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RESEARCH ARTICLE

CONTRIBUTION TO IMPROVING HYDROPOWER AT THE YERIPAO MICRO-DAM IN THE REPUBLIC OF BENIN

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ABSTRACT

Hydropower is a key factor in the socioeconomic development of various regions of the Republic of Benin. This study focuses on modeling the main components of the Yéripao hydroelectric power plant in northern Benin, which has a generating capacity of 500 kW, with the aim of addressing the energy challenges hindering the region's development while making the most of available hydropower resources. The purpose of this article is to model the various components of the power plant, namely the penstock and the hydraulic turbine. The tools of choice for addressing this type of problem are hydrological analysis and mathematical simulation models. The results focused on two cases deemed to be priorities: the 800-mm-diameter, 2,300-meter-long penstock with a flow rate of 0.8 m^3/s and a head of 120 m, delivering 800 kW of hydraulic power through the turbine, and the 650-mm-diameter pipeline, 1,750 m long, with a flow rate of 0.5 m^3/s and a head of 100 m, providing 420 kW of hydraulic power through the turbine. These results, which are currently preliminary, mean that the watercourse flow has not been regulated and that a reserve capacity must be set aside for the dry seasons of the year, when the hydroelectric power plant will be unable to meet the demand of the town of Yéripao. The use of this methodology has proven highly effective in finding solutions to the challenges of balancing needs and resources in developing countries. Given that the development of hydropower will play a decisive role in ensuring the stability of the electric power system in the future, policymakers will need to consider several measures to make the most of it.

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INTRODUCTION

Hydropower is energy generated by moving water (watercourses) and can be used to generate electricity. It is produced by a hydroelectric power plant that harnesses the potential energy of a watercourse (rivers, streams, waterfalls, ocean currents, etc.). It is one of the most established forms of electricity generation (1). These days, it is important to note that continuous access to electricity is one of the essential prerequisites for a country's socioeconomic development (2-3). In an electric power system that requires greater flexibility, hydroelectric power plants are perfectly capable of supplying large volumes to today's and tomorrow's electricity markets and power systems (4). Storage plants and pumped-storage stations can be brought online in just a few minutes, and their output can be adjusted in a matter of seconds. Hydropower plants are therefore capable of responding to even significant fluctuations in real time (4). In Europe, hydropower—that is, water power—is currently the most efficient storage technology and the only one capable of large-scale storage. It is a major industry with a two-thirds share of the global market, providing thousands of highly skilled jobs across the continent. The total installed storage capacity in Europe amounts to more than 180 TWh, providing short-, medium-, and long-term storage capacity depending on the size of the reservoirs (4). In Africa, faced with the challenges of electrifying national territories and meeting growing energy demand, hydropower is emerging as a promising solution that is already being implemented. The construction of hydroelectric power plants in Africa—whether small-scale hydropower (generally less than 10 MW) or large dams (with a height greater than 15 meters, or, if between 5 and 15 meters, with a reservoir capacity of at least 5 millions m^3) — only truly makes sense within the context of rural and urban electrification goals and interconnections between different energy grids (national and regional) (5). Electricity and water are two key issues in Africa in general. Access to these essential resources is a central issue in local and national politics and is frequently the subject of patronage-based relationships between the political class and the population (5). In Benin, the electricity sector is characterized by very low national production and limited access to electricity for the population. In 2017, the electrification rate in rural areas was 9 percent, six times lower than the urban electrification rate (54 percent) (6). This energy challenge stems primarily from Benin's heavy dependence on other countries for its electricity supply. Approximately 86.57% of the electricity consumed in Benin comes from neighboring countries, notably Ghana, Côte d'Ivoire, and Nigeria (7). As a result, it will be necessary to increase the supply of electricity and make it more accessible to people in rural areas. Furthermore, Benin has only one hydroelectric power plant in the entire country. This is the Yéripao hydroelectric power plant, located in northern Benin, with a generating capacity of 500 kW. The hydrological characteristics of the river at the Yéripao site are marked by long periods of low water, which result in a sharp decrease in flow rates, thereby limiting hydropower production. This led the government of Benin to initiate the redevelopment of the Yéripao hydroelectric power plant and its expansion, which is part of Benin's Millennium Challenge Account (MCA II) (8). The objective of this study is to help Benin meet its own electricity production needs in the town of Yéripao. This is the fundamental reason for this article on the hydropower resources at the Yéripao site. To achieve the objective of this study, a methodology based on hydrological analysis and mathematical modeling of the infrastructure was adopted. Hydrological data for the site were collected and analyzed to determine the technical parameters essential for the mathematical modeling. The results obtained demonstrate the system's ability to improve the living conditions of the residents of Yéripao.

