Optimization software tool review and the need of alternative means for handling the problems of excess energy and mini-grid configuration: a case study from Laos

Sengprasong Phrakonkham[12], Jean-Yves Le Chenadec[3], Demba Diallo [1], Senior Member IEEE, Claude Marchand[1], Member IEEE,
1 - Laboratoire de Génie Electrique de Paris (LGEP) / SPEE-Labs,
CNRS UMR 8507; SUPELEC; Université Pierre et Marie Curie P6; Université Paris-Sud 11;
11 rue Joliot Curie, Plateau de Moulon F91192 Gif sur Yvette CEDEX
2 - Department of Electrical Engineering, National University of Laos, NUOL, Laos
3 - Université Paris Sud 11, IUT de Cachan
Email: sengprasong.phrakonkham@lgep.supelec.fr, sengprasong@fe-nuol.edu.la

Abstract - Renewable hybrid systems have been widely and successfully used as an alternative way to produce electrical energy in the off-grid areas where the grid connection is by far not economic to be accessed. Several software tools have been designed to simulate and optimize hybrid systems. However, not many of them provide a hydroelectric component as an energy source in addition to the standard ones such as PV, wind turbines and generators. Moreover, only a few integrate a multi-objective optimization where net present cost (NPC), CO_2 emission and the unmet load are the parameters in their simulation processes. In this paper, firstly, case study with two optimization criteria is performed. In the first one, only the NPC and the CO_2 emission are treated and in the second one, the NPC, the CO_2 emission and the unmet load are all taken into account. The optimization is carried out using two different simulation software tools. The optimization results are then compared regarding the unmet load. Next, the problem of an unused excess of energy is then summarized and discussed. Lastly, the need to facilitate the connections among the components making up the hybrid system via power electronic devices to the system load (mini-grid configuration) is raised and discussed.

Key words - Renewable hybrid systems, software tools, hydroelectric, multi-objective optimization, unmet load, excess of energy and mini-grid configuration

I. INTRODUCTION

Autonomous off-grid rural electrification based on the production of renewable energy on site have been proven capable of delivering some degree of quality and reliable electricity for powering rural villages i.e. lighting, cooking, communication etc. In [1] it is reported that off-grid renewable energy technologies satisfy energy demand directly and avoid the need for long and expensive distribution infrastructures. Combinations of different but complementary energy generation systems based on renewable energy or mixed (renewable energy with a backup biofuel/diesel generator) are known as a renewable hybrid system.

When dealing with a hybrid system for the production of electrical energy, various aspects have to be considered. Cost, reliability and environment impact (CO_2 emission) are among others to be considered. Reliability means that energy produced must be available whenever it is needed to satisfy the system load. It is reported in [2] that multi-objective design methods have been applied successfully in several fields of engineering and several mathematical techniques. Then a multi-objective optimization combining these various criteria is therefore crucial for the investment of a hybrid system. The study results will be then used as parts of the decision making process for the investment. This paper discusses on what is left off in the multi-objective optimization and on the flexibility issues of the mini-grid configuration. Precisely, both issues are focused regarding the existing optimization tools.

II. ELECTRIFICATION IN LAOS

Of about 5.5 millions of inhabitants in Laos, only 54 % (in 2006) could benefit the national grid to satisfy their daily living such as lighting, cooking, cleaning, entertaining, etc. In the rest of the country, especially in the small villages or communities in the remote and mountainous area, an access to energy is practically impossible due to the non profitability of the grid extension.

Report in [3] cited that the highest priorities of the Government of the Lao PDR’s (GOL) 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 list through economic growth based on the sustainable use of the country’s natural resource base. It was reported in [4] that on the energy sector, the country is engaged to electrify 90 % of the country households by the year 2020 with the intermediate target of 79 % by 2015. This goal will be achieved through the on-grid household and off-grid household electrification. The latter requires using hybrid renewable systems to produce electricity in rural communities.

Geographically, Laos situates at the latitude of 18° north and 108° east where the availability of sun is around 300 days per year. The sun radiation on the horizontal surface fluctuates between 3.5 – 6.2 kWh/m^2/day [4]. This would give a relatively good possibility of engaging the photovoltaic (PV) technique and technology to produce clean energy.

As a relatively mountainous country, Laos occupies immense water resources. Villages and communities in remote areas where an access to a grid is not possible could then benefit from these natural renewable resources.

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 (http://eosweb.larc.nasa.gov/), unfortunately, it is too low to be used to produce the electrical energy in an economic manner.

