International Journal of Engineering Research in Africa
ISSN: 1663-4144, Vol. 44, pp 182-199
doi:10.4028/www.scientific.net/JERA.44.182

Submitted: 2018-09-13
Revised: 2019-07-04
Accepted: 2019-07-05
Online: 2019-08-29

Estimation of Electromechanical Equipment Cost for Hydropower Plants taking into Account of Continental Factors

Amèdédjihundé Hypolite Jordâo Hounnou[1,2,a*], Frédéric Dubas[2,b],
François-Xavier Fifatin [1,c], Christelle Bloch[3,d], Didier Chamagne[2,e]
and Antoine Vianou[1,f]

[1]Department of Electrical Engineering, Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, 01BP2009, Benin.

[2]Département ENERGIE, FEMTO-ST, CNRS, Univ. Bourgogne Franche-Comté, Belfort, France.

[3]Département DISC, FEMTO-ST, CNRS, Univ. Bourgogne Franche-Comté, Montbéliard, France.

[a]jorhyam@yahoo.fr, [b]fdubas@gmail.com, [c]fxfifatin@yahoo.fr, [d]christelle.bloch@univ-fcomte.fr, [e]didier.chamagne@univ-fcomte.fr, [f]avianou@yahoo.fr

* Corresponding author

Keywords: Continental factors, Electromechanical equipment cost, Hydropower plants, Pearson product-moment correlation coefficient.

Abstract. Development of small hydropower plants depends on its economic and financial feasibility, which must be evaluated by cost estimates before construction. Cost of electromechanical (EM) equipment represents the major portion of the total plant budget. The paper presents new cost estimation approach for EM equipment of hydropower plants. Compared to the literature approaches, the proposed cost correlation is elaborated basing on dataset of hydropower plants located in different continents. Furthermore, the transport cost has been considered of continental factors. Mono- and multi-objective genetic algorithm (GA) optimization have been both applied and compared to determine the best cost correlation. The accuracy of this best cost correlation is validated by using statistical analysis tools to compare it with the equation deduced from the best model reviewed in the literature. The results have shown that the bivariate correlation, viz., the Pearson Product Moment Correlation Coefficient (PPMCC), is slightly improved from 98 % to 99 %. The Mean Square Relative Error (MSRE) is substantially improved from 4.47 % to 1.82 %, and the Utmost Square Relative Error (USRE) from 45.2 % to 11.4 %. Indeed, the proposed cost correlation gives a more accurate estimate of EM equipment cost of hydropower plants in different continents.

Introduction

Context of this Paper. The mature technology and second most important source of total electricity is hydroelectricity [1], [2]. It is reliable [3], high efficient, economically attractive [4], and large storage capacity [5]. It has ability to balance variability from other renewable energy sources, such as wind [6], [7]. The investment cost of hydropower plant is the largest economic challenge facing it relative to competing other electrical energy sources. Indeed, a large proportion in the total budget of the hydropower plant project is occupied by its investment cost. Thus, the viability of a hydroelectric plant project is affected by its investment cost [8]. Therefore, its estimation is necessary to carry out preliminary economic analysis and assess the feasibility before starting construction. The investment cost of hydropower plant can be divided into three main parts [9]: i) electromechanical (EM) equipment costs, ii) civil works costs, and iii) engineering and administration costs. The EM equipment cost in small hydropower plants consists the major portion of the total plant budget (about 30-40%) [10]. It is then more important to estimate the EM equipment cost. The following paragraph presents a literature review on the different methods available for estimating this cost.

State-of-the-art: Estimation of EM equipment cost. Several methods for estimating of EM equipment costs have been developed in the literature. There are graphs, which can approximately estimate this cost, but they have not recently been updated. Furthermore, turbines and alternators manufacturers do not supply any information about cost, since every installation is different and complex [11]. Nevertheless, in the literature, the EM equipment cost can also be determined using the mathematical models [12], [13].

Gordon et al. (1979) [12] were pioneers in proposing the first models of cost derived from Swedish experience:

$$C_{EM} = a \times P^b \times H^c \tag{1}$$

where P represents the installed capacity, H the net head, $\{a, b, c\}$ the coefficients statistically determined on the basic of the available database of small hydropower plants. This experience indicates that for units below 1.5 MW capacity, the equipment cost is a function of head and flow, and can be shown graphically as a series of curves indicating decreasing cost per kW for increasing head. Afterwards another formula based on North American experience, which is applicable for units below 5 MW capacity was proposed. The result indicated that Eq. 1 was accurate within ±11 % over the intended range of equipment sizes up to a maximum of 5 MW capacity. Above this capacity, equipment is no longer standardized, hence higher unit costs can be expected.

These models have been the basis of majority of the subsequent research on cost estimation modeling. Gulliver *et al.* (1984) [14] in their guidelines for the estimation of the total project cost, have proposed the equation to estimate the EM cost. The reference database was built by considering power plants located in the USA. Voros *et al.* (2000) [15] used this approach with reference database to Greece, in the works consisting to specify the parameters that are crucial to the financial investment viability of a potential small hydropower system project. The EM equipment cost was estimated for plants located in Greece by using this approach in [16] and [17], [18]. Nouni *et al.* (2006) [19] examined techno-economic feasibility of micro hydropower plants for decentralised power supply in remote locations of India. They noted that the cost estimates for the EM equipment was considerably different for the same capacity. One of the primary reasons for such a large difference in cost estimates was due to the possibility of procuring equipment from local as well as from foreign suppliers. The price of imported equipment can be higher or lower than that of the indigenously available equipment depending on a variety of factors such as marketing and pricing strategies, import duties, incentives for export, quality of the equipment, etc. Singal *et al.* (2007) [20] proposed an analytical approach for cost estimation of low head small hydropower plants as function of head and capacity. The method used was regression analysis with a maximum deviation of +12 %. In 2008, the same authors determined the correlations for the cost of different components of low head small hydropower plants as function of head and capacity [21]. The obtained results gave maximum errors equal to ±10 % for EM equipment and ±16 % for small hydropower plants. Correlations for the small hydropower plants cost were developed considering different turbines and generators types for the plant cost by Singal *et al.* (2008) [22], the numbers of generating units by Singal *et al.* (2008) [23]. Ogayar *et al.* (2009) [24] developed the correlation for determining the EM equipment cost of small hydropower plant up to 2 MW installed capacity. Depending upon the turbine typology (i.e., semi Kaplan, Kaplan, Pelton and Francis), they developed correlation to determine the EM equipment cost. The errors were limited to a fluctuation range of ±20 %, +22.27 % for Pelton and -15.83 %, +23.50 % for Francis and -18.53 % for Kaplan. Semi Kaplan has same fluctuation range as Kaplan. They concluded that these equations developed were useful for the determination of the initial investment while planning renovation or new construction of small hydropower plant project. In order to solve the difficulty implied, by a viability study on the refurbishment of a small hydropower plant, Ogayar *et al.* (2009) [25] presented the cost analysis for the refurbishment of small hydropower plants. The equations elaborated in [24] were used for viable study on the refurbishment of a small hydropower based on the economic optimization of the different elements. Singal et al. (2010) [26] developed correlations for the small hydropower plants cost considering the quantity and the prevailing market price of each item for all the components. The variation of plant cost was within ±11 %. Aggidis *et al.* (2010) [9] noted that earlier empirical formulas used to estimate the EM equipment cost, were based on outdated data and a lot of small scale hydro sites had been developed since that time. They developed another based on recent data obtained in Salford Report [27] and from companies such as Alstom, Andritz, Gilbert Gilkes & Gordon Ltd, NHT and Voith Siemens. Other relations were determined by Mishra *et al.* (2011) [28] using three different methods: i) sigma plot method, ii) linest method, and iii) logest method. The cost correlations obtained from these techniques are than compared with the actual cost existing hydropower plant installed recently. The results gave maximum error equal to ±10 % for sigma plot method, ±5 % for linest method, and ±18% for logest method. The mathematical model obtained from sigma plot and linest method were found very close to the actual cost of EM equipment and could be used for the prediction of such cost for planning purpose. Mishra *et al.* (2011) [29] made a review on existing models developed to evaluate the investment cost of small hydropower plants. It was showed that number of contributions existing to estimate this cost used the head H and the capacity P as cost influencing parameter. Other parameters such as discharge, speed of the generator, number of poles of the generator were not used for determination of this cost. Santolin *et al.* (2011) [30] used the equation elaborated in [24] to determine the machine cost in works of techno-economical analyses of a small hydropower plant. A correlation based on the head H and the capacity P, for the EM equipment cost was developped by Mishra *et al.* (2012) [31]. The least square method was used to fit the best curve through and a maximum deviation of ±10 % had been observed. In [32], the same authors made a review on the different types of models and transfer function developed to evaluate the performance of the EM equipment of small hydropower plants. Head H and power P had been used as decision parameters for cost estimation. It was proposed that the cost correlations could be improved by incorporating more parameters such as discharge, speed, runner diameter and setting of the turbine. Fen *et al.* (2012) [33] based on the same methodology to developed equations for total project costs and EM equipment costs for different turbine types in the US. Mishra *et al.* (2013) [34] developed the cost correlation for the different components of EM equipment in high head small hydropower plants. Different cost influencing parameters were considered for each component of EM equipment with a maximum deviation of ±9 %. Elbatran *et al.* (2014) [35] presented a review focusing on categories, performance, operation and cost of low head micro hydropower turbines. Based on the equation elaborated in [24], they noted that the cost increased when the head increased. They concluded that Pelton turbine had the lowest cost and was preferable in micro hydropower scales compared with other turbines. The economic correlations proposed in [9] and [17] were used in works of the economic sustainability analyse by Manfrida *et al.* (2014) [36] and Barros *et al.* (2015) [37], who analysed the economic sustainability of seawater pumped storage solutions for photovoltaic energy systems and of mini-hydropower plants. The EM equations were proposed for turbine with governing system and for generator with excitation system or capacitor bank by Mishra *et al.* (2018) [38] for high head run-of-river small hydropower plants. The cost-influencing parameters considered were capacity P and head H with a maximum deviation of ±9 %.

