Ensuring sustainability in Libya with renewable energy and pumped hydro storage

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Abstract. A radical transformation is occurring in the global energy system, with solar PV and wind energy contributing to three-quarters of new electricity generation capacity due to their affordability. This shift towards renewable electrification of energy services, such as transportation, heating, and industry, will gradually replace fossil fuels in the coming decades. This paper highlights Libya's potential to achieve energy self-sufficiency in the twenty-first century. In addition to its fossil energy resources, Libya possesses favourable conditions for solar, wind, and moderate hydroelectric energy. The solar energy potential alone is approximately 100 times greater than what is needed to support a fully solar-powered system that provides energy consumption similar to developed countries for all Libyan citizens, without relying on fossil fuels. Moreover, Libya's Green Mountain range offers substantial opportunities for low-cost pumped off-river hydropower storage. Therefore, the integration of solar and wind energy, complemented by hydropower and battery storage, is likely to be the primary pathway for the rapid growth of Libya's renewable electricity sector.

Keywords: solar PV, pumped hydro storage, biomass, renewable energy, Libya.

1. Introduction

Libya, located in North Africa, shares borders with the Mediterranean Sea to the north, Egypt to the east, Sudan to the southeast, Chad and Niger to the south, and Tunisia and Algeria to the west. At 2018, the population of Libya reached approximately 637,500, with an annual growth rate of 1.3% in 2019. Covering an area of 1.8 million square kilometres, Libya is the fourth-largest country in Africa and the 17th largest in the world. The majority of its land consists of shrubs, desert, and semidesert (EU, 2020; IMF, 2020). It ranks ninth among countries with the largest proven oil reserves globally. However, the majority of the

Libyan population, around 80%, resides in three main urban areas: the Eastern Region, the Western Region, and the Southern District. The eastern region is characterized by mountain ranges and a Mediterranean coastline that stretches for 1,850 km. The western region is marked by hills near the mountains, while the southern region includes part of the Sahara Desert (Elmnifi et al., 2018). Libya can be divided into five distinct climatic regions, with the prevailing climates being Mediterranean, hot summer, and desert climates (classified as BWh by the Canadian Space Agency). The coastal lowlands experience a Mediterranean climate with hot summers, mild winters, and relatively light rainfall. The highlands have cooler temperatures, and frost occurs at higher altitudes. While summers are scorching in the interior desert region, the temperature is relatively high. Until recently, part of the Libyan economy was tourism. And although it was not possible to find targeted studies on the impact of tourism on environmental quality in Libya, tourism nevertheless affects the environmental sustainability of the region (Rauf et al., 2022; Tang et al., 2024).

Energy in Libya is currently mainly produced from fossil fuels, which has negative consequences such as depletion of reserves and harmful emissions into the environment such as greenhouse gases and dioxins (Jeffry et al., 2021; Vambol et al., 2016). In addition, deposition of nitrogen and heavy metals has been observed (Li et al., 2021; Bebber, 2021), which requires appropriate measures (Lahori et al., 2023; Yuan et al., 2023; Ziarati et al., 2020; Zahorodniuk et al., 2019). The weakened ecological situation and poor quality of water and air contribute to the rapid development of diseases and epidemics (El Morabet et al., 2023; Grinzovskyy et al., 2017).

By focusing on the development of energy from renewable sources, many problems can be avoided. Renewable sources mean hydropower, biomass, bio waste, solar energy, and wind energy (Vambol et al., 2023; Fang et al., 2022; Khan et al., 2022). These sources can be utilized to meet a significant portion of the electricity demand and promote sustainable development (Ahmad & Samara, 2023; Mohamed et al., 2013; Rajab et al., 2017). By adopting renewable energy and energy conservation measures, we can address environmental issues and their impact on human health. This approach will also lead to a reduction in greenhouse gas emissions, fossil fuel consumption, and the demand for coal and other non-renewable resources. Numerous studies have been conducted in Libya, highlighting the effectiveness of solar photovoltaic (PV) cells, concentrated solar energy (CSP), and wind energy technologies (Jenkins et al., 2019; Bindra & Salih, 2014). The Libyan government is actively working towards achieving sustainable development by implementing the 2013-2030 plan, which encompasses environmental, social, and economic sustainability goals. The adoption of renewable energy will not only help reduce carbon dioxide emissions but also boost revenues, generate employment opportunities, and attract investments (Bindra & Salih, 2014). A rapid and radical shift towards a sustainable global energy system is currently taking place.

