Design and Performance Analysis of a Grid-Connected Solar Power System for Energy Efficient AR Building

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***Abstract*—In 2020, nearly all Saudi Arabia's electricity generation was fueled by natural gas (61%) and crude oil (39%). As part of Saudi Arabia's vision 2030, the Saudi government plans to diversify fuels to increase crude oil exports and reduce carbon dioxide emissions. In Saudi Arabia, the solar irradiance averages 5.2 kWh/m^2/day, photovoltaic (PV) technology is being embraced to achieve green growth and increase power generation. As a result of the technology's proximity to the point of consumption, it ensures a continuous supply of energy while reducing the country's transmission and distribution losses. A key parameter affecting the performance of PV panels in a photovoltaic system is the solar radiation incident on the panel. The tilt and azimuth angles of PV modules are two important factors in designing the PV system for the best performance. This study starts by utilizing Excel software to calculate the azimuth angle for the best adjustment of solar modules. Then, PVSyst software is used to design and simulate a grid-connected PV system for the Admission and Registration Building (AR) at Effat University in Jeddah. The study compares the solar system's performance for mono-crystalline, poly-crystalline, and thin-film photovoltaic modules. The simulation results showed the effectiveness of the design in terms of the produced energy, meeting the estimated needs of the AR building, the save CO_2, and the annual savings using Saudi Arabia's current electricity tariffs.**

***Index Terms*—energy production, azimuth angle, monocrystalline photovoltaic modules, polycrystalline photovoltaic modules, thin film photovoltaic modules, PVsyst software, KSA tariffs**

I. Introduction

The General Authority for Statistics stated that the total population in Saudi Arabia was about 34.1 million in mid-2021, which stood at a total population of 35.0 million in mid 2022. Saudi Arabia ranks as the 11^{th} biggest energy consumer worldwide and the 2^{nd}-biggest in the Middle East. The total generated electrical energy in 2020 was 338,031 GWh compared with 335,445 GWh in 2019, with an increase of 0.77% in 2020. The electrical consumption reached 289,333 GWh in 2020 and 288,713 GWh in 2019, with an increase of 0.21%. The residential sector consumption in 2020 accounted for 47.58% of the total electrical energy consumption, followed by the industrial sector at 20%, then the commercial sector at 14.2%, then the government sector at 12.51%, and finally, the other sectors at 5.71%. Due to population growth and the continuous demand for energy resources, there is a need to establish alternative sources of energy that are clean and harmless to the environment. The Saudi National Renewable Energy Program has solar energy projects of 4,470 MW, which is about 91.8% of total renewable projects. Their aim amounts to 15,108,701 MWh/year by 2024. The amount of fossil fuel consumption will be reduced, which would contribute to decreasing carbon dioxide (CO_2) emissions by 9,828,156 Ton/year. In Saudi Arabia, the global horizontal irradiance is about 27,615 Wh/m^2/day, the total diffused horizontal irradiance is about 9,572 Wh/m^2/day [1].

The orientation of solar panels significantly affect the amount of captured light, in a way that the selection of the tilt and azimuth angles affects the generated solar energy. The main objective of this study is to determine the optimum tilt and azimuth angles of solar collectors in Jeddah, which is located in the western part of Saudi Arabia; by utilizing Excel software and the use of Jeddah's solar data. After that the impact of tilt and azimuth angles on a solar system's performance are assessed by the PVSyst software that is used to model and simulate a grid-connected PV system for the Admission and Registration Building (AR) at Effat University in Jeddah. The study performed a comparative analysis of performance and economic feasibility of three different solar photovoltaic technologies, namely, mono-crystalline, poly-crystalline, and thin film. The reduction of the electricity bill and the saving on CO_2 emissions are calculated.

II. The Sun's Position

The tilt angle describes the vertical angle of a solar panel while the azimuth angle describes the horizontal facing the equator, as in Fig. 1. Solar panels should face toward the equator for best results. If the building's location is in the northern hemisphere, the solar panel should face the south and vice versa. Specifically, panels have to point toward true south/true north as opposed to the reading on the compass, which is magnetic south/magnetic north, respectively. Based on the location, the compass reading is inaccurate by about 25°. Assuming a location that exists in the northern hemisphere, and the magnetic declination is east (positive), then the solar panels should face the east to maximize their exposure to sunlight and increase the amount of generated solar power.