OVERVIEW OF THE STUDY AREA AND THE STUDY SITE

Overview of the Study Area : Benin is a country in the sub-Saharan African subregion, more specifically in the Gulf of Guinea region, between the Tropic of Cancer and the Equator. It is bordered to the north by the Republics of Niger and Burkina Faso, to the south by the Atlantic Ocean, to the east by the Republic of Nigeria, and to the west by the Republic of Togo (Fig.1). Benin's climate is equatorial in the south, with two dry seasons and two rainy seasons. From the center to the north of the country, the climate is tropical, with one dry season and one rainy season.

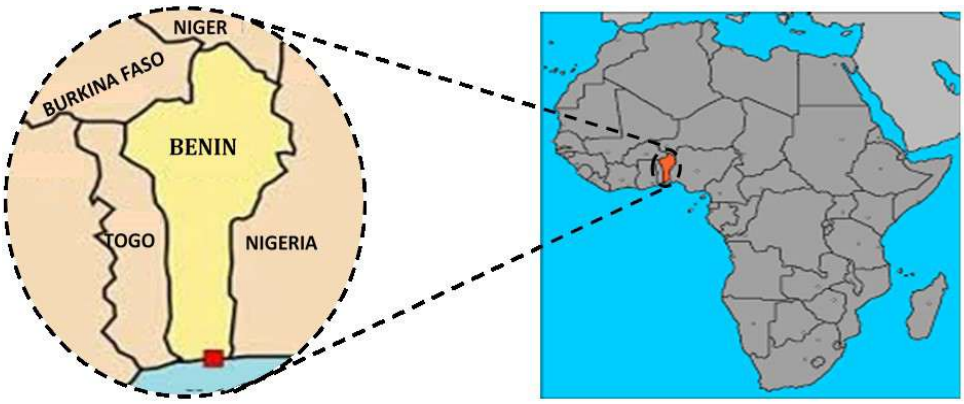

Fig. 1. Geographical location of Benin

Overview of the study site : This study focuses on the water resources at the Yéripao site. This site is located in the municipality of Natitingou (northwestern Benin). Its geographic coordinates are 10°15'21.06" N latitude, 1°25'43.57" E longitude, and an elevation of 430 m (Fig.2). The hydroelectric power plant at the Yéripao site is located on the Tiatiko River, approximately 9 km from the village.

