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## Article

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## Bootstrapping the Cost Modelling of Hydropower Projects in Sub-Saharan Africa: Case of Chinese Financed Projects

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### ABSTRACT

In last decades, many scholars have studied the cost of hydropower plants based on the capacity and head. The different correlation equations obtained depend mostly on geographical locations and electro-mechanical characteristics. As Sub-Saharan Africa remains the region with the largest untapped hydropower potential, coupled with the need of expansion of Chinese energy companies, this paper aims to estimate the cost of hydropower projects financed and constructed by Chinese companies in Sub-Saharan Africa. The data used in this study were rigorously selected. After refinement of the raw data, screening was performed to improve the quality of the database suitable for the log transformed linear regression. Furthermore, a bootstrap resampling with replacement was applied to assure the robustness of the model. The results show a good accuracy of the model confirmed by the high value of the coefficient of determination and an average error <20%.

**Keywords:** Hydropower Project Cost, Capex Modelling, Bootstrap Resampling, Sub-Saharan Africa, Chinese Investment

**JEL Classifications:** A100, Q400, C390

### 1. INTRODUCTION

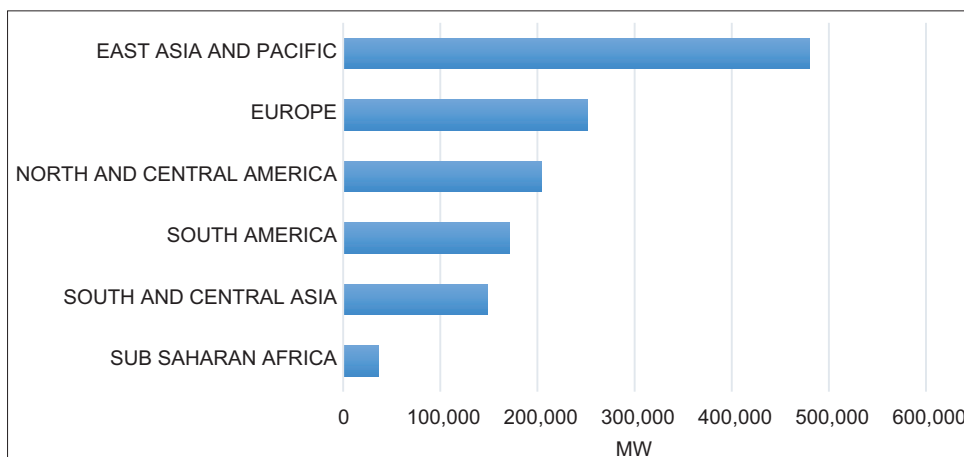
Hydropower generates almost two-thirds of the world's renewable electricity and is making a major contribution to delivering on the ambition of the Paris Agreement and the Sustainable Development Goals as a low carbon mature technology. According to IHA (2019) and Brown et al. (2011), without hydropower, the objective of limiting climate change to 1.5 or 2° above pre-industrial levels would likely be out of reach. Hydropower is the lowest cost source of electricity generation. It is not only a reliable mature electricity generation, but also a flexible and cost effective energy generation source responsible for 86% of all non-fossil fuel energy use.

Despite its vast renewable energy resources, Africa is the continent with the highest percentage of untapped technical hydropower potential in the world (89% untapped potential). As seen in Figure 1, Sub-Saharan Africa lags far behind other regions in the

world in term of hydropower generation capacity and its population continues to rely mostly on oil and gas along with traditional biomass combustion for energy consumption.

The African Union and African Development Bank supported Program for Infrastructure Development in Africa (PIDA) regards hydropower development as a priority, alongside interconnections for regional power pools. The PIDA estimates that the region's total generating capacity needs to increase by 6%/year to 2040 from the current total of 125 GW to keep pace with rising electricity demand. Africa's hydropower installed capacity is expected to grow by about 4,700 MW over the next 2 to 3 years providing great opportunities for construction. Unfortunately, Dumisani (2016) analyzed that Sub-Saharan Africa struggles to attract investment for hydropower projects while Zhao et al. (2016) in line with Zhao and Atchike (2015) concluded that investors seeking a new energy frontier are slowly beginning to recognize the region's rich potential.

**Figure 1:** Hydropower installed capacity per regions



Source: Processed from IEA (2016)

The role of China as a hydropower developer has changed significantly in recent years. From 1950 to 2000, Chinese hydropower development was highly dependent on foreign assistance from multilateral organizations such as the Asian Development Bank or from other governments such as Russia. After funding many of its domestic projects, China has also started investing heavily in hydropower development projects in neighboring countries and Africa since 2000. Following the “going out strategy” where infrastructure deficits have historically been a bottleneck to economic growth and investment, hydropower is one area in which Chinese financial resources and domestic expertise could contribute to energy infrastructure and security. Chen and Landry (2016) found out that the boom of China’s hydropower in Africa emerged at a time when the World Bank had started to develop some major safeguard policies and accountability mechanisms in order to address and mitigate some of the negative environmental and social impacts of large hydropower projects. China has thus become a significant player in infrastructure construction around the world particularly in low-income countries in Africa and Asia. Kong and Gallagher (2017) stated that Chinese energy companies entered the global market through large amounts of financing provided by China’s two global policy banks, the China Development Bank and the Export–Import Bank of China. Brautigam et al. (2015) further explained that China Exim Bank has five types of loan instruments: export seller’s credits, export buyer’s credits, preferential export buyer’s credits, concessional foreign aid loans (CL), and special state loans. Export buyer’s credits are usually issued at competitive commercial interest rates that parallel the rate set for China’s government bonds. China Exim Bank is the only Chinese bank authorized to provide preferential or concessional loans (i.e. with interest rates subsidized by the Chinese government). Concessional foreign aid loans require a loan framework agreement signed between the two governments, while export buyer’s and seller’s credits can be signed directly with the agency approved to borrow. Some of those financed project have suffered delays and cost overrun. As little quantitative research has investigated the cost of hydropower investment in Sub-Saharan Africa, this paper aims to fill this gap of knowledge by developing an equation of the Chinese financed hydropower projects depending on the net head and capacity.

