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LARGE-SCALE PV SOLAR POWER PLANT & ENERGY STORAGE SYSTEM

Middle East & North Africa

Author: Andreas Deeb

SAVONIA UNIVERSITY OF APPLIED SCIENCES

THESIS
Abstract

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Author:

Andreas Deeb

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Juhani Rouvali & Jari Ijäs

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Abstract

This study aims to determine the approximate requirements of a large-scale PV solar power plant with a large storage system. Then applying these requirements on different sites in the countries of the Middle East & North Africa, to achieve optimal utilization of abundant solar energy and to provide these countries an ideal solution for their energy crisis.

The study was applied in 3 locations. The first location was near Riyadh, Saudi Arabia, the second was near Cairo, Egypt and the third was near Amman, Jordan. After the locations were specified, the required area of the solar array was calculated. Then the solar array area was divided into groups in order to determine the number of required inverters. After that, the total area of the PV solar plant was determined and finally the requirement of installing a 100 MWh storage system beside the PV solar plant was calculated.

The results of this study provide an accurate method and step-by-step guide of how to calculate and specify the exact number of required solar panels, land area, and inverters, in addition to the whole process of installing a large-scale PV solar power plant (utility-scale) in the Middle East and North Africa.

This study could be generalized to determine the requirements of installing large-scale solar power plant (utility-scale) in any size and anywhere.

Keywords
Large-scale PV Solar power plant, energy storage system

CONTENTS

Abbreviations:

MENA	Middle East & North Africa
GCC	Gulf Cooperation Council
PV	photovoltaics
W	Watt
kW	Kilowatt
kWh	Kilowatt hour
kWp	Kilowatt peak
MW	Megawatt
MWh	Megawatt hour
STC	Special test condition
A	Ampere
V	Volt
DC	Direct current
AC	Alternating current
GHI	Global horizontal irradiation
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
OPTA	Optimum angle of PV modules
Isc	Current under short-circuit
Imp	Current at maximum power
Vmp	Voltage at Maximum Power
Voc	Voltage Open Circuit

Figures

1 INTRODUCTION

Solar energy is produced from the power and heat of the sun’s rays and could be converted into electricity. It is renewable, free and infinite, so it will not run out, unlike conventional energy.

In comparison with other energy sources, solar energy has the least negative impact on the environment. It does not release any harmful emission or other heat-trapping gases into the air that contribute to climate change so, it is environmentally friendly.

The growth of solar power adoption has been happening so fast. Nowadays the percentage of solar energy production is over 1 % of the total energy production in the world. According to the international energy agency study in 2014, solar energy production could contribute 27 % of global electricity generation by 2050. This figure seems to be very encouraging to start investing in solar energy. (Breakthrough Institute 2014; World Energy Council 2016.)

The Middle East and North Africa countries include 22 nations, they comprise together 6 % of the world’s population. These countries are classified as energy exporter and energy importer. Usually, the energy importer countries are suffering from the shortage of energy, while energy exporter countries have 100 % access to electricity, depending on their oil and gas. However, these resources are not finite. As a result of oil price volatility, most of energy exporter countries in MENA were obliged to look for diversifying their energy resources by moving towards solar energy.

There are many factors that make the utilization of solar energy an ideal solution to the energy shortage in the Middle East and North Africa. First, these countries are in the sun belt of the world. This unique location makes them enjoy a high amount of solar radiation throughout the year. Second, they have large empty areas not suitable for any agriculture, it can be utilized to produce solar energy. Furthermore, the solar power plant has low operating costs because it doesn’t require any fuel to operate. (Hochstrasser 2015.)

1.1 BACKGROUND OF THE PROJECT

The rapid growth of population, economy, and urbanization in the Middle East and North Africa always increases the pressure on these countries' infrastructure and energy, causing a lack of access to electricity for more than 28 million people. (World Bank 2010.)

The total installed solar power in the Middle East and North Africa countries in 2015 was around 1.39 GW. This amount represents only 0.6 % of the total solar energy generating in the world, which looks so small compared to the total global production. (World Energy Council 2016.)

Figure 1 represents the percentage of producing solar energy in MENA countries among the world.

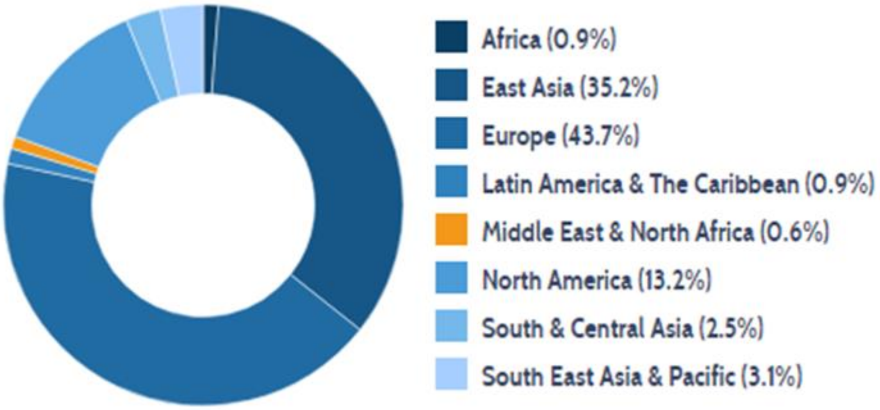

FIGURE 1. Solar installed capacity by region (World Energy Council 2016).

Figure 2 illustrates the amount of produced solar power per MW in some Middle East and North Africa countries.

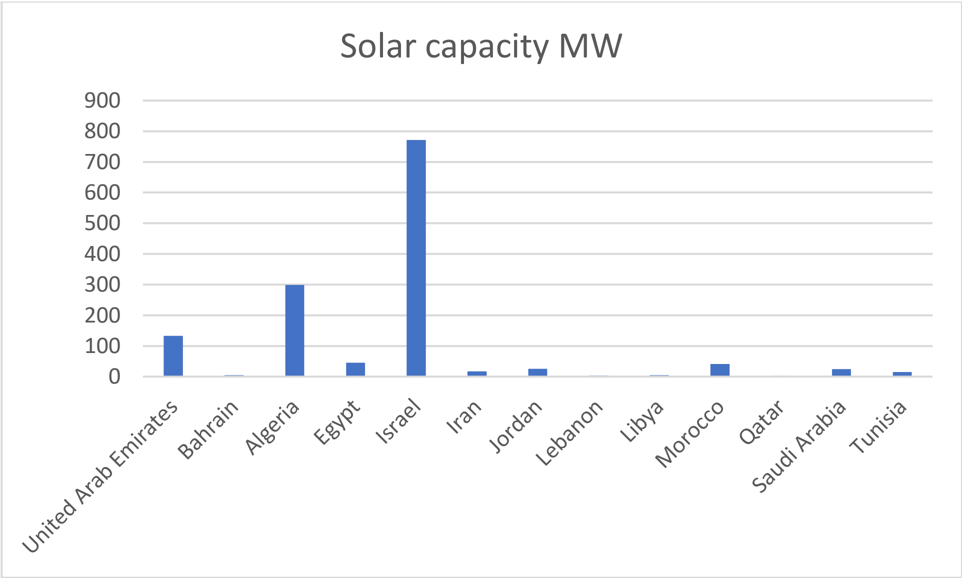

FIGURE 2. Amount of producing solar power in MENA countries (World Energy Council 2016).

1.2 Research objective

The research objective is to present a study of how to install 10 MW large-scale PV solar power plants with a 100 MWh storage system (peaking power plant) in the Middle East and North African countries to provide a feasible solution for their energy crisis.

FIGURE 3. Targeted study area in MENA (World Energy Council 2016).

1.3 Definition of keywords

Large-scale PV solar power plant is defined as a large photovoltaics power station, designed to generate and supply power into the electricity grid and typically has at least 1 MW capacity.

Energy storage system refers to the equipment that can be used to store a large amount of energy in an efficient way in order to reuse it in peak demand and avoid power outage.

1.4 Research materials

The research materials in my study were available online. Publications in the form of e-reports, analysis, suggestions and up to date statistics were obtained from World Bank, International renewable energy Agency (IRENA), National Renewable Energy Laboratory in the USA (NREL) and the United States Environmental Protection Agency (EPA).

