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Optimized Sizing of AC Coupled Hybrid Sources for Isolated Villages

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ABSTRACT –This paper deals with the optimization of the annualized least cost of energy of an AC coupled hybrid system designed for remote villages with very low incomes. First, the electrification status and renewable resources in Laos and Senegal are briefly highlighted. Then, as an example, the paper focuses on the design of a hybrid system composed of a pico hydroelectric turbines, PV panels and energy storage devices for a village in Northern Laos. For the optimization, a genetic algorithm is used, taking into account the forced outage rates (FOR) of pico hydroelectric turbines. Finally, the results of the system sizing are presented and concluded.

RESUME – Cet article traite de l'optimisation d'un site de production d'énergie électrique pour des villages en milieu rural. Le faible revenu des habitants oblige à trouver une solution optimale du point de vue du coût de l'énergie produite. L'approche utilisée s'appuie d'abord sur une analyse des énergies renouvelables disponibles et des moyens de stockage adaptés. Un algorithme génétique est ensuite utilisé pour minimiser le coût de l'énergie produite sans dégrader la disponibilité en tenant compte des taux de panne des turbines pico hydroélectriques. Les résultats obtenus sont satisfaisants tant du point de vue de la simplicité des équipements que du coût de l'énergie produite.

KEYWORDS – Energy resources, Energy systems, Hydroelectric generators, Photovoltaic power systems, Genetic Algorithms.

1. Introduction

The Document of Strategy of Reduction of Poverty issued by the Government of Senegal aims to reduce the poverty by half during the period 1990-2015 [1]. The Letter of Development Policy of the Sector of Energy [2] points out the major importance of energy as a key variable of any economical policy. The same conclusions are drawn from the Government of Lao (GOL). That is, the highest priorities of the government's socio-economic development strategy to 2020 are addressing poverty, improving the living standards of the population, and removing the country from the Least Developed Country (LDC) list through economic growth based on the sustainable use of the country's natural resource base [3]. One of the crucial and significant contributing factors is country electrification.

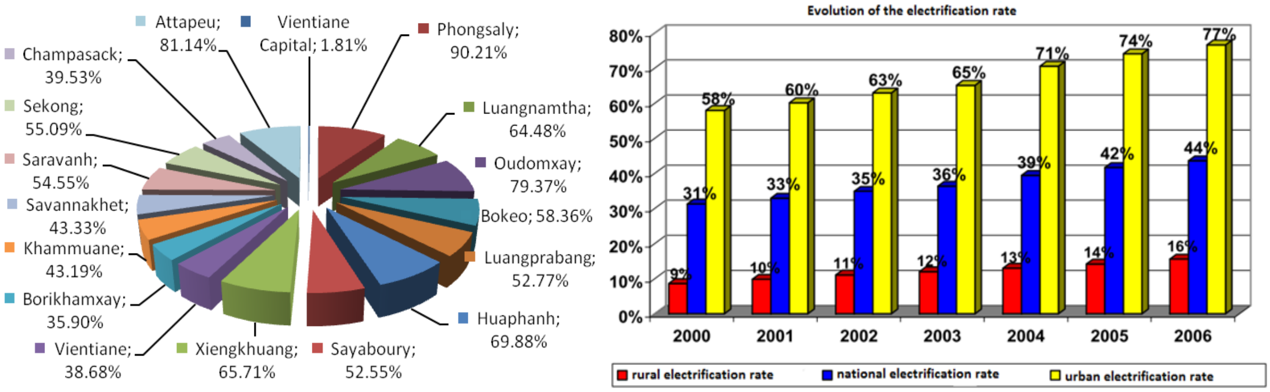
It is more economical and reasonable to electrify remote areas with a micro-grid by means of existing renewable energy sources available locally. For meeting electrical energy demands in rural areas, micro hydroelectric generators are very often found. However, when supplying a small village or a family house, pico hydro could be much less expensive to carry out, especially for the context of rural electrification in Laos. This is due to their very low local retail prices [4] and [5]. Nevertheless, optimized sizing of production costs to suit income and expenses of local people is essential.