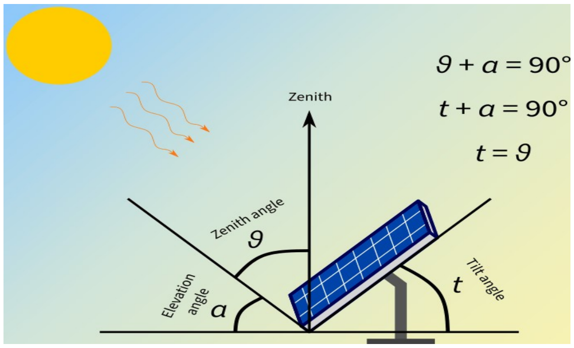


Fig. 1: The Sun Zenith, tilt, and Azimuth Angles.

A. The Tilt Angle

Placing solar panels facing the sun ensures the maximum achieved power. Thus, solar rays striking solar panels must be perpendicular to the panels, and this only happens when the tilt of the panel equals the latitude of the place, as in Fig. 2. In this study, located in Jeddah, we considered the latitude and longitude to be 21.5N and 39.5E, respectively.

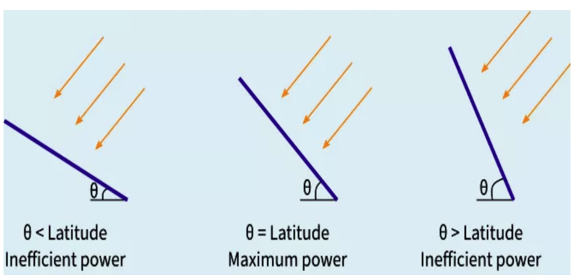


Fig. 2: Solar panel at different tilt angles.

B. The Azimuth Angle

Facing the solar panels directly towards the sun to generate the most solar power is nearly impossible because of the continuous change of the sun's position, solar azimuth, and solar irradiance. However, placing solar panels in a fixed optimal azimuth angle that almost gives maximum sunlight exposure to solar panels over the entire year near noon (11:00 AM to 2:00 PM) is the solution. Many researchers tackled the problem of finding the best azimuth angle, and many estimated equations are derived [2], [3], [4], [5], [6], and [7]. According to [8], the best azimuth angle is estimated in (1).

$$
\begin{aligned}
&A = 360 - \cos^{-1}\left(\frac{\sin(\delta)\cos(\phi) - \cos(\delta)\sin(\phi)\cos(h)}{\cos(\alpha)}\right) \\
&\delta = -23.44 \times \cos\left(\frac{360}{365}(d+10)\right) \\
&h = 15 \times (LST - 12) \\
&\sin(\alpha) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(h) \qquad (1)
\end{aligned}
$$

where A is the azimuth angle, δ is the declination angle, ϕ is the latitude, h is the hour angle, α is the solar elevation angle, LST is the local solar time in hours, and d is the number of days, considering (d = 1) for January first.

III. Admission and Registration Building (AR)

In this study, we started by collecting geographical and meteorological information about the Admission and Registration (AR) building at Effat University, Jeddah, Saudi Arabia. The building composes of four floors with a total area of 14405 m^2. The facades are designed independently from the structure using a lot of glass and modern design with areas of 1662 m^2 for each of the south and north faces and 1753.4 m^2 for each of the east and west faces.

IV. PV Solar Technologies

The first solar generation is the Crystalline Silicon (c-Si) that is produced from silicon wafers with high manufacturing costs. It is sub-categorized into mono-crystalline (m-Si) and poly-crystalline (p-Si) types. This technology is non-toxic and possesses a long-term performance of (20-30) years of durability under outdoor exposure.

