Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2011) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

Conference Title

# Pico vs Micro Hydro based Optimized Sizing of a Centralized AC Coupled Hybrid Source for villages in Laos

S. Phrakonkham[a*,b], G. Remy[a], D. Diallo[a], C. Marchand[a]

[a]*Laboratoire de Génie Electrique de Paris (LGEP) / SPEE-Labs, CNRS UMR 8507; SUPELEC, Université Paris-Sud, Université Pierre et Marie Curie P6; 11 rue Joliot Curie, Plateau de Moulon F91192 Gif sur Yvette CEDEX,*
[b]*Faculty of Engineering, National University of Laos, 01000 Vientiane, Lao PDR*

**Abstract**

This paper deals with the design of an electrical supply off-grid for a remote village without access to a utility grid and with very low incomes in Northern Laos. Environmental issues and cost minimization lead to a hybrid system composed of pico/micro hydroelectric turbines, PV panels, a water reservoir as an energy storage device and a backup genset. The annualized least cost of energy is optimized thanks to a genetic algorithm (GA). The forced outage rates (FOR) of pico and micro hydro turbines are taken into account in the optimization process. Finally, the results of the system sizing are presented and compared.



Keywords: Energy resources; Energy systems; Hydroelectric generators; Photovoltaic power systems

## 1. Introduction

The highest priorities of the socio-economic development strategy to 2020 of the Government of Laos (GoL) are addressing poverty, improving the living standards of the population through economic growth based on the sustainable use of the country's natural resource base [1].

It is more economical and reasonable to electrify remote areas with an off-grid by means of existing renewable energy sources available locally. For meeting electrical energy demands in rural areas, micro (> 1 kW) hydroelectric turbine is found very often in uses. However, when supplying a small village pico hydro (<= 1 kW) could be much less expensive to carry out especially for the context of rural electrification in Laos, particularly, for people living in remote and rural villages with very low yearly incomes. Electrochemical storage device i.e. battery is prohibited to respect environmental constraints and to reduce the overall cost.

* Corresponding author. Tel.: +33 (0)1 69851633; fax: +33 (0)1 69418318.
*E-mail address*: sengprasong.phrakonkham@lgep.supelec.fr.

## 2. Hybrid Systems

One of the main characteristics of the 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 energy availability through the whole day, combination of different energy sources and storage devices is compulsory to build the hybrid electrical energy system.

In Laos, up to now, there are few AC coupled hybrid systems being installed and operated in hilly remote villages [2]. In most cases, micro hydroelectric turbines are used as a part of the hybrid systems. However, pico hydroelectric turbines have become widespread used in Lao rural area since 1990 [3]. Based on surveys made in several Lao northern villages on their uses, an estimated of about 60,000 units may have been installed and used particularly in the northern part of Laos [3], [4]. For small, remote villages with a daily power consumption of a few kW, particularly for household scales with an average yearly family income of approximately $333 [5], it is therefore essential and crucial for them that electricity should be supplied with an affordable price by a hybrid system. To achieve this objective, the system must be designed to have the lowest overall cost as possible. In this paper, a centralized AC coupled hybrid system composed of hydroelectric turbines, PV panels, an energy storage device (storage pump) and a backup (genset) is designed to supply electrical energy to a Northern Lao rural village.

### *2.1. Load profile and system modeling*

For the purpose of this study, a load profile of a village in Northern Lao is considered. Moreover, it is assumed that this load profile is similar to that of a village considered for the study in [5], as illustrated in Fig. 1a. Since electrical energy is purely used for lighting and entertaining purposes in such a village, it is assumed that there is no significant monthly or seasonally difference of the load profile. Also depicted in Fig. 1a is a scenario where the power initially produced only by the PV arrays (1 kW peak) as well as its difference Delta P compared to the load. This figure shows the necessity of combining different sources and storage devices to fulfill the energy demand.

