# A SIMULATION STUDY ON THE ECONOMIC ASPECTS OF HYBRID ENERGY SYSTEMS FOR REMOTE INDIGENUOS COMMUNITIES IN MEXICO

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**ABSTRACT**
This paper report an investigation on the economic aspects of a typical hybrid energy system for remote communities in Oaxaca, Mexico. In addition to the utilization of renewable energy, the study has based on different electrical load profiles simulating typical usage within a year. The simulation study and the optimization of hybrid energy system are based on a computer program called HOGA, as the simulation tool. From the economic analysis, the capital cost, net present cost and cost of energy are determined for different types of system configuration. Results from the study will be useful to aid business and investment decisions on choosing the most appropriate system for the communities.

## 1. INTRODUCTION

Renewable energies offer important opportunities for applications in regions where conventional energy is still absent, or has only a partial presence. This is particularly useful in the rural sector, among populations with a high level of poverty. The lack of energy in the isolated rural communities constitutes a critical situation, as this associated with the absence of telecommunications, education, health services, and in many cases, drinking water [1].

Although Mexico has a relatively high coverage regarding the provision of electricity (around 95%, ac [illegible]

The Hybrid Renewable Energy System (HES) is a viable alternative solution as comparated to system which rely entirely on hydrocarbon fuel. Apart from the mobility of the systems, it also has longer life cycle[2]. In particular, the integrated approach makes a hybrid system to be the most appropriate for isolated communities as remote communities in Mexico.

A typical hybrid energy system comprises of an electric generator, renewable energy inputs based on photovoltaic (PV) module and/or wind generator, storage battery and a bi-directional inverter. The function of the inverter is to enable the energy to be taken in or out of the battery. So far, the research on hybrid energy systems has concentrated in technical and economical analysis [2]. The decisions to be made are:

Centralized or individuals
System configurations
Component sizing
Expansion potential
Initial and long term cost

Comparison study has been made between a centralized systems supplying to a number of consumers and individual approach. However, the users have preferred the centralized systems because it [illegible] were based on D.C.

## 2.- EXPERIENCIES AND LESSONS LEARNED

Until recently, the only realistic options for rural electrification in Mexico were grid-extension and diesel mini-grids.

Since 1991, eight hybrid systems have been installed in five different Mexican states. The towns are Isla Guadalupe, Ignacio Allende, La Grunidora, El Junco, El Calabazal, Aguas Benditas, X- Calak, and Santa Maria Magdelena. These are inland, coastal, and island sites. These projects are a combination of technical demonstrations and precommercial pilots[3].

The basic system architecture of these installations is as follows:

wind is the primary energy

source modular

systems high DC voltage (120-220VDC)

18-36 hours of storage

AC output simple controls

Four of the installations have a diesel generator backup. All but Isla Guadalupe use PV.

Some information on the wind resource was available from the US National Renewable Energy Laboratory (NREL). The best available information was compiled, but not verified. The one exception was the X-Calak installation, where the wind speed was tested and averaged 6.5 m/s. Unfortunately, the developers found less wind than they expected, and in some sites there is very low (about 4 m/s) wind speed 3 months of the year. [3]

The largest installation is at X-Calak, a remote fishing and tourist village.X-Calak is located in the Mexican Yucatan, across the bay from Chetumal, in the State of Quintana Roo. The village was destroyed by Hurricane Janet in 1952. When the village was rebuilt, a diesel powered minigrid was installed. Diesel operation has often proved problematic for these types of villages, with the high maintenance requirements and fuel supply problems. Power was only available for 4-6 hours during the evening.

Celiac users historically paid a flat monthly fee for electrical service when the diesel was operational. Even with diesel operation, fuel availability was inconsistent and would sometimes be appropriated by the village for the community fishing vessel. Prior to the hybrid system, the typical load consisted of lights, television, and radio, since electricity was only available for a few hours. Village refrigerators and ice makers were previously propane powered. [3]

In 1991 the State of Quintana Roo decided to augment the system with renewable energy and secured funding through Pranosol. CONDUMEX, S.A. de C.V. designed and installed the hybrid. The system is under the care of the CFE, the Mexican national utility, Sandia National Labs (a US government national laboratory), Instituto de Investigaciones Electricas (a Mexican government agency) and Southwest Technology Development Institute (located at New Mexico State University) provided consulting services. The system began operation in August 1992.

