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RESEARCH ARTICLE RENEWABLE ENERGY

Exploring Promised Sites for Establishing Hydropower Energy Storage (PHES) Stations in Libya by Using the Geographic Information Systems (GIS)

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ABSTRACT

This study aims to identify optimal locations for establishing pumped hydropower energy storage (PHES) stations in Libya using Geographic Information Systems (GIS). The goal is to harness the region's natural resources to support Libya's strategic objectives of addressing energy deficits and increasing the share of renewable and clean energy in the national energy mix to over 50% by 2050. The study identifies several promising sites across Libya for the development of PHES stations, which could alleviate electricity shortages by storing surplus energy for use during peak demand, thus enhancing grid stability. Additionally, these stations can serve as energy storage solutions for renewable and hybrid energy systems. The findings indicate that approximately 24.73% of Libya's total area could be suitable for PHES development. The identified locations were classified into three categories based on a decision-making matrix integrated into GIS: high suitability (4.90%), medium suitability (6.15%), and low suitability (13.68%). The elevations of the most promising sites range from 188m to 2200m above sea level. The potential PHES capacities for these locations were estimated to range between 384-4,496 Wh/m³ of upper reservoir volume.

تحديد المواقع الواعدة لإنشاء محطات تخزين الطاقة الكهرومائية بالضخ باستخدام منصة نظم المعلومات الجغرافية في ليبيا

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الكلمات المفتاحية

نظم المعلومات الجغرافية
الطاقات المتجددة
تخزين الطاقة الكهرومائية بالضخ
العجز في امدادات الطاقة
ليبيا

الملخص

يهدف هذا البحث لتحديد المواقع الواعدة لإنشاء محطات تخزين الطاقة الكهرومائية بالضخ (PHES) في ليبيا باستخدام نظم المعلومات الجغرافية (GIS). وذلك لتحقيق أهداف استراتيجية الدولة الليبية في التخفيف من العجز في الشبكة بالإضافة لجعل مساهمة الطاقات المتجددة والنظيفة أكبر من 50% في مزيج الطاقة المنتجة بحلول عام 2050. بينت الدراسة وجود العديد من الاماكن الواعدة في ليبيا لإنشاء محطات تخزين الطاقة الكهرومائية، والتي من شأنها أن تقلل العجز في الطاقة الكهربائية إذا ما تم تخزين الفائض منها لاسترجاعها عند الطلب، وكذلك لضمان استقرار الشبكة. وايضا يمكن استخدامها كمصدر لتخزين الطاقة في منظومات الطاقات المتجددة والهجينة. كشفت الدراسة ان حوالي 24.73% من اجمالي مساحة ليبيا يمكن ان تشكل هدفا لإنشاء محطات تخزين الطاقة الكهرومائية بالضخ. ولتحديد الانسب تم تصنيف الاماكن الواعدة الى ثلاثة مستويات استنادا على دمج عدة طبقات والتي يشكل GIS على اساسها مصفوفة اتخاذ القرار. بداية من الأماكن ذات الملائمة العالية والتي شكلت حوالي 4.90%، في حين تمثل الأماكن المتوسطة الملائمة حوالي 6.15%، بينما تشكل الأماكن المنخفضة نحو 13.68% من إجمالي مساحة الاراضي الليبية. وتراوحت الارتفاعات للاماكن الواعدة بين 188- 2200 متر عن سطح الارض، كما تم حساب الطاقة المتاحة لتخزين الطاقة الكهرومائية بالضخ وتراوحت بين 384 – 4,496 وات ساعة لكل متر مكعب من حجم الخزان.

Introduction

Driven by environmental concerns, there has been a significant global shift towards generating energy from renewable and eco-friendly sources. In 2023, the total installed capacity of renewable energy reached approximately 3,865 GW, marking an increase of 473 GW from 2022. Solar energy contributed about 36.7%, hydropower 32.7%, wind energy 26.3%, biomass 3.9%, and geothermal energy 0.4%

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[1]. However, due to the intermittent nature of most renewable energy sources, which often do not align with energy demand, there has been a growing interest in energy storage technologies. Energy storage is considered one of the most effective engineering solutions to address the temporal mismatch between supply and demand. Pumped hydro storage systems are among the most widely used energy storage solutions globally. Over the past decade, the global capacity of pumped hydro storage has increased by more than 30%, reaching over 139.9 GW in 2023, accounting for 79.8% of the world's total storage capacity [2]. Libya faces significant challenges in its energy sector, as the electricity generation system relies entirely on fossil fuels, contributing to increased greenhouse gas emissions. Additionally, the sector suffers from electricity supply shortages, with total electricity generation in 2023 reaching approximately 38,396.3 MWh, while energy demand was around 48,140.3 MWh, resulting in a supply deficit of 9,744.03 MWh. This gap necessitates the identification of sustainable solutions to overcome the energy crisis. Studies have shown that Libya possesses substantial potential for harnessing renewable energy resources [3-12], prompting Libyan authorities to integrate renewable energy into their strategic plan for the next 25 years (2025-2050) within the electricity sector. This plan aims to increase the share of renewable and clean energy to 30% by 2030, and to over 50% by 2050 [13]. Although several studies have confirmed the economic, environmental, and technical feasibility of integrating pumped hydroelectric energy storage (PHES) systems with renewable energy systems [14-17], no comprehensive study has been conducted to assess the potential for PHES in Libya. This study aims to identify promising sites for establishing PHES plants in Libya, contributing to the national goals of transitioning to renewable energy and reducing the carbon footprint [18,19].
In this context, Geographic Information Systems (GIS) are considered a vital tool for identifying suitable locations for renewable energy projects [20] due to their ability to analyze geographical, topographical, urban, infrastructure, and hydrological data. GIS employs various techniques for data visualization and remote sensing. To the authors' knowledge, GIS has not yet been applied to identify potential sites for PHES plants in Libya. However, GIS has been used to determine optimal locations for solar power plants [21,22] and wind farms [23], as well as for environmental applications such as assessing dam integrity and evaluating flood risks in regions like Derna and Ghadames [25], and monitoring pollution in oil facilities [26]. It is important to note that GIS usage in Libya is still in its early stages. Despite numerous studies worldwide (as shown in Figure 1) demonstrating how GIS has contributed to improving infrastructure planning and implementation in various countries, the application of advanced technologies like GIS in this field remains limited in Libya. This technology has not been fully utilized, partly due to the lack of accurate climatic and geographical data, which creates uncertainty in decision-making for renewable energy projects. Moreover, there are still significant knowledge gaps in GIS and in understanding the factors that influence site selection for renewable energy projects, which require further research and development [19]. For example, a study in Spain highlighted the effectiveness of GIS in identifying optimal locations for hydraulic energy storage [27]. In Egypt, Ahmed et al. developed GIS model criteria using the Weighted Linear Combination (WLC) technique, incorporating elevation and slope data from the global digital elevation model. They also considered electricity grid data, road networks, land use, and restricted areas as spatial analysis criteria in ArcGIS. The results identified several suitable sites for PHES, covering a total area of 10,428 km². Maps of promising PHES locations in Egypt were subsequently presented [28].