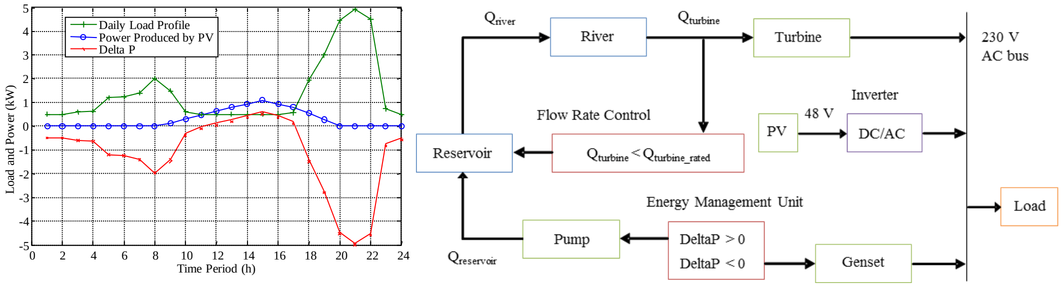


Fig. 1. (a) Daily load profile, (b) Hybrid system modeling

River water is considered as a hydro energy source (run-of-river hydro). Micro hydroelectric turbines are of Francis type while pico are low head propeller type. Two different unit powers of *i.e.* 3 and 2 kW and 1 and 0.5 kW are considered for micro and pico turbines respectively. The average yearly solar irradiation and temperature in Luangprabang are assumed as parameters for PV arrays [6]. For PV panels two single crystalline solar with a power of 130 and 50 Wp, voltage module of 24 and 12 V are considered respectively. A 3 kW per unit pump is used to fill a reservoir to assure the rated flow rate for hydroelectric turbines. A gasoline genset of 2.9 kW rated unit power and 230 V AC voltage, is considered as a backup. Inverters are assumed being a DC/AC power condition for PV panels

### *2.2. Optimization, control strategies and simulation*

The optimization of the system is carried out for the period of 20 years corresponding to a general average lifetime of PV panels. It is assumed that the profile of the load and the renewable energy sources remain unchanged over this period. The system is to be optimized with only one objective function namely the annualized least cost of energy (LCE) and subjected to the static constraints on PV, hydroelectric turbine, genset characteristics and zero Loss of Power Supply Probability (LPSP). With the exception of the storage pump all other components are subjects to the optimization. Table 1 summarizes the optimization variables of the hybrid system designed.

Table 1 Optimization variables

| | System components | | | |
|---|---|---|---|---|
| | HT | PV | Inv | Gen |
| Optimization variables | Nht | Npv | Ninv | Ngen |

Nht - Number of hydroelectric turbines, Npv - Number of PV panels, Ninv - Number of inverters, 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, GA has been used commonly in optimization software [7]. Furthermore, as [8] enlightens that the GA is a useful technique for combinatorial problems, Besides, GA also appears to be an efficient technique for optimizing processes and apparatus that feature discrete-valued parameters. Indeed, a GA approach often serves as a solver to finding a good starting point for a deterministic Non Linear Programming (NLP) procedure. So the GA framework is used to calculate optimal values of continuous variables, and it results from the fact that the GA approach is not considered an efficient technique for NLP problems but for combinatorial ones. The key advantage of the genetic algorithm is that it can easily be parallelized. This work is carried out on the perspective of investors. That is, energy must be supplied with a high reliability by considering the outage rates of hydroelectric turbines, particularly those of pico hydroelectric turbines that are subjected to frequent breakdowns. Therefore, as parameters for the optimization, various forced outage rates (FOR) are used for hydroelectric turbines. The optimization algorithm is illustrated in Fig. 2.

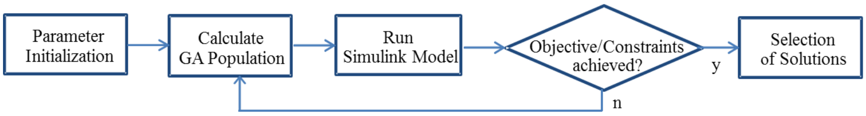


Fig. 2. Optimization algorithm

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 electrical supply. Therefore, we have developed a simple and non-optimized control strategy, described in the following.

The energy excess produced by the hybrid system is 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, 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 turbines.

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. In the first case, pico hydroelectric turbines are used as the hydro system component while in the second one, micro turbines are considered.

## 3. Results

### *3.1. System with pico hydro*

As it can be seen from Table 2 the least cost of energy and annualized cost of system caused by the pico hydroelectric turbines is smaller than those produced by PV panels paired with inverters with the exception of 30 % FOR. Furthermore, it is observed that only the cost of pico hydroelectric turbines increases while those of other component remain unchanged when introducing FOR into the system.

Table 2 Optimized system least costs of energy and annualized cost of system (Pico hydro)

| FOR (%) | LCE ($cent/kWh) | | | | | ACS (k$) | | | | | Power (kW) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | System | HT | PV | Inv | Others | System | HT | PV | Inv | Others | Des | Dis |
| 0 | 5.64 | 0.43 | 0.26 | 0.24 | 4.72 | 47.923 | 3.613 | 2.197 | 2.039 | 40.073 | 4.85 | 5.21 |
| 10 | 5.64 | 0.43 | 0.26 | 0.24 | 4.72 | 47.923 | 3.613 | 2.197 | 2.039 | 40.073 | 5.03 | 5.23 |
| 20 | 5.64 | 0.43 | 0.26 | 0.24 | 4.72 | 47.923 | 3.613 | 2.197 | 2.039 | 40.073 | 5.20 | 5.23 |
| 30 | 5.84 | 0.62 | 0.26 | 0.24 | 4.72 | 49.594 | 5.285 | 2.197 | 2.039 | 40.073 | 5.51 | 5.78 |

HT – Hydroelectric turbine, PV - Photo voltaic panel, Inv - Inverter, Others – Genset, low voltage grid and storage pump, Des – Designed, Dis – Discretized

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 3a. Of this, costs of turbine bearings and generator windings take more than 74 % as confirmed by Figure 3b.

