A 50 MW very large-scale photovoltaic power plant for Al-Kufra, Libya: energetic, economic and environmental impact analysis

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Abstract

Libya has a growing demand for electricity and presently generates almost all of its electrical energy using fossil-fuelled generation plant. An opportunity exists to use the naturally high solar radiation resource that occurs in the south of the country to meet this demand with a renewable energy source. This paper describes the design of a 50 MW photovoltaic (PV) power plant which has been modelled on the conditions pertaining to Al-Kufra. The general energy situation within Libya is described, along with the solar conditions at the proposed location of the power plant. An HIT type PV module has been selected and modelled. The effectiveness of the use of a cooling jacket on the modules has been evaluated. The results show an average increase in efficiency of 0.6%; however, this is not considered to be a justifiable expense. The optimum tilt angle and array layout have been evaluated for the proposed site. The projected energy output has been determined to be 114 GWh per annum with a payback time of 2.7 years and a reduction of CO₂ pollution by 76 thousand tonnes per year. It is recommended that very large-scale PV plants of this type are installed within Libya for the sake of benign environmental impact and diversification of the electrical generation mix.

Keywords: solar energy; very large-scale photovoltaic power plant; energy from the desert

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1 INTRODUCTION

Large-scale use of solar energy for electricity production is currently in the demonstration phase. Lessons learnt from the pilot project will benefit the implementation of future power plants. Presently, key examples of such pilot projects are presented. These examples lead to the conclusion that the most economic implementation will be very large-scale, grid-connected PV systems.

The scope of this paper is to examine and evaluate the potential of very large-scale of PV power generation systems in the southern region of Libya at Al-Kufra.

Temperature has an important effect on the power output and efficiency of the photovoltaic (PV) cells. The present study shall present a simulation model for a 50 MW [very large-scale PV (VLS-PV)] power plant with a cooling system using water as the working fluid. A system without cooling is also presented.

2 VLS-PV INSTALLATIONS AROUND THE WORLD

PV production has been increasing by an average of some 20% each year since 2002, making it a fast-growing energy technology. At the end of 2009, the cumulative global PV installations surpassed 21 000 MW [1, 2].

As of November 2010, the largest PV power plants in the world are the Finsterwalde Solar Park (Germany, 80.7 MW), Sarnia PV Power Plant (Canada, 80 MW), Olmedilla PV Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), the Lieberose PV Park (Germany, 53 MW) and the Puertollano PV Park (Spain, 50 MW) [3].

From these examples, it is obvious that MW-scale PV systems are not a rarity. As the capacity of the MW-scale PV systems expands, year by year, the capacity will reach 100 MW in a few years time. A GW-scale PV plant consisting of several...
100 MW-scale PV systems is expected to be realized by the mid-twenty-first century.

3 LIBYAN ENERGY SUPPLY AND DEMAND

3.1 The country
Libya is an oil-producing country located in the middle of North Africa, with a coast of ~2000 km length on the Mediterranean. Libya has a land area of 1 750 000 km² and 88% of this land is desert. The population of the country is 6 million, mostly located along a thin strip along the coastline [4]. According to the UN, the annual population growth rate for 2000–05 was 1.93%, with a projected population of 6.9 million for the year 2015.

3.2 Hydrocarbon supply and export
According to the Oil and Gas Journal, Libya contained an estimated 74.3 ZWh of proven oil reserves. Libya accounts for 32% of the total reserves for Africa [5]. Figure 1 shows the top African oil proven reserve holders.

Libya had 16.4 PWh of proven natural gas reserves as of January 2009. Some Libyan experts believe that with more exploration, reserves may possibly reach 20.4–29.2 PWh mark. Libyan natural gas production and exports are increasing, with the opening of the ‘Greenstream’ pipeline to Europe in late 2004 [5]. Figure 2 shows the top African Natural Gas proven reserve holders, 2009, and Table 1 shows the Libyan oil and gas production for the year 2008.

3.3 The Libyan electricity generation situation
The General Electric Company of Libya (GECOL) is totally government-owned and is responsible for the operation of the entire power sector in the country. All power plants in Libya have been installed by GECOL since it was established in 1984. Figure 3 shows the location of the installed power plants in Libya.

Libya has a total installed power generation capacity of 6.3 GW. The electrical energy consumption per capita has increased from 2227 kWh in 2000 to 3871 kWh in 2007 [31]. The national electric network is accessible to 99% of the population. Most of the electric network is concentrated on the coast, where most of the inhabitants live [6].

Fossil fuel-fired thermal power plants are used to meet all of the electrical energy demand. In Libya, all of the electrical energy demand comes from fossil-fuelled power plants. Libya’s power demand is growing rapidly (around 6–8% annually) and is therefore expected to reach 8 GW by 2015 (Figure 4).

3.4 Environmental impact
The main emitters of CO₂ in Libya are fuel combustion in the power generation sector, the transport sector and in industry. In total, energy-related emissions are responsible for almost all CO₂ emissions in the country. In 2003, petroleum accounted for more than 60% of carbon emissions in Libya and natural gas was responsible for around 40%. Figure 5 shows the CO₂ emission by sector [7].

Renewable sources such as solar energy are a potential candidate to meet the national energy requirements in a sustainable way. Consequently, there is clearly a significant incentive to use solar energy in Libya in order to reduce the CO₂ emissions arising from current electricity production.

3.5 The Libyan Desert
There are many good reasons for building solar power plants in the Libyan Desert; first, the prevalent solar energy income and secondly, the available area.

