Multi-Objective Optimization of Run-of-River Small Hydro-PV Hybrid Power Systems

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***Abstract*—This paper presents the sizing of run-of-river small hydro-PV hybrid power system using the Non-dominated Sorting Genetic Algorithm (NSGA-II). The two objective functions are the total generated energy and the energy production cost of hybrid system. The total energy has been maximized whereas the energy production cost of hybrid system has been minimized. The nominal turbine flow rate (Q_{Tr}), the number of hydropower units (n_{hyd}), and the number of PV modules (n_{PV}) are considered as decision variables in this problem. The Yeripao site in Benin has been considered as case study. The optimal solutions converge to Pareto front which represent the best trade-offs between total generated energy and energy production cost. The results have shown that energy production cost increases with the total generated energy. Thus, minimizing the energy production cost is contradictory with maximizing the total generated energy. Moreover, the sensitivities analysis of Q_{Tr} and n_{hyd} on the total generated energy and on energy production cost have been conducted in this study. It is relevant to note that the optimal solutions are grouped into four categories according to $n_{hyd} = 1, 2, 3\ or\ 4$. For each category, the total generated energies, energy production costs and cost per kWh increase with the Q_{Tr}. For $n_{hyd} = 1$ the lowest values of energy production costs, total generated energies and costs per kWh have been recorded. Moreover, $n_{hyd} = 4$ match with the solutions that present the highest total generated energies and costs. The lowest overall cost per kWh is € 0.363/kWh. The conducted study can be applied to other sites by using their hydro and solar resources characteristics.**

Keywords—cost, energy generation, hydro-PV hybrid system, multi-objective optimization