According to Alvarado Ancieta (2009) [39], a formula based on parameters such as head, design discharge, power and/or number of units could not be easy applied for cost estimation of EM equipment of the different type of units. They proposed a methodology based on the appliance of cost estimation diagrams taking into consideration the parameters available for a hydro plant. The used dataset was obtained from 81 hydropower plants equipped with different turbine types and spread across 32 countries.

Cavazzini et al. (2016) [13] found that earlier approaches, based on the installed capacity and the net head, were too simplified to properly estimate the EM equipment cost. They have proposed the following model, according to which the final cost was divided into three terms (i.e., the first two of which represent the mechanical equipment cost, and third the electrical equipment cost), defined by

$$C_{EM} = a \times H^b + c \times Q^d + e \times P^f + g \tag{2}$$

where *H [m]* represent the net head, *Q [l/s]* the design flow rate, *P [kW]* the installed capacity, $\{a$ [€/m], b [−], c [€/l/s], d [−], e [€/kW], f [−], g [€]$\}$ the constants determined by applying the adaptive search diversification in particle swarm optimization (ASD-PSO) algorithm. The mean error was smaller than 10 % for Pelton and Francis turbines, and smaller than 20 % for Kaplan turbines.

They are concluded that their proposed correlation model seemed to generate a better approximation of the real EM equipment cost for small hydropower plants.

Proposed innovations. The Cavazzini's correlation [13] seems to generate a better approximation of the real EM equipment cost for small hydropower plants. The model is based on data from two European countries (Italy and Spain). The innovation of this study is to improve this model in order to extend it to a dataset of small hydropower plants in different continents. In this case, the cost estimated for the EM equipment can be different for the same characteristics (i.e., head H, capacity P, and flow Q), due to the possibility of procuring equipment from local and/or foreign suppliers. Therefore, it is necessary to consider the transport cost in the model of EM equipment cost. First, the last two terms of the Cavazzini's model are assumed to represent the transport cost as represented by:

$$C_{EM} = \underbrace{(a \times H^b + c \times Q^d)}_{\boldsymbol{Purchase\ cost}} + \underbrace{(e \times P^f + g)}_{\boldsymbol{Transport\ cost}} \tag{3}$$

Indeed, the transport cost will be estimate as function of capacity P. Besides, we noted that the price of imported equipment can be higher or lower than that of the indigenously available equipment depending on a variety of factors such as marketing and pricing strategies, import duties, incentives for export, quality of the equipment, etc. [19]. Moreover, the cost of mobilization is a function of the distance between resource and point of use, the size and day-rate of vessel, and the transport method [40], [41]. Therefore, this first proposition is limited. A second expression integrating geographic coordinates (i.e., latitude and longitude) can be proposed for transport cost:

$$C_{EM} = \underbrace{(a \times H^b + c \times Q^d + e \times P^f)}_{\boldsymbol{Purchase\ cost}} + \underbrace{(g - lat) \times h^{long}}_{\boldsymbol{Transport\ cost}} \tag{4}$$

where lat and $long$ represent latitude and longitude, respectively. The aim of this proposition is to consider the distance. Nevertheless, it will be also limited because not only the other factors are ignored, but it is also difficult to estimate the distance and predict the transport method with geographic coordinates. Consequently, a novel model of correlation cost is proposed by using continental factor K_j. Similar idea of the continental differentiation is used when investing in real estate. The proposed model is defined by:

$$C_{EM} = \left(a \times {H_i}^b + c \times {Q_i}^d + e \times {P_i}^f\right) \times K_j + g \tag{5}$$

where $\{a\ [€/m], b\ [-], c\ [€/l/s], d\ [-], e\ [€/kW], f\ [-], g\ [€]\}$ are the coefficients statistically determined on the basic of the database of small hydropower (Tables 1-4).

The structure of the paper is organized as follows. Section 2 is focused on the study area and presents the hydropower plants, whose dataset are used to develop the different models in this paper. In Section 3, basing on the dataset used by Cavazzini et al. [13], a first cost correlation of EM equipment (i.e., "Cost correlation N°1") is developed by using Eq. 2. The optimization process used is Genetic Algorithm (GA). The "Cost correlation N°1" is then compared with cost correlation obtained by Cavazzini et al. [13] with Particle Swarm Optimization ASD-PSO algorithm. The purpose of this comparison is to obtain same results in order to validate the GA optimization process used in this paper. In Section 4, the Cavazzini's model Eq. 2 is also used to elaborate a second cost correlation of EM equipment (i.e., "Cost correlation N°2") by basing on a dataset of hydropower plants from different continents [see Tables 1-4]. Section 5 presents a third cost correlation (i.e., "Cost correlation N°3") proposed for hydropower plants located in different continents by considering the continental factor K_j, Eq. 5. A comparison between the proposed cost correlation model and Cavazzini's correlation model is presented. The conclusion and perspective of the paper are drawn in Section 6.

Presentation of Study Area and Dataset

This paper is focused on EM equipment, equipped with Pelton turbine, of hydropower plants used in the works of Alvarado-Ancieta [39] and Cavazzini et al. [13], added to hydropower plant located in Benin [42]. The geographical location of these hydropower plants on the map is shown in Fig. 1. The dataset of their EM equipment is given in Tables 1-4.

Table 1: Hydropower plants equipped with Pelton turbine selected in Africa [39] and [42], [43].

Country	Plant	*Q [l/s]*	*H [m]*	*P [kW]*	C_{real} *[€]*
Benin	Yeripao	490	119.5	500	740,899
Madagascar	Ahanivotry	3,500	240	7,000	2,640,400
Sudan	Gibe II	3,000	487	105,000	8,223,990

Table 2: Hydropower plants equipped with Pelton turbine selected in Europe [13].

Country	Plant	*Q [l/s]*	*H [m]*	*P [kW]*	C_{real} *[€]*
Italy	F.dra	25	353	72	59,241
	I.ra	100	228	186	125,253
	Val.Min.	57	425	196	97,113
	Chl.Alp	600	157	812	261,822
	Abb.San Sal.	230	275	515	173,390
	Gos.da	284	467	1,088	220,822
	Fium.ero P1	430	146	510	184,176
	Fium.ero P2	1255	146	1,502	381,823
	Car.lio	300	409	1,017	203,052
	val. Min.re	300	410	1,017	216,690
	kat.na P1	276	264	604	213,678
	kat.na P2	414	264	905	276,667
	Acq.sta	300	45	109	157,620
Spain	M.gio	200	28	43	89,000
	N.vi V.lia	250	140	351	165,430
	Mor.x	325	395	1,056	206,700
	Santa Isabel	34.13	88	25	35,000
	Santa Isabel 2	40.96	88	30	37,000
	Ntra Sra de Tiscar	81.98	85	58	60,000
	Rio Frio	62.01	155	80	85,000
	Rio Frio	497.14	145	600	243,408
	Rio Frio	775.11	155	1,000	390,660
	Sp-P1	285.14	75	178	140,001
	Sp-P2	75.42	180	113	90,000
	Sp-P3	111.73	100	93	95,000
	Mata Begid	150.18	80	100	120,000
	La Toba	285.34	80	190	145,000
	Cerrada de Utrero	274.07	160	365	169,999
	Cerrada de Utrero	563.17	160	750	270,458
	Acequia Hijuela de la Majà	291.25	165	400	189,320
	Valdepenas	562.13	109	510	200,002
	Valdepenas	982.98	110	900	378,639
	Acequia Almegijar	400.47	225	750	265,050
	Alhori II	965.43	112	900	378,639
	Sabinar-canarie	600.71	200	1,000	288,490
	Sabinar 2-canarie	400.47	300	1,000	265,050
	Mor 1-Morocco	266.98	90	200	155,000
	Manteigas-Portugal	202.49	178	300	174,900
	Cartignano-Italy	240.28	150	300	170,100

Table 3: Hydropower plants equipped with Pelton turbine selected in America [39].

Country	Plant	Q [l/s]	H [m]	P [kW]	C_{real} [€]
Ecuador	Pilaton-Sarapullo	22,500	120	25,000	19,803,000
	Toachi-Alluriquin	41,200	191	70,000	54,656,280
Peru	Pucara	15,000	475	65,000	20,208,490
	Machu Picchu II	32,000	345	99,000	50,516,510
	El Platanal	22,500	600	110,000	30,647,500
Rep. Dominicana	Pinalito	5,000	590	25,000	4,950,750

Table 4: Hydropower plants equipped with Pelton turbine selected in Asia [39].