The solar data and related solar energy assessment were collected from Global Solar Atlas, whereas the Information about the latest technologies and components used in installing large-scale PV solar power plants were obtained from suppliers.

2 SOME IMPORTANT FACTORS TO BE CONSIDERED BEFORE PLACING A PV SOLAR PLANT

In order to have a successful and productive PV solar power plant, the following important factors should be taken into consideration before installing the PV power plant.

2.1 The location of solar plant:

The location of the solar plant should fulfill specific criteria. First, it should be flat and has enough space to install a solar plant. Second, it should be subject to the safety, health and environmental examination moreover, the location should be exposed to sunlight without any obstacles.

2.2 The grid connection point

In order to avoid the cost of upgrading or installing a new grid and to reduce the energy waste. The grid connection point should be close to the solar plant location. Moreover, the grid network should have the ability to transmit and absorb the full output capacity of the solar plant. (Solar Dao 2017.)

3 THE MAJOR COMPONENT OF PV SOLAR SYSTEM

3.1 PV Solar panels or modules

The main function of PV solar panels is to convert the sunlight into DC electricity. To build a large-scale solar power plant, we need to use ten thousand solar panels or more depending on the capacity of the solar plant and the amount of solar radiation that hit the location.

There are many types of PV solar panels but the most common PV ones in the market these days are listed and classified as follows:

3.1.1 Monocrystalline

One of the most efficient solar panels among others, this type of solar panel has an efficiency rate between 15 -20 %. Which means the panel can convert 15 to 20 % from receiving sunlight into DC electricity.

Advantages:

- They have been made from the purest form of silicone, which makes them the most efficient.
- They are the most space-efficient, so they require less space than other solar panels.
- They have the longest life span with a manufacturer’s warranty for up to 25 years.
- They are a good option for cloudy areas, as their performance better in low sunlight.

Disadvantages:

- They are the most expensive among other options
- They produce a lot of silicone waste due to silicone cut.

FIGURE 4. Monocrystalline solar panel (Sendy 2019).

3.1.2 Polycrystalline

This type of solar panel has a different manufacturing process than monocrystalline as the silicone in this type is melted and then poured into a square template. This manufacturing process reduces the cost of manufacturing which makes them cheaper in comparison to polycrystalline solar panels.

Advantages:

- Cheaper compared to monocrystalline solar panel.
- No silicone waste.
- Easier to manufacture.

Disadvantages:

- Not the most efficient solar panel in the market due to the lower purity of silicone, as their efficiency rate ranges between 13 – 16 %.
- Lower space efficiency, due to the lower output rate, so it requires to install more solar panels for more output.
- Power performance in high temperatures is a little worse than monocrystalline solar panels.
- They have less life span, as heat can shorten their life span.

FIGURE 5. Polycrystalline solar panel (Sendy 2019).

3.1.3 Thin Film

Thin film solar panel is made up from one or more thin layer of the following substrates:

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Selenide (CIGS)

Advantages:

- Simple production process makes them potentially cheaper option than crystalline solar panels.
- High temperature has less impact on the thin film solar panel performance.
- Lightest available solar panel.
- Easy to install, so they have Less Installation cost.

Disadvantages:

- Lowest power efficiency among other technologies, their efficiency rate range between 7 -13 %.
- Lowest space efficiency, they are not a good choice when space matters.
- They degrade faster than polycrystalline and monocrystalline based solar panel.
- Short life span, so they come with a shorter warranty.

Due to low efficiency in this type of solar panels, they may require up to 50 % more space for a given project size, which does not make them the right choice for large-scale solar power plants. As well as the cost of installing, support structure and cables will increase also.

FIGURE 6. Thin film solar panel (Sendy 2018).

Regardless of the type of solar panel, to get the maximum efficiency for each type, the solar panels should be installed in the right way to take the full advantage of sunlight. (Sendy 2019.)

3.1.4 Amerisolar Panels Manufacturer & Supplier

The technology and manufacturing methods of solar panels are improving so fast. Many manufacturers these days started to produce solar panels with special specifications to operate in the desert areas, and it comes with warranties up to 30 years.

Amerisolar panel's manufacturer and supplier had succeeded to develop a special type of PV desert solar panels. These types of solar panels can stand a very hard climate condition. They had passed all the required tests to operate successfully in the desert areas. They are dust resistant and can work perfectly under very hot temperatures.

This supplier had gained TUV Nord and the TUV Rheinland certification. This certificate proves that Amerisolar panel can operate in the desert and in low humidity climate which makes it a good choice for the Middle East and North Africa climate. (Amerisolar PV solar panels for the desert area.)

3.2 PV ground-mounted system

To get the maximum energy output from the Solar PV modules. It is recommended to set their absorbing surface perpendicular to the sun radiation. Accordingly, there are many technics to mount the solar systems to maximize energy output.

- Fixed tilt solar system refers to solar modules placed at a fixed angle because the solar panel absorbs solar radiation more efficiently when it is placed perpendicular to the sun's rays. In this type of system, two important angles should be determined while installing the array to maximize the collection of solar radiation.

    - The Azimuth angle is described as the compass direction from which the sunlight is coming (North, South, East or West). In the countries that located in the Northern hemisphere the solar panels should be set to face south. For example, the solar panels in the Middle East & North Africa countries should be set to face south.

    - Tilt angle specifies the angle between the solar panel and horizontal ground. It ranges between $0°$ which means the solar panel is lying flat on the ground and $90°$ degree which means the solar panel is perpendicular to the ground.

- Sun tracking frames: in this system, solar modules are fixed on a rotating axis, which allows the modules to rotate and change their orientation between East-West to track the sunlight throughout the day. To maximize sun radiation capture, as well as increasing the energy output up to 25 %. (Pickerel 2017; Marcy 2018; Alternative Energy Tutorials 2019.)

3.3 Solar charge controller

The main function of the solar charge controller is to control the charge going from solar panels into the storage system (battery), to prevent the battery from overcharging and reverse current flow when needed.

Advantages of the solar charge controller

- Increasing the efficiency of solar systems.
- Minimizing the use of utility power.
- Maximizing the life of the battery and other PV system components.

The solar charge controller should be big enough to handle the current produced from the solar array.

3.4 Combiner boxes

The main function of Combiner boxes is to connect many solar arrays to the inverter, in addition to the following:

- Combining the output of many solar strings together.
- Reducing the required cabling.
- Providing protection from additional overvoltage.

3.5 Inverter

Inverter is an electrical converter and one of the most important part of the solar power system. Its main function is to convert the generated or battery-stored direct current (DC) electricity into alternating current (AC) electricity to be used for domestic appliances.

The inverter may have also the following functions:

- Battery storage management.
- Monitoring and controlling the system performing.
- Helping to improve the efficiency and stability of the grid.
- Synchronizes optimal power delivery to the grid & battery.

One of the most popular inverters for large-scale PV solar power plants is the centralized inverter. This type of inverter is an ideal solution for large solar power plants that require high-performance solar inverters.

Central inverter is connected to the arrays of PV solar modules to convert the DC electricity supplied from the PV array into AC electricity to be transferred by the grid.

The central inverter power ranges between 50 kW and 2 MW, it is a ground-mounted and can be used outdoor and indoor. ABB is manufacturing central inverters with a power range up to 2 MW. (ABB.)

3.6 Cables

Cables are required to transfer produced electricity from solar panels to inverter and from the inverter to the load so, they should be strong enough to withstand the different environmental conditions.

3.7 DC & AC disconnectors

DC disconnectors are electronic switches that cut off the output DC power from the solar array before reaching the inverter. They are an important part of the solar system when it comes to making service or maintenance for the solar panels, and they should handle the full power output from the array.

AC disconnectors are electronic switches for separating the inverter from the electrical grid. (Fedkin; Dutton 2018.)

Figure 7 illustrates the placements of AC and DC disconnect switches in photovoltaics applications.