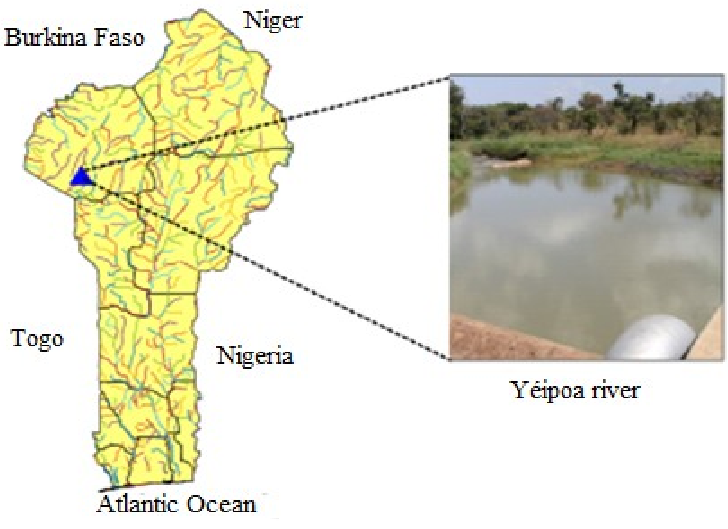

Fig.2 Geographic Location of the River at the Yéripao Site

Hydrological and climatic data for the Yéripao site

Daily Assessment of River Flow Rates at the Yéripao Site : The daily variation in river flow during the 2016–2017 period is shown by the curve in Fig.3. The flow data for the 2016–2017 period were determined by extrapolation from the 1988 flow rates (9) and precipitation and evapotranspiration data (10) for the site.

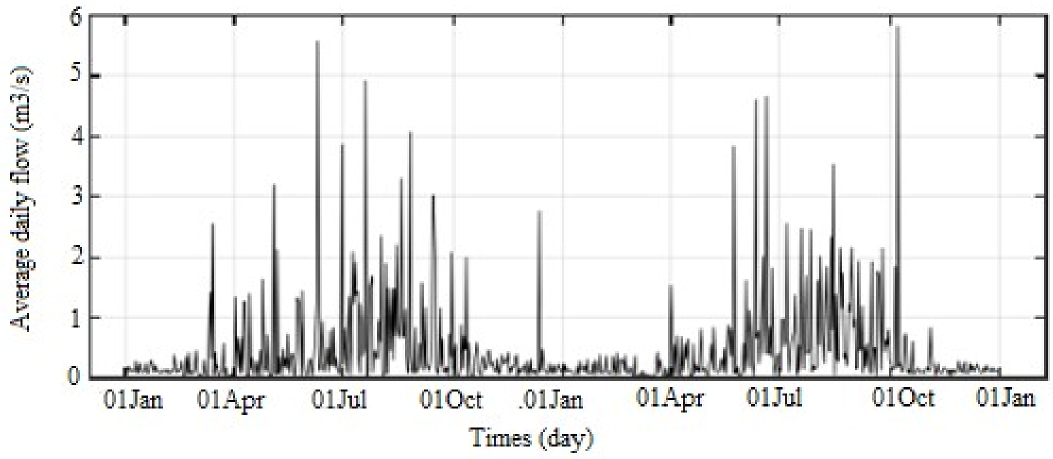

Fig.3 Changes in the average daily flow rates of the river at the Yéripao site for the period from 2016 to 2017

Daily Assessment of Radiation Levels in the River at the Yéripao Site : The daily variation in total radiation during the 2016–2017 period is shown in Fig.4. These data were obtained from the SoDa website (10).

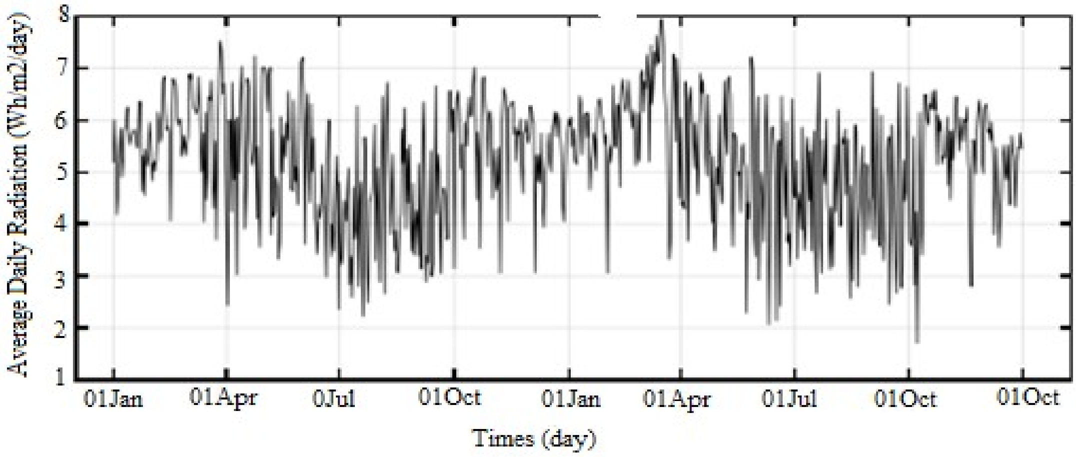

Fig.4. Trends in Average Daily Radiation Levels in the River at the Yéripao Site for the Period from 2016 to 2017

Daily measurement of the ambient temperature along the river at the Yéripao site : The daily variation in ambient temperature during the 2016–2017 period is shown in Fig.5. These data were also obtained from the SoDa website (10).