Cadmium Telluride (CdTe), Copper Indium Gallium Selenide Sulfide (Cu In, Ga, Se2, CIGS), and Amorphous Silicon (a-Si) are the second generation of thin-film technology. This technology absorbs the solar spectrum much more efficiently than (c-Si). Investigations and experiments showed that the (a-Si) module offered 14% higher energy than (c-Si) in summer while 6% less in winter [9, 10]. The (CdTe) PV cells consist of a heavy and toxic cadmium and a rare in-nature telluride, leading to a high price but environmentally-friendly CdTe solar cells [11, 12].

V. Methodology

For this study, we selected six different PV modules from different companies and ABB inverters. These solar modules are: Jinko mono/poly-crystalline, Hanwha mono/poly crystalline, AE mono/poly-crystalline, and First-solar/Calyx CdTe. We got the electrical specifications for all mentioned solar modules and inverters from their data sheets, and we performed the PV systems' design, modeling, and simulation by the PVSyst software (version 7.2) [13]. The input data to the software are the AR latitude of 21.48°N, longitude of 39.21°E, altitude of 13 m, time zone of +3, tilt angle equal to the location's latitude and an optimum calculated azimuth angle. Fig. 3 shows the architectural solar system model.

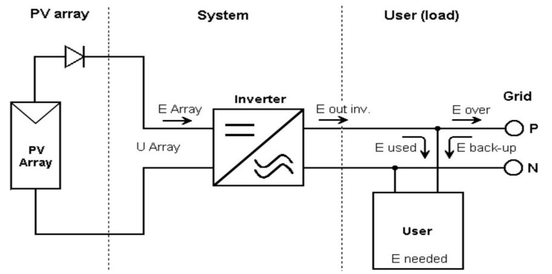
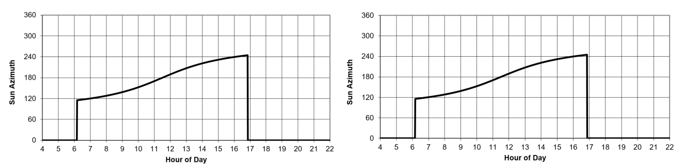


Fig. 3: The solar system model.

VI. Simulation Results

A. Azimuth Angle

The variation of the azimuth angle with hours of the day in different seasons is calculated. A sample of the results is shown in Fig. 4, for the days with numbers 173, and 357 that correspond to June 21, and December 22, respectively. Thus, for the AR building, the best azimuth angle is about 180°.



(a) June 21, 2022 (b) December 22, 2022

Fig. 4: Azimuth angle variations with the hour of the day.

B. AR building yearly electricity consumption and cost

The recent monthly electricity bills of the AR show that the average annual consumed energy is 1304.96 MWh with a cost of SR 71,900.58, Fig. 5.

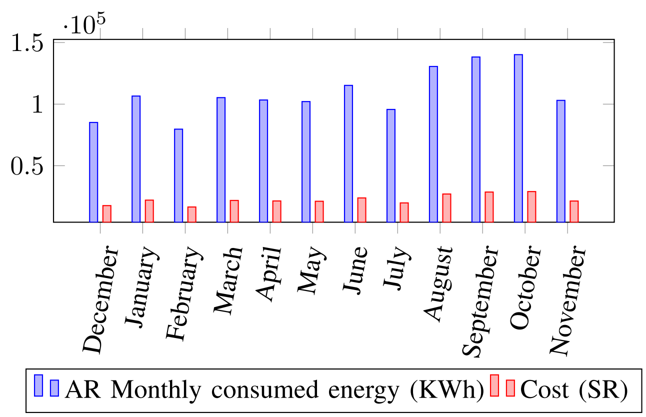


Fig. 5: AR monthly energy consumption and cost.

C. PVSysyst Results

1) Models design: The specifications of the selected components and the design results are shown in the Tables I, II, III, IV, V, VI, and VII.

TABLE I: Design of JinkoSolar Mono-crystalline System.