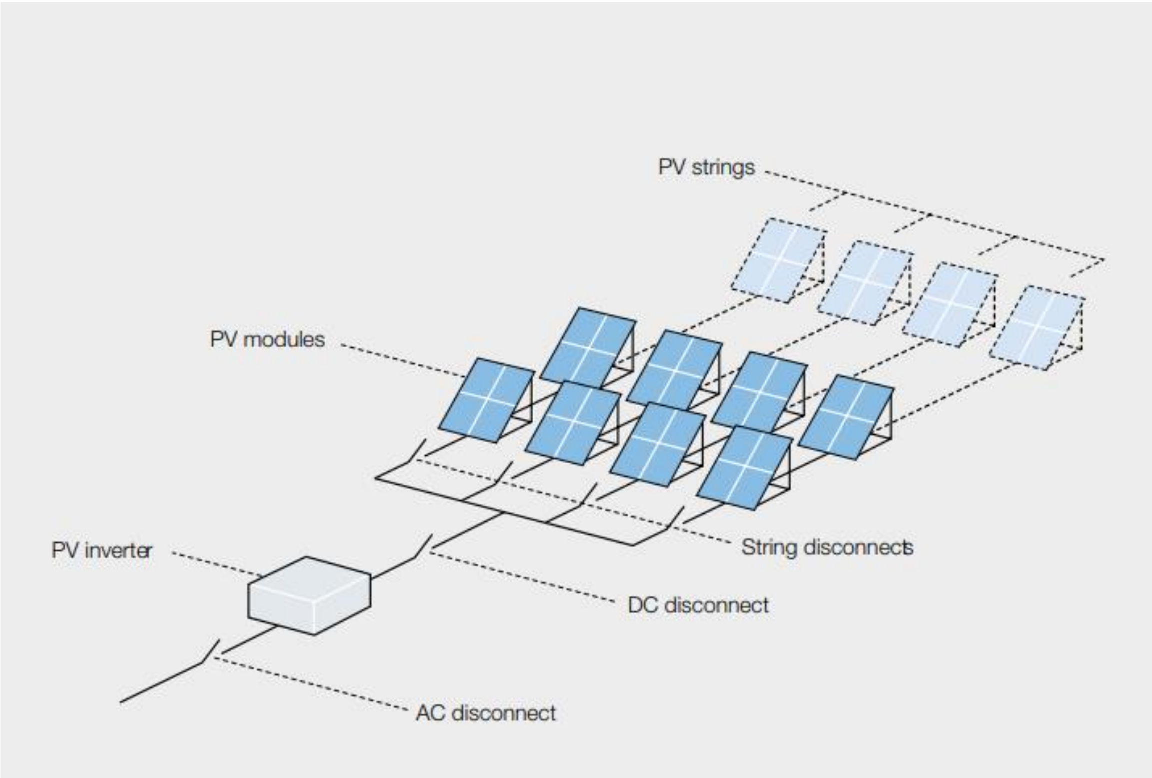

FIGURE 7. AC & DC disconnect switches (ABB 2009, 3).

4 BATTERY & ENERGY STORAGE

Energy storage is an important component in the PV solar power plant because sunlight is not available 24 hours per day. So, it is very important to use an effective storage system to store the solar energy and keep supplying the grid at night or in peak demand.

- Capacity & power

Capacity is the total amount of electricity that the solar storage system can store, and it is measured by kWh. While the power rating is the amount of electricity that the storage system can release or provide at a specific moment and it is measured by kW.

- Depth of discharge (DOD)

It refers to how deep the battery is discharged. The higher the battery depth of discharge the higher capacity can be used from it. For example, if the depth of charge for 100 kWh battery is 90 %, it is not suggested to discharge the battery more than 90 kWh before recharging it.

- Round trip efficiency

Round trip efficiency is defined as the ratio of energy recovered from the storage device and the energy put into the device. Round trip efficiency can be determined from the equation (Farrell 2018):

$$Round\ trip\ efficiency\ =\ Energy\ recovered/energy\ input\ \cdot\ 100\ \% \qquad (1)$$

It is not possible for round trip efficiency to be 100 % due to some losses in storage e.g. heat losses.

For example, if we stored 100 kWh of electricity in battery. Then we could get back only 88 kWh of electricity, so the round-trip efficiency in this case is:

$88/100 \cdot 100 =\ 88\ \%$ So, there will be 12 % of the energy losses.

4.1 Grid energy storage system

Grid energy storage or large-scale energy storage is the method used to store electricity in a large battery. The electrical energy is stored when the power production from the solar power plant during the peak time exceeds the consumption, to reuse it again when consumption exceeds production in peak demand.

FIGURE 8. Grid-scale energy storage (Nicholls 2018).

Energy storage has been a very challenging issue for the last few years for the PV solar power providers Because the difficulties of keeping the flow of energy steady and stable in addition to balance the supply with the demand on Energy at night. Accordingly, the energy providers have been using fossil fueled Peaking power plants to intensify energy production and to meet the increased demand for energy at night. These challenges have made the need for energy storage very important, to reduce energy waste and at the same time the dependency on fossil fuel. (Diehl 2015.)

4.1.1 Tesla Powerpack energy storage battery

Tesla had succeeded to make a huge change on energy storage, by installing a 129 MWh Powerpacks large battery at low cost. This large battery can store the produced energy from the solar power plant and improve the stability of the grid.

Tesla Powerpacks battery is an integrated battery system, it is equipped with everything needed to be connected easily and efficiently with utility networks. This integrated system offers benefits far superior to standalone batteries.

Tesla power pack batteries are designed to power entire cities. In addition to providing the grid with the same energy as peaking power plants, but it is cheaper, faster and emission-free.

Each powerpack battery is composed of 16 individual battery pods. Each one comes with an isolated DC-AC converter in addition to a cooling and heating system.

Powerpack battery can store solar energy and it can work as a backup generator as well it draws the energy from the grid when the consumption is low. (Tesla; Lambert 2018.)

FIGURE 9. Tesla 100MW/129 MWh Powerpack battery (Lambert 2018).

4.1.2 Tesla Powerpack System specifications

Tesla Powerpack is a large DC energy storage battery and each one powerpack has the following Technical specification:

- Bi-Directional Inverter, the inverter converts AC grid power to DC for Powerpack storage, then converts this DC power back to AC for grid interconnection (Tesla).
- AC Voltage: 3 phase voltage 380 to 480V.
- Inverter: IP66/NEMA 4
- Scalable Inverter Power from 50kVA to 625kVA (at 480V)
- Energy Capacity: 210 kWh (AC) (capacity refers to the amount of charge stored in batteries)
- Operating Temperature: from -30°C to 50°C
- Power: 50 kW (AC) per Powerpack (power refers to the amount of energy delivered from the battery)
- System Efficiency (AC) * 88 % round-trip (2-hour system).
- Depth of Discharge 100 % (DOD means how deeply the battery discharge when it delivers the stored energy) in this system 100 % means the battery is delivering 100 % of its stored energy.
- Dimensions of each Powerpack:
  - length 1.308 m
  - width 0.822 m
  - height 2.185 m
  - weight 1622 kg (Tesla).

5 CALCULATING THE DAILY ENERGY OUTPUT OF PV SOLAR POWER PLANT

The total electricity generated from the PV solar power system can be determined from the formula (EPA 2018; NREL 2019):

$$E = H \cdot A \cdot I \cdot PR \quad (2)$$

where:

E: is the total produced energy per day, and it is measured by (kWh)

H: is the solar panel efficiency, which ranges in the most modern panels between 15 – 20 % and can be calculated from the following formula (NREL 2019):

$$H = \left(\frac{Power\ rating\ (W)}{Surface\ area\ (m^2) \cdot 1000\ (\frac{W}{m^2})} \right) \times 100\ \% \quad (3)$$

$where\ 1\ kW/m^2$ is the sun radiation under standard test condition.

A: is the total area of solar array, it is measured by (m^2)

I: is the daily average global solar irradiation on tilted panels.

PR: is the performance ratio**,** solar system losses. Its value ranges between 0.5 and 0.9.
Its default value = 0.75 (NREL 2019).

Solar system losses are e.g. (heating, inverter losses, AC & DC cable losses, losses because of snow and dust, in addition to temperature losses). (EPA 2018; NREL 2019.)

