IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

Volume 1 | Number 3 | July-September 2023 | Pages 27-43

Research Article

Solar and Wind Atlas for Libya

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Received: May 01, 2023 Accepted: July 03, 2023 Published: July 11, 2023

Abstract: The development and utilization of renewable energy sources have become crucial for countries worldwide, aiming to reduce reliance on fossil fuels and mitigate environmental concerns. In this context, the creation of solar and wind atlases plays a pivotal role in guiding the transition towards sustainable energy systems. The solar and wind atlas for Libya serves as a roadmap for the country's transition towards environmentally friendly and sustainable renewable energy. Drawing upon fifteen years (2004-2019) of meticulously validated historical weather data from twenty-two carefully selected cities across Libya, this atlas provides comprehensive information on solar irradiance, ambient temperature, wind speed and direction, rainfall, relative humidity, and pressure. These valuable datasets are obtained from the SolarGis-database platform. The findings reveal that Libya possesses abundant resources, positioning the country as a pioneer in the region's renewable energy industry. The atlas highlights the suitability and viability of solar and wind power generation in Libya, offering insights into optimal locations for renewable energy projects. The impact of the solar and wind atlas is multi-faceted. Firstly, it provides policymakers, energy planners, and investors with valuable information to make informed decisions regarding the development of renewable energy infrastructure in Libya. Secondly, the atlas facilitates the integration of solar and wind energy into the existing power grid, fostering energy security and reducing dependence on conventional energy sources. Moreover, the solar and wind atlas promotes knowledge dissemination and capacity building within Libya's energy sector. This, in turn, encourages the development of local expertise, innovation, and job opportunities in the renewable energy field. In conclusion, the solar and wind atlas for Libya plays a pivotal role in driving the transition towards sustainable and environmentally friendly renewable energy sources. By leveraging the potential of solar and wind energy, Libya can emerge as a regional leader in the renewable energy industry, contributing to a greener and more sustainable future.

Keywords: Renewable Energy; Solar; Wind; Atlas; Libya

1. Introduction

The energy crises have gained significant attention due to the escalating demand, particularly in developing nations, in recent years [1,2]. Fossil fuel-based electricity generation stands as a prominent anthropogenic source of increased CO2 emissions and heightened environmental concerns. Long-term projections indicate a rise in electricity demand, which implies a corresponding increase in fossil fuel consumption for power generation [3,4]. Consequently, the exploration of alternative energy sources, such as wind and solar, emerges as a viable solution to reduce reliance on fossil fuels and mitigate carbon dioxide emissions. Libya stands as a country abundant in renewable energy resources, specifically wind and solar energy [5-7]. The wind power density across the country ranges from 164 to 426 W/m^2, while the annual average PV power varies from 1753 kWh/kW_p in certain coastal regions to 2045 kWh/kW_p in the southern areas, as depicted in the wind and solar atlas maps. Moreover, the average annual sunshine duration extends from 3100 to 3900 hours. These findings highlight the favorable conditions for harnessing wind and solar energy in Libya, further emphasizing the potential for reducing reliance on traditional energy sources and curbing carbon emissions [9-11].

In this regard, Libya possesses abundant solar and wind energy resources, owing to its strategic location in the heart of North Africa. With a vast territory spanning 1,759,540 km2 and a lengthy coastline of 1900 km along the Mediterranean Sea, a significant portion of approximately 88% of its landmass comprises desert regions. These desert areas exhibit immense potential for harnessing solar and wind energy, making them ideal for electricity generation through various conversion methods such as thermal, photovoltaic, and solar energy technologies. Exploiting these renewable energy sources can contribute significantly to Libya's sustainable development and energy independence [5,11].

Currently, more than 65% of the total electrical and thermal energy generated in the world is produced by burning fossil fuels in conventional power plants. The electricity in Libya is generated almost 100% based on fired fossil fuel putting the energy industry in the first place in terms of greenhouse gas emissions among all other human activities accounting for about 36% of the country's CO2 emissions [11,12]. Figure 1, illustrates the global and Libyan breakdown of energy use in electricity generation in 2021. To decline the Earth's temperature by 1.5°C, efforts and collective action must be combined to reduce emissions of air pollutants. In line with the necessity of the stage, the Libyan government has launched its strategic plan for the year 2050 regarding the generation of electric power and its gradual transition from traditional generation based on fossil fuels to clean and sustainable generation; as the electric power industry sector is the most polluted of all other sectors in the country [13,14]. The Libya strategy aims to achieve a contribution of renewable energies to the electric energy mix of 25% by 2030 and reaches 60% by 2050; this will come mainly from concentrated solar power, photovoltaic solar energy, solar heating systems and wind energy [15]. To begin this transition, authors must identify opportunities and know how to exploit them, identify challenges and know how to overcome them.

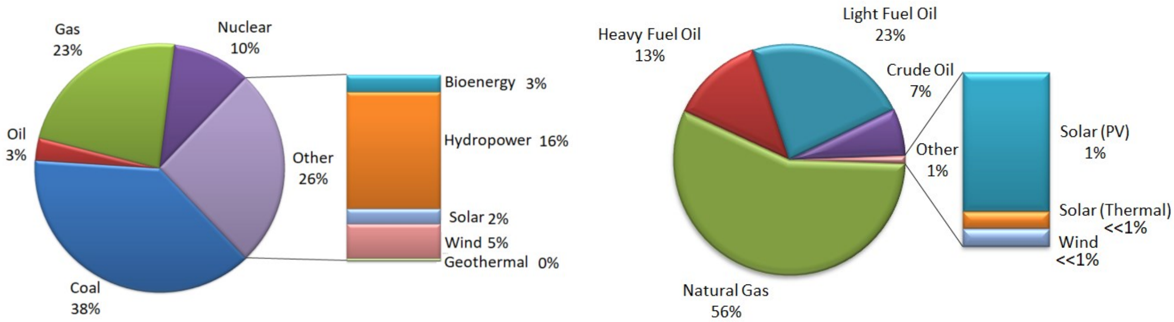


Figure 1. Breakdown of electricity generation, world (right), and Libya (left)

In this context, Libya has many opportunities to make a smooth transition from a traditional generation based on fossil fuels to an environmentally friendly and sustainable generation. The authors investigate these opportunities and challenges while reviewing the relevant literature [13-16]. Figure 2, reveals the increase in the expanded demand for electricity in Libya, while the annual increase in demand for electricity is estimated at between 8-10% and this demand is expected to increase to 14 Gigawatts by 2030. The analysis of electricity and energy consumption patterns in Libya reveals that approximately 31% of the total energy is consumed in the residential sector. Notably, the summer season exhibits the highest energy demand, characterized by two consumption peaks occurring in July and winter. This highlights the significant contribution of space heating and cooling activities to overall energy usage in buildings. Figure 3, provides a visual representation of the monthly distribution of electrical loads and the proportion of each type in the total annual consumption.