Solar photovoltaic (PV) and wind power account for 75% of the world's new electricity generation capacity (Fig. 1). The remaining 25% is made up of coal, oil, gas, nuclear power, hydro, and other renewable sources (https://www.iea.org/data-and-statistics/charts/net-renewable-electricity-capacity-additions-by-technology-2017-2024).

The purpose of this paper is to explore the potential for Libya to meet its energy needs through solar PV, in order to maximally displace energy based on fossil fuels. It suggests that even after Libya reaches the same level of per capita energy consumption as developed countries and transitions to fully electrified energy services without the use of fossil fuels (increasing electricity production by 70 times), it can still rely on covering just 1% of its area with solar panels. Additionally, the current paper aims to make the case that coastal pumped hydro is a viable and cost-effective solution for water storage in Libya. This is due to the fact that Libya has an abundance of coastal sites for pumped hydropower storage, which can meet its needs even in a fossil-fuel-free scenario. Furthermore, pumped hydropower storage is found to be significantly cheaper than overnight battery storage.

To maintain a consistent and logical presentation of the research results, the research methodology was designed as follows:

- assessment of renewable energy options, aiming to achieve 100% application;
- research into methods for balancing high levels of solar photovoltaic energy;
- justification for economic restrictions followed by a conclusion.

2. Current situation and opportunities for renewable energy in Libya

Energy generated from fossil fuels, predominantly oil, has historically dominated Libya's domestic energy supply (Ali & Harvie, 2013). However, there is a growing recognition of the increasing importance of electricity. Traditionally, developing countries have relied heavily on fossil fuels as they industrialize and improve the living standards of their populations. Libya's fossil fuel resources could be exhausted within three to four decades. They also indicate that the adoption of a solar-hydrogen energy system will increase the availability of fossil fuel resources, reduce environmental pollution, and create a sustainable energy system for Libya (ElJrushi & Veziroğlu, 1990).

However, it is expected that the country could switch to using biomass for energy production, or solar and wind power, bypassing the fossil fuel era entirely (Nassar et al., 2023a). This transition holds the potential for the Libyan people to achieve a high standard of living throughout the twenty-first century. In developed nations like the European Union countries, Japan, China, the United States, Singapore, and Australia, per capita electricity consumption ranges from 5-15 MWh per person annually. By electrifying all energy services with renewable sources and eliminating oil, gas, and coal, these countries have significantly reduced their greenhouse gas emissions.

By the second half of the twenty-first century, the per capita electricity consumption in Libya is projected to reach 15 megawatt hours per person per year for a population of 7 million. Based on these projections, electricity consumption in Libya could potentially reach 105 TWh annually, which is referred to as the 105 TWh target" in this paper. It is important to note that the exact number cannot be reliably predicted, but these assumptions are used to illustrate the potential increase in Libya's electricity consumption, aligning with trends observed in developed countries. To put this target into perspective, the current annual electricity consumption in Libya is approximately 25.55 TWh, as shown in Figure 1 (https://www.iea.org/data-and-statistics/charts/net-renewable-electricity-capacity-additions-by-technology-2017-2024).

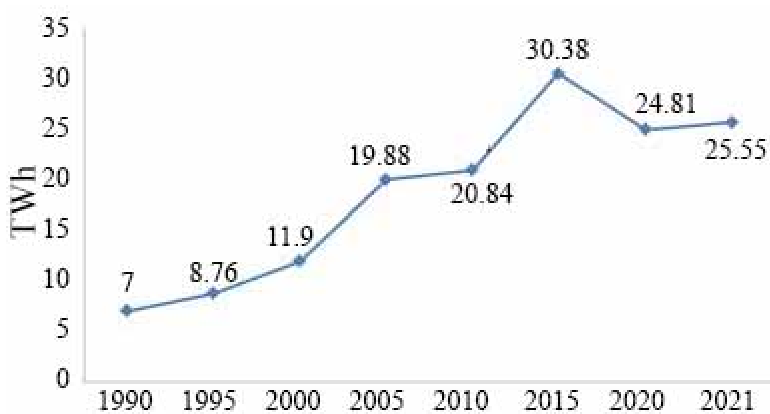

Figure 1. Annual electricity consumption in Libya 2021

Based on the above, the following assumptions can be made:

(1) Libya will catch up with developed countries in electricity consumption;

(2) The country's goal is to fully electrify Libya's energy systems, including transport, heating and industry, without the use of fossil fuels (Fig. 2).