2. Electrification in Laos and Senegal

2.1 Status and development plan

Among the about 5.5 million inhabitants in Laos, only 54 % can benefit from the national grid to support their daily living such as lighting, cooking, cleaning, entertainment, *etc*. In the rest of the country, especially in small villages in remote and mountainous areas, access to electric energy is practically impossible due to the non-profitability of a grid extension. More than 45% of the population does not have access to electricity. Extracted from the database in [6] and [7], Figure 1a illustrates the rates of non-electrification of households in all the provinces throughout the country. Rural electrification can be done most cheaply by means of promoting the uses of low cost renewable energy sources available locally.

In Senegal, among about 12 million inhabitants, the number of subscribers has increased from 398 000 (3 million people) to 885 000 households (7 million) as reported in [8] from 2000 to 2010. As reported in [9], the rate of electrification varies from one region to the other. In general, this rate is more important in cities than in rural areas. As of 2006, in urban area it varies from 56 to 80% with an average of 77%. In rural areas, however, the rate ranges from 3 to 34% with an average of 16%. The evolution of the electrification rate from 2000 till 2006 is shown in Figure 1b.



(a) (b)

Figure 1 : Percentage (a) of non-electrified households in Laos, (b) electrification rate in Senegal

2.2 Energy Consumption

In Laos, energy consumption is largely different between consumers in the northern and central parts, and between cities and rural villages. It is estimated that a household in a northern rural village without road access typically consumes around 75 kWh/year (*e.g.* 2x11 W lamps, 1x5 W lamp and 1x15 W radio for around 5, 6.5 and 4.5 hours of use per day respectively) while a village in a central city needs around 900 kWh/year to satisfy its consumption. However, energy consumption in such villages is forecast to increase by 4 % every year [7].

In Senegal, needs for electricity in rural areas are essentially for lighting and entertainment, while in cities electricity is used for comfort (fan, air conditioning, *etc*.). The average electricity consumption is 125 kWh/year per person throughout the country [10]. The figure increases by 8 to 10% yearly.

2.3 Renewable Energy Sources

2.3.1 Photovoltaic Energy

Geographically, Laos is located between the latitude of 13° to 22° north and 100° to 108° east, where the availability of the sun is around 300 days a year. As reported in [11], the monthly and yearly average solar radiation throughout the country is 16.06 and 15.8 MJ/m^2-day respectively. PV arrays in the form of Solar Home Systems (SHS) were introduced to Laos in the late 1980s. By now, there are more than 14,000 units with a total installed capacity of about 300 kW (as of 2006) [6] countrywide.

Senegal is situated at 12°8-16°41 of latitude north and 11°21-17°32 of longitude west. Solar radiation is 29.6 MJ/m^2/-day for an illumination of 1000W/m^2 registered during 3000 hours a year (8 hours/day). Several projects have been made or are in progress *e.g.* installation of 11 solar power plants (10 - 40kWp) on the islands of Saloum (4000 households), installation of 2648 solar lanterns, electrification of 662 community centers (health centers, schools, mosques, churches), a solar power plant of 7MW in Ziguinchor (on study) [10].

2.3.2 Hydro and Other Resources

As a relatively mountainous country, Laos has immense water resources with different sizes and capacities. Villages in remote areas could then benefit from these natural renewable resources in the forms of micro (<100 kW) or pico hydro (<1 kW) [5]. Up to now, its development and implementation in Laos have been merely on the household scale with a unit installed capacity of 100 - 1000 W, mostly in the hilly areas of Northern provinces [12]. It is furthermore reported that wind speed is relatively weak throughout the country, even in Northern Laos along the border to Vietnam. With an average of 1.9 to 2.8 m/s throughout the year, it is unfortunately too low to be used to produce electrical energy efficiently.