Country	Plant	Q [l/s]	H [m]	P [kW]	C_{real} [€]
Armenia	Gegharot	1,000	297	2,500	773,260
Nepal	Upper Tamakoshi	11,000	802	79,300	16,738,250
Pakistan	Daral Khawar	6,500	293	12,700	7,855,190
	Allai Khwar	10,500	662	60,500	12,871,950
	Duber Khwar	14,500	516	65,000	18,907,150
Turkey	Yaprak-1	3,000	81	4,800	2,376,360
	Yaprak-2	3,000	144	5,400	2,527,240
	Tuna	10,000	502	16,900	11,108,540
	Akocak	11,500	250	40,000	12,730,500

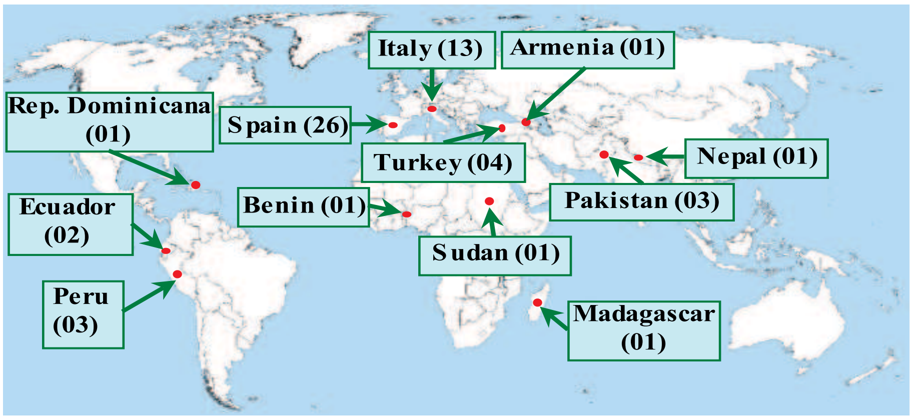

Figure 1: Location of hydropower plants equipped with Pelton turbine.

Cost correlation N°1 (C_{sim1})

The purpose of this section is to validate the GA optimization process. Therefore, a first cost correlation of EM equipment is elaborated and compared with that of Cavazzini et al. [13].

Elaboration of Cost Correlation N°1. Cost correlation N°1 (C_{sim1}) of EM equipment is elaborated basing on dataset [see Table 2] of hydropower plants equipped with Pelton turbine used by Cavazzini et al. [13]. The optimization process used is GA.
The GA concept was described by John Holland in 1960s and developed with his students and colleagues in the 1960s and 1970s [44]. GA is an evolutionary algorithm that uses evolutionary biological techniques such as inheritance, mutation, selection and recombination. The GA optimization is used in finding true or approximate solutions for the optimization and search problems. This kind of artificial intelligence algorithms have already been widely used in various application fields, among which the sizing of power systems. For instance, Xu et al. [45] used a GA for sizing a standalone hybrid photovoltaic/wind power system for a year, while minimizing the total capital cost of the system, with constrained loss of power supply probability [46]. But, to our knowledge, no similar approach has been developed until now for the optimization problem at hand in our contribution. The flow chart of the GA optimization process for EM equipment cost estimation is illustrated in Fig. 2.

The objective function is focused on minimization of the Mean Square Relative Error (MSRE) given by:

$$MSRE = \sigma^2 = \frac{1}{n_C - 1}\sum_{i=1}^{n_C}\left(\frac{(C_{sim1})_i - (C_{real})_i}{(C_{real})_i}\right)^2 \tag{6}$$

with n_C is the number of hydropower plants equal to 39 in this section, $(C_{real})_i$ is the real cost (see Table 2) of EM equipment for hydropower plant i, and $(C_{sim1})_i$ is the estimated cost of EM equipment for hydropower plant i Eq. 7:

$$(C_{sim1})_i = a \times {H_i}^b + c \times {Q_i}^d + e \times {P_i}^f + g \tag{7}$$

where H_i, Q_i and $\mathrm{P_i}$ are respectively the net head, the design flow rate and the installed capacity of EM equipment for hydropower plant i [see Table 2], $\{a, b, c, d, e, f, \ g\}$ the correlation constants. The cost correlation resulting from the optimization process is given by Eq. 8:

$$(C_{sim1})_i = 86{,}226.335 \times {H_i}^{0.1092} + 7{,}727.811 \times {Q_i}^{0.52} + 12{,}299.464 \times {P_i}^{0.3012} - 188{,}900.684 \tag{8}$$

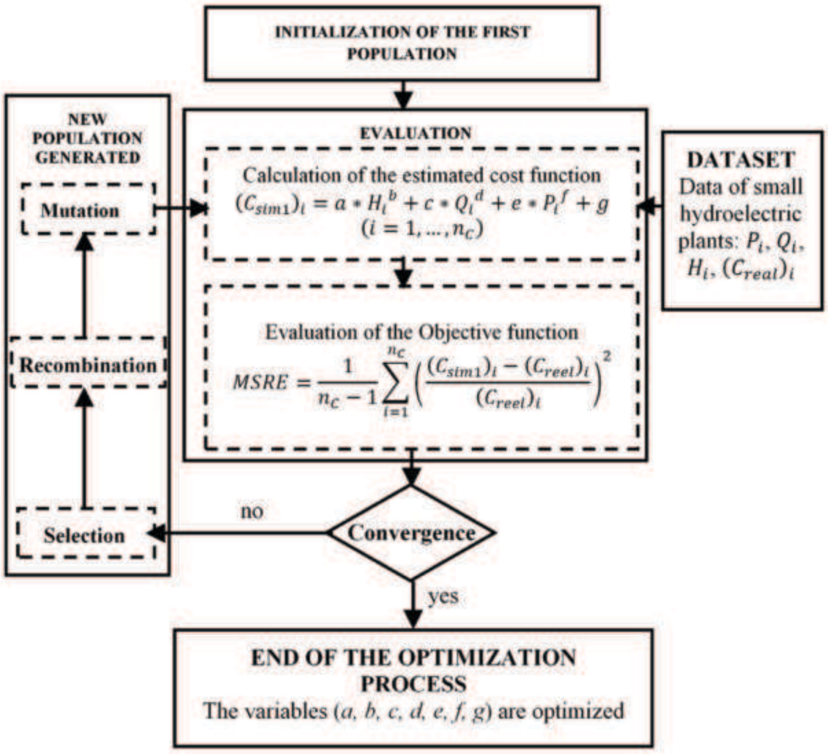

Figure 2: Flow chart of the GA optimization process.

Comparison of Cost Correlation N°1 (C_{sim1}) with that of Cavazzini et al. (C_{cava}). Statistical analysis methods are used to compare the two costs correlations. The bivariate correlation or the Pearson Product Moment Correlation Coefficient (PPMCC) (ρ_{XY}), given by Eq. 9, is widely used to measure the strength of linear dependence between two variables [47]. For example, PPMCC is used to study the complementarity between wind and solar of energy resources in [48], and between wind and hydro-sources of energy resources in [49]. In these cases, PPMCC is negative. PPMCC is also used to compare two methods [50], [51].

$$\rho_{XY} = \frac{\sum_{i=1}^{n_c}\left[\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)\right]}{\sqrt{\sum_{i=1}^{n_c}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n_c}\left(Y_i - \overline{Y}\right)^2}} \quad (9)$$

The both compared methods will be considered as equivalent when ρ_{XY} closes to +1 and their MSRE are approximatively equal. Yi et al. [48] classified the correlation coefficient between two methods into three grades: i) $|\rho_{\mathrm{XY}}|<0.4$ for low degree of correlation, ii) $0.4\leq|\rho_{\mathrm{XY}}|<0.7$ for remarkable correlation, and iii) $|\rho_{\mathrm{XY}}|\geq0.7$ for high degree of correlation.

In keeping with this logic, Cost correlation N°1 is compared with that of Cavazzini et al. [13]. The comparison of real cost with each cost correlation is indicated in Figs. 3-5. Fig. 3 shows the bar diagram of (C_{real}) and of cost correlation obtained with the two methods based on dataset of Table 2 (viz., 39 hydropower plants in Europe). The bar diagram in red color indicates the real cost (C_{real}). (C_{sim1}) is identified by the bar diagram in green color. The bar diagram in blue color is the cost correlation (C_{cava}) obtained with the equation of Cavazzini et al. [13]. The results of statistical analysis are shown by Figs. 4-5, which show the Square Relative Error (SRE) and correlation, respectively, obtained with each method. The bar diagram in grey color represents the SRE obtained with (C_{sim1}). The bar diagram representing the SRE obtained with (C_{cava}) is in black color. (C_{sim1}) and that of Cavazzini et al. [13] have given MSRE which are equal to 1.03 % and 1.08 %, respectively. The least square relative error (LSRE) obtained are equal to $4.97\text{x}10^{-3}$ % and $1.58\text{x}10^{-3}$ %, respectively. The Utmost Square Relative Error (USRE) obtained are equal to 4.81 % and 5.39 %, respectively. We observed that the two methods give approximatively the same MSRE, LSRE and USRE. The correlation matrix in Fig. 5 presents the relationship between the costs estimated with the two methods and real cost. The PPMCC between (C_{sim1}) and (C_{real}), and that between (C_{cava}) and (C_{real}) are same and equal to 0.97. Summary, the two methods have same SRE and same PPMCC with (C_{real}). Then, the two methods give the equivalent results. Hence, the optimization procedure used is validated.

Cost correlation N°2 (C_{sim2})

The objective is to see if the Cavazzini's model can be applied on dataset of hydropower plants located in different continents. Cost correlation N°2 (C_{sim2}) is elaborated by using Eq. 2 and basing on dataset [see Tables 1-4] of 57 hydropower plants which are located in different continents [see Fig. 1]. (C_{sim2}) resulting from the GA optimization process is given by:

$$\begin{aligned}(C_{sim2})_i = {} & 3{,}725{,}128.22 \times H_i^{-1.6958} + 13.8 \times Q_i^{1.4509} + 346{,}421.923 \times P_i^{0.0706} \\ & - 405{,}169.65\end{aligned} \quad (10)$$

(C_{sim2}) and (C_{real}) are plotted in Fig.6. The SRE between (C_{sim2}) and (C_{real}) are illustrated in Fig. 7. MSRE (equal to 4.47 %) and USRE (equal to 45.2 %) obtained are great. This great difference between (C_{sim2}) and (C_{real}) is due to the fact that Eq. 2 has not taken into account the factors such as marketing and pricing strategies, import duties, incentives for export, quality of the equipment, etc. The cost estimated for the EM equipment can be different for the same characteristics (i.e., head *H*, capacity *P*, and flow *Q*), due to the possibility of procuring equipment from local as well as from foreign suppliers. The following paragraph presents methods to minimize MSRE noticed between estimated cost and real cost (C_{real}) of EM equipment.