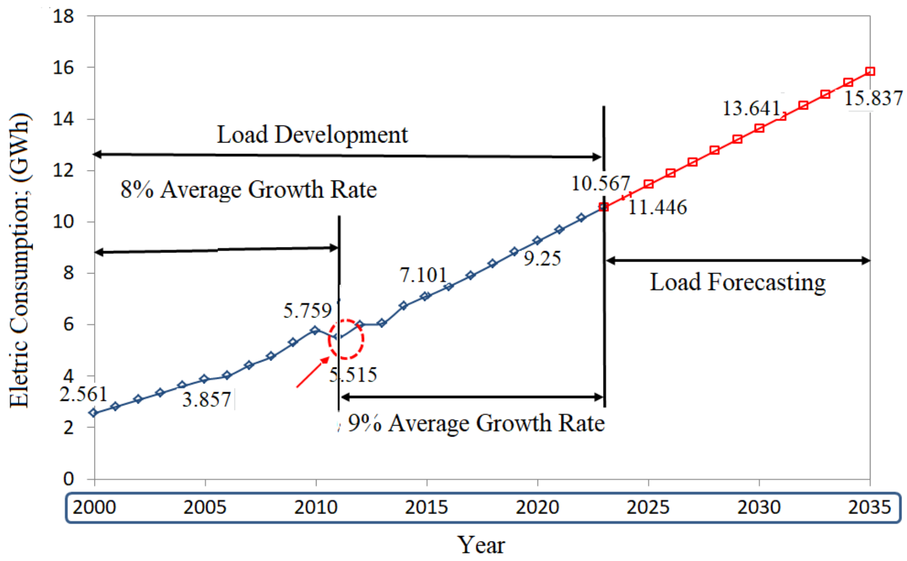


Figure 2. Evolution of the increase in electrical energy demand

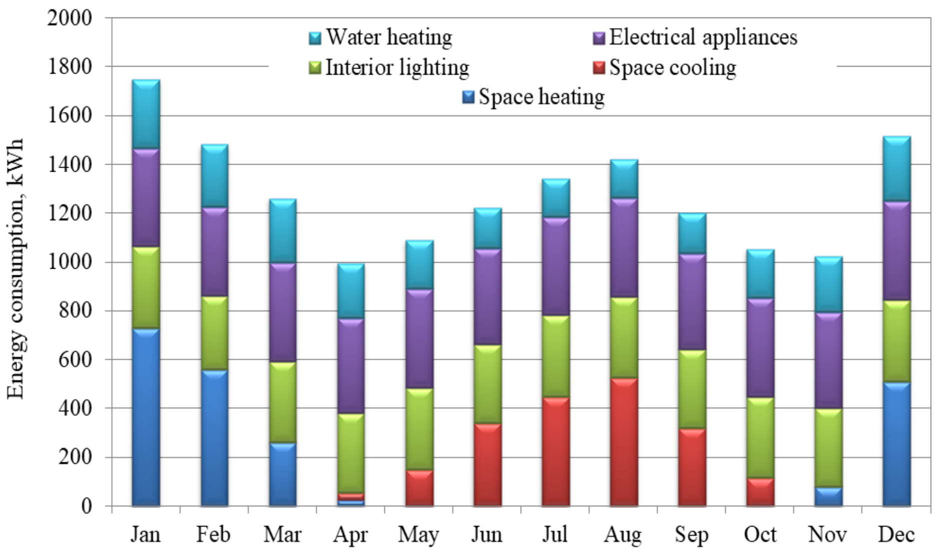


Figure 3. Monthly electrical load distribution and the share of each type in the total annual consumption.

Numerous scholarly investigations have extensively evaluated the substantial capacity of renewable energy sources, encompassing solar and wind energy. Kadem et al. [17] conducted a comprehensive assessment of the techno-economic factors of a 14 MW photovoltaic (PV) plant located in Houn City, Libya. The study findings revealed the economic feasibility and sustainability of the PV power plant. Embirsh and Ikshadah [18] focused on analyzing the monthly mean solar radiation and sunlight duration in Tripoli City, Libya, to examine the radiation characteristics and duration of sun exposure. The researchers concluded that solar energy holds significant potential as a primary source of renewable energy in Libya. Similarly, Khaleel et al. [19] highlighted the role of solar power in addressing the persistent electricity challenges faced by residents. Their study emphasized the importance of solar energy as a solution to mitigate these challenges. Mohamed and Masood [20] presented an overview of the potential utilization of renewable energy resources in Libya, with a specific focus on solar and wind energy. The study demonstrated the vast renewable energy potential in Libya, particularly in solar and wind resources, and explored various applications for these resources. Aldali et al. [21] implemented a 50 MW PV solar plant in Al-Kufra, Libya, and reported an energy output of 114 GWh/year with a payback time of 2.7 years. Additionally, Al-Refai [22] conducted a feasibility study on a 100 MW grid-connected PV plant in Tripoli, Libya, estimating the cost of generated electricity to be approximately 0.0321$/kWh. Furthermore, the Libyan Minister of Electricity expressed intentions to construct a solar power station to fulfill one-fifth of the country's electricity requirements, reducing reliance on fossil fuels [23]. Additionally, a member of the Board of Directors of the General Electricity Company in southern Libya revealed the government's plans to establish a 100 MW PV system to address the electricity challenges in southern Libyan cities [24]. Moreover, the Renewable Energies and Environment (REEO) envisions the desert renewable energy project as a significant endeavor with the potential to supply Europe with energy derived from solar radiation in North Africa, including Libya and the Middle East. This project can generate 250 GW per year and contribute to the reduction of approximately 150,000 tons of carbon dioxide emissions. Based on the research conducted by Alasal et al. [25], the power sector in Libya encountered significant challenges in terms of nominal capacity and available generating capacity. In 2019, the nominal capacity of power plants reached approximately 14,500 MW. However, due to political and security circumstances, the total available generating capacity was limited to only 44% of the nominal capacity, amounting to 6,320 MW. Consequently, there was a substantial deficit of 1,200 MW, as the maximum load in 2019 exceeded the available power generation capacity of 7,500 MW. This resulted in prolonged power outages experienced across various regions in Libya throughout the day.

The development of a comprehensive solar and wind atlas for Libya constitutes a significant contribution to the field of renewable energy research and implementation. This atlas plays a crucial role in assessing, understanding, and harnessing the solar and wind energy potential of Libya, ultimately guiding the country's transition towards a sustainable and low-carbon energy sector. The following aspects highlight the importance and impact of the solar and wind atlas for Libya:

- Resource Assessment: The solar and wind atlas provides a detailed and accurate assessment of the solar irradiance and wind patterns across different regions of Libya. It offers valuable information regarding the spatial and temporal distribution of solar energy and wind resources, enabling policymakers, energy planners, and investors to identify areas with the highest renewable energy potential. This assessment is fundamental in facilitating the efficient and effective utilization of solar and wind resources for electricity generation.
- Energy Planning and Investment: The solar and wind atlas serve as a crucial tool for energy planning and investment decisions in Libya. It provides a comprehensive overview of the solar and wind energy potential, allowing stakeholders to identify suitable locations for the establishment of solar power plants and wind farms. This information enables informed decision-making regarding the allocation of resources, investment strategies, and the development of renewable energy projects. It also attracts local and international investments, leading to the growth of the renewable energy industry in Libya.
- Policy Development and Implementation: The solar and wind atlas offers valuable insights for policymakers in the formulation and implementation of renewable energy policies and regulations. It provides a scientific basis for setting renewable energy targets, defining feed-in tariff schemes, and implementing supportive policies to encourage the adoption of solar and wind technologies. The atlas also aids in the integration of renewable energy into the existing energy infrastructure, contributing to the diversification of the energy mix and reducing dependence on fossil fuels.
- Environmental and Socioeconomic Benefits: The solar and wind atlas plays a pivotal role in promoting environmental sustainability and mitigating climate change impacts. By facilitating the development of solar and wind energy projects, it enables the reduction of greenhouse gas emissions, contributing to global efforts in combating climate change. Moreover, the deployment of renewable energy technologies in Libya creates new job opportunities, stimulates economic growth, and enhances energy security, leading to socioeconomic development and improving the quality of life for local communities.