The Libyan Desert covers the entire range of Libyan longitude 11°44' to 23°58'E and a latitude range of 24°17' through to 30°31'N, thus covering an area of 1 750 000 km². Around 88% of Libya’s land area is desert. The country is wealthy in solar radiation income with the daily average radiation on a horizontal plane being 8.1 kWh/m²/day in the

Table 1. Libyan oil and gas production for the year 2008 [5].

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Production</th>
<th>Consumption</th>
<th>Export</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>0.16 PWh/annum</td>
<td>&lt;0.056 PWh/annum</td>
<td>0.1 PWh/annum</td>
</tr>
<tr>
<td>Oil</td>
<td>3.3 PWh/day</td>
<td>0.5 PWh/day</td>
<td>2.9 PWh/day</td>
</tr>
</tbody>
</table>
The number of sunshine hours amounts to more than 3500 h per year. The amount of solar radiation incident upon a surface is dependent upon the time of the day, the day of the year, the location, and orientation and tilt of the receiving surface.

Although the Libyan Desert is truly arid and the average annual rainfall is \(100\, \text{mm}\) over 93% of its surface area, there are, however, great reserves of groundwater, mostly located to the south.

There are four major underground basins, the Al-Kufra basin, Sirt basin, the Morzuk basin and the Hamada basin. The combined reserves of the first three of these basins are 35 000 km\(^3\) of water [8].

### 3.6 Technical know-how

Libya has a well-documented history of undertaking large-scale engineering projects as demonstrated by the following projects.

#### 3.6.1 Al-Kufra agriculture project

In the early 1970s, Libya launched a cultivation project in Kufra aimed at developing agriculture in the desert. Low Energy Precision Application type irrigation draws its water from beneath the ground surface. Rotating sprinklers then provide the irrigation in circles of up to 1 km diameter that are large enough to be seen from outer space.

#### 3.6.2 Industrial river project

The great man-made river project is one of the world’s largest civil engineering projects and conveys 3.68 million m\(^3\) of water...
per day from groundwater resources in the Sahara Desert to the coastal population of Libya. Concrete pipes of 4 m diameter run for over 1500 km to convey the water.

3.6.3 PV application within the rural sector
PV systems were first used in Libya in 1976 and since then the number of application types and their role has grown considerably. The first system was the one which supplied cathodic protection for an oil pipe line. Communication systems deployed PV systems from 1980, the first being used to supply energy to a microwave repeater station near Zella. Other applications include water pumping and rural electrification and illumination [9].

Finally, the electricity grid reaches every city in the Libyan Desert. There would thus be no problem in connecting the VLS-PV system to a national power grid.

3.7 Climate data used in the present work
At a macroscopic level, two regions of distinct Libyan weather can be identified,

(1) hot and arid Saharan desert climate,
(2) relatively moderate coastal climate.

3.7.1 Arid Sahara climate
The Sahara region of the desert makes it nearly inhabitable and thus the bulk of the population lives near the coast. The world's highest temperature in shade (≏58°C) has been recorded in El Azizia (32.32N 13.35E) in the Sahara [10]. The annual precipitation moving inland from the coast declines and its variability increases. This can be quantified by the fact that the annual rainfall is <25 mm and that the world's most arid region, with only 10 mm of precipitation, Sebha, is present in this region. In many areas, over 200 consecutive days without rainfall have been recorded. Most rainfall occurs on a few days between November and January.

The Gibli, which is a major feature of Libyan climate, is the hot, arid wind that blows from the south over the entire country. This wind normally carries large quantities of sand dust, which immensely reduces visibility, turning the sky red. Gibli can occur several times a year. From a thermodynamic perspective, it is important to note that the heat of this wind can dramatically cause a drop in relative humidity within hours [10].

3.7.2 Coastal climate
Along the coast, the climate is cool and rainy during winter and becomes hot and dry during summer with July and August being the warmest months. Average temperatures during the summer in Tripoli and Benghazi (that fall in the Mediterranean Zone) reach between the low 21°C and mid 27°C, and the low 16°C and mid 27°C, respectively. The influence of the Saharan weather is evident in this zone and becomes stronger in the summer. Between October and March, prevailing westerly winds bring cyclonic storms and rain across northern Libya (Table 2).

3.7.3 Climate in Al-Kufra
Al-Kufra is a small oasis town in the south of Libya and thus falls in the arid Saharan region.

There are many technical and economic issues relating to using solar energy technologies in Al-Kufra, for example, high potential of solar energy, no cloud cover throughout the year, availability of large volumes of potable water from underground aquifers and large flat area. Furthermore, the average sun duration is more than 3500 h per year [11]. With these factors, it is important to study the climate of Al-Kufra.

The mean monthly values of temperature, wind speed and relative humidity are illustrated in Figure 6. The maximum average wind speed is ≏5 m/s in June and the minimum value is 3.8 m/s in December. It is clear from Figure 6 that the wind speed is most active in summer and autumn season when conditions are appropriate for solar energy capture. The average maximum temperature in Al-Kufra is 34.9°C in August, while the minimum is 14.5°C in January. As shown in Figure 6, the humidity is low throughout the year, i.e. in January, the relative humidity is 39.9% but in July, it is 18.8%.

