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# Exploring Solar and Wind Energy as a Power Generation Source for Solving the Electricity Crisis in Libya

**Youssef Kassem [1,2,*], Hüseyin Çamur [1] and Ramzi Aateg Faraj Aateg [1]**

1 Department of Mechanical Engineering, Faculty of Engineering, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus; huseyin.camur@neu.edu.tr (H.Ç.); ramziaateg@gmail.com (R.A.F.A.)

2 Department of Civil Engineering, Faculty of Civil and Environmental Engineering, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus

* Correspondence: yousseuf.kassem@neu.edu.tr; Tel.: +90-(392)-2236464

Received: 3 June 2020; Accepted: 15 July 2020; Published: 18 July 2020

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**Abstract:** The current study is focused on the economic and financial assessments of solar and wind power potential for nine selected regions in Libya for the first time. As the existing meteorological data, including wind speed and global solar radiation, are extremely limited due to the civil war in the country, it was therefore decided to use the NASA (National Aeronautics and Space Administration) database as a source of meteorological information to assess the wind and solar potential. The results showed that the country has huge solar energy potential compared to wind energy potential. Additionally, it is found that Al Kufrah is a suitable region for the future installation of the Photovoltaic (PV) power plant due to high annual solar radiation. Based on the actual wind speed analysis, Benghazi and Dernah are the best regions for large-scale wind farm installation in the future taking into account existing meteorological data limitations. The values of the wind power density in all regions are considerable and small-scale wind turbines can be used to generate electricity based on NASA average monthly wind data for 37 years (1982–2019). Moreover, this work aimed to evaluate the wind/PV systems technical and economically through RETScreen Expert (Version 6.0, CanmetENERGY Varennes Research Centre of Natural Resources Canada, Varennes, Canada). Focusing on the power supply crisis in the country, the potential of electricity production by 5 kW grid-connected residential/household rooftop PV in all regions is proposed and presented. Additionally, this paper evaluated a techno-economic analysis of the 50MW wind/PV system in suitable places. The performance of a 5 kW and 50 MW PV solar system with three PV technologies, namely mono-crystalline silicon, poly-crystalline silicon, and thin-film (CdTe), was also analyzed. The results demonstrated that the development of the wind/PV system in the selected regions is both technically and economically feasible. The outcomes of this study can help decision-makers in designing and installing PV power plants as an alternative source for the future.

**Keywords:** wind potential; solar potential; NASA database; Libya; small-scale grid-connected; large-scale grid-connected; economic feasibility analysis; PV technologies

## 1. Introduction

Climate change is the most important environmental issue nowadays due to the increase in greenhouse gas (GHG) emissions from fossil fuel combustion [1]. Therefore, scientific researchers have encouraged the search for alternative sources of energy that would be able to generate energy and protect the environment [2–4]. Wind and solar energy are a renewable energy source, clean, and it can be cost-effective for generating electricity. Wind and solar energy can be converted to electricity by using a wind turbine and photovoltaic (PV) module, respectively. The utilization of wind and PV systems has met the electricity demand in many countries.

The use of wind and solar energy for generating electricity has been investigated by many scientific researchers. For instance, Zhou et al. [5] utilized meteorological data from 1979 to 2008 to investigate the potential of onshore wind energy in China. They found that onshore wind farms could produce about 146,336 GWh in the region. Ahmed [6] evaluated the techno-economic of the developed two wind farms with a capacity of 300 MW in Egypt. The results indicated that the developed wind farms produced about 1130 GWh and the electricity cost was expected to be within the range of 1.96–2.09 € cents/kWh. Dabar et al. [7] investigated the feasibility of the wind energy potential at GaliMa-aba, Ghoubbet, and Bada Wein in the Republic of Djibouti. The results indicated that annual electricity production was estimated to be 1073 GWh/year with the expected cost ranging from 7.03 USDcent/kWh to 9.67 USDcent/kWh. Chadee et al. [8] estimated the electricity cost generated from wind in Trinidad and Tobago islands. The authors found that cost electricity was less than the current subsidized residential tariff in the islands. Parikh et al. [9] investigated the solar energy potential using various solar panels. The results demonstrated that the amount of maximum electricity produced from the proposed solar PV plant was found to be 173.6 MW. Moreover, the feasibility of the 10 MW grid-connected PV system at 44 locations in Saudi Arabia was investigated by Rehman et al. [10]. They found that Bisha was the best site for the installation of PV plants in the future. Adaramola [11] utilized Homer software to evaluate the techno-economic analysis of a solar PV system in Jos, Nigeria. It was found that the capacity factor of the proposed plant was found to be 40.4% with an annual electricity generation of 331.536 GWh.

### *1.1. Energy Situation in Libya*

In general, the energy crisis has significantly impacted all aspects of life in the country for many years. Because of Libya's ongoing civil war, Libya has faced a chronic power shortage, and various power plants have been damaged, which has caused a reduction in the generation capacity in the most populated area. The Libyan electricity sector depends on a public network linking each power station to provide energy demand to all regions of Libya, where the total electrical energy produced during 2012 in the generation stations reached 33.980 GWh. In 2017, the General Electricity Company of Libya (GECOL) stated that the available products for the network were 4900 MW, while the demand reached 6500 MW, with a deficit of 130 MW in the east and 1470 MW in the west. As a result, the power outage crisis has increased in most of the regions in Libya, i.e., the western region has 5 to 8 hours of blackouts per day and the eastern region has 1 to 4 hours of blackouts per day. According to the statistics of GECOL, the peak load was 7000 MW in 2016. The electricity of Libya is nationalized under the control of the Ministry of Energy. The power plants in Libya are categorized as thermal power plants. There are several power plants in Libya, the most important of which are West of Tripoli (600 MW), East of Tripoli (1400 MW), Misratah (600 MW), and Tobruk (740 MW). Additionally, GECOL stated that it is expected that the maximum load will increase to 10795 by 2020, then to 14,834 by 2030 and 21,669 MW by 2050 based on the increasing in energy demand. Therefore, it can be concluded that the amount of $CO_2$ and GHG emissions released will rise as a result of increasing energy consumption in Libya. Moreover, according to a report showing fossil $CO_2$ emissions of all world countries [12], carbon dioxide ($CO_2$) emissions from energy usage and particularly from fossil fuel in Libya have been on the rise since 1970. Additionally, Libya has one of the world's fastest-growing $CO_2$ emissions rates according to Global Carbon Atlas [13]. Besides, $CO_2$ territorial emissions for Libya were estimated to be 54 $MtCO_2$ in 2018 with a rank of 55 in the world by emissions [13]. According to the World Bank data, 56,996.181 kt of $CO_2$ was released as a result of energy consumption in Libya. Additionally, it is noticed that the electricity consumption was reduced from 2839.083 kWh/capita in 2011 to 1811.05 kWh/capita in 2014. This is due to the power cuts that have persisted for seven years without proven solutions during the civil war. According to Alarab news in 2019, the Chairman of the Directors Board of the GECOL stated that the energy demand increased, and Libya faced a chronic power shortage due to the damaging of various power plants in the country. Therefore, the deficit in the production of electrical energy in the country is estimated to be 2000 MW, but the energy currently available is only about 5000 MW, while the required energy to produce is 7000 MW. Besides, he stated that the continuation of power outages for most of the day has become a common occurrence across the country during the summer season in light of high temperatures that make the demand for electricity increase using air conditioners.

### *1.2. Renewable Energy Potential in Libya*

The energy crises have been receiving greater attention because of the rapidly growing demand in recent years, especially in developing countries. Generating electricity using fossil fuels is a significant anthropogenic source for increasing the amount of $CO_2$ emission and exacerbating environmental problems. According to Asheibi and Khalil [14], the demand for electricity will be increased in the long term, which implies that the amount of fossil fuel used for electricity production will also increase in the future. Therefore, alternative energy sources, such as wind or solar, could be the best solution to reduce fossil fuel demand and carbon dioxide emissions in the country.

Libya is one of the countries that is rich in renewable energy sources (wind and solar energy) as the average wind power density varies from 164 to 426 W/m$^2$ in the country, and the annual average PV power ranges from 1753 kWh/kW$_p$ in some coastal strip regions to 2045 kWh/kW$_p$ in the southern regions according to the wind and solar atlas maps, respectively. Moreover, the average duration of sunshine during the year reaches 3100–3900 hours.

Several scientific studies have assessed renewable energy's potential, including solar and wind energy, in the country. Mohamed et al. [15] investigated the current utilization and the future of renewable energy in Libya. It was found that renewable energy could cover the energy demand in the country. Alweheshi et al. [16] investigated utilizing renewable energies as a power source for improving the energy situation in Libya. The results indicated that these energies could help to decrease the consumption of fossil fuel. Khalil et al. [17] investigated the feasibility of replacing the grid-connected HPS (high pressure sodium) lamps street lighting system with a solar-powered LED (light-emitting diode) street lighting system for a 4-km road in Libya. The results indicated the proposed system reduced $CO_2$ emission and fuel consumption and is economically feasible. Zuheir et al. [18] proposed PV solar water heating and PV-thermal systems to replace electrical heaters and reduce the maximum energy demand in the Libyan electric grid for households. The results showed that the PV-thermal system has higher efficiency compared to another proposed system. Kadem et al. [19] evaluated the techno-economic factors of a 14 MW PV plant in Houn city, Libya. The results showed that the PV power plant is economically feasible and sustainable. Embirsh and Ikshadah [20] assessed the mean monthly solar radiation and sunlight duration to analyze the characteristics of radiation and duration of sun rays over Tripoli city in Libya. The authors concluded that solar energy is considered as a major source of renewable energy in Libya. Moreover, according to Bodetti [21], solar power will help to solve the electricity problem, which residents in this country have been suffering from a lot for the last years. Mohamed and Masood [22] provided an overview of utilizing renewable energy for future Libya. The results showed that Libya has a huge renewable energy potential, especially solar and wind, which could be used for various purposes. Aldali et al. [23] developed a 50 MW PV solar plant in Al-Kufra, Libya. The results indicated that the amount of energy output was found to be 114 GWh/year with a payback time of 2.7 years. Al-Refai [24] evaluated the feasibility of a 100 MW grid-connected PV plant in Tripoli, Libya. The results indicated that the cost of generated electricity is estimated to be 0.0321$ /kWh. In addition, the Libyan Minister of Electricity stated that Libya intends to build a solar power station to reduce one-fifth of its electricity needs from fossil fuel [25]. Besides, according to a member of the Board of Directors of the General Electricity Company in southern Libya, the Libyan government aims to construct a 100 MW PV system to solve the electricity problem in southern Libyan cities [26]. Moreover, according to the vision of the Renewable Energies and Environment (REEO), the desert renewable energy project is one of the best projects in the world, which aims to supply

Europe with energy extracted from the sun's rays in North Africa, mainly Libya and the Middle East. The project can produce 250 GW per year, preventing the emission of 150,000 tons of carbon dioxide.