1) PV Module	
Specifications	***Design Results***
• JinkoSolar • JKM400M-72H • mono-Si • V_{mpp} (60C^0) = 35.5 V • V_{OC} (-10C^0)= 54.9 V • Unit P_{nom} = 400 W_P	• 55 strings × 15 in series • total 825 modules • Total P_{nom} = 330 KW_p • Cell area = 1473 m^2 • Module area = 1660 m^2 • Operating conditions (50 C^0): – V_mpp = 557 V – I_mpp =541 A – P_mpp = 301 KW_p
2) ABB Inverter	
Specifications	***Design Results***
• PVS800-57-0100KWA • With 1 MPPT • (450-825)V • P = 100 KW_{ac}	• Three inverters • P_{total} = 300 KW_{ac} • Operating voltage: (450–825) V • P_{nom} ratio (DC:AC)= 1.1
3) The Whole Solar System	
Losses	***Design Results***
• Collection loss = 16% • System loss = 2.4%	• $E_{Produced}$ = 615.2 MWh/year • $E_{Spec.}$ = 1864 KWh/KWp/year • PR = 81.56% • At plane irradiance 1000W/m^2 and 50 C^0: – I_{mpp} = 541 A – I_{sc} = 570 A – P_{max} = 301 KW – P_{nom} = 330 KW_P – V_{mpp} (60 C^0) = 557 V – V_{mpp} (20 C^0) = 626 V – V_{OC} (-10 C^0) = 823 V

2) The best solar system: The solar system suffers from many sources of losses, such as thermal, DC wiring, module quality, module mismatch, strings mismatch, and the incident angle modifier. These losses are calculated by the simulator and mentioned in the previous Tables. Fig. 6 shows the produced net energy from each solar system, associated with the efficiencies. The results show that the AE mono-crystalline solar system provides the highest net energy of 668.9 MWh/year with an efficiency of 82.7%. Thus, this AE mono-crystalline solar system can provide the AR building by 51.3% (668.9/1304.96) of its annual consumed energy saving about $ 36914.58.

The Carbon Balance tool in the PVsyst estimates the expected saving in the CO_2 emissions for the PV system. The calculation includes the total life cycle of components, energy amount, production, operation, maintenance, disposal, and others. The total carbon balance is the difference between produced and saved CO_2 emissions that depends on the grid's annual production considering an annual degradation of about 1% due to aging of the PV components, the system's lifetime in years, and the grid's Life Cycle Emissions (LCE) (in gCO_2/kWh) that represents the average amount of CO_2 emissions per energy unit. A detailed calculation of the CO_2

TABLE II: Design of JinkoSolar Poly-crystalline System.

1) PV Module	
Specifications	***Design Results***

• JKM-340PP-72
• poly-Si
• V_{mpp} ($60C^0$) = 33.3 V
• V_{OC} ($-10C^0$)= 53 V
• Unit P_{nom} = 340 W_P
	• 50 strings × 17 in series
	• total 850 modules
	• Total P_{nom} = 340 KW_p
	• Cell area = 1489 m^2
	• Module area = 1649 m^2
	• Operating conditions (50 C^0):
	  – V_{mpp} = 595 V
	  – I_{mpp} = 439 A
	  – P_{mpp} = 261 KW_p

2) ABB Inverter	
Specifications	***Design Results***
• PVS-100-TL • With 6 MPPT • (360-1000) V • P = 100 KW_{ac}	• 2.2 (3 units with 0.8 unused) • 13 MPPT 17% • P_{total} = 217 KW_{ac} • Operating voltage (360-1000)V • P_{nom} ratio (DC:AC)= 1.33
3) The Whole Solar System	
Losses	***Design Results***

• Collection loss = 18%
• System loss = 1.7%
	• $E_{Produced}$ = 529.5 MWh/year
	• $E_{Spec.}$ = 1832 KWh/KWp/year
	• PR = 80.17%
	• At plane irradiance 1000W/m^2 and 50 C^0:
	  – I_{mpp} = 439 A
	  – I_{sc} = 461 A
	  – P_{max} = 301 KW
	  – P_{nom} = 330 KW_P
	  – V_{mpp} (60 C^0) = 566 V
	  – V_{mpp} (20 C^0) = 679 V
	  – V_{OC} (-10 C^0) = 901 V

TABLE III: Design of Hanwha Mono-crystalline System.

