

REVIEWS ON MICRO-GRID CONFIGURATION AND DEDICATED HYBRID SYSTEM OPTIMIZATION SOFTWARE TOOLS: APPLICATION TO LAOS

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ABSTRACT

Connecting the electric grid to rural and remote areas is very uneconomical to carry out. Moreover, the utility network is not designed to fulfill the growing needs of the population and may be destabilized by new consumers. Therefore, it is more economical to electrify those areas with a micro-grid by means of existing renewable energy sources available locally. The micro-grid configuration represents the energy distribution architecture from the producing sites to consumers and eventually the interconnection between several sites and several consumers. The design and study of such a grid configuration is realized using simulation tools and has to be considered from the system level with economical matters in addition to the technical aspects. As for the optimization of a hybrid/micro-grid system, several software tools have been developed and designed to simulate and optimize hybrid systems. In this paper, an analysis of the current status of electrification in Laos is presented. Then, a literature review of the existing micro-grid configuration is presented and a case study of a typical rural, remote and isolated village in Laos is simulated, using some of the selected software tools.

KEYWORDS

energy excess, hybrid systems, micro-grid, multi-objective optimization, renewable energy

I. Introduction

Autonomous off-grid rural electrification based on the on-site production of renewable energy has been proven to be capable of delivering a 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 or mixed energy (renewable energy with a backup bio-fuel/diesel generator) are known as a renewable energy hybrid system. The grid formed by this system is known as a micro-grid due to its size compared to the main grid. According to energy conversion technologies, different micro-grid configurations have been studied, developed and implemented worldwide to meet the energy demands of off-grid modern societies.

When designing a hybrid system for the production of electrical energy, various aspects have to be considered, such as cost and environmental impact (CO₂ emission). Availability and reliability will be, however, among the key issues. Therefore, the design of the micro-grid is a multi-objective problem. It is reported in [2] that multi-objective design methods have been applied successfully in several fields of engineering with several mathematical techniques. The study results will then be used as part of the decision-making process for investing.

In this paper, firstly, the status and development of electrification as well as the available renewable energy sources in Laos are presented in the second section. In the third section, the review of research on different micro-grid configurations is summarized, concluding with the current implementation in Laos. In the fourth section, a short review of existing simulation tools is presented. Then, a case study, with respect to economic optimization for a selected Northern Lao village, is performed using two different simulation software tools. The optimization results are then compared, regarding the unmet load and the unused energy excess. Furthermore, the need to optimize excess energy as a part of the optimization criteria and the demand of more flexible software tools, with respect to the sizing and optimizing of micro-grid components, are raised and discussed. Finally, the unavoidable needs of micro-grids for the development of rural electrification in Laos are highlighted.

II. Electrification in Laos

2.1 2006 Status and Development Plan

Of the about 5.5 million inhabitants in Laos, only 54 % can benefit from the national grid to satisfy their daily lives for lighting, cooking, cleaning, entertaining, etc. In the rest of the country, especially in the small villages or communities in the remote and mountainous areas, access to electric energy is practically impossible due to the non-profitability of grid extension.

The 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 (LDC) list through economic growth based on the sustainable use of the country's natural resource base. The Lao power sector is still in its infancy with more than 45 % of the population with no access to electricity. Extracted from the database in [4], [6], Figure 1 and 2 illustrate the provincial rates of electrification of villages and households respectively throughout the country.

It is clearly seen in Figure 1 that nearly all of the provinces, with the exception of three, namely Vientiane Capital, Vientiane province and Sayaboury, have an un-electrification rate above the country average value (40%). Like the case of the villages, Figure 2 shows that with the exception of Vientiane Capital, Vientiane province, Borikhamxay and Champasack, all of the provinces have a non-electrification rate of higher than 40%.

Figure 1
Percentage of un-electrified villages

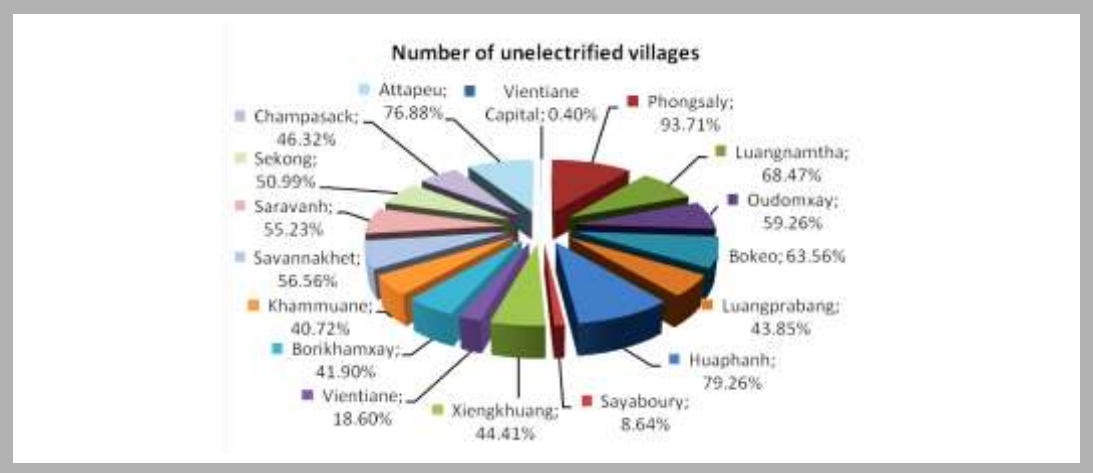
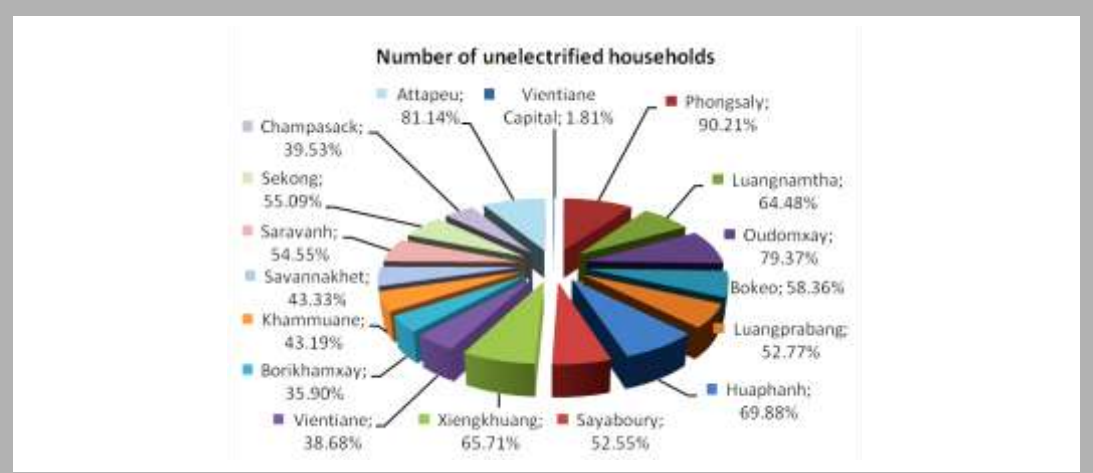
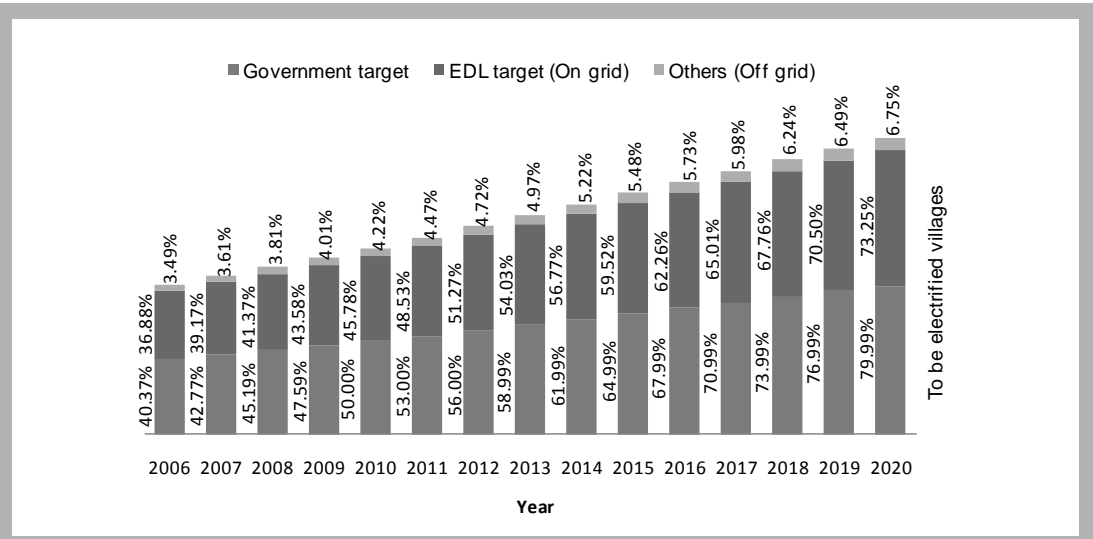