I. INTRODUCTION

Hybrid power plants are becoming increasingly attractive owing to their most efficiency. They are technically and economically approved in diverse cases. Existing hybrid systems are generally composed of hydro–PV system [1]–[4], wind-PV system [5], [6], hydro-wind system [7], [8], hydro-PV-wind system [9], [10], and hydro-PV-wind-Diesel system [11], [12]. Hydro-PV systems are becoming more and more popular among these diverse hybrid systems, because of the low costs and operational flexibility of hydropower plants [13]. Moreover, the solar energy is highly available on all world. Studies addressing on hydro-PV plants are mainly focus on complementarity analysis between two power sources [14]–[18]. Beluco *et al.* [14] evaluated the complementarity effect between solar and hydro energy concluding that the determination of complementarity characteristics were required for designing the hybrid power system and could improve efficiency of the system. Kougias *et al.* [16] presented a methodology to improve the time complementarity between solar PV systems and small hydropower plants. François *et al.* [17] analyzed the complementarity between run-of-river energy and solar in Northern Italy. They noted that the system stability was improved by hydropower at small temporal scale (hourly) and by solar power generation at larger temporal scales (daily and monthly). François *et al.* [15] predicted complementarity between PV and run-of-river hydropower by studying the skill of different hydrological prediction methods. Li *et al.* [18] used long-term stochastic optimization approaches to improve the performance of long-term complementary operation for a large-scale hydro-PV hybrid power plant. The operations management of hydro-PV hybrid power system are discussed in other papers. Sheng *et al.* [19] analyzed operation characteristics of small hydro-PV hybrid power system and proposed control strategies to maintain balance between generations and loads. Yang *et al.* [20] designed parallel and interactive operation modes for hydro-PV hybrid power system. Zhou *et al.* [21] focused their study on the stability of the hydro-PV hybrid power system by using a PSCAD simulation. Meshram et al. presented simulation modeling of PV-hydro hybrid power system connected to grid [22], analysed the system and noted that it could feed the community [23]. The authors also studied the power management strategy and the performance analysis of the system for determining the active power dispatching [24]. Wei *et al.* [25] proposed frequency restoring method to control output active power of hydro-PV hybrid system. Rezkallah *et al.* [26] proposed control algorithm for regulating voltage and frequency and extracting the maximum power from standalone micro hydro-PV hybrid system. An *et al.* [27] described the principle of hydro-PV hybrid system operation and concluded that hydropower could improve the power quality of PV system in short-term scheduling and PV system could compensate the hydropower energy in mid- to long-term scheduling and during peak load periods. Li *et al.* [28] developed a multi-objective optimization model for hydro-PV hybrid system, while considering the power regularity and the total annual power generated by the system as objective functions. The authors used NSGA-II for optimizing the multi-objective problem. Jena *et al.* [29] used a Fuzzy Controlled STATCOM to improve the voltage and frequency stabilization in a micro hydro-PV-battery hybrid system. Jurasz *et al.* [30] maximized the energy and controlled the variability of run-of-river PV hybrid power plants by using mixed integer mathematical programming. The dynamic programming method has been used in [31] for optimizing the long-term operating of hydro-PV hybrid power system in China's Longyangxia. The study's objectives were to maximize the total produced energy and system reliability simultaneously. Reddy [32] applied constant current controller to supervise the hydro-PV hybrid power plants. Das *et al.* [33] presented an overall control strategy for the power management from isolated micro hydro-PV-battery hybrid system. Liu *et al.* [34] developed a multi-objective approach for optimal integration of hydro-PV hybrid power systems. The goals of their study were to maximize total power output and minimize the energy balance. Ming *et al.* [35] used three-layer nested approach for improving daily production planning of large hydro-PV power plant. Other studies dressed the size of hydro-PV hybrid power plants [36]–[43]. Glasnovic *et al.* [36] developed simulation-dynamic programming model for optimal sizing of hydro-PV hybrid power system. Mahmoudimehr *et al.* [39] proposed an operational strategy and Genetic Algorithm for optimal designing of PV-hydro hybrid power system by considering loss of power supply probability and investment cost as objective functions. Silvério *et al.* [41] described technical and economical methodologies used for sizing floating PV-hydro hybrid power system. Fang *et al.* [37] optimized the size of hydro-PV hybrid power system by maximizing its net revenue during its lifetime. A model of multi-objective optimization by using NSGA-II was proposed by Li *et al.* [42] for maximizing the total amount of annual energy generation and minimizing the gap between energy demand and supply for hydro-PV hybrid power plant. Ming *et al.* [38] applied cost-benefit analyses to optimize the size of PV-hydro hybrid power plant. Ming *et al.* [43] developed a nesting model for optimal sizing of PV-hydro hybrid power system by minimizing the water consumption of hydro plant when external load requests are imposed to the hybrid system. Kumar *et al.* [40] optimized sizing of hybrid energy system through Particle Swarm Optimization method.

The objective of this paper is to propose a multi-objective optimization method for the optimal sizing of run-of-river small hydro-PV hybrid power system by using NSGA-II as the optimization algorithm. Our interest in this paper is to maximize the total generated energy and minimize the energy production cost, simultaneously. We consider three decision variables such as: the nominal turbine flow rate (Q_{Tr}), the number of hydropower units (n_{hyd}), and number of PV modules (n_{PV}). The best trade-offs between the total generated energy and the energy production cost of run-of-river small hydro-PV hybrid power system are determined. The influences of Q_{Tr} and n_{hyd} on objective functions are also investigated.

The paper is organized as follow. In Section II, material and methods are presented. Results and discussion are provided in Section III followed by conclusion in Section IV.

II. MATERIAL AND METHODS

A. *Simulation Data*

The optimization procedure is carried out for hydro and solar resources of Yeripao (latitude: 10°15'21.06" N, longitude: 1°25'43.57" E, altitude: 430 m), which is located in Natitingou, city in northwest of Benin, as shown in Fig. 1. The daily average water flows, global irradiation and ambient temperature over two years (2016-2017) of Yeripao site are shown in Figs. 2-4, respectively. The water flows data of Yeripao river are deducted from data in [44] by using extrapolation method. The global irradiation (G_r) and the ambient temperature (T_a) are obtained from soda site [45]. The profile of load to be satisfied in this study is for a village in rural areas (Fig. 5). This load profile is determined by basing on a similar case which is for rural electrification in developing countries [46].