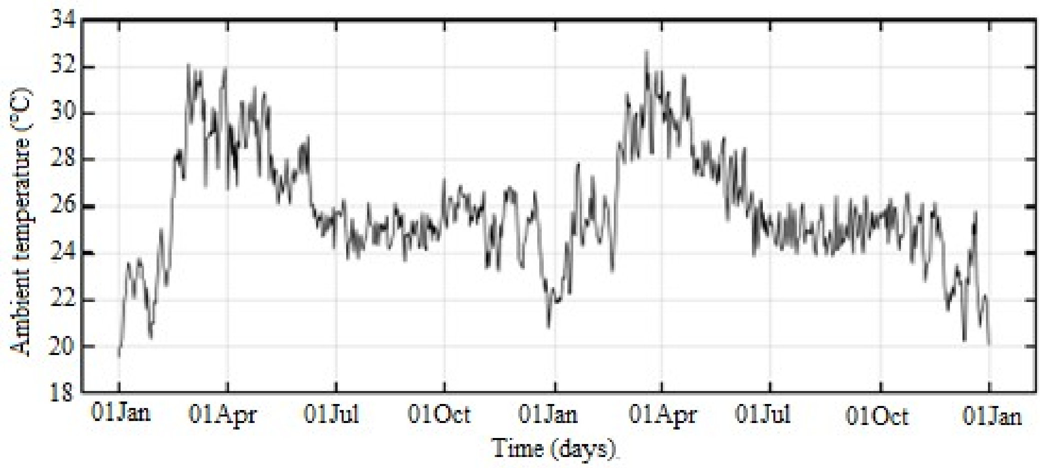

Fig.5. Changes in Average Daily Temperatures on the River at the Yéripao Site for the Period from 2016 to 2017

The need to ensure the river's good ecological quality requires maintaining a minimum water flow in the riverbed, known as the reserved flow. The Law on Water and Aquatic Environments (LEMA), adopted on December 30, 2006 (11-12), recommends that this flow be at least one-tenth of the interannual average flow. Thus, for the purposes of this study, we estimate it to be one-tenth of the average flow for the two-year period from 2016 to 2017.

MATERIALS AND METHODS

How a Hydroelectric Power Plant Works : Fig.6 illustrates how a hydroelectric power plant works. The penstock channels the water (under pressure) to the turbine. The water's energy is transferred to the turbine blades, which begin to rotate and drive the generator that produces electricity. In effect, the water's potential energy is transformed into mechanical energy, which is ultimately converted into electricity by the generator. Next, a transformer steps up the voltage of the electricity produced by the generator so that it can be transmitted more easily. Finally, the water that has driven the turbine returns to the river via the tailrace.