### Table 2. The future electricity infrastructure-generation expansion [31].

<table>
<thead>
<tr>
<th>Under construction</th>
<th>Contract awarded</th>
<th>Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>750 MW Benghazi</td>
<td>750 MW Sebha</td>
<td>750 MW Tripoli East</td>
</tr>
<tr>
<td>750 MW Misurata</td>
<td>1400 MW Tripoli West</td>
<td>750 MW Derna</td>
</tr>
<tr>
<td>312 MW West Mountain</td>
<td>500 MW Zwitina</td>
<td>750 MW Butraba</td>
</tr>
<tr>
<td>750 Srir West</td>
<td>750 MW Tobruk</td>
<td>600 MW Misurata</td>
</tr>
<tr>
<td>1400 MW Srir Gulf</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4 PROPOSED DESIGN FOR A STATIONARY PV SYSTEM

4.1 Modelling the PV I–V characteristics
In sizing and designing PV power systems, it is important to model their electrical output. The electrical output of a PV module (and consequently PV arrays) is given by its current–voltage (I–V) characteristic. A precise I–V characteristic of a PV module is necessary to accurately estimate its performance, select appropriate components and improve efficiency.

This section is concerned with mathematically describing the PV current–voltage (I–V) characteristic and suggesting a simple method for constructing the I–V curve.

This is done for a system where the PV array is in a fixed position. Relationships between the theoretical parameters in the PV-I–V equation and measurable quantities (usually supplied by the manufacturers) are provided in this section. More
importantly, however, a method for translating the PV $I$–$V$ characteristic from reference conditions of irradiance and module temperature (supplied by manufacturer or measured) to any general set of conditions is also provided herein.

4.1.1 The PV equations

The current produced by a PV module is calculated from

$$I = I_G - I_D$$

(1)

where $I_G$ is the light-generated current and $I_D$ the diode current.

$$I_D = I_o(e^{V+I_R/S_A} - 1)$$

(2)

where $I_o$ is the reverse saturation current, $V$ the voltage across the PV module, $R_s$ the internal series resistance and $A$ the curve fitting parameter.

By substituting Equation (2) in Equation (1), we obtain the PV $I$–$V$ characteristic equation,

$$I = I_G - I_o(e^{V+I_R/S_A} - 1)$$

(3)

It is clear from Equation (3) that in order to fully describe the PV $I$–$V$ characteristic, four parameters, namely, $I_G$, $I_o$, $R_s$ and $A$, need to be determined.

4.1.2 The PV $I$–$V$ curve

A typical $I$–$V$ characteristic is shown in Figure 7. The main features of a PV $I$–$V$ curve are the short-circuit current ($I_{sc}$), the open-circuit voltage ($V_{oc}$), the maximum power ($P_m$), the current at the maximum power ($I_m$) and the voltage at the maximum power ($V_m$). These parameters are defined below.

The short-circuit current, $I_{sc}$, is the current flowing through the PV module at zero voltage (i.e. when the impedance is low). It is calculated at zero voltage. For an ideal PV circuit, $I_{sc}$ is equal to the thermally generated current, $I_G$ [12].

The open-circuit voltage, $V_{oc}$, is the voltage across the PV module when no current flows through it (i.e. $I = 0$). When a solar panel is not connected to a load and if the voltage across its leads is measured, a voltage close to its nominal voltage will be observed.

The maximum power, $P_m$, is the point on the $I$–$V$ curve where the current times voltage product is a maximum. $I_m$ is the current at the maximum power. Typically, this current is only slightly lower than the short-circuit current. Like $I_{sc}$, it also increases with irradiance and temperature. $V_m$ is the voltage at the maximum power. Like $V_{oc}$, it usually increases with irradiance and decreases with cell temperature.

The curve in Figure 7 is based on Equation (3). While some manufacturers of PV modules provide the $I$–$V$ curve as part of their data, the majority of manufacturers give data of $I_{sc}$, $V_{oc}$, $P_m$, $I_m$ and $V_m$ at some reference conditions of air mass (AM),

Figure 6. Monthly average ambient temperature, relative humidity and wind speed for Al-Kufra.

Figure 7. Typical IV characteristic of a PV module.
irradiance \((G, \text{W/m}^2)\) and cell temperature \((T_c, ^\circ \text{C})\). Typically, standard test conditions (STC) used by the manufacturers refer to 1.5 AM, 1000 W/m² and 25°C. However, some manufacturers use other reference temperatures.

If the four parameters in Equation (3), i.e. \(A\), \(I_G\), \(I_o\), and \(R_s\), are known, values of \(V\) can be assumed, \(I\) values calculated and the \(I-V\) curve plotted. However, in Equation (3), \(I\) is an implicit function of \(V\). As a result, for each value of \(V\), \(I\) must be solved iteratively. By rearranging Equation (3) and taking the natural log of both sides, Equation (4) may thus be written,

\[
V = A \ln \left( \frac{I_G - I + I_o}{I_o} \right) - IR_s \tag{4}
\]

Using Equation (4), values of \(I\) are assumed first and \(V\) is calculated for each of these values. The \(I-V\) curve can then be plotted.

### 4.1.3 Estimation of the PV module parameters from manufacturer's data

The values of \(I_{sc}\), \(V_{oc}\), \(V_m\) and \(I_m\) refer to the manufacturer’s data. So the resulting \(I-V\) characteristic is that at reference conditions, \(I_G\) can be assumed equal to \(I_{sc}\) with no significant error.

\[
I_G = I_{sc} \tag{5}
\]

An expression for \(I_o\) can be obtained by using the point \((V_{oc}, 0)\) on the \(I-V\) curve. Letting \(I = 0\) in Equation (10), using \(I_{sc}\) for \(I_G\) (note that, \(I_o\) is very small compared with \(I_G - I\)). The following equation is thus obtained,

\[
I_o = I_{sc}e^{-V_{oc}/A} \tag{6}
\]

The series resistance \(R_s\) can be estimated based on a method described by Kunz and Wagner [13].

\[
R_s = -M \frac{I_{sc}}{I_m} + \frac{V_m}{I_m} \left( 1 - \frac{I_{sc}}{I_m} \right) \tag{7}
\]

where

\[
M = \frac{V_{oc}}{I_{sc}} \left( -5.411 \frac{I_m V_m}{I_{sc} V_{oc}} + 6.450 \frac{V_m}{V_{oc}} + 3.417 \frac{I_m}{I_{sc}} - 4.422 \right) \tag{8}
\]

The constants in Equation (8) are not empirical constants and have been determined from numerical methods and are independent of material properties.