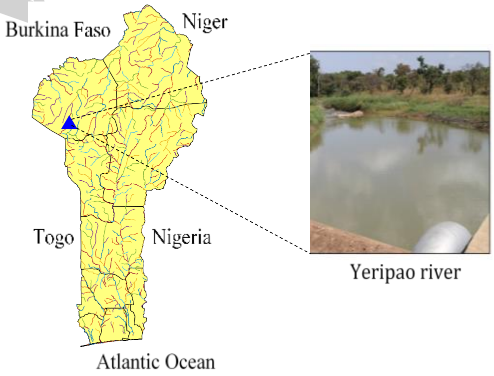

Fig. 1 Location of Yeripao site on hydrological map of Benin.

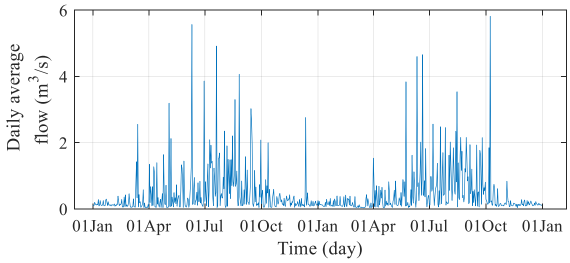

Fig. 2 Daily average water flows over two years (2016-2017) of Yeripao site.

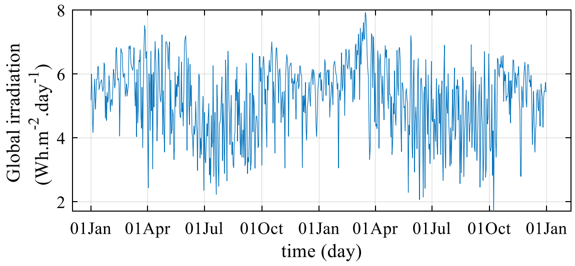

Fig. 3 Global daily irradiation over two years (2016-2017) of Yeripao site.

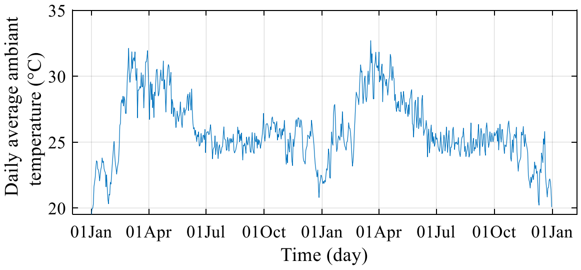

Fig. 4 Daily average ambient temperature over two years (2016-2017) of Yeripao site.

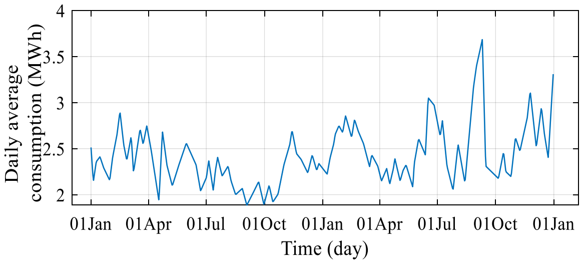

Fig. 5 Profile of daily average energy consumed by a village in rural areas.

B. *Model of Energy Generated by Solar Photovoltaic Plant*

The energy E_{PV} (1) [kWh] yield of the PV plant over period *t* [day] depends on energy conversion efficiency of the PV module η_{PV} (2) [%] , the global irradiation Gr_{PV} $[kWh.m^{-2}.day^{-1}]$, the ambient air temperature $T\,[°C]$, the surface area of a PV module A_{PV} $[m^2]$, and the number of PV modules n_{PV}. The PV module which is used in this work is PHOTON SOLAR SC-280P [47].

$$E_{PV}(t) = \eta_{PV}(t)\cdot Gr_{PV}(t)\cdot A_{PV}\cdot n_{PV} \qquad (1)$$

The energy conversion efficiency of the module (2) [%] is the product efficiencies due to dust η_{du}, the adaptability of PV modules η_{ad}, the inclination of PV modules η_{in}, Joules in cables η_{jo}, and the temperature η_{tem}.