## 2. LITERATURE REVIEW

Over the past years, several scholars have estimated the cost of hydropower (Gordon and Penman (1979), Lasu and Persson (1979), Gulliver and Dotan (1984), Whittington et al. (1988), Voros et al. (2000), Chenal (2000), Doujak and Angerer (2001), Papantonis (2001), Gordon (2003), Kaldellis (2007), Singal and Saini (2008), Ogayar et al. (2009) by considering the electro mechanical cost. According to ETRI (2014), for most of hydropower projects, electro-mechanical cost represent about 30-40% of the total cost (37% as seen in Figure 2). The correlations are dependent on the power (P) and the net head (H) according to the following equation model:

$$\text{Cost} = \alpha P^\beta H \tag{1}$$

Where  $\alpha, \beta, \phi$  are determined through linear regression of the existing database.

Gordon and Penman (1979) first developed a correlation of electro-mechanical cost for projects below 5 MW in North America obtaining the equation:

$$c = 9000 P^{0.7} H^{-0.35} \tag{2}$$

Many other researchers such as Gordon and Penman (1979), Lasu and Persson (1979), Gulliver and Dotan (1984), Whittington et al. (1988), Voros et al. (2000) and Chenal (2000) followed Gordon’s work by estimating different equations in different parts of the world.

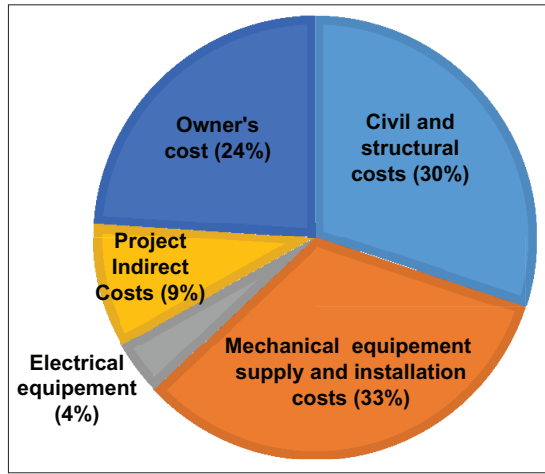
Later in 2001, Doujak and Angerer (2001) innovated by developing an estimation of the investment costs for projects with  $P < 2$  MW and  $H < 15$  m and obtained the equation:

$$C_i = K P^m H^{-0.3} \tag{3}$$

Where  $C_i$  represents the cost of investment including direct and indirect investment costs instead of the electro-mechanical cost.

In 2001, Papantonis (2001) estimated the costs of different components of the hydro plants by detailing the costs of electro-mechanical equipment (turbine, speed control and generator), the costs of different types of turbines (Kaplan, Francis and Pelton),

**Figure 2:** Capex breakdown of hydropower plant



Data Source: ETRI (2014)

cost of generators, speed controls, dams and intakes as function of hydraulic characteristics of a hydro site (head and flow or head and capacity). The cost of electromechanical equipment aligned with Gordon's equation with an inflation rate adjustment:

$$C_{EM, \epsilon} = 9600 P^{0.82} H^{-0.35} \quad (4)$$

Gordon (2003) further introduced a location factor  $F$ , a site factor  $S$  and a factor ( $k$ ) related to the standard project design cost in 2003. Replacing the average values of the coefficients  $F$ ,  $S$  and  $K$ , the following equation was obtained:

$$\text{Cost}_{\epsilon/kW} = 12900 P^{0.82} H^{-0.246} \quad (5)$$

In 2009, based on Spanish data for a project below 2 MW, Ogayar et al. (2009) introduced an empirical equation to estimate the cost of electromechanical equipment, taking into account the great diversity in the typology of turbines and alternators. The correlation was developed for each of the 3 most common types of turbines:

Pelton:

$$C_{EM, \epsilon/kW} = 17693 P^{-0.3644725} H^{-0.281735} \quad (6)$$

Francis:

$$C_{EM, \epsilon/kW} = 25698 P^{-0.560135} H^{-0.127243} \quad (7)$$

Kaplan:

$$C_{EM, \epsilon} = 19498 P^{-0.58338} H^{-0.113901} \quad (8)$$

In 2010, Aggidis et al. (2010) developed a new correlation for overall plant and electro-mechanical equipment based on project data for hydro sites in the northwestern region of the UK.

$$CC_{EM, \epsilon} = 12000 (P/H^{0.2})^{0.5} \quad (9)$$

Cavazzini et al. (2016) presented in 2016 a new approach for the estimation of the cost of electro-mechanical equipment decomposed in the cost of the mechanical equipment (turbine, automatic valve and regulation elements) and the cost of the electrical equipment (cost of the alternator) adding the design flow rate parameter to the power and net head.