El-Osta et al. [27] investigated the most suitable places for installing small wind farms in Tripoli. The results indicated the Zwara has the maximum mean wind speed and wind power density (WPD), which was chosen for the installation of a wind farm. Ahwide et al. [28] analyzed the long-term wind speed data at the Darnah site, Libya using the Weibull distribution function. The results indicated that wind turbines with a power rating greater than 1000 kW at Darnah station were recommended. Glaisa et al. [29] conducted a techno-economic analysis of the potential for a hybrid system to power a school in Misratah, Libya. It was found that the hybrid power system could significantly cover the demand for electricity in the school. Al-Behadili and El-Osta [30] evaluated the life cycle assessment of the first wind farm to be installed in Darnah, Libya. The results indicated that wind energy would help to reduce $CO_2$ emissions from fossil fuel consumption. Additionally, the results indicated that the energy payback period is 0.475 years (5.7 months), and the payback ratio is 42.1. Kassem et al. [31] examined the feasibility of a wind energy project in the Tobruk area of Libya. The results showed that the annual value of WPD was found to be 50.90 W/m$^2$ and the energy generated from the proposed wind farm varied from 28.33 to 199.74 kWh. Kassem et al. [32] analyzed the wind speed characteristics of three locations in Libya, namely Tripoli, Nalut, and Espiaa, and estimated the electricity cost of 24 wind turbines with various power ratings and types by utilizing the present value cost method. It was found that the highest mean wind power of 50.3 W/m$^2$ was recorded in Nalut and the lowest cost of electricity was obtained from the Finn Wind Tuule C 200 model.

In summary, most researchers have investigated the wind and solar potential in different parts of Libya. They found that Libya has significant potential for harnessing wind and solar energy, which could be used to generate electricity. Besides, the studies indicated that electricity generated from wind and solar energy could help to reduce the electricity sector's emissions and fossil fuel consumption. Furthermore, according to the Regional Center for Renewable Energy and Energy Efficiency (RCREEE), the Libyan government plans to utilize renewable energy, especially wind and solar energy, for generating electricity in the country. By 2030, it is expected that 22% of electricity will be generated from renewable energy.

### *1.3. Scope of the Study*

To the best of our knowledge, there are no detailed studies in the literature about the feasibility of residential/household rooftop PV systems in Libya. Additionally, no studies have evaluated the economic feasibility of large-scale wind/PV projects in the country. The very few existing ones evaluated the feasibility of 14, 50, and 100 MW grid-connected PV power plants in Houn, Al-Kufra, and Tripoli, respectively [19,23,24]. Additionally, no studies have analyzed the wind or solar energy potential to examine the suitable region for the future installation of a wind or PV system. Besides, none of the previous studies assessed the sustainability of a grid-connected wind/PV power project using RETScreen Expert (Version 6.0, CanmetENERGY Varennes Research Centre of Natural Resources Canada, Varennes, Canada).

Therefore, to develop wind and solar energy as an energy source, this study analyzed the distribution of wind and solar energy in nine selected regions and estimated the wind and solar energy potential from three aspects: Geography, technology, and economy. Moreover, utilizing solar or wind energy as a power source may help to reduce GHG emissions and solve the energy crisis in the country. In this regard, a 5 kW grid-connected residential/household rooftop system was analyzed technicality and economically for all selected regions. Additionally, the feasibility of a large-scale (50 MW) grid-connected Wind/PV system was evaluated for suitable places for future installation of a wind/PV system. Additionally, the performance of the PV system with three different PV technologies (mono-crystalline silicon, poly-crystalline silicon, and thin-film (CdTe)) was analyzed.

## 2. Materials and Methods

Economic analysis of the solar and wind power potential at nine chosen regions in Libya was provided. For wind energy potential assessment, the Weibull distribution function and power-law method were employed to study the wind speed characteristics at various heights based on measurement and NASA data. Furthermore, to investigate the solar energy potential in the selected regions, NASA data were utilized. Moreover, the feasibility of small-scale and large-scale wind/PV systems is discussed in this section. The analysis procedure of this study is presented in Figure 1.

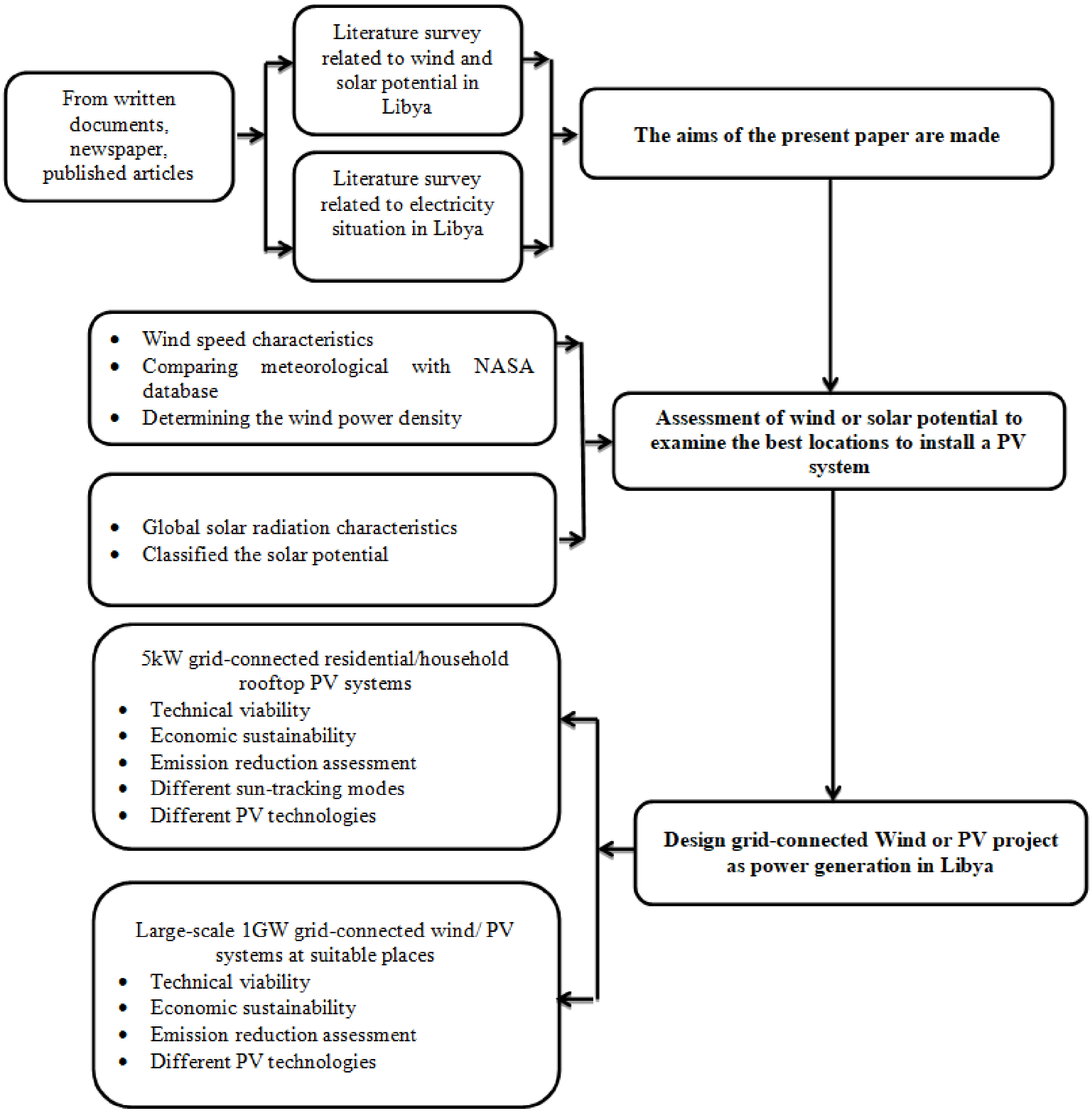



**Figure 1.** Schematic description for the proposed methodology.

### 2.1. Wind Data Analysis Procedure

#### 2.1.1. Wind Speed Data

Based on previous studies [27–32], the investigation period of evaluating the wind energy potential at different locations in Libya varied from 1995 to 2010. Due to the Civil War in Libya, there are a lack of instruments that are used to measure the wind speed along with the direction. Thus, NASA wind speed data for new periods were used to study the characteristics of wind speed in different locations in Libya. Besides, several studies have used NASA data for the future installation of a wind farm in a specific region. For instance, Arreyndip et al. [33] evaluated the potential of wind at different locations in Cameroon using NASA data (1983–2013) for the future installation of a wind farm. Rafique et al. [34] studied the feasibility of a 100 MW grid-connected wind farm in Saudi Arabia using RETScreen software. Additionally, the authors described the wind speed characteristics for all selected cities using NASA average monthly wind speed data. For example, Gökçekuş et al. [35] used the open source database to investigate the distribution of wind speed at 8 locations in Lebanon. Therefore, to evaluate the wind energy potential in the country, actual data and NASA average monthly wind data for 37 years (1982–2019) were used, which are provided by NASA's POWER Data Access Viewer website. The information and location of the selected regions are shown in Table 1 and Figure 2.

**Table 1.** Information for the selected regions.

| Region | Longitude (°E) | Latitude (°N) | Altitude (m) | NASA Period Records | Actual Period Records | Measured Height (m) |
|---|---|---|---|---|---|---|
| Tripoli | 32.892 | 13.173 | 81 | 1982–2019 | 1981–2010 | 10 |
| Nalut | 31.874 | 10.979 | 568 | 1982–2019 | 1981–2010 | 10 |
| Espiaa | 32.537 | 13.177 | 73 | 1982–2019 | 1993–2009 | 10 |
| Al bayda | 32.754 | 21.757 | 626 | 1982–2019 | 2000–2009 | 10 |
| Benghazi | 32.129 | 20.082 | 2 | 1982–2019 | 2000–2009 | 10 |
| Al-kufrah | 24.199 | 23.293 | 394 | 1982–2019 | 2000–2009 | 10 |
| Misratah | 32.375 | 15.090 | 8 | 1982–2019 | 1996–2010 | 10 |
| Sabha | 27.033 | 14.432 | 426 | 1982–2019 | 1995–2010 | 10 |
| Darnah | 32.766 | 22.624 | 48 | 1982–2019 | 2000–2009 | 10 |

### 2.1.2. Weibull Probability Density Function

In the literature, the two-parameter Weibull distribution function (2W) is commonly used to study the distribution of wind speed ($v$) at the selected region. The 2W is represented as [36–39]:

Probability distribution function ($f(v)$):

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k}. \tag{1}$$

Cumulative distribution function ($F(v)$):

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^k\right]. \tag{2}$$

In addition, Equation (3) is used to estimate the mean velocity as a function of Weibull parameters:

$$\overline{v} = c\Gamma\left(1 + \frac{1}{k}\right), \tag{3}$$

where $c$ is the scale parameter in m/s and $k$ is the shape factor of the distribution.

