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Multi-Objective Optimization of Run-of-River Small-Hydropower Plants Considering Both Investment Cost and Annual Energy Generation

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Abstract**—**This paper presents the techno-economic evaluation of run-of-river small-hydropower plants. In this regard, a multi-objective optimization procedure is proposed for the optimal sizing of the hydropower plants, and NSGAII is employed as the optimization algorithm. Annual generated energy and investment cost are considered as the objective functions, and number of generator units (*n*) and nominal turbine flow rate (Q_T) constitute the decision variables. Site of Yeripao in Benin is considered as the case study. We have categorized the river of this site using its environmental characteristics: gross head, and first quartile, median, third quartile and mean of flow. Effects of each decision variable on the objective functions are analysed. The results gave Pareto Front which represents the trade-offs between annual energy generation and the investment cost of hydropower plants, as well as the recommended optimal solutions. We noted that with the increase of the annual energy generation, the investment cost rises. Thus, maximizing energy generation is contradictory with minimizing the investment cost. Moreover, we have noted that the solutions of Pareto Front are grouped according to the number of generator units (*n).* The results also illustrate that the costs per kWh are grouped according to the *n* and rise with the increase of the nominal turbine flow rate. The lowest investment costs per kWh are obtained for *n* equal to one and are between 0.065 and 0.180 €/kWh. Following the values of n (equal to 1, 2, 3 or 4), the investment cost and investment cost per kWh increase almost linearly with increasing the nominal turbine flowrate while annual generated. Energy increases logarithmically with increasing of the nominal turbine flowrate. This study made for the Yeripao river can be applied to other rivers with their own characteristics.

Keywords**—**Hydropower plant, investment cost, multi-objective optimization, number of generator units.

I. INTRODUCTION

ELECTRIC power is a crucial factor for the development of a country and has seen a remarkable rise since the second world war. Its generation with hydropower plant constitutes the most promising power technology. It is an awesome opportunity for increasing electrification rate and reducing the poverty level [1] for rural regions in developing countries. Indeed, hydropower plant can participate in development of small scale industries with a cheap source [2]. It has impressive operational flexibility [3] and is predictable when enough water supply is available [4]. Hydropower plant has good reliability [5], important efficiency, low maintenance cost and has significant capacity of storage [6]. A small-scale hydropower plant is one of the most cost-effective and environmentally friendly energy source [7], and it plays an important and vital role for rural electrification in less developed countries [8]. In comparison with small petrol/diesel generators, wind turbines or photovoltaic systems, hydropower plant presents a lower generation cost [9], [10] and can be adapted as the most economical option for rural electrification [11].

A major barrier to starting hydropower plant project is an understanding of how much the scheme will cost [12]. The investment cost occupies a large proportion in the total budget of the hydropower plant project. Investment cost is the most economic challenge faced by small-hydropower plant [13]. It affects the viability of a hydroelectric plant project [14]. Thus, techno-economic analyses play a very important role for small hydropower plants design. Feasibility and operations management of small hydropower plants has been presented in several studies. Mandelli et al. [15] developed model for techno-economic feasibility analysis of run-of-river small hydropower plants. The model was developed in Microsoft Excel. The sizing process and the empirical functions used were based on the "Guide on How to Develop a Small Hydropower plant" developed by European Small Hydropower Association (ESHA) [16]. Nair and Nithiyananthan [17] focused their study on the technical, theoretical and financial analysis of a hydropower plant. They optimized the design of mini hydro using the RETScreen Clean Energy Project Analysis software. The flow rate of 0.21 m³/s was used for this project. Zema et al. [18] developed a simple method for choosing location and power output of turbines, assessing the costs and revenues and being decision guide for micro hydropower plant design. They noted that operating time was factor which noticeably influences the economic viability of micro hydropower systems. Beforehand, they supposed that the micro hydropower turbines operated for at least seven months per year outside the 5-month irrigation period. Further simulations were carried out by hypothesizing an operating time of 6- month and 4-month irrigation period, typical values for a dry or wet year. Girma [19] studied the