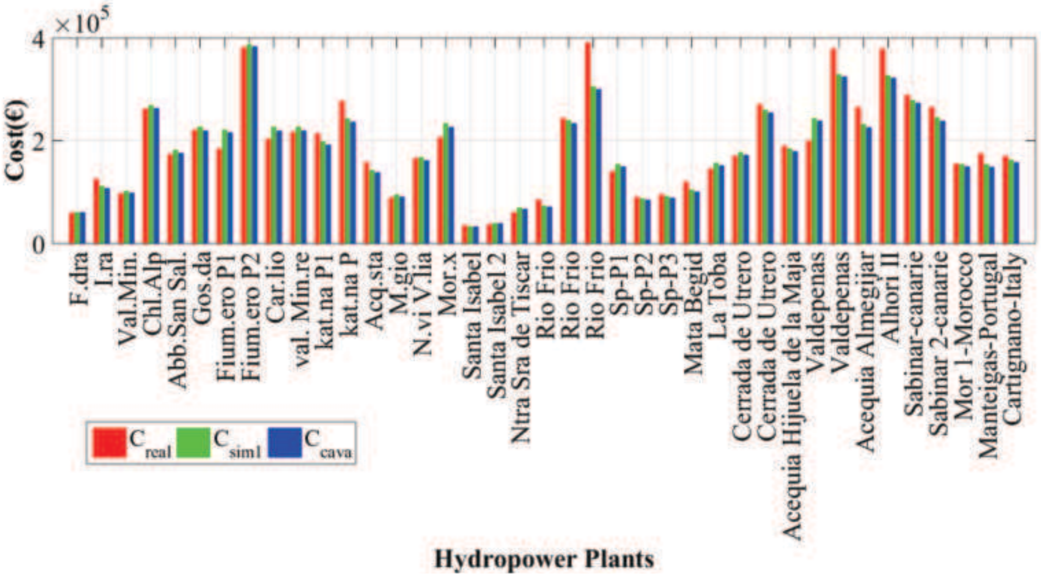

Figure 3: Comparison of Cost correlation N°1 (C_{sim1}) with that of Cavazzini et al. [13] and with real cost for EM equipment.

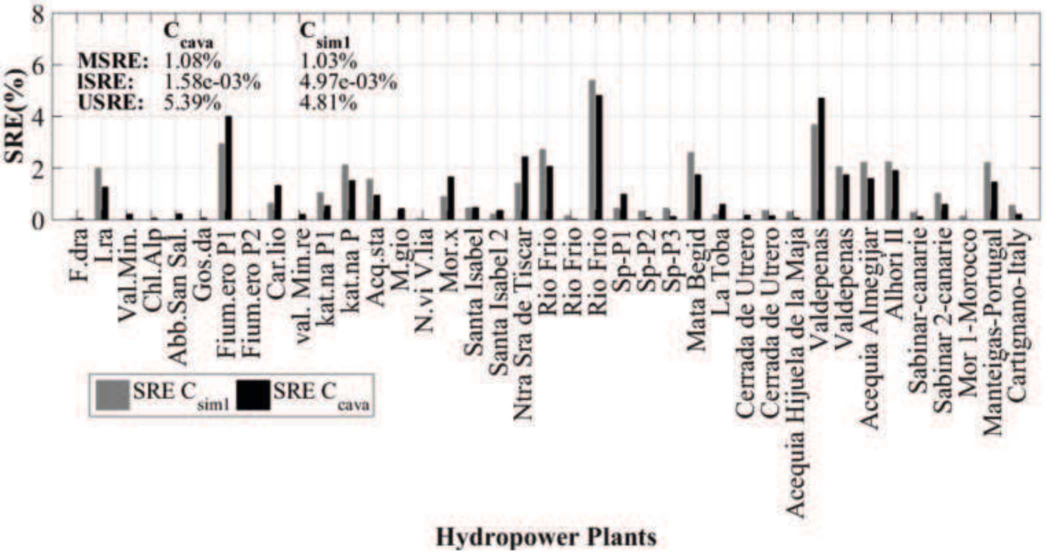

Figure 4: Comparison of SRE obtained with each method.

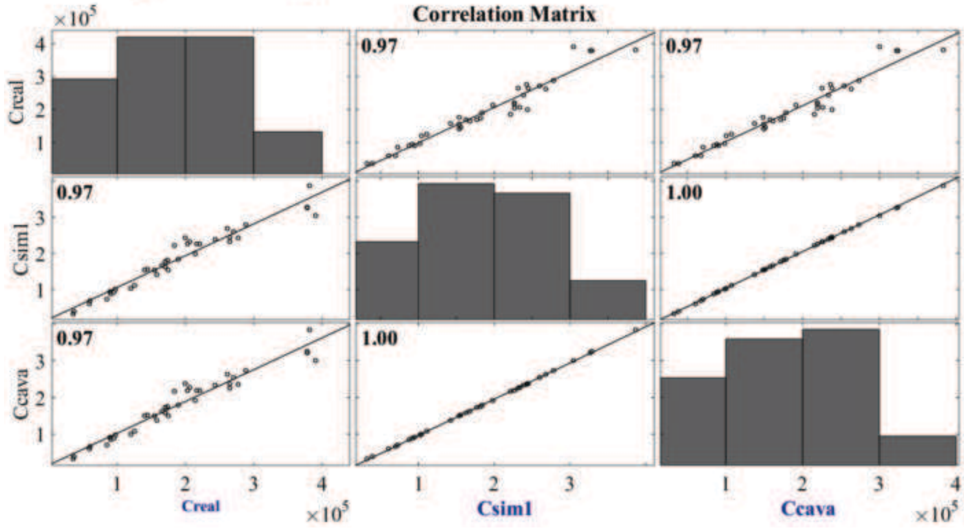

Figure 5: Correlations between the costs estimated with the two methods and real cost.

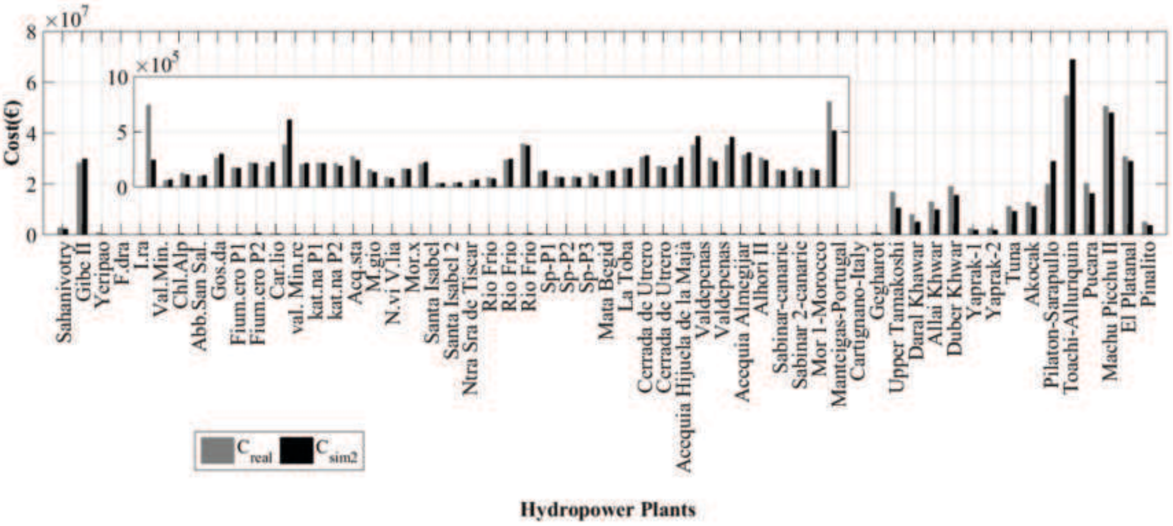

Figure 6: Comparison of Cost correlation N°2 ($\mathrm{C_{sim2}}$) with real cost ($\mathrm{C_{real}}$) for EM equipment.

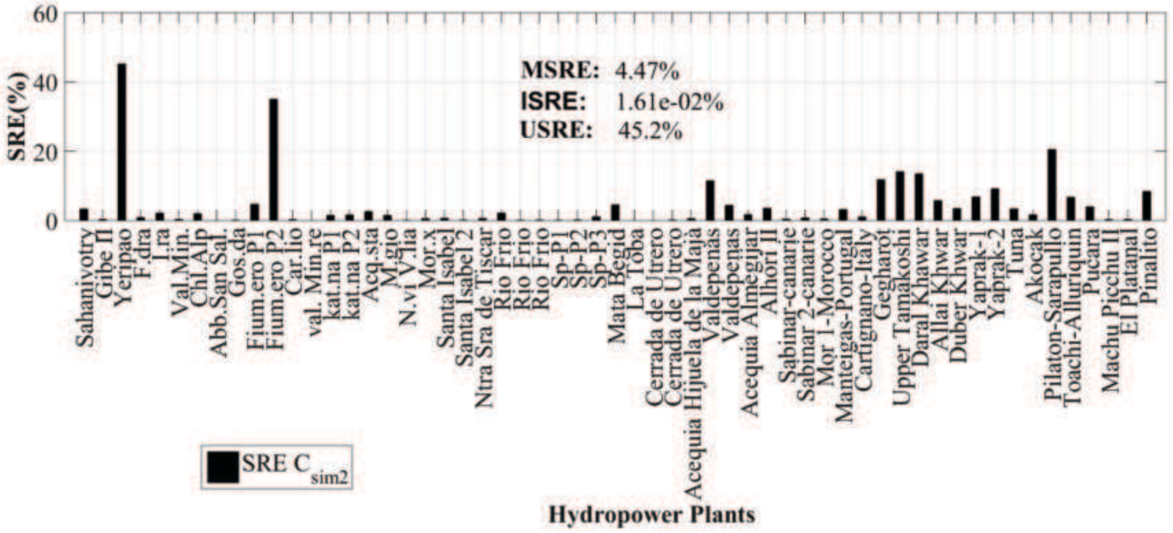

Figure 7: SRE obtained for Cost correlation N°2 ($\mathrm{C_{sim2}}$).