The parameters of 2W are estimated using the maximum likelihood method. The equation that determines these parameters can be expressed as follows [36–39]:

$$k = \left(\frac{\sum_1^n v_i^k ln(v_i)}{\sum_1^n v_i^k} - \frac{\sum_1^n ln(v_i)}{n}\right)^{-1}, \tag{4}$$

$$c = \left(\frac{1}{n}\sum\nolimits_1^n v_i^k\right)^{1/k}. \tag{5}$$


**Figure 2.** Map of Libya.

### 2.1.3. Wind Power Density

The wind power density value is a quantitative measure of wind energy available at any location. It is considered a critical indicator for wind energy potential. Additionally, two other essential wind speed indicators [40,41] are:

Probable wind speed ($V_{mp}$):

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k}. \tag{6}$$

Maximum energy-carrying wind speed ($V_{maxE}$):

$$V_{maxE} = c\left(1 + \frac{2}{k}\right)^{1/k}. \quad (7)$$

Generally, the wind power density (WPD) evaluates the wind available at the site [42]. It is expressed as:

$$\frac{P}{A} = \frac{1}{2}\rho v^3, \quad (8)$$

$$\frac{P}{A} = \frac{1}{2}\rho v^3 f(v). \quad (9)$$

Additionally, it can be computed as a function of the Weibull parameters as below [43]:

$$\left(\frac{P}{A}\right)_W = \int_0^\infty \frac{1}{2}\rho v^3 f(v)dv = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right). \quad (10)$$

Furthermore, Equation (11) is used to calculate the mean WPD [44]:

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho \overline{v}^3, \quad (11)$$

where $P$ is the wind power density in Watt/m$^2$, $\overline{P}$ is the mean wind power density in Watt/m$^2$, $A$ is the swept area in m$^2$, $\rho$ is the air density in kg/m$^3$, $f(v)$ is the probability density function (PDF), and $\overline{v}$ is the mean wind speed in m/s.

Furthermore, Equation (12) is used to calculate the error between the actual and estimated value of WPD:

$$Error = \left| \frac{\left(\frac{P}{A}\right)_W - \left(\frac{P}{A}\right)_A}{\left(\frac{P}{A}\right)_W} \right| \times 100\%, \quad (12)$$

where $\left(\frac{P}{A}\right)_A$ is the actual WPD and $\left(\frac{P}{A}\right)_W$ is the estimated WPD by 2W.

2.1.4. Wind Data Adjustment

To calculate the wind speed ($v$) at various wind turbine heights ($z$), the power-law model is used. It is expressed as [40–43]:

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^\alpha, \quad (13)$$

where $v_{10}$ is the wind speed at the measured height $z_{10}$, and $\alpha$ is the surface roughness coefficient (Equation (14)):

$$\alpha = \frac{0.37 - 0.088ln(v_{10})}{1 - 0.088ln(z_{10}/10)}. \quad (14)$$

## *2.2. Solar Radiation Data*

Several studies used satellite data to evaluate the solar source available at the site. For example, Obeng et al. [45] assessed the solar potential at UENR (University of Energy and Natural Resources) Nsoatre Campus using NASA SSE solar irradiation. Owolabi et al. [46] evaluated the solar potential at six different locations in Nigeria using the NASA database. Furthermore, numerous studies have compared the measured global solar radiation with estimated data (satellite databases) to show the accuracy of satellite databases. For instance, Kassem et al. [47] compared the actual monthly global solar radiation with satellite imagery database for various regions in northern Cyprus. The results indicated that the estimated data of global solar radiation (GSR) were close to the actual data. Gairaa and Bakelli [48] assessed the solar potential of Ghardaïa area, Algeria using measured solar radiation, the NASA SSE (Surface meteorology and Solar Energy service) model, and the Solar-Med-Atlas. The results showed that the measurements data were in agreement with the estimated database. Belkilani et al. [49] analyzed and compared the actual result of the monthly GSR for three sites in Tunisia with the satellite radiation databases. The results demonstrated that estimated data showed good correlation with the actual GSR data. Consequently, NASA's average monthly was utilized to evaluate the potential of solar energy in the selected regions.

### 2.3. Design and Development of the Wind or PV Project

#### 2.3.1. Design of the Wind Project

In general, the air flux through the area of interest is considered an important factor for estimating the wind power turbine ($P_w$), which can be estimated as:

$$P_w = \frac{\mathrm{dE}}{\mathrm{dt}} = 0.5 \times v^2 \times \frac{dm}{dt}, \tag{15}$$

where $E$ is the energy in Watt, $v$ is the wind speed in m/s, $t$ is the time in second, and $m$ is the mass flow in kg.

The mass flow rate ($\dot{m}$) is given by:

$$\frac{d\dot{m}}{dt} = \rho \times A_f \times \frac{dx}{dt} = \rho \times A_f \times v, \tag{16}$$

where $\rho$ is the air density ($\rho$ = 1.25 kg/m$^3$), $A_f$ is the swept area in m$^2$, and $x$ is the distance in m.

By combining Equations (15) and (16), the $P_w$ can be estimated as follows [50]:

$$P_w = 0.5 \times \rho \times A_f \times v^3. \tag{17}$$

In fact, the efficiency of the wind turbine depends on the wind speed of the site; thus, the $P_w$ can be expressed as function of coefficient ($C_{max}$):

$$P_w = 0.5 \times C_{max} \times \rho \times A_f \times v^3. \tag{18}$$

Generally, the important factors for selecting the wind turbine are the wind speed measurement and characteristics of the wind turbine. Furthermore, the availability factor ($AF$) is an essential factor for determining the amount of the time that the system can produce electricity during the investigating period, which is defined as:

$$AF = 1 - \frac{n}{N}, \tag{19}$$

where $n$ is the number of months in which the wind speed is lower than the cut-in speed of the wind turbine and $N$ is the total number of months during the investigation period.

#### 2.3.2. Design of the PV Power System

According to Owolabi et al. [46] and Kassem et al. [47], the important parameters that are considered for designing a PV power plant are:

Power generating factor:

$$PGE = \frac{Solar\ irradiance \times Sunshine\ hours}{Standard\ test\ condition\ irradiance}. \tag{20}$$

Solar PV energy required:

$$The\ energy\ required\ from\ PV\ modules = Peak\ energy\ requirement \times Energy\ lost\ in\ the\ system. \tag{21}$$

PV module sizing:

$$Total\ Watt\ peak\ rating = \frac{Solar\ PV\ energy\ required}{panel\ generation\ factor}, \tag{22}$$

$$PV\ module\ size = \frac{Total\ Watt\ peak\ rating}{PV\ output\ \ power\ rating}. \tag{23}$$

Inverter sizing:

$$Inverter\ size = Peak\ energy\ requirement \times Factor\ of\ safety. \tag{24}$$

### *2.4. Proposed Wind/PV Systems Specifications*

In general, because of population and industrial growth, the energy demand is increasing rapidly in Libya. Therefore, renewable energy sources like wind or solar are key to the future of energy. As a result, it is important to study the feasibility of small-scale and large-scale wind/solar projects in Libya, which was the main goal of the present study.

Referring to the previous sections, this section aimed to investigate the technical and economic feasibility of grid-connected 5 kW rooftop wind/PV systems in all selected regions. Additionally, this section presents an economic analysis of grid-connected 50 MW wind/PV systems for all regions. The economic feasibility of the projects was determined using RETScreen software.

#### 2.4.1. Grid-Connected 5 kW Residential Rooftop Wind/PV System

Three different PV technologies were considered for the proposed 5 kW grid-connected rooftop, namely, mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), and cadmium telluride (CdTe) from thin-film technology. To build the 5kW grid-connected residential/household rooftop in the chosen locations, 17 modules of the selected modules (mono-Si-CS6X-300M, poly-Si-CS6X-310P) were required. Additionally, 50 modules of the CdTe modules were required to build a 5kW rooftop PV system. Table 2 lists the specifications of the selected PV modules at standard test conditions. In addition, the Growatt 5500MTL-S Dual MPPT 6KW Solar Inverter was used for the proposed PV system with a total capacity of 6000 W. Table 3 shows the specification of the selected inverter.

**Table 2.** Technical specification of the Photovoltaic (PV) modules.

| PV Module Technology | Mono-si | Poly-si | CdTe |
|---|---|---|---|
| Manufacturer | Canadian Solar | Canadian Solar | First Solar |
| Model | mono-Si-CS6X-300M | poly-Si-CS6X-310P | CdTe-FS-4100 |
| Nominal power (W) | 300 | 310 | 100 |
| Open-circuit voltage (V) | 45 | 44.9 | 87.6 |
| Short-circuit current (A) | 8.74 | 9.08 | 1.57 |
| Voltage at point of maximum power (V) | 36.5 | 36.4 | 69.4 |
| Current at point of maximum power (A) | 8.22 | 8.52 | 1.44 |
| Module area ($m^2$) | 1.919 | 1.918 | 0.72 |
| Efficiency (%) | 15.63 | 16.16 | 13.89 |
| Warranty (Year) | 25 | 25 | 25 |
| Cost (USD/$W_{dc}$) | 0.83 | 0.8 | 2.5 |

**Table 3.** Technical specification of the selected inverter.

| PV Module Technology | Value |
|---|---|
| Rated power (W) | 6000 |
| Min PPT voltage (V) | 100 |
| Max PPT voltage (V) | 550 |
| DC startup voltage (V) | 100 |
| DC shutdown voltage (V) | 80 |
| Max input voltage (V) | 550 |
| Max DC power (W) | 6500 |
| Max AC power (W) | 5000 |
| Max DC current (A) | 30 |
| Warranty (year) | 10 |
| Efficiency (%) | 97.9 |
| Cost (USD) | 550 |

#### 2.4.2. Grid-Connected 50 MW Wind/PV System

##### 2.4.2.1. MW Grid-Connected Wind Farm

In general, a wind turbine is a machine that is used to convert the kinetic energy of wind into mechanical energy, which is then harvested to generate electricity. It is classified under two general categories called the horizontal and vertical axis, whereas the horizontal axis wind turbine was used in this study. As mentioned previously, the WPD is the estimated wind available at the site; hence, selecting the wind turbine depends on the class of WPD. In addition, wind speed determines the amount of energy generated by a wind turbine. Consequently, based on the annual output of the region and number of turbines required, E-82 E4 with a capacity of 3000 kW was selected in this study. The specification of the selected wind turbine is shown in Table 4.

**Table 4.** Specifications of the wind turbine.

| Parameter | Unit | Value |
|---|---|---|
| Power capacity per turbine | kW | 3000 |
| Manufacture | Enercon | - |
| Model | E-82 E4 | - |
| Wind class | IEC/EN IA and IEC/EN IIA | - |
| Number of turbines | - | 334 |
| Hub height | M | 84 |
| Rotor diameter per turbine | M | 82 |
| Swept area per turbine | $m^2$ | 5281 |
| Cut-in wind speed | m/s | 3.0 |
| Rated wind speed | m/s | 16.0 |
| Cut-out wind speed | m/s | 25.0 |
| Number of blades | - | 3 |
| Shape factor | - | 2 |
| Array losses | % | 3 |
| Airfoil losses | % | 2 |
| Miscellaneous losses | % | 3 |
| Availability | % | 97 |

##### 2.4.2.2. MW Grid-Connected PV Plant

A 50 MW PV capacity was proposed and its performance with three PV technologies namely, mono-Si, poly-Si, and CdTe, was also analyzed. To build the 50 MW grid-connected PV plant in the suitable region, 166,667, 161,291, and 500,000 of mono-Si, poly-Si, and CdTe modules were required. The area needed for these modules was estimated as 319,898, 309,407, and 359,971 $m^2$ for mono-Si, poly-Si, and CdTe systems, respectively. In addition, an SMA Sunny Central 2500-EV inverter was used for the proposed PV system with a total capacity of 2500 kW. Specifications of the used inverter are listed in Table 5.