In conclusion, the development of a solar and wind atlas for Libya represents a significant contribution that empowers decision-makers, investors, and researchers in harnessing the country's abundant renewable energy resources. By providing accurate and comprehensive information on solar irradiance and wind patterns, the atlas fosters sustainable energy planning, facilitates investment in renewable energy projects, supports policy development, and promotes socioeconomic and environmental benefits. Ultimately, the solar and wind atlas paves the way for a greener, more sustainable future for Libya.

This manuscript encompasses four key sections. **Section 2** explores the opportunities that arise from the development of a solar and wind atlas for Libya. **In Section 3**, the methodology employed in creating the atlas is described. **Section 4** presents the results and discussion obtained from the analysis of solar irradiance, wind patterns, and other climate variables. Finally, **Section 5** offers a concise conclusion summarizing the main findings and emphasizing the significance of the solar and wind atlas for Libya's transition towards a sustainable and renewable energy sector.

2. Opportunities of Solar and Wind Atlas for Libya

Libya has a vast area and most of it is uninhabited, and therefore, massive projects can be established without harassing the local population or putting pressure on the local environment. Libya is located in the "solar belt" region; it means the largest amount of solar radiation in the world, which can be exploited in the generation of thermal or electrical energy directly utilizing photovoltaic solar systems (PV) [6-12] or indirectly by concentrating solar power technologies (CSP) [13-16]. Libya also has capabilities in some mountainous areas, such as Derna, Msallata, and other coastal and desert areas, to establish wind energy farms [17-23]. The same applies to biomass energy; although Libya is not an agricultural country, solid waste and sewage can constitute an important source of thermal and electrical energy production, thus becoming a blessing after it was an ordeal for local communities, in this approach, we protect the local environment from the disastrous consequences of burning human waste [24-31]. The Libyan terrain is also characterized by a wide variation, as there are plains, valleys, plateaus, mountain heights, vast deserts and oases. Mountain heights can be exploited as a tool for energy storage as a pumped hydroelectric storage (PHS) [32]. In addition, the integration of more than one energy source into one system with or without storage, or the so-called hybrid energy systems, increases the chances of relying on renewable energy systems. Figure 4, shows a block diagram of possible typical hybrid systems. Extensive research has been conducted on this topic, as evidenced by the multitude of published works [33-43]. For this reason, the European Council approved the regional plan to generate 20 Gigawatts of electricity from solar and wind energy in countries around the Mediterranean. The solar plan is centred on a grid connecting North Africa and Europe that will harness North Africa's vast solar and wind resources to feed clean energy to Africa and Europe [44-50]. Figure 5, demonstrates Europe's Plan to exploit solar and wind energy in the Middle East and North Africa.

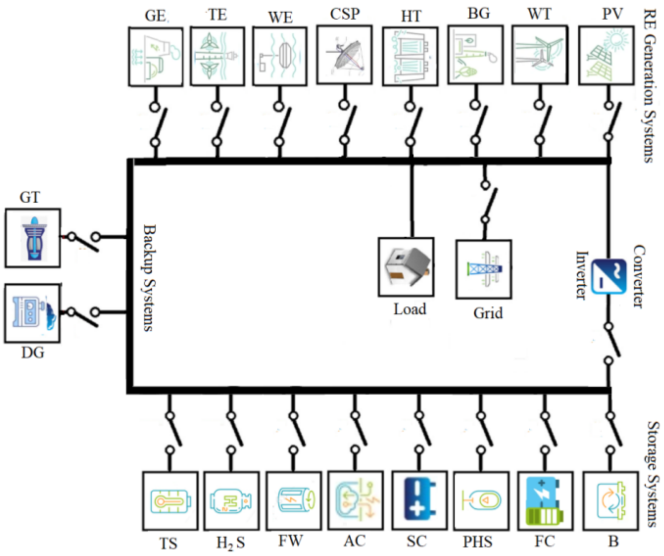


Figure 4. Block diagram of possible typical hybrid systems.

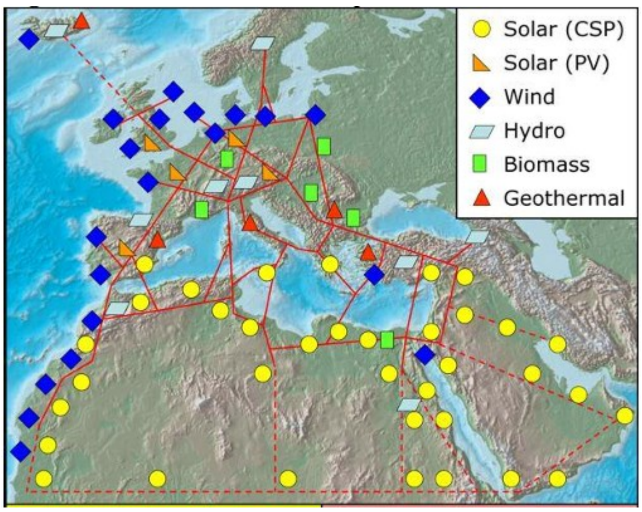


Figure 5. Europe's Plan to exploit solar and wind energy in the Middle East and North Africa

3. Methodology

The methodology for the manuscript is outlined in Figure 6, which presents a flowchart depicting the approach followed in the study. The process initiates with the determination of the geographical location and the acquisition of essential climate information needed to conduct simulations. It emphasizes the significance of preparing the necessary infrastructure to accommodate emerging technologies and facilitate the transition towards sustainable power generation. To ensure the accuracy and reliability of simulation results, it is crucial to minimize uncertainties, primarily originating from climate data. This necessitates the establishment of precise meteorological stations capable of measuring and recording all the required data for the simulation process. Additionally, it is essential to validate the programs utilized for simulation, as well as verify the validity and reliability of other energetic, technical, economic, and environmental information sources. Table 1, provides a compilation of commercial programs specializing in the simulation and design of solar energy systems, along with the corresponding transposition model [51-55]. These resources offer valuable tools for the accurate and effective analysis of solar energy systems within the context of the manuscript.

4. Results and Discussions

To overcome the challenge of limited climate data availability, the Research Center for Renewable Energy and Sustainable Development (RCRESD) at Wadi Alshatti University agreed with Solargis database company No. ICO: 45354766. This collaboration granted Solargis complete access to climate data for 22 cities in Libya. The selected cities represent a comprehensive coverage of the entire Libyan territory. Historical weather data from a period of fifteen years (2004-2019) with a time resolution of 15 minutes was obtained and validated for all the specified sites. This dataset included crucial information such as solar irradiance (global horizontal, beam direct, sky-diffuse, direct normal, global inclined, albedo, and extraretinal), ambient temperature, wind speed and direction, rainfall, relative humidity, and pressure. With this data, contour charts depicting the main weather parameters across all regions of Libya were created, enabling a comprehensive assessment of solar and wind energy potential. Figure 7, showcases the average daily global horizontal solar irradiation in Wh/m^2. Upon examining the contour maps, a notable disparity in the spatial distribution of global horizontal solar radiation across Libyan territory is observed.

This discrepancy can be attributed to the significant variations in topography, which significantly influence the allocation of natural and human resources throughout the country. In January, the intensity of horizontal solar radiation exhibits a relatively uniform distribution across the nation, with its highest values recorded in the southern region at approximately 4600 W/m². As we progress northwards towards the coastal areas, the intensity gradually decreases to approximately 3200 W/m², while the eastern highlands experience the lowest levels of solar radiation at approximately 2800 W/m².