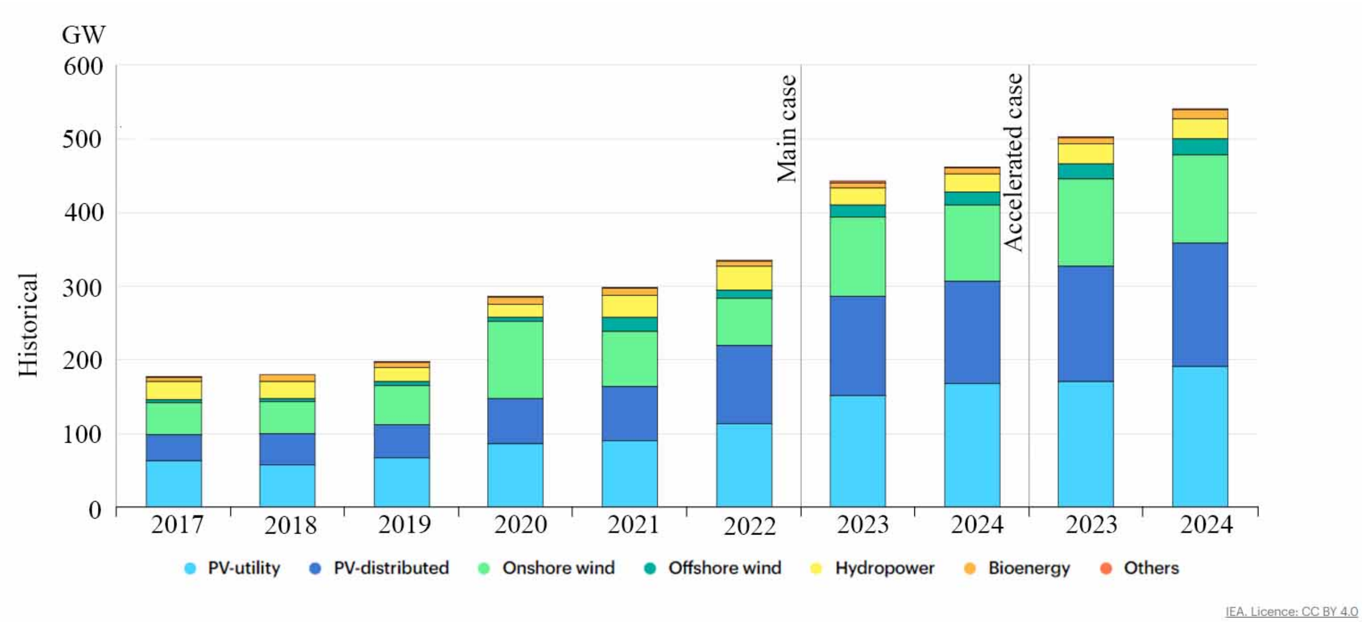

Figure 2. Displays the global additions of new electricity generation capacity (https://www.iea.org/data-and-statistics/charts/net-renewable-electricity-capacity-additions-by-technology-2017-2024)

2.1. Solar Energy

Solar energy is the largest and most sustainable energy resource in Libya. It exceeds Libya requirement to meet the 500-TWh goal by two orders of magnitude. The significant decrease in the price of solar PV has created vast opportunities in developed and developing countries. Solar energy is a promising and abundant source of power in Libya. The country benefits from an average of 3500 hours of sunlight per year, with a solar radiation intensity of 7.1 kW/m^2/day in the north and 8.1 kW/m^2/day in the south (Moria & Elmnifi, 2020; Elmnifi et al., 2018). Figure 3 illustrates the solar radiation intensity across all regions of Libya as of 2020. Most governorates have recorded high levels of solar radiation, ranging from 6 to over 7 kWh/m^2/day. The city of Kufra, particularly its northern and southern regions, has shown the highest potential. The average annual GHI concentration ranges from 5.6 to 6.7 kWh/m^2, with higher values inland and lower values along the coast. PV installations in Libya have proven to be successful (Jenkins et al., 2019; Nassar et al., 2023b). The average daily DNI ranges from 4.2 to over 7.2 kWh/m^2, with the highest values observed in the north-south region. Figure 8 provides a visual representation of the average direct sunlight in different Libyan cities. These findings, especially concerning CSP technology, highlight the region's suitability for solar thermal collector installations (Majdi et al., 2022). Additionally, the Libyan desert contains silica, a crucial component in the production of photovoltaic cells. Therefore, solar energy holds great potential as a significant source of electricity in Libya.