In China, a study evaluated the feasibility of constructing pumped hydro energy storage (PHES) plants in three different terrains in northern China by developing a PHES site selection criteria model using ArcGIS Pro. A multi-criteria spatial decision-making method was employed to classify the sites. The results identified 994 suitable locations in northwest China, with a total energy storage capacity of 2.8 terawatt-hours. The sites were categorized into three levels: 34, 843, and 118 potential locations for PHES plants, respectively. The corresponding total energy storage capacities were approximately 162.8, 1,979.9, and 678.1GWh. The sites with the highest composite scores were primarily concentrated in the Xinjiang Altai region, the central region of Gansu, and the northeastern part of Qinghai [29].

Additionally, a study conducted in Australia developed a method based on GIS and the Analytical Hierarchy Process (AHP) to independently identify PHES sites using a set of environmental and technical criteria. The Levelized Cost of Energy (LCOE) was also calculated for a limited number of promising sites, along with their potential to reduce carbon emissions. This approach identified 14 potential sites, with a total estimated energy capacity of approximately 366.94 terawatt-hours over their lifetime, preventing the emission of around 300 kilotons of CO_2. The LCOE for these 14 PHES sites ranged from 0.04 to 0.27 Australian dollars per kilowatt-hour. This developed approach significantly contributes to improving energy management and supports the transition to a zero-emission economy [30].

In Iran, a study assessed the technical potential of PHES plants using GIS-based automated models based on four key pillars. Two of these pillars focused on the presence of upper and lower reservoirs, while the third pillar, developed based on the country's permanent rivers, identified additional alternative sites. The fourth pillar evaluated the potential for supplying PHES plants with seawater as a solution for regions facing freshwater scarcity. The TOPSIS method was applied to integrate economic sensitivity into the evaluation process. The results indicated that Iran has favorable terrain for establishing PHES plants, with a technical potential of up to 5,108 GWh across 250 identified sites, considering a maximum distance of 20 km between PHES reservoirs [31].

A study conducted in Hungary used GIS to evaluate the potential for small-scale pumped hydro energy storage (Small-PHES). Topographic analysis was employed to identify natural water bodies and land depressions suitable for energy storage. The study revealed that storage potential ranges from 14 to 33 GWh, representing approximately 8% to 18% of the country's current hydro storage capacity [32].

The present study aims to bridge the research gap in this field by utilizing Geographic Information Systems (GIS) to identify promising sites for establishing PHES plants in Libya. The site selection is based on multiple criteria, including elevation, slope, proximity to electricity grid infrastructure, transportation routes, water sources, and land use. Additionally, digital maps indicating spatial suitability scores were created to support the planning and

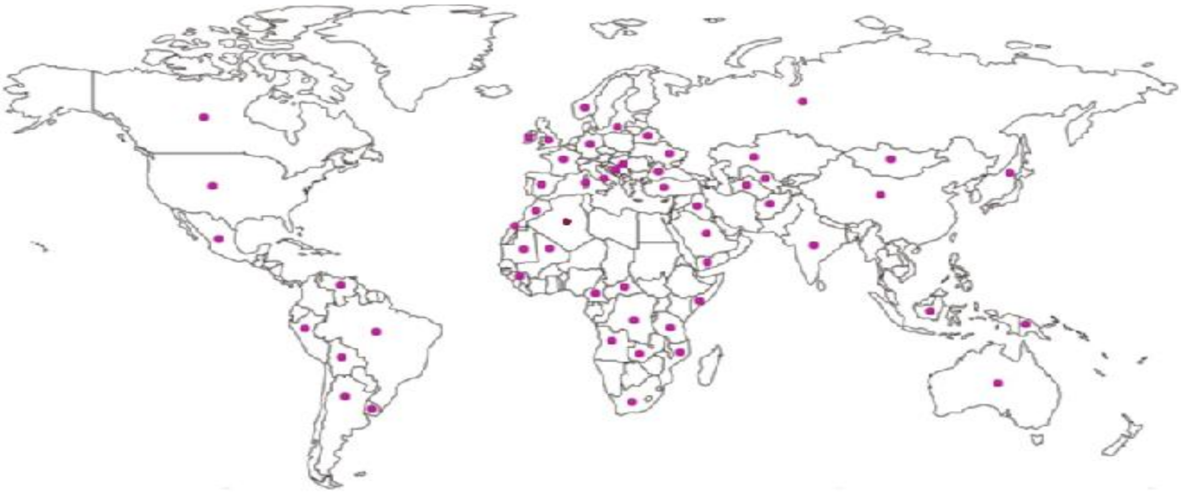

Fig.1: The Geographical Distribution of GIS Applications in Studies for Identifying PHES Plant Locations

implementation of PHES projects. The study provides recommendations based on the analysis results to improve future planning for energy storage projects in Libya, ensuring economic efficiency. This research highlights the country's favorable topographic and demographic resources, demonstrating that Libya possesses ideal terrain for investment in such projects. It offers valuable insights for decision-makers and investors in the energy sector by helping to identify promising sites for the development of PHES plants.

