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Integration of Hydropower and Solar Photovoltaic Generation into Distribution System: Case of South Sudan

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Abstract**—**Hydropower and solar photovoltaic (PV) generation are crucial in sustainability and transitioning from fossil fuel to clean energy. Integrating renewable energy sources such as hydropower and solar PV into the distributed networks contributes to achieving energy balance, pollution mitigation, and cost reduction. Frequent power outages and a lack of load reliability characterize the current South Sudan electricity distribution system. The country's electricity demand is 300 MW; however, the installed capacity is around 212.4 MW. Insufficient funds to build new electricity facilities and expand generation are the reasons for the gap in installed capacity. The South Sudan Ministry of Energy and Dams gave a contract to an Egyptian Elsewedy Electric Company that completed the construction of a solar PV plant in 2023. The plant has a 35 MWh battery storage and 20 MW solar PV system capacity. The construction of Juba Solar PV Park started in 2022 to increase the current installed capacity in Juba City to 53 MW. The plant will begin serving 59000 residents in Juba and save 10,886.2 t of carbon dioxide (CO_2) annually.

Keywords**—**Renewable energy, hydropower, solar energy, photovoltaic, South Sudan.

I. Introduction

DEPENDENCY on fossil fuels has raised concerns among environmental experts who turned their focus on renewable energy sources such as hydro, solar, wind, etc. Unfortunately, the most widely used type of energy is fossil fuel, with 80% of the world's energy consumption [1]. Some renewable energy sources' benefits are replacing fossil fuels responsible for carbon dioxide emissions, decentralized electricity generation, and reducing the need for transmission lines [2]. Two renewable energy sources, hydro and solar PV generation, play a crucial role in energy sustainability and transitioning from fossil fuel to clean energy. Integrating hydropower and solar PV generation through distributed generators into the grid is essential to achieving energy balance and reducing pollution and costs [3]. Distributed generators are small power generator techniques from different sources, ranging from a few kilowatts (kW) to 50 MW [4].

This paper reviews the current and future electricity distribution in South Sudan. The advantages and disadvantages of integrating hydropower and solar PV generation-based distributed generators are also discussed. The Juba solar PV plant is ready to be integrated into the local distribution system and will be presented as a case study.

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II. Electricity Distribution in South Sudan

Up to 2019, the South Sudan Electricity Corporation, the independent electricity corporation, has provided electricity distribution under the Ministry of Energy and Dams regulations. Due to a lack of fuel and spare parts, the South Sudan Electricity Corporation's operation has not been effective since 2013. The country's electricity demand stands at 300 MW. However, the installed capacity is around 212.4 MW [5]. The gap in installed capacity indicates insufficient funds to expand generation and build new electricity infrastructure. So far, the Public Private Partnership has not yet been a business model in the electricity sector to attract investment in renewable energy sources in the country.

In 2015, the Ministry of Energy and Dams and the Ezra Construction and Development Group developed a joint venture and constructed the Ezra Power Plant (100 MW) to address deficient access to electricity in Juba City. In 2019, Ezra Power Plant, which started construction in 2017, launched 33 MW, the first operation phase for Juba residents. The African Development Bank funded a distribution system of 33 MW/0.415 kV. The generated electricity is distributed to consumers through three feeders that use two transmission line systems: 132 kV and 33 MW/0.415 kV. Ezra Power Plant and Distribution System cost 290 million and 38 million, respectively. Starting from 2019, Ezra will operate the plant for the next 17 years [5].

The current South Sudan electricity distribution system is characterized by frequent power outages and a lack of load reliability. Out of the installed capacity of 212.4, 33 MW is operational in Juba. 5.6 MW in Wau, 5MW in Renk, 97 MW in Paloch, and 58 MW in Tharjath. Paloch and Tharjath Power Plants' diesel fuel-based generation cover the oilfield's central facilities, Malut and Bentiu towns. Diesel is the only fuel used to generate electricity, whereas most people depend on burning biomass to meet basic electricity needs. Table I shows installed electricity capacities in the country [5]-[7].