5.1 Photovoltaic Electricity Potential in Middle East and North Africa

The PV electricity potential is defined as the expected amount of converted energy into electricity (kWh/kWp), from a PV solar system according to the geographical location condition and arrangement of solar system.

Figure 9 shows the long-term average of (PVOUT) in the Middle East and North Africa between 1994 and 2015, the closer the area for equator the greater solar energy potential it has.

The potential solar power energy in the Middle East and North Africa range between 3.6 kWh/kWp and 5.6 kWh/kWp per day. (Global Solar Atlas; Solargis.)

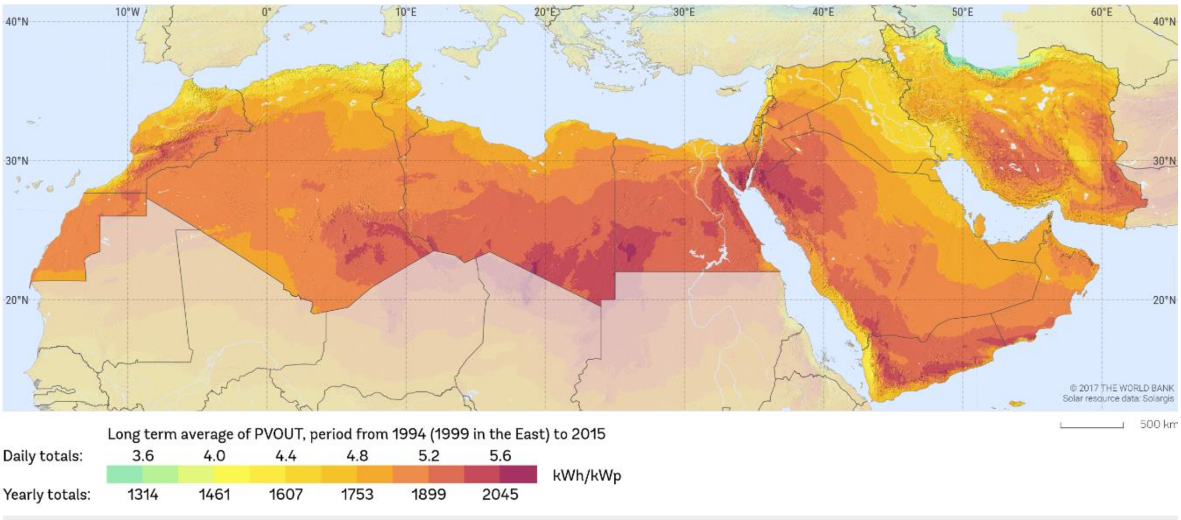

FIGURE 10. Potential solar energy in MENA (Global Solar Atlas; Solargis).

5.2 Direct Normal Irradiation in Middle East and North Africa

DNI is defined as the amount of solar radiation reaching the earth per unit area by a surface that held perpendicular (or normal) to the direct rays coming from the sun at its current position in the sky (Ammonit Measurement GmbH 2019).

Figure 11 shows the range of direct normal irradiation in the Middle East and North Africa between $3.2\ kWh/m^2$ and $7.6\ kWh/m^2$ per day.

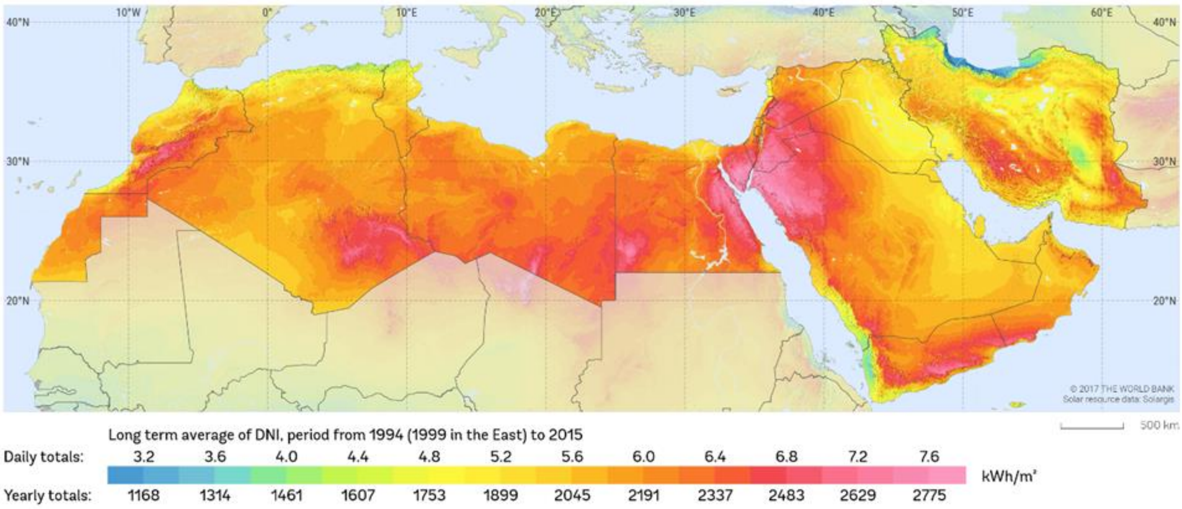

FIGURE 11. Average DNI in MENA (Global Solar Atlas; Solargis).

5.3 Global Horizontal Irradiation Middle East and North Africa

GHI Global Horizontal Irradiance (GHI) is defined as the total amount of solar radiation received from above by a horizontal surface. The value of GHI comprised of Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation.

- GTI or Global Tilted Irradiation

  GTI is defined as the total amount of direct and diffuse radiation received from above by a tilted surface. Usually Global tilted Irradiation GTI is the value of the energy output measurement of fixed installed tilted PV panels.

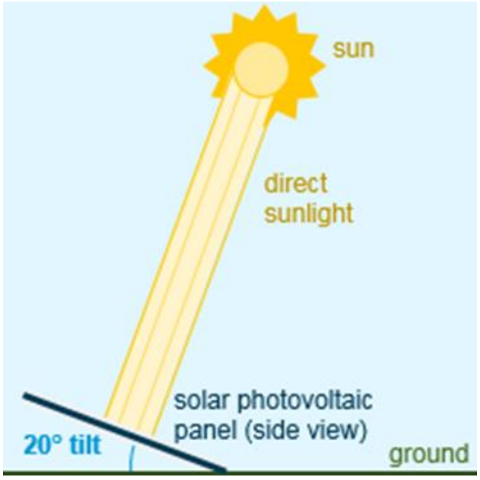

FIGURE 12. Tilt angle (Marcy 2018).

- Calculating Global Horizontal Irradiation (GHI)

  The sun radiation is usually combined from Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation (DHI).

  In order to have a successful and productive solar power plants, we should measure the global sun irradiation at the targeted location to estimate the approximate energy production of the PV system.

  Figure 13 shows global horizontal irradiation in Middle East and North African range between 4 kWh/m^2 And 6.8 kWh/m^2 per day.

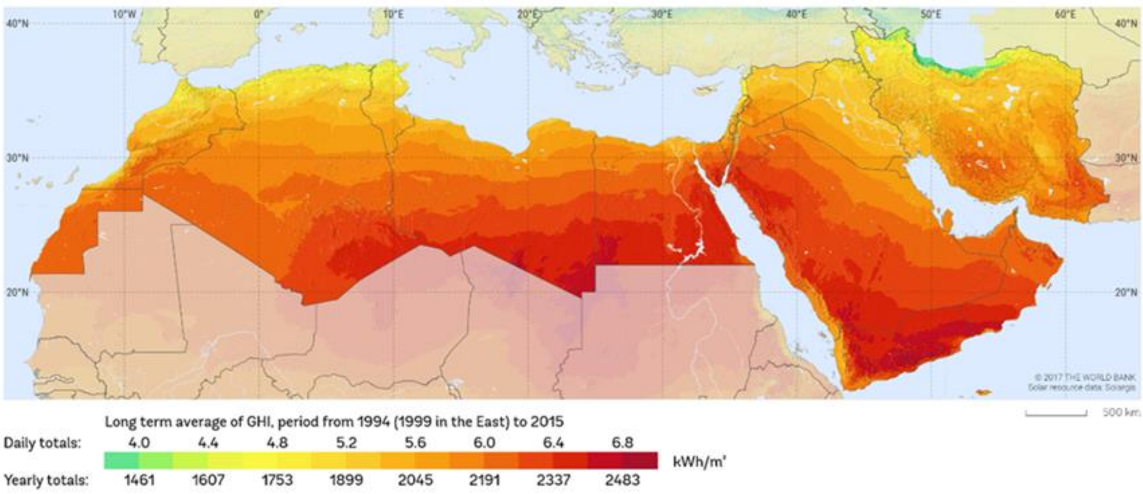

FIGURE 13. Average GHI in MENA (Global Solar Atlas; Solargis).