In contrast, studies led by various researchers and organizations reveal important wind potential along the “Grande Côte” in Senegal. In this area, the wind speed measured at 10 m high ranges from 3.8 to 4.2 m/s. Currently, several wind farm projects are considered and planned *e.g.* Saint Louis (50MW), Taïba NDiaye (125 MW), Kayar (10.2 MW), Potou (10.2 MW), area of MBoro (40 to 60 MW) [13]. Regarding its 500 km of coast, Senegal has genuine marine energy potentials (tides, waves, *etc.*) that could be exploited in the future.

3. Hybrid Systems

One of the main characteristics of renewable energy sources is the intermittence of the production due to solar radiation or water flow rate variations. Therefore, to guarantee a high rate of availability through the whole day, a combination of different energy sources and storage devices is compulsory to build a hybrid electrical energy system.

In the following, only the case of rural remote villages in Laos will be treated. Therefore, the hybrid system configuration considered for the optimization will be based on pico hydroelectric turbines, PV solar panels and storage devices.

Nevertheless, the modeling, simulation as well as strategies of control could be adapted to a hybrid system designed for Senegal.

In Laos, up to now, there are few AC coupled hybrid systems being installed and operated in remote hilly villages [14]. As they combine different energy resources, their potential usages should be more thoroughly explored. For small, remote villages with a daily power consumption of a few kW, especially for household scales with an average yearly family income of approximately 256 € [15], it is therefore essential and crucial for their electricity to be supplied of an affordable price by a hybrid system. To achieve this objective, the system must be designed to have the lowest possible overall cost. For example, the materials should be available in close proximity or locally with fewer costs. Among others, pico hydroelectric turbines and lead-acid batteries can be, with fewer difficulties, bought locally though they are not domestic products. Despite the very low quality of the turbines and their accessories and hence their short lifetime, pico hydroelectric turbines are considered as the main and essential energy production part of the hybrid system since their initial costs are very low. These costs are so low that even villagers can purchase turbines with their own yearly incomes. In this paper, a centralized AC coupled hybrid system is designed to supply electrical energy to Ban Thapene, a village in Luangprabang province, Laos with 50 households and about 130 inhabitants.

3.1 Load profile and System Modeling

A daily load profile of the considered village mentioned in 3 is illustrated in Figure 2, with the peak loads occurring during the time period of 06:30-08:30 (2 kW) and 19:30-22:30 (5 kW) [15]. Since electrical energy is purely used for lighting and entertaining purposes in such a village, there is no significant monthly or seasonal difference of the load profile. Also depicted in Figure 2 is a scenario where the power is initially produced only by the PV arrays (1 kW peak) as well as its difference delta P compared to the load. The hybrid system designed will therefore require the combination of PV arrays, an additional source (here pico hydroelectric turbines), with energy storage devices (storage pump, batteries) and a genset as backup. The system modeling, shown in Figure 3, is carried out under the Matlab/Simulink® environment.

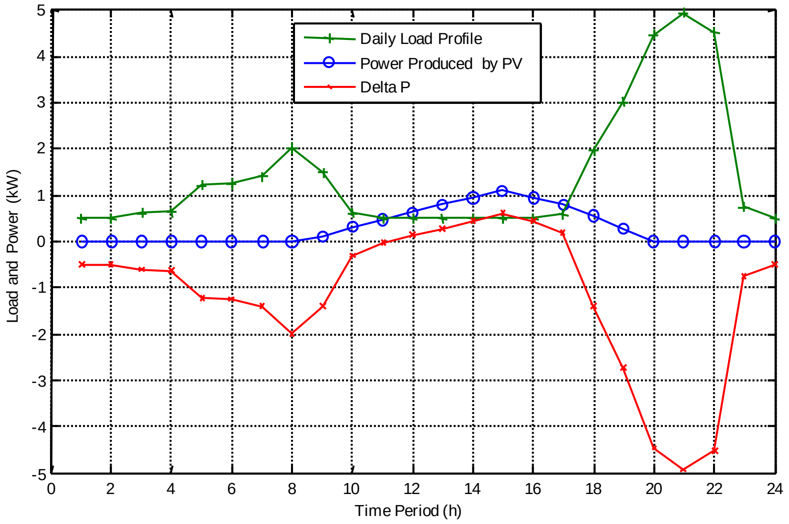


Figure 2: Daily load profile of Thapene Village [14]