In May, the scenario alters slightly, as the intensity of solar radiation forms concentric circles with their center situated in the western region of the country. The lowest values of solar radiation are found in the mountainous regions of the west, reaching around 5800 W/m², and subsequently increase radially towards the north, south, and west, culminating at the highest levels of approximately 7200 W/m² at the northern, southern, and eastern peripheries of Libya. Figure 8, depicts the average daily Direct Normal Irradiation (DNI) in Wh/m². The measurement of DNI holds significant importance as it serves as an indicator of the feasibility of harnessing concentrated solar energy. Additionally, DNI enables the estimation of direct beam solar radiation, a crucial component of global horizontal solar radiation. The measurement of DNI is carried out using a Pyrheliometer instrument. The general trend of the DNI distribution among the Libyan territory is the same as the distribution of global horizontal solar radiation. In short, the southeastern region can be promising for the exploitation of solar energy in electricity generation employing solar concentrating power technologies. At a time when thermal conversion systems for concentrated solar energy require DNI levels of not less than (2500 W/m2) [56,57]. Figure 9, illustrates the average daily ambient temperature °C. There is no doubt that knowing the temperature is very important and is used in all applications, especially in conducting energy audits of buildings. And also calculating the efficiency of all solar energy systems, whether thermal or photovoltaic modules. During the transition from autumn to winter (specifically in November and

December), the southern region of Libya experiences the lowest temperatures ranging between 11-15°C, which gradually increase as one moves towards the northern areas. This temperature variation can be attributed to the moderating effect of the sea, which mitigates rapid temperature fluctuations compared to the desert regions. In the western highlands of the country, the air temperature reaches its lowest point of approximately 6°C during the winter season, mainly influenced by the seasonal westerly winds. Conversely, in the summer months, the southern desert regions, located farther away from the sea, become the hottest areas in Libya, with temperatures reaching around 34°C, while the northern regions do not exceed 29°C. Figure 10, displays the average daily wind speed in meters per second (m/s). The wind speed data represented on the map corresponds to measurements taken at a height of 10 meters above the ground. Understanding wind speed and direction is crucial not only for evaluating the efficiency of wind energy utilization but also for various applications such as air navigation, building design, and other environmental assessments. Wind speeds at elevated heights can be estimated using the exponent law, as described by Eq. (1).

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\propto} \tag{1}$$

where, V_1 and V_2 are wind speeds at elevations Z_1 and Z_2 respectively, and $\propto$ is the wind shear coefficient. Several studies recommended several values for $\propto$ [18], however, the most commonly used value is 1/7. As shown in Figure 10, the wind speed changes according to the geographical location and time, representing five categories of wind, power classes 2 through 6, which are defined in Table 2. Most of the current wind farms are located at sites with wind class 5 and higher. Based on the classification and evaluation conducted, it has been identified that the Green Mountain and Western Mountains regions in Libya possess significant potential for the establishment of wind energy farms. These areas exhibit favorable characteristics such as suitable wind patterns, topographical features, and wind resource availability. The Green Mountain, also known as Jebel Akhdar, is a range of mountains located in northeastern Libya. It is characterized by elevated terrain and favorable wind conditions, which make it conducive for harnessing wind energy. The region benefits from the influence of the Mediterranean Sea, which can create consistent and relatively strong winds that are ideal for wind power generation. Similarly, the Western Mountains region, situated in the western part of Libya, offers promising conditions for wind energy development. This mountainous area experiences suitable wind speeds and patterns due to its geographical location and proximity to the coast [58-60].

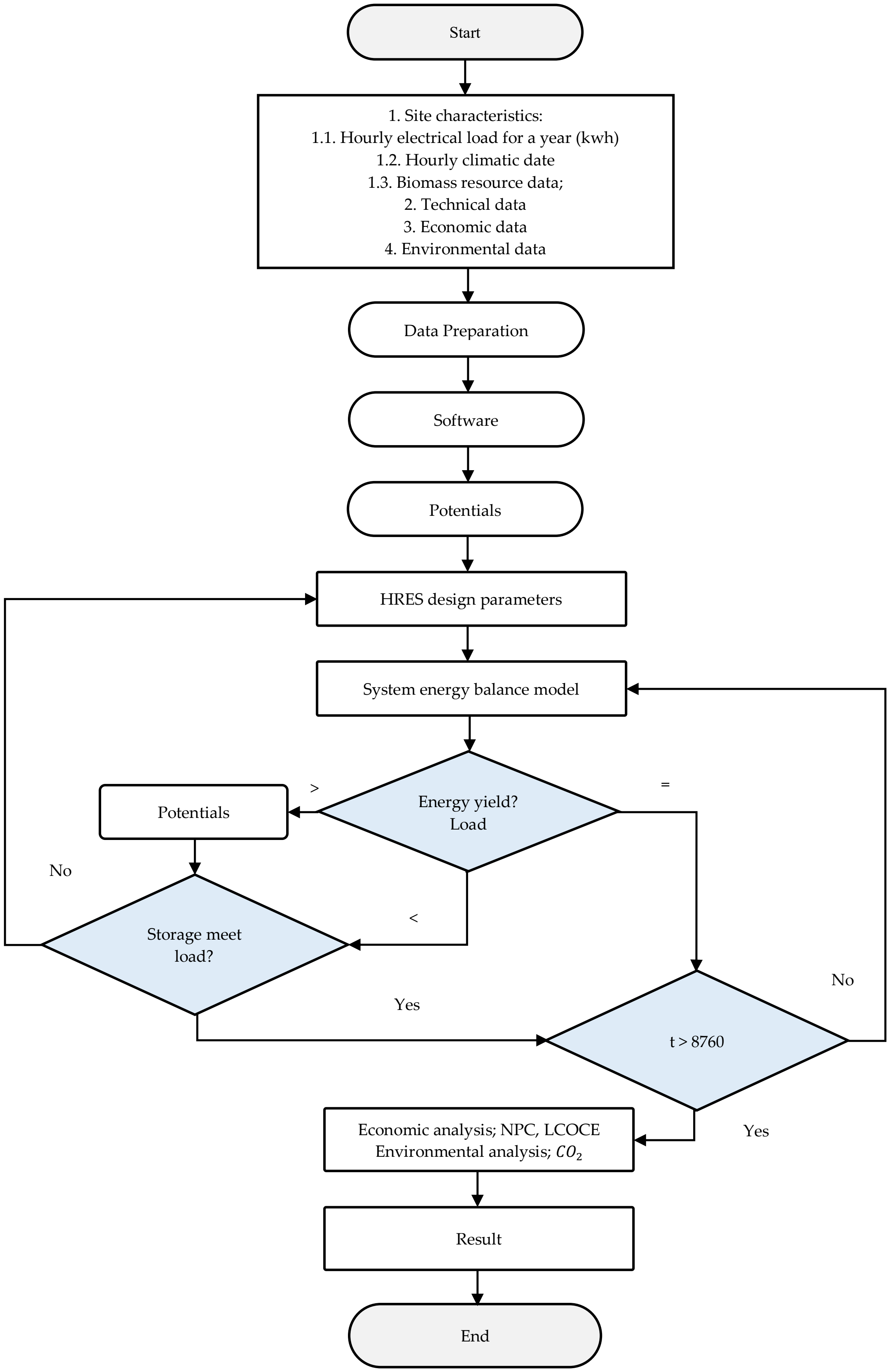
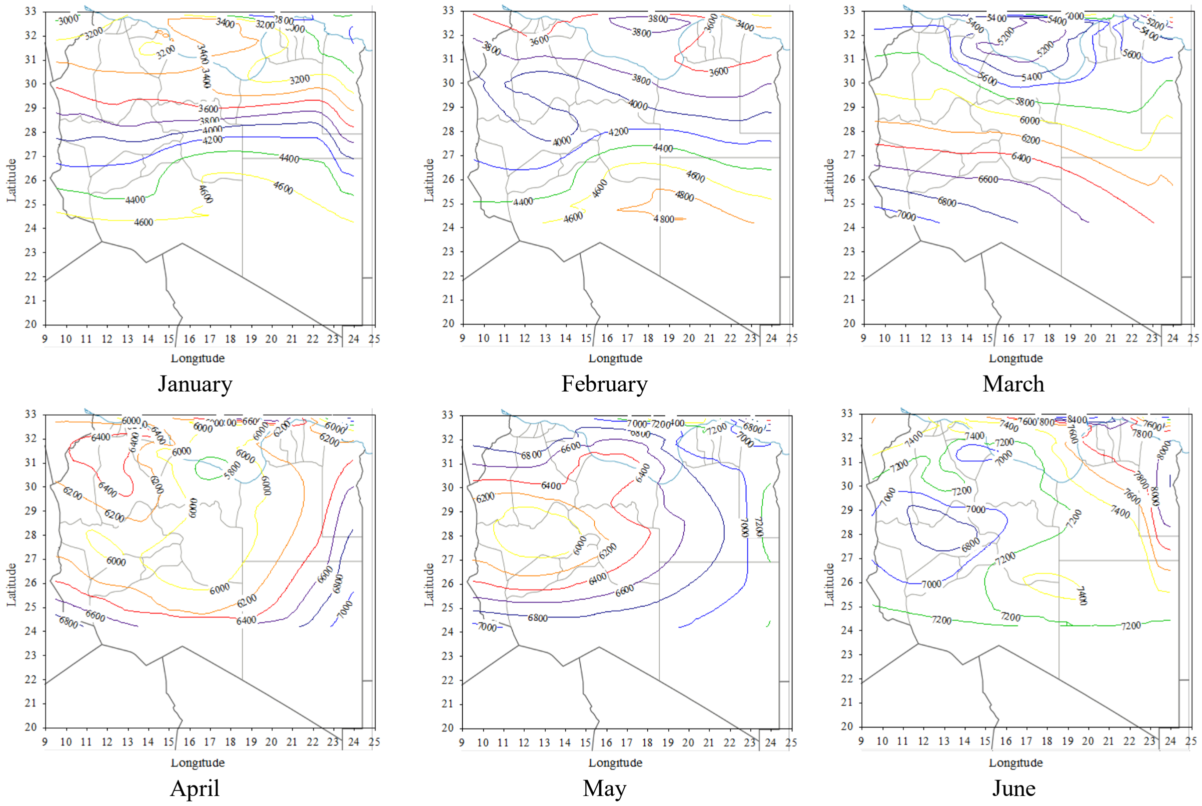