Cost correlation N°3 (C_{sim3})

The purpose of this section is to minimize the difference noticed between estimated cost and real cost (C_{real}) of EM equipment. Indeed, cost correlation N°3 (C_{sim3}) is proposed basing on dataset [see Tables 1-4], and given by Eq. 11. This equation depends not only on head H, capacity P, and flow Q but also on continental factor K_j, which is defined for representing the factors such as marketing and pricing strategies, import duties, incentives for export, equipment quality, etc. GA optimization method is used to determined K_j for each continent. In the first stage, mono-objective optimization is adopted to minimize MSRE. Afterwards, multi-objective optimization is used in the second stage considering MSRE and USRE as objective functions. The better solution is selected in third step. Finally, in the fourth step, the selected solution is compared with (C_{sim2}), which is obtained with the Cavazzini's model [13].

$$(C_{sim})_i = \left(a \times {H_i}^b + c \times {Q_i}^d + e \times {P_i}^f\right) \times K_j + g \tag{11}$$

Stage 1: Mono-objective optimization (C_{sim3}). The continental factors K_j and the coefficients {a, b, c, d, e, f, g} in Eq. 11 are decision variables used to minimize the objective function MSRE, viz. Eq. 12,

$$MSRE = \sigma^2 = \frac{1}{n_C - 1}\sum_{i=1}^{n_C}\left(\frac{(C_{sim})_i - (C_{real})_i}{(C_{real})_i}\right)^2 \tag{12}$$

The resulting cost correlation is given by Eq. 13:

$$(C_{sim3})_i = \left(147{,}141.11 \times {H_i}^{-0.6704} + 3.698 \times {Q_i}^{1.432} + 54{,}495.468 \times {P_i}^{0.1519}\right) \times K_j - 212{,}478.498 \tag{13}$$

and K_j are given in Table 5. (C_{sim3}) and (C_{real}) are plotted in Fig. 8. The SRE between (C_{sim3}) and (C_{real}) are given in Fig. 9. Fig. 10 shows correlation matrix of bivariate correlations between (C_{sim3}) and (C_{real}). The PPMCC ($\rho_{XY} = 0.99$) is statistically significant and shows a strong correlation between (C_{sim3}) and (C_{real}). The MSRE and USRE are respectively equal to 1.82 % and 11.4 %. The continental factor K_j have substantially improved the MSRE and USRE, which decreased from 4.47 % to 1.82 % and from 45.2 % to 11.4 %, respectively.

Table 5: Continental factors K_j obtained with mono-objective optimization.

	Africa	Europe	America	Asia
K_j	4.674	2.546	4.064	4,859

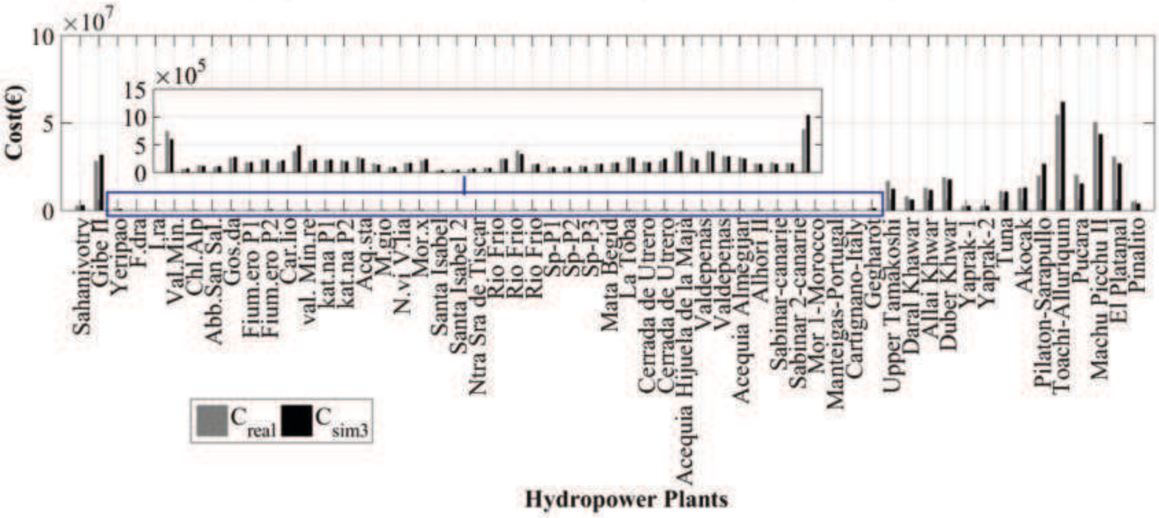

Figure 8: Comparison of Cost correlation N°3 (C_{sim3}) with real cost (C_{real}) for EM equipment.

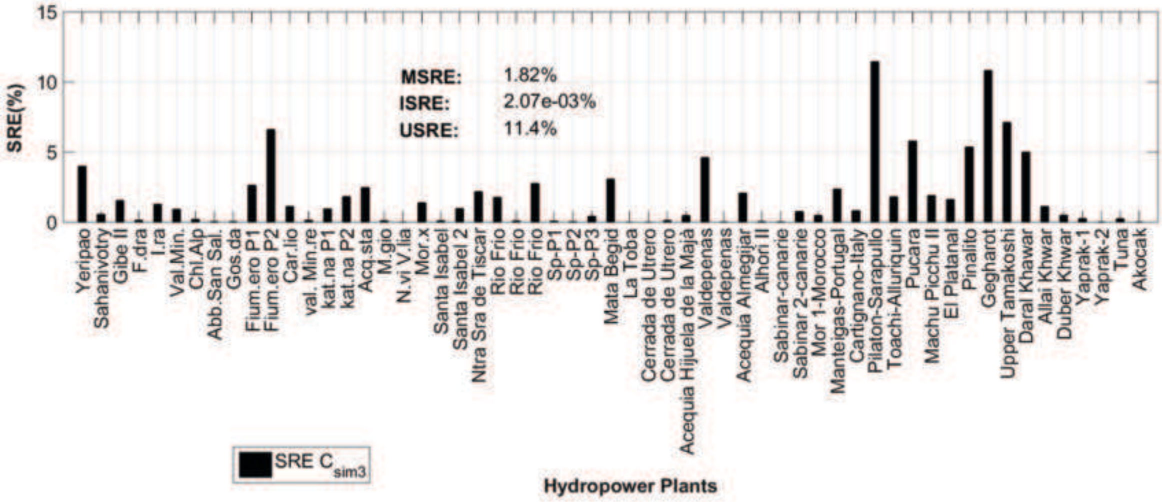

Figure 9: SRE obtained for Cost correlation N°3 (C_{sim3}).

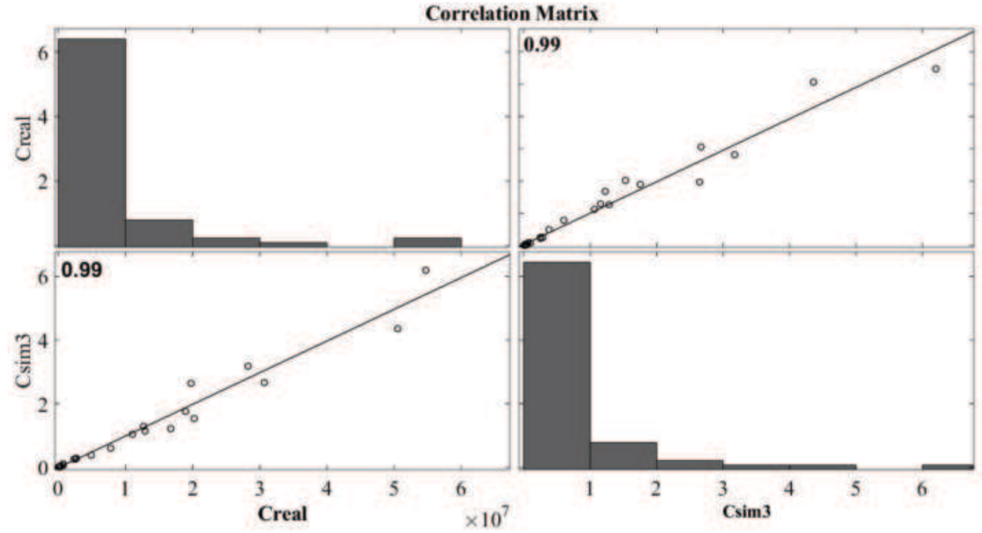

Figure 10: Correlations between Cost correlation N°3 (C_{sim3}) and real cost (C_{real}).