**Table 5.** The technical details of the selected invertor.

| Input DC Parameters | Value |
|---|---|
| MPP voltage range $V_{DC}$ (at 25 °C/at 50 °C) | 850 V to 1425 V/1275 V |
| Min. input voltage $V_{DC,min}$/Start voltage $V_{DC,Start}$ | 778 V/878 V |
| Max. input voltage $V_{DC,\ max}$ | 1500 V |
| Max. input current $I_{DC,\ max}$ (at 25 °C/at 50 °C) | 3000 A/2700 A |
| Max. short-circuit current rating | 4300 A |
| **Output DC parameters** | **Value** |
| Nominal AC power at cos φ =1 (at 25 °C/at 40 °C/at 50 °C) | 2500 kVA/2350 kVA/2250 kVA |
| Nominal AC power at cos φ =0.8 (at 25 °C/at 40 °C/at 50 °C) | 2000 kW/1880 kW/1800 kW |
| Nominal AC current IAC, nom = Max. output current $I_{AC,\ max}$ | 2624 A |
| Nominal AC voltage / nominal AC voltage range | 550 V/440 V to 660 V |
| Max. efficiency | 98.6% |

### *2.5. Economic Analysis*

To determine the economic feasibility indicators of the project, RETScreen Expert software was employed. The following indicators, defined as an equation, are given below:

Net present value (NPV):

$$\mathrm{NPV} = \sum\nolimits_{n=0}^{N} \frac{C_n}{(1+r)^n}. \tag{25}$$

Levelized cost of energy (LCOE):

$$\mathrm{LCOE} = \frac{sum\ of\ cost\ over\ lifetime}{s\ of\ electricity\ generated\ over\ the\ lifetime}. \tag{26}$$

The internal rate of return (IRR):

$$O = \sum\nolimits_{n=0}^{N} \frac{C_n}{(1+\mathrm{IRR})^n}. \tag{27}$$

Simple payback (SP):

$$\mathrm{SP} = \frac{C - IG}{\left(C_{ener} + C_{capa} + C_{RE} + C_{GHG}\right) - \left(C_{o\&M} + C_{fuel}\right)}. \tag{28}$$

Equity payback (EP):

$$\mathrm{EP} = \sum\nolimits_{n=0}^{N} C_n. \tag{29}$$

Annual life cycle savings (ALCS):

$$\mathrm{ALCS} = \frac{\mathrm{NPV}}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)}. \tag{30}$$

GHG emission reduction cost (GHGERC):

$$GRC = \frac{ALCS}{\Delta_{GHG}}. \tag{31}$$

Benefit-Cost ratio (B-C):

$$\mathrm{B-C} = \frac{\mathrm{NPV} + (1 - f_d)C}{(1 - f_d)C}. \quad (32)$$

Capacity factor (CF):

$$\mathrm{CF} = \frac{P_{out}}{P \times 8760}, \quad (33)$$

where $P_{out}$ is the energy generated per year, $P$ is the installed capacity, $N$ is the project life in years, $C_n$ is the after-tax cash flow in year $n$, $r$ is the discount rate, $C$ is the total initial cost of the project, $f_d$ is the debt ratio, $B$ is the total benefit of the project, $IG$ is the incentives and grants, $C_{ener}$ is the annual energy savings or income, $C_{capa}$ is the annual capacity savings or income, $C_{RE}$ is the annual renewable energy (RE) production credit income, $C_{GHG}$ is the GHG (greenhouse gas) reduction income, $C_{o\&M}$. is the yearly operation and maintenance costs incurred by the clean energy project, $C_{fuel}$. is the annual cost of fuel, which is zero for renewable projects, and $\Delta_{GHG}$ is the annual GHG emission reduction.

## 3. Results

### 3.1. Wind Energy Potential

#### 3.1.1. Wind Speed Characteristics

The mean monthly wind speed data for all chosen locations are shown in Figure 3. It was found that the maximum and minimum average monthly wind speeds were recorded in April with a value of 6.910 m/s and October with a value of 1.722 m/s for Benghazi and Espiaa, respectively. For the Benghazi region, the highest and lowest wind speeds were obtained in April (6.910 m/s) and November (4.620 m/s), respectively. Moreover, the monthly mean wind speeds were in the range of 3.028 and 4.843 m/s for Tripoli, Nalut, Al bayda, and Misurata. In addition, the minimum and maximum monthly wind speed values were 5.034 and 6.125 m/s for Al-Kofra, 4.358 and 6.321 m/s for Sabha, and 5.143 and 6.583 m/s for Derna.

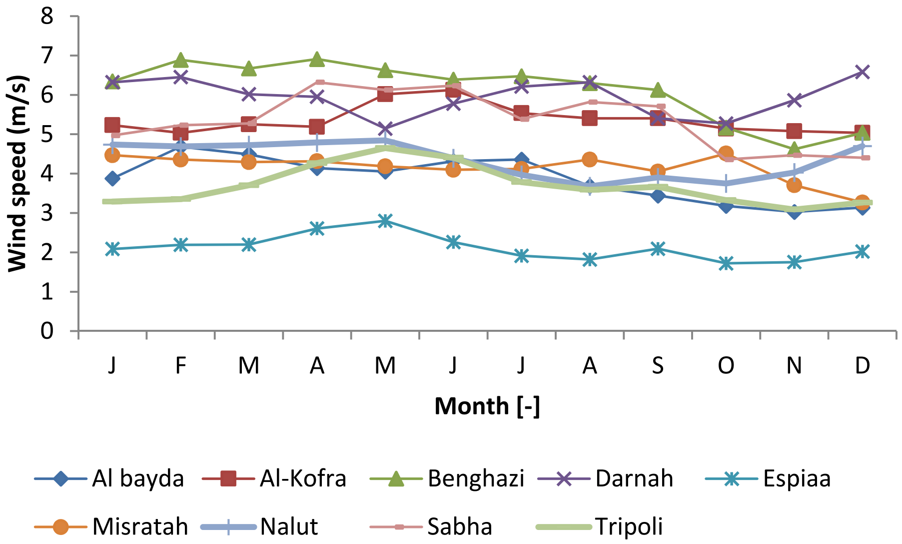



**Figure 3.** Actual mean monthly wind speed for all selected regions in Libya.

Furthermore, Figure 4 illustrates NASA's mean monthly wind speed for all regions between 1982 and 2019. It is noticed that Darnah has a maximum monthly wind speed, which occurred in January with a value of 6.177 m/s followed by Benghazi with a value of 6.006 m/s recorded in February. The lowest wind speed value of 3.351 m/s was recorded in December for Al-Kufrah.

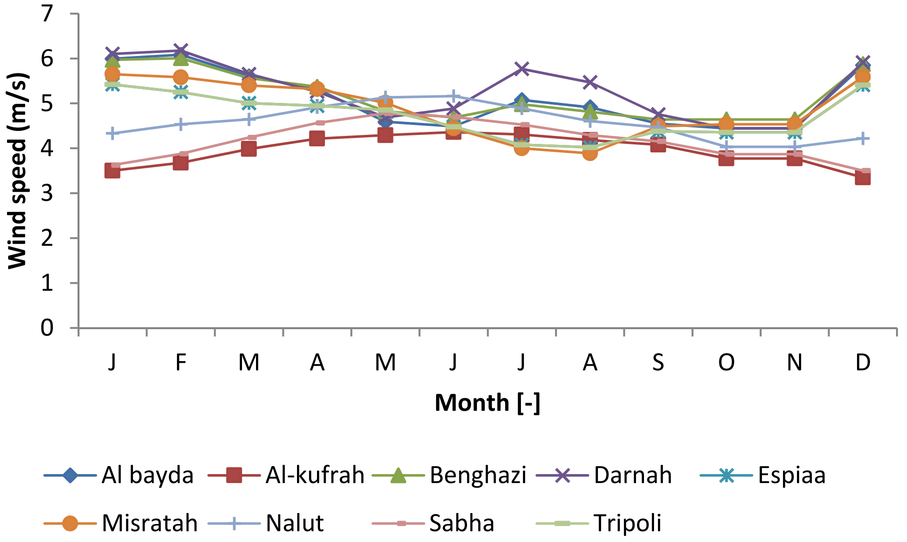



**Figure 4.** NASA mean monthly wind speed for all selected regions in Libya.

Moreover, to show the difference between the actual and NASA data, the percentage difference formula was used (Equation (33)):

$$Percentage\ Difference = \frac{|x_1 - x_2|}{\left[\frac{x_1+x_2}{2}\right]} \times 100. \tag{34}$$

For comparison, it was observed that the percentage difference between the mean annual actual data and NASA data is within the range of 5.19–75.86% as shown in Figure 5. The minimum and maximum percentage difference values were estimated in Nalut and Espiaa regions, respectively, as shown in Figure 5. Additionally, it is noticed that the percentage change values between the actual and NASA data varied from 11.49% to 30.26% for Al-kufrah, Benghazi, Darnah, Misratah, Sabha, and Tripoli (see Figure 5).

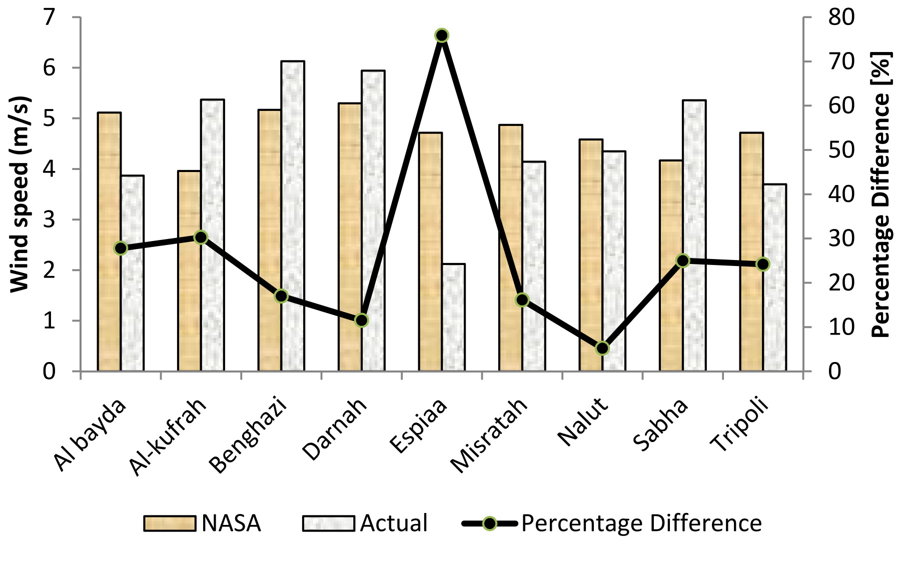



**Figure 5.** Comparison between actual and NASA data of the mean annual and percentage difference between both data.

### 3.1.2. Determination of Weibull Parameters and Wind Power Density at a Height of 10 m

The Weibull parameters were estimated using the monthly wind speed (actual and NASA data) for the whole investigated period. EasyFit software was utilized for calculating the Weibull parameters, mean velocity, and standard deviation (SD) of Weibull distribution for all selected regions.