Figure 6. The approach for determining the size of the HRES system.

Table 1: A list of some programs specialized in simulating and designing solar energy systems.

Num.	Software	Country	Adopted transposition model
1	EnergyPro	Denmark	HDKR
2	HOMER	USA	HDKR
3	INSEL	Germany	Liu & Jordan, Temps & Coulson, Bugler, Klucher, Hay, Willmott, Skartveit & Olseth, Perez and HDKR
4	Matlab (Simulink)	USA	Perez
5	Meteonorm	Germany	Hay, Skartveit & Olseth and Gueymard
6	Polysun	Switzerland	HDKR
7	PV F-chart	USA	Liu & Jordan
8	PV*Sol	Germany	Skartveit & Olseth, HDKR and Perez
9	PVDesign Pro	England	HDKR and Perez
10	PVForm	USA	Perez
11	PVGIS	Slovakia	Muneer
12	PVplanner	Slovakia	Perez
13	PVSyst	Switzerland	Hay and Perez
14	PVToolbox	Canada	Liu & Jordan
15	PVWatts	USA	Perez
16	RAPSIM	Australia	Unknown
17	RETscreen	Canada	Liu & Jordan
18	SAM	USA	Liu & Jordan, Perez, and HDKR
19	SimulationX	Germany	Liu & Jordan
20	Solar Pro	Japan	Unknown
21	SolarSizer	France	Unknown
24	TRNSYS	USA	HDKR



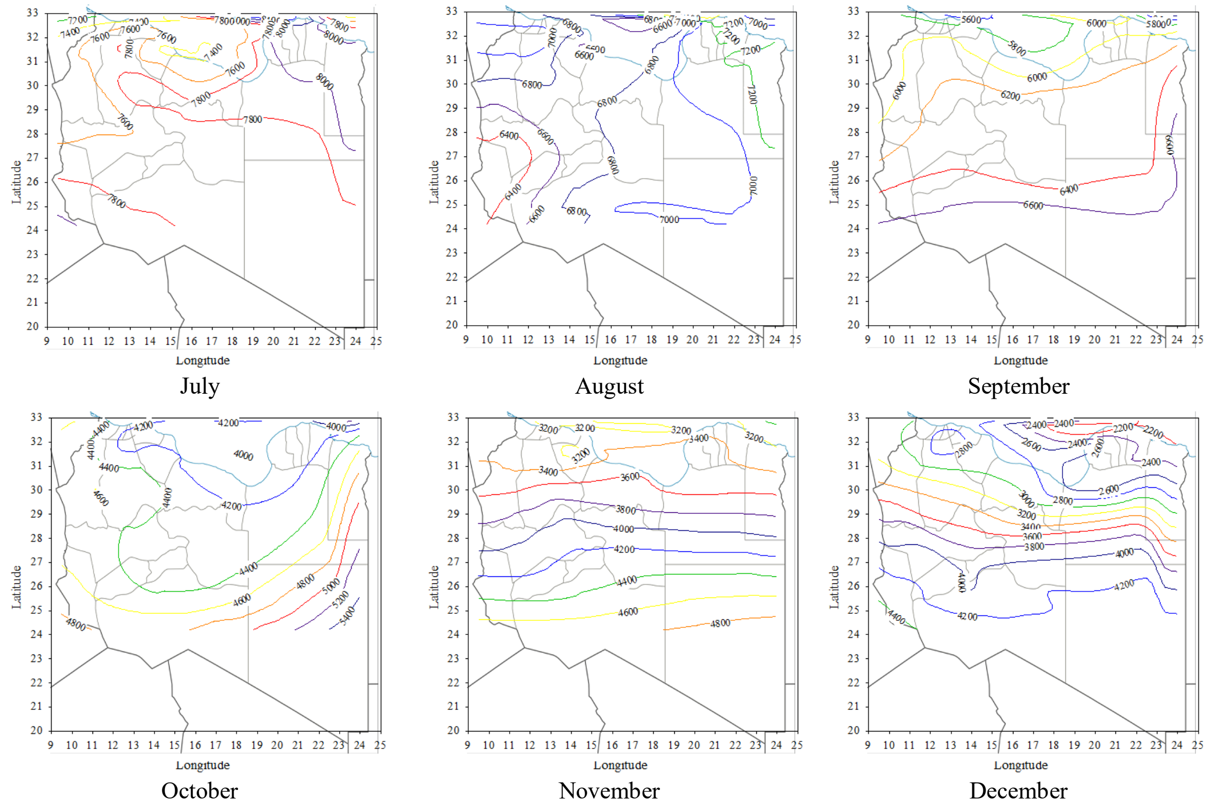
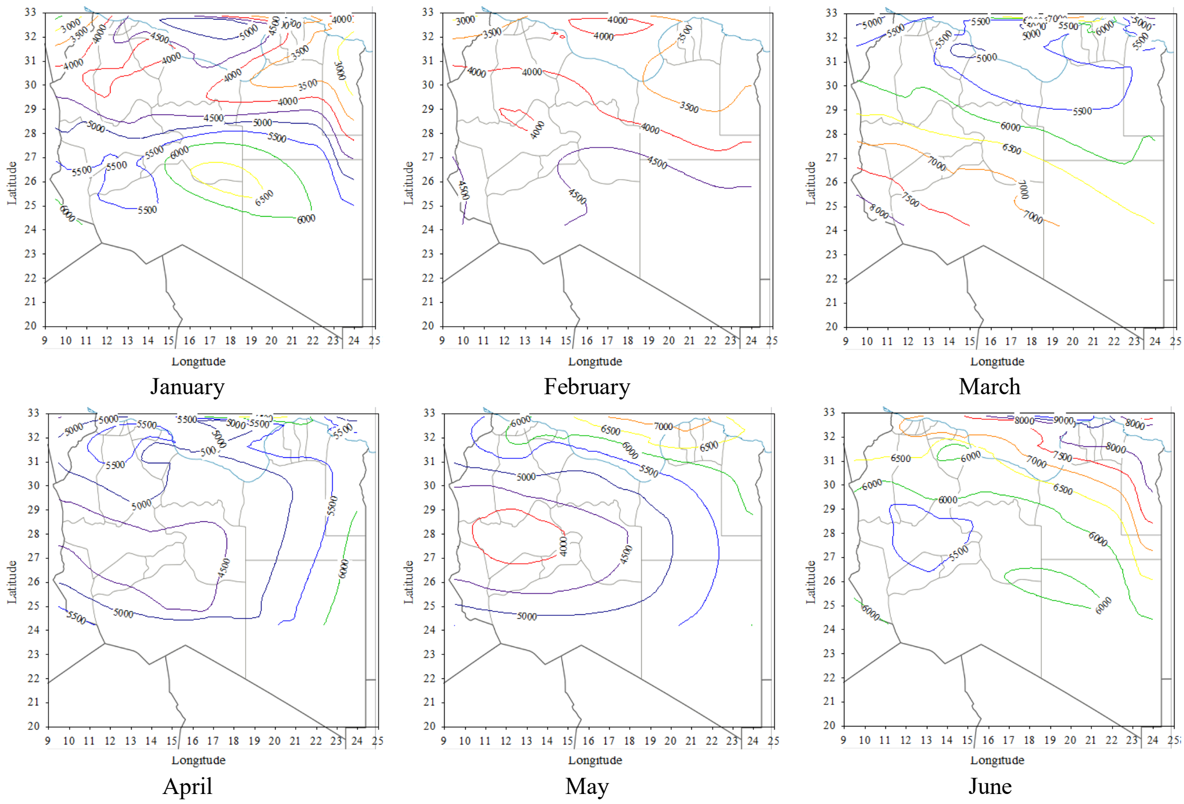


