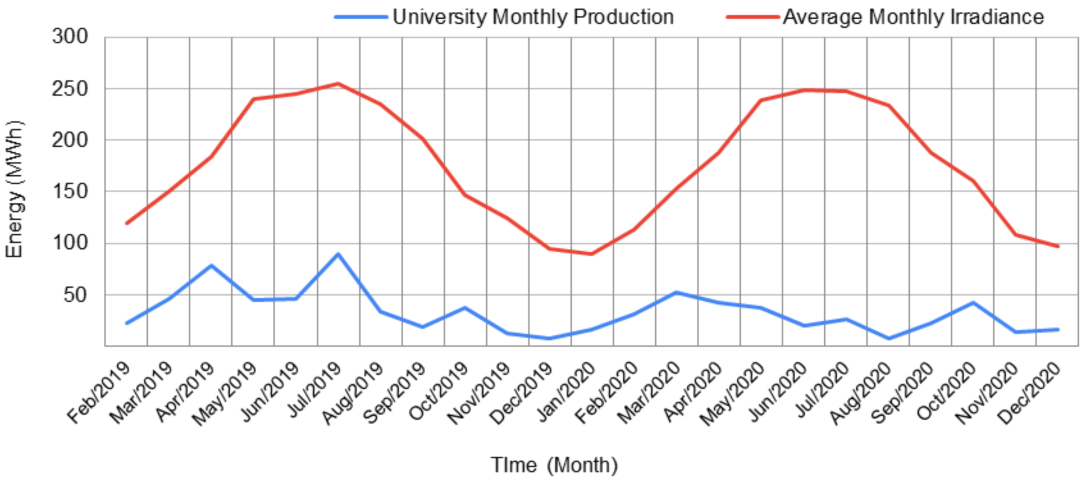

Fig. 4: Monthly university energy production and average monthly irradiance available.

Another comparison was used to show how much the energy production of the thin-film system deviated from the expected. Figure 4 shows the university average available monthly irradiance across the span of two years plotted with the actual monthly production of the thin-film system. Comparing the two sets of data immediately reveals a sharp contrast contrary to what the normal case should be. The curves do not show a strong correspondence in their fluctuations, and the difference in value is clearly observed. Table 5 presents the percentage change in generation and the percentage change in irradiance for every month between the years 2019 and 2020. The differences between the irradiance and production values should be close but with a small yearly increasing difference due to permanent loss in generation from light induced degradation and other factors such as soiling. Most of the thin-film solar panels installed at MEU campus are closely mounted which makes the cleaning process very complicated.

Several causes can be attributed to low system performance and in this work, three of them are investigated, which are the effect of temperature, faulty operations and the lack of proper maintenance and installation practices.

The first probable cause investigated was the module temperature loss. As seen in Figure 3, the PR values were sometimes extremely lower in summer than in winter and as a reason the theoretical cell temperatures of the thin-film modules were calculated for 2021 using their nominal operating cell temperature as shown in Table 2, then compared to actual cell temperatures obtained from the on-site monitoring system for a string of modules that was operating for that whole year without interruptions. Both actual and theoretical cell temperatures are presented in Figure 5. It is seen that the actual cell temperatures were below the theoretical values, and even lower in winter due to the region windy climate that aids in cooling. Moreover, after calculations using the temperature power coefficient of the modules with the actual cell temperature readings we have performed, the thin-film PV solar system appeared to have lost of about 6% of its energy output due to the effect of temperature on its arrays which is well correlated to what is expected.

Table 4: Summary of thin-film system performance parameters for 2019 and 2020

Year	2019	2020
Final System Yield, Y_f (kWh/kW)	464.8	343.3
Reference Yield, Y_r (hours)	2130.2	2067.7
Performance Ratio, PR	22.1%	16.6%

Table 5: Percentage change in generation irradiance for every month of 2020 in respect with 2019.