Research Methodology

Site selection is a critical step in establishing pumped hydro energy storage (PHES) plants. An analysis is required to assess site suitability based on both technical and economic criteria, as defined by the designer. The Shuttle Radar Topography Mission (SRTM) digital elevation model, with a spatial resolution of approximately 30 meters, was utilized as the primary topographic data source to establish elevation differences and terrain slope criteria. Additional spatial data, including road networks, electricity distribution networks, water sources, and land use constraints, were also analyzed. The spatial analysis tool in ArcGIS Pro 3 was employed to identify the most suitable upper reservoir sites in Libya. The Weighted Linear Combination (WLC) technique served as the core method in the proposed methodology [23].

2.1 Key information on Libya

Libya is located between longitudes 9°–25°E of the Greenwich Meridian and latitudes 19°–33°N of the equator. It is bordered by the Mediterranean Sea to the north, Chad and Niger to the south, Egypt and Sudan to the east, and Tunisia and Algeria to the west. The country covers an area of approximately 1,660,000 km² and has a Mediterranean coastline that extends about 1,900 km [24]. Figure 2 illustrates the geographical location of Libya. The wind and solar energy potentials of the country are illustrated in Figures 3 and 4.

Energy situation of the Country

Behavioural analysis of the Alshatti district subgrid for the year 2024 reveals that there is no electricity generation deficit. The total annual generated power was 605,879.5 MWh, while the load was 590,018.7 MWh. Therefore, the issue is not a generation shortfall, as the analysis indicates a surplus of approximately 15,860.8 MWh, as illustrated in Figure 5. The problem, however, lies in the timing mismatch between generation and load. In such cases, energy storage is considered a practical solution to address this issue.

Geographic Information Systems (GIS) Technology

GIS technology enables users to accurately and efficiently analyze geographic locations, as well as collect and interpret spatial data to understand spatial relationships and make informed decisions. This geographic data includes natural landscapes, topography, natural resources, infrastructure, and more.

Fig.2: Political map of Libya.
[Source: https://maps.lib.utexas.edu/maps/libya.html]

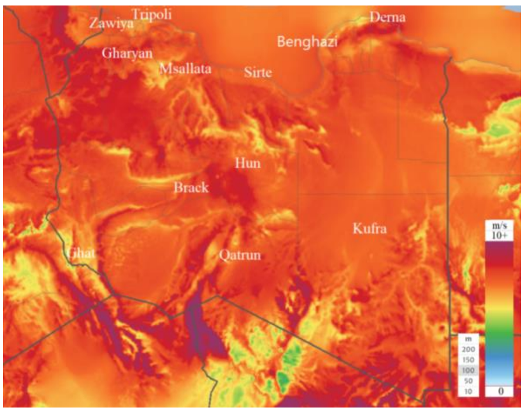

Fig.3: Location and wind speed at 100 m of the 12 selected sites.
[Source: https://globalwindatlas.info/area/Libya/]