Moreover, the actual and estimated wind power density at a 10-m height were calculated and are summarized in Table 6. The results indicate that the highest and lowest value of WPD using the actual wind speed data occurred in Benghazi and Espiaa with values of 134.615 and 5.284 W/m$^2$, respectively. Besides, it is noticed that the absolute error varied from 3.627% and 10.660%, which indicates good agreement between the actual and estimated value for wind power density. By using NASA monthly wind speed data, it is noticed that the highest wind power density value was recorded in Darnah followed by Benghazi with a value of 85.844 and 80.046 W/m$^2$, respectively, as shown in Table 6. Moreover, based on the wind atlas map, the value of WPD for the chosen regions varied from 25 to 100 W/m$^2$.

**Table 6.** Weibull parameters, most probable wind speed and maximum energy carrying wind speed values, and wind power density over the investigation period at a 10-m height.

| Type of Data | Parameters | Al bayda | Al-kufrah | Benghazi | Darnah | Espiaa | Misratah | Nalut | Sabha | Tripoli |
|---|---|---|---|---|---|---|---|---|---|---|
| Actual wind speed data | Actual mean (m/s) | 3.866 | 5.370 | 6.128 | 5.943 | 2.121 | 4.144 | 4.349 | 5.358 | 3.698 |
| | Mean of Weibull (m/s) | 3.775 | 5.286 | 6.035 | 5.862 | 2.051 | 4.095 | 4.287 | 5.247 | 3.597 |
| | SD (m/s) | 0.640 | 0.391 | 0.983 | 0.554 | 0.308 | 0.471 | 0.557 | 0.813 | 0.510 |
| | k | 6.932 | 16.639 | 7.241 | 12.900 | 7.906 | 10.487 | 9.224 | 7.641 | 8.403 |
| | c (m/s) | 4.038 | 5.457 | 6.440 | 6.101 | 2.179 | 4.296 | 4.522 | 5.584 | 3.810 |
| | Kolmogorov Smirnov test | 0.142 | 0.230 | 0.251 | 0.140 | 0.150 | 0.253 | 0.251 | 0.140 | 0.174 |
| | $V_{mp}$ | 3.948 | 5.436 | 6.309 | 6.063 | 2.142 | 4.255 | 4.466 | 5.483 | 3.753 |
| | $V_{maxE}$ | 4.188 | 5.494 | 6.661 | 6.169 | 2.242 | 4.368 | 4.619 | 5.757 | 3.908 |
| | Actual WPD (W/m$^2$) | 35.385 | 94.872 | 140.966 | 128.558 | 5.847 | 43.582 | 50.394 | 94.200 | 30.964 |
| | WPD of Weibull (W/m$^2$) | 32.950 | 90.451 | 134.615 | 123.361 | 5.284 | 42.057 | 48.251 | 88.489 | 28.496 |
| | Error (%) | 7.390 | 4.888 | 4.718 | 4.213 | 10.660 | 3.627 | 4.441 | 6.454 | 8.661 |
| NASA wind speed data | Actual mean (m/s) | 5.113 | 3.959 | 5.169 | 5.297 | 4.714 | 4.871 | 4.581 | 4.168 | 4.714 |
| | Mean of Weibull (m/s) | 5.006 | 3.906 | 5.075 | 5.194 | 4.630 | 4.779 | 4.510 | 4.094 | 4.630 |
| | SD (m/s) | 0.734 | 0.403 | 0.666 | 0.732 | 0.572 | 0.743 | 0.441 | 0.478 | 0.572 |
| | k | 8.106 | 11.754 | 9.124 | 8.452 | 9.722 | 7.607 | 12.455 | 10.323 | 9.215 |
| | c (m/s) | 5.312 | 4.079 | 5.356 | 5.501 | 4.872 | 5.087 | 4.700 | 4.298 | 4.872 |
| | Kolmogorov Smirnov test | 0.209 | 0.157 | 0.238 | 0.152 | 0.143 | 0.171 | 0.138 | 0.153 | 0.143 |
| | $V_{mp}$ | 5.226 | 4.048 | 5.288 | 5.420 | 4.818 | 4.994 | 4.668 | 4.255 | 4.812 |
| | $V_{maxE}$ | 5.458 | 4.134 | 5.473 | 5.641 | 4.967 | 5.246 | 4.756 | 4.372 | 4.977 |
| | Actual WPD (W/m$^2$) | 81.868 | 38.004 | 84.568 | 91.039 | 64.149 | 70.774 | 58.887 | 44.343 | 64.149 |
| | WPD of Weibull (W/m$^2$) | 76.829 | 36.501 | 80.046 | 85.844 | 60.773 | 66.857 | 56.183 | 42.029 | 60.773 |
| | Error (%) | 6.558 | 4.117 | 5.650 | 6.051 | 5.555 | 5.860 | 4.812 | 5.505 | 5.555 |

Furthermore, the wind energy potential classification according to the value of WPD was discussed according to Yüzügüllu [51] and Fazelpour et al. [52]. Based on actual wind speed data, it was observed that the WPD value of Benghazi and Darnah is classified as class 2, which indicates marginal wind power potential, while the other selected regions are considered as class 1, which indicates poor wind potential. Consequently, it can be concluded that a small wind turbine could be used to generate electricity in Tripoli, Nalut, Espiaa, Al-bayda, Al-kufrah, Mitah, tah, and Sabha. Nevertheless, small-scale wind turbines could be used to produce electricity in the regions. In addition, according to Fazelpour et al. [52], the wind density of Benghazi and Darnah is classified as fairly good. Consequently, it is concluded that high-capacity wind turbines (MWs) are feasible for further investigation in Benghazi. Based on NASA wind speed data, it is noticed that values of wind power density for all regions are below 100W/m$^2$, which is classified as class 1 (poor wind potential).

According to the previous scientific studies, the growth of populations and complexity of building geometries and configurations are considered the most important parameters that affect the wind speed and direction [53]. According to Stathopoulos et al. [53], the mean wind speeds in urban areas are lower than in rural areas. According to Cui and Shi [54], the wind speed values were significantly reduced over the period due to the growth of an urban heat island. Additionally, according to Liu et al. [55], there was a positive relationship between urbanization and wind speed over the period, i.e., the changes from a suburban to an urban district over a period led to decrease in the atmospheric wind speed.

Moreover, based on [56], population in Libya changed from 1,124,515 in 1950 to 6,871,292 in 2020, which indicates construction increased also. Therefore, it can be concluded that the evaluation of wind energy potential in the selected regions should be based on a new measurement of wind speed for all selected regions. As mentioned before, due to the Civil War in Libya, there is a lack of instruments to measure wind speed and direction. Consequently, the authors concluded that the potential of wind energy in the chosen regions is classified as poor based on the NASA data and wind atlas map.

### 3.2. *Solar Energy Potential*

Global horizontal irradiation (GHI) and direct normal irradiation (DNI) are essential parameters to assess the energy generation for flat-plate photovoltaic, concentrating solar power, and concentrating photovoltaic systems [57]. Additionally, air temperature (AT) is one of the most essential parameters for estimations of the performance of the PV system [47].

#### 3.2.1. Global Solar Characteristics

The average monthly GHI, DNI, and AT for all regions are illustrated in Figure 6. It is observed that the monthly values of GHI are within the range of 95.608–240.239 kWh/m$^2$. Additionally, it is noticed that the maximum value of GHI and DNI was recorded in the Al bayda region with a value of 240.239 and 285.231 kWh/m$^2$, respectively. Additionally, it was found that the highest and lowest AT values were obtained in the Sabha and Nalut regions with a value of 33.34 (June) and 9.754 °C (January), respectively.

Moreover, Table 7 shows the annual GH, DNI, and AT for all regions. It was found that the maximum annual GHI and DNI were obtained in Al-Kofra with a value of 2277.154 kWh/m$^2$ and in Misratah with a value of 2429.203 kWh/m$^2$. The lowest GHI and DNI values were recorded in Espiaa and Sabha with a value of 2015.617 and 2271.847 kWh/m$^2$, respectively. Additionally, it is noticed that the maximum and minimum value of air temperatures were recorded in Sabha and Al bayda with a value of 24.84 and 17.38 °C, respectively.

**Table 7.** Annual mean GHI, DNI, and AT for all selected regions.

| Parameters | Al bayda | Al-Kofra | Benghazi | Darnah | Espiaa | Misratah | Nalut | Sabha | Tripoli |
|---|---|---|---|---|---|---|---|---|---|
| GHI (kWh/m$^2$) | 2029.123 | 2277.154 | 2064.809 | 2067.452 | 2015.617 | 2062.196 | 2084.97 | 2144.901 | 2038.268 |
| DNI (kWh/m$^2$) | 2314.207 | 2377.798 | 2400.542 | 2425.942 | 2303.489 | 2429.203 | 2381.454 | 2271.847 | 2411.97 |
| AT (°C) | 17.38 | 24.14 | 21.39 | 20.30 | 21.66 | 22.09 | 20.71 | 24.84 | 22.24 |

#### 3.2.2. Solar Potential Classification

As aforementioned, GHI and DNI were used to evaluate the solar energy potential in the country. Based on solar potential classes (Table 8), the classification of solar resource for the selected locations based on the annual global horizontal irradiation is listed in Table 9. It can be observed that the selected areas have high solar resources and were categorized as excellent, outstanding, or superb potential classes. Additionally, it was observed that the solar resource of the Al-kufrah location was classified as superb (class 7). Consequently, it is concluded that Al-kufrah is the most appropriate region for installing large-scale photovoltaic systems due to the high value of global solar radiation (GHI). Furthermore, the analysis of the DNI indicates that the solar energy potential for all selected regions was classified as class 6 (outstanding). Therefore, it can be noticed that all chosen regions are appropriate for installing PV/flat-plate and CSP systems.