Pelton:

$$C_{EM} = 1358677.167 H^{0.014} + 8489.85Q^{0.515} + 3382.1P^{0.416} - 1479160.63 \quad (10)$$

Francis:

$$C_{EM} = 190.37 H^{1.27963} + 1441610.56 Q^{0.03064} - 9.62402 P^{1.28487} - 1621571.28 \quad (11)$$

Kaplan:

$$C_{EM} = 139318.161 H^{0.02156} + 0.06372 Q^{1.45636} - 155227.37 P^{0.11053} - 302038.27 \quad (12)$$

Finally, Davitti (2018) developed the total cost of capital expenditure for hydropower projects in developing countries obtaining the following equations:

Saharan & Western Africa:

$$\text{CAPEX} = 12\,638\,378 P^{0.7664} H^{-0.0104} \quad (13)$$

Eastern & Southern Africa:

$$\text{CAPEX} = 9\,969\,795 P^{0.8618} H^{-0.1279} \quad (14)$$

Central Africa:

$$\text{CAPEX} = 7\,776\,450 P^{0.9073} H^{-0.1180} \quad (15)$$

South-East and Pacific Asia:

$$\text{CAPEX} = 6\,619\,254 P^{0.8594} H^{-0.0686} \quad (16)$$

Eastern Europe and Middle East:

$$\text{CAPEX} = 9\,696\,625 P^{0.8545} H^{-0.1207} \quad (17)$$

Latin America:

$$\text{CAPEX} = 3\,117\,530 P^{0.9798} H^{-0.0320} \quad (18)$$

The results of these studies summarized in Table 1 present a variety of correlations depending on the region and the period of time of the study but none of those studies have investigated the correlation of investment cost of hydropower projects financed by China and constructed by Chinese companies in Sub-Saharan Africa since those projects have great particularities.

### 3. METHODOLOGY

#### 3.1. Data Collection

Fichtner (2015) noticed that total investment costs for hydropower vary significantly depending on the site, design choices and the cost of local labor and materials. Hydropower projects constructed across Sub-Saharan Africa have a lot of particularities that make them very diversified. This analysis include small, medium and large hydropower projects costs from feasibility studies and actual data. To assure the quality of this study, projects with Chinese involvement in Sub-Saharan Africa were carefully selected. Due to the scarcity of hydropower projects in the untapped potential of Africa, combined with the focus of this study on Chinese involvement and the strict selection criteria, 21 hydropower projects were verified and selected for this study.

To avoid dispersion in the database that can weaken the results, the selection of projects was made based on the following criteria:

**Table 1: Previous studies on cost correlations of hydropower plant**

Equation	Year	Region	Author
$C_{EM,S} = 9000P^{0.7}H^{-0.35}$	1979	North America	Gordon [12]
$C_{EM,S} = 97.436P^{0.53}H^{-0.53}$	1979	Sweden	Lasu [13]
$C_{EM,S} = 9600P^{0.82}H^{-0.35}$	1984	U.S.A	Gulliver [14]
$C_{EM,S/kW} = 31.500P^{0.25}H^{-0.75}$	1988	UK	Whittington [15]
$C_{EM,S} = 40.000P^{0.70}H^{-0.35}$	2000	Greece	Voros [16]
$C_{EM,€/kW} = 10^3(34.12 + 16.99P^{0.91}H^{-0.14})$	2000	Switzerland	Chenal [17]
$C_{I.ATS} = KP^mH^{-0.3}$	2001	Austria	Doujak [18]
$C_{EM,€} = 9600P^{0.82}H^{-0.35}$	2001	Europe	Papantonis [19]
$C_{EM,S/kW} = 12.9P^{0.82}H^{-0.246}$	2003	U.S.A.	Gordon [20]
$C_{EM,€/kW} = 3.300P^{-0.122}H^{-0.107}$	2007	Greece	Kaldelis [21]
$C_{EM,RS/kW} = 63346P^{-0.1913}H^{-0.2171}$	2008		Singal [22]
pelton	2009	Spain	Ogayar [23]
$C_{EM,€/kW} = 17693P^{-0.3644725}H^{-0.281735}$			
Francis			
$C_{EM,€/kW} = 25698P^{-0.560135}H^{-0.127243}$			
Kaplan			
$C_{EM,€/kW} = 19498P^{-0.58338}H^{-0.113901}$			
$C_{EM,£/kW} = 12000(P/H^{0.2})^{0.56}$	2010	England and Northern Ireland	Aggidis [24]
Pelton	2016	-	Cavazzini [25]
$C_{EM} = 1358677.167H^{0.014} + 8489.85Q^{0.515} + 3382.1P^{0.416} - 1479160.63$			
Francis			
$C_{EM} = 190.37H^{1.27963} + 1441610.56Q^{0.03064} - 9.62402P^{1.28487} - 1621571.28$			
Kaplan			
$C_{EM} = 139318.161H^{0.02156} + 0.06372Q^{1.45636} - 155227.37P^{0.11053} - 302038.27$			
Saharan and Western Africa	2018	Developing countries	Davitti [26]
CAPEX=12 638 378 P <sup>0.7664</sup> H <sup>-0.0104</sup>			
Eastern and Southern Africa			
CAPEX=9 969 795 P <sup>0.8618</sup> H <sup>-0.1279</sup>			
Central Africa			
CAPEX=7 776 450 P <sup>0.9073</sup> H <sup>-0.1180</sup>			
South-East Asia & Pacific			
CAPEX=6 619 254 P <sup>0.8594</sup> H <sup>-0.0686</sup>			
Eastern Europe & Middle East			
CAPEX=9 696 625 P <sup>0.8545</sup> H <sup>-0.1207</sup>			
Latin America			
CAPEX=3 117 530 P <sup>0.9798</sup> H <sup>-0.0320</sup>			

- Project financing source: as this study is focused on Chinese financed and constructed hydropower projects, African hydropower projects with no Chinese involvement were not considered (such as projects financed by international institutions and executed by western companies) as well as projects located in North Africa.
- Project age: based on the Chinese Going Out Strategy, only projects contracted after 2000 were selected to assure uniformity and reduce inaccuracy due to long projects age gap. As a consequence, projects like the Tekeze dam witch construction began in 1999 were considered less representative and excluded from the data base.
- Project status: only projects witch constructions have already physically been completed were included in the database. These include projects which are already commissioned and operational.
- Project purpose: projects referenced as dam projects but do not have hydropower generation as main purpose were not included in our database. Lotsane Dam in Botswana for example, was financed and built in 2012 by Chinese SMEC but was an irrigation project and therefore was excluded from our database.