Stage 2: Multi-objective optimization (C_{simA} and C_{simB}). The purpose of this stage is to minimize both MSRE (i.e., Eq. 12) and USRE (i.e., Eq. 14):

$$USRE = maxi\left(\left(\frac{(C_{sim})_i - (C_{real})_i}{(C_{real})_i}\right)^2\right)\Bigg|_{i=1,2,\ldots,57} \tag{14}$$

with fast elitist non-dominated sorting genetic algorithm (NSGA-II), which suits well for any evolutionary algorithms [52]. The resulting Pareto front shown in Fig. 11 represents the non-dominated solutions. The points A and B indicate the two extreme solutions given by:

$$(C_{simA})_i = \left(156{,}732 \times {H_i}^{-0.7197} + 4.604 \times {Q_i}^{1.4143} + 57{,}621.6 \times {P_i}^{0.1475}\right) \times K_{jA} - 208{,}540 \tag{15}$$

$$(C_{simB})_i = \left(153{,}450 \times {H_i}^{-0.9171} + 4.626 \times {Q_i}^{1.4143} + 57{,}129.5 \times {P_i}^{0.1448}\right) \times K_{jB} - 203{,}958 \tag{16}$$

with K_{jA} and K_{jB} the continental factors defined in Table 6. Their MSRE and USRE are shown in Table 7.

Table 6: Continental factors K_{jA} and K_{jB} of extreme solutions.

	Africa	Europe	America	Asia
K_{jA}	4.455	2.439	3.901	4.633
K_{jB}	4.673	2.481	3.706	4.588

Table 7: MSRE and USRE of extreme solutions of Pareto front.

Points	MSRE	USRE	Comment
A	1.83%	11.39%	Smallest MSRE and highest USRE
B	2.01%	07.52%	Smallest USRE and highest MSRE

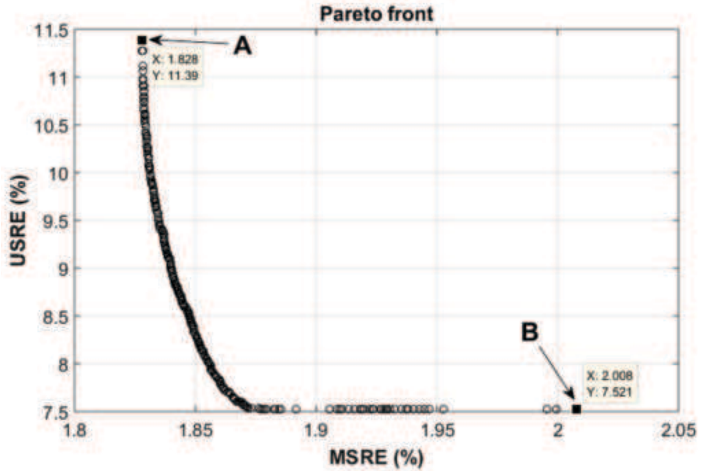

Figure 11: Pareto front of MSRE and USRE.

Stage 3: Selected solution. The better solution is chosen by comparing (C_{sim3}) obtained with mono-objective optimization and those of extreme solutions obtained with multi-objective optimization [i.e., (C_{simA}) and (C_{simB})]. (C_{real}) and these different costs correlation are plotted in Fig. 12. Their SRE are presented in Fig. 13. (C_{sim3}) has given the smallest MSRE and equal to 1.82 %. Accordingly, (C_{sim3}) is chosen as best solution.

Stage 4: Comparison of (C_{sim3}) and (C_{sim2}). The essential purpose of this paragraph is to validate the accuracy of (C_{sim3}) proposed with continental factors. This validation consists more precisely in comparing its statistical performance to that of (C_{sim2}) proposed without continental factors. The results of costs estimated with each of the two equations and (C_{real}) are presented in Fig. 14. Their PPMCC and SRE are respectively plotted in Figs. 15 and 16. In Fig. 15, the result shows that the two costs correlation have strong correlation with (C_{real}). The PPMCC are equal to 0.98 for (C_{sim2}) and 0.99 for (C_{sim3}). There is not a great difference between the two PPMCC. This demonstrate that the two costs correlation (C_{sim2}) and (C_{sim3}) give a good correlation with the real costs (C_{real}) of EM equipment. It can be noticed at Fig. 16, that the SRE of (C_{sim3}) are overall better than those of (C_{sim2}). The MSRE obtained for (C_{sim2}) and (C_{sim3}) are respectively equal to 4.47 % and 1.82 %. As for USRE, 45.2 % and 11.4 % are respectively obtained for (C_{sim2}) and (C_{sim3}). Indeed, the cost correlation of (C_{sim3}) proposed with continental factors is more accurate for estimating the cost of EM equipment of hydropower plants located in different continents. It is especially suitable for countries where there are very few hydropower plants already installed. This is the case, for example, of Benin having only one hydropower plant (i.e., Yeripao in Table 1) already installed. The SRE are equal to 45.2 % for (C_{sim2}) and 4 % for (C_{sim3}.

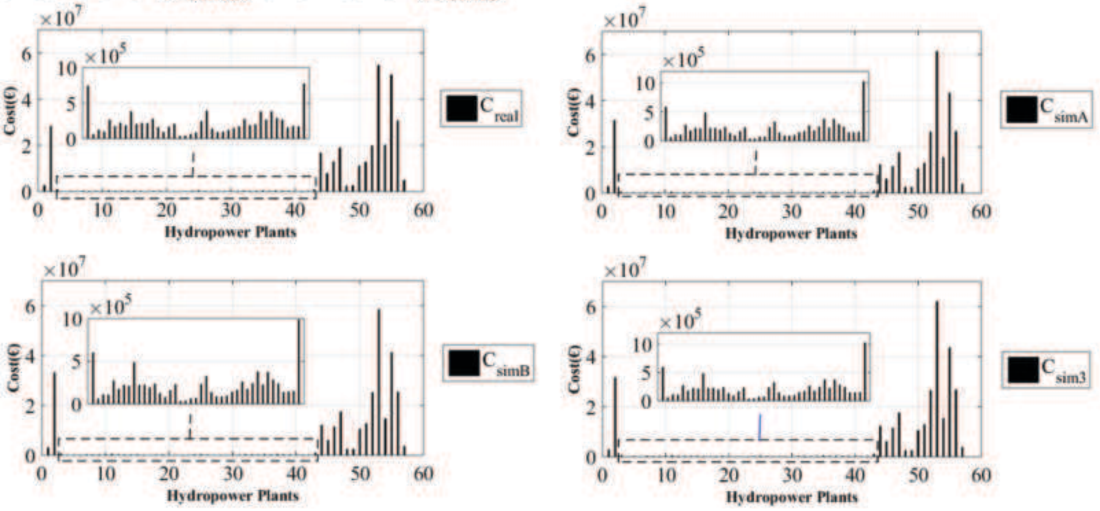

Figure 12: Comparison of (C_{simA}) & (C_{simB}) for multi-objective, (C_{sim3}) for mono-objective, and (C_{real}). The abscissas correspond to the Hydropower Plants number, in order shown in Fig. 8.

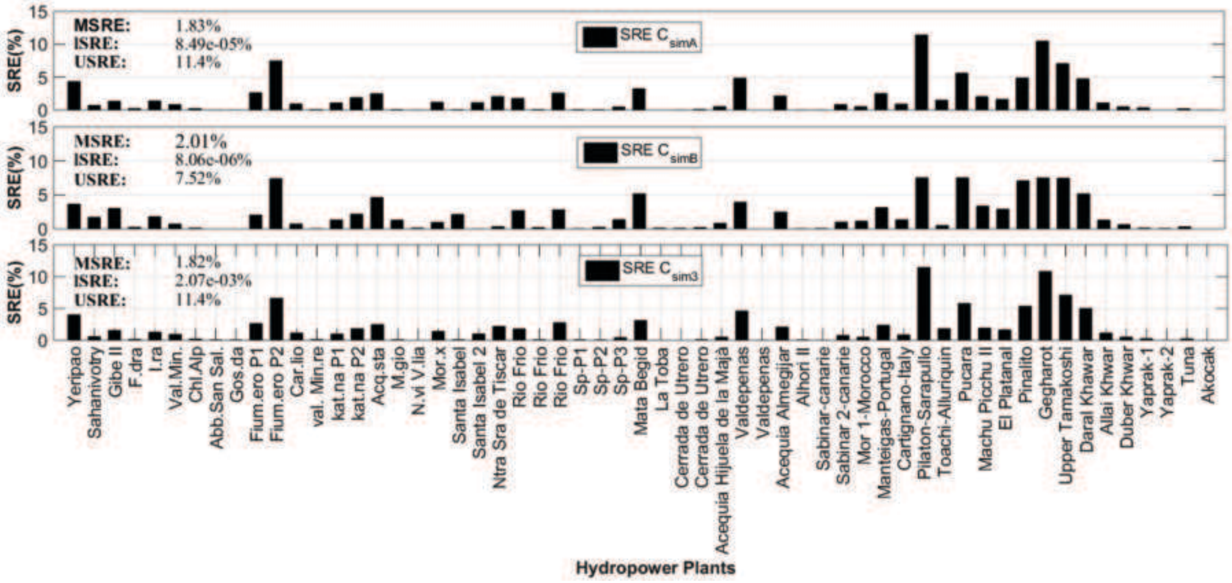

Figure 13: SRE obtained for (C_{simA}), (C_{simB}), and (C_{sim3}).