$$\eta_{PV}(t) = \eta_{du}(t)\cdot\eta_{ad}(t)\cdot\eta_{in}(t)\cdot\eta_{jo}(t)\cdot\eta_{tem}(t) \qquad (2)$$

The efficiencies η_{du}, η_{ad}, η_{in} and η_{jo} are respectively estimated at 98%, 96%, 97.3% and 97.8% [48]-[49]. η_{tem} depends on other parameters and expressed by :

$$\eta_{tem}(t) = \eta_{PV\_STC}\cdot[1-\beta\cdot(T_C-25)] \qquad (3)$$

where η_{PV_STC} is the energy conversion efficiency of the PV module (%) defined in *STC* (viz., air mass (*AM*) 1.5 and temperature of 25 °*C*), and β is the cell maximum power temperature coefficient (equal to 0.0043 $°C^{-1}$ [47]; it can vary from 0.003 to 0.005 $°C^{-1}$ in crystalline silicon [50]). The cell junction temperature T_C can be determined as follows :

$$T_C(t) = \frac{NOCT-20}{800}\cdot\frac{G_r(t)}{D_r(t)} + T_a \qquad (4)$$

where NOCT is the nominal operating cell temperature and equal to 45 °C [47], and D_r is the sun duration [51].

C. *Model of Energy Generated by Run-of-River Small Hydropower Plant*

The Energy E_{hyd} [kWh] of run-of-river small hydropower plant can be calculated by basing on:

$$E_{hyd}(t) = 24\cdot\rho\cdot g\cdot Q_T(t)\cdot H_{net}\cdot\eta_T(t)\cdot\eta_G \qquad (5)$$

where ρ is the water mass density $[kg/m^3]$, g is the gravity acceleration, Q_T is the daily average turbined flow $[m^3/s]$ of the day *t*, H_{net} is the net water head $[m]$, η_G and η_T are respectively the efficiencies of electrical generator and turbine. The electrical generator efficiency is about 90% [52]. A Pelton turbine is suitable for Yeripao hydropower plant [53]. The turbine efficiency is expressed in [54] by :

$$\eta_T(t) = \left[a\cdot\left(\frac{Q_T(t)}{Q_{Tr}}\right)^2 + b\cdot\left(\frac{Q_T(t)}{Q_{Tr}}\right) + c\right]\cdot\eta_{Tr} \qquad (6)$$

where η_{Tr} and Q_{Tr} are respectively the nominal turbine efficiency and the nominal turbine flow rate, and $\{a,b,c\}$ are coefficients defined in [54].

D. *Model of Energy Production Cost of Solar Photovoltaic Plants*

Energy production cost of solar photovoltaic plant C_{pv} [€] (7) is computed as the sum of investment cost C_{pv_i} [€], maintenance cost C_{pv_m} [€] and inverters cost $C_{inv_{pv}}$ [€] of solar photovoltaic plant.

$$C_{pv} = C_{pv_i} + C_{pv_m} + C_{inv_{pv}} \qquad (7)$$

C_{pv_i} is calculated through the formula (8) [55]. C_{pv_m} is estimated as 2% of C_{pv_i} [56].

$$C_{pv_i}[€] = P_{pv_i}\cdot\left(C_{pv/Wp} + C_{pv_{ins}/Wp}\right) \qquad (8)$$

Where:

$C_{pv/Wp}$ and $C_{pv_{ins}/Wp}$ are the proportional constants associated with the PV acquisition and installation, respectively. They are estimated around US$ 341/kWp (€ 300.79/kWp) and US$ 450/kWp (€ 396.94/kWp), respectively [55].

P_{pv_i} $[kW]$ is the installed peak power of n_{PV} that is equal to:

$$P_{pv_i}[kW] = n_{PV}\cdot P_{pv_u} \qquad (9)$$

Where P_{pv_u} $[kW]$ is equal the installed peak power of one PV module, equal to 0.280 kW [47], and n_{PV} is considered as decision variable in our study case.

$C_{inv_{pv}}$ is calculated through the formula (10) [55].

$$C_{inv_{pv}}[€] = P_{pv_i}\cdot C_{inv/Wp} \qquad (10)$$

Where: $C_{inv/Wp}$ is the proportional constant associated with the PV inverters. Its value is estimated around US$ 71/kWp (€ 62.91/kWp) [55].