1) PV Module	
Specifications	***Design Results***

• Hanwha Q cells
• Q.Peak-Duo-XLG11.3-590
• mono-Si
• V_{mpp} ($60C^0$) = 39.8 V
• V_{OC} ($-10C^0$)= 59.2 V
• Unit P_{nom}= 590 W_P
	• 43 strings × 14 in series
	• total 602 modules
	• Total P_{nom} = 355 KW_p
	• Module area = 1649 m^2
	• Operating conditions (50 C^0):
	  – V_{mpp} = 580 V
	  – I_{mpp} =560 A
	  – P_{mpp} = 325 KW_p

2) ABB Inverter	
Specifications	***Design Results***
• PVS800-57-0100KWA • With 1 MPPT • (450-825)V • P = 100 KW_{ac}	• Three inverters • P_{total} = 300 KW_{ac} • Operating voltage: (450–825) V • P_{nom} ratio (DC:AC)= 1.18.
3) The Whole Solar System	
Losses	***Design Results***

• Collection loss = 15.7%
• System loss = 2.5%
	• $E_{Produced}$ = 664.0 MWh/year
	• $E_{Spec.}$ = 1870 KWh/KWp/year
	• PR = 81.79%
	• At plane irradiance 1000W/m^2 and 50 C^0:
	  – I_{mpp} = 560 A
	  – I_{sc} = 584 A
	  – P_{max} = 325 KW
	  – P_{nom} = 355 KW_P
	  – V_{mpp} (60 C^0) = 557 V
	  – V_{mpp} (20 C^0) = 646 V
	  – V_{OC} (-10 C^0) = 829 V

emissions of the Jinko mono-crystalline solar system is as follows:

1) ***system LCE:*** LCE/module = 1713 $kgCO_2/KW_p$, LCE for 330 KW_p = 565198 $kgCO_2$, LCE/Kg (Supports) = 4.96 $kgCO_2$/kg, LCE for 8250 kg = 40885 $kgCO_2$, LCE/Inverter = 491 $kgCO_2$, LCE for 3 inverters = 1743 $kgCO_2$, and total LCE = 607.56 tCO_2.
2) ***Replaced Emission:*** System production = 615.16 MWh/year, Grid life cycle emission = 743 gCO_2/KWh, Life time = 30 years, Annual degradation = 1%, and total = 13712.0 tCO_2.
3) ***Saved CO_2 Emissions = 11289.9 tons.***

The simulation results showed that the saved CO_2 emissions are 11289.9, 9638.8, 12234.7, 9675.0, 12329.5, 9504.1, 11143.4, and 10110.1, for JinkoMono/poly, HanwhaMono/poly, AEMono/poly, and FirstSolar/Calyxo-CdTe, respectively.

VII. Conclusion

As stated by the Saudi General Authority for Statistics, the total population in Saudi Arabia is increasing, reaching about 35 million in 2021. This increase in population led

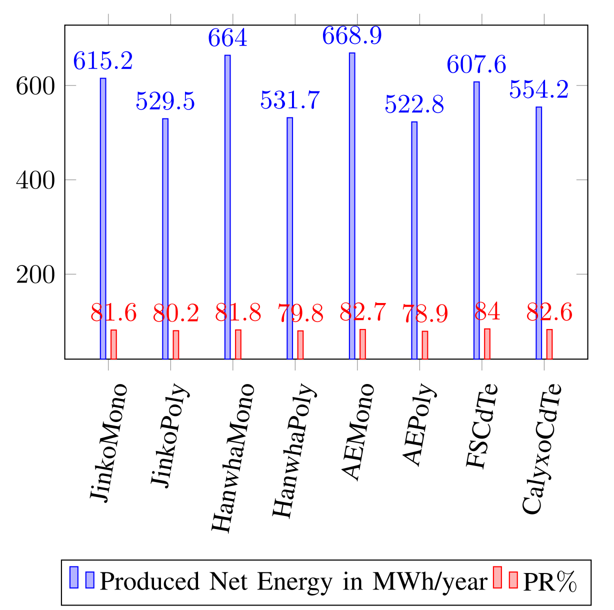


Fig. 6: The net produced energy for each solar technology.