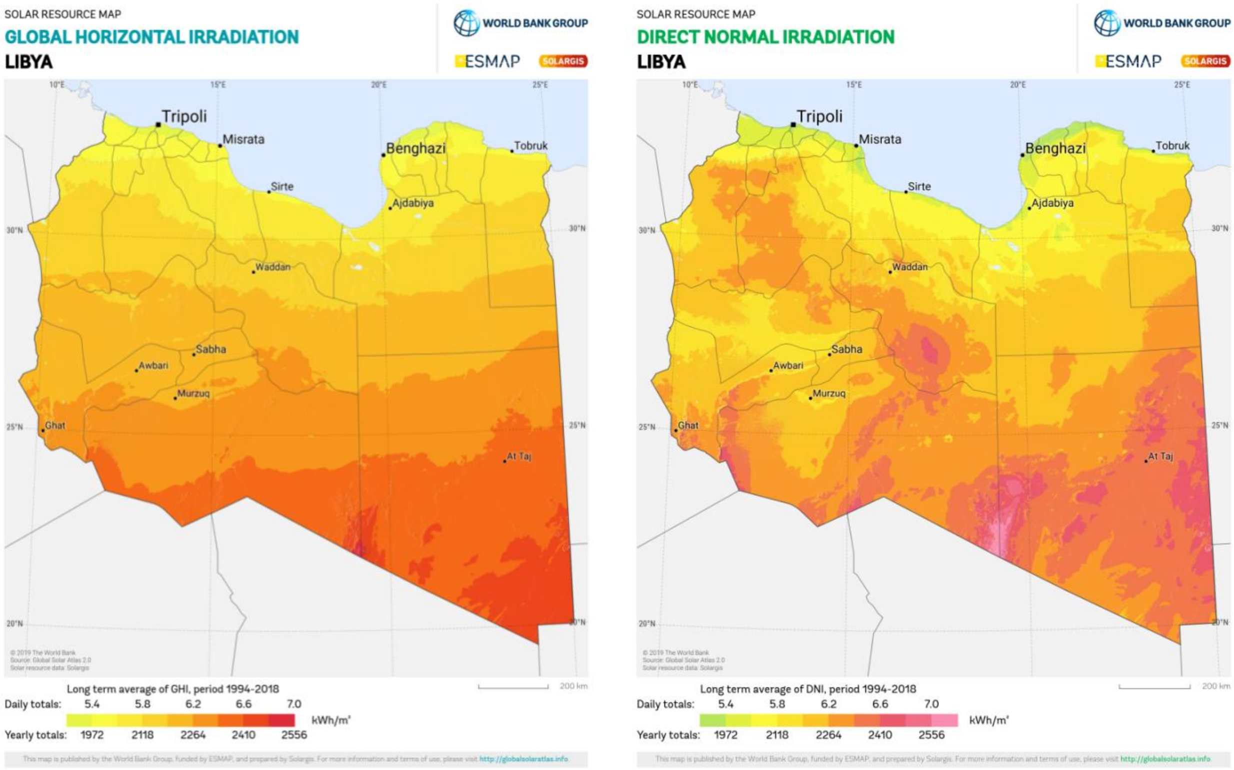

Fig.4: Annual average global horizontal and Direct Normal Irradiation in Libya.
[Source: https://solargis.com/maps-and-gis-data/download/libya]

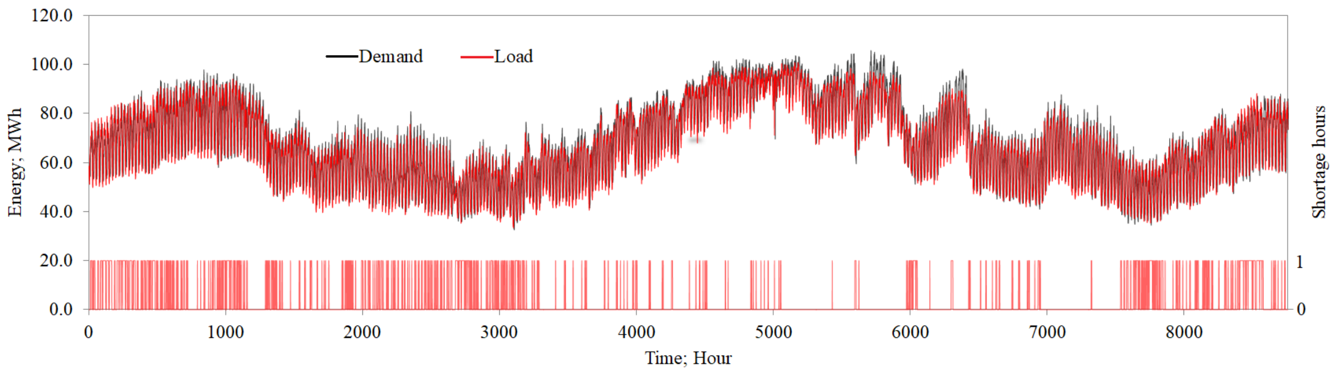

Fig.5: Hourly energy generated, load and shortage hours in Libya [17]

GIS plays a crucial role in environmental analysis, resource planning, disaster management, market analysis, strategic decision-making, and remote sensing. Additionally, it enhances operational efficiency, improves forecasting, and supports future planning [33]. With technological advancements, GIS can now be integrated with various applications and systems, which enhances its ability to analyze and present data more effectively and rapidly. This, in turn, strengthens its role across multiple fields, particularly in identifying optimal locations for renewable energy generation and storage projects.

Currently, multi-criteria analysis (MCA) using GIS is a powerful tool for determining promising locations for various projects. The number and type of criteria used depend primarily on the nature of the project. In this study, the goal is to identify suitable locations for PHES plants in Libya. Therefore, these criteria were classified and weighted using ranking weight coefficients.

Topographic and Demographic Criteria Analysis

The geomorphological characteristics necessary for establishing PHES plants are analyzed using GIS to determine optimal locations based on the following criteria:

- Elevation difference between the upper and lower reservoirs.
- Topographic slope, ensuring a suitable gradient for water flow.
- Proximity to water sources, as sites should be near water to minimize transportation costs.
- Distance from the electrical grid, power distribution lines, and transportation networks.
- Proximity to populated areas.
- Land use analysis, ensuring minimal negative impact on ecological systems.

There are no absolute criteria, as they are relative measures. Suitability values range from high to low, with reclassification values from 1 to 5, where 5 represents the most suitable locations, as shown in Table 1.

Table 1: Ranking and weighting distribution of data layers [25]

No	Category	Level	Rank	Suitability	Weight
1	Elevation	High	**5**	2200 m	**40%**
		Medium		550 m	
		Low		188 m	
2	Slope	High	**1**	5-10 m	**5%**
		Medium		10-20 m	
		Low		20-75 m	
3	Water Sources	Seawater	**4**	35 km	**25%**
		Treated wastewater		40 km	
4	Proximity to the Electrical Grid		**3**	20-50 km	**15%**
5	Proximity to Transport Networks and Roads		**3**	50-80 km	**10%**
6	Land Use	Agricultural Land	**2**	40 km²	**5%**
		Urban Areas			
		Environmental Reserves			

Implementation Steps

1. Collect topographic data using the Digital Elevation Model (DEM) from the USGS EXPLOR Data provided by the United States Geological Survey (USGS), along with land use data.
2. Import the DEM into ArcGIS Pro 3 and process any missing values.
3. Slope Analysis: This step involves calculating the elevation change between adjacent points to determine the steepness of the slope.
4. Flow Accumulation Analysis: Hydrological analysis is used to determine the natural flow paths of water, which helps in selecting suitable sites for lower reservoirs that can naturally accumulate water.
5. Classify criteria based on their importance using ranking coefficients and weights.
6. Select reservoir sites by identifying areas with appropriate elevations and slopes for water storage and designating them as upper reservoirs. Sites near valleys or low-lying areas, which could naturally collect water, are selected as lower reservoirs.
7. Using weighted overlay techniques, promising sites for PHES plants are identified, and final suitability maps for the study areas are generated.