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technical and economic feasibility of grid connected small scale hydropower construction, by using HOMER, RETscreen, and SMARTMini-IDRO software. He showed the overall situation of small hydropower and its technical and economic feasibility by using simulation. Other existing studies focused on optimal sizing of small hydropower plants. Anagnostopoulos and Papantonis [20] applied a stochastic evolutionary algorithm method to size a hydropower plant which is composed of two hydro turbines working in parallel. The optimization problem was studied in single and bi-objectives modes. In the single-objective optimization, some operation value or economic parameters were optimized to converge to the minimum cost function value. The bi-objective optimization study investigated the interdependence of some of the objectives. Net Present Value and load coefficient were optimized in the first bi-objective optimization problem. The second bi-objective optimization combined Net Present Value and energy production index. It was noted that this second bi-objective optimization was the best alternative design for the scheme. Xu et al. [21] built a sizing optimization model of run-of-river small hydropower. The minimal loss of distribution network and maximal clean energy generation ratio were taken as the objective functions under constraints of qualified voltage level. Koko et al. [22] used the Legacy Version of HOMER to determine the optimal size of a river-based micro-hydrokinetic pumped-hydro-storage hybrid system.

The objectives of this paper are to: (1) propose a multi-objective optimization procedure for the optimal sizing of hydropower plants, using NSGAII as the optimization algorithm, considering annual generated energy and investment cost as objective functions, and number of generator units (n) and nominal turbine flow rate (QT) as decision variables; (2) investigate the influence of decision variables on objective functions. The best trade-offs between annual generated energy and the investment cost of hydropower plants are determined.

The paper is organized as follows. In Section II, materials and methods are presented. Section III provides the results and discussion and is followed by conclusions in Section IV.

II. Materials and Methods

A. Materials

The case study is focused on hydro resources of Yeripao river (latitude: 10°15'21.06" N, longitude: 1°25'43.57" E, altitude: 430 m) in Natitingou, a town located in northwest of Benin. We choose this site because rehabilitation activity of the Yeripao Hydropower Plant and its extension are inscribed in Benin Program for the Millennium Challenge Account (MCA II) [23]. The objective of the MCA II program is to support Benin in meeting its electricity needs, increasing its production capacity [24]. The hydro resources of Yeripao river are obtained from [25]. Fig. 1 shows the mean daily water flows. From these mean daily water flows, we establish flow duration curve (Fig. 2) for investigating available flow that allows us to choose the suitable turbine. We will choose in following section, the suitable turbine for Yeripao Hydropower Plant, using simultaneously the net water head $(H_{net} = 119.5\,m)$ and four characteristic flows, namely, first quartile $(Q_{75\%} = 0.06275\,m^3/s)$, median $(Q_{50\%} = 0.15\,m^3/s)$, third quartile $(Q_{25\%} = 0.485\,m^3/s)$ and mean annual flow $(Q_{mean} = 0.491\,m^3/s)$.