All component models used in the system model are analytic. Table 1 summarizes their modeling parameters:

Table 1. Parameters of model components

a) Pico hydroelectric turbines

Type	Gravity (m^2/s)	Head (m)	Rated flow rate (m^3/s)		Efficiency	Lifetime (year)			Cost ($/unit)	
			HT1*	HT2*		Turbine	Bearing	Winding	HT1	HT2
AC	0.981	1.5	0.125	0.065	0.56	3	0.4	0.5	85	40

* HT1 – Hydroelectric Turbine 1, HT2 – Hydroelectric Turbine 2,

b) PV panels

Type	Isc (A)*		Voc (V)*		Rs (Ω)*	Rsh (Ω)*	Lifetime (year)		Cost ($/Wp)*
	PV1	PV2	PV1	PV2			PV1	PV2	
DC	4.5	3.22	42.8	21.2	1.233	160.82	25	20	3.47

* Isc – Short circuit current, Voc – Open circuit voltage, Rs – Series resistance, Rsh – Shunt resistance, Wp – Watt peak

c) Batteries

Type	Nominal discharge current (A)	Fully charged voltage (V)	Capacity (Ah)		Lifetime (year)	Cost ($/Wh)
			Maximum	Rated		
Lead-acid	15	13.0658	78.125	75	5	0.245

d) Storage pump

Type	Water specific density (Kg/m^3)	Gravity (m^2/s)	Efficiency	Head loss (%)	Head (m)	Lifetime (year)	Cost ($/kW)
AC	1,000	0.981	0.4	10	5	25	5,000

e) Genset

Type	Fuel consumption (l/h)	Operating Time (h)	Efficiency	Lifetime (year)	Fuel cost ($/l)	Cost ($/kW)
AC	15	3	0.2	25	1.5	92

f) Inverter

Type	DC Voltage (V)	Power (W)	Efficiency	Lifetime (year)	Cost ($/kW)
DC/AC	48	1,000	0.95	10	715

g) Charge controller

Type	Current (A)	Voltage (V)	Efficiency	Lifetime (year)	Cost ($/kW)
AC/DC	15	12	0.92	10	1,000