Figure 2
Percentage of un-electrified households



The Lao power sector has the potential to play a crucial role in achieving the Lao Government's socio-economic development objectives. This is achieved by means of promoting the uses of low cost, reliable electricity, i.e., from renewable hybrid systems within the country. As the target of the government [5, 6, 8], the country has therefore set to electrify 80 and 90 % of the country villages and households by the 2020, with intermediate targets of 65 and 81 % by 2015 respectively. Figure 3 and 4 illustrate the village and household electrification rate throughout the country as of 2006 and its forecast between 2007 and 2020 [5] - [6], [8].

Figure 3
Forecast of electrified villages (2007-2020)



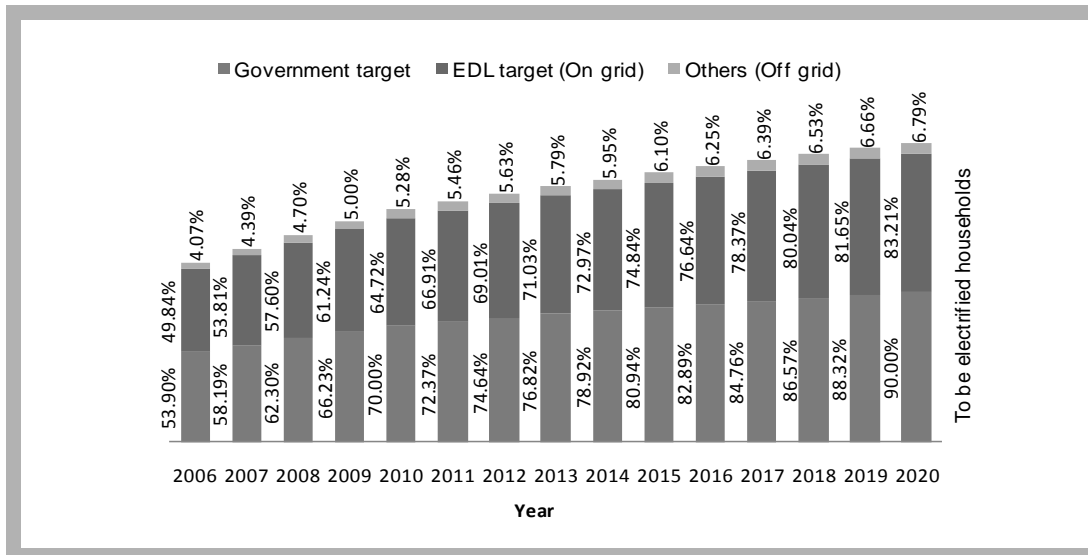


Figure 4
Forecast of electrified households (2007-2020)

The goal will be achieved through on- and off-grid electrification. The former will be carried out in the form of grid expansion through the existing high, medium and low voltage grids. The latter requires the usage of hybrid renewable systems to produce electricity in rural, remote and isolated communities. The Électricité du Laos Company (EDL) is in charge of on-grid electrification, while off-grid electrification is the responsibility of the Rural Electrification Division. Both agencies are, however, under the supervision of the Department of Electricity, Ministry of Energy and Mines.

Electrification won't be, however, equally distributed across all provinces and regions. For instance, the 100% village and household electrification rate by 2020 is targeted only to certain provinces e.g. Vientiane Capital, Sayaboury and Vientiane province. Other provinces in northern Laos like Phongsaly, Luangnamtha and Oudomxay won't be 100% electrified even by 2035, due to the very low penetration in their rural, remote and isolated areas that typically mark the provincial landscape [6].

2.2 Renewable Energy Sources

2.2.1 Photovoltaic Energy

Geographically, Laos is situated between the latitudes of 13° to 22° north and 100° to 108° east, where the availability of sun is around 300 days per year. Research work in [7] used images of three satellites covering Laos, namely GMS 5, GOES 9 and MTSAT, taken during the period from 1995 to 2005 to calculate a monthly and yearly average daily global sun radiation throughout the country. The monthly and yearly average of daily solar radiation is found to be respectively 16.06 and 15.8 MJ/m²-day throughout the country. Figure 5 and Figure 6 summarize the geographical distribution of the monthly (January to December) and yearly average daily solar radiation.

We can see that radiation fluctuates seasonally. It is relatively low in the northern and eastern parts of the country during January. The entire country is exposed to the highest radiation during February to June, with April being the highest exposed period. The radiation decreases gradually for the rest of the year. November and December have the lowest radiation. The yearly highest average daily solar radiation of 18-19 MJ/m²-day is recorded in the south of the country. The western part is exposed to 17-18 MJ/m²-day or radiation, whilst the east and the mountainous areas have the lowest radiation.