Figure 7. Average daily global horizontal solar irradiation Wh/m²



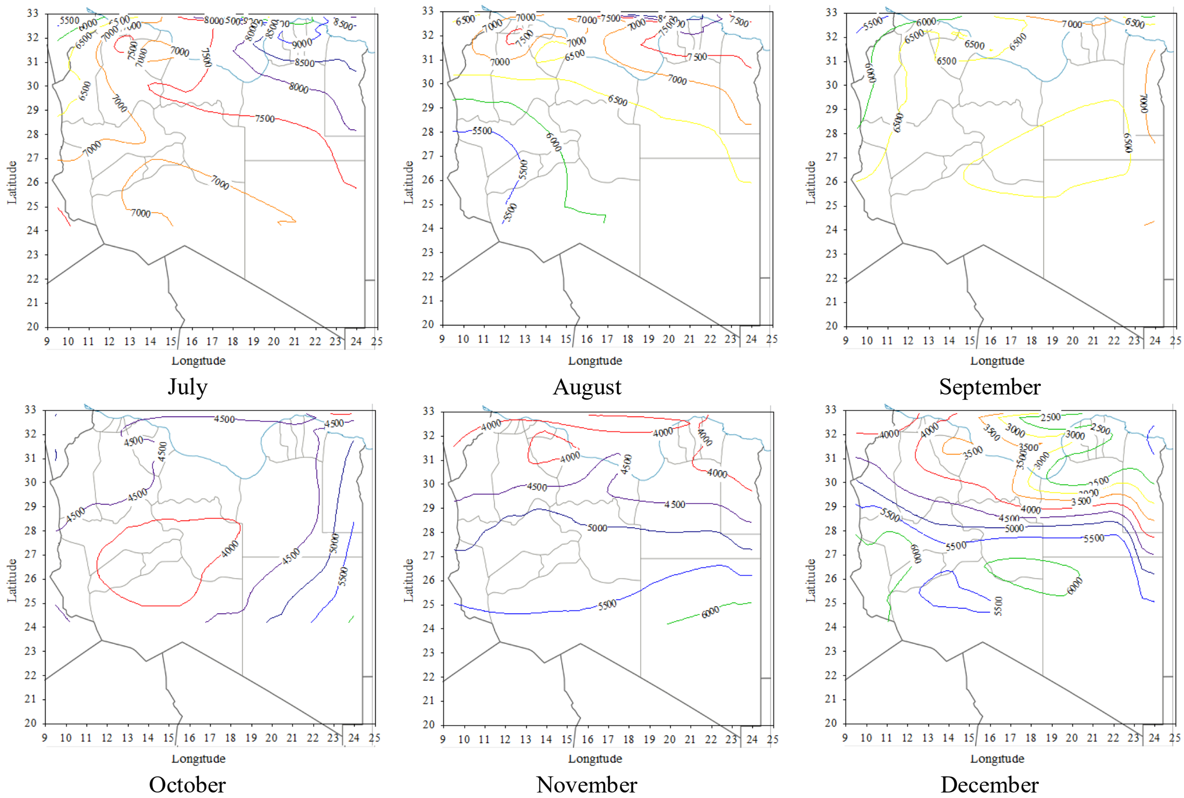
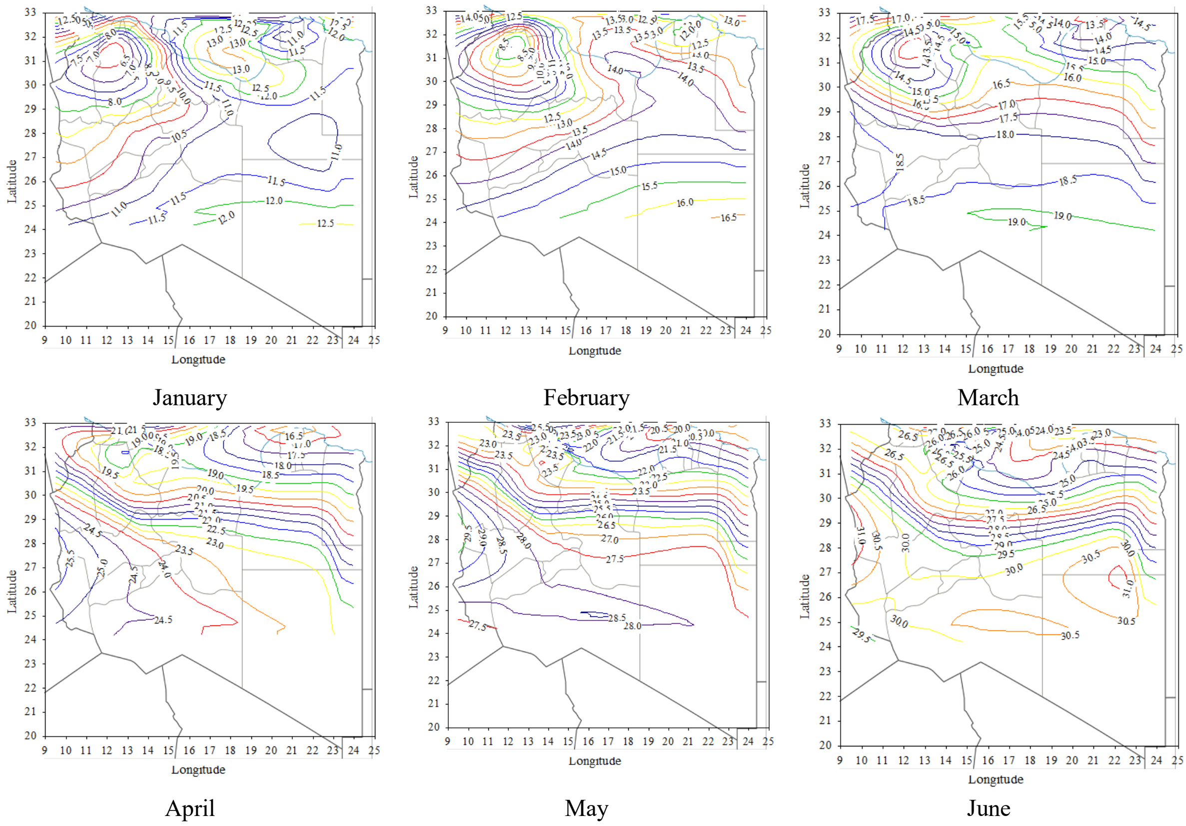