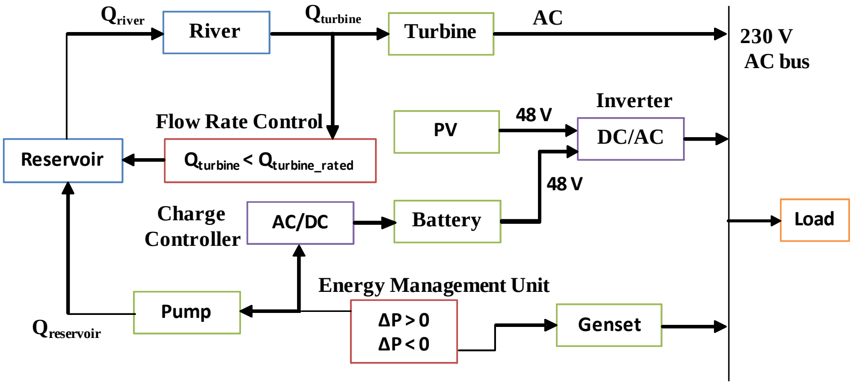


Figure 3: An AC coupled hybrid system

River water is considered as a hydro energy source (run-of-river hydro). Pico hydroelectric turbines are of 1 and 0.5 kW low head propeller types [4]. The yearly average temperature and solar irradiation in Luangprabang are assumed as parameters for PV arrays [11]. Single crystalline solar cells are used for PV panels of type SP130 and BP 250, with a power of 130 and 50 Wp, voltage module of 24 and 12 V respectively. A 12 V and 75 Ah lead-acid battery is considered for the system. A 3 kW per unit pump is used to fill a reservoir to ensure the rated flow rate for pico hydroelectric turbines. A gasoline genset of 2.9 kW rated unit power, 230 V voltage, is considered as a backup. Inverters are assumed to be DC/AC power condition for both PV panels and batteries. Similarly, a charge controller with a battery charger regulator is also considered as AC/DC power condition.

3.2 Optimization, Control strategies and Simulation

3.2.1 Optimization

The optimization of the system is carried out for a period of 20 years, corresponding to the average lifetime of PV panels. It is assumed that the profile of the load and the renewable energy sources remain unchanged over 20 years. With the exception of pico hydroelectric turbines, whose price is locally justified, a local price factor of 50 % is added to all component costs indicated in Table 1b - 1g. All costs are converted into Euro with the average exchange rate of 1.3 US$/€.

The system is to be optimized with only one objective function, namely the annualized least cost of energy (LCE) of the hybrid system. Subjected to the static constraints on PV, turbines, batteries, genset characteristics and zero Loss of Power Supply Probability (LPSP), the optimization is carried out first with all the system components and second without batteries. With the exception of the storage pump, all the other components are subjects for optimization. Table 2 summarizes the optimization variables.

Table 2. Optimization variables

	System components*					
	HT	PV	Inv	Bat	CC	Gen
Optimization parameters	Nht	Npvp	Ninv	Nbatp	Ncc	Ngen

* Nht – Number of hydroelectric turbines, Npvp – Number of parallel connected PV panels, Ninv – Number of inverters, Nbatp – Number of parallel connected batteries, Ncc – Number of charge controllers, Ngen – Number of genset

The genetic algorithm (GA), integrated in the Global Optimization Toolbox of Matlab/Simulink, is used as the optimization tool. Indeed for sizing renewable sources to isolated rural village, GA has been used commonly in optimization software [16]. Furthermore, as [17] summarizes: "When high-dimensional non-smooth or discontinuous problems with numerous local optima are considered, only the simulated annealing and the genetic algorithm, which are both characterized by a weak search heuristic, are successful in finding the optimal region in parameter space. The key advantage of the genetic algorithm is that it can easily be parallelized". This work is carried out from the perspective of investors. That is, energy must be supplied with high reliability by considering the forced outage rates (FOR) of pico hydroelectric turbines that are subjected to frequent breakdowns. Therefore, as parameters for optimization, various forced outage rates are used for pico hydroelectric turbines. The optimization algorithm is illustrated in Figure 4.

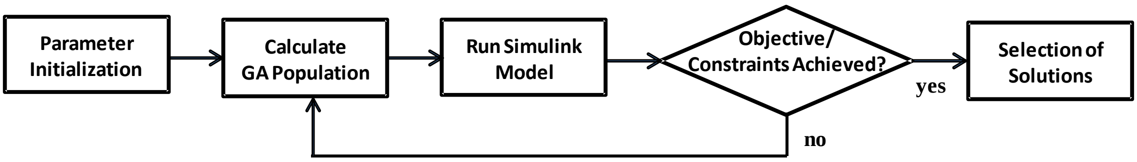


Figure 4: Optimization algorithm

3.2.2 Control Strategies and Simulation

Despite the fact that most of the work is dedicated to the sizing of the system components, an energy management strategy is necessary to evaluate the design of the energy sources. Therefore, we have developed a simple and non-optimized control strategy (described in the following).

The energy excess produced by the hybrid system is first used to charge batteries by means of a charge controller (AC/DC converter and battery charger) depending on the battery state of charge (SOC). When the batteries are fully charged, the energy excess, if still any, is then used to pump water to a reservoir. The water pumping stops when either there is no more energy excess or the reservoir is fully filled.