Mathematical Representation

This section presents the formula used to calculate the storage capacity of the pumped hydro energy storage (PHES) systems identified for establishing PHES plants through GIS, as given in the following mathematical expression [14]:

$$P_{PHES} = \rho \, g \, h \, \dot{Q} \, \eta \qquad (1)$$

Where: E is the reservoir capacity (W), ρ is the water density (1000kg/m³), g: Ground gravity (0.81 m/s²), h is the elevation difference between the upper and lower reservoirs (m), $\dot{Q}$ is the volumetric water flow rate from upper reservoir (m³/s) and η is the efficiency of the turbine and pump (75%) [14].

Mathematical modeling, control, calculation of the optimal volume, and dynamic analysis of the energy level in the upper reservoir have been discussed in several specialized studies, such as [14, 17].

Results and Discussion

Figure 6 shows the Digital Elevation Model (DEM), which is represented digitally in raster format. Each pixel in the DEM contains a numerical value that corresponds to the average elevation above sea level within the area of that pixel, typically at a large scale. This model is useful for planning purposes, and the study relied on the DEM for analysis.

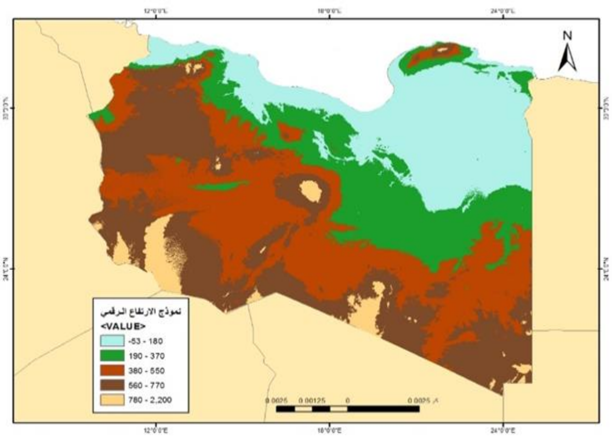

Fig.6: Map Representing the Digital Elevation Model (DEM) of Libya

As shown in Figure 6, the elevations in Libya range from -53 meters to 2,200 meters above sea level, with the elevation difference between two points being a primary criterion for selecting promising locations. Libya is a desert country with limited renewable water resources, heavily relying on groundwater to meet its water needs, which accounts for over 97% of the water used. Renewable groundwater basins are found in the north, in areas such as the Jafara Plain, the Green Mountain, and part of the Red Hamada, while non-renewable sedimentary basins are located in the south, including Murzuq, Kufra, and Al-Sarir. The renewable groundwater is estimated to be between 600 and 650 million cubic meters per year [34]. To enhance the efficiency of PHES projects,

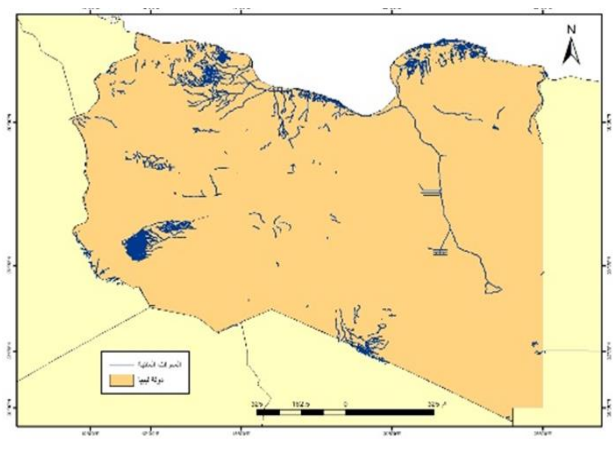

Fig.7: Map of Water Resources in Libya

utilizing treated wastewater presents an innovative solution to supply the required water for the plants. This approach reduces dependence on natural water resources and increases the sustainability of these projects. The daily treated wastewater produced in Libya is estimated at approximately 1,324,054 cubic meters [35].

Figure 7 illustrates the distribution of hydrological resources in Libya, with blue areas indicating surface and seasonal water accumulation sites. This layer serves as a crucial tool to support decision-making based on both hydrological and geographic analysis.

Libya is a large country, covering an area of approximately 1,759,540 square kilometers. The cities are connected by a road network that spans 83,200 kilometers, of which 47,590 kilometers are paved and about 35,610 kilometers are unpaved. Additionally, there are more than 100 airports and landing pads across various cities in Libya [36]. Figure 8 presents the paved road network in Libya. This map is an essential tool for analyzing infrastructure when selecting the most suitable site for PHES projects, as the road network plays a pivotal role in evaluating both accessibility and the logistical costs associated with the project.