In 2018, under the Power Purchase Agreement, the Ministry of Energy and Dams gave the roles and powers of the South Sudan Electricity Corporation to Ezra Construction and Development Group and Juba Electricity Distribution Company. The Ministry of Energy and Dams regulated operation, maintenance and revenue collection from Ezra Power Plant and Juba Electricity and Distribution Company

through a Special Purpose Vehicle. The current electricity tariff ranges from US$ 0.316/kWh to US$ 0.45 k/kWh, which is expensive and not affordable. The tariff covered customers in domestic, government, commercial, and industry settlements [5].

TABLE I
INSTALLED NINE DIESEL POWER PLANTS IN DIFFERENT LOCATIONS

Location	Fuel	Capacity (MW)	Status	Year
Ezra Power Plant Juba	Diesel	33	Operational	2019
Malakal Power Plant	Diesel	4.8	Not Operational	1982
Wau Power Plant	Diesel	5.6	Operational	2008
Bor Power Plant	Diesel	3	Not Operational	2009
Rumbek Power Plant	Diesel	3	Not Operational	2009
Yambio Power Plant	Diesel	3	Not Operational	2009
Renk Interconnection Substation	Water	5	Operational	2007
Paloch Power Plant	Diesel	97	Operational	2005
Tharjath Power Plant	Diesel	58	Operational	2005
Total		212.4		

III. RENEWABLE ENERGY SOURCES

Hydropower and solar energy are abundant renewable energy sources in South Sudan. Hydropower is characterized by high initial costs but low operation costs, and it can be divided into large and small according to capacity [8], [9]. The hydropower generation potential is high and estimated at 5,583 MW, while the installed capacity is approximately 2777.5 MW [10]. Four large hydropower plants for electricity generation with completed feasibility studies are located in Central Equatoria State. These four large hydropower sites include Fula (1,080 MW), Shukoli (291 MW), Lakki (456 MW), and Bedden (780 MW) [11], [9]. Ayik et al. [12] studied 82 small hydropower plant sites in central Equatoria with a total power capacity of 1651 MW. The capacities of around 28.2 MW and 98.9 MW are found between Rejaf and Mongalla at a distance of 10.46 km from Juba. The farthest point between these sites is 20 km (Fig. 1).

Sunshine is 10 to 11 hours daily, with radiation on the horizontal surface from 5.5 to 6.0 kWh/square meter/day in South Sudan. Therefore, integrating solar PV generation offers a practical, off-grid solution, systems with battery backup used to form hybrid systems [9], [13]. All these renewable energy sources (hydro and solar) provide the potential for distribution generation and the possibility of their integration into the South Sudan distribution system.