E. *Model of Energy Production Cost of Run-of-River Small Hydropower Plants.*

Energy production cost of run-of-river small hydropower plant C_{hyd} [€] (11) is also sum of the investment cost C_{hyd_i} [€] and maintenance cost C_{hyd_m} [€] of run-of-river small hydropower plant.

$$C_{hyd} = C_{hyd_i} + C_{hyd_m} \qquad (11)$$

The models proposed in [57] are used to determine C_{hyd_i}. These models were chosen because they depend not only on net head [m] and output Power [kW], but also on n_{hyd}, which is considered as decision variable in this work. C_{hyd_m} is estimated as 5% of the investment cost [58].

F. Optimization Problem Formulation

This study concerns the optimal sizing of a run-of-river small hydro-PV hybrid power system for rural electrification. The dual objective functions of the problem are to maximize the total generated energy $E(T)$ and minimize the energy production cost C_T of the system, as shown in (12) and (13), respectively. Q_{Tr} , n_{hyd} , and n_{pv} constitute the design variables of the problem.

Objective 1:

$$E(T) = max \sum_{t=1}^{T} \left[E_{hyd}(t) + E_{PV}(t) \right] \qquad (12)$$

where T is the total number of days (i.e. 731 days) in the time period studied (i.e. two years 2016-2017).

Objective 2:

$$C_T = min\left(C_{hyd} + C_{pv} \right) \qquad (13)$$

NSGA-II, proposed in [59], [60] , is employed to solve the multi-objective optimization problem raised. The detailed description of the optimization process for hydro-PV hybrid power system is presented by the flowchart in Fig. 6.

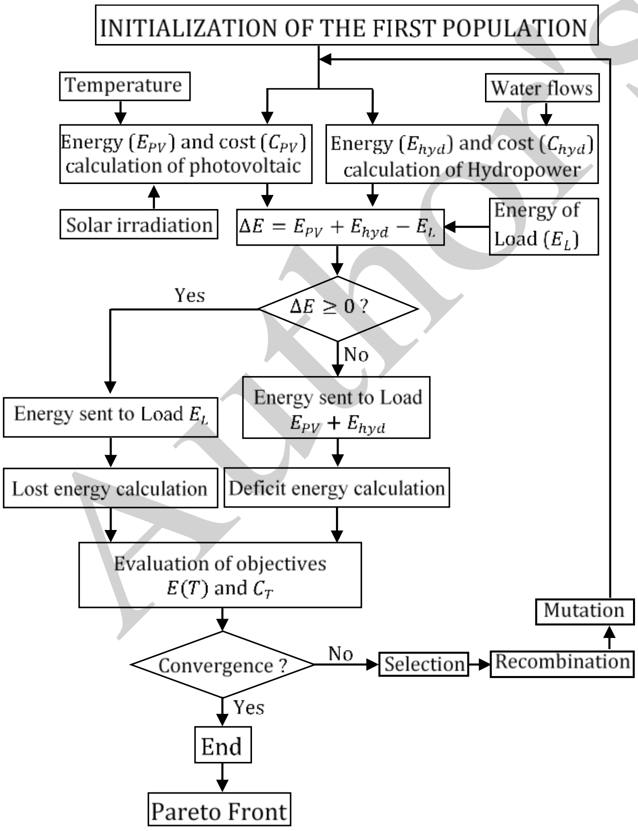

Fig. 6 Proposed optimization process of hydro-PV hybrid system.