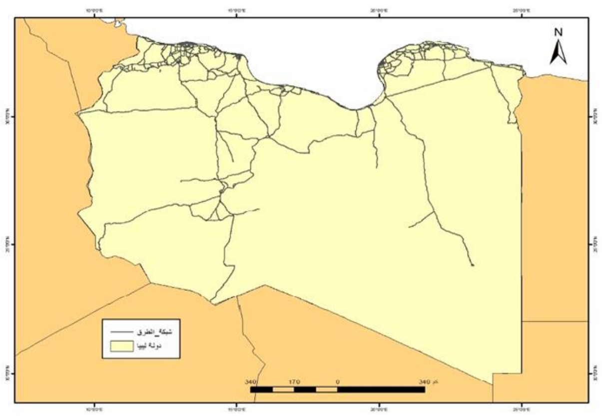

Fig.8: Road Network in Libya

The map indicates that the most suitable locations for these projects are those situated near the main roads, particularly in the northern coastal areas where water resources are available. This integration helps reduce logistical costs and environmental impacts, while ensuring the efficient operation of the project. In Libya, electricity is distributed through 220 kV and 400 kV high-voltage transmission lines, with energy further distributed via medium-voltage transmission lines (30 kV and 60 kV), covering all urban areas in the country. The total length of the 400 kV ultra-high voltage transmission lines is 2,290 kilometers, while the 220 kV high-voltage networks span 13,706 kilometers. Additionally, the total length of the medium-voltage 30 kV and 60 kV networks is approximately 25,453 kilometers [37].

Figure 9 illustrates the electricity distribution network in Libya, highlighting the proximity of the transmission and distribution lines to potential sites for the establishment of hydroelectric storage plants.

It is evident from the Figure 9 that the extensive network of electricity transmission lines, spanning long distances and covering much of Libyan territory, enhances the potential opportunities for selecting promising locations for PHES projects based on this criterion. Land use and land management practices significantly impact natural resources, including water, soil, plants, and animals. GIS technology can identify land use patterns, monitor changes, and provide solutions to resource management issues, such as agriculture, grazing, forests, urban development, nature reserves, and archaeological sites.

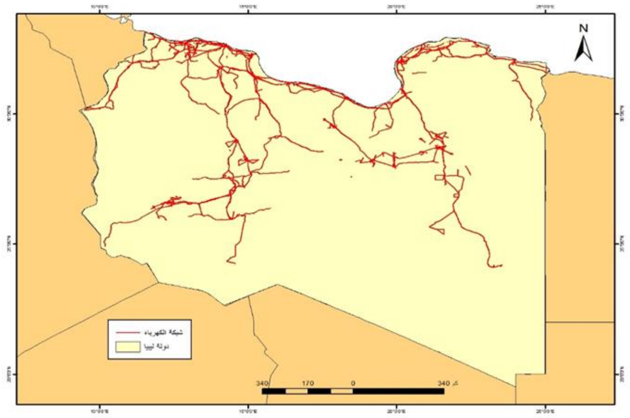

Fig.9: Electricity Grid in Libya

Figure 10 illustrates the vegetation cover, land use, and distribution of environmental resources in Libya.

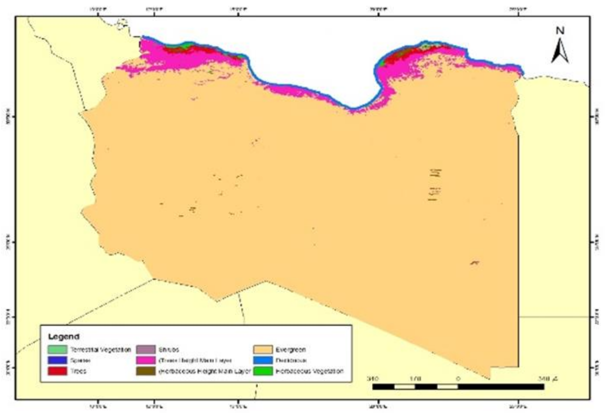

Fig.10: Land Use Map

Figure 10 illustrates the relationship between water availability, the ecosystem, and the geographical features, with population centers and agricultural activities concentrated along the narrow coastal strip. The land use layer is a critical tool in supporting the selection of the most suitable locations for establishing PHES plants, assisting in decision-making based on available on-the-ground data. As shown on the map, much of Libya’s land remains underutilized, presenting significant opportunities to harness these areas for renewable energy projects without imposing additional impacts on the local environment.

Figure 11 presents the final map of promising locations, created by intersecting the five layers, which were classified into three suitability levels based on the established criteria.

As shown in Figure 11, approximately 24.73% of the total land area can be considered as potential sites for establishing PHES plants. Figure 12, on the other hand, presents a filtered version of the high suitability level, derived from the combined layers in Figure 11.

Figures 11 and 12 show that the best sites for establishing hydropower energy storage plants in Libya are concentrated in areas with mountainous terrain. Starting from the highly suitable areas (in red), which accounted for about 4.90%,

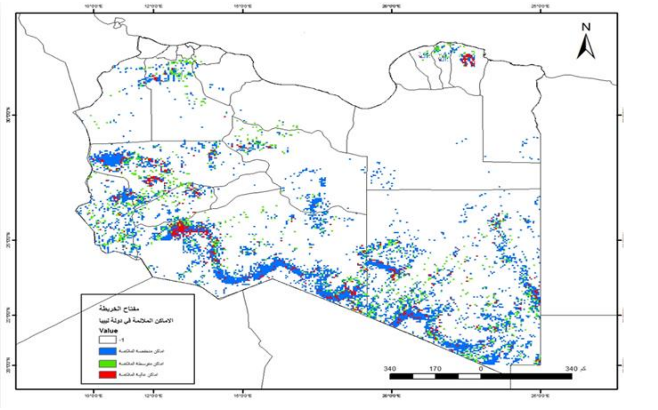

Fig.11: Promising Locations for the Construction of Pumped Hydro Energy Storage Plants