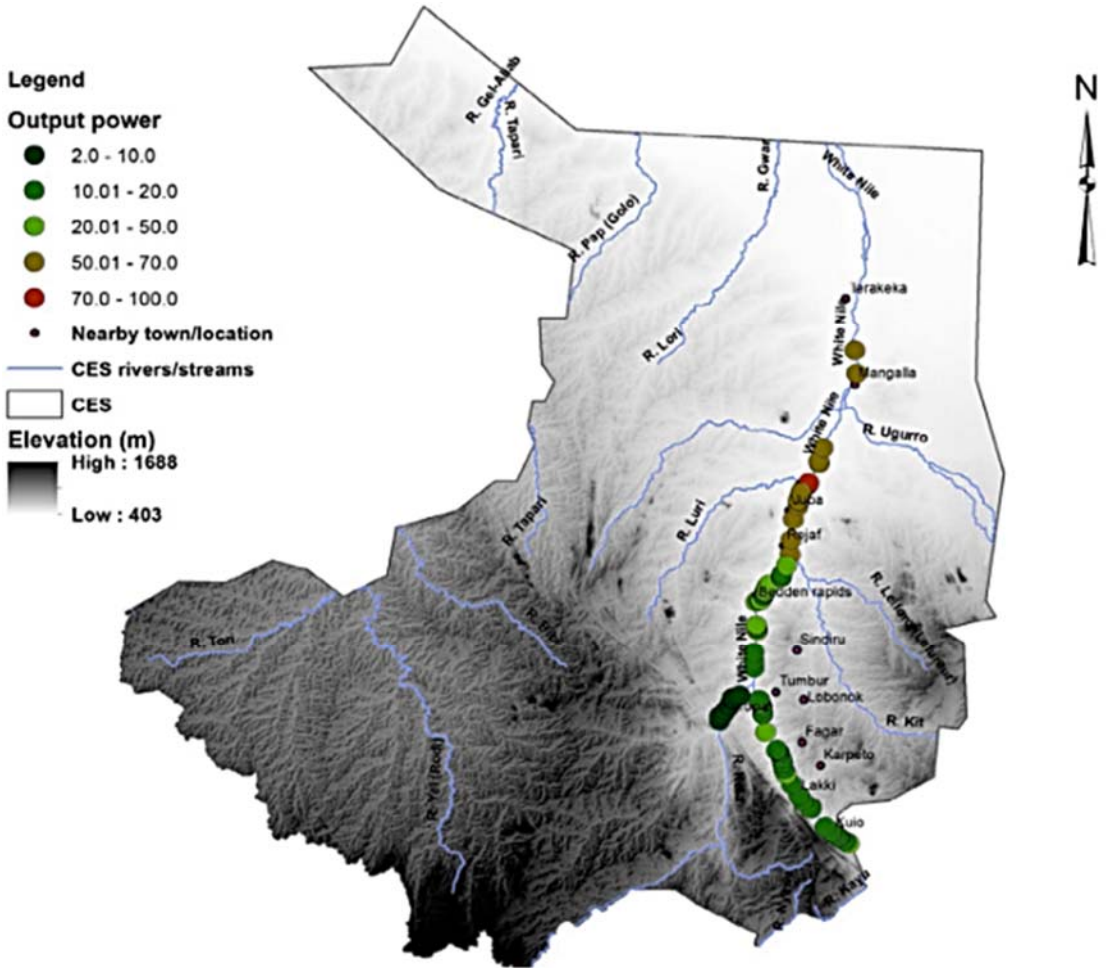

Fig. 1 Potential locations for small hydropower plants in central Equatoria

IV. National Electricity Institutions

A. Ministry of Energy and Dams, MoED

It was first established under the Minister of Electricity, Dams, Irrigation, and Water Resources after independence in 2011. Its current name is the Ministry of Energy and Dams. The Ministry is responsible for developing and implementing government policies and regulations in the electricity sector. Its primary responsibilities include formulating and developing policies, regulations, and strategies for developing and maintaining the electricity sector. In addition, it oversees the various sector actors' compliance with relevant laws, sets tariffs, identifies electricity sources, and facilitates their development. Furthermore, the Ministry of Energy and Dams is to identify potential business partners and enable private participation in developing the electricity sector in South Sudan [14].

B. South Sudan Electricity Corporation, SSEC

The South Sudan Electricity Corporation is the leading national electricity company in South Sudan. It was established in 2006 with a mandate for expanding and operating the country's generation, transmission, and distribution facilities, in addition to setting up and managing these facilities, purchasing electricity from Independent Power Producers, selling electricity in bulk to distributors, and promoting electricity imports and exports with neighboring countries. The South Sudan Electricity Corporation's employees lacked the necessary technical capacities to effectively support the company's operations. Thus, its role in electricity service has deteriorated following dismantling many of its assets and the privatization of the Juba power system. However, ownership of the Juba grid and other non-operational grid infrastructure in smaller cities remains with the South Sudan Electricity Corporation. Currently, the only operational South Sudan Electricity Corporation facility is the 30 MW substation at Renk and other towns [14], [5].