\(A\) can be determined from Equation (9) [14]. This equation can be derived from Equation (4) by using the point \((V_m, I_m)\) on the \(I-V\) curve and making use of Equation (5) and then rearranging the resulting equation.

\[
A = \frac{V_m - V_{oc} + I_m R_s}{\ln(1 - (I_m/I_{sc}))} \tag{9}
\]

Now the manufacturer’s data can be transferred into an \(I-V\) curve.

This \(I-V\) curve will be needed in order to be able to estimate the performance of a PV system by using cell temperature, and that procedure is described in Sections 4.2.1.1.3 and 4.2.1.2.2.

The PV \(I-V\) characteristic can be determined for any irradiance and cell temperature from reference (i.e. manufacturer’s data). The four parameters in Equation (4) need to be expressed as functions of \(G\) and \(T_c\) (which in turn is a function of ambient temperature, \(T_a\), and wind speed, \(v\)).

In the SANDSTROM model by Buresch [15], an \(I-V\) curve is generated from a reference curve by correcting every single \((V, I)\) data point for temperature and irradiance. It can be described by the following equations:

\[
V = V_{ref} + \mu_{voc}(T_c - T_c, ref) - R_s \Delta I \tag{10}
\]

\[ I = I_{ref} + \Delta I \tag{11} \]

where

\[
\Delta I = \left( \mu_{voc} \left( \frac{G}{G_{ref}} \right) (T_c - T_c, ref) \right) + \left( \frac{G - G_{ref}}{G_{ref}} \right) I_{sc, ref} \tag{12}
\]

and \(I\) can be calculated from Equation (3).

\(V\) and \(I\) are, respectively, the voltage and its corresponding current on the \(I-V\) curve at the desired values of \(G\) and \(T_c\), the subscript ‘ref’ represents measurements at reference conditions and \(\mu_{voc}\) and \(\mu_{isc}\) are, respectively, the open-circuit voltage and short-circuit current temperature coefficients. The series resistance, \(R_s\), is assumed constant. The equations above also assume that the voltage and current temperature coefficients are constant and equal to \(\mu_{voc}\) and \(\mu_{isc}\), respectively.

The SANDSTROM model for generation of \(I-V\) data from reference conditions provides accurate predictions when compared with measurements.

### 4.1.4 Mathematical method for the optimum slope for a stationary PV system

In order to estimate the long-term performance of PV systems, radiation data are required; these data are usually available on a monthly-averaged or daily basis.

Solar radiation incident on any given surface can be decomposed into two components, the direct or beam component emanating from the sun, and a diffuse component that results from multiple reflections and scattering due to particles in the atmosphere. The diffuse component may also include reflections from the ground and local surroundings, where the surface in question is sloped rather than horizontal. Differentiating between the two components is vital for
accurate calculations in most solar energy applications; however, a number of steps may be required to arrive at realistic estimates at an appropriate level of detail for a given location depending on the basic data available. For this paper, the daily global radiation on the horizontal plane was made available for Al-Kufra by the Libyan Meteorological Office. Figure 8 shows the computational flow for any general surface, that is, one which may have a given orientation and slope. Furthermore, meteorological data such as hourly dry and wet bulb temperature, wind speed and relative humidity were also obtained.

4.1.5 Slope solar irradiation
The slope solar irradiation has three components that is beam, diffuse and ground reflected.

\[ I_S = I_{BT} + I_{DT} + I_g \]  

where \( I_S \) is the slope radiation, \( I_{BT} \) the slope beam irradiance, \( I_{DT} \) the sky-diffuse irradiance and \( I_g \) the ground-reflected radiation.

According to Duffie et al. [16], the optimum tilt for a fixed (non-tracking) system would be around 24° (angle=latitude) for Al-Kufra. Based on this, the PV system was modelled at a tilt angle of 24° facing south.

The hourly slope beam irradiance is obtained via,

\[ I_{BT} = I_B \left( \frac{\cos \theta}{\sin \varphi} \right) \]  

If measured directly, \( I_B \) can be observed as the difference between the hourly horizontal global \( I_G \) and the diffuse irradiance \( I_D \).

Muneer’s model [17] for tilted surface diffuse radiation is given by,

\[ I_{DT} = I_D \cos^2 \left( \frac{\beta}{2} \right) + \left( \frac{2b}{\pi(3+2b)} \right) \sin \beta - \beta \cos \beta - \pi \sin^2 \left( \frac{\beta}{2} \right) \]  

where \( I_D \) is the diffuse irradiance on a horizontal plane and \( 2b/\pi(3+2b) \) is given by

\[ \frac{2b}{\pi(3+2b)} = 0.04 - 0.82F - 0.0260F^2 \]  

(16)

\( F \) is the sky clarity index, that is

\[ F = \frac{I_G - I_D}{I_E} \]  

(17)

where \( I_E \) is the horizontal extraterrestrial irradiance and can be estimated by the following formula:

\[ I_E = 1367 \left[ 1 + 0.033 \cos(0.0172024 \ DN) \right] \sin \varphi \]  

(18)

where \( DN \) is the day number.