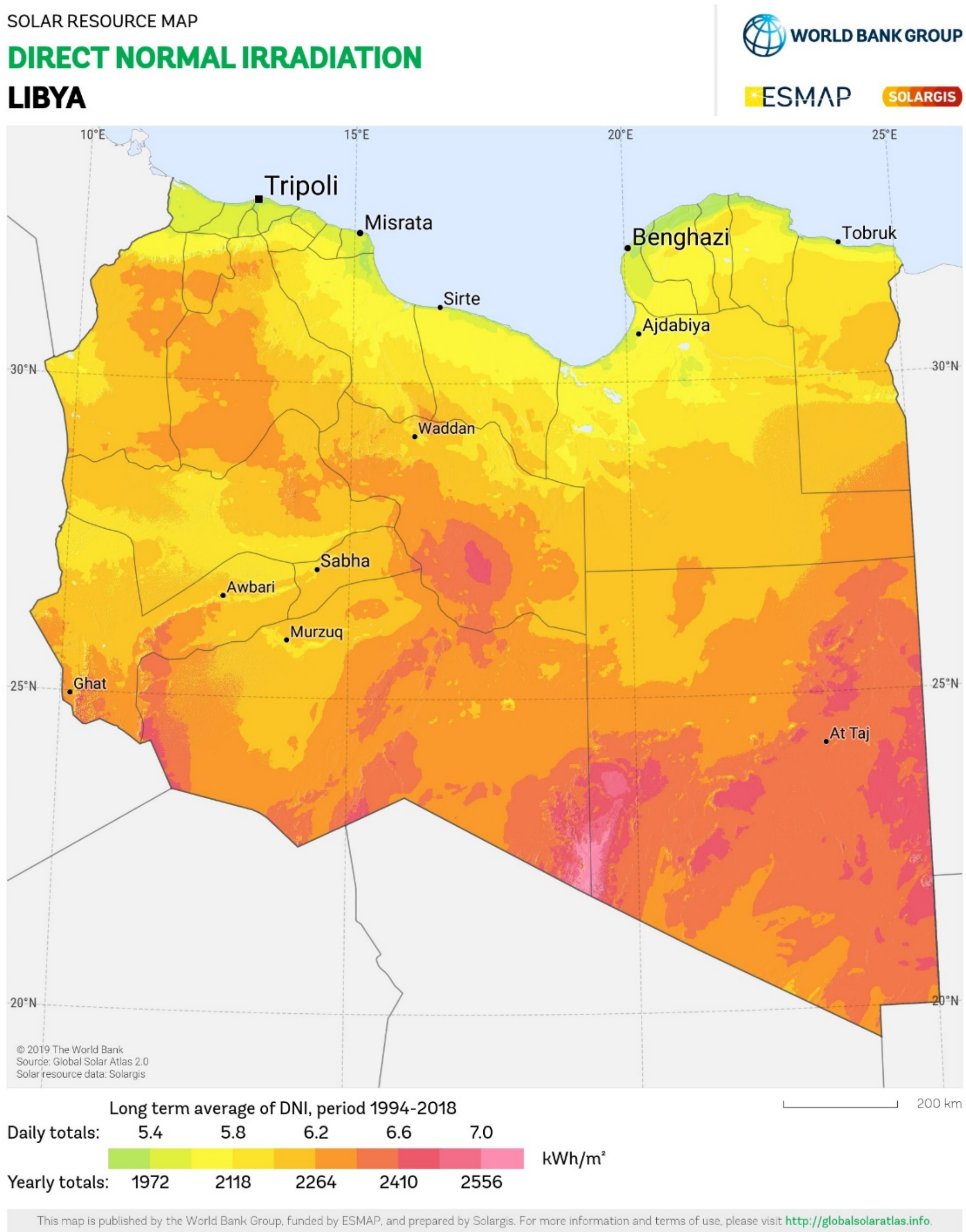

Figure 3. The solar irradiation in Libya

The rapid price reductions in the global solar industry have led to its fast development, necessitating updates to previous reports on energy options. With its location at a longitudes 9° and 25° east, and latitudes 25° 18 and 33° north. and over 200 sunny days annually, Libya experiences relatively high insolation, averaging around 15 MJ/m^2 /day (equivalent to 1.5 TWh per square kilometer per year), with an average of 6.8 daily sunshine hours. This makes Libya a country with significant solar potential (https://globalsolaratlas.info/map (10 October 2020)). As depicted in Figure 3, all regions of the country are suitable for solar energy.

The upcoming availability of solar power systems with a conversion efficiency of 20% (using solar cells with 25% efficiency) (https://itrpv.vdma.org/en/) will result in an output of 0.2 GW per square kilometer when densely packed into an array. Considering Libya's area of 1,760,000 square kilometers, a complete coverage of solar cells could generate 40,000 TWh/year $(1{,}760{,}000\ km^2 x\ 1.5\ TWh/km^2/year\ x\ 20\%\ conversion\ efficiency)$. This would give a nominal power capacity of 343 GW. These rough calculations indicate that Libya has the potential to generate 100 times more solar electricity than needed to achieve the 500 TWh target for high per capita consumption, equivalent to developed countries, and achieve full electrification of energy services while eliminating the reliance on fossil fuels. Alternatively, covering 1% of Libya area (176,000 km²) with solar panels would suffice.