The value of GHI can be calculated from the formula (Ammonit Measurement GmbH 2019):

$$GHI = DHI + DNI \cdot \cos(\theta) \quad (4)$$

Where DHI is diffuse horizontal irradiation, DNI is direct normal irradiation and θ is the solar zenith angle which is the angle between the zenith and the center of the Sun's disc (figure 14).

DHI or Diffuse Horizontal Irradiance is defined as the solar radiation reaching the Earth’s surface per unit area that does not arrive on a direct path from the sun but has been diffused by molecules and particles in the atmosphere. It is the illumination that comes from clouds and the blue sky. (Ammonit Measurement GmbH 2019).

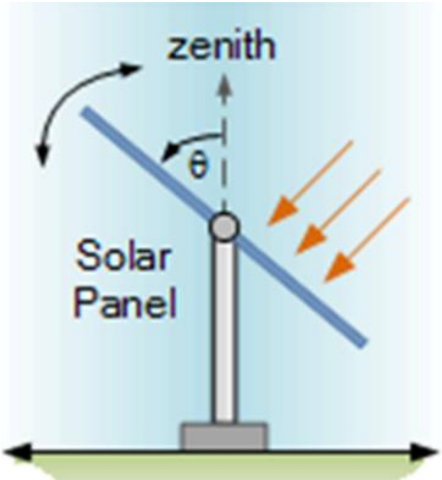

FIGURE 14. Zenith angle (Alternative Energy Tutorials 2019).

6 SIZING THE PV SOLAR POWER PLANT:

In this section, I will calculate the requirement of sizing a 10 MW PV solar power plant with a 100 MWh energy storage system (battery) in three different sites in Middle East & North Africa:

6.1 Sizing a 10 MW PV solar power plant near Al Riyadh, Ar Riyadh, Saudi Arabia:

To size a 10 MW PV solar power plant, we should determine first the average daily global tilted Irradiation and the average daily PVOUT in the targeted locations.

Average daily GTI	$6.616\, kWh/m^2$
Average daily PVOUT	$5.019\, kWh/kWp$

OPTA	$24°/180°$
Tilt angle	$24°$
Azimuth	$180°$

The tilt angle of the solar array should be 24° degrees to collect solar radiation more efficiently

By multiplying solar power plant size with the average daily PVOUT in the targeted location, we determine the total output energy per day in the targeted location (Global solar Atlas).

$$10\ MWp \cdot 5.019\ \ MWh/MWp = 50.19\ MWh$$

6.1.1 Determining the required number of PV solar panels:

To determine the required number of PV solar panels, we need to define first the type and the specifications of the solar panels.

In all sites in this project, we are going to use (Amerisolar AS-6P 300) solar panels, which have the following specifications (Amerisolar AS-6P 300).

TABLE 1. Amerisolar PV solar panel specifications (Amerisolar AS-6P 300).

STC Power Rating	$300\ Wp$
Peak Efficiency	15.46%
DC Current Imp	$8.18\ A$
Vmp DC Voltage	$36{,}7\ V$
Open Circuit Voltage Voc	$45.3\ V$
Short Circuit Current Isc	$8.68\ A$
Solar panel area	$1.94\ m^2$
Length of solar panel	$1956\ mm$
Width of solar panel	$992\ mm$

The efficiency of solar panel can be determined from the formula (3):

$$\text{Solar panel Peak efficiency} = \frac{300\ (W)}{1.94\ \ (m^2)\cdot 1000\ (\frac{W}{m^2})} \times 100\ \% = 15.46\ \%$$

Table 2 illustrates the needed requirements to calculate the active area of the solar array and the number of solar panels.

TABLE 2. Calculating the required area of solar array

Capacity of the PV solar plant	$10\ MWp$
Average PVOUT per day in Al Riyadh, Ar Riyadh, Saudi Arabia	$5.019\ kWh/kWp$
Total energy produced per day	$50.19\ MWh$
Average daily GTI in Al Riyadh, Ar Riyadh, Saudi Arabia countries	$6.616\ kWh/m^2$
Performance ratio, coefficient of losses	0.75

The required active area of solar array can be calculated from the formula (2):

$$E = H \cdot A \cdot L \cdot PR$$

Where A is an active area of the solar array per (m^2)

$$50.19\ (MWh) = 15.46\ (\%) \cdot\ A\ (m^2) \cdot 6.616\ \ (kWh/m^2) \cdot 0.75$$

From the equation (2) we calculate the required area of solar panels which is $65426\ m^2$.

The surface area of one Amerisolar AS-6P 300 (300Wp) Solar Panel is $1.94\ m^2$

To calculate the required number of solar panels we need to divide the total active area by the area of one solar panel:

$$Total\ number\ of\ required\ solar\ panels = 65426\ m^2/1.94\ m^2 \approx 33725$$

To install a 10 MW PV solar power plant near Al Riyadh, Ar Riyadh, Saudi Arabia we need around 33725 (Amerisolar AS-6P 300) solar panels.

6.1.2 String sizing:

The output voltage of the solar array is very important for inverter function because inverter has a minimum and maximum operating voltage. If the output voltage of the solar array is lower or over the operating range, the inverter will not work.

- Minimum string size:

We can determine the minimum string size by dividing inverter lower range DC voltage (figure 17) by the solar panel voltage maximum power:

$$inverter\ lower\ range\ DC\ voltage\ mmp/panel\ Vmp$$

$$850V/36.7V = 23.16$$

So, the minimum number of solar panels in one string should not be under 23 solar panels.

- Calculating maximum string size:

The maximum string size can be determined by dividing inverter maximum voltage input (figure 17) to the solar panel open circuit voltage:

$$maximum\ DC\ voltage\ input/panel\ Voc$$

$$1500V/45.3V = 33$$

The maximum number of solar panels in one string should not exceed 33 solar panels.

- Solar array sizing:

To have an equal number of solar panels in each string for more efficient inverter performance, we increase the number of panels to 33660.

Then 33660 solar panels will be divided into 6 groups, each group contains 5610 solar panels.

Wiring the solar panels in a series circuit can increase the voltage whereas wiring them in a parallel can increase the current. (Punyani 2014.)

We have 6 groups of solar arrays. Each group will be divided into 187 strings connected in a parallel circuit. Also, each string contains 30 solar panels connected in a series circuit.

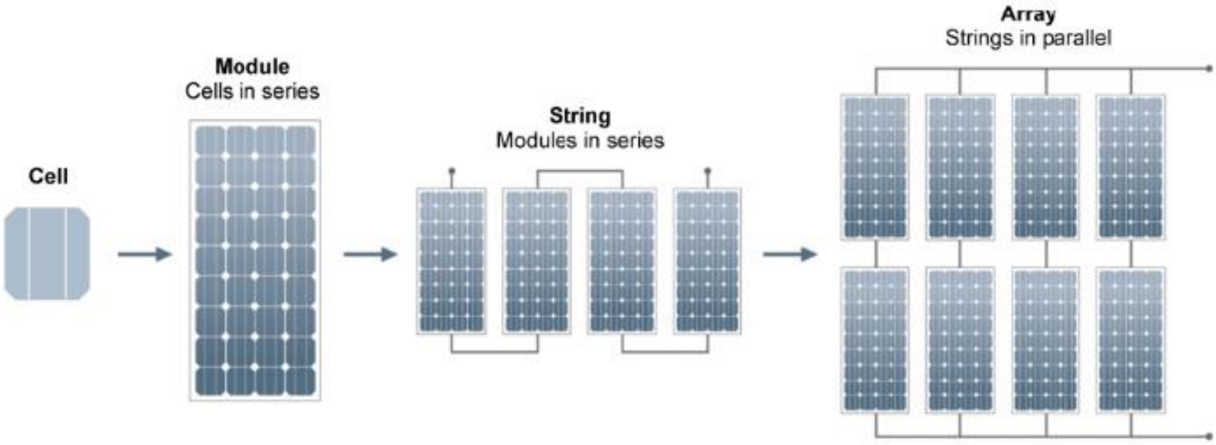

FIGURE 15. PV solar module, string and array (Reardon; Riedy 2013).