The ground-reflected radiation can be obtained from Equation (20),

\[ I_g = \rho I_D \sin^2 \left( \frac{\beta}{2} \right) \]  

(19)

where \( \rho \) is the average albedo of the ground.

Note that the surface albedo for sand is set to 0.34 (for white sand, the range is from 0.34 to 0.40) [18].

4.2 Thermal performance
It is well known that the efficiency of a PV solar cell decreases with an increase in solar cell temperature which plays a significant role in the PV cell performance and overall annual yield.

Two different methods of PV module operation are studied in this paper: namely operation with and without a module cooling system. Mattei et al. [19] have proposed a fairly accurate model for calculation of the cell temperature that is based on the energy balance and that procedure is described below.

4.2.1 Cell temperature calculations
Cell temperature \( T_c \) influences the \( I-V \) characteristics and therefore the electrical efficiency of the PV module. The normal operation cell temperature (NOCT) is the most common mode to determine the cell temperature and this parameter is given by the manufacture's data for PV [19]. NOCT is defined as the cell or module temperature that is reached when the cells are mounted in their normal way at a solar radiation level of \( G_T = 800 \text{ W/m}^2 \), a wind speed of 1 m/s, an ambient temperature \( T_a = 20^\circ \text{C} \) and no-load operation (module efficiency \( \eta_c = 0 \)). According to Duffie et al. [14], the cell temperature at any condition is found from,

\[ T_c = \left( \frac{G_T \tau \alpha}{U_k} \right) \left( 1 - \left( \frac{\eta_c}{\tau \alpha} \right) \right) \]  

(20)

where \( U_k \) is the overall heat transfer coefficient and \( \tau \alpha \) the transmission–absorption coefficient.
The ratio (\(\tau a/U_L\)) can be determined from:

\[
\frac{\tau a}{U_L} = \frac{T_{c,NOCT} - T_a}{G_{T,NOCT}}
\]  

(21)

In this paper, the energy balance has been used to compute the cell temperature with the following hypothesis:

- The radiation loss from the back-side of the PV module to ground has been neglected.
- The temperature on the PV surface is considered uniform.

Thermal losses from the PV module to its surroundings are an important factor, limiting the thermal performance of a PV thermal system. Such losses can be associated with all modes of heat transfer, i.e. conduction, convection and radiation.

In the case of a PV thermal system, thermal losses (Figure 9a) with and (Figure 9b) without a cooling system can be represented by thermal network diagrams as shown in Figure 9.

The analysis for the energy balance for steady-state conditions is provided in the following sections.

4.2.1.1 Operation without a water cooling system The energy balance equation is given by

\[
I_S \tau a (1 - \eta_{cell}) = (h_{cs} \times T_c - h_{cs} \times T_{SKY}) + (h_{ca} \times T_c - h_{ca} \times T_a)
\]  

(22)

where \(T_c\) is the cell temperature, \(T_{SKY}\) the sky temperature, \(T_a\) the ambient temperature, \(h_{cs}\) the heat transfer coefficient from the solar cell to the sky and \(h_{ca}\) the surface heat transfer coefficient for the front and back surfaces of the PV module.

4.2.1.1.1 Sky temperature calculations According to EnergyPlus Engineering [20], the default calculation for the sky temperature is:

\[
T_{SKY} = \left( \frac{\text{Horizontal_{IR}}}{\sigma} \right)^{0.25} - T_a
\]  

(23)

where Horizontal_{IR} is the horizontal infrared radiation intensity and \(T_a\) the ambient temperature.

Horizontal infrared radiation intensity is given by,

\[
\text{Horizontal_{IR}} = \varepsilon_{sky} \alpha T_a^4
\]  

(24)

where \(\varepsilon_{sky}\) is the sky emissivity and \(\alpha\) the Stefan–Boltzmann constant, \(5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4\).

The \(\varepsilon_{sky}\) is given by:

\[
\varepsilon_{sky} = \left(0.787 + 0.764 \ln \left(\frac{T_{dp}}{273}\right)\right) (1 + 0.0224N + 0.0035N^2 + 0.00028N^3)
\]  

(25)

where \(T_{dp}\) is the dew-point temperature and \(N\) the opaque sky cover. For a clear sky, \(N = 0\).

The dew-point temperature may be obtained from:

\[
T_{dp} = 6.091 \alpha + 0.4959 \alpha^2
\]  

(26)

where

\[
\alpha = \ln(P_w)
\]  

(27)

where \(P_w\) is the partial pressure of water vapour.

The partial pressure of water vapour is given by:

\[
P_w = \frac{P_{atm} \times W_h}{0.62198 + W_h}
\]  

(28)

where \(W_h\) is the humidity ratio and \(P_{atm}\) the atmospheric pressure.

4.2.1.1.2 Wind heat transfer coefficient Duffie et al. [16] suggest the use of the expression given by McAdams for flat plates exposed to outside winds,

\[
h_{ca} = 5.67 + 3.8v
\]  

(29)

where \(h_{ca}\) is the heat transfer coefficient for the flat surface and \(v\) the wind speed.

According to Cole and Sturrock [21], \(2 \times h_{ca}\) is the heat exchange coefficient corresponding to the total surface area of the module, i.e. two times the surface area corresponding to \(h_{ca}\) because the heat is lost by the two faces of the PV module.