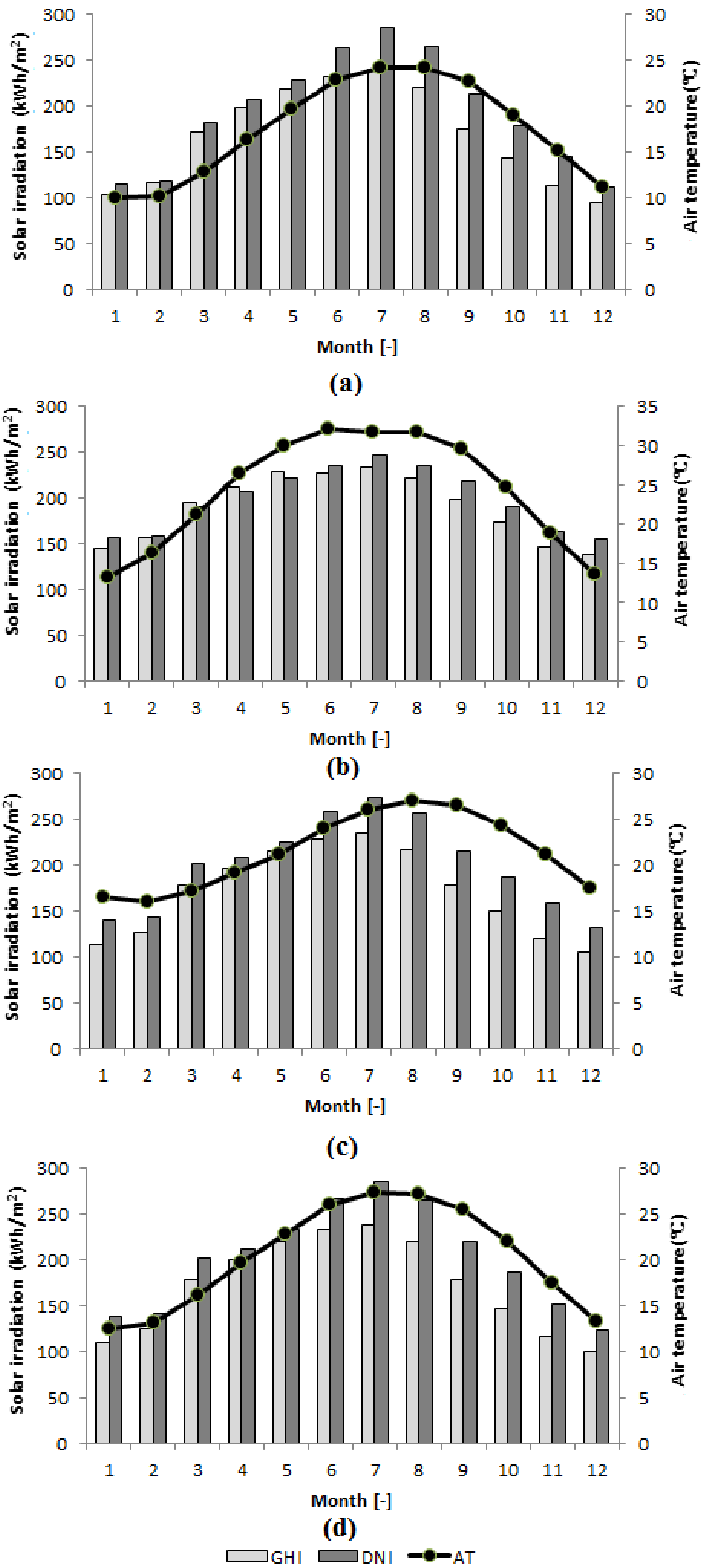
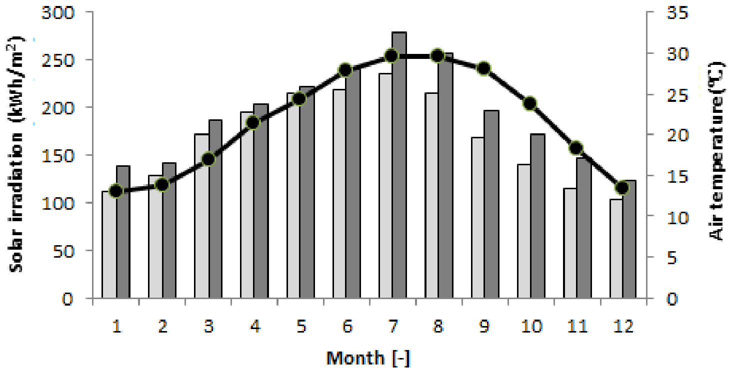



**Figure 6.** *Cont.*

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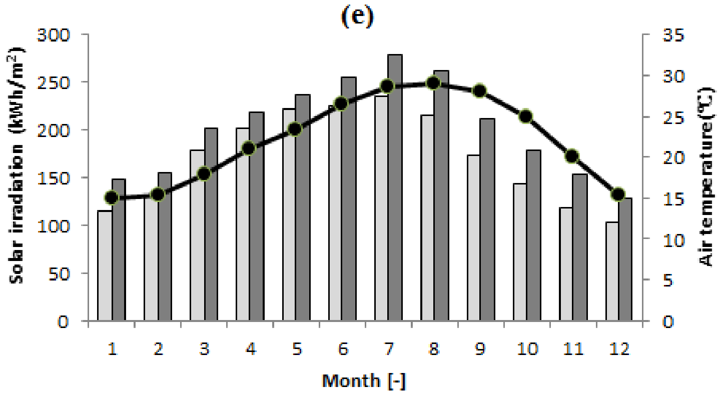


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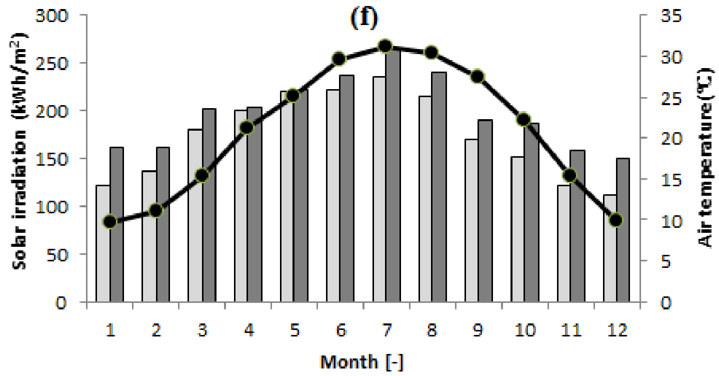


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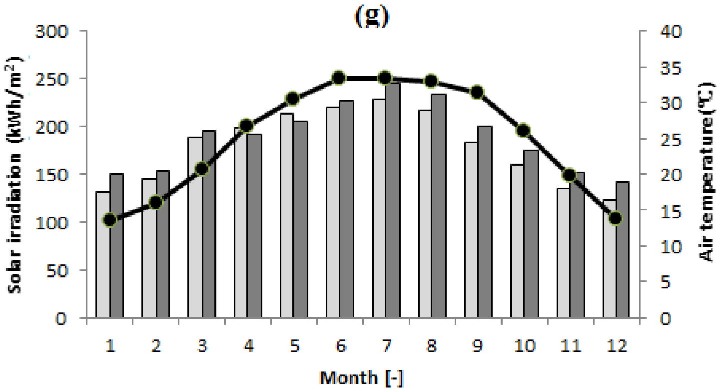


**(h)**

GHI DNI AT

**Figure 6.** *Cont.*

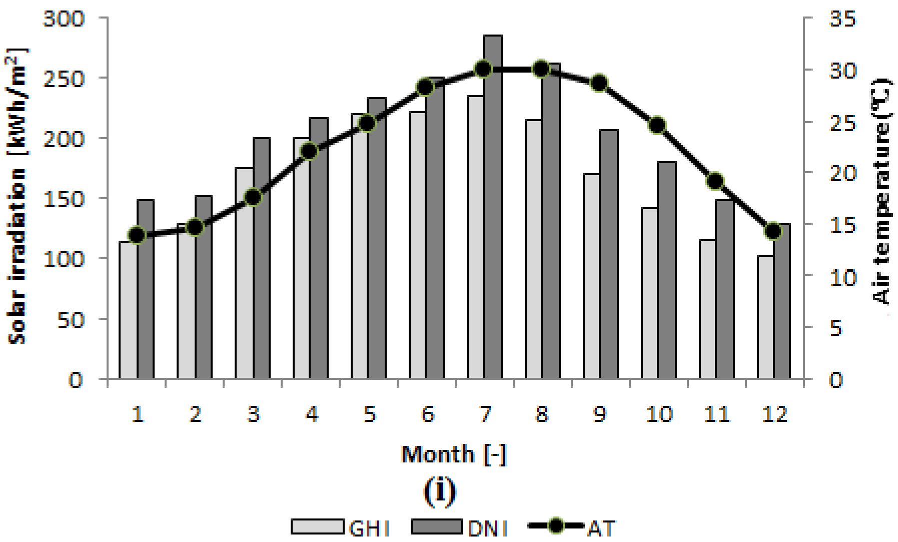


**Figure 6.** Mean monthly global horizontal irradiation, direct normal irradiation and air temperature for all selected regions in Libya; (**a**) Al bayda, (**b**) Al-kufrah, (**c**) Benghazi, (**d**) Darnah, (**e**) Espiaa, (**f**) Misratah, (**g**) Nalut, (**h**) Sabha, and (**i**) Tripoli.

**Table 8.** Solar potential classification based on annual GHI and DNI [58].

| Class | Annual GHI (kWh/m$^2$) | Class | Annual DNI (kWh/m$^2$) |
|---|---|---|---|
| 1 (Poor) | <1191.8 | 1 (Poor) | <936.9 |
| 2 (marginal) | 1191.8–1419.7 | 2 (marginal) | 936.9–1255.7 |
| 3 (fair) | 1419.7–1641.8 | 3 (fair) | 1255.7–1546.8 |
| 4 (good) | 1641.8–1843.8 | 4 (good) | 1546.8–1840.9 |
| 5 (excellent) | 1641.8–2035.9 | 5 (excellent) | 1840.9–2149.9 |
| 6 (outstanding) | 2035.9–2221.8 | 6 (outstanding) | 2149.9–2533.7 |
| 7 (superb) | >2221.8 | 7 (superb) | >2533.7 |

**Table 9.** GHI and DNI classification.

| Regions | Classification based on NASA Data | |
|---|---|---|
| | GHI | DNI |
| Al bayda | Excellent | Outstanding |
| Al-Kofra | Superb | Outstanding |
| Benghazi | Outstanding | Outstanding |
| Darnah | Outstanding | Outstanding |
| Espiaa | Excellent | Outstanding |
| Misratah | Outstanding | Outstanding |
| Nalut | Outstanding | Outstanding |
| Sabha | Outstanding | Outstanding |
| Tripoli | Outstanding | Outstanding |

### *3.3. Evaluation of Solar and Wind Potential Energy Resources in Libya: Summary*

Libya's solar energy potential is reasonably large, and power plants could be economically possible in all regions based on the solar atlas map and the current analysis. Based on the findings, the solar potential exhibits much more variability with respect to the wind one, with the estimated energy production ranging from 1868 kWh/kWp up to 1936 kWh/kWp. An examination of the potential wind energy resources in the nine selected regions over 37 years showed that the 37-year mean wind power density of Libya was about 66.42 W/m$^2$, which was classified as poor wind energy potential. It should be noted that the NASA average monthly wind data collected at the height of 10m was synthesized to the height of 84 m using the power-law method, which is the height of most of the 1 MW or above capacity wind turbine. Therefore, Libya has a huge solar energy potential compared to wind energy potential.

### 3.4. Economic Analysis and Feasibility Study of a 5 kW Grid-Connected PV System

Based on the analysis, it was found that the values of WPD for all regions are considerable and can be exploited using small-scale wind turbines. Additionally, the results indicated that the selected regions have high solar resources and were categorized as excellent, outstanding, or superb potential classes. Moreover, according to International Renewable Energy Agency (IRENA), the price of the PV system is continuously dropping with a percentage of 80% since 2009, while the percentage of reducing the price of the wind turbine system has ranged between 30% and 40% since 2009. Therefore, this price drop has encouraged the utilization of small-scale PV systems worldwide. Consequently, this section presents the economic analysis of a grid-connected residential/household rooftop PV system in all selected regions.