Month	Monthly change in irradiance of 2020 in respect with 2019	Monthly change in production 2020 in respect with 2019
Jan	14.20%	80.73%
Feb	7.02%	-22.09%
Mar	-17.14%	-9.86%
Apr	-4.77%	38.66%
May	1.44%	14.74%
Jun	-1.67%	-46.32%
Jul	-0.52%	-17.06%
Aug	1.59%	-56.19%
Sep	-2.80%	-70.43%
Oct	-0.26%	-75.96%
Nov	-3.85%	18.37%
Dec	5.51%	13.79%

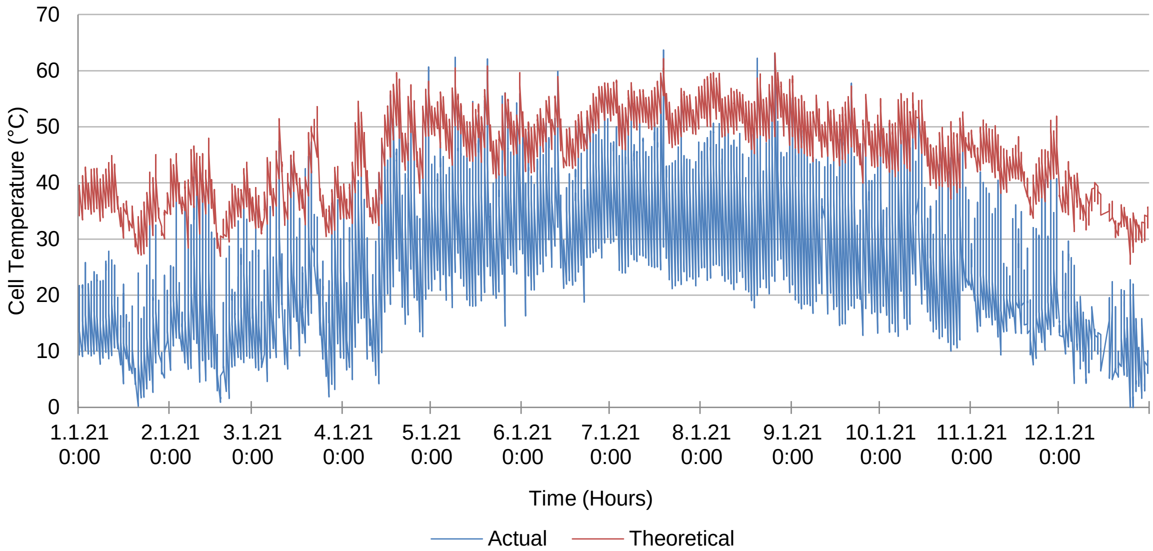

Figure 5: Actual and theoretical cell temperatures.

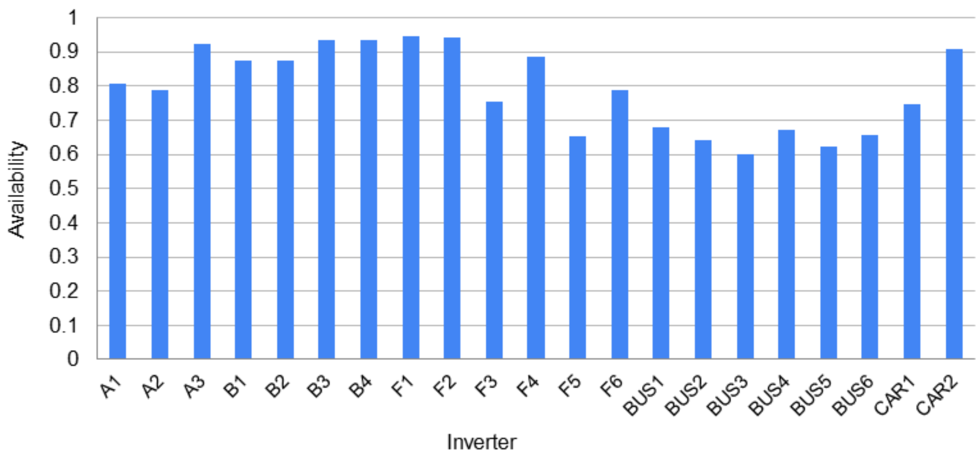

Fig. 6: System inverter availability over the two years 2019 and 2020.

The second subject investigated was the inverters' operation and availability. The AC power data for each inverter in the system across the analysis period showed continuous interruptions due to many automatic shutdowns and continual dips in production. To measure how much time each inverter was out of service, the availability of each inverter, shown in Figure 6, was found by checking its operating hours during the day. This was accomplished by figuring out the actual number of hours of operation from the total number of irradiation available to produce power within the minimum operating limits of the inverters.