Whenever the load demands are higher than the energy produced, batteries will supply the difference. If, however, there is still a need of energy a genset is used to help supplying the loads. The genset will be running at least with a 50 % rated power once it is in operation. Water stored in the reservoir will be used whenever the river is unable to supply the flow rate required by the hydroelectric turbines. In other word, the water flow rate required to run hydro turbines controls the amount of water flowing from the reservoir back to the river.

The simulation of the system is conducted for 2 case studies under the Matlab/Simulink® environment for a period of 24 h with a sampling time of 1 h. The first case will include all the system components while in the second one, batteries won't be considered.

4. Results

4.1 System with all Components

Extracted from the optimization results, sorted LCE, annualized cost of energy (ACS), power produced (designed) and available (discretized) are listed according to various FORs as shown in Table 3a and 3b.

Table 3. Optimized system least cost of energy of systems

a) Optimized system least cost of energy of systems*

FOR (%)	LCE (€cent/kWh)									Power (kW)	
	System	HT	PV	Inv	Bat	CC	Gen	LVG	SP	Des	Dis
0	2.96	0.33	0.23	0.46	0.58	0.33	0.05	0.99	0.00	4.903	5.66
0	5.44	0.33	0.23	0.46	0.58	0.33	0.05	0.99	2.48	4.907	5.66
10	5.48	0.36	0.23	0.46	0.58	0.33	0.05	0.99	2.48	5.111	5.66
20	5.51	0.40	0.23	0.46	0.58	0.33	0.05	0.99	2.48	5.314	6.16
30	5.55	0.43	0.23	0.46	0.58	0.33	0.05	0.99	2.48	5.518	6.66