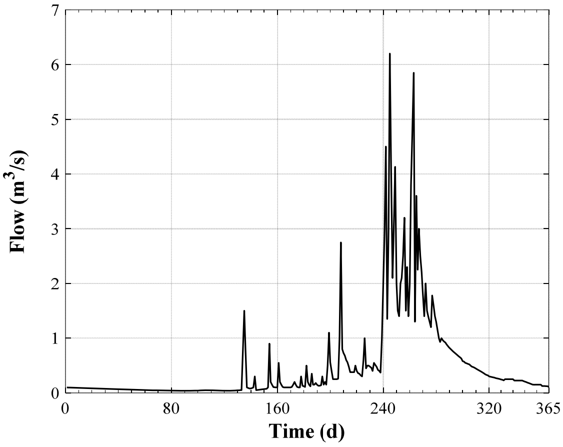

Fig. 1 Mean Daily Water Flows for Yeripao River

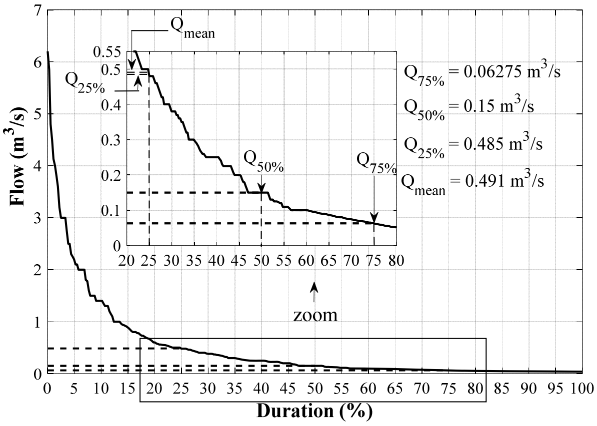

Fig. 2 Flow Duration Curve of Yeripao River

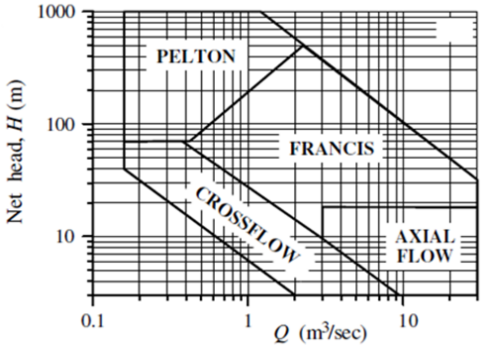

Fig. 3 Turbine selection nomograph [20]

B. Turbine Type Selection

The choice of turbine type for any hydropower plant depends on the site characteristics such as the net water head and flow rate of the river. The classification of hydro turbines according to their net water head and flow rate is shown by the nomograph (Fig. 3) This nomopgraph can be used for selecting the most suitable hydro turbine type for Yeripao Hydropower Plant. Considering H_{net}, $Q_{75\%}$, $Q_{50\%}$, $Q_{25\%}$ and Q_{mean} of Yeripao River, it is evident that the nearest is the Pelton turbine. Thus, the Pelton turbine is considered for using in this study.

C. Model of Annual Energy Generated by Small-Hydropower Plant

Hydro-turbine transforms the water potential energy into mechanical energy, which is finally converted to electrical energy by electrical generator.

The formula for calculating annual energy generation of Hydropower plant E (kWh) is shown in (1):

$$E = 24\sum_{d=1}^{365} \eta_T \eta_G \rho g Q_T(d)\, H_{net} \tag{1}$$

where ρ is the water mass density $\left(\frac{kg}{m^3}\right)$, g is the gravity acceleration, H_{net} is the net water head (m), $Q_T(d)$ is the mean daily turbined flow (m^3/s) of the day d, η_T and η_G are efficiencies of the turbine and electrical generator respectively. The electrical generator efficiency is about 90% [26]. An empirical expression is proposed in [27] for representing the turbine efficiency variation:

$$\eta_T(d) = \left[a\left(\frac{Q_T(d)}{Q_{Tr}}\right)^2 + b\left(\frac{Q_T(d)}{Q_{Tr}}\right) + c\right]\eta_{Tr} \tag{2}$$

where Q_{Tr} and η_{Tr} are nominal turbine flow rate and efficiency respectively, a, b and c are coefficients, of which values are defined in [27].

D. Models of Investment Cost of Small-Hydropower Plants

We use the models developed in [28] for estimating investment cost of small-hydropower plants. Note that these models were chosen because they depend not only on output power (kW) and net head (m), but also on number of generator units (*n*) which is a decision variable in our study.

E. Optimization Problem Formulation

The objective is to maximize annual energy generation (3) and to minimize the investment cost (4), simultaneously, of *n* units of hydropower plants. We will find the trade-offs between these two objective functions using NSGA II. Number of generator units (*n*) and nominal turbine flow rate (Q_{Tr}) constitute the two decision variables for optimization.

$$Obj1 = max\{24n\sum_{d=1}^{365} \eta_T \eta_G \rho g Q_T(d)\, H_{net}\} \tag{3}$$

$$Obj2 = min\{C_{inv}(H_{net}, P, n)\} \tag{4}$$

where $C_{inv}(H_{net}, P, n)$ is investment cost of n units of hydropower plants developed in [28]. P is power output delivered by the n generator units.