Assuming an annual electricity consumption of 15 MWh per person, solar parks require an average land area of 44 square meters per person with a nominal capacity of approximately 9 kW.

Significant amounts of solar PV energy can be harnessed in urban areas through residential, commercial, and industrial rooftops, as well as building facades. Australia, a global leader in per capita rooftop solar, has 3 million rooftop solar systems with a combined capacity of around 13 GW (equivalent to 550 W per person) (http://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-smallscale-installations). While most of these systems are installed in residential buildings, other sectors are also experiencing rapid growth. Under the Australian Energy Market Operator's phase change scenario, rooftop solar capacity in Australia could increase to 3.7 kW per person (https://aemo.com.au/energysystems/major-publications/integrated-system-plan-isp/2020-integrated-system-plan-isp). This would represent 40% of the target capacity of 9 kW per person required to achieve Libya's 500 TW goal. Solar PV systems can also be integrated into agricultural areas (known as Agrivoltaics or APV), where solar panels are spaced apart to occupy only 10-30% of the crop or pasture. This approach causes a modest decrease in production because the reduction in sunlight is compensated by lower wind speeds and evaporation (Goetzberger & Zastrow, 1982). Various crops such as corn, wheat, jute, sugarcane, tea, coffee, soybeans, beans, lentils, fruits, and vegetables could potentially be suitable for APV in Libya's agricultural projects.

2.2. Hydropower Energy

During heavy winter rains, large pools of surface water form, providing a temporary water storage solution. This water can be utilized as a source of hydroelectric power generation. Approximately 16 major dams have been constructed to collect rainfall, with a combined capacity of 385 mm^3 and an average annual storage capacity of 61 mm. The water held in these dams is used for agricultural, industrial, and sometimes domestic purposes (Moria & Elmnifi, 2020). The three largest dams, namely Wadi Qattara, Wadi Qaa, and

Wadi Al-Mujinin, Boumansour have capacities of 135 mm^3, 111 mm^3, and 58 mm^3 respectively. Additionally, plans are underway for the construction of numerous modern dams, which are expected to collect a total of 120 mm^3 of water annually (Moria & Elmnifi, 2020). It is essential to conduct economic feasibility studies and research in order to assess the potential and viability of this technology as a renewable energy resource. Hydropower is one of the two energy sources in Libya that can play an important role in Libya's future economy. However, hydro potential represents a small fraction of solar PV potential. Figure 4 represents the annual energy estimates and energy potential for the major dams: Wadi Al-Qattara, Boumansour, Jazza, and Al-Majnin Dam.

Hydro-connected solar PV potential type

Status	Operational since 1978
Dam height	75 m
Reservoir area	1.2 km²
Reservoir capacity	22300000 m³
River	Abu Mansur

Hydro-connected solar PV potential type

Status	Operational since 1984
Dam height	38 m
Reservoir area	0.19 km²
Reservoir capacity	2000000 m³
River	Zaza

Hydro-connected solar PV potential type

Purpose	Irrigation
Status	Operational since 1973
Dam height	55 m
Reservoir area	18 km²
Reservoir capacity	135000000 m³
River	Qattara

Hydro-connected solar PV potential type

Purpose	Irrigation
Status	Operational since 1972
Dam height	42 m
Reservoir area	0.36 km²
Reservoir capacity	58000000 m³
River	Mejenin

Figure 4. Represents the annual energy potential for the major dams

2.3. Wind energy

Libya has a moderate potential for large-scale wind energy use (Figure 5) (https://globalwindatlas.info/). Typical expected capacity factors are less than 20%, with the exception of the high hills of Al Jabal Al Akhdar and Al Jabal Al Gharbi, from which a significant proportion of energy can be obtained by wind turbines.