#### 3.4.1. Assessment of PV Systems Performance

For the proposed system, a fixed-tilt system was considered for a rooftop solar PV system in all chosen cities. Additionally, the PVGIS simulation tool was used to find the optimum angles in terms of the slope angle and azimuth angle for all selected locations. Table 10 lists the optimum angle for the future installation PV system for all chosen regions. RETScreen software was utilized to investigate the economic feasibility of a grid-connected 5 kW PV system in the selected locations. The annual electricity generation and capacity factor from the proposed system with three PV technologies along with the performance ratio are shown in Figure 7. It is observed that the highest annual electricity generation was recorded at Al Kufrah and the lowest one was obtained at Al bayda. The performance analysis showed that mono-crystalline silicon, poly-crystalline silicon, and thin film (CdTe) systems would annually export 9457.66, 9772.62, and 9611.52 kWh, respectively, to the grid in the Al Kufrah region. Additionally, it was noticed that the highest electricity exported to the grid was produced by poly-crystalline silicon system compared to the other systems. Moreover, it was observed that the maximum capacity factor is for the climatic conditions of Al Kufrah within a range of 21.17–21.97% as shown in Figure 7. Additionally, it was noticed that the values of capacity factor (CF) are within the range of 17.33–21.97%; hence, these values indicate that the selected regions are suitable for developing PV projects. According to the results of [10,46], the results indicate that the development of solar PV plants in Libya as a PV system is technically sustainable. Among the proposed three systems, the thin-film (CdTe) system performed better than mono-crystalline silicon and poly-crystalline silicon based on the value of the performance ratio as shown in Figure 7.

**Table 10.** Optimum angles for the PV system for all selected regions.

| Location | Al bayda | Al-Kofra | Benghazi | Darnah | Espiaa | Misratah | Nalut | Sabha | Tripoli |
|---|---|---|---|---|---|---|---|---|---|
| **Slope angle (°)** | 27 | 25 | 29 | 28 | 30 | 30 | 31 | 27 | 30 |
| **Azimuth angle (°)** | 2 | 1 | 1 | 1 | 1 | 2 | 1 | −2 | 4 |

#### 3.4.2. Simulation Results of Financial and Emission Reduction Analysis

The economic analysis is an essential analysis in order to know if the project is economically viable and sustainable. Studying the economic viability of the PV power plant benefits and informs both investors and policymakers. Table 11 shows the financial parameters used in this study. Based on the input variables, NPV, ALCS, LCOE, SP, and EP were determined by the RETScreen software. It should be noted that the financial parameters were selected based on other African countries.

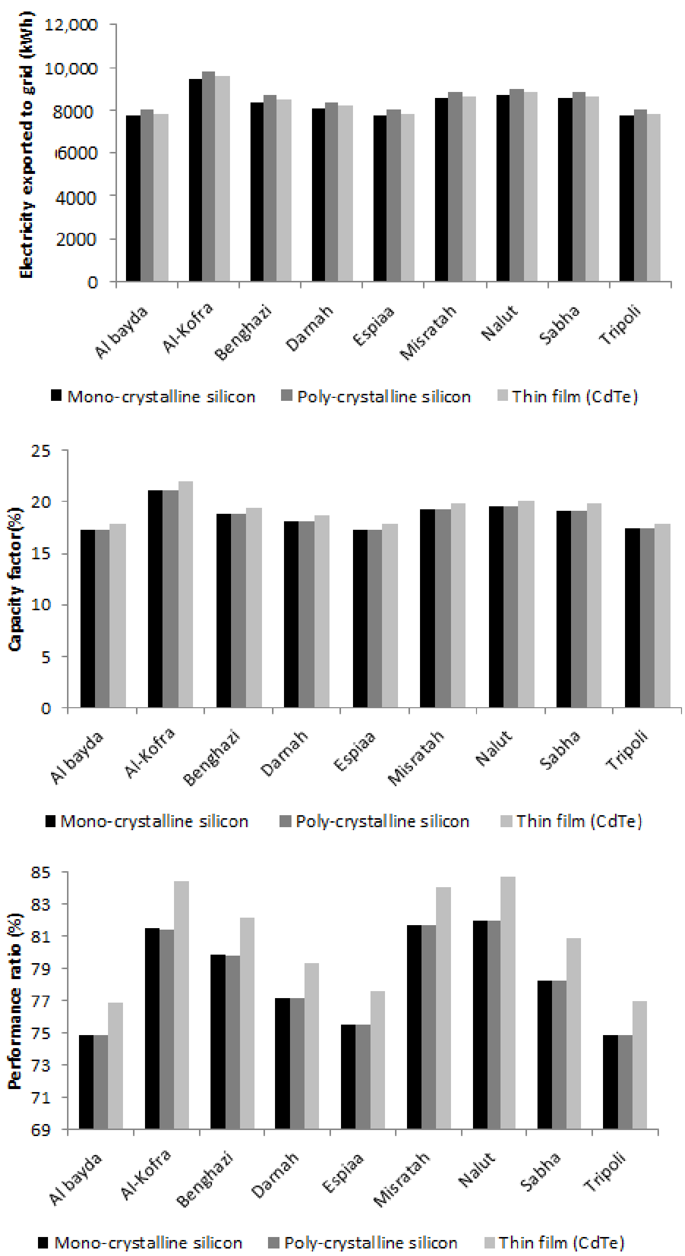


**Figure 7.** Annual electricity generation, capacity factor, and performance ratio of the proposed systems.

**Table 11.** Financial parameters.

| Factor | Unit | Value |
|---|---|---|
| Inflation rate | % | 2.5 [52,53] |
| Discount rate | % | 0 |
| Reinvestment rate | % | 9 |
| Project life | year | 25 for PV [54,55] and 20 for wind turbine [55,56] |
| Debt ratio | % | 50 [52] |
| Debt interest rate | % | 0 [52] |
| Debt term | year | 20 [52,57] |
| Electricity export escalation rate | % | 5 [54,57] |

In fact, NPV and the payback period are the main economic viability factors to measure the PV project according to [46]. Therefore, the analysis results indicate that NPV values for all regions are positive (see Figure 8), which indicated that the proposed project was estimated to be financially and economically feasible according to [10,46].

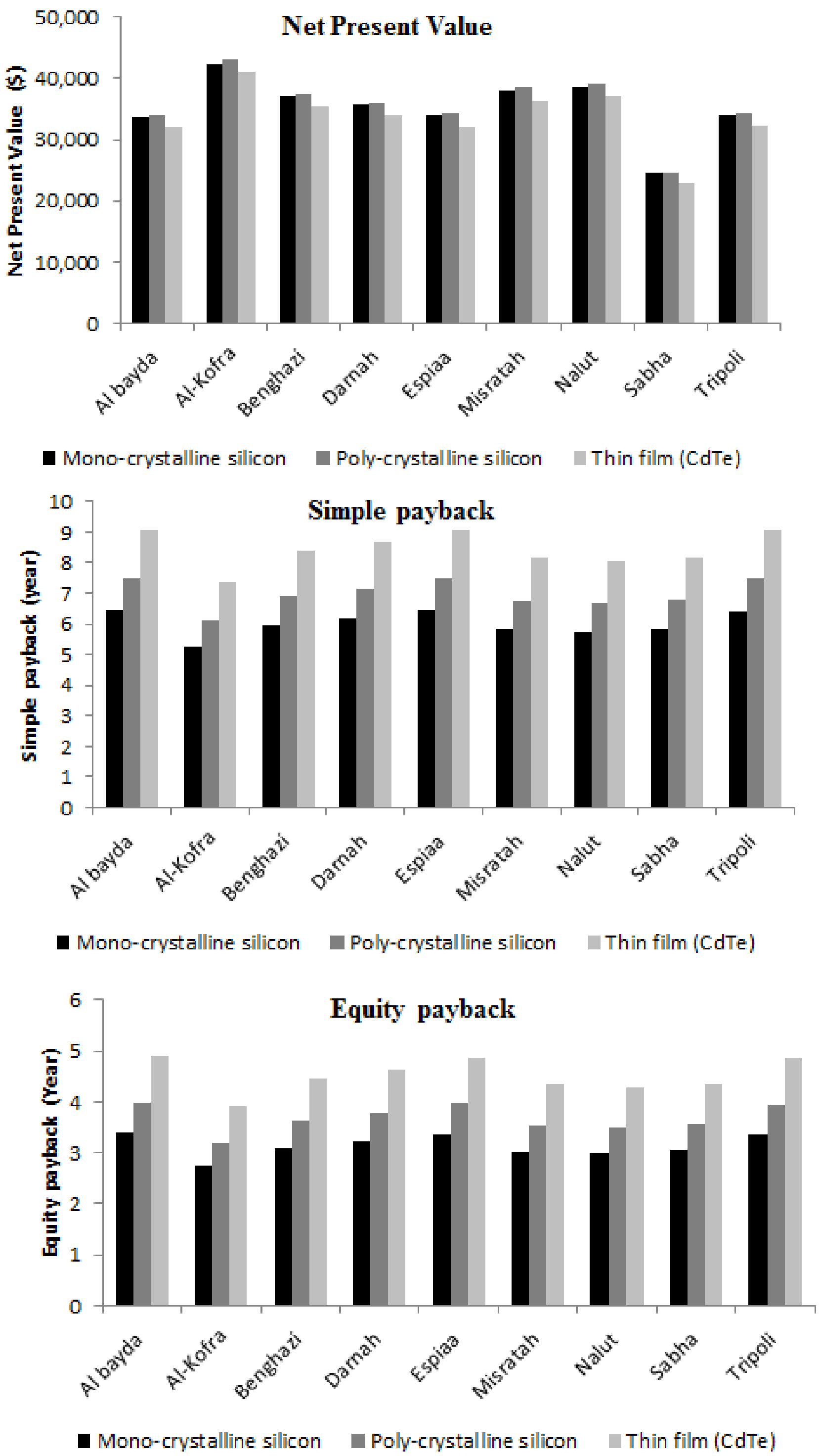


**Figure 8.** *Cont.*

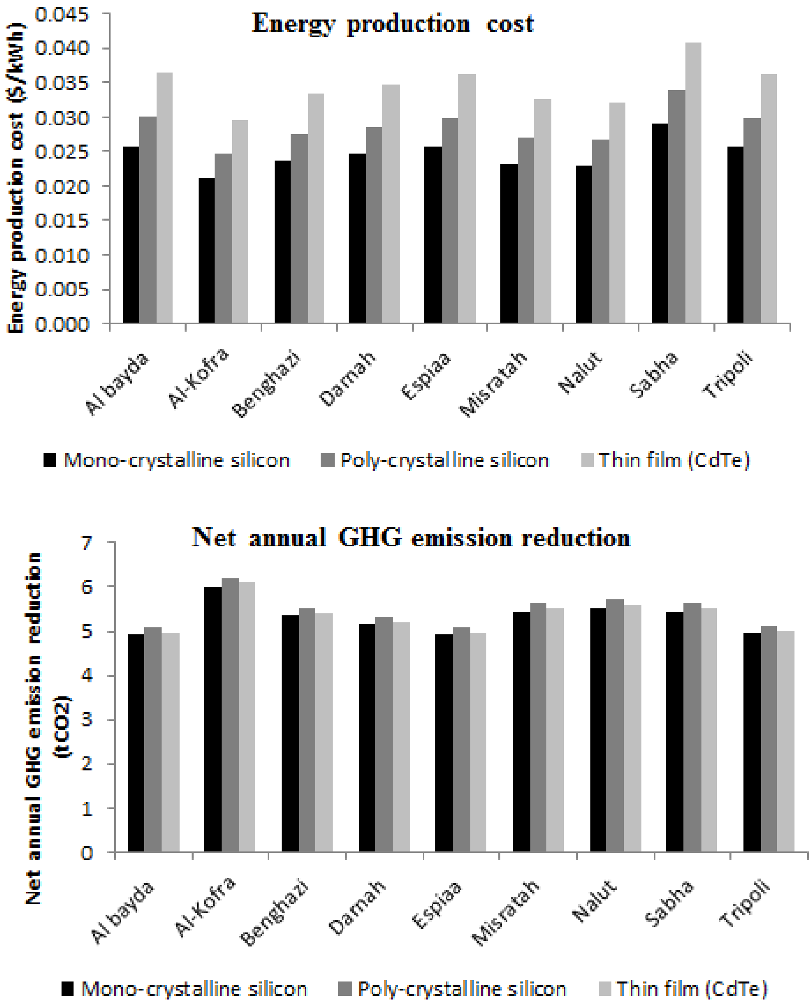


**Figure 8.** Sensitivity analysis for the 5kW grid-connected solar PV system.

Moreover, the proposed PV project in the Al bayda region has the longest payback period, which varied from 6.5 to 9.1 years followed by the one in Espiaa region within a range of 6.4–9.1 years, while the Al Kufrah region has the shortest payback period, which ranged between 5.3 and 7.4 years, as shown in Figure 8. In addition, Al bayda and Espiaa have the highest equity payback, while the one in Al Kufrah has the least, which varied from 2.7 to 3.9 years, as shown in Figure 8.