In the Asian Development Bank report [5] it is estimated that about 92 % of households use wood-fuels for cooking. However, the huge quantity of wood used in the long term perspective will lead to the deforestation when it is not properly managed. Though being the rice predominant country, Laos has not been by far making used of rice husks as a source of energy. The dispersed allocation and the size of rice mills are one of the limiting factors for the use of rice husks.

Animal and human wastes are generally available within rural areas, and there would appear to be potential for a larger biogas digester program for cooking, lighting and other purposes within the country.

In recent years, driven by the oil price crisis biofuel becomes one of the development issues in Laos. Many projects were granted by the government for the plantation of biofuel related crops. The main plantation crops include para rubber, eucalyptus, palm tree, kathinnalong, jatropha and sugarcane.

III. REVIEW OF SOFTWARE TOOLS

In order to optimize the use of several natural resources available with the least cost, simulation and optimization software tools are needed. Up to this time several software tools have been deployed for the sizing and simulation of hybrid systems. Based on the form and purpose and taking PV hybrid systems as a case study, research work in [6] classified these tools into pre-feasibility, sizing, simulation and open architecture research tools. A pre-feasibility tool assists engineers to determine whether a PV system can be used in view of energy provided and the life-cycle cost of energy. Among the tools, RETScreen is a renewable energy awareness, decision support and capacity building tool developed by the CANMET Energy Diversification Research Laboratory (CEDRL) in Canada. Sizing tools carry out the optimal sizing of different components making up a hybrid system when an energy requirement is given. Developed by NREL (National Renewable Energy Laboratory, USA), HOMER is the most-used sizing software for hybrid systems. Unlike sizing tools, simulation tools provide a detail analysis of the performance of the system with the pre-specified data such as nature and size of each component made by the user. Hybrid2 also developed by NREL is among this kind of software. As the name said, open architecture research tools provide a selection of routines describing components and platform for linking the routines together. As a result, a high degree of flexibility is available to the user to choose or modify the algorithms determining the behaviors and interactions of the individual components. The most used software for this category is the famous Matlab/Simulink developed by the Mathworks.

In [7], various simulation and optimization software tools on PV hybrid systems have been reviewed in the literature. Table 1 summarizes the characteristics of available software tools.

Table 1 Selected simulation software tools

	Software tools				
Characteristics and components	HOMER	Hybrid2	HOGA	INSEL	ARES
Free download and use	X	X	X		
PV	X	X	X	X	X
Diesel Generators	X	X	X	X	X
Batteries	X	X	X	X	X
Wind	X	X	X	X	X
Mini-hydro	X		X		
Fuel cell; electrolyzers and H_2 tank	X	X	X		
Loads	X	X	X	X	X
Simulation	X	X	X	X	X
Control strategies	X	X	X		
Multi-objective optimization (economical and technical)	X		X		

As it can be seen from Table 1, in addition to the basic components such as PV, wind turbines and generators only HOMER and HOGA propose mini-hydro turbines as sources. Apart of the simulation capability commonly used by all tools, some offer control strategies but only two of them integrate furthermore an economic aspect in the multi-objective optimization apart of the technical one.

IV. TARGET LOCATION AND PROPOSED HYBRID SYSTEM

Remote villages without access to the national grid in northern part of Laos are targets of the case study and research activities. Site surveys and studies will be carried out later on selected villages in various Northern provinces. These regions are less developed and less electrified than those of central and southern part due to their geographical locations which are rather mountainous. However, according to the database available through http://eosweb.larc.nasa.gov/ Northern provinces have the highest sun radiation of the country.

A stand-alone renewable hybrid system composed of PV panels and a hydroelectric turbine as renewable energy sources, a diesel AC generator as a backup for a peak load and batteries as an electrical energy storage device is considered. For the time being, the load profile is based on an average energy demand per household reported in [5] (75 to 600 kWh/year without and with road access respectively) in typical rural villages in Northern Laos.

A. Suitable Software Tools

Since a hydroelectric turbine is used as a source component and a multi-objective optimization is needed for the proposed hybrid system, among various sizing or simulation software tools presented in Table 1 only HOMER [8] and HOGA [9] are suitable.

a. HOMER

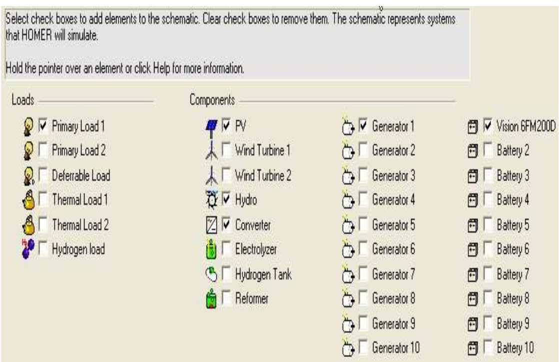

Fig. 1 HOMER available hybrid system components

HOMER is a simulation and optimization program developed by the National Renewable Energy Laboratory (NREL). It consists of libraries including photovoltaic generators, batteries, wind turbines, hydraulic turbines, ac generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers. The loads can be AC, DC, and/or hydrogen loads, as well as thermal loads (Fig. 1). The user must select the components of the model to represent the architecture of his network.