There is potential for small turbines in some suitable locations. Many government and private organizations are taking initiatives to promote small-scale wind energy in Libya (Jary et al., 2021). At present, there is no ongoing wind turbine installation project that uses wind energy alone (Ayed et al., 2022).Wind energy usage is currently very low and requires regular maintenance and inspections. In 2000, the National Electricity Company contracted a German consortium to construct a 25MW wind power farm. Multiple suitable sites for installation were studied, and wind rate surveys were conducted over the course of a year. Technical specifications for all components of the experimental wind farm were prepared, but the project was not completed. The Renewable Energy Resources Development Plan 2008-2012 includes several wind farm projects totaling a capacity of 1000 MW. These projects include:

- Dernah: The first phase (60 MW) is currently under construction.
- Al Maqrun: The contract for the first phase (120 MW) is being awarded.
- Al Maqrun: The contract for the second phase (120 MW) is currently under negotiation.
- Western region: Meslata, Tarhunah, and Asabap (250 MW) are projected for development.
- Southern region: Surveys for possible sites in Gallo, Almasarra, Alkofra, Tazrbo Aliofra, Sabha, and Gatt, Ashwairef (250 MW) are projected (Moria & Elmnifi, 2020).

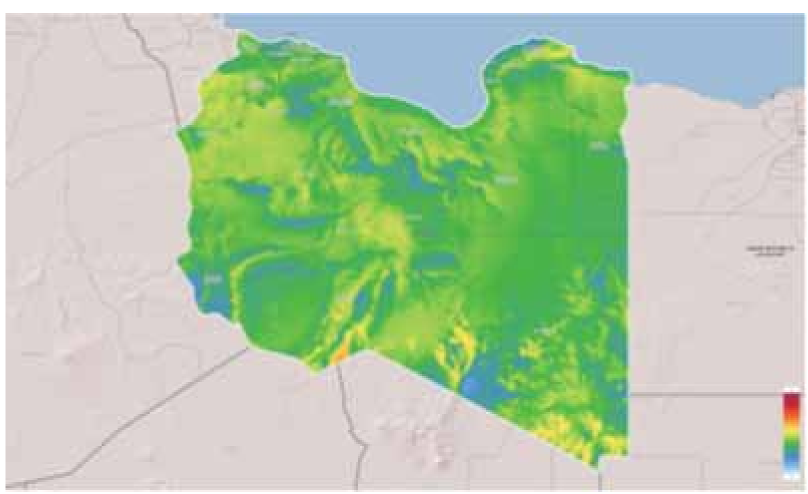

Figure 5. Illustrates the wind capacity factors in Libya, with redder shades indicating better performance (https://globalwindatlas.info/)

2.4. Biomass

Biomass, such as wood, agricultural waste, animal manure, and biogas, serves as a significant small-scale energy source for millions of people in Libya. However, it cannot be relied upon as a large-scale energy source due to its low efficiency in converting solar energy into usable energy compared to solar PV. This inefficiency necessitates a large amount of land, which directly competes with food and timber production and environmental conservation. In contrast, electricity can readily replace biomass and fossil fuels for heating, cooking, and lighting while also eliminating indoor air pollution. As economies develop, many countries have experienced a decline in biomass usage, and the same trend may be expected in Libya over the coming decades. Libya faces the challenge of managing a substantial volume of organic solid waste, fertilizer, sewage sludge, and various types of organic industrial waste. Proper management is crucial for environmental protection, and landfilling is not a sustainable option. An environmentally beneficial and energy-efficient waste management solution is anaerobic digestion. This process allows for the recovery of biogas (approximately 60% methane) and digested sludge, which can then be used as organic fertilizer. This approach helps Libya reduce its reliance on chemical fertilizers and provides biogas for cooking, heating, and industrial applications. Waste includes renewable energy sources like wind and solar energy. Proper waste management, such as recycling and electricity generation, can help reduce the negative impact of waste on the environment and alleviate the burden on other renewable energy sources. The estimated annual generation of municipal solid waste is 27 million tons, with an average daily rate of 1.3 kg per person (https://globalsolaratlas.info/map). The capital city, Tripoli, has the highest waste production due to its high population density, as depicted in Figure 6. Organic waste, primarily from food, accounts for 56.3% of the waste, followed by plastic waste at 13.5%. Other waste components include textiles (10.8%), glass (2.6%), and metals (3.7%) (https://globalsolaratlas.info/map). Currently, solid municipal waste is collected and disposed of in landfills, while recycling, reuse, and energy recovery processes are still being researched. The private sector is involved in extracting paper, plastic, and metals from waste and leading the recycling and export activities. Disposing waste in open landfills leads to severe environmental issues such as land and water pollution, the spread of diseases, and loss of biodiversity. Effective management of municipal solid waste can be achieved through recycling and energy recovery, reducing disposable waste and greenhouse gas emissions, and transforming waste into energy. This can be achieved through Waste to Energy (WTE) initiatives.