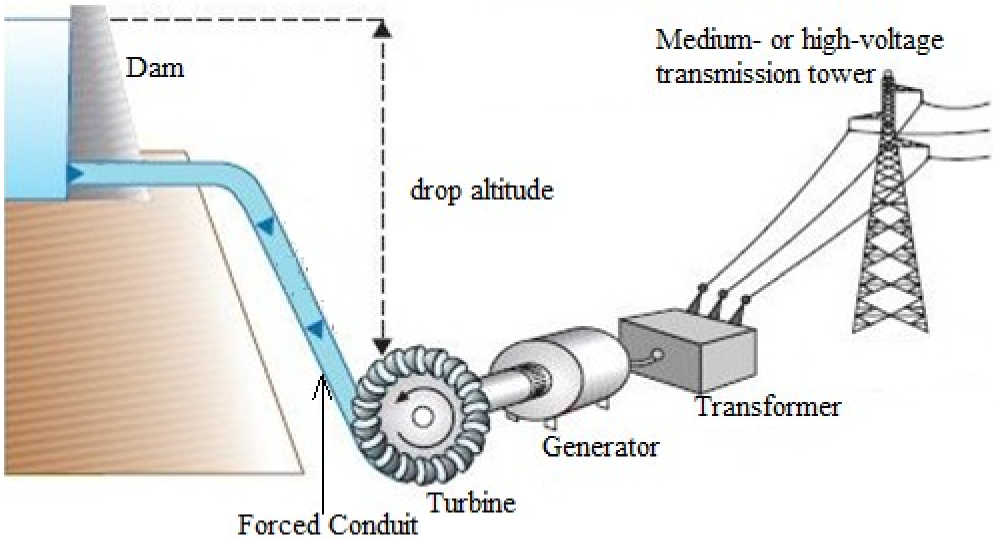

Fig. 6. How a Hydroelectric Power Plant Works (1)

Methodological Approach : The study involved analyzing the daily averages and flow rates of the river at the Yéripao site, as well as the power demand in Natitingou. As for the flow rates, we simulated the water releases—and thus the amounts of water available for electricity generation—based on the size of the penstock to be designed.

Model of the penstock : The design of the return pressure pipe is of paramount importance (13). The design involved determining the diameter (D_{cond}) and the length of the pressure pipe (L_{cond}).

The diameter is determined as follows:

$$Q_{moy} = VS \tag{1}$$

$$S = \frac{\pi D_{cond}^2}{4} \tag{2}$$

$$Q_{moy} = \frac{V\pi D_{cond}^2}{4} \tag{3}$$

$$D_{cond} = \sqrt{\frac{4Q_{moy}}{\pi V}} \tag{4}$$

with:

Q_{moy} : average annual flow of the river

D : diameter of the penstock

V : average flow velocity

S : cross-section of the penstock

As for determining the length of the pipe L_{cond} , we have :

$$h_f = f\frac{V^2 L_{cond}}{2gD_{cond}} \quad (5)$$

$$L_{cond} = \frac{2gh_f D_{cond}}{fV^2} \quad (6)$$

with:

L_{cond} : length of the penstock

h_f : friction pressure losses in the penstock

g : gravitational acceleration

f : coefficient of friction

Model of Average Hydraulic Power : The model for average annual hydropower is defined based on two factors: the flow rate and the head of the watercourse at the site where the hydroelectric power plant is located. It is expressed as follows:

$$P_{cond} = \rho g Q_{moy}\left(H_b - h_f - h_l\right) \quad (7)$$

with :

ρ : density of water equal to 1kg/l

g : gravitational acceleration, which is approximately 9.81 m^2/s

Q_{moy} : average annual flow of the river

H_b : gross drop altitude

h_f : friction pressure losses in the penstock

h_l : local (or singular) pressure drops in the penstock

Friction-induced pressure losses in the penstock: The model most commonly used in the literature to determine friction head losses in a penstock is the Darcy-Weisbach model, given by the equation:

$$h_f = f\frac{V^2 L_{cond}}{2gD_{cond}} \quad (8)$$

$$V = \frac{4Q_{moy}}{\pi D_{cond}^2} \quad (9)$$

$$h_f = \frac{8fQ_{moy}^2 L_{cond}}{g\pi^2 D_{cond}^5} \quad (10)$$

The advantage of this model is that the friction coefficient f is dimensionless and depends on the Reynolds number R_e, which defines the characteristics of the watercourse flow (discharge). The expression for f varies depending on the nature of the watercourse flow.