The system includes a 11.2 kW photovoltaic array, six 10 kW wind turbines, 1738 Ah of 220-volt GNB 6-7C23 deep-cycle flooded lead-acid batteries, a 40 kW AES sine wave inverter, and a 125 kW SELMEC diesel generator. It cost$750,000 and serves approximately 300 people.[4 ]This amounts to $25,000 per person for electricity, plus continuing operation and maintenance expenses. Without the 35% import duty on the equipment, the total cost would have been $565,000, or $18,833 per person. The diesel generator was the one already on-site. However, it was inoperative until mid-1995. Even now, the back-up generator is used infrequently due to high operating costs. The system was designed to supply 150 kWh/day during the low wind months. The output of the system is 220 VAC-3phase and is stepped up to 2400VAC-3 phase for distribution. The village load can be disconnected from the automated PV/Wind generator and connected to the diesel generator with a manual switch.

The system has worked well technically, though a few electronics problems have occurred and one wind turbine alternator was damaged in 1993 due to a wiring fault. Salt corrosion has also been a problem. The system is performing better than expected, but, unfortunately, the wind/solar generators can not satisfy the current local demand because consumption has grown to more than three times the original projection. The higher electrical demand is at least partly the result of the fact that the villagers are not currently charged for electricity. Also, the distribution wiring in the town is in poor shape.[ 4 ]

Electricity is typically available 8-16 hours a day, depending primarily on the wind resources. This is a significant improvement from the previous system’s 4-6 evening hours. Wind power provides ~85% of the generated electricity. The PV panels provide the rest. In October, when there is the least amount of wind, 140 kWh/day is provided to the village. In the high wind months, an average of 240 kWh/day is provided. A number of institutional and technical improvements (including more wind generators) are under consideration [4 ].

The system is extensively instrumented and is being monitored by the U.S.National Renewable Energy Laboratory and Sandia Labs to learn more about the real world performance of village hybrid systems. Sandia National Laboratory , Instituto de Investigaciones Electricas, Southwest Technology Development Institute, and CONDUMEX installed a data acquisition system in March 1993 to monitor performance of the wind/pv/diesel village hybrid power system. Average hourly data is recorded via cellular phone.

A typical decentralized hybrid energy system integrates PV modules, wind generator, diesel generator (s), battery bank and inverter. The main objective is to provide 24 hours grid quality AC power in remote communities. In general, there are different types of configuration, the parallel, series and switched mode. The parallel hybrid systems has more advantages than the series and switched modes of hybrid systems. It is able to meet optimal system loading, maximize the generator efficiency and minimize the generator maintenance requirements. In addition, by incorporating appropriate power conditioning and control algorithm, the hybrid system may be expected to provide a near optimal load on the diesel generator, extract maximum PV power, reduce peak capacities of diesel generator and inverter, and increase the overall capacity of system [2].

In this study, it is aimed to investigate a full range of conventional and renewable options for the generation and supply of electricity energy using analytical tools. The results of this study will lead to planning and design of the final system on the communities.

The problem to solve has a great number of possible solutions (combinations of solar and wind generator, batteries, Diesel generator and strategy variables), for this reason it is difficult to solve this problem with classical mathematical techniques (for example with mixed-integer programming). [5]

## 3. DEVELOPED ALGORITHM

The genetic Algorithms (GA) technique works with individuals (possible solutions). An individual can be represented by a vector whose components represent the parameters of the system using an integer code. The GA developed in HOGA is divided in two parts: main and secondary algorithm. [5]

### 3.1 Main algorithm

Main Algorithm works with an integer vector with the number of PV panels in parallel (a), the solar generator type code (PV panel)(b), the wind generator (c), the battery type code (d), the numbers of batteries in parallel (e), and the diesel generator type code (f): $|a||b||c||d||e||f|$ .[5]

Each solar generator is from a different manufacturer and their characteristics are: power, voltage, $I_{max}$ and acquisition cost.