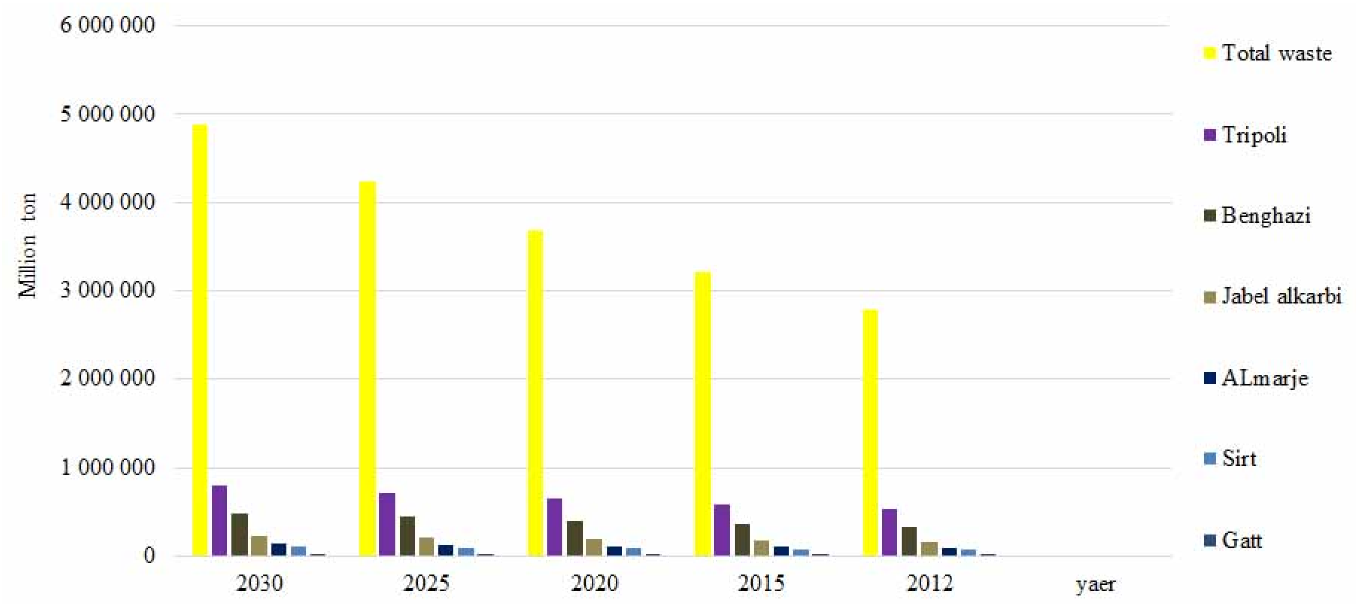

Figure 6. Municipal solid waste in various Libyan cities

3. Balancing High Levels of Solar Electricity

Balancing high levels of variable solar energy throughout the year is a simple task. Storage options, such as batteries and pumped hydro, enable us to manage the daily solar cycle effectively. To address local weather and demand fluctuations, power sharing across Libya is facilitated by high-power transmission lines that stretch from east to west. Australia is leading the world in per capita installation of variable solar and wind energy. However, as hydroelectric generation only accounts for 6% of Australia's electricity, the country lacks the smoothing capabilities provided by large dams. To address this, Australia is implementing multiple MW of new off-river pumped hydro, as well as MW-scale batteries and transmission infrastructure (Blakers et al., 2021). Furthermore, large-scale demand management strategies are being employed through pricing structures to encourage consumers to shift their energy consumption to periods of abundant renewable energy availability.

3.1. Pumped-Hydro-Energy Storage (PHES)

PHES involves pumping water from a lower reservoir to an upper reservoir during times of excess solar energy. The stored water is then released through a turbine at a later time to recover the energy. The typical round-trip efficiency of PHES is 80%. PHES accounts for approximately 95% of global electricity storage power, which is around 170 GW, and a higher proportion of storage energy. Most existing pumped-hydro systems are associated with hydroelectric projects that have large reservoirs, often resulting in the flooding of extensive areas of land. However, PHES systems can also be located away from rivers. Since the majority of Earth's land surface is not adjacent to a river, there are significantly more potential sites available for off-river (closed-loop) PHES compared to river-based PHES. Off-river PHES consists of a pair of reservoirs, ranging from 20 to 500 hectares in size, positioned a few kilometers apart and at different altitudes (with a difference in elevation, known as "head," ranging from 200 to 1200 m). These reservoirs are connected by a pipe or tunnel (see Figure 7). The system operates by pumping water uphill on sunny or windy days and then recovering the energy by allowing the stored water to flow back through the turbine. This process of water movement between the two reservoirs continues indefinitely. To provide an example, a pair of reservoirs each covering an area of 100 hectares, with a head of 600 m, an average depth of 20 m, a usable water fraction of 90%, and a round-trip efficiency of 80% (considering losses), can store 18 gig liters of water. This stored water has an energy potential of 24 GWh, allowing the system to operate at a power output of 1 GW for an extended period. These reservoirs are much smaller than river-based hydropower systems. The water needs, which include initial fill and evaporation minus rainfall, are also significantly lower compared to a coal-fired power station with a cooling tower.