For laminar flow ($R_e < 2400$) (14), f is determined by Poiseuille's formula:

$$f = \frac{64}{Re} \quad (11)$$

For turbulent flow $\left(R_e \geq 2400\right)$, the relationship proposed by Zingrang and Sylvester (15) is used to determine 5. This relationship is less dependent on 55 and more dependent on the relative roughness e / D_{cond} where e et D_{cond} represent, respectively, the average wall roughness equal to 0.6 55 and the diameter of the penstock:

$$f=\left[-2\log_{10}\left\{\frac{\frac{e}{D_{cond}}}{3.7}-\frac{5.02}{Re}\log_{10}\left(\frac{\frac{e}{D_{cond}}}{3.7}-\frac{5.02}{Re}\log_{10}\left(\frac{\frac{e}{D_{cond}}}{3.7}+\frac{13}{Re}\right)\right)\right\}\right]^{-2} \quad (12)$$

Singular pressure drops : Local pressure losses (h_l) are the sum of the losses in the grates (h_g), at the pipe inlet (h_e), in the valves (h_v), in the bends (h_b), and those due to sudden changes (narrowing or widening) in the pipe diameter (h_c) :

$$h_l = h_g + h_e + h_v + h_b + h_c \quad (13)$$

The recommendations in the European Small Hydropower Association's guide (16) were used to determine each component of the specific losses. Specifically, h_g is estimated using Kirschmer's formula :

$$h_g = k_g k_\beta \left(\frac{e_b}{b}\right)^{4/3}\left(\frac{V^2}{2g}\right)\sin\phi \quad (14)$$

with:
e_b : bar thickness
b : spacing between bars
ϕ : angle of inclination relative to the horizontal
k_g : coefficient whose form depends on the bars
k_β : coefficient whose value depends on the angle β between the grid and the flow.
The other specific losses (h_e, h_v, h_b, h_c) are proportional to $\frac{V^2}{2g}$, and their sum is given by:

$$h_\delta = (k_e + k_v + k_b + k_c)\frac{V^2}{2g} \quad (15)$$

with :
k_e : singular inlet pressure drop coefficient
k_v : singular pressure drop coefficient for flow through the valves
k_b : singular pressure drop coefficient for flow in curves
k_c : singular pressure loss coefficient for flow through abrupt pipe expansions and constrictions.

Table 1 below lists the values of the singular pressure drop coefficients.

Table 1. Coefficients of local pressure drops (16).

t	b	ϕ	k_g	k_β	k_e	k_v	k_b	k_c
12 mm	70 mm	60°	2.4	1	0.04	0.6	0.08	0.1512

with:
t: bar thickness
b : spacing between bars

RESULTS AND DISCUSSION

Fig.7 shows the river flow rates at the Yéripao site throughout the year, as well as the hydraulic power.

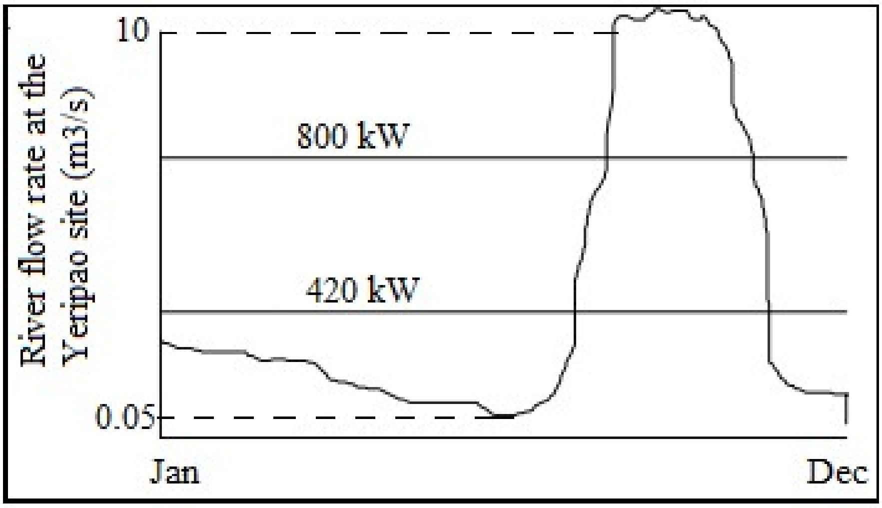

Fig.7 River flow at the Yéripao site throughout the year and power plant capacity