It is important to note that Figure 6 shows the percentage of time where the inverters were operating, irrelevant of the available energy produced from the modules at the time and does not visualize the effect of the low inverter power output which will decrease the power output even further. There are multiple causes for grid-connected inverter shutdowns but assuming correct system design, it is usually because of inverters operating near specification limits of grid frequency or voltage levels hence triggering shutdowns [19]. However, the reason for inverters low power output is reaching current or voltage limits from the DC array side and reducing output to avoid exceeding those limits by the MPPT. This happens when PV system designers neglect accounting for the maximum operating voltages and currents of both PV modules and inverters.

Finally, it should be pointed out that the system installation was not carried out according to appropriate standards. The fragility of thin-film modules makes them particularly sensitive and prone to damage if subjected to lateral forces. There is reason to believe that such damage was inflicted during installation. Additionally, whenever parts of the system experienced shutdowns, no proper actions were taken to investigate the incident and its causes. As mentioned earlier the system was not subjected to any cleaning procedure since installation as many arrays like those in the bus park and on building F had no proper access.

The New Proposed PV System based on Crystalline Silicon Technology

A completely new proposed on-grid monocrystalline silicon (c-Si) based PV solar system is designed to replace the old thin-film PV solar system. The new PV system will independently act as the main system to fulfil the campus energy needs. The rest of the remaining old rooftop systems will remain intact and act as extra nonessential energy sources. The motivation for the new proposed system is to bridge the gap between energy demand and production.

For the five old PV system locations, three of them are installed on building rooftops while the other two are installed on metal support structures above two parking areas on campus. Since the energy output of the new c-Si modules is higher compared to the old modules, they would require less space. Therefore, the new system can replace one of the two existing park structure locations, or be built on a new structure in the southernmost area of the campus. The former option will allow benefitting from the already existing metal structure, taking into account that the base where the modules are mounted requires modifications to fit the new proposed c-Si modules. However, the overall cost for such modifications will be less in comparison with building a new metal structure. On the other hand, a new structure is required for the latter option to install the c-Si modules, where the overall cost will be higher. However, the new structure will be built taking into account the proper spacing between the arrays to facilitate the cleaning and maintenance measures. Therefore, any faulty modules can be diagnosed and changed easily. Indeed, the extra cost will be compensated by resolving the outstanding problems inherent in the previous system. The calculations for the new proposed PV solar system will be conducted for the second option.

The new PV system is designed to use monocrystalline silicon modules with better electrical and mechanical characteristics than thin-film modules. A comparison between the old thin-film and the new monocrystalline silicon module specifications can be found in tables 6 and 7. The advantages of installing monocrystalline modules are:

- Greater power production.

The new system will be able to produce more energy compared to the old system.

- Higher energy production density.

Although new modules are larger, they provide 1.62 times more power per unit area.

- Higher module efficiency.

New modules are more efficient than the old modules in converting solar radiation to electricity.

- Less overall weight.

Although a single new module is heavier, a fewer number is required. Therefore, the total new weight of the modules will be less than the old ones, addressing concerns regarding weight limitations if chosen to be built on any existing structures.

Table 6: Electrical Specification of Thin-film Modules vs. Monocrystalline Modules.

Module Type	Thin-film	Monocrystalline
Peak DC Power (W)	140	670
Module Efficiency %	13.3	21.6
Max Power Voltage (V)	46.1	38.2
Max Power Current (A)	3.04	17.55
Max String Voltage (V)	600	1500
Module Power per Unit Area (W/m^2)	132.8	215.7

Table 7: Mechanical specifications of Thin-film vs. Monocrystalline Modules.

Module Type	Thin-film	Monocrystalline
Weight per Unit Power (kg/W)	0.12	0.05
Area (m^2)	1.054	3.106
NOCT (°C)	40	43
Power Temperature Coefficient (%/°C)	-0.39	-0.34

The following subsections discuss the new system design, the modeling calculations and the factors influencing them, the system performance, and finally the economical aspect of the proposed project.