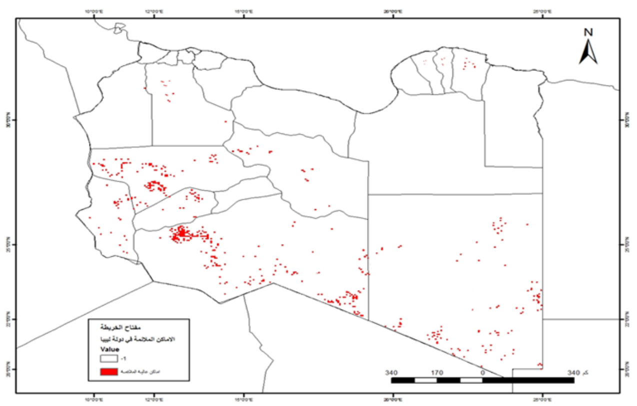

Fig.12: Most Suitable Locations for the Construction of Pumped Hydro Energy Storage Plants

While, the moderately suitable areas (in green) represent around 6.15%, and the low suitability areas (in blue) make up approximately 13.68% of the total land area of Libya. The elevations of the promising sites range between 188 and 2200 meters above sea level. The available storage capacity for hydropower energy storage was calculated for all three suitability levels, ranging between 391 and 4,583 watt-hours per cubic meter of upper reservoir volume.

Table 2 presents the coordinates of the promising sites from the third level in various regions of Libya, based on GIS maps, along with the estimated storage capacities for pumped hydropower plants derived from equation (1), assuming a turbine/pump efficiency of around 75% [14].

Table 2 is important due to its general nature, where storage capacities for each cubic meter of upper reservoir volume are determined. This volume is calculated based on economic considerations and the energy balance between generation and energy requirements for each site individually. Based on a study by Nassar et al. [17] conducted in the Wadi Alshatti district, to cover an electrical load of approximately 1.2 MW, the reservoir volume was estimated to be about 166,532 cubic meters. Therefore, readers can estimate the total storage capacities for these sites, providing a clearer understanding of their potential to meet local energy demands.

This table helps in identifying the most promising locations for establishing PHES plants based on their elevation difference, geographical location, and the calculated storage capacity. By incorporating these factors, it becomes possible to prioritize sites that offer the most efficient energy storage potential while minimizing logistical and environmental challenges. The inclusion of this information is crucial for optimizing energy storage solutions in Libya, ensuring that the selected sites can handle significant energy storage requirements efficiently. Additionally, these findings will aid in strategic planning, offering insights into the scalability and economic feasibility of PHES projects across different regions of the country. This, in turn, can support future energy sustainability and resilience in Libya's power grid.

As a case study, the energy storage capacity for the Brack Alshatti subgrid has been estimated and found about 177.3 MWh. The hourly energy level in the upper reservoir is illustrated in Figure 13. Eqn. (1) may be rewritten as the water density is (1000 kg/m^3), the ground gravity is (9.81 m/s^2), and the turbine/pump efficiency is considered a constant as (75%), as in Figure 14.

$$P_{PHES}(t) = 7.3575\, h\, \dot{Q}(t); kW \qquad (2)$$

Accordingly, the relationship between the key parameters of the PHES system (Energy capacity; Elevation and Volumetric water flow rate) is illustrated as a counter diagram in Figure 14.

The hourly analysis shows that the maximum energy flows to/from the upper reservoir are 11.3/6.1 MWh. According to eqn. (1) and Table 2, with elevation of 560 m, the mass flow rates and the turbine/pump capacities are estimated directly from eqn. (2) as:

Table 2: The most promised locations in Libya for establishing PHES stations

City	Elevation difference (meters)	Coordinates (Latitude, Longitude)	Storage Capacity (Wh/m³)
Kufra	200	24.17º ،23.31º	409
Ajdabiya	188	30.75º ،20.22º	384
Tobruk	192	32.08º ،23.96º	392
Sirte	340	31.20º ،16.58º	695
Murzuq	690	25.91º ،13.91º	1410
Nalut	640	31.52º ،10.59º	1308
Al-Marj	410	32.48º ،20.83º	838
Obari	490	26.58º ،12.76º	1001
Derna	620	32.76º ،22.63º	1267
Wadi Alshatti	560	27.54º ،14.26º	1145
Jufra	840	29.12º ،15.94º	1717
Green Mountain	910	32.40º ،21.66º	1860
Western Mountain	990	30.26º ،12.80º	2023
Ghat	2200	24.96º ،10.16º	4496
		Total	18,946

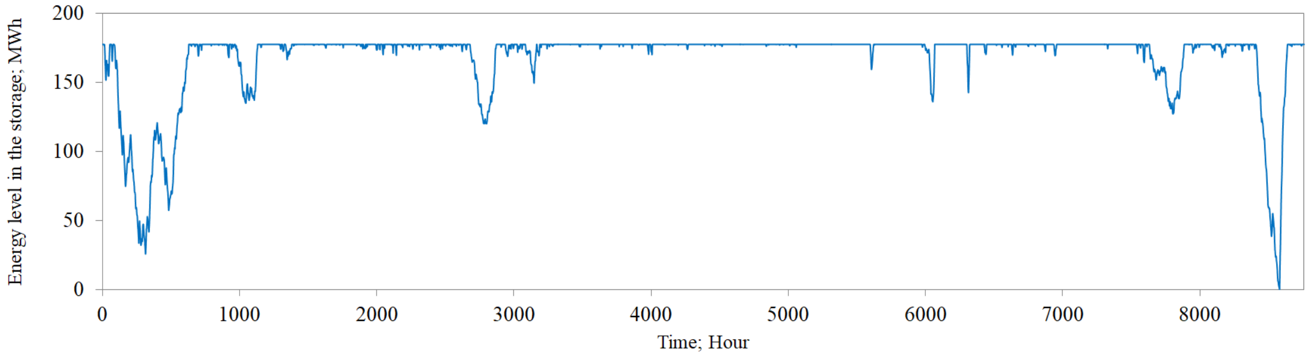

Fig.13: Instantaneous energy level in the upper reservoir for Brack Alshatti subgrid