III. Results and Discussion

A. Front of Pareto

The Pareto front, shown in Fig. 4, presents 200 optimal solutions which result after computation of 100 generations. Each solution contains a set of optimal parameters for sizing of hydropower plant. These solutions constitute the best trade-offs between annual generated energy and the investment cost of hydropower plant. We can note that with the increase in the annual generated energy, the investment cost rises. Thus, maximizing annual generated energy is contradictory with minimizing the investment cost.

In Fig. 4, solution A provides the lowest overall annual generated energy, and the least investment cost. Likewise, solution C offers the highest overall annual generated energy and as expected, it is the most expensive. The middle solution B provides an intermediate investment cost and annual generated energy.

Optimal decision variables corresponding to solution A, B and C are presented in Table I. We can remark that for these solutions, decision variables rise with increasing of the both objective functions. The following paragraph will present the sensitivity of decision variables of all solutions of Pareto front.

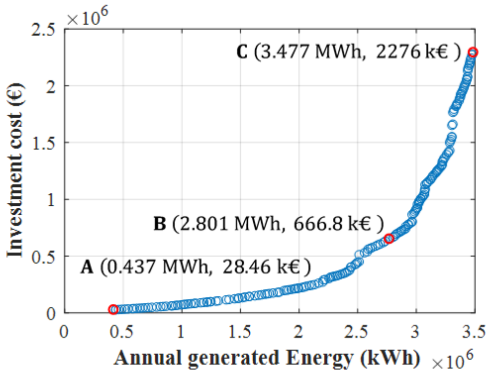

Fig. 4 Annual generated energy-Investment cost optimization results for Yeripao Hydropower Plant

TABLE I
Decision Variables Corresponding to Typical Optimal Solutions

	A	B	C
Nominal turbine flowrate (m^3/s)	0.038	0.5608	0.6413
number of generator units	1	2	4

B. Sensitivity Analysis of Decision Variables on Objective Functions

Figs. 5-7 illustrate the sensitivity of number of generator units and nominal turbine flowrate on investment cost, annual generated energy, and investment cost per kWh, respectively. Each figure shows that the Pareto optimal solutions are grouped into four categories according to number of generator units (*n*): black color (*n* = 1), blue color (*n* = 2), green color (*n* = 3) and red color (*n* = 4). We can also note that the investment cost (Fig. 5) and investment cost per kWh (Fig. 7) increase almost linearly with increasing of the nominal turbine flowrate while annual generated energy increases logarithmically with increasing of the nominal turbine flowrate (Fig. 6). In Table II, the number of optimal solutions, the ranges of variation of nominal turbine flow rate, of investment cost, of annual generated energy and of investment cost per kWh are presented following the number of generator units (equal to 1, 2, 3 or 4).

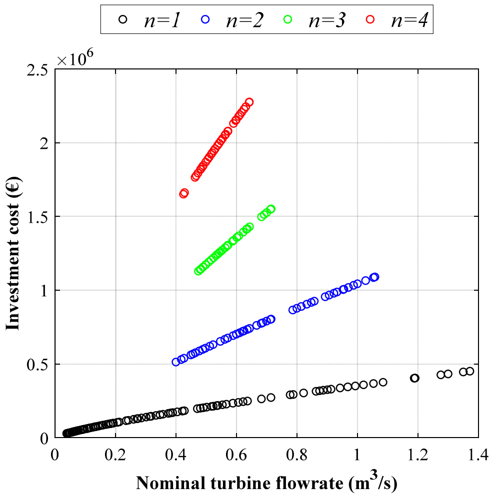

Fig. 5 Sensitivity analysis of decision variables on investment cost of hydropower plant