Fig.7 shows that the river at the Yéripao site has a highly irregular flow rate, ranging from 0.05 m³/s during the dry season to more than 10 m³/s during the rainy season floods. The two horizontal lines indicate hydraulic power ratings of 800 kW and 420 kW. The reservoir capacity at the Yéripao dam site is approximately 6,400 m³. During peak floods, this reservoir fills in 10 minutes and empties while generating 800 kW of hydroelectric power in less than 2 hours. It must therefore be concluded that the Yéripao micro-dam hydropower project is a “run-of-the-river” system, rather than a “dam” system. Table 2 below presents the results for flow rates and hydraulic power as a function of head at the Yéripao river site.

Table 2. Flow rates and hydraulic power as a function of head

Flow rate of the penstock in m³/s	Estimated annual flow in m³/year	Hydraulic power	
		120-meter drop kW	100-meter drop kW
1,0	10,240,659	1,000	840
0,9	9,381,901	900	755
0,8	9,385,213	800	670
0,7	8,897,744	700	590
0,6	8,371,741	600	500
0,5	7,779,555	500	420

The data in this table represent the physical maximum values based on hydraulic capacity. Two cases are considered priorities: the 800-mm-diameter pipe with a flow rate of 0.8 m³/s and a head of 120 m, providing 800 kW of hydraulic power ; and the 650-mm-diameter pipe with a flow rate of 0.5 m³/s and a head of 100 m, providing 420 kW of hydraulic power. In addition to pipe diameters, two length options were considered. The length corresponding to the 800-mm-diameter pipe with a head of 120 m is 2,300 m, and that for the 650-mm-diameter pipe with a head of 100 m is 1,750 m. These results have a significant implication for the hydroelectric power plant. Specifically, the river’s flow will not be regulated, and therefore the benefits expected from such regulation will not materialize. The observation made earlier also means that backup power must be provided for the dry seasons of the year, when the hydroelectric power plant will be unable to meet the demand of the town of Yéripao. As long as this town is not connected to Benin’s national grid or to the grid of a neighboring country, it will be necessary to provide double the power generation capacity for that town. For the immediate future, it is suggested that the Yéripao Dam be upgraded to ensure the regulation of the river’s flow and optimal hydroelectric power generation, as well as to double power generation capacity in order to resolve the problem. These results corroborate those of (17) and the (18). According to the first author, a study of the environmental impacts of hydroelectric developments at the Manantali Dam in Senegal shows that the dam ensures river flow regulation, hydroelectric power generation, agricultural development in the three countries (Mali, Mauritania, Senegal), and, in the near future, navigation. The second author (IEA) notes that global electricity generation capacity from renewable energy sources, including hydropower, is expected to double by 2030. At COP 28 in the United Arab Emirates in November 2023, nearly 200 countries, including Benin, committed to tripling global renewable energy capacity by 2030. This goal remains achievable if countries adopt stronger policies to bridge the gaps in ambition and implementation. They will need to minimize political uncertainties, reduce permitting delays, increase investment in grid infrastructure, and enhance flexibility to facilitate the integration of renewable energy sources—including hydropower—to ensure the stability of the electric grid in the future.

CONCLUSION

This article has outlined the context of hydropower in Benin. It is important to note that Benin continues to face significant energy crises despite its enormous energy potential, particularly in the country's rural areas, as is the case in the town of Yéripao. Benin's heavy reliance on neighboring countries for its electricity supply is the main cause of its energy challenges. In summary, these preliminary findings indicate that there is no regulation of the river's water flow and that a reserve capacity is needed for the dry seasons of the year, when the hydroelectric power plant will be unable to meet the demand of the town of Yéripao. The investment cost model for the pressure pipeline and the hydroelectric turbine appears to be a desirable complement to the models studied in this paper.

Author's Contributions: All authors contributed to the conception, data analysis, and drafting of the manuscript, and approved the final version.

Conflit of Interest: The authors declare that they have no conflict of interest.

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