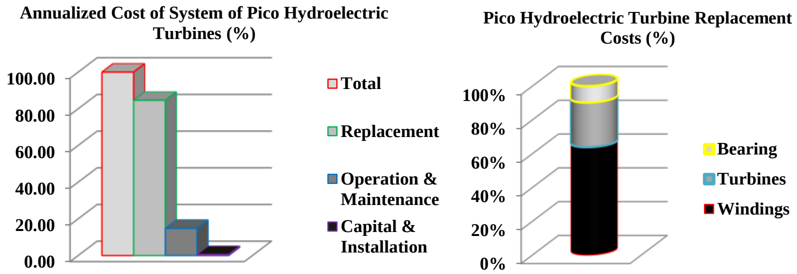


Fig. 3. ACS caused by pico hydroelectric turbines at 0% FOR (a) Cost repartition, (b) Replacement costs

### *3.2. System with micro hydro*

As shown in Table 3, the cost of energy produced by micro hydro is greater than those of PV panels coupled with inverters. That is, it is due to the large capital and installation cost of the turbines. As depicted in Fig. 4, accounting for more than 77 % the operation and maintenance cost, occurred during the whole period of operation, is the major part of the micro hydroelectric turbine cost.

Table 3 Optimized system least costs of energy and annualized cost of system (Micro hydro)

| FOR (%) | LCE ($cent/kWh) | | | | | ACS (k$) | | | | | Power (kW) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | System | HT | PV | Inv | Others | System | HT | PV | Inv | Others | Des | Dis |
| 0 | 5.85 | 0.64 | 0.26 | 0.24 | 4.72 | 49.734 | 5.425 | 2.197 | 2.039 | 40.073 | 4.85 | 5.32 |
| 10 | 5.85 | 0.64 | 0.26 | 0.24 | 4.76 | 49.734 | 5.425 | 2.197 | 2.039 | 40.073 | 5.12 | 5.32 |
| 20 | 5.99 | 0.65 | 0.32 | 0.24 | 4.72 | 50.212 | 5.425 | 2.675 | 2.039 | 40.073 | 5.27 | 5.51 |
| 30 | 6.01 | 0.65 | 0.32 | 0.24 | 4.72 | 50.212 | 5.425 | 2.675 | 2.039 | 40.073 | 5.50 | 5.51 |

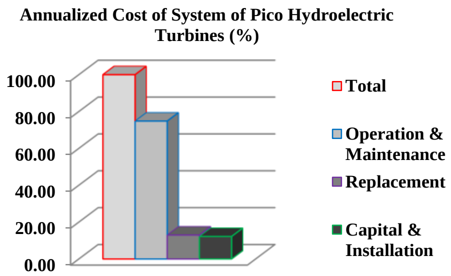


Fig. 4. ACS caused by micro hydroelectric turbines

### *3.3. Comparisons*

Comparing the simulation results shown in Table 2 against those of Table 3, it is seen with 30 % FOR the system with pico hydro can produce electrical energy (5.84 $cent/kWh) less expensive than that with micro hydro (6.01 $cent/kWh). The energy cost different is not much significant. Similarly, the annualized cost of system using pico hydro (k$50.212) is smaller than that of by micro hydro (k$49.594). It is observed from Table 4 that energy produced by pico hydro (3 kW) is ensured by several units ($HT_1$: 2x1, $HT_2$: 2x0.5 kW) while micro hydro produces the same amount with only one unit ($HT_1$: 1x3kW).

Table 4 Number of optimized hydroelectric turbines and their power produced (FOR = 30 %)

| Pico hydro | | | | | Micro hydro | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number of turbines | | Discretized Power (kW) | | | Number of turbines | | Discretized Power (kW) | | |
| $HT_1$ | $HT_2$ | $HT_1$ | $HT_2$ | HT | $HT_1$ | $HT_2$ | $HT_1$ | $HT_2$ | HT |
| 2 | 2 | 2 | 1 | 3 | 1 | 0 | 3 | 0 | 3 |

In order to reflex the true cost of energy to be paid by consumers, a return on investment (ROI) and taxes of 5 and 10 % respectively are taken into account for the cost of energy. Furthermore, a connection fee of $0.13/month per household is added (around $31.2 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 be estimated and compared to their respective income. As shown in Table 4, the different of the monthly energy expense produced by two turbine types is not significantly large.