System design

The new system arrays would be laid out onto five metal structures as shown in Figure 7 with 15-meter separation to allow for a higher tilt angle without shading from adjacent arrays. The top surfaces have a tilt of 29.55° to the horizontal and have an azimuth bearing of 26° from true south to align with the land underneath and be more aesthetically appealing. The arrays are 4 meters high at their lowest point and 7.56 meters at their highest and have a total tilted top area of approximately 2329m^2.They would fit 720 new modules separated by a 4 cm all-round spacing and have a total DC peak capacity of 482.4 kW$_P$. A total of eight 50 kW inverters will be used with 90 modules per inverter laid out as shown in Figure 8.

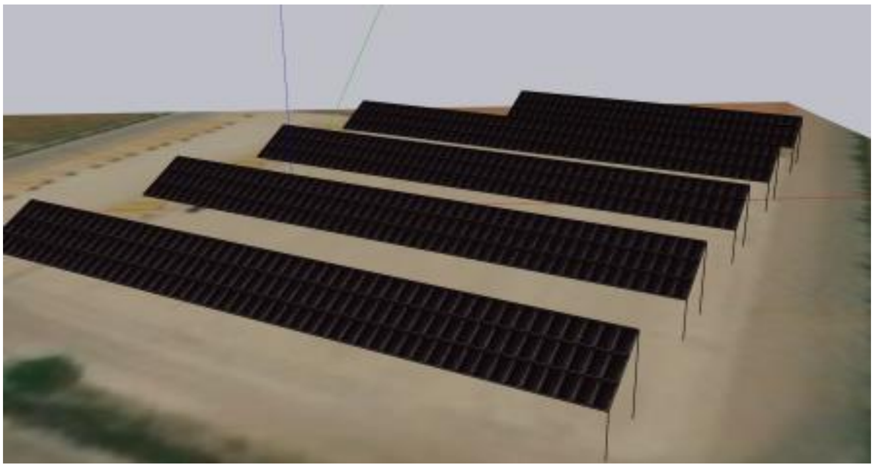

Fig. 7: 3D model of the new PV system arrays

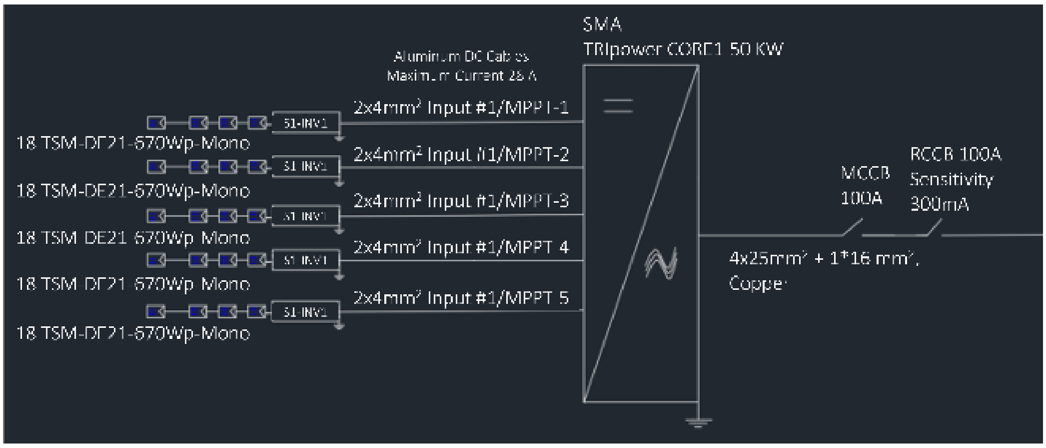

Fig. 8: System single line diagram for a single inverter and breakers

Every 3-phase inverter output has a 100A main circuit current breaker and a 100A residual circuit current breaker that connects to a main junction box with a larger 900A main circuit current breaker. All breaker ratings are chosen considering code safety factors and the maximum current output depending on the availability of components in the local market. All system components were designed in accordance with local codes and standards from the National Jordanian Building Codes manual published by the Jordan National Building Council under the Ministry of Public Works and Housing. The process of choosing the main components such as the PV modules and inverters was also dependent on the certificates and safety standards held by each. The Trina Solar photovoltaic cells had several health, environmental and quality ISO standards in addition to IEC PV standards. The SMA inverters selected had the required IEEE standards and were tested and certified according to UL standards of safety.