For the optimization purpose technical and financial data for each selected component must be entered.

HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, it compares the electric demand in the hour to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the system. The tool also decides for each hour how to operate the generators and whether to charge or discharge the batteries (dispatch strategies: cycle charging and load following). When sensitivity variables are selected as inputs, HOMER repeats the optimization process for each sensitivity variable specified. At the end of the simulation, the different system configurations are classified by their total NPCs.

b. HOGA

HOGA (Hybrid Optimization by Genetic Algorithms) is a simulation and optimization program developed in C++ by José L. Bernal-Agustín and Rodolfo Dufo-López, University of Zaragoza, Spain, for hybrid renewable systems for generation of electrical energy and/or hydrogen. The hybrid system comprises photovoltaic (PV) panels, wind turbines, hydroelectric turbines, fuel cells, H_2 tanks, and electrolyzers, as well as batteries, battery charge regulators, inverters, rectifiers and AC generators (Fig. 2).

Fig. 2 HOGA available hybrid system components

Different system loads are possible: electric AC, electric DC, hydrogen and water pumping load. The program allows for selling AC surplus unused energy to the grid, or surplus hydrogen, produced in the electrolyzer and stored in the tank.

Optimization is achieved by minimizing total system costs throughout the whole of its useful lifespan, when those costs are referred to or updated for the initial investment (Net Present Cost). Optimization is therefore financial (mono-objective). However, the program allows multi-objective optimization, where additional variables may also be minimized: CO_2 emissions or unmet load (energy not served), as selected by the user. Since the cost, emissions, or unmet load are mutually counterproductive in many cases, more than one solution is offered by the program, when multi-objective optimization is sought.

HOGA makes use of Genetic Algorithms (GA) for optimization, both for the system components (main genetic algorithm), and for the control strategy (secondary genetic algorithm). Genetic algorithms may produce adequate solutions when applied to highly complex problems [8].

B. Case Study and Simulation

As mentioned before, PV panels, a hydroelelectric turbine, a backup AC generator and batteries as an electrical energy-storing device are used. A location Northern Laos with the latitude of 20.5° north and 102.5° east is selected. The corresponding daily solar radiation is depicted in Fig. 3. A load profile of about 8,000 kWh/year representing 20 households with 2 x 18 W fluorescent light bulbs (8 h/day), a 25 W entertainment set (10 h/day) and a 40 W electric fan (12 h/day) is assumed.

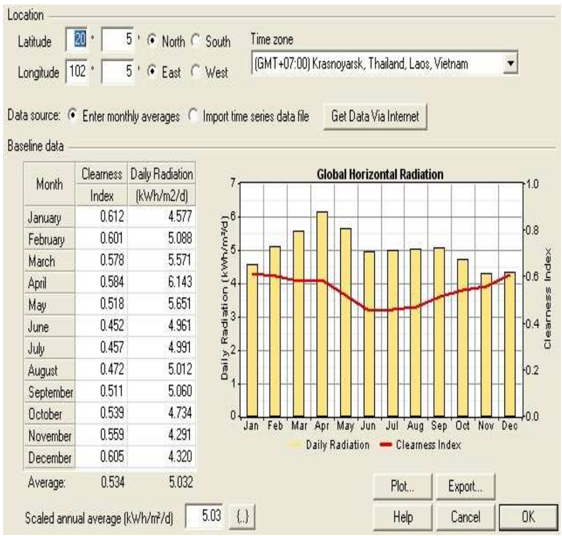

Fig. 3 Daily solar radiation at latitude 20.5 north

HOMER and HOGA are used as test tools for optimizing a hybrid system with this case study. There is, however, no possibility for choosing the AC/DC connections via power electronic devices among components making up the hybrid system and from components to the loads. Moreover in HOMER, there is also no possibility to input a voltage value and hence a maximal number of PV panels to be connected while it exists in HOGA.