TABLE IV: Design of Hanwha Poly-crystalline System.

1) PV Module	
Specifications	***Design Results***
• Hanwha Q cells • Q.PLUS L-G4.1 350 • Si-Poly • V_{mpp} (60C^0) = 33 V • V_{OC} (-10C^0)= 52.9 V • Unit P_{nom} = 345 W_P	• 49 strings × 17 in series • total 833 modules • Total P_{nom} = 292 KW_p • Cell area = 1460 m^2 • Module area = 1661 m^2 • Operating conditions (50 C^0): – V_mpp = 588 V – I_mpp = 446 A – P_mpp = 262 KW_p
2) ABB Inverter	
Specifications	***Design Results***
• PVS800-57-0250KWA • With 1 MPPT • (450-825)V • P = 250 KW_{ac}	• One inverter • P_{total} = 250 KW_{ac} • Operating voltage: (450–825) V • P_{nom} ratio (DC:AC)= 1.166
3) The Whole Solar System	
Losses	***Design Results***
• Collection loss = 17.8% • System loss = 2.5%	• $E_{Produced}$ = 531.7 MWh/year • $E_{Spec.}$ = 1824 KWh/KWp/year • PR = 79.78% • At plane irradiance 1000W/m^2 and 50 C^0: – I_{mpp} = 446 A – I_{sc} = 475 A – P_{max} = 262 KW – P_{nom} = 292 KW_P – V_{mpp} (60 C^0) = 561 V – V_{mpp} (20 C^0) = 667 V – V_{OC} (-10 C^0) = 899 V

TABLE V: Design of AE Mono-crystalline System.

1) PV Module	
Specifications	***Design Results***
• AE Solar • AE665ME-132 • Si-Mono • V_{mpp} (60C^0) = 33.3 V • V_{OC} (-10C^0)= 50.5 V • Unit P_{nom} = 665 W_P	• 28 strings × 19 in series • total 532 modules • Total P_{nom} = 354 KW_p • Cell area = 1548 m^2 • Module area = 1653 m^2 • Operating conditions (50 C^0): – V_mpp = 660 V – I_mpp = 491 A – P_mpp = 324 KW_p
2) ABB Inverter	
Specifications	***Design Results***
• PVS800-57-0315KW-B • With 1 MPPT • (450-825)V • P = 315 KW_{ac}	• One inverter • P_{total} = 315 KW_{ac} • Operating voltage: (450–825) V • P_{nom} ratio (DC:AC)= 1.12
3) The Whole Solar System	
Losses	***Design Results***
• Collection loss = 15.5% • System loss = 1.8%	• $E_{Produced}$ = 668.9 MWh/year • $E_{Spec.}$ = 1891 KWh/KWp/year • PR = 82.72% • At plane irradiance 1000W/m^2 and 50 C^0: – I_{mpp} = 491 A – I_{sc} = 518 A – P_{max} = 324 KW – P_{nom} = 354 KW_P – V_{mpp} (60 C^0) = 634 V – V_{mpp} (20 C^0) = 735 V – V_{OC} (-10 C^0) = 959 V

to an increase in electrical energy consumption, reaching about 289,333 GWh in 2020. Saudi Arabia is working to find innovative solutions to increase Saudi Arabia's share in the production of renewable energy and diversify local energy sources. The amount of fossil fuel consumption will be reduced, contributing to decreasing carbon dioxide (CO_2) emissions. Because of the location of Saudi Arabia, solar energy is a vital renewable energy source to be considered.

The amount of light that reaches a solar panel is greatly affected by its slope and orientation. In this study, the optimization of solar tilt and azimuth angles for the Admission and Registration (AR) building in Jeddah, Saudi Arabia, is investigated through the EXCEL software to gain the highest solar power. The algorithm is general and can be implemented for any region on the earth. This work agreed with the other researchers, stating that the annual optimum tilt angle is approximately equal to the location latitude. At the same time, the Excel results showed that the optimum azimuth angle is about 180°.