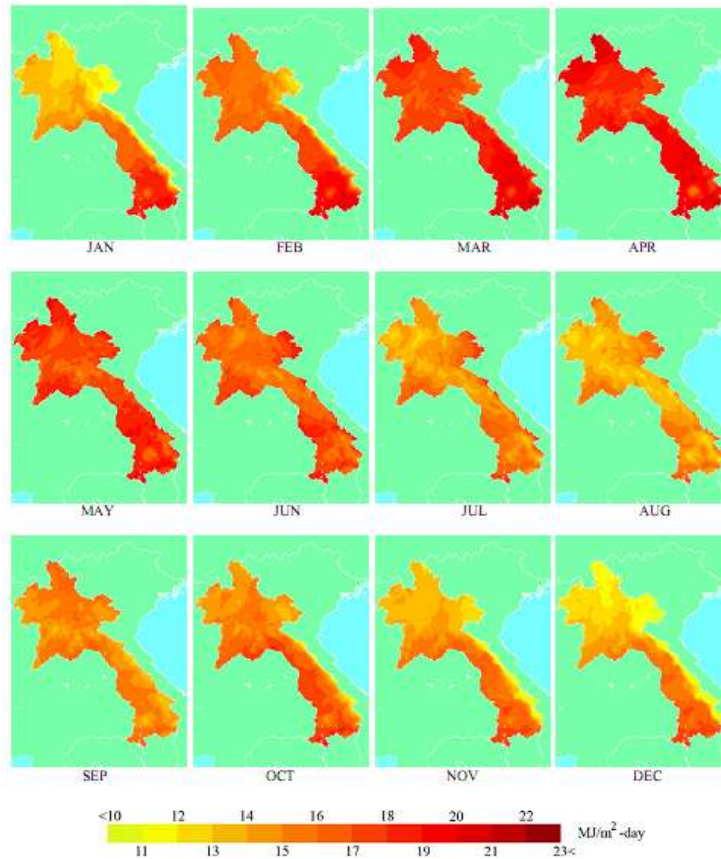


Figure 5
Graphical distribution
of monthly average of
daily solar radiation
(Jan. – Dec.) [7]

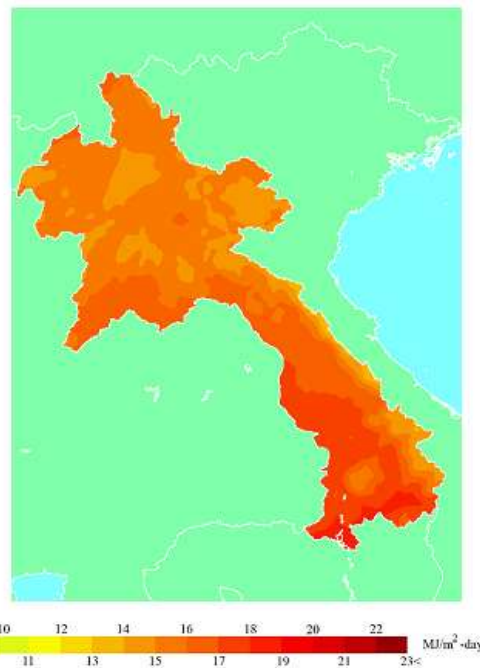


Figure 6
Graphical distribution
of yearly average of
daily solar radiation
[7]

Projected countrywide, an average solar radiation of 15-16 MJ/m²-day accounts for more than 43 % of the surface. The highest radiation covers 2.2 % of the country, in contrast to 1.1 % being exposed to the lowest radiation. This statistical distribution is illustrated in Figure 7.

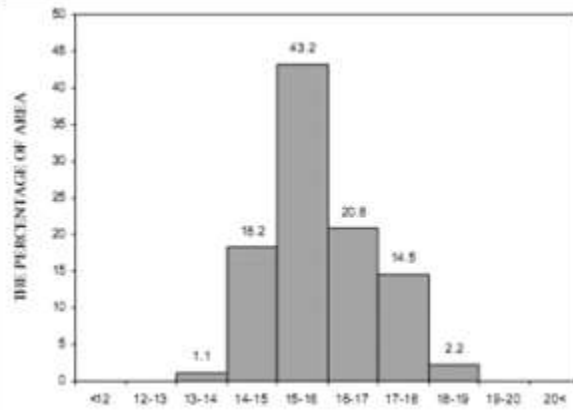


Figure 7
Statistical distribution
of solar radiation over
the country area [7]

In summary, the average solar radiation in Laos is relatively high. This would give a relatively good possibility and opportunity to engage the photovoltaic (PV) technique and technology as a component of a hybrid renewable energy system, in order to produce clean energy for villages and communities in remote, rural and isolated areas. In fact, PV solar home systems (SHS) as shown in Figure 8 were introduced in Laos in the late 1980s. By now there are more than 14,000, with a total installed capacity of about 300 kW (as of 2006) [4, 5, 8], throughout the country, with a tendency towards increase. These have been implemented in line with the promotion of the use of renewable energy encouraged by the government policy.



Figure 8
PV panels installed
on a house roof
(SHS)

2.2.2 Hydroelectric Resources

As a relatively mountainous country, Laos benefits from massive water resources with different sizes and capacity (Figure 9). Villages and communities in remote areas where an access to a grid is not possible could then benefit from these natural renewable resources, in the forms of mini, micro and pico hydroelectric solutions. The latter is sometimes referred to as village hydro systems, as shown in Figure 10, according to the installed capacity of < 1 MW, < 100 kW and < 1 kW respectively. The first two types are connected to the national utility grid, while the latter has the objective, as the name suggests, to satisfy the needs of individual households, villages or communities. Up to now, their development and implementation in Laos has been merely on the household scale with a unit installed capacity of 100 - 300 W [8], mostly in the hilly areas of the Northern provinces. This is due to the fact that large units require large budgets which unfortunately poor villagers cannot afford.

Figure 9
A waterfall in a
village in Oudomxay



Figure 10
A village pico hydro
system [8]



It is worth noting that with the help and support from financial institution a village-or community-scale pico hydro could be one of the essential tools for rural electrification in Laos, using renewable energy resources available locally.

2.2.3 Other Natural Resources

Wind speed is relatively weak throughout the country even in Northern Laos along the border with 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 electrical energy cheaply.

It is estimated that about 92 % of households use wood fuel for cooking. However, the huge quantity of wood used in the long term perspective will lead to deforestation if it is not properly managed. Though being a rice predominant country, Laos has not been by far making use of rice husks as a source of energy. The dispersed distribution and the size of rice mills are one of the limiting factors for the use of husks. Animal and human waste 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, bio-fuel has become one of the development issues in Laos. Many projects were granted by the government for the plantation of bio-fuel related crops. The main plantation crops include para rubber, eucalyptus, palm tree, kathinnalong, jatropa and sugar cane [8].

The availability and the variety of renewable sources is a great potential for the development and implementation of micro-grids for Lao rural electrification in the near future.

III. Micro-Grid

3.1 Definition and Concept

There are several different definitions of micro-grid as many as there are research projects about it [12]-[27]. In summary, however, a micro-grid can be seen as a semi-independent grouping of generating sources and controllable end-use loads. The supply sources may consist of conventional generator sets, micro turbines, fuel cells, photovoltaic (PV), small scale renewable generators, heat recovery from thermal generation, and storage devices [18]. In fact, it is a small scale power supply grid that is designed to provide energy for a small community. The small community may be a house, an isolated rural community, a mixed suburban environment, a commercial area, an industrial site or a municipal region. The key concept that differentiates a micro-grid from a conventional power utility grid is that the power generators are small (often referred to as micro or distributed generators, of a similar size to the loads within the micro-grid), they are usually geographically distributed, and they are located in close proximity to the energy users. The generators and loads are controlled to meet the consumer's energy demand while achieving a local energy and power balance [19].

Figure 11 represents a micro-grid architecture consisting of a group of radial feeders, which may be part of a distribution system. There is a single point of connection to the utility, called the point of common coupling (PCC). Feeders A, B and C have sensitive loads, which require local generation. The non-critical load feeders do not have any local generation. Feeders A-C can be isolated from the grid using the static switch in less than a cycle.