As fixed parameters, a lifespan of 25 years, a replacement and an O&M cost of 120 €/year and 2.95 €/year per PV panel respectively are considered. An acquisition cost of 229 and 450 €/panel for a power of 0.054 and 0.125 per panel respectively is considered as variable parameters for HOGA while an acquisition cost of 3600 €/kW and a power range from 1 to 3 kW with a step of 0.5 are entered in HOMER.

For the hydro-electric turbines a 30 years lifespan, a 4 % penstock loss, a 75 % efficiency and an O&M cost of 130 €/year are considered as fixed parameters for both HOGA and HOMER. As variable parameters, available drop heights of 6-9 m and flow rates of 17-18 l/s are assumed and considered as a sensitivity analysis in HOMER whilst HOGA uses the 17 and 18 l/s flow rates and an acquisition cost of 4,500 and 5,500 € respectively as a variable parameters.

HOGA and HOMER use a lifetime of 7,000 hrs (operating throughout the week), a 30 % minimal power and an O&M cost of 0.15 €/hr as fixed parameters. For calculating the CO_2 emission, a CO_2 emission factor of 4.75 $KgCO_2/l$ is used by HOGA, whilst HOMER makes use of a 5.5 gCO/l CO emission factor instead. As for the acquisition, HOGA uses a range of cost i.e. 400, 650, 850 and 1,215 € for the unit power of 0.8, 1, 1.5 and 2 respectively as variable parameters whereas only a 650 €/kW cost is used for all powers in HOMER.

Only one type of battery can be selected by HOMER at a time whilst HOGA could consider many of them. Therefore, only fixed parameters are used in HOMER. A voltage of 12 V, a float life of 10 years, an 80 % efficiency, a 40 % minimum State of Charge (SOC), a replacement cost of 138 € and an O&M cost of 5 €/year are common as fixed parameters for both simulation tools. HOMER considers furthermore an acquisition cost of 138 € and a 200 Ah capacity as fixed parameters whilst in HOGA an acquisition cost of 125 and 138 € are taken as variable parameters for a capacity of 144 and 200 Ah respectively.

C. Results

1st optimization criterion: NPC and CO_2 emission

The maximal flow rate of 18 l/s selected by HOGA is considered as the case to be discussed. As a result, both simulation tools could optimize well the NPC by providing a list of different components sorted by this cost and the CO_2 emission (Table 2).

Table 2 Energy balance (NPC-CO_2 emission)

	UL kWh/year	EE kWh/year	CO_2E kg/year	NPC €
HOMER	86.0	1,278	1,255	35,005
HOGA	93.8	730	1,507	35,735

Table 3 PV and battery sizes (series and parallel)

	PV (S x P)	Bat. (S x P)
HOMER	N/A	4 x 2
HOGA1-1*	4 x 2	4 x 2
HOGA1-2*	4 x 4	4 x 2

** HOGAi-j; i is the criteria number (1 or 2) and j represents the selected result of the optimization process.*

Since in HOMER the PV generators considered are not made up of individual panels but taken as a one, the size of PV panels is not outputted whilst the battery sizing is presented in Table 3. The third and fourth row of this table (HOGA1-1 and HOGA1-2) shows the increasing in size of PV panels when a lower unmet load was sought. It is seen from Fig. 4 that the unmet load did not change too much since it was not optimized alongside the NPC and CO_2 emission. The CO_2 emission decreased whilst the excess of energy increased.

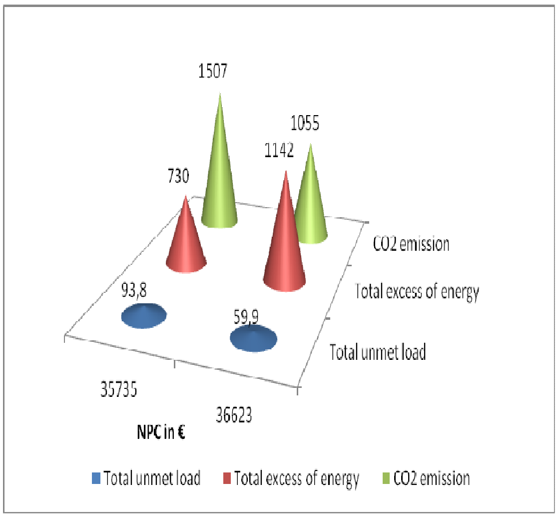

Fig. 4 Graphical representation of NPC-CO_2 optimization results (using HOGA results)

2nd optimization criterion: NPC, CO_2 emission and unmet load (HOGA only)

The effect of the triple optimization can be seen from Table 4 (HOGA1-1 & HOGA2-1) that the unmet load (UL) decreased (from 93.8 to 58.5 kWh/year) on the expenses of the NPC and the excess of energy (EE) while the CO_2 emission was lower. In keeping the unmet load further decreasing (to 9.8 kWh/year) the excess of energy reduced from 1,179 to 936 kWh/year. However, the CO_2 emission and the NPC remained increasing (Table 3 – HOGA2-1 & HOGA2-2).