C. Ezra Power Plant, Juba

The Eritrean Company Ezra Construction and Development Group launched Ezra Juba Power Plant in 2019 as an Independent Power Producer that currently operates Juba's only functional Power Plant. A 33 MW diesel plant following the signature of an Implementation Agreement and a Power Purchase Agreement with the government in August 2017. The Ezra will operate the plant for the next 17 years and then transfer ownership to the government of South Sudan. The plant will run at an average tariff of USD 0.373/kWh with a total contract value of USD 290 million. The term of the contract calls for a total of 100 MW fossil fuel-based plant to be built and operated in four phases: 30 MW, 30 MW, 20 MW, and 20 MW.

Currently, the first phase is the only one in operation, while the remaining phases are scheduled to be completed later. This arrangement is the superior Power Purchase Agreement in South Sudan's electricity service sector. It was awarded after bilateral discussions between the developer and government without a structured Power Purchase Agreement procurement process. The greasing corruption in the form of the Power Purchase Agreement has helped reduce electricity service poverty in Juba after years of severe conflict. The negative part of it has shown a one-sided arrangement that continues to pressure the electricity service sector and consumers.

The Power Purchase Agreement has raised serious concerns about the buried role of the South Sudan Electricity Corporation. Both the Power Purchase Agreement and Implementation Agreement were signed between the Independent Power Purchase and the government in the absence of the South Sudan Electricity Corporation, which has contributed to the ambiguous role of the company. Usually, an Independent Power Purchase would sign separate agreements such as a Resource Supply Agreement, Construction Contract, Operational and Maintenance Agreements, etc. In the case of Ezra, these agreements are either missing or lumped into the Power Purchase Agreement and Implementation Agreement. This has reduced incentives for Ezra to pursue cost-saving opportunities. The Power Purchase Agreement guarantees the Independent Power Purchase a high degree of protection from various sectors and financial risks. The government should provide fuel and hard currency liquidation, while the Independent Power Purchase is granted extended tax exemptions on corporate profits and equipment import duties [14].

D. Juba Electricity Distribution Company, JEDCO

The Juba Electricity and Distribution Company was established in 2018 as a joint venture between the Ministry of Energy and Dams, with shares of 48% and the remaining 52% going to Ezra. Juba Electricity and Distribution Company is the only company providing electricity and distributing it to consumers in Juba. The joint venture was created separately as a risk mitigation mechanism for Juba Electricity and Distribution Company to manage customer revenue collection directly without having to depend on transfers from the SSEC [14].

V. Integration of Hydropower and Solar PV into the Electrical Distribution

Typically, renewable energy sources such as geothermal, biomass, solar PV, hydropower, and wind can be integrated into the distribution systems with low and medium voltages. The power generated by renewable energies can be integrated into a grid-based or stand-alone system. A solar PV system combines solar panels, power electronics devices, and battery storage systems to convert generated electricity from DC to AC or vice versa. The electricity produced depends on solar radiation and the tilt of PV panels [4].

A. Advantages and Disadvantages of Hydropower and Solar PV in Distribution System

The advantages of integrating renewable energy sources into distribution systems are improved reliability, power quality stability, and loss of electromechanical energy conversion in power systems. The reliability of the distributed generators should adequately serve a quality and affordable load. This can

be achieved through timely maintenance and reduced annual power breaks [4], [15]. Inappropriate sizing, distance and poor planning of renewable energy integration into distributed systems may cause terrible power losses and overvoltage [16].

The typical applications for solar PV are household, commercial, stand-alone or off-grid systems, while hydropower is electricity generation and irrigation. The known advantages of PV solar are low operation and maintenance costs, freedom from emissions, etc. However, solar PV has disadvantages that include impact on land and biodiversity and electromechanical energy conversion. Hydropower has low operation costs but high initial costs and water variation levels. Details of solar PV and hydropower applications and the different characteristics, advantages, and disadvantages of hydropower and solar PV applications are described in Table II.