### 3.2. Data Source

Data used in this study were collected from open sources such as world bank, Africa Development Bank, Aidata, International Hydropower Association, International Rivers, Sinohydro and Gezhouba websites, Official government websites, projects websites and regional power pool websites. The rigorous selection database presented in Hwang et al. (2015) by the China Africa Research Initiative lead by Prof. Deborah Brautigam served as the starting point of data collection for this research.

In order to assure the quality of data, some investigations were made. Embassies of selected Sub – Saharan African countries were contacted as well as the Direction of planning in different ministries of energy in the concerned countries.

At the end of data collection, some differences were noticed mainly about the total construction cost of some projects, the total investment cost and the Chinese contribution’s interest rate. Attempts to have some officials interviews failed for poor response. Projects that have contradictory data that could not been verified were simply excluded from our database.

### 3.3. Data Quality

A common problem encountered when evaluating cost data from open sources is that the definition of the sub-components of the CAPEX varies since different sources do not contain the same cost components ETRI (2014). For example, some components such as the owner’s cost are not included in all estimates. A breakdown of the capital costs was established to verify and correct such discrepancies. These breakdowns were then used to correct the CAPEX estimates for each data source. However, when collecting data, it was often difficult to provide a precise CAPEX breakdown since the sources did mostly not provide detailed information about their assumptions in this respect. Following the general rule, the capital costs were broken down as given in Table 2.

As a result of the breakdown, only 18 projects out of the 21 selected were considered for this study.

### 3.4. Calculation of Price Escalation in Contractual Works

Hydropower projects constructed by Chinese Companies are all across Sub-Saharan Africa and were financed and constructed at different periods of time. Since data collected spans almost two decades, to avoid price contingencies, it was necessary that all plants costs be escalated to a 2018 price basis following the equation:

$$ICOST_t = ICOST_0 * (1+i)^t \tag{19}$$

Where:

- ICOST<sub>t</sub> is the escalated investment cost in year 2018;
- ICOST<sub>0</sub> is the initial investment cost;
- *i* is the escalation rate;
- *t* is the difference between year 2018 and the year of the investment.

#### 3.4.1. Determination of the escalation rate *i*

The escalation rate *i* depends on a variety of factors such as the inflation rate, labor indices, and material cost indices. Hydropower projects constructed in Africa involve a wide range of actors from different economic zones operating in different currencies. For example, the Bui dam was constructed in Ghana (where the local currency is Cedi), was financed by China Exim Bank and executed by a Chinese company (using the Chinese Yuan as local currency) and some equipment materials were imported from Europe (using Euro as local currency). In line with O’Connor et al. (2015a,b), to avoid disparities in estimation, this study adopted the US dollar as international currency and escalation rate *i* was derived from the Construction Cost Trends of the US Bureau of Reclamation, USBR (2018) with the assumption that the rate *i* generally vary between 2 and 4% as considered by Davitti (2018). The average escalation rate for composite trend indexes was calculated between 2000 and 2018 (see Table 3).

According to Table 3, the average value obtained after calculation is 319.7945 which corresponds to 3.2% variation.

Replacing *i* = 3.2% in equation (1), the escalated Capex values of hydropower projects completed before 2018 were obtained.

### 3.5. Selected Data Validation

In order to confirm the homogeneity of data selected, the cost of project per capacity was observed. Figures 1 and 2 show that the costs per megawatt of most projects are in the same range except for the Upper Atbara project. This can be explained by the fact that the twin dam complex is located in remote area with no adequate infrastructure previously in place. As a consequence, a

**Table 2: Overview of sub-components of the CAPEX and their groupings**

Components	Design documentation	
Project development/ Engineering/Environmental and social costs	Engineering	
	Supervision	
	Administration	
	Environmental studies and mitigation costs	
	Social studies and mitigation cost	
	Resettlement action plan and costs	
	Permits and licenses	
	Civil works	Mobilization/demobilization
		Access roads
		Diversion works
		Intake
		Headrace and waterways
		Surge tank
E&M equipment	Spillway	
	Penstock	
	Dam	
	Powerhouse	
	Digging of riverbeds/taillrace	
	Fishpass	
	Turbine	
	Governor	
	Valves	
	Controller	
	Generator	
Other equipment/construction	Hydraulic steel structures	
	Accommodation camp/bungalows	
	Dredging equipment	
	Other	
Grid connection	Switchyard	
	Transmission lines	
	Other grid connection	
Contingencies	Contingencies for the various sub-items	

**Table 3: Variation of composite trends from 2000 to 2018. USBR (2018)**

	2000 to 2003	2004 to 2007	2008 to 2011	2012 to 2015	2016 to 2018
228	244	293	337	363	379
231	247	298	328	368	377
231	248	301	327	367	380
233	250	303	329	368	385
234	252	305	332	372	386
234	259	309	338	374	390
235	265	314	340	372	377
236	274	316	342	374	380
236	277	318	346	375	391
237	280	325	353	379	395
240	283	340	358	381	399
242	288	345	360	383	401
Average					319.7945

costly transmission line from the project site to the city was added to the project cost.

Total investment costs for hydropower projects can vary significantly depending on specifications such as the site, the design choices and the cost of local labor and materials. Since each project is unique, a wide range of unit costs is observed in Figures 3-6. Due to the individual nature of hydropower plants and their incomparability, the projects considered as outliers in regard of the head are different from the projects occurred as outliers in regard of the capacity in Figures 4 and 6.