4.2.1.1.3 Radiative heat transfer coefficient The radiative heat transfer coefficient \(h_{cs}\) is determined by

\[
h_{cs} = \frac{\alpha e_c (T_c^4 - T_{SKY}^4)}{T_c - T_{SKY}}
\]  

(30)

where \(e_c\) is the emissivity of the PV module cover for long wavelength radiation.
For operation without a cooling system, the initialization of the temperature $T_c$ was first made as:

$$T_c = T_a + 10$$

$$T_c = \frac{I_S \tau a (1 - \eta_{cell}) + (h_{cs} \times T_{SKY} + 2 \times h_{ca} \times T_a)}{h_{cs} + 2 \times h_{ca}}$$  \(31\)

To set up the calculation iterative routine, $T_c$ is assumed to be 10°C above the dry-bulb temperature. With the given input of dry- and wet-bulb temperatures, the dew-point and sky temperatures are obtained from Equations (26 and 27). Then using Equations (30–32), the improved value of $T_c$, i.e. $T_{co}$ is obtained. This improved value, i.e. $T_{co}$, is checked against its old value of $T_c$ and further iterations were carried out until the absolute of the difference between $T_{co}$ and $T_c$ was <0.01.

### 4.2.1.1.4 Maximum power and efficiency of the PV module

The maximum power is given by,

$$P_{max} = IV$$  \(32\)

where $I$ and $V$ can be calculated from Equations (10–12).

The maximum power point efficiency $\eta_{mp}$ of a module is given by:

$$\eta_{mp} = \frac{P_{max}}{A_c I_S}$$  \(33\)

where $A_c$ is the module area.

The fill factor is a commonly used performance parameter to collectively describe the degree to which $V_m$ matches $V_{oc}$ and $I_m$ matches $I_{sc}$. Fill factor (FF) is given by,

$$FF = \frac{P_{max}}{I_{sc} V_{oc}}$$  \(34\)

### 4.2.1.2 Operation with a cooling system

This section covers the investigation of cooling the PV modules by the attachment of an aluminium water jacket at the back of the PV module. Figure 10 shows the geometry details of an experimental water-cooled jacket that was used for the present investigation.

The energy balance equation in this case is given by,

$$I_S \tau a (1 - \eta_{cell}) = \frac{(h_{cs} \times T_c - (h_{cs} \times T_{SKY}))}{h_{cw}} + \frac{((h_{ca} \times T_c - (h_{ca} \times T_a)) + ((h_{cw} \times T_c - H_{cw} \times T_w))}{h_{cw}}$$  \(35\)

where $T_w$ is the water inlet temperature and $h_{cw}$ is the heat transfer coefficient from the solar cell to the working fluid (water).

### 4.2.1.2.1 Convective heat transfer coefficient from the back panel of the PV module to the working fluid (cooling system)

The convective heat transfer coefficient in enclosed spaces is calculated by the Nusselt number which is given by,

$$h_{cw} = \frac{Nuk_f}{D_c}$$  \(36\)
The selected module specifications are summarized in Table 3.

4.4.1.2.2 Maximum power and efficiency operation with a cooling system

The maximum power for operation with a cooling system is given by:

\[ P_{\text{max cooling}} = IV \]  

(45)

where \( I \) and \( V \) can be calculated from Equations (10–12).

The maximum power point efficiency of a module with a cooling system is given by:

\[ \eta_{\text{mpcooling}} = \frac{P_{\text{max cooling}}}{A_c I_S} \]  

(46)

where \( \eta_{\text{mp}} \) is the maximum power point efficiency and \( A_c \) the module area.

4.3 Selection of the PV module

Most commercial PV modules now available in the market have widely different characteristics. Consequently, it is important that selection criteria are used to select a PV module to suit the climatic conditions in Libya. These criteria include improved efficiency at high temperature.

The HIT PV module from Sanyo, rated at 200 W, has been used in this study. These solar panels use hetero-junction with intrinsic thin layer technology which combines both monocrystalline and amorphous silicon in the one structure. It is composed of a textured n-type c-Si wafer sandwich between p-type/i-type (Ultra-thin amorphous silicon layer) and i-type/n-type [25].

HIT technology offers the following advantages:

1. The claimed cell efficiency is in excess of 19% with a module efficiency of 17%.
2. The modules have good temperature characteristics.
4.4 The computer model
A detailed flow chart of the model is shown in Figure 11. The model of the PV module was implemented using VBA, which also made use of the processing features of Microsoft Excel. The model parameters are evaluated during execution using the equations listed in Sections 4.1, 4.1.4 and 4.2. This program has been used to compute dew-point, slope radiation, sky and cell temperature, module efficiency and maximum power for operation of the PV modules. Furthermore, the program calculates the current, voltage and fill factor. The program is designed to compute results for 10 h each day for a period of 1 year. The results of this program are given in Section 6.

Table 3. Specifications of the PV module [25].