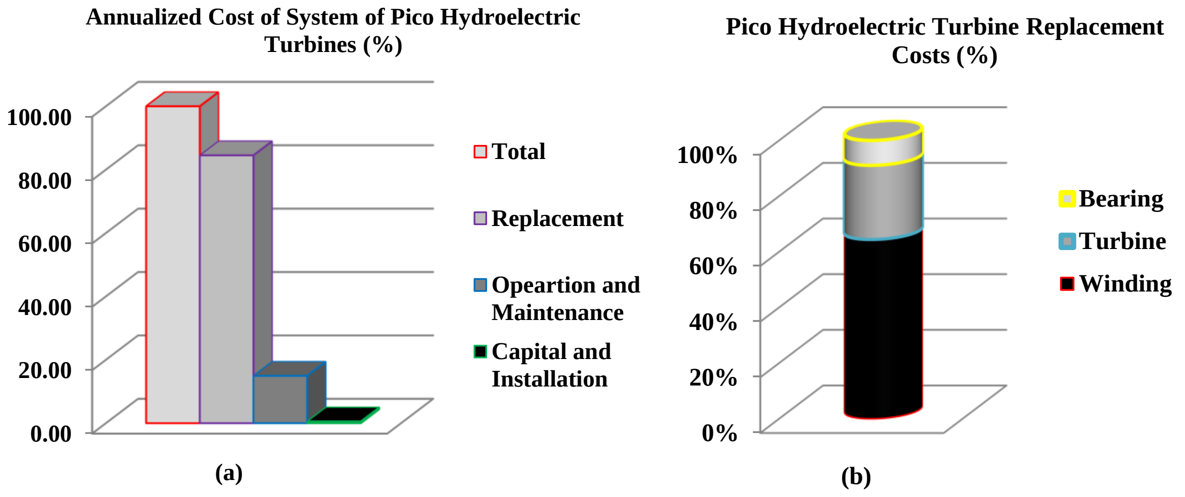
b) Annualized cost of system*

FOR (%)	ACS (€)									Power (kW)	
	System	HT	PV	Inv	Bat	CC	Gen	LVG	SP	Des	Dis
0	25,460.18	2,806.27	1,994.91	3,913.01	4,941.14	2,843.66	422.51	8,538.38	0.00	4.903	5.66
0	46,798.75	2,808.39	1,997.88	3,916.81	4,944.28	2,845.29	422.51	8,538.38	21,135.2	4.907	5.66
10	47,102.81	3,112.45	1,997.88	3,916.81	4,944.28	2,845.29	422.51	8,538.38	21,135.2	5.111	5.66
20	47,406.87	3,416.52	1,997.88	3,916.81	4,944.28	2,845.29	422.51	8,538.38	21,135.2	5.314	6.16
30	47,710.93	3,720.58	1,997.88	3,916.81	4,944.28	2,845.29	422.51	8,538.38	21,135.2	5.518	6.66

* HT – Hydroelectric turbines, PV – PV panels, Inv – Inverters, Bat – Batteries, CC – Charge controllers, Gen – Generator, LVG – Low Voltage Grid, SP – Storage Pump, Des – Designed, Dis – Discretized

As it can be seen from Table 3a the least cost of energy caused by the pico hydroelectric turbines is smaller than those produced by PV panels coupled with inverters. It is significantly smaller than that produced by small scale hydroelectric turbines which account for around 7 €cent/kWh, as reported in [18]. Furthermore, it is observed that only the cost of pico hydroelectric turbines increases while those of other component remain unchanged when introducing forced outage rates on the turbines. It is worth noting that when the storage pump is excluded from the operation, the overall cost of energy and the annualized cost of systems (Table 3b) are reduced significantly. This is confirmed by the first raw data in Table 3a and 3b (FOR = 0 %).

Among the parts composing the annualized cost of system of hydroelectric turbines, the replacement costs account for more than 84% of their total costs as depicted in Figure 5a. This is due to the very low quality of the turbines, their bearings and especially generator windings that take more than 64% of the turbine costs. This is confirmed by Figure 5b. The data illustrated in Figure 5a and 5b is from the case of zero forced outage rate.



(a) (b)

Figure 5: Cost repartition of pico hydroelectric turbine components

Since the numbers of the hybrid system components have to be given as full digits (discretized), a solution is to over dimension the system. Therefore, even if the cost (Dis - discretized) is higher than initially (Des - designed), the availability of energy supply is increased despite the FOR of system components. The discretization of the number of turbines is based on a comparison of their annualized costs while that of other system components is using a round up principle with its own selection criteria. This is confirmed by the selected data in Table 4a and 4b.

Table 4. FORs as means for the justification of the systems over dimensioning

FOR (%)	a) Number of designed hybrid system components												ACS (€)
	HT$_1$	HT$_2$	PVp$_1$	PVs$_2$	PVp$_2$	PVs$_2$	Inv	Batp	Bats	CC	SP	Gen	Des
0	1.018	2.036	2.091	2	2.718	4	2.497	1.175	4	4.699	1	0.439	46,798.75
10	1.018	2.443	2.091	2	2.718	4	2.497	1.175	4	4.699	1	0.439	47,102.81
20	1.018	2.85	2.091	2	2.718	4	2.497	1.175	4	4.699	1	0.439	47,406.87
30	1.018	3.257	2.091	2	2.718	4	2.497	1.175	4	4.699	1	0.439	47,710.93

* HT$_1$, HT$_2$ – Hydroelectric turbine 1 and 2, PVp$_1$, PVp$_2$, PVs$_1$, PVs$_2$ – Parallel and series connected PV panels 1 and 2, Batp, Bats – Parallel and series connected batteries

FOR (%)	b) Number of discretized hybrid system components												ACS (€)
	HT$_1$	HT$_2$	PVp$_1$	PVs$_2$	PVp$_2$	PVs$_2$	Inv	Batp	Bats	CC	SP	Gen	Dis
0	1	2	2	2	3	4	3	1	4	4	1	1	46 977.70
10	1	2	2	2	3	4	3	1	4	4	1	1	46 977.70
20	2	1	2	2	3	4	3	1	4	4	1	1	47 496.36
30	2	2	2	2	3	4	3	1	4	4	1	1	48 243.17