These variations can be related to the site, location, size, hydrology, geology and topography.

As observed in Figure 2, the plant with the lowest unit costs per MW is the one with the highest installed capacity since small hydropower projects are slightly higher because they lack economies of scale (IRENA, 2017).

### 3.6. Data Refinement for Model

In order to assure the robustness of the model, of the 18 projects selected after cost breakdown, another 5 were excluded due to a lack of hydraulic head information or considered outliers and subsequently removed, leaving 13 plants for regression.

For example, because they were extension projects, the capex of 2 projects were very low (1.84 \$M/MW and 1.37\$M/MW respectively) compared to the average of 2.96 \$M/MW; those projects were therefore removed from the data base.

Gilgel Gibe III is the third hydropower dam constructed in the series of the Gibe cascade. As Gibe I (184 MW) and Gibe II (420 MW) were already constructed as mentioned by International Rivers (2009), Gibe III cannot be considered as greenfield project and the project costs have increased 11% since 2006. This can explain the low capex per MW for this project. Gilgel Gibe III was therefore discarded from the database.

### 3.7. Bootstrap Resampling

Due to the short size of the data selected for the analysis and in order to obtain a robust model, a bootstrap resampling with replacement first presented by Efron (1979) was conducted with xlstat 2015 in Excel. This study adopted 1000 replications with replacement according to the method of Andrews and Buchinsky (2000) in order to minimize experimental randomness. In line with Gurgul and Lach (2012) and Wesseh and Zoumara (2012), the goal was to choose a value of number of replications which would ensure that the relative error of establishing the critical value would not exceed 5% with a probability equal to 0.95.

Figure 3: Distribution of Capex per MW versus Head installed capacity

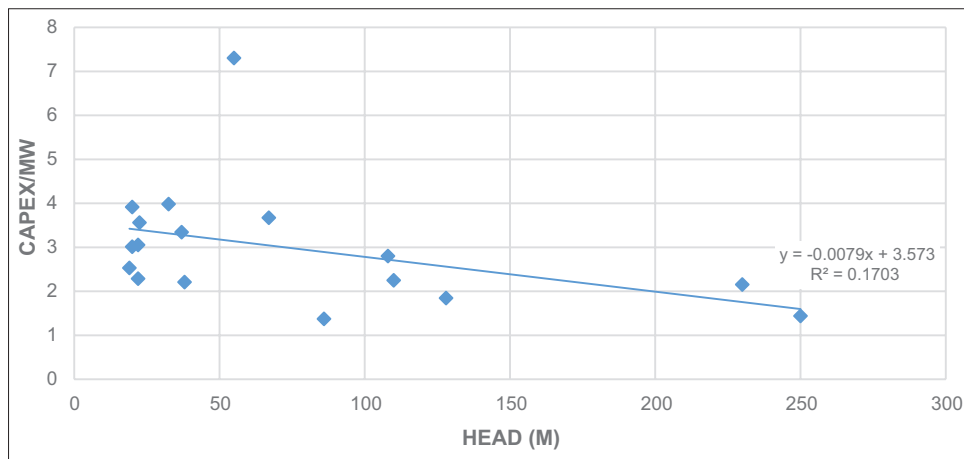
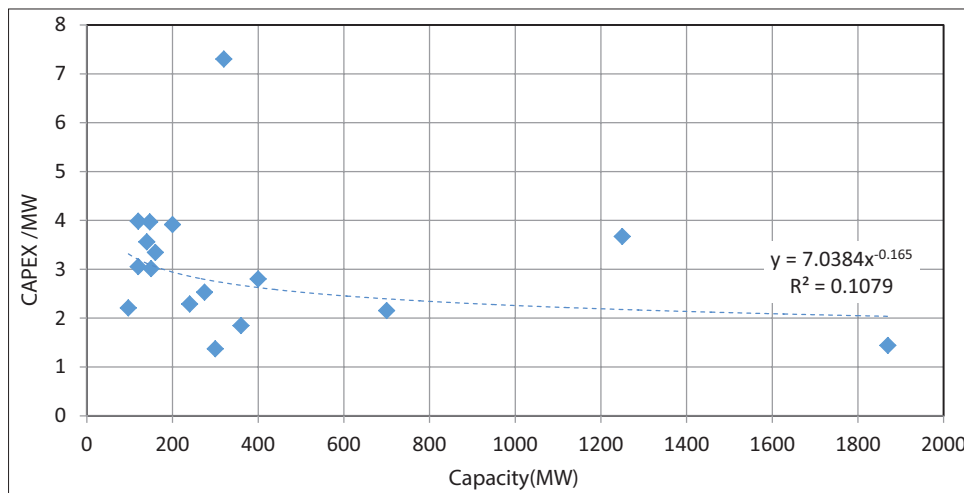
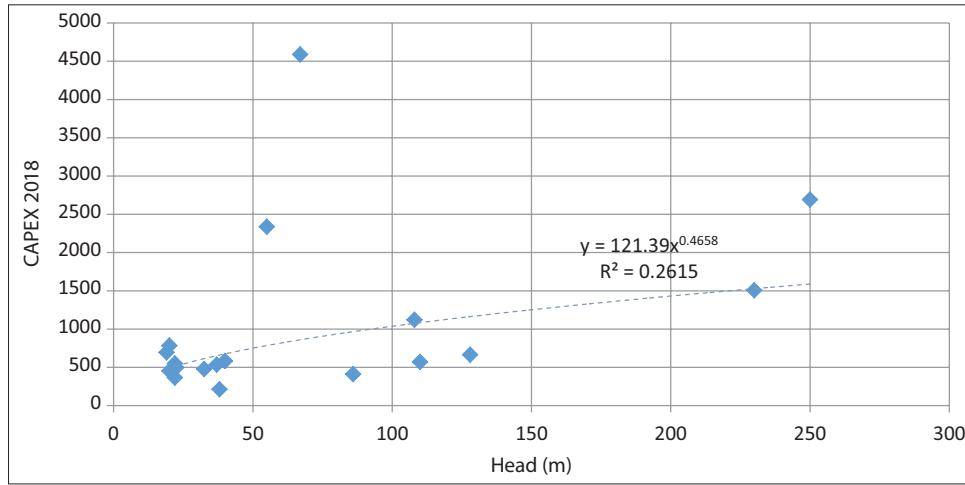