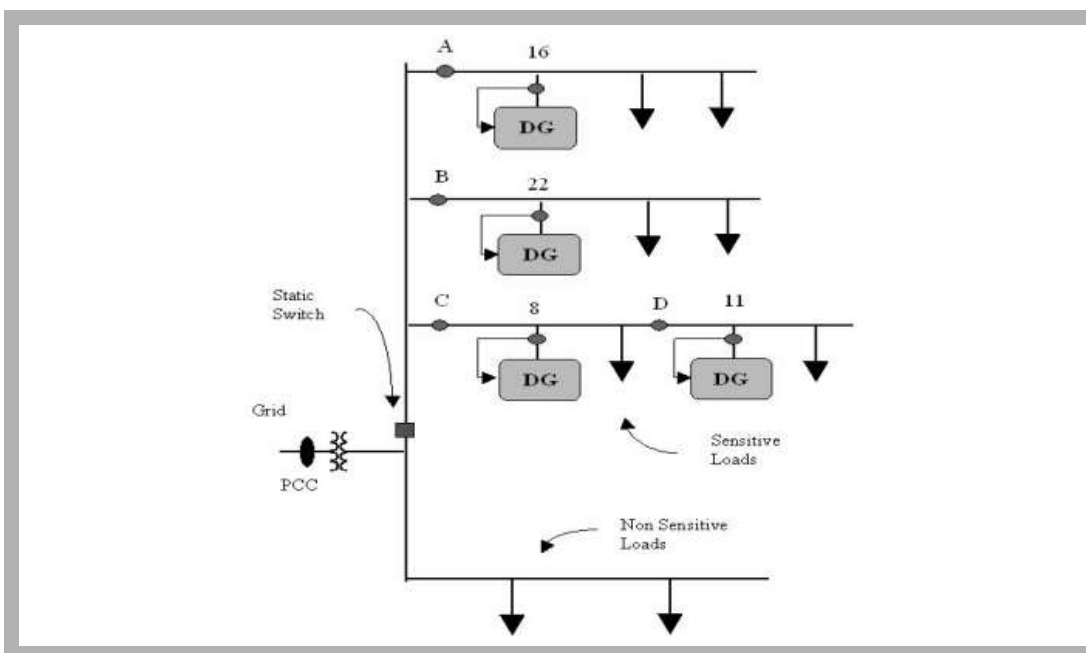


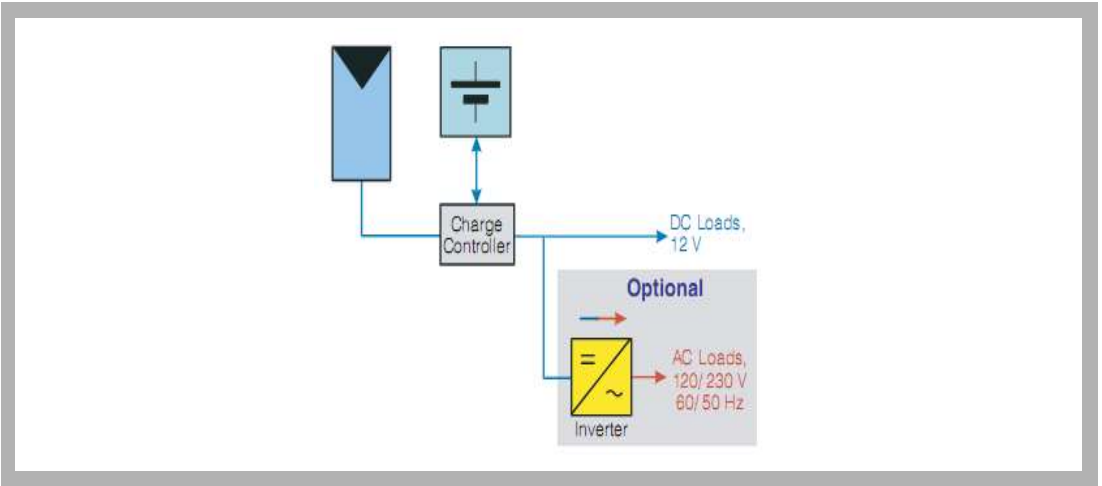
Figure 11
Micro-grid architecture
[20]

3.2 Micro-Grid Configurations

Different micro-grid configurations have been presented in several research works [1], [28] - [39]. They are generally, however, grouped into 3 types: DC coupled, AC coupled and AC and DC coupled configurations.

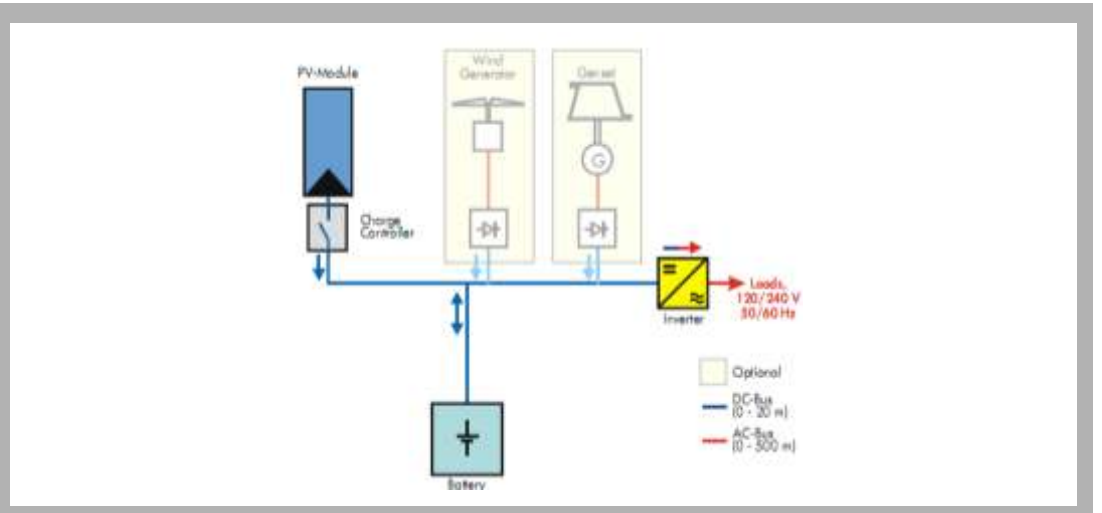
In a DC coupled configuration, all energy sources are linked together on the DC side before being connected to the AC side (loads and/or grid) via inverters [29], [30]. Nowadays, DC coupled configurations are used mostly for smaller hybrid systems up to a certain size (a few kW), depending on various external parameters [31]. Solar home systems are a simple form of a standalone DC coupled micro-grid configuration, where only PV generators are used to provide energy to consumers, such as houses or small first aid stations at the scale of a village. Up to now, several hundred thousand SHSs, in the power range of about 200 W, have been installed mainly in remote rural and isolated areas of Asia, Africa and South America. They are supported by an additional small inverter, so the consumer can use the DC system to supply any standardized AC load (Figure 12) [34].