Figure 8. Average daily direct normal solar irradiation DNI Wh/m^2



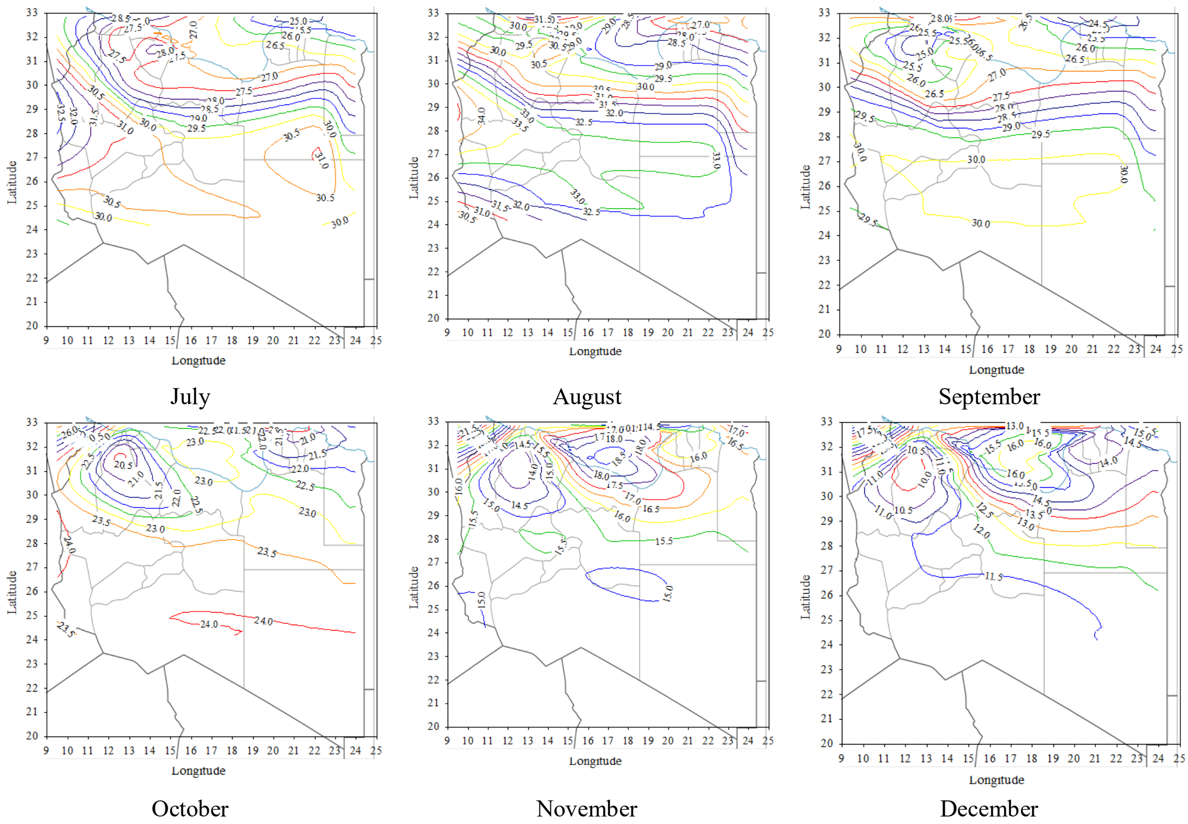
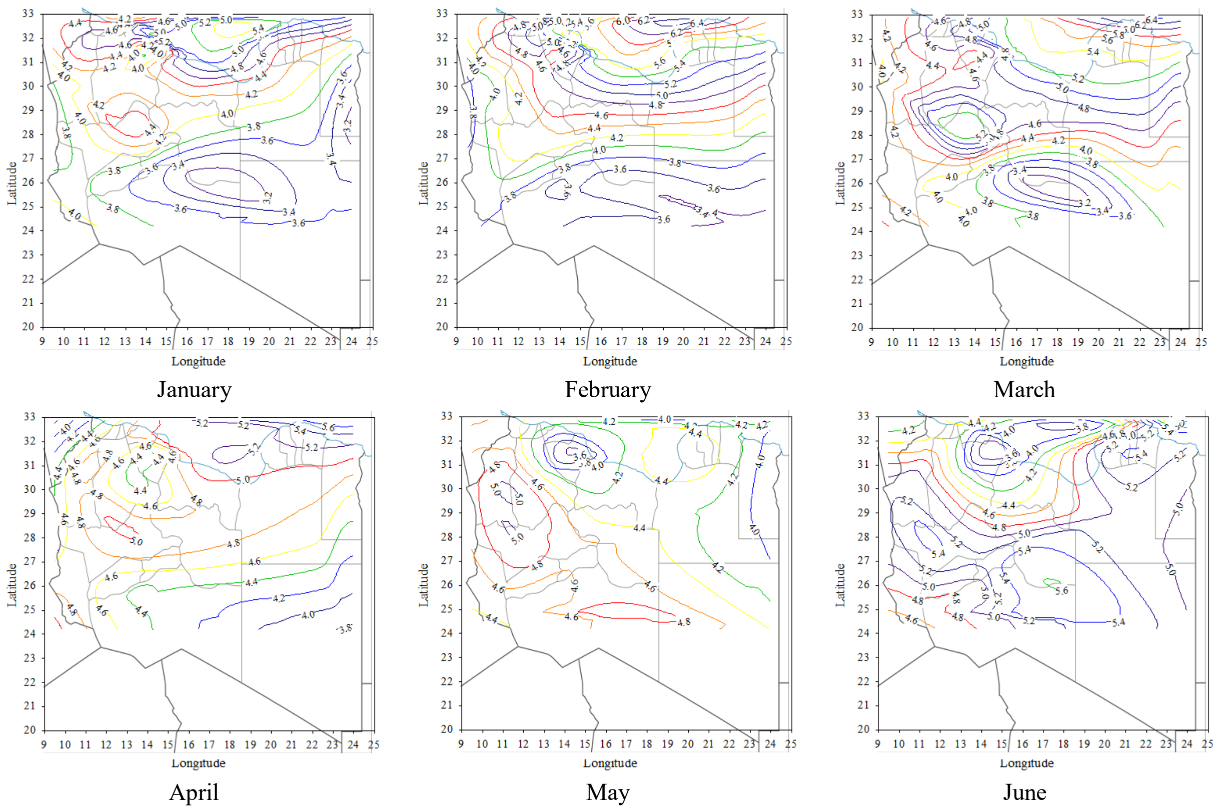


Figure 9. Average daily temperature, °C.