Figure 7. PHES off-river

Libya has significant potential for PHES beyond rivers. The Global Water Storage Atlas (Stocks et al., 2020) identifies around 280 well sites in Libya with a total storage capacity of 50 TWh (Fig. 8). To provide some context, a developed economy typically requires one day of energy usage to offset 100% renewable energy (Stocks et al., 2021).The variation in solar energy supply throughout the seasons in Libya is moderate, ranging from 75% of the average in winter to 125% in spring (Nassar et al., 2023b). This implies a need for substantial seasonal storage. A suggested upper limit for seasonal storage is 50 TWh, which can be achieved through pumped off-river hydro storage (Blakers et al., 2021). However, in reality, much less storage capacity would be necessary. The required storage amount depends on the trade-off between the cost of storage and the cost of increasing solar generation to meet winter demand. This means that there is a surplus of solar electricity during the summer. As the cost of solar systems continues to decrease, it would be more economically favorable to overbuild solar capacity rather than relying heavily on seasonal storage. By connecting with neighboring countries in the north and south, which have significant solar and wind resources, surplus summer solar power can be stored seasonally and exported.

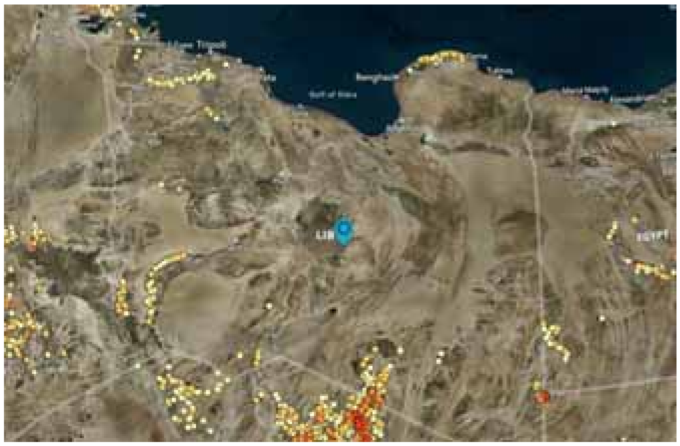

Figure 8. Off-river hydroelectric pumping sites in Libya with a capacity of 50 GWh

4. Economic difficulties

Natural gas is a cleaner energy source compared to coal and oil for power generation. Libya possesses the eighth largest reserves of natural gas in the Arab world, amounting to 1.5 trillion cubic meters. As a result, the domestic selling price of natural gas in Libya is among the lowest globally ($2.2/mmBtu). This affordability encourages its consumption and drives up demand (https://re100.anu.edu.au). Given its status as clean energy, availability, and low price, natural gas poses a significant and formidable competition to renewable energy in Libya.

- The cost of electricity and gas is considerably lower in comparison to the price of renewable energy.
- The absence of a regulatory law governing investor contracts hinders financing.
- Renewable energy cannot meet the current energy demand rate due to the absence of an energy consumption rationalization system.
- Efforts in rationalization, awareness, and training are needed in the field of renewable energy.
- There is a lack of expertise and specialists in the field of renewable energy.

5. Conclusion

According to international standards, Libya possesses good solar resources, as well as moderate water and wind resources. However, the main source of energy production in the country is fossil fuels. Solar energy resource outshines hydro and wind resources by two times, making it a potential contender against other energy sources. The state energy maps created before 2011 are outdated due to the rapid advancements in solar energy. To achieve the same per capita energy consumption as developed countries that do not rely on fossil fuels, Libya would need solar parks equivalent to 1% of its land area. This would involve electrifying transportation, heating, and industry, with solar panels being installed on rooftops, integrated with agriculture, and placed on unproductive lands and lakes. Since most of Libya's hydropower is off-river, there is a need for substantial storage to support the solar-based energy system. Off-river Pumped Hydro Energy Storage (PHES) systems offer great potential for Libya, as they have lower environmental and social impacts compared to on-river hydropower storage. In a mature and competitive market, solar PV has clear economic advantages over fossil fuels and hydropower. However, there are obstacles to the rapid deployment of solar PV. The relatively high cost of solar energy persists until there is a critical mass of skilled individuals and established supply chains, after which costs will decrease rapidly towards international standards.

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