6.1.3 Land sizing

To accommodate the solar module system and considering spaces between the mounting racks for maintenance and cabling. The estimated land area should be approximately doubled of the area of the active solar array.

Table 3 illustrates how to calculate the required land area of a 10 MW PV solar power plant in Al Riyadh, Ar Riyadh, Saudi Arabia.

TABLE 3. Calculating solar plant area

Total number of solar panels	33660
Solar panel dimension	$1.956\ mm \times 992\ mm$
Number of solar modules in each string	30
Width of each group	$30 \times 0.992\ m \approx 30\ m$
Total number of solar panels in each group	5610
Number of rows in one group	$5610 \div 30 = 187$
Inter-row space	$2\ m$
The total length of one group	$187 \cdot (1.956\ m + 2m) \approx 740\ m$

Area for one group	$30\ m \times 740\ m \approx 22200\ m^2$
Number of groups	6
Total area of the PV solar power plant	$22200 \times 6 = 133200\ m^2 \approx 0.133\ km^2$

- Electrical calculation of the PV Solar power plant:

  After sizing the land and dividing the PV solar plant into groups. I will calculate the nameplate output voltage and current for each group and then for the whole plant.

  Table 4 illustrates how to calculate the maximum electrical output of the solar plant. The power output of the PV solar plant can be determined by multiplying the current with the voltage

$$Power(W) = Voltage(V) \times Current(A)$$

TABLE 4. Calculating Electrical output of the solar plant

String open circuit voltage	$30 \times 45.3 = 1359 VDC$
String maximum output voltage	$36.7 \times 30 = 1100\ VDC$
String output current	$8.18\ ADC$
Output current of one group	$8.18 \times 187 = 1529.6\ ADC$
Output power of each string	$8.18 \times 1100 = 9\ kW$
Output power of each group	$9\ kW \times 187 = 1.68\ MW$
Maximum output power of the PV solar plant	$1.68 \times 6 = 10.08\ MW$

6.1.4 ABB central inverter (PVS980-58)

ABB is a solar inverter manufacturer. They are manufacturing a high efficiency central solar inverter, which has a high DC input voltage up to 1500 VDC system. (ABB 2018.)

Features of ABB central inverter (PVS980):

- Contain a high efficiency cooling system.
- High performance and efficiency.
- Robust construction designed for outdoor use.

FIGURE 16. ABB central inverter PVS980 (ABB Central Inverters 2018, 1).

Figure 16 shows the specifications of PVS980 ABB central inverter. Solar array will be divided according to the inverter specification.

Type designation	PVS980-58-1818kVA-I	PVS980-58-1909kVA-J	PVS980-58-2000kVA-K	PVS980-58-2091kVA-L
Input (DC)				
Maximum recommended PV power ($P_{PV, max}$) [1]	2910 kWp	3055 kWp	3200 kWp	3346 kWp
Maximum DC current ($I_{max (DC)}$)	2400 A	2400 A	2400 A	2400 A
DC voltage range, mpp ($U_{DC, mpp}$) at 35 °C	850 to 1500 V	893 to 1500 V	935 to 1500 V	978 to 1500 V
DC voltage range, mpp ($U_{DC, mpp}$) at 50 °C	850 to 1100 V	893 to 1100 V	935 to 1100 V	978 to 1100 V
Maximum DC voltage ($U_{max (DC)}$)	1500 V	1500 V	1500 V	1500 V
Number of MPPT trackers	1	1	1	1
Number of protected DC inputs	8 [2] to 24 (+/-)	8 [2] to 24 (+/-)	8 [2] to 24 (+/-)	8 [2] to 24 (+/-)
Output (AC)				
Maximum power ($S_{max (AC)}$) [3]	2000 kVA	2100 kVA	2200 kVA	2300 kVA
Nominal power ($S_{N(AC)}$) [4]	1818 kVA	1909 kVA	2000 kVA	2091 kVA
Maximum AC current ($I_{max (AC)}$)	1925 A	1925 A	1925 A	1925 A
Nominal AC current ($I_{N(AC)}$)	1750 A	1750 A	1750 A	1750 A
Nominal output voltage ($U_{N(AC)}$) [5]	600 V	630 V	660 V	690 V
Output frequency [5]	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
Harmonic distortion, current [6]	< 3%	< 3%	< 3%	< 3%
Distribution network type [7]	TN and IT	TN and IT	TN and IT	TN and IT
Efficiency				
Maximum [8]	98.8%	98.8%	98.8%	98.8%
Euro-eta [8]	98.6%	98.6%	98.6%	98.6%
CEC efficiency [9]	98.0%	98.5%	98.5%	98.5%
Power consumption				
Self consumption in normal operation	≤ 2500 W	≤ 2500 W	≤ 2500 W	≤ 2500 W
Standby operation consumption	235 W	235 W	235 W	235 W
Auxiliary voltage source [10]	External, 1-phase	External, 1-phase	External, 1-phase	External, 1-phase

FIGURE 17. ABB PVS980 inverter specifications (ABB Central Inverters 2018, 4).

- Inverter sizing:

The PV solar plant is divided into 6 groups, each group has an output power of 1.6 MW, for this output power we need 6 ABB PVS980-58-I central inverters, each group will be connected with one inverter.

6.1.5 Requirements of installing 100 MWh Tesla Powerpack battery near Al Riyadh, Ar Riyadh, Saudi Arabia:

To ensure the flow of energy to the utility grid, we should take into consideration that on the cloudy days or at night the solar plant has zero power generation. To solve this issue, we need to install a high capacity storage system (100 MWh) to store energy to meet the peak demand. This storage system is an independent system will work as a peaking power plant.

- Calculating the required solar panels needed to charge 100 MWh Tesla battery

To charge a 100 MWh battery every day, we need to install additional solar panels. The additional numbers of solar panels can be determined from the formula (2):

$$100\ (MWh) = 15.46(\ \%)\ \cdot A\ (m^2) \cdot 6.616\ (kWh/m^2) \cdot (0.75) \cdot (0.88)$$

where 0.88 is the efficiency of the battery

From the equation (2) we calculate the required area of the solar panels which is $A = 148126\ m^2$

The number of solar panels $148126 m^2/1.94 m^2 = 76354\ solar\ panels$

So, we need 76354 additional solar panels in order to charge a 100 MWh battery.

- Requirements of installing a 10 MW solar plant with a 100 MWh storage system near Al Riyadh, Ar Riyadh, Saudi Arabia:

In this section, I will determine the total requirements of installing a 10 MW solar power plant with a 100 MWh storage system.

Table 6 illustrates how to calculate the total requirements of the PV solar power plant with the storage system.

TABLE 6. Total Requirements for the PV solar plant with the storage system

Total Number of solar panels	$33660 + 76354 = 110014$
The ratio between required solar panels for the battery and required solar panels for the solar plant.	$76354\ \div 33660 = 2.26$
Land area of a 100 MWh storage system	$133200\ m^2 \times 2.26 = 301032\ m^2$ $\approx 0.3 km^2$
Total land area (storage system with solar power plant)	$133200\ m^2 + 301032\ m^2\ = 434232\ m^2$ $\approx 0.434 km^2$

Total generated energy per day from the solar plant & the storage system	$50.19\ MWh + 100\ MWh$ $\approx 150.19\ MWh\ per\ day$

6.2 Sizing a 10 MW PV solar power plant near Cairo, Egypt:

From the global solar atlas, we determine the required value of GTI and PVOUT near Cairo, Egypt

Average daily GTI is $6.304\ kWh/m^2$

Average daily PVOUT is $4.888\ kWh/kWp$

OPTA $26°/180°$

Total generated power per day $10\ MWp \times 4.888\ kWh/kWp = 48.88\ MWh$

Table 7 illustrates the requirements to calculate the area of solar array and the total number of solar panels.