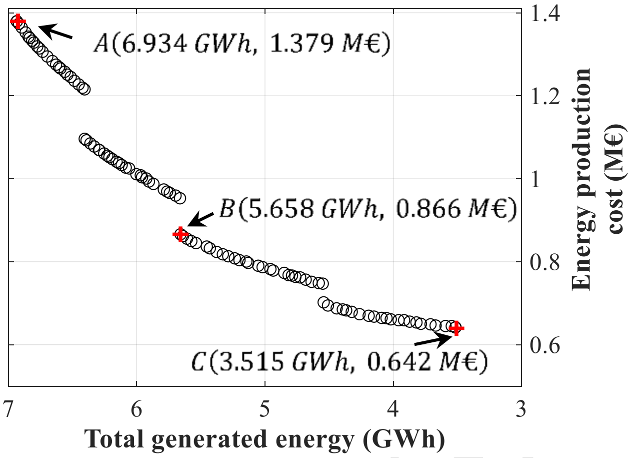

Fig. 7 Pareto front of the case study.

III. RESULTS AND DISCUSSION

In this section, the Pareto front of the case study is presented; followed by the influences of Q_T and n_{hyd} on objective functions.

A. Pareto Front

In multi-objective optimization, a solution is dominant if this solution is better than other solution for at least one objective and is not worse than any objective. The set of all non-dominated solutions of optimization is called the Pareto front. In Fig. 7, the Pareto front presents 100 optimal solutions resulting from the computation of 80 generations. These optimal solutions correspond to the best trade-offs between the total generated energy and the energy production cost of the hydro-PV hybrid power system. Indeed, the energy production cost increases with total generated energy. Minimization of the energy production cost is then contradictory with maximization of total generated energy. Each solution contains optimal decision variables for sizing the PV-hydro hybrid power system. In Fig. 7, solution A provides the highest overall total generated energy and is the most expensive. Likewise, solution C represents the solution which offers the least energy production cost, and the lowest overall total generated energy. Solution B gives intermediate energy production cost and total generated energy.

B. Variation Analysis of Objective Functions as Function of Decision Variables

The influences of hydropower units number and nominal turbine flow rate on total generated energy, energy production cost, and on cost per kWh are illustrated in Figs. 8-10, respectively. These solutions are grouped into four categories according to the number of hydropower units: triangle marker $\left(n_{hyd} = 1\right)$, cross marker $\left(n_{hyd} = 2\right)$, square marker$\left(n_{hyd} = 3\right)$ and circle marker $\left(n_{hyd} = 4\right)$. For each category, the curve increases with nominal turbine flow rate. These figures show that the category which corresponds to the lowest total generated energies and least energy production costs, is that of which $n_{hyd}$is equal to one . For n_{hyd} equal to four, the solutions are most expensive and generate the highest total energy. The intermediate solutions are grouped into categories that n_{hyd} is equal to two or three. The variation ranges of nominal turbine flow rate, energy production costs, total generated energies and of cost per kWh are detailed in table I.

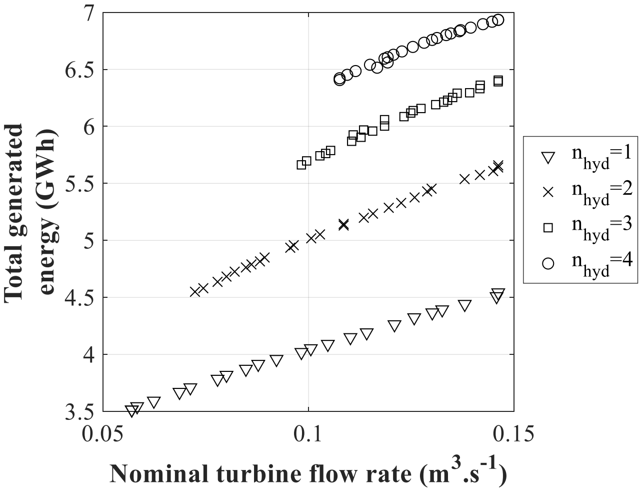

Fig 8 Variation of total generated energy.