TABLE II
APPLICATION, ADVANTAGES AND DISADVANTAGES OF HYDROPOWER AND SOLAR PV

Distributed Generator Type	Solar PV	Hydropower
Applications	Household, industrial, commercial, communications, navigation and transportation systems and off-grid	Power generation and irrigation
Advantages	Low operation and maintenance costs, sustainable, modular and no emissions	Low operation and maintenance costs, no environmental impact, reliable and flexible operation
Disadvantages	Electromechanical energy conversion and environmental impacts effects on land and biodiversity	High initial cost, variation in water level

VI. JUBA SOLAR PV PARK

In 2019, the Ministry of Energy and Dams announced a tender to build a solar power plant in an area of 25.000 Hectares (250,000 square meters) with a latitude of 4.84696 and a longitude of 31.58070 in the Nesitu site 20 km South of Juba city (Fig. 2). The Egyptian Elsewedy Electric Company completed the construction of solar PV in 2023, which started in 2020. The plant has a 20 MW Solar PV system capacity with 35 MWh Battery Storage. The project cost is US$ 45 million, financed by the African Export-Import Bank. Other involved parties include Asunim U.K. Ltd, which provides Engineering, Procurement and Construction services. The current status of the plant is at the financial stage. Upon clearing all remaining payments, the plant will start to service 59000 residents in Juba and save 10,886.2 tons of carbon dioxide emissions (CO_2) annually. The project construction is expected to commence in 2024. After that, it will enter into commercial operation by 2025. The plant components include PV solar panels, an inverter station, and a battery storage system (Figs. 3 and 4). The PV panels' fixed mounting structure tilt angle is 8 degrees south orientation (Fig. 5).

Juba Solar PV Park will construct a 33 kV transmission line, including a Ring Medium Unit (RMU), before being connected to the Juba distribution network system. Shobole et al. [17] stated that integrating solar PV might affect the protection system because of a fault occurrence in a substation. Fig. 6 illustrates the adverse effects of solar PV integration into the distribution system. Such blinding protection systems happen at long feeders and concentrated distributed generations. Fault current will trigger dangerous overvoltage to other equipment in the system. The location of the fault, grid impedance, distributed generator capacity and short circuit current determine the danger of the fault.

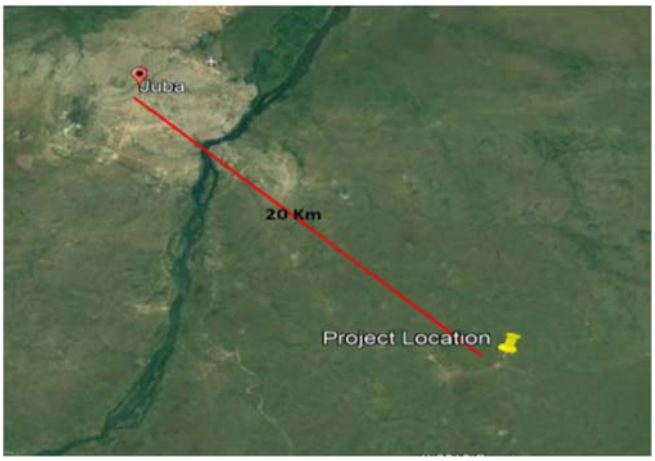

Fig. 2 Location of Juba Solar PV Park

Fig. 3 PV inverter station

Fig. 4 Battery storage system station

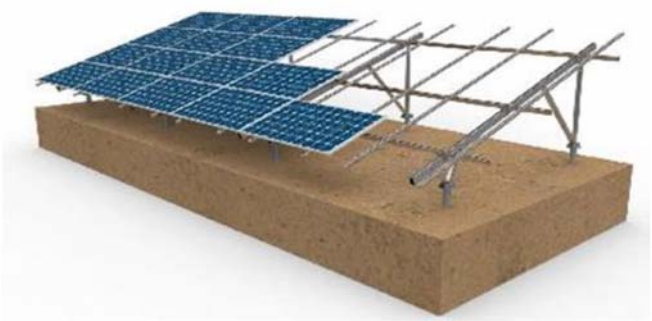

Fig. 5 PV panels' fixed mounting structure tilt angle is 8 degrees south orientation