Figure 12
Solar home system
[34]



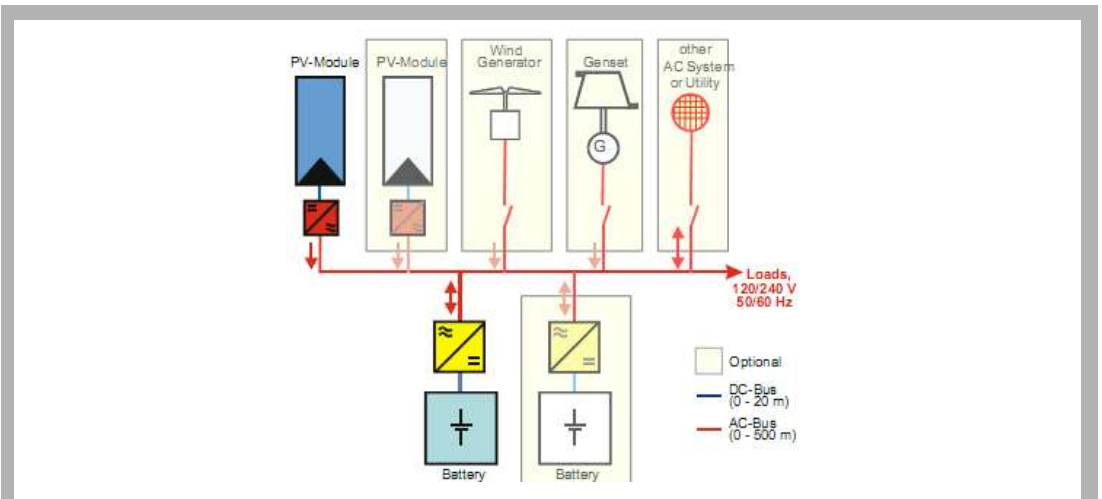
However, if higher power or energy is demanded and cannot be met in a cost-effective manner by the SHS, several generators must be inserted into the system. Additional generators are typically wind, hydro, conventional or bio-diesel generators. In such a system, represented here by Figure 13, all the AC energy sources, such as wind generators and gensets, are converted to DC and coupled to the battery. The power range for a DC coupled configuration is extremely broad and can be used cost-effectively for various off-grid applications.

Figure 13
DC coupled
configuration [35]



In general, when systems increase in size, they are implemented as AC coupled hybrid systems. Using the concept of “modular system technology” [31], DC coupling is completely avoided and batteries, as well as PV modules, are equipped with extra power electronics (Figure 14). More flexible systems with modularly structured components are achieved by coupling all consumers and generators on the AC side, as presented in Figure 15.

Figure 14
A modular AC coupled
configuration [36]



Depending on the application type and available energy resources, different conventional and renewable energy generators could be added to the system to form a hybrid energy system. Furthermore, this configuration can easily be expanded by integrating further components or generators in order to cover the rising energy demand. Such systems are used to supply all electrical consumers, especially rural villages or communities in developing and threshold countries where electricity, water pumping and water disinfection are basic needs [34]. Various applications are also implemented in Europe e.g. on the isolated island of Kythnos, Greece [37], [39]. Nowadays, the AC coupled technology is commonly used in the power range above several kW and can be realized in both single and three phase structures.

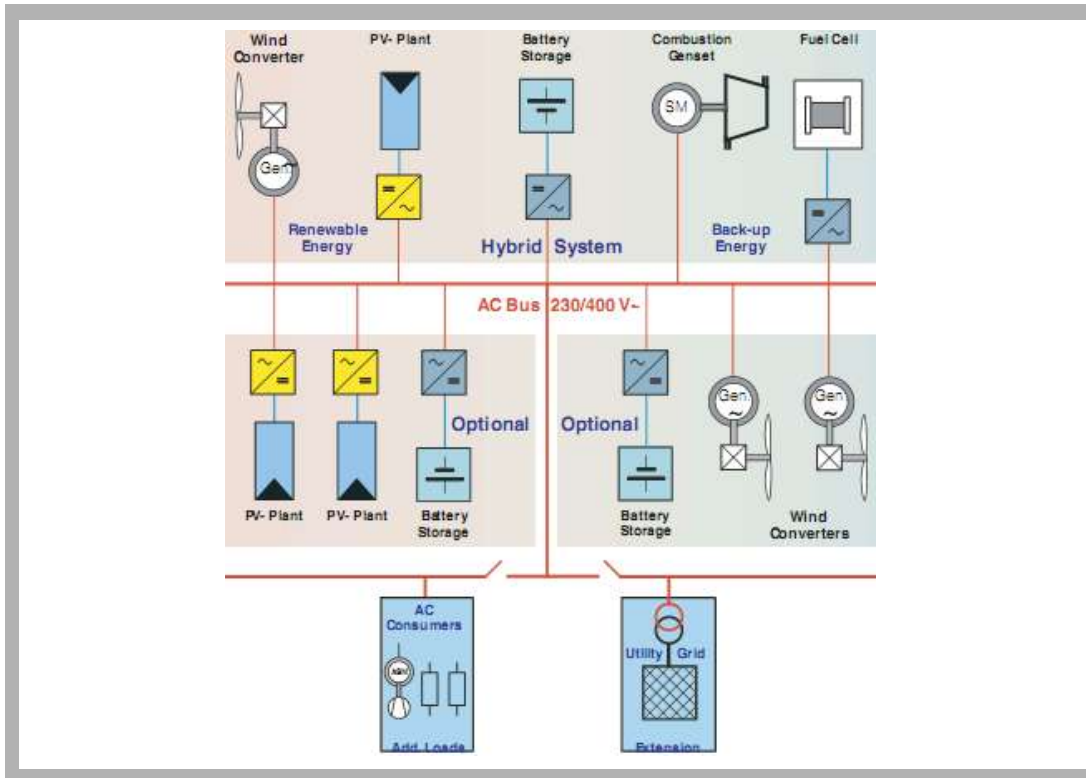


Figure 15
An expanded modular AC coupled configuration [34]

As mentioned earlier, DC coupling is the natural solution in small systems, but in large systems, AC coupling is advantageous. In the wide range in between, it is also possible to combine AC and DC coupled in one system, namely, an AC and DC coupled configuration. This technology has emerged due to the need to supply (medium power) AC loads by DC

power sources and to charge the battery on the DC-side also via combustion generators, such as diesel gensets, as illustrated in Figure 16. Such a configuration is used to supply remote or rural consumers who have larger energy demands than the SHS (e.g. small villages, farms etc.). The common power range is between 1 and 5 kW and the DC-voltage range is between 12 and 48 V [31].

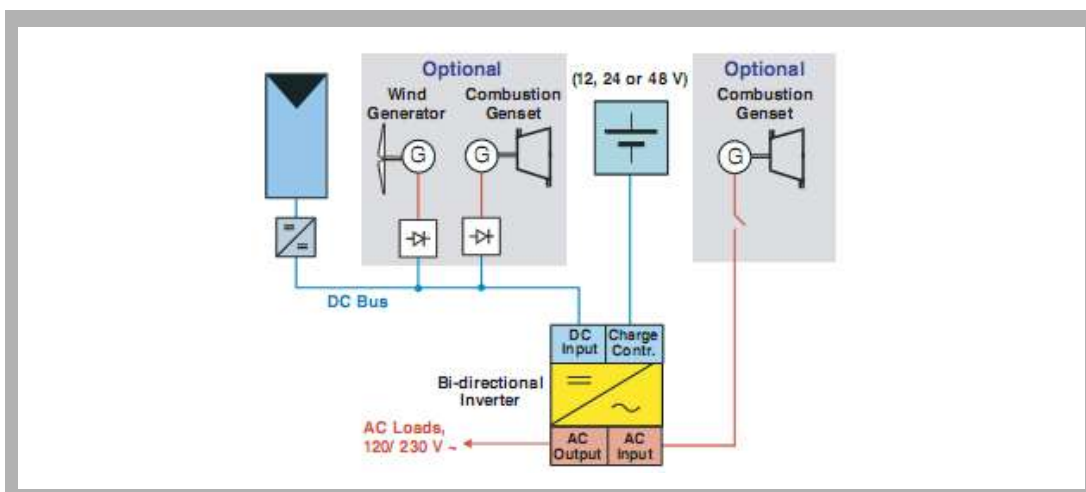


Figure 16
AC and DC coupled configuration [31]

The AC and DC coupled configuration is developed and implemented in the form of a hybrid PV-genset DC/AC bus configuration, mainly in North America [33], [38]. The research in [38] reveals that when compared to the AC and DC bus configuration, it can satisfy AC loads directly (compared to DC system) and has a smaller genset runtime and hence reduced annual energy consumption than the AC system.