With the use of these optimum solar angles, investigation about the best solar system design in terms of the highest generated power and the highest saved CO_2 emissions are modeled and simulated by PVSyst. We compared the selected solar systems' responses: Jinko mono crystalline, Jinko poly-crystalline, Hanwha Q-cells mono, Hanwha poly-crystalline, AE mono, AE poly-crystalline, first solar CdTe, and Calyx CdTe solar systems with selected ABB inverters. The result showed that the AE mono crystalline solar system provides the best performance in 668.9 MWh/year and saves CO_2 emissions of 12,329.5 tons/year. Thus, for the AR building case study, this proposed solar system can provide about 51% of its annual electrical power needs and, in turn, decrease the annual electrical bill dramatically. As a future work, we investigate the installation of BIPV solar system on the AR building [14].

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TABLE VI: Design of AE Poly-crystalline System.

1) PV Module	
Specifications	***Design Results***

• AE Solar
• AE345DGP6-72(1500)
• Si-Poly
• V_{mpp} ($60C^0$) = 33.6 V
• V_{OC} ($-10C^0$)= 54.5 V
• Unit P_{nom} = 345 W_P
	• 56 strings × 15 in series
	• total 840 modules
	• Total P_{nom} = 290 KW_p
	• Cell area = 1654 m^2
	• Module area = 1486 m^2
	• Operating conditions (50 C^0):
	  – V_mpp = 533 V
	  – I_mpp = 488 A
	  – P_mpp = 260 KW_p

2) ABB Inverter	
Specifications	***Design Results***
• PVS800-57-0250KWA • With 1 MPPT • (450-825)V • P = 250 KW_{ac}	• One inverter • P_{total} = 250 KW_{ac} • Operating voltage: (450–825) V • P_{nom} ratio (DC:AC)= 1.16
3) The Whole Solar System	
Losses	***Design Results***

• Collection loss = 18.9%
• System loss = 2.1%
	• $E_{Produced}$ = 522.8 MWh/year
	• $E_{Spec.}$ = 1804 KWh/KWp/year
	• PR = 78.93%
	• At plane irradiance 1000W/m^2 and 50 C^0:
	  – I_{mpp} = 488 A
	  – I_{sc} = 511 A
	  – P_{max} = 260 KW
	  – P_{nom} = 290 KW_P
	  – V_{mpp} (60 C^0) = 504 V
	  – V_{mpp} (20 C^0) = 615 V
	  – V_{OC} (-10 C^0) = 818 V

TABLE VII: Design of First Solar CdTe System.

1) PV Module	
Specifications	***Design Results***

• First Solar
• FS-6480A-C
• CdTe
• V_{mpp} ($60C^0$) = 171 V
• V_{OC} ($-10C^0$)= 244.1V
• Unit P_{nom} = 480 W_P
	• 659 strings × 1 in series
	• total 659 modules
	• Total P_{nom} = 316 KW_p
	• Cell area = 1566 m^2
	• Module area = 1661 m^2
	• Operating conditions (50 C^0):
	  – V_mpp = 176 V
	  – I_mpp = 1677 A
	  – P_mpp = 295 KW_p

2) ABB Inverter	
Specifications	***Design Results***
• PVI-4.2-OUTD-S-US • With 2 MPPTs • (120-530)V • P = 4.2 KW_{ac}	• 118 MPPTs 50% 59 inverters • P_{total} = 248 KW_{ac} • Operating voltage: (120-530) V • P_{nom} ratio (DC:AC)= 1.277
3) The Whole Solar System	
Losses	***Design Results***

• Collection loss = 12%
• System loss = 3.9%
	• $E_{Produced}$ = 607.6 MWh/year
	• $E_{Spec.}$ = 1921 KWh/KWp/year
	• PR = 84.04%
	• At plane irradiance 1000W/m^2 and 50 C^0:
	  – I_{mpp} = 1677 A
	  – I_{sc} = 1760 A
	  – P_{max} = 295 KW
	  – P_{nom} = 316 KW_P
	  – V_{mpp} (60 C^0) = 171 V
	  – V_{mpp} (20 C^0) = 193 V
	  – V_{OC} (-10 C^0) = 244 V

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