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical specification</strong></td>
<td></td>
</tr>
<tr>
<td>Model</td>
<td>HIT Power 200</td>
</tr>
<tr>
<td>Rated power ($P_{\text{max}}$)</td>
<td>200 W</td>
</tr>
<tr>
<td>Maximum power voltage ($V_{\text{pm}}$)</td>
<td>55.8 V</td>
</tr>
<tr>
<td>Maximum power current ($I_{\text{pm}}$)</td>
<td>3.59 A</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{\text{oc}}$)</td>
<td>68.7 V</td>
</tr>
<tr>
<td>Short-circuit current ($I_{\text{sc}}$)</td>
<td>68.7 V</td>
</tr>
<tr>
<td>Temperature coefficient ($P_{\text{max}}$)</td>
<td>$-0.29%/\degree\text{C}$</td>
</tr>
<tr>
<td>Temperature coefficient ($V_{\text{oc}}$)</td>
<td>$-0.172\ V/\degree\text{C}$</td>
</tr>
<tr>
<td>Temperature coefficient ($I_{\text{sc}}$)</td>
<td>0.88 mA/$\degree\text{C}$</td>
</tr>
<tr>
<td>Cell efficiency</td>
<td>19.7%</td>
</tr>
<tr>
<td>Module efficiency</td>
<td>17.2%</td>
</tr>
<tr>
<td><strong>Mechanical specification</strong></td>
<td></td>
</tr>
<tr>
<td>Module area</td>
<td>1.16 m²</td>
</tr>
<tr>
<td>Weight</td>
<td>15 kg</td>
</tr>
<tr>
<td>Dimensions $L \times W \times H$</td>
<td>1319 $\times$ 880 $\times$ 46 mm</td>
</tr>
<tr>
<td><strong>Operating conditions</strong></td>
<td></td>
</tr>
<tr>
<td>Ambient operating temperature</td>
<td>$-20^\circ\text{C}$ to $46^\circ\text{C}$</td>
</tr>
<tr>
<td>NOCT</td>
<td>46.9°C</td>
</tr>
</tbody>
</table>

*STC: Cell Temp. 25°C, AM 1.5, 1000 W/m².

5. THE PROPOSED 50 MW PV POWER STATION FOR AL-KUFRA

5.1 System design
The proposed 50 MW PV power plant would be divided into 50 substations of 1 MW each and each 1 MW substation would be divided into five channels each rated at 200 kW. Each substation would feed the generated electricity to the 11 kV grid through a 1000 kVA transformer and each 200 kW PV channel has been equipped with a grid-connected inverter to convert the DC power from the PV into three-phase AC power for the primary of the 1000 kVA transformer. The output from the

Figure 11. Flow chart for the computer model.
50 MW station connects to the national grid (220 kV) through a 50 MVA transformer. Figure 12 shows the schematic diagram of the power station.

In this power plant, each 1 MW substation and each channel are independent of the other channels. This design has the following advantages:

1. easier troubleshooting and maintenance;
2. ability to install different types of PV systems.

5.2 Requirements of the PV system components

Figure 13 shows the configuration of the basic array which consists of 25 modules, five modules in series and five series in parallel. Forty basic arrays make one 200 kW PV substation, connected to one inverter. The array unit consist of 5000 modules for the 1 MW. The specification of the proposed inverter is shown in Table 4.

5.3 Field requirements

It is important that the PV modules do not shade each other. In this study, a fixed array has been used hence only the sun’s apparent motion across the sky needs to be taken into consideration in order to optimize the spacing between rows of modules.

Figure 13a shows the configuration of the basic array whose dimensions are 6.59 m in length and 4.4 m width.

To avoid any shadowing, the distance between the PV subarrays is 6 m which has been calculated from Equation (48) [26],

\[
\frac{d}{a} = \cos \beta + \frac{\sin \beta}{\tan \varepsilon}
\]  

where \( \beta \) is the tilt angle and \( \varepsilon \) can be estimated by the geographical latitude \( \phi \) and the ecliptic angle \( \delta = 23.5^\circ \)

\[
\varepsilon = 90 - \delta - \phi
\]

The area required for a 1 MW PV substation is 7776 m².

A 50 MW system and a proposed image for a 50 MW LS-PV system is shown in Figure 14. According to Kurokawa and Keiichi [27], a 50 MW power plant requires 50 500 t of steel and 70 000 t of concrete and the length of cable required is 650 km. In addition to 250 sets of inverters, it would need

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**Figure 12. Schematic circuit diagram of the 50 MW power station.**
Based on this design, and by consideration of the need for utility buildings, the land requirements were calculated for the proposed 50 MW PV power station at Al-Kufra at ≈ 0.55 km².

5.4 Financial analysis and payback period

A number of economic criteria are available for evaluating solar energy systems. In order to conduct a financial analysis for this project, the total cost of the PV power plant is calculated based on the DOE \[32\]. The cost per Watt of VLS-PV power plant $C_w$ includes the cost per Watt of: PV module cost, design cost $C_d(\$0.08)$, inverters cost $C_i(\$0.4)$, balance of system development cost $C_b(\$0.25)$ and installation cost $C_{in}(\$0.4)$. The cost of the PV modules is changing lastingly. According to Gupta \[28\], for the year for 2010, the module cost was $C_m = \$1.7/W$. Thus, the total cost of very large scale of the PV power plant is the product of cost per Watt and the rated power.

According to DOE, the cost per Watt is,

\[
C_w = C_m + C_d + C_i + C_b + C_{in}
\]

\[
C_w = \$2.8/W
\]

The total cost for 50 MW PV power plant would thus be $140$ million.

The payback time method is used here. The following steps may be used in order to estimate the present payback period:

- The solar energy on 1 m²/year is 2300 kWh/m²/year.
- Feed-in tariff rate is assumed to be $(C_{max}) \$0.45/kWh$.
- Cell efficiency $\eta_{cell} = 16.5\%$.
- The energy output of 1 m² of cells is: $E_y = 2300 \times 0.165 = 379.5$ kWh/m². The cost of 1 m² of the PV power plant is estimated to be: $C_{m2} = 2.8 \times 165 = $462/m², where $2.8/W$ is the total cost of 1 W.
- The saving due to the PV system usage is: $S_{pv} = E_y C_{max} = 379.5 \times 0.45 = $170.77/m²/year.
- The payback time is: $P_b = C_{m2}/S_{pv} = 462/170.77 = 2.7$ years.

The payback period was thus found to be 2.7 years.