In Laos, up to now, the DC coupled configuration in the form of a solar home system, a PV battery charging station (BCS) as shown in Figure 17, a PV water pumping system and an AC coupled micro-grid, have been implemented for the off-grid villages and/or communities [9], [10], [11]. The latter is, however, a very rare case and accounted only for only a fraction of the former. The reason for the few usages of the AC configuration is due to small available budgets supporting technology development and implementation in the country.

Figure 17
A battery charging station in a Northern Lao village



Whatever the application, the selection of the micro-grid configuration and the design of all the components are handled by the use of simulation tools. In fact, the complexity of the hybrid system requires a system-level approach, appropriate models and an efficient optimization algorithm.

IV. Review of Software Tools

In order to optimize the use of several available natural resources 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 [40] has classified these tools into pre-feasibility, sizing, simulation and open architecture research tools. A pre-feasibility tool assists engineers in determining whether a PV system can be used in view of the 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 pre-specified data, such as nature and size of each component, provided by the user. Hybrid2, also developed by NREL, is among this kind of software. As the name suggests, open architecture research tools provide a selection of routines describing components and platforms 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 Mathworks.

In [41], 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										
	Free download and use	PV	Genset	Battery	Wind	Mini-hydro	Fuel cell; electrolyzer and H ₂ tank	Loads	Simulation	Control strategies	Multi-objective optimization (economical and technical)
HOMER	X	X	X	X	X	X	X	X	X	X	X
Hybrid2	X	X	X	X	X		X	X	X	X	
HOGA	X	X	X	X	X	X	X	X	X	X	X
INSEL	X	X	X	X	X			X	X		
ARES	X	X	X	X	X			X	X		

As 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 from the simulation capability commonly used by all tools, some offer control strategies, but only two of them also integrate an economic aspect in the multi-objective optimization apart from the technical one.

V. Target Location and Proposed Hybrid System

Remote villages without access to the national grid in the 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 as mentioned in 2.1 [5, 6] than those of the central and southern parts, due to their geographical locations, which are rather mountainous with scattered villages. In addition, according to the work in [7], Northern provinces have a relatively high sun radiation.

A standalone 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 [6] (75 to 600 kWh/year without and with road access respectively) in typical rural villages in Northern Laos.

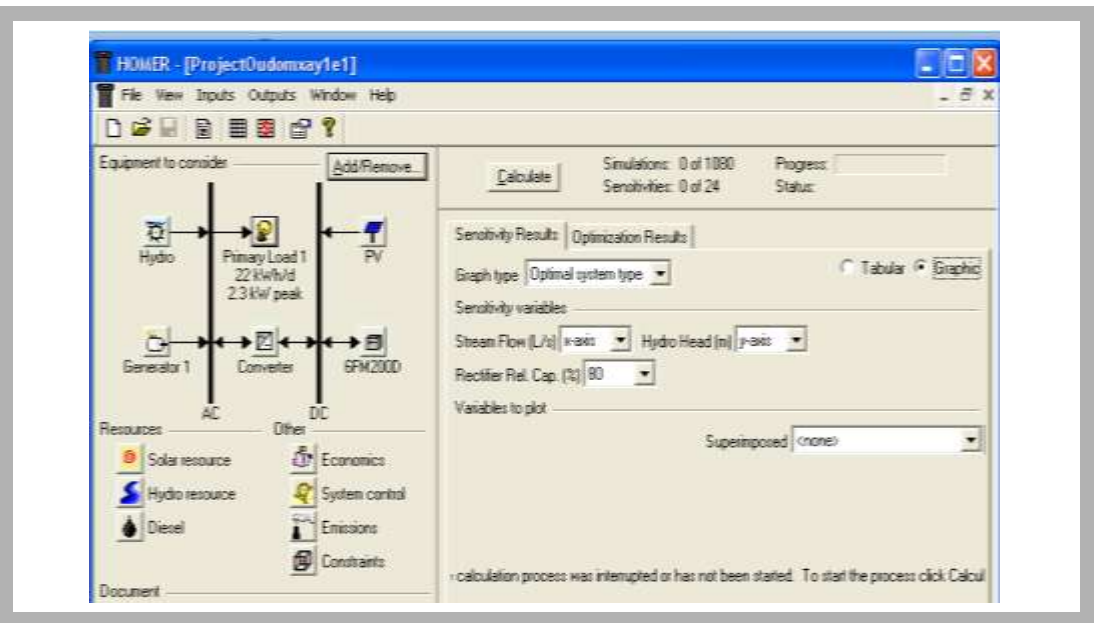
5.1 Suitable Software Tools

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 [42] and HOGA [43] are suitable.

5.1.1 HOMER

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 (Figure 18). The loads can be AC, DC, and/or hydrogen loads, as well as thermal loads. The user must select the components of the model to represent the architecture of his network. For optimization purposes, technical and financial data for each selected component must be entered.

Figure 18
Main configuration panel of HOMER



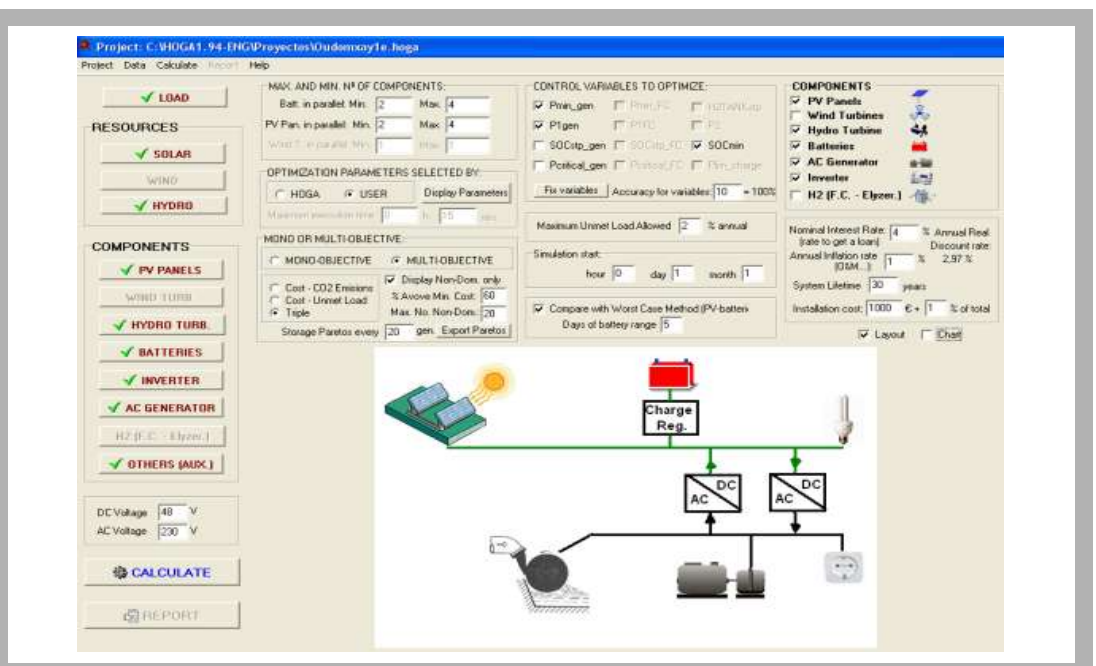
HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, it compares the electric demand in the hour to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the 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 NPC's.