TABLE 7. Calculating the area of solar array

Capacity of the PV solar plant	$10\ MWp$
Total energy production per day	$48.88\ MWh$
Average GHI in Cairo per day	$6.304\ kWh/m^2$
Performance ratio, coefficient of losses	0.75

$$48.88\ (MWh) = 15.46\ (\%)\ \cdot A\ (m^2) \cdot 6.304\ (kWh/m^2) \cdot (0.75)$$

From the equation (2) we calculate the required area of solar panels which is $66872\ m^2$

$$required\ number\ of\ solar\ panels = 66872\ m^2/1.94\ m^2 \approx 34470$$

Table 8 illustrates how to size the solar array and solar power plant.

TABLE 8. Sizing the solar array

Number of groups	6
Number of solar panels in each group	$34470 \div 6 = 5745$
Number of solar panels in each string connected in series circuit in one group	30
Number of strings connected in parallel circuit in one group	$5725 \div 30 \approx 191$

- Land sizing

Table 9 illustrates how to calculate the required land area of a 10 MW solar power plant near Cairo, Egypt.

In order to have an equal number of solar panels in each string and for more efficient inverter performance, I decreased the total solar panels to 34380.

TABLE 9. Calculating the required land area

The total number of solar panels	34380
Solar panel dimension	$1956\ mm \times 992\ mm$
Number of solar panels in each string	30
Width of each group	$30 \times 0.992 \approx 30\ m$
The total number of solar panels in each group	5730
Number of rows in one group	191
Inter-row space	$2\ m$
The total length of one group	$191 \cdot (1.956 + 2) \approx 756\ m$
The required area for one group	$30\ m \times 756\ m \approx 22680\ m^2$
Total area of the solar power plant	$22680\ m^2 \times 6 = 136080\ m^2$ $\approx 0.136\ km^2$

- Electrical calculation of the solar plant near Cairo, Egypt:

Table 10 illustrates how to calculate the maximum electrical output of the solar plant in Cairo, Egypt.

TABLE 10. Calculating the total Electrical output of the solar plant

String open circuit voltage	$30 \times 45.3\ = 1359\ VDC$
String output voltage	$36.7 \times 30 = 1100\ VDC$
String output current	$8.18\ ADC$
Output current of one group	$8.18 \times 191 = 1562\ ADC$
Output power of each string	$1100 \times 8.18 = 12008\ W\ \approx 9\ kW$
Output power of each group	$9 \times 191 = 1.7\ MW$
Maximum output power of the PV solar plant	$1.7 \times 6 = 10.2\ MW$

6.2.1 Requirements of installing a 100 MWh Tesla Powerpack battery near Cairo, Egypt:

In this section, I will calculate the requirements of installing a 100 MWh storage battery near Cairo, Egypt, and then calculating the total requirements for installing the PV solar plant with the storage battery.

$$100\ (MWh) = 15.46\ (\%) \cdot\ A\ (m^2) \cdot 6.304\ \ (kWh/m^2) \cdot (0.75) \cdot (0.88)$$
$$A \approx 155465m^2$$

$$Number\ of\ required\ solar\ panels = 155465m^2/1.94m^2$$
$$= 80137\ solar\ panels$$

To charge a 100 MWh storage battery near Cairo, Egypt we need around 80137 additional solar panels.

- Requirements of installing a 10 MW solar plant with 100 MWh storage system in Cairo, Egypt:

Table 11 illustrates how to calculate the total number of solar panels and the land area for installing a 10 MW solar power plant with a 100 MWh storage system near Cairo, Egypt.

TABLE 11. Total Requirements for the solar plant with the storage system.

Total Number of solar panels	$34380 + 80137 = 114517$
The ratio between the required solar panels for the battery and the required solar panels for the solar plant.	$80137\ \div 34380 = 2.33$
Land area of a 100 MWh storage system	$136080\ m^2 \times 2.33 = 317066\ m^2$
Total land area (storage system with solar power plant)	$317066\ m^2 + 136080\ m^2 = 453146m^2$ $\approx 0.453\ km^2$
Total generated energy from the solar plant & the storage system	$48.88\ MWh + 100\ MWh$ $\approx 148.88\ MWh\ per\ day$

6.3 Sizing a 10 MW PV solar power plant near Amman, Jordan:

In this section, I will calculate the requirements of installing a 10 MW PV solar power plant with a 100 MWh storage system near Amman, Jordan.

The values of daily GTI and PVOUT were collected from the global solar atlas.

Average daily GTI is $6.447\ kWh/m^2$
Average daily PVOUT is $5.058\ \ kWh/kWp$

OPTA $27°/180°$

Total energy production per day $10\ MWp \times 5.058\ kWh/kWp = 50.58\ MWh$

Table 12 illustrates the requirements to calculate the required area of active solar array and the number of solar panels.

TABLE 12. Calculating the active area of solar array

Capacity of the PV solar plant	$10\ MWp$
Total power produced per day	$50.58\ MWh$
Average daily GHI in Amman	$6.447\ kWh/m^2$
Performance ratio, coefficient of losses	0.75

$$50.58\ (MWh) = 15.46\ (\%)\ \cdot A\ (m^2) \cdot 6.447\ \ (kWh/m^2) \cdot (0.75)$$

$$A \approx 65900\ m^2$$

Required numbers of solar panels: $65900m^2/1.94m^2 = 33969$

- Solar array sizing:

  In order to have an equal number of solar panels in every string and for more efficient inverter performance we increase the total solar panels to 34020.

  Table 13 illustrates how to size the solar panels and solar the power plant in Amman, Jordan.

TABLE 13. Sizing the solar panels

Number of groups	6
Number of solar panels in each group	$34020 \div 6 = 5670$
Number of solar panels in each string connected in series circuit in one group	30
Number of strings connected in parallel circuit in one group	$5670 \div 30 \approx 189$

- Land sizing:

Table 14 illustrates how to calculate the required land area of a 10 MW solar power plant near Amman, Jordan.

TABLE 14. Calculating required land area

Total number of solar panels	34020
Solar panel dimension	$1956\ mm \times 992\ mm$
Number of solar panels in each string	30
Width of one group	$30 \times 0.992\ m \approx 30\ m$
Total number of solar panels in each group	5670
Number of rows in one group	189
Inter-row space	$2\ m$
The total length of one group	$189 \cdot (1.956 + 2) = 748\ m$
required area for one group	$30m \times 748m \approx 22440\ m^2$
Number of groups	6
Total area of solar power plant	$22440\ m^2 \times 6 = 134640\ m^2$ $\approx 0.1346\ km^2$

- Calculating the total Electrical output of the solar plant

Table 15 illustrates how to calculate the total electrical output of solar plant near Amman, Jordan.

TABLE 15. Calculating the total Electrical output of the solar plant

String open circuit voltage	$30 \times 45.3 = 1359\ VDC$
String output voltage	$36.7 \times 30 = 1100\ VDC$
String output current	$8.18\ ADC$
Output current of one group	$8.18 \times 189 = 1546\ ADC$
Output power of each string	$1100 \times 8.18 = 8998\ W \approx 9\ kW$
Output power of each group	$9 \times 189 = 1.7\ MW$
Maximum output power of the whole solar plant	$1.7 \times 6 = 10.2\ MW$

6.3.1 Requirements of installing a 100 MWh Tesla Powerpack battery near Amman, Jordan:

Calculating the required number of solar panels to charge a 100 MWh storage battery near Amman, Jordan.

$$100\ (MWh) = 15.46\ (\%) \cdot\ A\ (m^2) \cdot 6.447\ \ (kWh/m^2) \cdot (0.75) \cdot (0.88)$$
$$A \approx 152016 m^2$$

Number of required solar panels $152016m^2/1.94m^2 = 78359\ solar\ panels$

Table 16 illustrates the total number of solar panels and the required land area to install a 10 MW solar power plant with a 100 MWh storage system near Amman, Jordan.