Table 5 Household monthly expense for energy, FOR = 30% (pico and micro hydro)

| Turbine | LCE ($cent/kWh) | | | | Energy consumption (kWh) | Income ($) | Connection fee ($) | Expense for energy | |
|---|---|---|---|---|---|---|---|---|---|
| | Produced | ROI | Taxes | Total | | | | Monthly | Percentage to monthly income |
| | | 5% | 20% | | Monthly | Monthly | Monthly | ($) | (%) |
| Pico | 5.84 | 0.36 | 1.44 | 730 | 6.25 | 27.73 | 0.13 | 0.59 | 2.11 |
| Micro | 6.01 | 0.37 | 1.47 | 7.51 | 6.25 | 27.73 | 0.13 | 0.60 | 2.16 |

## 4. Conclusions

In this paper an AC centralized hybrid system composed of hydroelectric turbines, PV arrays, a storage pump and a backup genset is designed and simulated to supply electrical energy to a village in Northern Lao. The system is optimized with one objective function namely its annualized least cost of energy for two cases. First, pico and then micro turbines are considered as a hydroelectric component of the system.

The simulation has shown that with the robust system components *i.e.* hydroelectric turbines the hybrid system designed can meet the energy demands of the village considered with very low overall cost of energy. Since turbines are robust and not difficult for maintenance, they are suitable to be used in remote rural villages where simple technology can be managed with fewer difficulties by people using it.

The lifetimes of pico hydroelectric turbine bearings and generator windings are very short. If these lifetimes could be lengthened their replacement costs and hence the energy and system cost would be reduced significantly. Although micro hydro turbines do not suffer from frequent breakdowns, their capital and installation costs are more expensive than that of pico. In contrast to pico, micro hydro turbines cannot be purchased easily particularly locally where the system is implemented. Although the energy cost different produced by the two turbines are not significant large, but unexpected breakdown of a turbine would lead to a zero energy production by micro hydro since only one unit is utilized. However, for the same case, the rest of pico hydro units could still ensure the energy production. Therefore, on the perspective of consumers and producer, the respective energy availability and reliability is better assured by pico than by micro hydro despite their small energy price different (Table 4).

Surveys made in a northern province of Laos revealed that on the average a household spends around 17% of its monthly income for energy *e.g.* cooking, lighting, *etc.* [9]. As justified by Table 5, accounted for less than 2.2 % of the monthly income, the monthly energy bill is thus affordable for villagers.

## Acknowledgements

The authors wish to gratefully acknowledge the French Embassy to Lao PDR for the scholarship funding.

## References

[1] Voladet, S. Sustainable development in the plantation industry in Laos: An examination of the role of the ministry of planning and investment. *International Institute for Sustainable Development (IISD)*; 2009, p. 10-11 (http://www.iisd.org, accessed in June 2009)

[2] Andy, S. Samuel, M. Profitable and affordable energy services for remote areas in Lao PDR: Private – Public Partnership as mutual leverage for Hybrid Village Grids in areas off the national grid. *4th European Conference on PV-hybrid systems and Mini-grids*, Athens, Greece, 29th and 30th May 2008; p. 1-9

[3] Mattijs, S. Neglected decentralized rural electricity production in Lao PDR. *Master Thesis, Wageningen University*, Netherlands, 2008.

[4] Mattijs, S., Simon, R.B. A light left in the dark: The practice and politics of pico hydropower in the Lao PDR. *ELSEVIER Energy Policy* (38), 2010, pp. 116-127

[5] Ketjoy, N. Photovoltaic Hybrid Systems for Rural Electrification in Mekong Countries. *PhD Thesis, Faculty of Electrical Engineering/Information Technology*, University of Kassel, Germany, 2005.

[6] Janjai, S. Assessment of Solar Energy Potentials for Lao's People Democratic Republic. Internal Report, Ministry of Energy and Mines, Lao PDR. *Solar Energy Research Laboratory, Silapakorn University*, Thailand, 2006.

[7] S. Phrakonkham, J.Y. Le Chenadec, D. Diallo, G. Remy, C. Marchand , "Reviews on Micro-Grid Configuration and Dedicated Hybrid System Optimization Software Tools: Application to Laos", Engineering Journal (IEEE)", doi: 10.4186/ej.2010.14.3.15, Vol. 14, Issue: 3, pp. 15-34, (2010).

[8] S. Sieniutycz, J.Jeżowski, "Energy Optimization in Process Systems", ELSEVIER, 2009, ISBN: 9780080451411

[9] Detailed Studies of the Priorities Villages Oudomxay Province. *Summary Report*, WP6, RESIRA, Laos, March 2009, pp. 1-15, http://ftpnrj.free.fr/resirea/update2009/Laos/, accessed July 2011