System modeling calculations

The peak DC power capacity does not reflect the actual expected energy output of the system since the peak rating of a module is measured under standard laboratory test conditions and does not account for the orientation and tilt angle of the system array nor does it consider the system inverter conversion efficiencies and electrical losses. Therefore, the system output was simulated while accounting for many derating factors to produce a reliable Figure for estimated system output. All calculations for derating factors that constantly change throughout the year, like temperature and solar insolation, were done on an hourly basis. The modeling process included several parts.

1. The solar Insolation

Hourly solar insolation values for the new system were obtained from satellite data available from [17] and are shown in Figure 9. The advantage of satellite data is that it accounts for cloud coverage and air mass variations. The peak sun hour data for the months of 2021 was obtained and then used to calculate the expected energy that would fall on the system year-round. Additionally, the data was used for other steps of the design that relied on the number of available sun hours for their calculations. The yearly average daily solar insolation value for 2021 was around 5.8 sun hours.

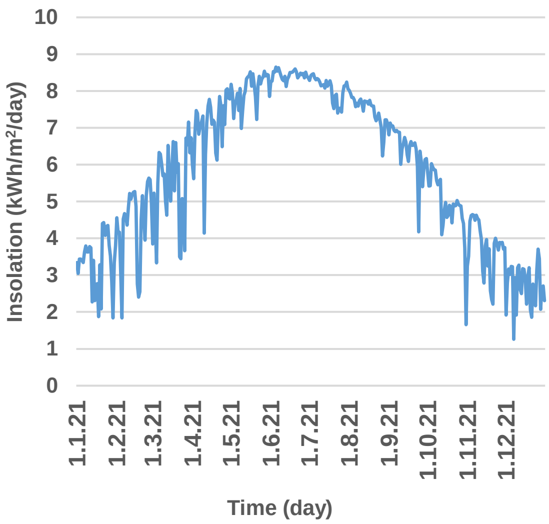

Fig. 9: Hourly satellite solar insolation for the new PV system location.

2. Tilt factor and effect of azimuth

Since the system is tilted at an angle of 29.55˚ to the horizontal, the solar insolation reaching the modules across the year is different compared to standard test conditions. As a result, a factor must be used known as the tilt factor (R_{Bt}). It is the ratio of the energy falling on a tilted surface to the energy falling on the same but horizontal surface, and measures how effectively solar insolation is reaching the tilted modules. This factor depends on multiple variables such as the declination angle and the hour angle which change constantly around the year in addition to the azimuth or horizontal bearing of the modules while tilted. Ideally, a system should be facing a couple of degrees towards the south but due to the land layout, the azimuth was around 26° and had to be accounted for. The tilt factor was calculated hourly using equation 4.

$$\mathbf{R_{Bt}} = \frac{\begin{matrix}\sin(\boldsymbol{\delta})\sin(\boldsymbol{\varphi})\cos(\boldsymbol{\beta}) \\ -\sin(\boldsymbol{\delta})\cos(\boldsymbol{\varphi})\sin(\boldsymbol{\beta})\cos(\boldsymbol{\gamma}) \\ +\cos(\boldsymbol{\delta})\cos(\boldsymbol{\varphi})\cos(\boldsymbol{\beta})\cos(\boldsymbol{\omega}) \\ +\cos(\boldsymbol{\delta})\sin(\boldsymbol{\varphi})\sin(\boldsymbol{\beta})\cos(\boldsymbol{\gamma})\cos(\boldsymbol{\omega}) \\ +\cos(\boldsymbol{\delta})\sin(\boldsymbol{\beta})\sin(\boldsymbol{\gamma})\sin(\boldsymbol{\omega})\end{matrix}}{\sin(\boldsymbol{\varphi})\sin(\boldsymbol{\delta}) + \cos(\boldsymbol{\varphi})\cos(\boldsymbol{\delta})\cos(\boldsymbol{\omega})} \quad (4)$$

where:
δ is the declination angle
φ is the latitude
β is the tilt angle of the module surface
γ is the azimuth
and ω is the hour angle