TABLE 16. Total requirements for the solar plant with the storage system.

Total Number of solar panels	$34020 + 78359 = 112379$
The ratio between the required solar panels for the battery and the required solar panels for the solar plant.	$78359\ \div 34020 = 2.3$
Land area of a 100 MWh storage system	$134640\ m^2 \times 2.3 = 309672m^2$
Total Land size (storage system with solar power plant)	$309672\ m^2 + 133500\ m^2$ $= 443172\ m^2$ $\approx 0.443\ km^2$
Total generated energy from the solar plant & the storage system	$50.58\ MWh + 100\ MWh$ $\approx 150.58\ MWh\ per\ day$

Tesla powerpack system is an independent system. It is a renewable peaking power plant that supplies the grid with energy when there is a high demand on energy and at night when the solar power plant is not running. So, this storage system may work also simultaneously with the PV solar power plant to meet peak demand on the grid.

The Tesla storage system and the PV solar power plant are connected to the same AC grid simultaneously and because the grid operates on one voltage level. So, there will be a need for transformer in order to unify the voltage.

7 COST OF THE LARGE-SCALE PV POWER PLANT

According to the National Renewable Energy Laboratory report 2017, the cost of the installed large-scale solar power plant has significantly dropped in recent years, reaching almost the wholesale cost of producing power from natural gas or other resources, as a result of the declining in the cost of PV solar panels and inverters prices.

The estimated cost of installed fixed-tilt PV solar power plant has declined to 1.03 US dollars per direct current watt (WDC). Practically, for example, 1 MW PV solar power plant will cost approximately 1 million US dollars. (NREL 2017.)

Hence, the cost of installing a 10 MW solar power plant will cost:

$$10{,}000{,}000\ W \times 1.03 = \$10{,}300{,}000$$

According to International Renewable Energy Agency IRENA, the cost of global weighted average levelized electricity (LCOE) for the PV project around the world has decreased by 73 % between 2010 and 2017 which range now between 6 and 10 US cents/kWh. (IRENA 2019.)

In figure 18 we notice the cost of energy producing from solar PV-crystalline utility scale range between $46 and $53 per MWh without the cost of storage, and it reaches $82 per MWh with an energy storage system. Whereas the cost of energy producing from solar PV-thin film utility scale range between $43 and $48 per MWh without the storage system, and $82 per MWh with the energy storage system. (Lazard 2017, 3-4.)

Figure 18 illustrates the comparison between the costs of alternative energy generation technologies and the cost of conventional generation technologies.

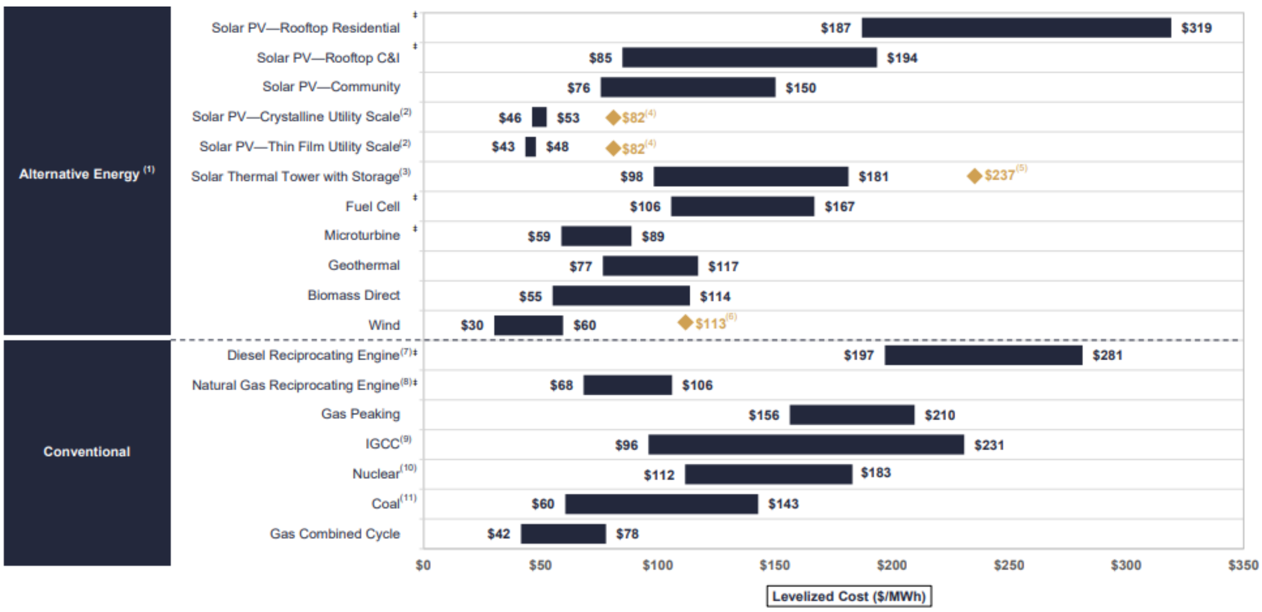

FIGURE 18. Unsubsidized levelized cost of energy comparison (Lazard 2017, 3).

8 CONCLUSION

The purpose of this study was to provide a reasonable solution for the energy crisis in the countries of MENA, by making a full analysis and study for the requirements of installing PV solar power plants with a storage system.

The results showed that the studied area should be highly considered for developing and installing large-scale PV solar power plants, as it has the best solar suitability in the world. For example, installing a 10 MW PV solar plant in Ar Riyadh, Saudi Arabia produces twice as much output as it would in Hamburg, Germany.

A 10 MW PV solar power plant will generate in average 50 MWh of energy in the daytime. This energy will be fed directly to the grid. At the same time the storage system will be charged a 100 MWh in the daytime, depending on its PV solar system.

The storage system will ensure the energy flow and supply the grid with required energy in the nighttime when the solar plant's production capacity is zero.

A 10 MW PV solar power plant with a 100 MWh storage system comprises together a complete solution for the energy shortage of the countries of the Middle East and North Africa. They can power an entire town without the need to using any fuels and with zero variable cost.

Installing a 10 MW PV solar power plant with a 100 MWh energy storage system in the MENA can power around 10,000 homes per day if the average daily electric consumption per household is around 15 kWh. Therefore, this project is good to be applied in rural areas, where they suffer more from the shortage of energy. Moreover, this study provides an accurate method of how to design and size the PV solar plant. Accordingly, the size of the PV solar power plant could be adjusted to correspond with the needs of energy.

Applying this project in rural and outlying areas has many benefits: First, reducing the amount and the cost of electricity transmissions. Second, supplying these areas with clean energy in order to reduce the emissions of CO_2. Third, it is free and requires only sunlight to generate energy which reduces the cost of fuel and transportation.

This project can be applied in many sites in the same country: for example, near the outlying towns that are located remote from the main generating stations or main cities, without the need for installing a new grid.

The high potential of solar radiation in most of the Middle East and North Africa countries in addition to the rapid innovation development in solar energy makes the installing of a PV solar power plant near the load center applicable, which has a high impact on reducing transmission losses.

The Middle East and North Africa countries have the chance to become the leaders in the field of producing electricity from solar energy and to prepare for the future of solar technologies by expanding the usage of solar energy, along with reducing the dependency on fossil fuel for achieving a cleaner environment and sustainability in energy.

Shifting from fossil fuel to solar energy to create electricity, could benefit the Middle East and North Africa countries by saving the cost of buying fossil fuel and gas, which contribute to the economic growth. Particularly, all reports and studies indicate that the cost of renewable energy will be more affordable relative to fossil fuel by 2020 which make the use of renewable energy not only an environmental decision but also economical.

Finally, the countries of the Middle East and North Africa should realize the importance of solar energy and its advantages to create an ideal solution for their energy crisis and supply their countries with sustainable and renewable energy.

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