In order to reflex the true cost of energy to be paid by consumers, a return on investment and taxes of 5 and 20 % respectively are taken into account for the cost of energy. €0.1/month per household is added (around €24 distributed throughout 20 years).This measure has the objective to avoid paying at one time a large amount by consumers. Using the monthly energy consumption and income of consumers, a monthly expense of energy can then be estimated and compared to their respective income. Table 5 summarizes this consideration for the case of 30 % forced outage rate.

Table 5. Monthly expense for energy (FOR = 30%)

LCE (€cent/kWh)				Energy consumption (kWh)		Income (€)		Connection Fee (€/month)	Expense for energy	
Produced	ROI (5%)	Taxes (20%)	Total	Monthly	Yearly	Monthly	Yearly		Monthly (€)	Percentage of monthly income (%)
5.55	0.281	1.11	6.94	6.25	75.00	21.33	256	0.1	0.53	2.50

* ROI – Return of investment

4.2 System without Batteries

Selected optimization results of this system configuration are illustrated in Table 6**.** As expected, the costs of energy caused by batteries and charge controller fail out. Moreover, it is noted that the cost of energy produced by inverters decreases from 0.46 (Table 3a) to 0.34 €cent/kWh (FOR = 0 %). This is due to the fact that only DC powers obtained from PV panels are converted as the system operates without batteries. As a result, the overall least costs of energy of systems decreases from 5.44 (Table 3a) to 4.58 €cent/kWh while powers produced still satisfy consumers' needs.

Table 6. Optimized system least cost of energy of systems (without batteries)

FOR (%)	LCE (€cent/kWh)									Power (kW)	
	System	HT	PV	Inv	Bat	CC	Gen	LVG	SP	Des	Dis
0	4.58	0.28	0.40	0.34	0.00	0.00	0.05	1.01	2.51	4.85	5.32
10	4.62	0.31	0.40	0.34	0.00	0.00	0.05	1.01	2.51	5.03	5.32
20	4.83	0.53	0.40	0.34	0.00	0.00	0.05	1.01	2.51	5.40	6.78
30	4.88	0.58	0.40	0.34	0.00	0.00	0.05	1.01	2.51	5.68	7.28

5. Conclusions

In this paper an AC centralized hybrid system composed of renewable energy sources *i.e.* pico hydroelectric turbines, PV arrays, energy storage devices namely batteries and a storage pump, and a genset as a backup is designed and simulated to supply electrical energy to a village in Luangprabang province in Northern Lao. The system is optimized with only one objective function namely its annualized least cost of energy (LCE).

The simulation has shown that with the robust system components *i.e.* hydroelectric turbines the system designed can meet the energy demands of the village considered with very low overall cost of energy. This low cost is due to the uses of pico hydro as a renewable energy source. The reasons of using this kind of hydroelectric turbine are three folds. First of all, it is robust and nearly free maintenance. As a second reason, turbines can be purchased locally with less difficulty. Although they are not domestic products its initial cost is very low which is considered as a third reason.

The large replacement cost of the pico hydroelectric turbines are due to the very low quality of the turbine, its bearing and the generator winding, and hence their very short lifetimes. If these lifetimes could be lengthened by enhancing the quality of the turbine, its bearing and the generator winding, their replacement costs and hence the overall energy and system cost would be reduced significantly. This would open opportunities to Lao engineers and university faculties to focus on the design of the turbine components particularly bearings and generator windings which are subjects to frequent breakdowns.

Surveys made in a northern province of Laos revealed that on average a household will spend around 17% of its monthly income for all sorts of energy *e.g.* for cooking, lighting, learning, *etc.* [19]. As justified by Table 5, the monthly energy bill accounts for 2.5 % of the monthly income. Therefore, this energy price is affordable for villagers.

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