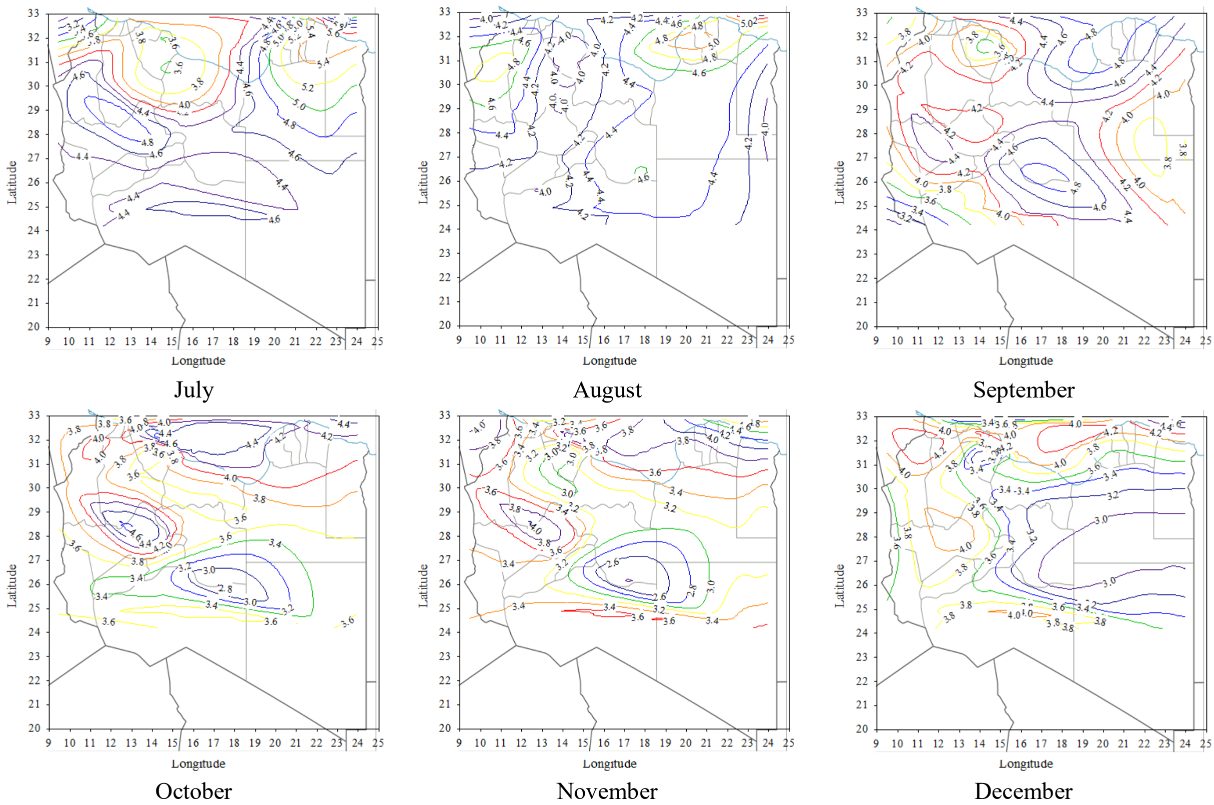


Figure 10. Average daily wind speed at 10 m above ground surface, m/s

Table 2. Classes of wind power density at 10m and 50m.

Wind speed classification	Elevations 10m / 50m	
	Wind power density; W/m²	Wind speed; m/s
Class 1	0/0	0/0
Class 2	100/200	4.4/5.6
Class 3	150/300	5.1/6.4
Class 4	200/400	5.6/7.0
Class 5	250/500	6.0/7.5
Class 6	300/600	6.4/8.0
Class 7	400/800	7.0/8.8
Class 8	1000/2000	9.4/11.9

The presence of ridges, valleys, and other topographical features within the Western Mountains further enhance the wind resources available for potential wind farms. The identification of these areas as promising locations for wind energy farms highlights the potential for renewable energy development in Libya. By harnessing the power of wind in these regions, Libya can diversify its energy mix, reduce dependence on fossil fuels, and contribute to the global transition towards sustainable and clean energy sources. It is important to note that further detailed assessments, including site-specific studies, feasibility analyses, and environmental considerations, are necessary to determine the viability and suitability of establishing wind energy farms in these regions. These assessments would involve factors such as wind resource assessment, infrastructure availability, grid connectivity, environmental impact assessments, and stakeholder consultations.

5. Conclusions

In this manuscript, an atlas of solar energy and wind energy was drawn up, which is considered a roadmap for the transition towards environmentally friendly and sustainable renewable energies. The study relied on fifteen years (2004-2019) -15 minutes' time series validated historical weather data of twenty-two cities that were carefully selected to cover all Libyan territory provided by the SolarGis-database platform. These valuable data included: solar irradiance (global horizontal, beam direct, sky-diffuse, direct normal, global inclined, albedo, and extraretinal), ambient temperature, wind speed and direction, rainfall, relative humidity and pressure. The results showed that Libya possesses huge potential for solar energy and wind energy that qualifies it to be a pioneer in the region in the renewable and environmentally friendly energies industry. This manuscript presents an extensive atlas of solar energy and wind energy, serving as a comprehensive guide towards the adoption of environmentally friendly and sustainable renewable energy sources. The manuscript utilized a robust dataset consisting of fifteen years (2004-2019) of validated historical weather data, captured at 15-minute intervals, from twenty-two strategically selected cities encompassing the entire territory of Libya. These datasets, obtained from the SolarGis-database platform, encompassed a wide range of valuable information, including solar irradiance parameters such as global horizontal, beam direct, sky-diffuse, direct normal, global inclined, albedo, and extraretinal measurements, as well as ambient temperature, wind speed and direction, rainfall, relative humidity, and atmospheric pressure. The findings of this manuscript unequivocally indicate that Libya possesses immense potential for solar energy and wind energy generation, positioning the country as a frontrunner in the renewable energy sector within the region. The comprehensive assessment of solar irradiance, wind speed, and related climatic parameters across different regions of Libya revealed a highly favorable environment for the utilization and development of solar and wind energy resources. The abundant solar irradiance levels and consistent wind patterns make Libya an attractive candidate for the deployment of solar energy systems and wind farms. The establishment of this atlas represents a significant contribution to the renewable energy sector, as it provides critical insights into the solar and wind energy potential of Libya. This information serves as a vital resource for policymakers, energy planners, and investors in making informed decisions regarding the development and implementation of renewable energy projects in the country. By capitalizing on its extensive solar and wind resources, Libya has the potential to achieve a remarkable transition towards a greener and more sustainable energy industry, fostering both economic growth and environmental preservation.

Author Contributions: All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgements: We would like to express our sincere gratitude and appreciation to Wadi Alshatti University for their invaluable support and assistance in the successful completion of our article.

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

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