3. Effect of temperature

Since module output power varies with its operating cell temperature, hourly ambient satellite temperature readings and solar irradiance values were taken from [17] for a whole year and were used to calculate the operating cell temperature (T_{cell}) using equation 5 below.

$$\mathbf{T_{cell}} = \mathbf{T_{amb}} + \left(\frac{\mathbf{NOCT - 20}}{\mathbf{0.8}}\right)\mathbf{S} \quad (5)$$

where:
T_{amb} is the ambient temperature in °C
$NOCT$ is the nominal operating cell temperature in °C
S is the solar irradiance in W/m^2

Afterwards, equation 6 uses the obtained cell temperature values and the module temperature power coefficient to calculate the new expected module output power (P_{new}).

$$\mathbf{P_{new}} = \mathbf{P_{mod}} * (\mathbf{1} - \mathbf{T_{Coef}}(\mathbf{T_{cell}} - \mathbf{25})) \quad (6)$$

where:
P_{mod} is the maximum module power output in W.
T_{Coef} is the temperature power coefficient in %/°C.

4. Module degradation and mismatch

PV modules suffer from light induced degradation [20]. This is when the cells structures in modules degrade from exposure to the UV radiation in solar irradiance and decrease their power output. When PV modules are manufactured they go through an initial LID process (as in the case of thin-film PV modulus), but since this process continually happens with sun exposure, it will keep decreasing the module power output after installation therefore affecting the generation of any PV system. This degradation is highest in the first year of installation and continues to take effect on a smaller scale in the following years. For the monocrystalline silicon PV modules, initial degradation is 2% and the annual degradation is 0.55%. Another phenomenon affecting system performance is mismatch. Mismatch occurs when the electrical outputs of cells differ from one another. The power loss by mismatch is in the range from 1.5 to 3% and an average of 2% was chosen for this design [2].

5. Component efficiencies

Two other causes of power loss were the inverters and wires with both having efficiencies around 97.8% and 99% respectively. The inverter efficiency was taken from its specification sheet while the wire losses value was taken from literature [2].

New system performance

After all factors affecting the system output were accounted for in the modeling the overall system performance can be calculated using the multiple performance parameters mentioned earlier in the paper. They are shown for the new system with the 2020 thin-film system parameters for comparison in table 8.

Table 8: Performance parameters for the current thin-film and new designed system.

Parameter	Monocrystalline 2021	Thin-film 2020
Final System Yield, Y_f (kWh/kW)	1763.8	343.3
Reference Yield, Y_r (hours)	2137.0	2067.7
Performance Ratio, PR (Dimensionless)	0.825	0.166

Table 9: System component costs.

Project component	Percentage Cost
Modules	43%
Inverters	10%
Structural BOS	20%
Electrical BOS	7%
Labor	7%
Shipping	11%
Permits and inspection	3%

New design economics

An economic analysis was performed for the designed monocrystalline system over a 20-year project operating period. In current 2023 monetary value, the system is projected to save around 2.44 million JOD and have a payback period of 2 years with an initial cost of 307,000 JOD based on the electric utility company tariff of 0.256 JOD/kWh. The project costs in table 9 are based on a combination of actual market pricing and estimates from other literature [2]. The university administration is continuously taking measures to reduce energy usage and as a result, consumption for the last 5 years has been decreasing. The economic analysis however was done based on fixed consumption figures from 2020 due to the unpredictability of the nature of future energy saving measures. Furthermore, additional increases in consumption are foreseen due to new building currently being erected across campus. The degradation of system performance from LID was also accounted for.

Conclusion

In this work, the performance of an existing thin-film system in the MENA region was analyzed using standardized PV performance parameters and by comparing irradiance and energy production trends. Both parameter values and changes in production trends indicated problems with the system power generation. Three possible causes were investigated to find the source of this problem: high module temperature losses, faulty operation of system components and lack of proper installation measures and poor maintenance. Issues harming the system generation were found in the latter two. System inverters had reduced availability due to continual shutdowns. Several reasons were put forward to explain the issues faced by the inverters.

A new system was designed as a solution to replace the thin-film system. Modeling employed satellite data and accounted for derating factors affecting the system like temperature losses, LID, tilt and azimuth angles, soiling, component mismatch and others. Performance parameters were again used to gauge system performance in addition to an economic analysis if the project is to be pursued.

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Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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