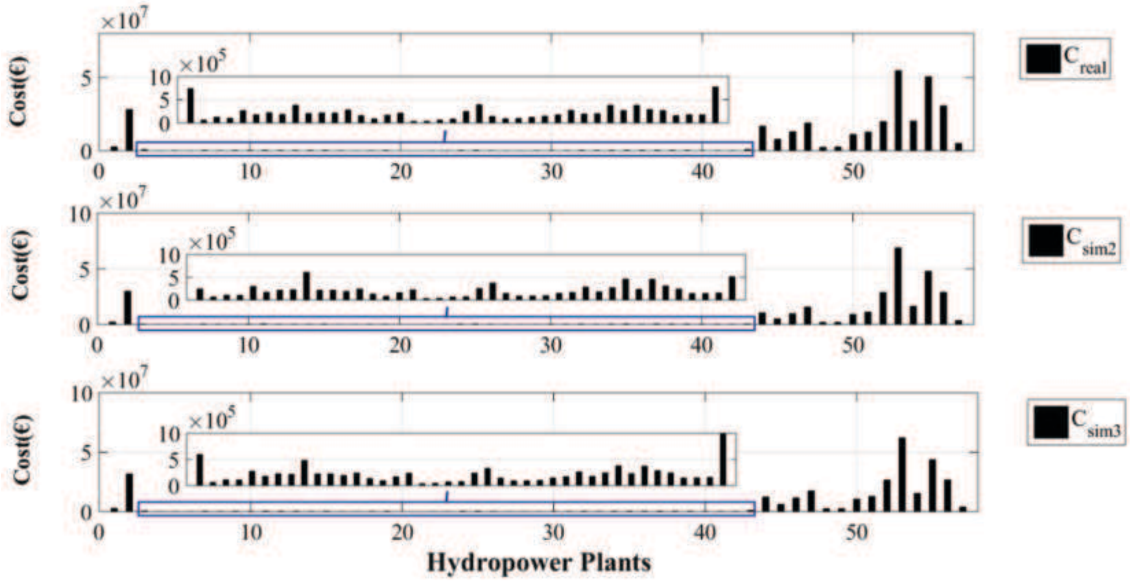

Figure 14: Comparison of (C_{sim2}), (C_{sim3}) and (C_{real}). The abscissas correspond to the Hydropower Plants number, in order shown in Fig. 8.

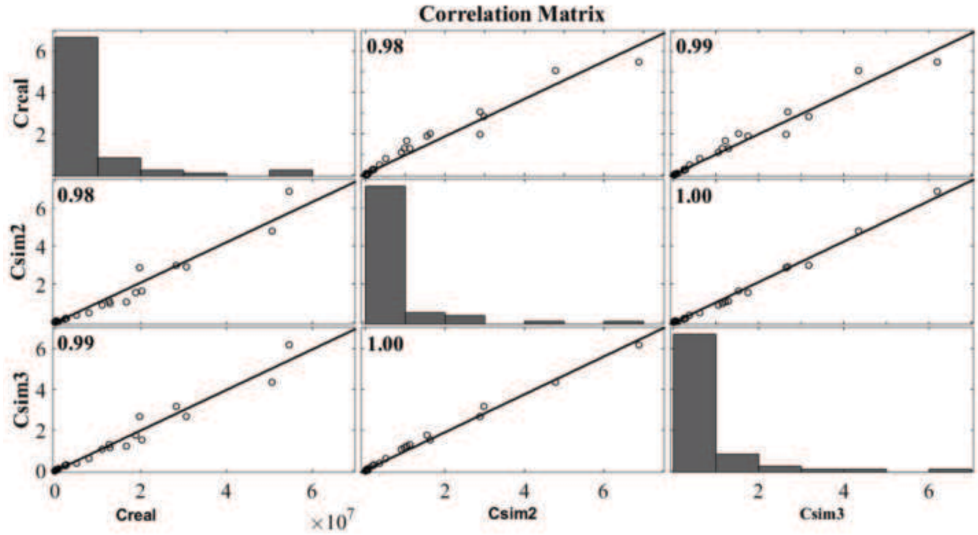

Figure 15: Correlations between (C_{sim2}), (C_{sim3}) and (C_{real}).

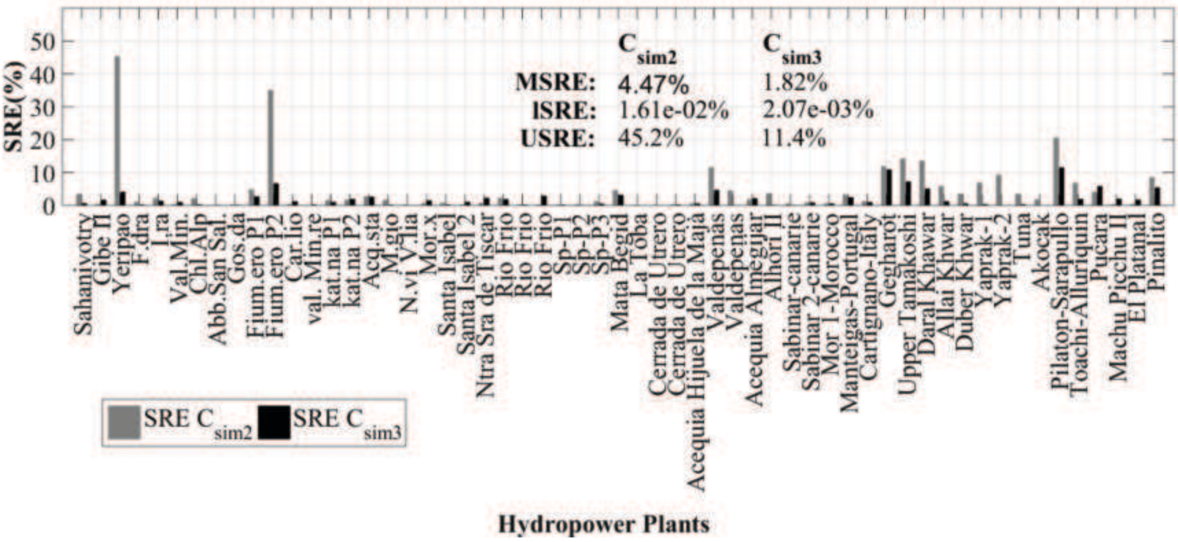

Figure 16: SRE obtained for (C_{sim2}) and (C_{sim3}).

Conclusion and Perspective

The paper has presented a cost estimation approach for EM equipment of hydropower plants in different continents. Differently from the literature correlations, the approach of cost estimation, proposed in this paper, is based on dataset of hydropower plants located in different continents. It has taken into account to the transport cost by determining continental factor K_j for each continent. Other alternatives have been explored for estimating the transport cost, but they have been more limited than using continental factor K_j. Similar idea of the continental differentiation is used when investing in real estate.. Furthermore, mono- and multi-objective GA optimization have been both applied and the results have been compared to determine the best decision variables and K_j. The statistical analysis tools, such as the MSRE and PPMCC, have been used to validate the accuracy of this proposed cost estimation approach. Indeed, its MSRE and PPMCC has been compared to those of the estimation model, not taking into account to K_j, deduced from the best model reviewed in the literature. The results have shown that the taken into account of K_j has slightly improved the PPMCC from 98 % to 99 %. This demonstrate that the two approaches give a good correlation with the real costs of EM equipment. The MSRE has been substantially improved from 4.47 % to 1.82 %, and the USRE from 45.2 % to 11.4 %. Therefore, the cost correlation considering K_j has given a more accurate estimate of the EM equipment cost for hydropower plants which are in different continents. It is especially suitable for countries where there are very few hydropower plants already installed.

It is necessary to notice that the proposed cost correlation has not taken into account maintenance cost. Furthermore, it has been elaborated for hydropower plants equipped with Pelton turbine. The same process can be used to elaborate cost correlation for other turbines type.

References

[1] B. Dursun and C. Gokcol, "The role of hydroelectric power and contribution of small hydropower plants for sustainable development in Turkey," *Renew. Energy*, vol. 36, no. 4, pp. 1227–1235, 2011 [Online]. Available: http://dx.doi.org/10.1016/j.renene.2010.10.001

[2] "La production d'électricité d'origine renouvelable dans le monde," 2013.

[3] S. M. H. Hosseini, F. Forouzbakhsh, and M. Rahimpoor, "Determination of the optimal installation capacity of small hydro-power plants through the use of technical , economic and reliability indices," *Energy Policy*, vol. 33, pp. 1948–1956, 2005.

[4] E. Moiseeva and M. R. Hesamzadeh, "Bayesian and Robust Nash Equilibria in Hydrodominated Systems Under Uncertainty," *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 818–830, 2018.

[5] K. S. Balkhair and K. U. Rahman, "Sustainable and economical small-scale and low-head hydropower generation: A promising alternative potential solution for energy generation at local and regional scale," *Appl. Energy*, vol. 188, pp. 378–391, 2017 [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2016.12.012

[6] L. V. L. Abreu, M. E. Khodayar, M. Shahidehpour, and L. Wu, "Risk-constrained coordination of cascaded hydro units with variable wind power generation," *IEEE Trans. Sustain. Energy*, vol. 3, no. 3, pp. 359–368, 2012.

[7] Y. Liu, C. Jiang, J. Shen, and J. Hu, "Coordination of Hydro Units With Wind Power Generation Using Interval Optimization," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 443–453, 2015.

[8] G. Lucio, T. Filho, I. Felipe, and R. M. Barros, "Cost estimate of small hydroelectric power plants based on the aspect factor," *Renew. Sustain. Energy Rev.*, vol. 77, no. March, pp. 229–238, 2017 [Online]. Available: http://dx.doi.org/10.1016/j.rser.2017.03.134

[9] G. A. Aggidis, E. Luchinskaya, R. Rothschild, and D. C. Howard, "The costs of small-scale hydro power production: Impact on the development of existing potential," *Renew. Energy*, vol. 35, no. 12, pp. 2632–2638, 2010 [Online]. Available: http://dx.doi.org/10.1016/j.renene.2010.04.008

[10] Adriana Castro, "Minicentrales hidroeléctricas," 2006 [Online]. Available: www.idae.es

[11] D. Antonio Zema, A. Nicotra, V. Tamburino, and S. Marcello Zimbone, "A simple method to evaluate the technical and economic feasibility of micro hydro power plants in existing irrigation systems," *Renew. Energy*, vol. 85, pp. 498–506, 2016 [Online]. Available: http://dx.doi.org/10.1016/j.renene.2015.06.066

[12] J. L. Gordon and A. C. Penman, "Quick estimating techniques for small hydro potential," *J. Water Power Dam Constr*, vol. 31, pp. 46–55, 1979.