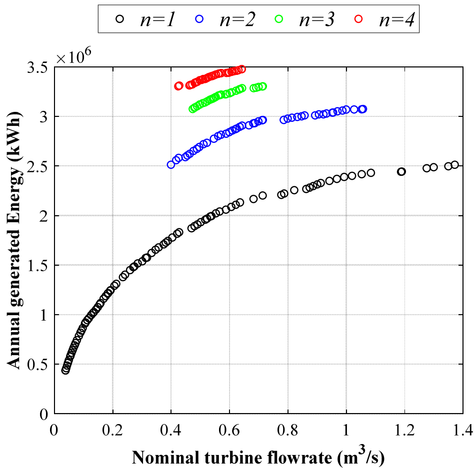

Fig. 6 Sensitivity analysis of decision variables on annual generated energy of hydropower plant

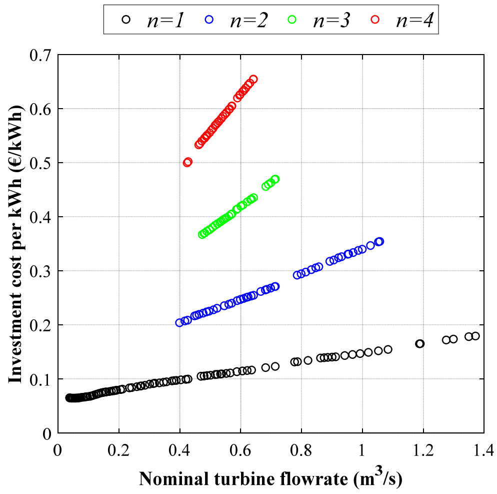

Fig. 7 Sensitivity analysis of decision variables on investment per kWh of hydropower plant

TABLE II
OBTAINED PARAMETERS FOR EACH CATEGORY OF PARETO OPTIMAL SOLUTIONS

	$n = 1$	$n = 2$	$n = 3$	$n = 4$
Number of optimal solutions	91	45	30	34
Nominal turbine flowrate (m^3/s)	[0.038 1.371]	[0.399 1.057]	[0.474 0.714]	[0.424 0.642]
Investment cost (k€)	[28.46 451]	[512.8 1,090]	[1,129 1,552]	[1,651 2,276]
Annual generated energy (GWh)	[0.437 2.512]	[2.512 3.075]	[3.075 3.304]	[3.304 3.477]
Investment cost per kWh (€/kWh)	[0.065 0.180]	[0.204 0.354]	[0.367 0.47]	[0.5 0.655]

IV. CONCLUSION

This study aimed to propose a multi-objective optimization procedure for the optimal sizing of hydropower plants, considering annual generated energy and investment cost simultaneously. Number of generating units and nominal turbine flow rate has constituted the decision variables, and NSGAII has been employed as the optimization algorithm. This procedure has been applied to Yeripao River, whose environmental characteristics have been investigated using gross head, and first quartile of flow, its median, its third quartile and its value mean. The result of investigation allowed to confirm that Pelton is the most suitable hydro turbine type for Yeripao Hydropower Plant. Optimal solutions from the multi-objective optimization have converged to the Pareto front. These solutions constitute the best trade-offs between annual generated energy and the investment cost of hydropower plant. Each solution contains a set of optimal parameters for sizing of hydropower plant. We have noted that with the increase in the annual generated energy, the investment cost rises. Thus, maximizing annual generated energy is contradictory with minimizing the investment cost. Sensitivity analysis of decision variables on both objective functions have shown that decision variables rise with increasing of the both objective functions. The Pareto optimal solutions have been grouped according to number of generator units. The investment cost and investment cost per kWh have increased almost linearly with increasing of the nominal turbine flowrate while annual generated energy has increased logarithmically with increasing of the nominal turbine flowrate. The results given in Table II show that the costs per kWh are grouped according to the number of generator units (n) and rise with the increasing of the nominal turbine flow rate. The lowest investment costs per kWh are obtained for n equal to one and are between 0.065 and 0.180 €/kWh. This study has been applied to case of Yeripao River; it can be also applied to other rivers with their environmental characteristics.

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