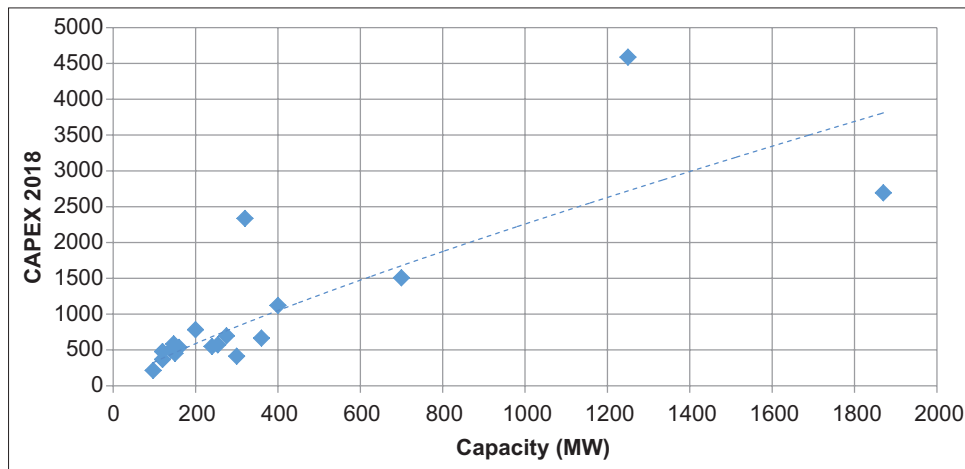
Figure 4: Distribution of Capex per MW versus capacity



**Figure 5:** Distribution of escalated Capex versus Head



**Figure 6:** Distribution of escalated Capex versus Capacity



**Table 4: Characteristics of the resampled data**

Number of observations	Capacity (MW)			Head (m)			Capex (\$M)		
	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.
1000	97	394.61	1870	19	72.61	250	154.67	793.12	2945

For the 1000 bootstrapped samples with size 13 each, the correspondent values of capacity and head were associated and the summary of the data span is shown in Table 4.

The distribution of the mean value of each sample is presented in Figure 7 while Table 5 summarizes the characteristics of the samples. As a result, out of the 17 previously selected projects, this study finally has 13 projects left for the model.

### 4. CAPEX MODEL

As mentioned by IRENA (2012), the capex models were developed using log transformed linear regression. A range of studies have reached the conclusion that the cost of the electromechanical equipment for small hydro plants can be used as a function of total plant size and head.

Following the cost breakdown in Table 2. The formula used is:

$$CAPEX = \alpha P^\beta H^\varphi \quad (1)$$

Where:

$P$  is the capacity in MW of the turbines;

$H$  is the head in meters;

$\alpha$  is a constant; and  $\beta$  and  $\varphi$  are the coefficients for power and head respectively.

Determination of coefficients

$$CAPEX = \alpha P^\beta H^\varphi$$

$$\log (CAPEX) = \log (\alpha) + \beta \log (P) + \varphi \log (H)$$

By changing variables, we obtain:

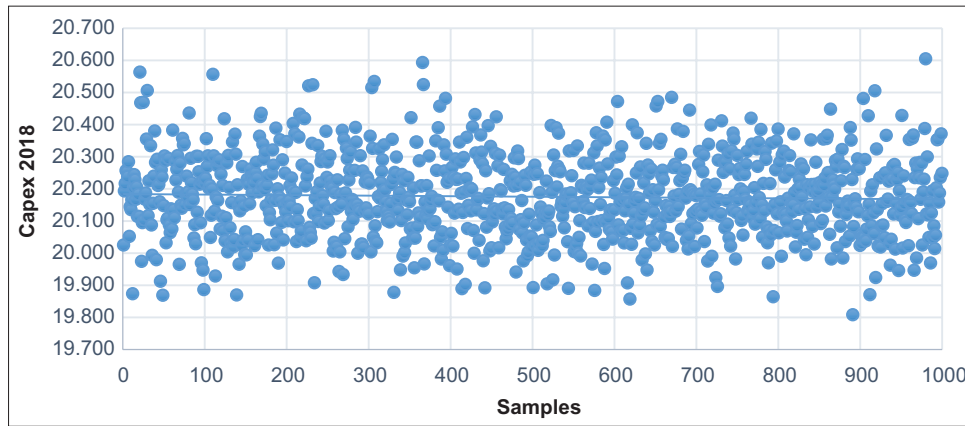
$$Y = \log (CAPEX), X = \log (P) \text{ and } Z = \log (H)$$

We thus obtain the simplified equation:

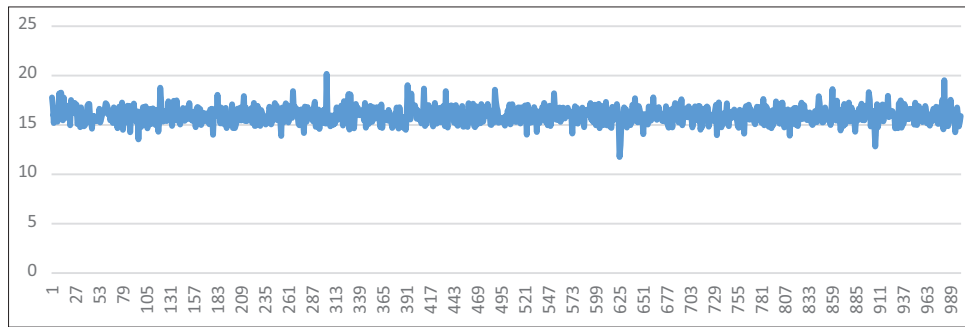
$$Y = \log (\alpha) + \beta X + \varphi Z$$



**Figure 7:** Distribution of mean values of the bootstrapped escalated capex values



**Figure 8:** Variation of the 1000 values of coefficient  $\alpha$



**Table 5: Summary statistics of the bootstrap resampling of escalated capex**

Parameters	Mean Bootstrap	Standard deviation Bootstrap	Lower bound (Standard bootstrap interval)	Upper bound (Standard bootstrap interval)	Lower bound (Simple percentile interval)	Upper bound (Simple percentile interval)	Lower bound (B.C. percentile interval)	Upper bound (B.C. percentile interval)
Sum	262.283	1.641	258.646	265.796	259.226	265.603	259.311	265.788
Mean	20.176	0.126	19.896	20.446	19.940	20.431	19.947	20.446
Variance (n)	0.198	0.089	0.022	0.410	0.048	0.384	0.079	0.432
Standard deviation (n)	0.433	0.103	0.239	0.690	0.218	0.620	0.282	0.657
Standard dev (n-1)	0.451	0.108	0.249	0.718	0.227	0.645	0.294	0.684
Median	20.132	0.092	19.923	20.323	19.985	20.360	19.929	20.185
1 <sup>st</sup> Quartile	19.971	0.126	19.711	20.259	19.719	20.163	19.182	20.098
3 <sup>rd</sup> Quartile	20.377	0.230	19.860	20.861	20.123	20.837	20.098	20.837
Variation coefficient	0.021	0.005	0.012	0.034	0.011	0.031	0.014	0.032
Standard mean error	0.125	0.030	0.069	0.199	0.063	0.179	0.081	0.190
Mean absolute deviation	0.328	0.090	0.133	0.525	0.151	0.497	0.167	0.514
Median absolute deviation	0.200	0.106	-0.038	0.426	0.061	0.444	0.061	0.452
1-Percentile	19.442	0.288	18.619	19.874	19.182	19.985	19.182	19.719
99-Percentile	20.959	0.229	20.600	21.596	20.360	21.133	20.339	21.133
2.5-Percentile	19.490	0.274	18.747	19.939	19.182	19.985	19.182	19.719
97.5-Percentile	20.777	0.286	20.244	21.490	20.214	21.133	20.202	21.133
5-Percentile	19.571	0.271	18.914	20.094	19.182	19.988	19.182	19.729
95-Percentile	20.847	0.248	20.415	21.496	20.302	21.133	20.255	21.133

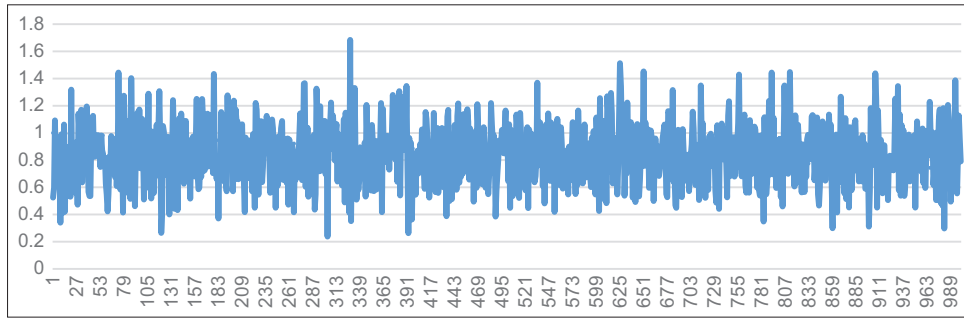
$$Y = \alpha' + \beta X + \phi z \tag{20}$$

#### 4.1. Results of Linear Regression

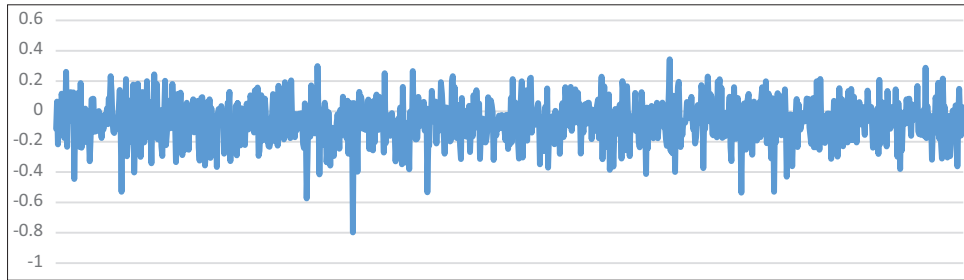
A multivariable regression analysis was carried out for the 1000 samples with Y as the dependent variable, X and Z as the two independent variables. Y represent the values of the escalated

capex to which the corresponding heads and capacities were associated for each of the 1000 samples. Table 6 summarizes the values of the coefficients  $\alpha$ ,  $\beta$  and  $\phi$  obtained after the linear regression while Figures 8-10 show the variation of the different values of the coefficients  $\alpha$ ,  $\beta$  and  $\phi$  respectively.