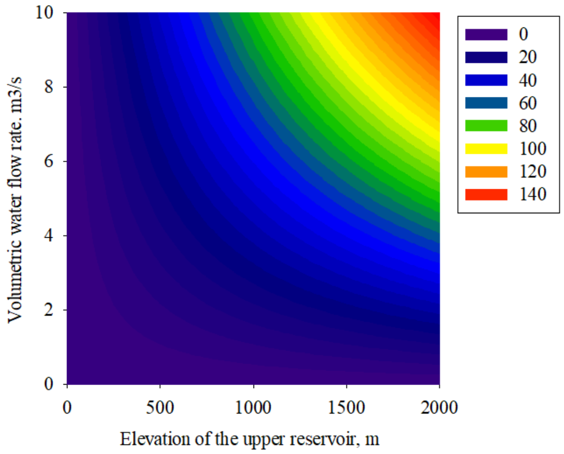

Fig.14: The impact of elevation on the turbine/pump and PHES system

$$P_{PHES}(t) = 4.120\,\dot{Q}(t), MW \qquad (3)$$

Figure 15 demonstrates the volumetric flow rate of water from/to the upper reservoir, as charging and discharging operation mode of the PHES system.

Conclusions and Future Studies

Achieving sustainability in energy systems requires the optimal utilization of renewable energy sources such as solar, wind, and biomass, which serve as clean alternatives to traditional energy sources. The effective integration of these renewable energy systems can be accomplished by utilizing advanced tools and information technologies, particularly Geographic Information Systems (GIS), Decision Support Systems (DSS), and Remote Sensing software. These technologies play a crucial role in identifying the most suitable geographical locations for establishing renewable energy projects, ensuring efficiency, cost-effectiveness, and minimal environmental impact.

This research presented a model for spatial data analysis aimed at identifying the most promising locations for establishing Pumped Hydro Energy Storage (PHES) plants in Libya. A variety of factors were incorporated into the analysis through different data layers, such as the Digital Elevation Model (DEM), slope degree, proximity to electricity networks, accessibility to roads and water sources, and land use patterns. The study's results revealed that the potential for PHES projects is distributed across the country. Approximately 24.73% of Libya's total area was identified as promising for such projects, with 4.90% of this area classified as highly suitable, 6.15% as moderately suitable, and 13.68% as low suitability. The elevations of the most promising locations ranged from 188 to 2200 meters above sea level. The estimated available storage capacities for hydroelectric energy storage at these sites varied from 384 to 4,496 watt-hours per cubic meter, further supporting the feasibility of PHES systems across Libya.

This study represents the first step in a broader research initiative aimed at advancing the use of GIS technology in renewable energy planning in Libya. Future studies will build upon this foundation and expand the focus to encompass several additional renewable energy applications:

1. Identifying promising locations for concentrated solar power (CSP) fields and solar photovoltaic (PV) systems: These systems are crucial for harnessing Libya's abundant solar resources, which can complement the energy storage capabilities of PHES plants.
2. Identifying promising locations for wind farms:Wind energy can provide a significant contribution to Libya's renewable energy generation, and this research will help pinpoint the optimal areas for wind farm development

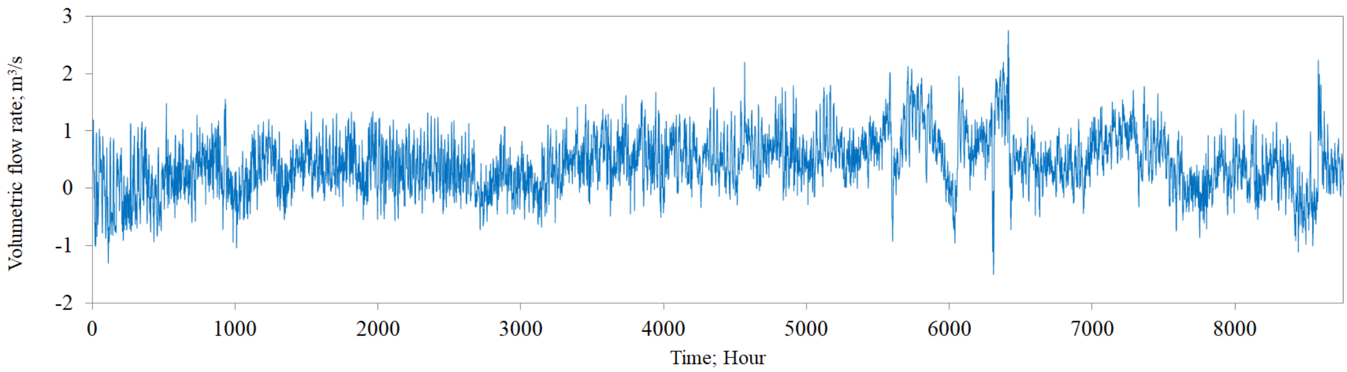

Fig.15: Instantaneous charge/discharge water volumetric flow to/from the upper reservoir in m^3/s

3. Identifying networks to connect integrated hybrid renewable energy generation systems and storage systems: As renewable energy sources like solar and wind are variable, integrating them with energy storage systems, such as PHES, will help stabilize and optimize grid operations.
4. Identifying locations for electric vehicle charging stations and developing the transportation sector in preparation for the transition to electric vehicles (EVs): This is essential to prepare for the future electrification of the transportation sector, ensuring efficient charging infrastructure and reducing the nation's carbon footprint.

By continuing to leverage GIS technology, these future studies will provide comprehensive insights into Libya's renewable energy potential, contributing to the country's transition to a sustainable, low-carbon energy future. This approach will also help align energy development with national and global climate goals, ensuring that Libya's energy infrastructure is both resilient and sustainable.

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