[13] G. Cavazzini, A. Santolin, G. Pavesi, and G. Ardizzon, "Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling," *Energy*, vol. 103, pp. 746–757, 2016 [Online]. Available: http://dx.doi.org/10.1016/j.energy.2016.03.024

[14] J. S. Gulliver, M. ASCE, and A. Dotan, "Cost estimated for hydropower at existing dams," *J. Energy Eng.*, vol. 110, no. 3, pp. 204–214, 1984.

[15] N. G. Voros, C. T. Kiranoudis, and Z. B. Maroulis, "Short-cut design of small hydroelectric plants," *Renew. Energy*, vol. 19, no. 4, pp. 545–563, 2000.

[16] J. K. Kaldellis, "The contribution of small hydro power stations to the electricity generation in Greece : Technical and economic considerations," *Energy Policy*, vol. 35, pp. 2187–2196, 2007.

[17] J. K. Kaldellis, D. S. Vlachou, and G. Korbakis, "Techno-economic evaluation of small hydro power plants in Greece : a complete sensitivity analysis," *Energy Policy*, vol. 33, pp. 1969–1985, 2005.

[18] J. S. Anagnostopoulos and D. E. Papantonis, "Optimal sizing of a run-of-river small hydropower plant," *Energy Convers. Manag.*, vol. 48, pp. 2663–2670, 2007.

[19] M. R. Nouni, S. C. Mullick, and T. C. Kandpal, "Techno-economics of micro-hydro projects for decentralized power supply in India," *Energy Policy*, vol. 34, pp. 1161–1174, 2006.

[20] S. K. Singal and R. P. Saini, "Analytical Approach for Cost Estimation of Low Head Small Hydro Power Schemes," *Int. Conf. Small Hydropower*, no. October, pp. 22–24, 2007.

[21] S. K. Singal and R. P. Saini, "Analytical approach for development of correlations for cost of canal-based SHP schemes," *Renew. Energy*, vol. 33, pp. 2549–2558, 2008.

[22] Singal S. K., Saini R. P, and Raghuvanshi C. S, "Cost Optimisation Based on Electro-Mechanical Equipment of Canal Based Low Head Small Hydropower Scheme," *Open Renew. Energy J.*, vol. 1, pp. 26–35, 2008.

[23] S. K. Singal and R. P. Saini, "Cost analysis of low-head dam-toe small hydropower plants based on number of generating units," *Energy Sustain. Dev.*, vol. 12, no. 3, pp. 55–60, 2008 [Online]. Available: http://dx.doi.org/10.1016/S0973-0826(08)60439-1

[24] B. Ogayar and P. G. Vidal, “Cost determination of the electro-mechanical equipment of a small hydro-power plant,” *Renew. Energy*, vol. 34, no. 1, pp. 6–13, 2009.

[25] B. Ogayar, P. G. Vidal, and J. C. Hernandez, “Analysis of the cost for the refurbishment of small hydropower plants,” *Renew. Energy*, vol. 34, no. 11, pp. 2501–2509, 2009 [Online]. Available: http://dx.doi.org/10.1016/j.renene.2009.03.027

[26] S. K. Singal, R. P. Saini, and C. S. Raghuvanshi, “Analysis for cost estimation of low head run-of-river small hydropower schemes,” *Energy Sustain. Dev.*, vol. 14, no. 2, pp. 117–126, 2010 [Online]. Available: http://dx.doi.org/10.1016/j.esd.2010.04.001

[27] “Small Scale Hydroelectric Generation Potential In the UK,” ETSU SSH 4063-P1-3, 1989 [Online]. Available: http://www.howardrudd.net/files/ETSU-SSH-4063-P1.pdf

[28] S. Mishra, S. Kumar Singal, and D. Kumar Khatod, “Approach for Cost Determination of Electro-Mechanical Equipment in RoR SHP Projects,” *Smart Grid Renew. Energy*, vol. 2, pp. 63–67, 2011.

[29] S. Mishra, S. K. Singal, and D. K. Khatod, “Optimal installation of small hydropower plant — A review,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 8, pp. 3862–3869, 2011 [Online]. Available: http://dx.doi.org/10.1016/j.rser.2011.07.008

[30] A. Santolin, G. Cavazzini, G. Pavesi, G. Ardizzon, and A. Rossetti, “Techno-economical method for the capacity sizing of a small hydropower plant,” *Energy Convers. Manag.*, vol. 52, no. 7, pp. 2533–2541, 2011 [Online]. Available: http://dx.doi.org/10.1016/j.enconman.2011.01.001

[31] S. Mishra, S. K. Singal, and D. K. Khatod, “Costing of a Small Hydropower Projects,” *IACSIT Int. J. Eng. Technol.*, vol. 4, no. 3, pp. 239–242, 2012.

[32] S. Mishra, S. K. Singal, and D. K. Khatod, “A review on electromechanical equipment applicable to small hydropower plants,” *Int. J. ENERGY Res.*, vol. 36, no. February, pp. 553–571, 2012.

[33] Q. Fen, K. Zhang, and B. Smith, “Small Hydropower Cost Reference Model,” 2012.

[34] S. Mishra, S. K. Singal, and D. K. Khatod, “Cost analysis for electromechanical equipment in small hydropower projects,” *Int. J. Green Energy*, vol. 10, no. 8, pp. 835–847, 2013.

[35] A. H. Elbatran, O. B. Yaakob, Y. M. Ahmed, and H. M. Shabara, “Operation, performance and economic analysis of low head micro-hydropower turbines for rural and remote areas: A review,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 40–50, 2015 [Online]. Available: http://dx.doi.org/10.1016/j.rser.2014.11.045

[36] G. Manfrida and R. Secchi, “Seawater pumping as an electricity storage solution for photovoltaic energy systems,” *Energy*, vol. 69, pp. 470–484, 2014 [Online]. Available: http://dx.doi.org/10.1016/j.energy.2014.03.040

[37] J. J. C. Barros, M. L. Coira, María Pilar de la Cruz López, and A. del Caño Gochi, “Assessing the global sustainability of different electricity generation systems,” *Energy*, vol. 89, pp. 473–489, 2015.

[38] S. Mishra, S. K. Singal, and D. K. Khatod, “Cost Optimization of High Head Run of River Small Hydropower Projects,” in *Application of Geographical Information Systems and Soft Computation Techniques in Water and Water Based Renewable Energy Problems*, Mrinmoy Majumder, Ed. 2018, pp. 141–166 [Online]. Available: http://www.springer.com/series/7009

[39] C. Alvarado Ancieta, “Estimating E & M powerhouse costs,” *Int. Water Power Dam Constr.* ·, vol. 61, pp. 21–25, 2009.

[40] M. J. Kaiser and B. F. Snyder, “Modeling offshore wind installation vessel day-rates in the United States,” *Marit. Econ. Logist.*, vol. 14, no. 2, pp. 220–248, 2012.

[41] M. Wild *et al.*, “Possible effect of torrefaction on biomass trade,” 2012.

[42] Sosiété Béninoise de l’Energie Electrique (SBEE), *Centrale hydroélectrique de Yéripao*. 2017.

[43] A. Verbruggen, “Projet micro hydro de Natitingou-Yéripao (Bénin): Rapport d’évaluation du projet et de projets alternatifs.,” 1993.

[44] J. H. Holland, “Adaptation in natural and artificial systems,” *Univ. of. Michigan Press*, vol. 18, no. 3, pp. 529–530, 1975.

[45] Daming Xu, Longyun Kang, Liuchen Chang, and Binggang Cao, "Optimal sizing of standalone hybrid wind/pv power systems using genetic algorithms," in *Canadian Conference on Electrical and Computer Engineering, 2005.*, 2005, no. May, pp. 1722–1725 [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1557315

[46] B. Bhandari, L. Kyung-Tae, C. Young-Man, and A. Sung-Hoon, "Optimization of Hybrid Renewable Energy Power system: A review," *Int. J. Precis. enginnering Manuf. Technol.*, vol. 2, no. 1, pp. 99–112, 2015 [Online]. Available: http://link.springer.com/article/10.1007/s40684-015-0013-z

[47] J. Liu, W. Fang, X. Zhang, and C. Yang, "An Improved Photovoltaic Power Forecasting An Improved Photovoltaic Power Forecasting Model With the Assistance of Aerosol Index Data," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 434–442, 2015.

[48] L. Yi, X. Liye, W. Haifeng, D. Shaotao, and Q. Zhiping, "Analysis on the hourly spatiotemporal complementarities between China's solar and wind energy resources spreading in a wide area," *Sci. CHINA Technol. Sci.*, vol. 56, no. 3, pp. 683–692, 2013.

[49] V. S. Lopes, C. L. T. Borges, and S. Member, "Impact of the Combined Integration of Wind Generation and Small Hydropower Plants on the System Reliability," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1169–1177, 2014.

[50] P. K. Revelou, M. G. Kokotou, and C. S. Pappas, "Journal of Food Composition and Analysis Direct determination of total isothiocyanate content in broccoli using attenuated total re fl ectance infrared Fourier transform spectroscopy," *J. Food Compos. Anal.*, vol. 61, pp. 47–51, 2017 [Online]. Available: http://dx.doi.org/10.1016/j.jfca.2017.01.020

[51] J. Guang *et al.*, "COMPARISON OF TWO METHODS FOR AEROSOL OPTICAL DEPTH RETRIEVAL OVER NORTH AFRICA FROM MSG / SEVIRI DATA," in *ieee*, 2014, pp. 335–338.

[52] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, 2002.