5.1.2 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 is comprised of photovoltaic (PV) panels, wind turbines, hydroelectric turbines, fuel cells, H₂ tanks, and electrolyzers, as well as batteries, battery charge regulators, inverters, rectifiers and AC generators (Figure 19). Different system loads are possible: electric AC, electric DC, hydrogen, and water pumping load.

Figure 19
Main configuration panel of HOGA



The program allows for selling surplus unused AC electricity 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: CO₂ 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 uses of Genetic Algorithms (GA) for optimization, both for the system components (main GA), and for the control strategy (secondary GA). They may produce adequate solutions when applied to highly complex problems [43].

5.2 Case Study and Simulation

As mentioned before, PV panels, a hydroelectric turbine, a backup AC generator and batteries as an electrical energy storing device are used. A location in Northern Laos with the latitude of 20.5° north and 102.5° east is selected. HOMER and HOGA are used as test tools for optimizing a hybrid system in this case study. The corresponding daily solar radiation is depicted in Figure 20. 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.

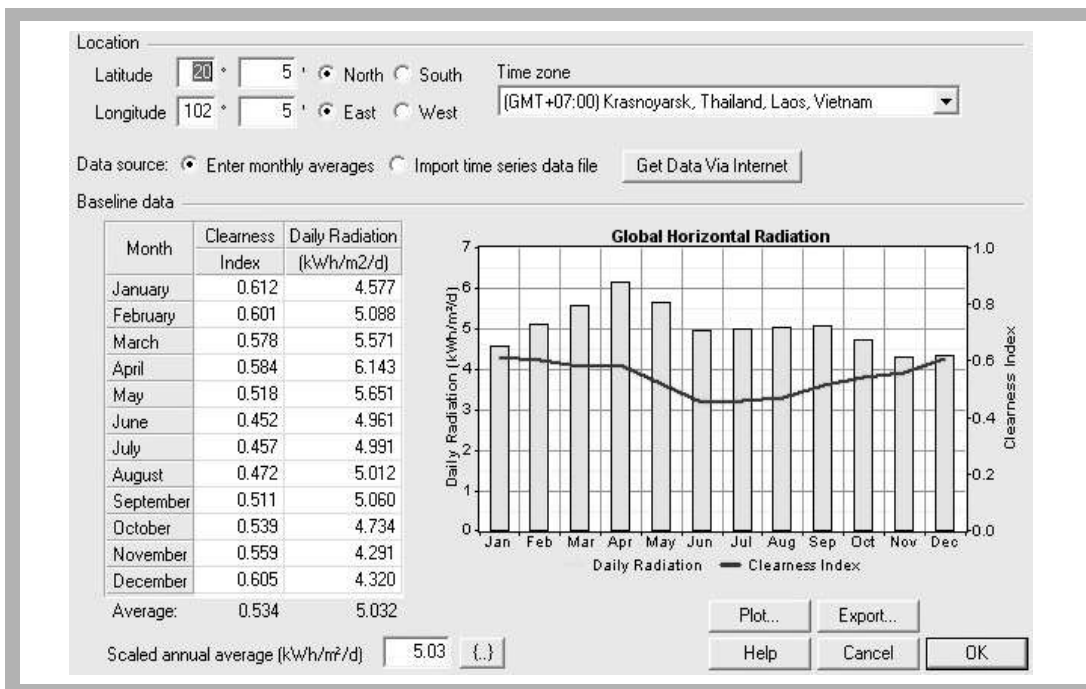


Figure 20
Daily solar radiation
(HOMER)

In both software tools, 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 are 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-year 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,

while HOGA uses the 17 and 18 l/s flow rates and an acquisition cost of €4,500 and 5,500 respectively as 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 CO₂ emission, a CO₂ emission factor of 4.75 KgCO₂/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 costs, 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 can consider many of them. 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. Furthermore, HOMER considers an acquisition cost of €138 and a 200 Ah capacity as fixed parameters, while in HOGA, acquisition costs of €125 and 138 are taken as variable parameters for a capacity of 144 and 200 Ah respectively.

5.3 Results

1st optimization criterion: NPC and CO₂ 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 the NPC well by providing a list of different components sorted by cost and the CO₂ emission (Table 2).

Table 2
Energy balance (NPC-
CO₂ emission)

Software Tools	Unmet Load (kWh/year)	Excess Energy (kWh/year)	CO ₂ Emission (kg/year)	NPC (€)
HOMER	86.0	1,278	1,255	35,005
HOGA	93.8	730	1,507	35,735

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 output, while 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.

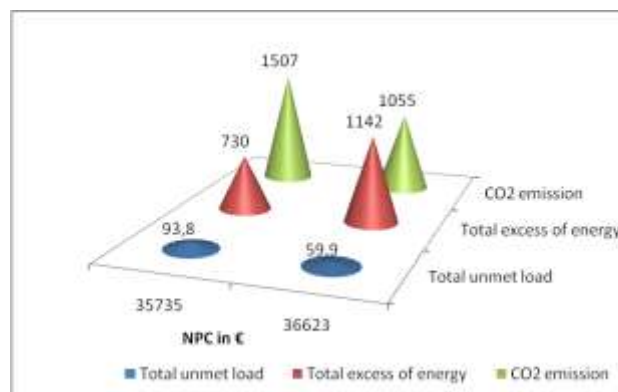
Table 3
PV and battery sizes
(series and parallel)

Software Tools	PV (Series x Parallel)	Batteries (Series x Parallel)
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

We can see from Figure 21 that the unmet load did not change too much since it was not optimized alongside the NPC and CO₂ emission. The CO₂ emission decreased while the energy excess increased.

Figure 21
Graphical representation of NPC-
CO₂ optimization results (using HOGA results)



2nd optimization criterion: NPC, CO₂ emission and unmet load (HOGA only)
The effect of the triple optimization can be seen in Table 4 (HOGA1-1 & HOGA2-1).

	Unmet Load (kWh/year)	Excess Energy (kWh/year)	CO ₂ Emission (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

Table 4
Energy balance (triple optimization)

The unmet load decreased (from 93.8 to 58.5 kWh/year) at the expense of the NPC and the excess energy, while the CO₂ emission was lower.

In keeping the unmet load from further decreasing (to 9.8 kWh/year), the excess energy reduced from 1,179 to 936 kWh/year. However, the CO₂ emission and the NPC kept increasing (Table 3 – HOGA2-1 & HOGA2-2).

Figure 22 graphically summarizes all the changes in the total unmet load, the total excess energy, the CO₂ emission and the total NPC as a result of the triple optimization.