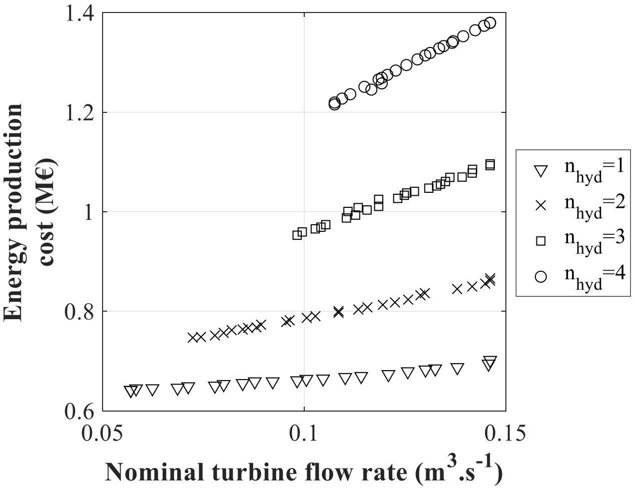

Fig 9 Variation of energy production cost.

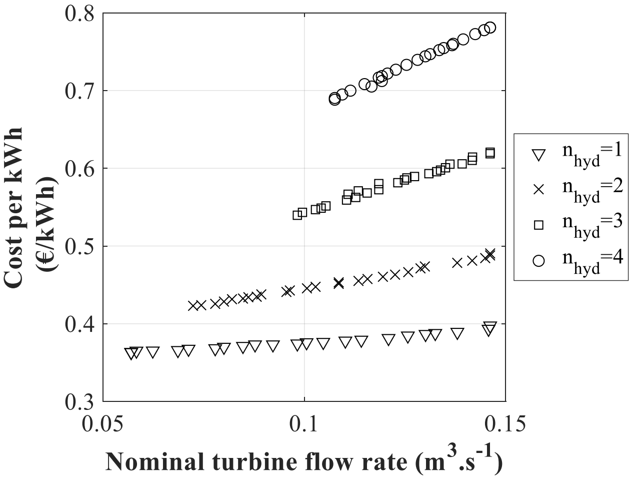

Fig 10 Variation of cost per kWh.

TABLE I VARIATION RANGES OF OPTIMAL SOLUTIONS

	$n_{hyd} = 1$	$n_{hyd} = 2$	$n_{hyd} = 3$	$n_{hyd} = 4$
Number of optimal solutions	23	27	26	24
Nominal turbine flow rate (m^3/s)	[0.057 0.146]	[0.072 0.146]	[0.098 0.146]	[0.108 0.146]
Energy production cost (M€)	[0.642 0.702]	[0.747 0.866]	[0.953 1.093]	[1.215 1.379]
Total generated energy (GWh)	[3.515 4.543]	[4.550 5.658]	[5.662 6.405]	[6.422 6.934]
Cost per kWh (€/kWh)	[0.363 0.398]	[0.423 0.491]	[0.540 0.621]	[0.691 0.781]

IV. CONCLUSION

This study proposed the optimal sizing of run-of-river small hydro-PV hybrid power system by using NSGAII. The total generated energy is maximized while the energy production cost is minimized. The nominal turbine flow rate Q_{Tr}, the number of hydropower units n_{hyd}, and the number of PV modules n_{PV} are used as decision variables in optimization procedure. The developed methodology is applied to hydro and solar resources of Yeripao site in Natitingou, a town located in northwest of Benin. The optimal solutions converge to Pareto front which represents the best trade-offs between total generated energy and energy production cost. The energy production cost increases with the total generated energy. Thus, minimizing the cost of energy production is contradictory with maximizing total generated energy. The influences of Q_T and n_{hyd} on total generated energy, energy production cost and on cost per kWh are also investigated. The results show that the solutions are grouped in four categories according to $n_{hyd} = 1, 2, 3\ or\ 4$. It is interesting to note that for each category, the total generated energies, energy production costs and cost per kWh increase with nominal turbine flow rate. The category, that $n_{hyd} = 1$, has given the lowest total generated energies, the least energy production costs and costs per kWh. Moreover, the category solutions with $n_{hyd} = 4$ generate the highest total energies but are more expensive. The lowest overall cost per kWh is € 0.363/kWh. This study applied to Yeripao site can be extended to other sites by considering their hydro and solar resources characteristics.

ACKNOWLEDGMENT

The authors would like to thank Governments of France and Benin for funding this research. They thank Société Béninoise de l'Energie Electrique (SBEE), and Solar Energy Services for providing data on hydro and solar resources of Yeripao in Benin.

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