Table 4 Energy balance (triple optimization).

	UL kWh/year	EE kWh/year	CO_2 Emiss-ion kg/year	NPC €
HOGA1-1	93.8	730	1,507	35,735
HOGA1-2	59.9	1,142	1,055	36,623
HOGA2-1	58.5	1,179	1,055	36,540
HOGA2-2	9.8	936	1,414	36,822

Fig. 5 graphically summarizes all the changes in the total unmet load, the total excess of energy, the CO_2 emission and the total NPC as a result of the triple optimization.

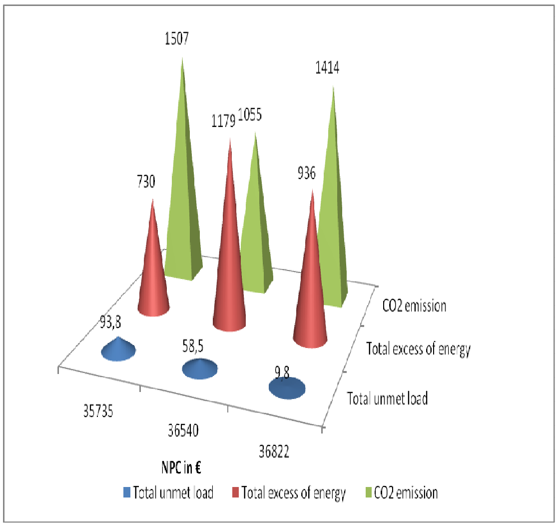

Fig. 5 Graphical representation of the triple optimization results

V. CONCLUSIONS AND DISCUSSIONS

Although the unmet load could be reduced from 93.8 to 59.9 kWh/year through the NPC-CO_2 optimization, this value is still much higher than 9.8 kWh/year obtained by the triple optimization (Fig. 4). It is also observed that the CO_2 emission is reduced, contrary to the NPC and the excess of energy. Through the triple optimization the unmet load could be heavily reduced from 93.8 to 9.8 kWh/year on the expense of the NPC. The CO_2 emission reduced first and then increased to a value relatively smaller than that of the NPC-CO_2 optimization. In contrast, the total excess of energy increased first and then reduced to a value relatively greater than that of the NPC-CO_2 optimization (Fig. 5).

Since the cost of energy (COE) is defined as the ratio of the annualized cost and the system load served, the increasing of the load served and/or the decreasing of the cost would reduce the COE. The excess of energy could be even reduced to zero by being sold to the grid. The selling of the excess of energy to the grid is only possible, however, if the hybrid system is grid connected. In HOGA, the user has the possibility to sell the excess of energy to the grid, while in HOMER he could not. Nevertheless, if an isolated hybrid system is desired, this excess of energy will be left unused or dissipated.

The mini-grid configuration could make significant effects on the safety, adequacy, energy efficiency and expansion of the stand-alone renewable hybrid system. The work in [10] suggested that a system is safe if it presents no greater hazard to the public than standard urban grid-based systems. It is adequate when it delivers sufficient power when and where needed, with the required degree of efficiency and service quality. System expandability implies the use of designs that minimize life-cycle cost by making provision for a certain degree of expansion, preventing the need to replace or rewire portions of the system as the load increases. An efficient system is one that provides an acceptable electric service at a minimum cost over the expected life of the installation.

Excess energy

The research work in [11] has shown that the excess energy could be reduced by increasing the load served while keeping the total NPC constant. Though the same objective, namely reducing the excess energy, the energy produced and thus the energy excess could be also better managed by allocating only the amount of energy required to the time when it is mostly needed by consumers.

Mini-grid configuration

As both software tools used for the optimization have not been designed to enable the connection flexibility among components making up a hybrid system via power electronics components to the system load (mini-grid), it is therefore essential to find or develop alternative means being able of handling the mini-grid configuration issues. Moreover, multi level and multi domain approaches, necessary to design and simulate such a complex system, require appropriate combination of suitable components' models.

Therefore a combination of simulation and optimization tools within an open architecture software such as Matlab/Simulink could eventually be used to cope with the multi-objective optimization and the mini-grid configuration of a stand-alone renewable hybrid system.

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