Furthermore, it was found that the Al Kufrah region has the lowest cost of electricity of 0.0251$/kWh followed by the Nalut region with an average value of 0.0270 $/kWh, while the Al bayda and Espiaa regions have the highest mean electricity cost of 0.0307 $/kWh as shown in Figure 8.

In this study, RETScreen software was used to estimate the gross annual GHG emission reduction for each of the nine regions and illustrated as shown in Figure 8. The project in Al Kufrah region has a maximum GHG emission reduction of 6.11 $tCO_2$. This is then followed by the project in the Nalut region, with the smallest emission reduction coming from the project in the Al bayda region.

### *3.5. Economic Analysis and Feasibility Study of 50 MW Grd-Connected PV System*

As aforementioned, for the future installation of a wind farm, Darnah and Benghazi are the best regions due to the high value of the wind speed, while Al-kufrah is a suitable place for the installation of solar projects in the future due to the highest value of solar radiation. The monthly value of electricity generation from the wind/PV project is shown in Figure 9. It was found that the maximum annual electricity generation of 134.309 GWh was produced by wind projects compared to the solar project (i.e., 64.5 GWh). It can be seen that the electricity production rate from the PV project is nearly almost the same over the 8 months, with an average of 8310.07 MWh. Additionally, it was observed that the maximum value of electricity production was recorded in March and January with a value of 15,812 and 18,570 MWh for Benghazi and Darnah, respectively. For PV solar plants, it was found that the maximum value of electricity production was recorded in March as shown in Figure 9. Moreover, the average capacity factor of each project was estimated to be 21.57% for the solar project and 29.45% for the wind project. Based on the analysis results the of wind project, it was found that the values the of capacity factor of the developed wind farm project were 28.8% and 30.1% for Benghazi and Darnah, respectively (Table 12). Additionally, it was found that the annual energy exported to the grid values was 128,780 and 134,309 MWh for Benghazi and Darnah, respectively (Table 12). Based on the finding of [34], the development of wind farms in Benghazi and Darnah is technically sustainable based on the acceptable value of the capacity factor and annual energy exported to the grid. In the solar energy potential assessment, it was found that the average annual energy exported to the grid and capacity factors of the proposed PV systems were in the range of 94.5 GWh and 21.57%, respectively (Table 12).

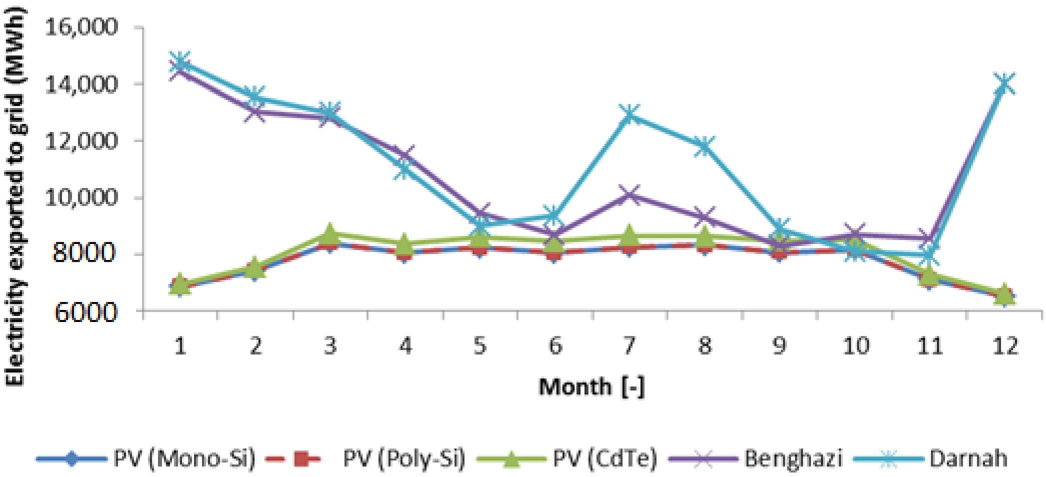


**Figure 9.** Monthly power exported to the grid for wind and solar projects in the selected regions.

**Table 12.** Financial parameters performance of 50Mri grid-connected wind and solar projects.

| Parameters | Al-kufrah | | | Benghazi | Darnah |
|---|---|---|---|---|---|
| | PV (Mono-Si) | PV (Poly-Si) | PV (CdTe) | | |
| Annual electricity exported to grid (MWh) | 93,385 | 93,386 | 96,802 | 128,780 | 134,309 |
| CF (%) | 21.3 | 21.3 | 22.1 | 28.8 | 30.1 |
| Gross annual GHG emission reduction ($tCO_2$) | 59,353 | 59,353 | 61,525 | 81,848 | 853,624 |
| Pre-tax Internal Rate of Return - assets (%) | 15 | 14 | 12 | 11 | 11 |
| Simple payback (Year) | 8.0 | 8.8 | 10.2 | 10.5 | 10.1 |
| Equity payback (Year) | 4.3 | 4.7 | 5.5 | 5.7 | 5.4 |
| Net Present Value ($) | 392,816,390 | 386,096,870 | 386,107,375 | 312,109,220 | 331,305,932 |
| Annual life cycle savings ($/year) | 15,712,656 | 15,712,656 | 15,712,656 | 15,605,461 | 16,565,297 |
| GHG reduction cost ($/tCO_2$) | −265 | −260 | −251 | −191 | −194 |
| Energy production cost ($/kWh) | 0.032 | 0.035 | 0.041 | 0.052 | 0.050 |
| Performance ratio (%) | 82.0 | 82.0 | 85.0 | - | - |

The initial investment cost of the three systems was estimated to be $75 million for mono-Si, $81 million for poly,-Si, and $96 million for CdTe PV systems. It should be noted that hte CdTe PV system has the highest cost compared to the other systems due to the high cost of the CdTe PV module. Additionally, the initial costs of the wind farm were estimated to be $135 million.

Furthermore, a feasibility analysis was used to determine the viability of the project to ensure the project is legally and technically feasible as well as economically justifiable. The financial parameters for the proposed systems that seem to be economically feasible are listed in Table 11. The results of this analysis are summarized in Table 12 for all projects. The electricity cost generated from the mono-Si, poly-Si, and CdTe systems was found to be 0.032, 0.035, and 0.041 $/kWh, respectively. Additionally, the energy production costs by wind farms in Benghazi and Darnah were found to be 0.052 and 0.05 $/kWh, respectively. The estimated electricity costs for all systems are expensive compared to the set feed-tariff of 0.014 $/kWh in Libya. Moreover, the estimated equity payback periods for the mono-Si, poly-Si, and CdTe systems are 4.3, 4.7, and 5.5 years, respectively. Overall, the mono-Si technology system presents a higher net present value (NPV) compared to the poly-Si and CdTe systems. The lower overall economic performance realized by CdTe technology is attributed to the high overall system costs. Additionally, the average estimated equity payback period for wind farms was found to be 5.6 years.

It is concluded that the proposed wind/PV projects are very promising in the selected regions due to the obtained results of economic performance. Furthermore, the analysis results demonstrated that the PV project is a more economical option than the wind project because of the higher values of NPV and ALCS, as well as lower values of EP and LCOE. Furthermore, as can be observed from Table 12, utilization of wind and solar energy helps to reduce greenhouse gas (GHG) emissions.

## 4. Conclusions

The electricity demand has increased rapidly due to the growth of the population and industrial sector in the country. Thus, the utilization of renewable energy, including wind and solar energy, can help to reduce GHG emissions and can be a best solution for solving the energy crises in the country. Consequently, this study aimed to investigate the wind and solar potential in nine selected regions in Libya.

For assessment of the wind energy potential, the Weibull distribution function was utilized for analyzing the characteristics of wind speed. Additionally, Weibull parameters, and then WPD were determined at a 10-m height. The analysis indicated that small-scale wind turbines could be suitable for generating electricity in the regions.

Moreover, for the future installation of the PV system in Libya, the solar energy potentials of nine chosen locations were assessed using monthly solar radiation. The results indicated all selected areas have high solar resources and were categorized as excellent, outstanding, or superb potential classes. Additionally, it was observed that the solar resource of the Al-kufrah location was classified as superb (class 7). Consequently, it is concluded that Al-kufrah is the most appropriate location for installing large-scale photovoltaic systems.

Furthermore, the economic feasibility of the proposed small-scale and large-scale renewable projects was studied by using RETScreen Expert software. For the PV system, three different PV technologies were used. Additionally, the E-82 E4 wind turbine manufactured by Enercon Company was chosen for the wind farm project. The results demonstrated that rooftop PV investors would be a solution to solve the energy crises in the country due to the high potential of solar and low prices for the PV system, which make the payback period of the systems decrease. Additionally, the results demonstrated that the most economical project was the solar PV plant due to the highest value of NPV and ALCS and lowest value of EP and LCOE compared to the wind farm project.

The main limitation of this study that influenced the interpretation of the findings from this research was the financial parameters. The assumptions of financial parameters used in the financial analyses were based on the historical values of African countries, particularly North African countries. In addition, the effect of climate parameters, mainly air temperature and relative humidity, which can be important parameters in PV performance analysis, were neglected. This was due to the main limitation of RETScreen software. In general, Libya has no solar PV industry, but the current low price of PV modules is encouraging for use of the PV system in the country. Future research directions that may improve the economic performance and the influence of economic parameters should be further investigated in detail.

Overall, developing a grid-connected solar PV system in the country will help to save energy, and reduce consumption and emissions in the country because of the high solar potential in the country, allowing significant cost reductions, and technological advances in the PV sector.

**Author Contributions:** R.A.F.A. collected the data. Y.K. and H.Ç. analyzed the data and wrote the paper. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** The authors would like to thank the Faculty of Engineering especially the Mechanical Engineering Department at Near East University for their support and encouragement.

**Conflicts of Interest:** The authors declare no conflict of interest.

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