5.5 Capacity factor and solar capacity factor

The capacity factor, $CF$, is defined as the ratio of the net electrical generation for the time considered to the energy that could have been generated, if the system were generating at continuous full power during the same period. The solar capacity factor (SCF) is defined as the ratio of the actual output of the PV power plant over a period of time and its output if it had operated at full nameplate capacity throughout the time of the day. The CF for the system was found to be 26% and the SCF was 62.5%.

5.6 Greenhouse gas pollution

Electric power plants that burn fossil fuels emit several pollutants linked to the environmental problems of acid rain, urban ozone (smog) and global climate change. As mentioned in Section 3.4, the main emitters of CO₂ in Libya are fuel combustion in the power generation sector, the transport sector and in industry. In total, energy-related emissions are responsible for almost all CO₂ emissions in the country.

In 2009, petroleum accounted for more than 53% of carbon emissions in Libya and natural gas was responsible for around 47%. In the same year, the total generation in Libya was 29 TWh, and taking into account the fact that the production of 1 kWh of electricity creates 0.760 kg CO₂ for oil and 0.560 kg CO₂ for natural gas \[29\], emissions of CO₂ from the generation of electricity at oil-fired plants and natural gas-fired plants were estimated at 19.3 billion tonnes in 2009.

Hence a 50 MW PV system with a total energy output of 114 GWh would reduce CO₂ pollution by 76 thousand tonnes of CO₂ each year.
6 RESULTS AND DISCUSSION

The results obtained from the computer model for conditions at Al-Kufra are shown in Figures 15–18. For comparison purposes, the hourly variation of the total energy output, average cell temperature and average efficiency of PV module operation with and without a cooling system are shown in Figures 15 and 16 for July and in Figures 17 and 18 for December.

The figures show that the average solar cell temperature is a maximum and the average efficiency for the PV module is a minimum as expected. Moreover, it is to be noted that the average efficiency decreases slightly with an increase in solar cell temperature and vice versa. Furthermore, the average efficiency of the PV module when operating with a cooling system is 17 and 17.3% in July and December, respectively, and falls to 16.2 and 16.8% in July and December, respectively, for operation of the PV module without a cooling system.

The maximum cell temperature for operation without a cooling system in July and December has been found to be 49 and 37°C, respectively. On the other hand, the maximum cell temperature when operating with a cooling system only reaches 28.2 and 20.3°C in July and December, respectively.
It is observed that the PV module operating with a cooling system gives higher total energy output (475 kWh/annum) than that operating without a cooling system (456 kWh/annum); this increase in total energy output is $\sim 4.2\%$.

Figure 19 shows the variation of the monthly average values of slope radiation, average cell temperature, average ambient temperature and average module efficiency without cooling system throughout of the year in Al-Kufra. It is to be noted that the higher value of slope radiation was observed in April because the direct solar radiation is falling perpendicular on the PV panel, with a tilt angle of 24° unlike the slope radiation in June, July and August.

The average cell temperature exceeded 49°C in June and has fallen to 20.8°C in January. Furthermore, it is seen that the cell temperature follows the ambient temperature. A strong inverse relationship between the average cell temperature and the average module efficiency can also be seen.

For operation with a cooling system, Figure 20 shows that the module efficiency slightly increases when the mass flow rate of the cooling water increases. However, the module efficiency only increases slightly with the mass flow rate. A steady-state condition is achieved with a mass flow rate in excess of 0.45 kg/s.

A prior requirement to the design of any PV system is knowledge of the optimum orientation and surface tilt at which the peak solar energy can be collected. To analyse the optimum inclination, the annual total energy output for tilt angles between 12° and 48° oriented due south (azimuth angle = 180°) were evaluated and Figure 21 shows those results.

The maximum total energy output is seen to accrue at a tilt angle of 24°. As the latitude of Al-Kufra is 24.28°N, the results support the argument that the optimum tilt angle for total energy output should be equal to the angle equivalent to the latitude of the location.
CONCLUSION

This article presented an extended analysis for placement of a 50 MW PV grid-connected power plant in Al-Kufra, Libya. Due to a growing economy and increasing use of air-conditioning units, electricity generation is currently growing at a rate of 6–8% a year in Libya. The country will need to have at least 9 GW of electricity capacity to meet total demand in 2015. Alternatives to fossil-fuelled power plants should be encouraged as evidence of compliance with the Kyoto protocol. One option would be the use of VLS-PV power plants. The HIT solar PV module from Sanyo, rated at 200 W, has been used in this study among the analysed PV modules due to its high efficiency and large module capacity/frame area ratio. Long-term meteorological parameters for Al-Kufra in Libya have been collected from Renewable Energy Authority (REAOL) Libya and the results confirm that Al-Kufra has a high content of annual solar radiation. The collected meteorological parameters were: long-term average daily global radiation, average daily sunshine hours, long-term hourly ambient temperature and average daily wind speed. A Microsoft Excel-VBA program has been constructed to compute slope radiation, dew-point, sky temperature, and then cell temperature, maximum power output and module efficiency for system, with and without a cooling. The results for energy production show that the total energy output is 114 GWh/year.
without a cooling system and 119 GWh/year with a cooling system. Also, the maximum cell temperature without a cooling system is 49.6°C on 21 June at noon and the minimum cell temperature is 9.4°C on 21 January at 7.30 a.m. The average module efficiency with and without a cooling system is 16.6 and 17.2%, respectively. These findings were consistent with the results of an experimental study conducted by Mosalam et al. [30]. The values of electricity generation CF and SCF were found to be 26 and 62.5%, respectively. The payback time for the proposed VLS-PV power plant was found to be 2.7 years. It is recommended to start building such plants at Al-Kufra without any delay.

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