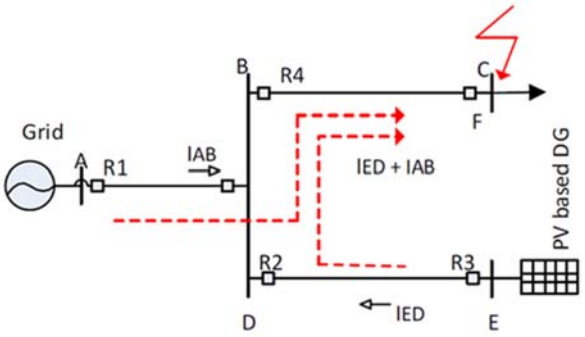

Fig. 6 Fault effect during solar PV integration into a network system

Most distribution systems are not designed to supply power in two ways; however, power flows in both directions for solar PV systems. In two cases, over or under-generation will cause instability in the distribution system. Solar radiation forecast tools, energy storage systems and avoiding underload are measures to overcome over/under voltage in the distribution system [18].

PV systems ranging from 1-25kW can generate electricity to low points of the distributed system of 600 V and below. Such systems reduce transmission line losses, increase grid power quality, and reduce generation costs. PV systems can mitigate load reliability issues connected to newly developed distributed systems. This can be achieved by introducing a standby capacity that provides stable power during poor power quality [18]. However, the largest PV systems, 10 MW and above, are typically far from customers requiring transmission lines. This arrangement involves cost and line losses. As a result, some of the energy is lost as heat during transportation [19].

International organizations for distributed generators integration into distribution systems include the Electric Power Research Institute, the International Council on Large Electric Systems (CIGRE), the Institute of Electrical and Electronics Engineers, and the International Energy Agency. These organizations offer standards and codes for integrating distributed generators according to distance, ratings, technology, etc. [20]. Electric Power Research Institute organizes the integration of solar PV generation of a few kW up to 50 MW and energy storage devices located near distributions [21]. The CIGRE focuses on generating systems with 50 MW and 100 MW capacity connected to the centralized or dispatched network [22]. The Institute of Electrical and Electronics Engineers deals with electricity generation from infrastructure relatively smaller than centralized distribution systems to allow near-to-power system sites [23]. The International Energy Agency coded for distributed generator integration into gird at distributed voltage levels to supply customers at the location and assist a distributed system. The distributed generators include combustion engines, turbines, fuel cells and PV systems [24]. Juba Solar PV Part considers all these international organizations for solar PV integration into the Juba Distribution system. This will ensure safe integration, reliable power supply and system instability.

VII. Conclusion

Hydropower and solar PV generation can be integrated into the distribution system in South Sudan. The Ministry of Energy and Dams contracted an Egyptian company, Elesewedy, to construct Juba Solar PV Park to reduce the thermal generation and increase the current 33 MW to 53 MW. The integration and stand-alone small hydropower generation should be the starting point for the national grid with growing demand in the future. The South Sudan Electricity Corporation's role in electricity generation under the Ministry of Energy and Dams policy objectives and regulations must be maintained—attracting international funding and expertise by easing investment rules and regulations in electricity generation. In addition, the South Sudan Electricity Corporation should increase awareness and promote possibilities in Small and Medium Enterprises for stand-alone generation and consumption to avoid electricity supply outages.

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