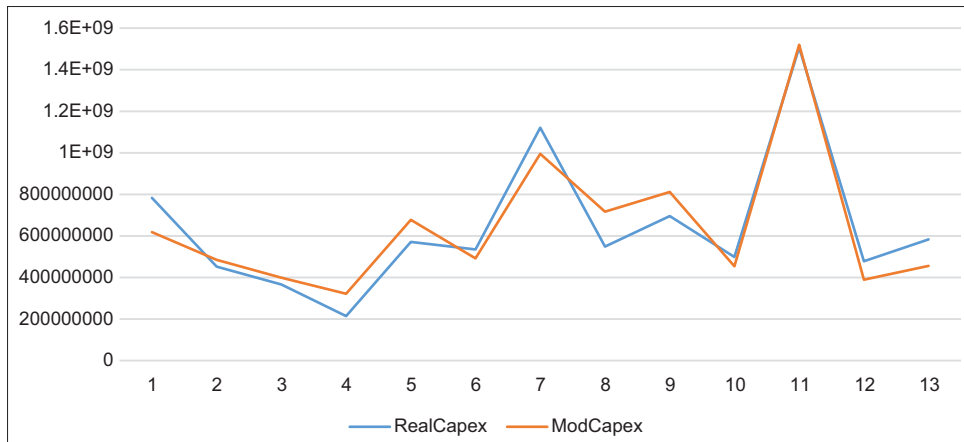
**Figure 9:** Variation of the 1000 values of coefficient  $\beta$



**Figure 10:** Variation of the 1000 values of coefficient  $\phi$



**Figure 11:** Similarities between real and modeled Capex



By replacing the average values of the coefficients in equation (20), we thus obtain:

$$Y = 15.95954 + 0.845062 X - 0.06489Z \quad (21)$$

Equation (2) can then be expressed as:

$$CAPEX = e^{15.95954} P^{0.845062} H^{-0.06489}$$

$$CAPEX = 8533754.71306661 P^{0.845062} H^{-0.06489} \quad (22)$$

With P in MW and H in meter.

## 5. RESULTS INTERPRETATION

The model developed for the estimation of hydropower costs was obtained by regression of the selected capital expenditure (Capex) data from the database, which are obtained by replacing the parametric values  $\alpha$ ,  $\beta$  and  $\phi$ .

The average value of the coefficient  $\phi$  is  $-0.06489$ . As expected from previous studies, the negative value of  $\phi$  means that the head coefficients have an inverse proportion between cost and head. The absolute values of the power coefficient ( $\beta$ ) are greater than the values of the head coefficient ( $\phi$ ) indicating a stronger correlation between power and cost was noticed rather than the correlation between head and cost.

The results show that the coefficient of determination  $R^2$  varies from an average of 0.82 to a maximum of 1 as seen in Table 6, indicating that the real costs in the database are mostly very close to the modelled costs replicated with the model equations (see Figure 11).

### 5.1. Model Validation

To assess the accuracy and validity of the model equations, the difference between the real costs (RealCapex) and the model simulated Capex (ModCapex) was estimated following the formula:

**Table 6: Value range of the coefficients**

Variables	Min.	Average	Max.
$\alpha$	11.74837	15.95954	20.16818
$\beta$	0.23726	0.845062	1.68388
$\phi$	-0.79742	-0.06489	0.34396
$R^2$	0.29927	0.825466	1

**Table 7: Comparison between real and simulated costs**

RealCapex	ModCapex	Error
783035643	618314033	-21.0363
451978646	484917870	7.287783
366420548	399131595	8.927187
214099453	321839182	50.32228
571313307	677352320	18.56057
534878719	492032888	-8.01038
1.121E+09	995261807	-11.1909
548769719	716817479	30.62264
695564445	811868733	16.72085
498487852	453978191	-8.92894
1.507E+09	1520268839	0.876712
477984403	389144352	-18.5864
583495000	455728867	-21.8967
	Average	$\pm 17.151357$

$$\text{Error} = (\text{ModCapex} - \text{RealCapex}) / \text{ModCapex} \quad (23)$$

As shown in Table 7, the errors, expressed in per cent, assume positive values in case the modelled cost overestimates the real observed cost for the same project, and negative values in case the modelled cost underestimates the real observed cost for the same project.

According to Table 7, the absolute average error of the model equations is estimated to be  $\pm 17.15\%$  with 69% of the projects having an error less than 20% and 92% of the projects having an error  $\leq 30\%$ .

## 6. CONCLUSION

For many decades, many scholars have studied the cost of hydropower plants based on the cost of electro-mechanical equipment and depending on capacity and head. The different correlation equations obtained depend on geographical location. The present study focused on sub-Saharan Africa with the particularity of hydropower projects financed and constructed by Chinese companies. Out of the 21 projects selected for this study, only 13 projects met the requirement to be kept in the database. The 13 projects qualified to be used for the regression analysis were first taken into a bootstrap resampling with replacement. A 1000 bootstrap resampling with replacement for projects with head between 97m and 1870m and of capacity between 19MW and 250MW were finally used for the multi regression analysis obtaining the equation:

$$\text{CAPEX} = 8\,533\,754.71 P^{0.845062} H^{-0.06489}$$

with P in MW and H in meter.

The average  $R^2$  value obtained is high (0.825466) confirming the validity of this result. The error term introduced shows an

average values of  $\pm 17.15$  meaning that the estimation of any China financed hydropower in the region should fall between the range of 17.15% underestimate or overestimate based on equation (22). These results are in line with Davitti's (2018) findings for the African region. As with any model, since hydro projects are site-specific, therefore cost estimates presented in this study should be applied carefully for a particular project of interest.

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