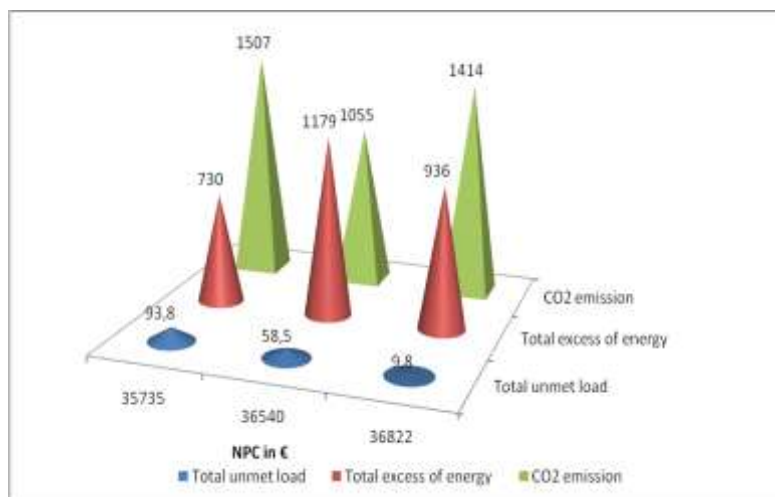


Figure 22
Graphical representation of the triple optimization

VI. Conclusions and Discussions

Although the unmet load could be reduced from 93.8 to 59.9 kWh/year through the NPC-CO₂ optimization, this value is still much higher than 9.8 kWh/year obtained by the triple optimization (Figure 21). It is also observed that the CO₂ emission is reduced, in contrast to the NPC and the excess energy. Through the triple optimization, the unmet load could be heavily reduced from 93.8 to 9.8 kWh/year at the expense of the NPC. The CO₂ emission first reduced and then increased to a value relatively smaller than that of the NPC-CO₂ optimization. In contrast, the total excess energy first increased and then reduced to a value relatively greater than that of the NPC-CO₂ optimization (Figure 22).

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

HOMER and HOGA do not provide much flexibility for the micro-grid configuration. It can be seen from Figure 23 and 24 that the micro-grid could be set up only as the centralized

configuration. This flexible configuration could, however, make significant effects on the safety, adequacy, energy efficiency and expansion of the standalone renewable energy hybrid system.

Figure 23
HOMER Micro-grid
configuration

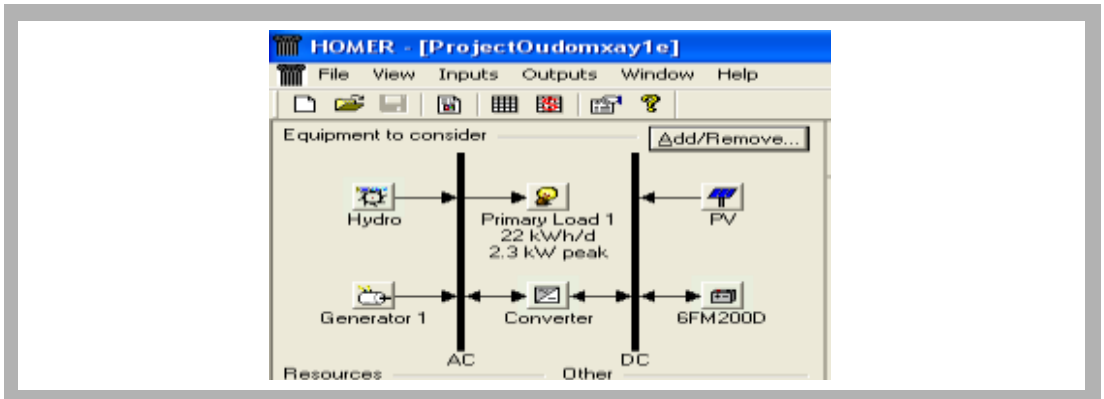
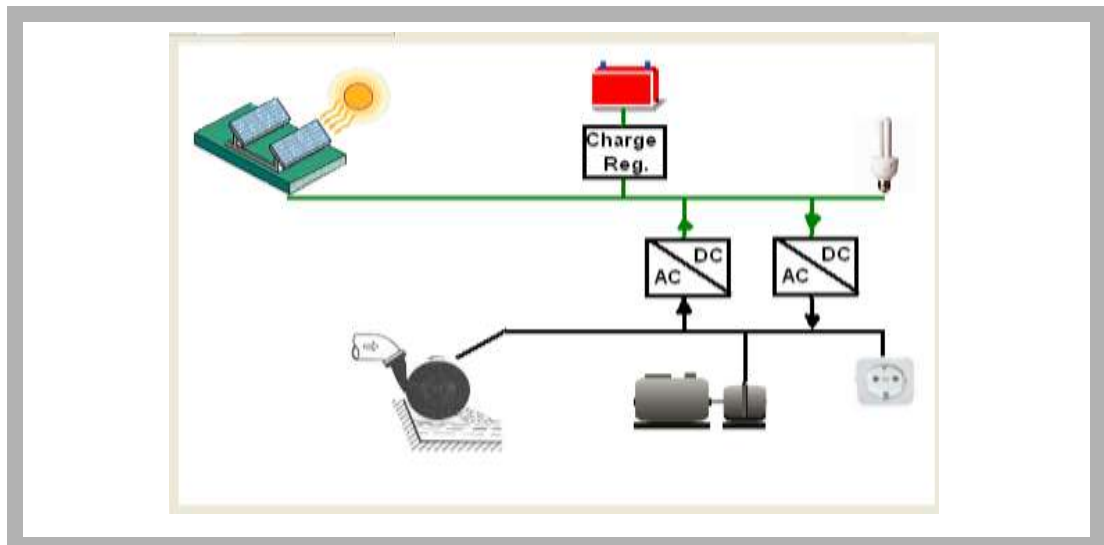


Figure 24
HOGA Micro-grid
configuration



The research work in [44] 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 costs by making provisions 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 [45] has shown that the excess energy could be reduced by increasing the load served while keeping the total NPC constant. However, 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.

Micro-grid configuration and multi objective optimization

Both software tools used for the optimization have not been specifically designed to enable connection flexibility among components making up a hybrid system via power electronics components to the system load (micro-grid). Moreover, the multi-level and-multi domain approaches that are necessary to design and simulate such a complex system require an appropriate combination of suitable components models. Therefore, a combination of simulation, design and optimization tools within open architecture software such as Matlab/Simulink could eventually be used to cope with the multi-objective optimization and the micro-grid configuration of a standalone renewable hybrid system.

Though Laos is still in the infancy of development and implementation of micro-grids, it is, nevertheless, essential for the context of rural electrification in the country to pursue this development and make the implementations and usage happen. Up to now, the off-grid configuration such as the solar home systems and the PV array with a central battery charging station have been the most socio-economic efficient approach used to electrify rural, remote and isolated villages and/or communities in Laos. This scheme will likely be taken further in the future for the rural electrification of the country. However, it is also worth noting that other configurations, namely the DC, pure AC and AC-DC hybrid coupled systems comprising PV, hydro and conventional, or bio-diesel backup gensets will be also of interest to be developed and implemented in Laos as another alternative off-grid means (in addition to the SHS and PV arrays). This approach will be in line with the promotion and development of renewable energy policies of the government from 2007 to 2020. It is also a significant part of the National Poverty Eradication Program issued by the government [5], [6] and [8].

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