Each battery is from a different manufacture and their characteristics are: rated capacity, voltage, acquisition cost, $DOD_{max}$ number of equivalent cycles and efficiency.

Each Diesel generator is from a different manufacturer and their characteristics are: power, voltage, acquisition cost, lifespan, minim output power, and O&M hourly cost.

The algorithm simultaneously uses $N_m$ vectors such as the one described beforehand.

The main algorithm obtains the optimal configuration of PV panels, wind generators, batteries and diesel generator, minimizing the Total Net Cost of the system ($C_{tot}$), which includes all the cost throughout the useful lifetime of the system, which are translated to the initial moment of the investment using the effective interest rate, according to standard economical procedures. [5]

$$C_{TOT} = C_{SEC} + C_{ACQ\_PV} + C_{ACQ\_WGEN} + C_{ACQ\_B} + C_{ACQ\_BCH} + C_{ACQ\_GEN} + C_{REP\_BCH} + C_{O\&M\_PV} + C_{O\&M\_WGEN} + C_{O\&MM\_B}$$

where,

$C_{sec}$ includes the cost that depend on the optimal strategy. It is evaluated in the secondary algorithm.

$C_{ACQ\_PV}$, $C_{ACQ\_WGEN}$, $C_{ACQ\_B}$, $C_{ACQ\_GEN}$ are the cost of the acquisition of the PV panels, the wind generator, the batteries, the battery charger and the Diesel generator.

$C_{REP\_BCH}$ is the cost of replacing the battery charger throughout the life of the system (it does not depend on the strategy because we assume it has fixed initial cost and life).

$C_{O\&M\_PV}$, $C_{O\&M\_WGEN}$, $C_{O\&M\_B}$ are, respectively, the cost of maintenance of the PV panels and the batteries (they do not depend on the strategy).

$C_{TOT}$ must be calculated for each combinations, represented by one of the $N_m$ vectors which constitute the population.

The fitness function of the combination *i* of the main algorithm is assigned according to is rank in the population (rank 1 for the best individual considering the objective function, and rank $N_m$ for the worst solution): [5]

$$fitness_{MAIN_i} = \frac{(N_m + 1) - i}{\sum_j [(N_m + 1) - j]} \quad j = 1 \ldots\ldots N_m$$

### 3.2 Secondary Algorithm

The secondary algorithm works with a Boolean vector with the dispatch strategies (Cycle charging or Combined), the "Frugal" option, and 5 bits that represent the SOC set point in Gray code (better than binary code for GA): $|g_0|g_1|g_2|g_3|g_4|$ .[5]

The load Following strategy is evaluated at the end, as this strategy has no *SOC* set point.

The algorithm use $N_{sec}$ vectors such as the one previously described.
For each vector of the main algorithm, the optimal strategy is obtained (minimizing the non-initial costs, including operation and maintenance costs, $C_{SEC}$) by means of the secondary algorithm.

$$C_{SEC} = C_{ACQ\_INV} + C_{ACQ\_REG} + C_{REP\_B} + C_{REP\_INV} + C_{REP\_REG} + C_{REP\_GEN} + C_{O\&M\_GEN} + C_{FUEL}$$

where,

$C_{ACQ\_INV}$, $C_{ACQ\_REG}$ are the acquisition cost of the inverter and the charger regulator respectively (the inverter maximum power and the charge regulator current depend on the strategy, so their cost must be here) [5].

$C_{REP\_B}$ , $C_{REP\_INV}$ , $C_{REP\_REG}$ , $C_{REP\_GEN}$ are the cost of replacing the batteries, the inverter, the charge regulator and the Diesel generator throughout the life of the system.

$C_{O\&M\_GEN}$ is the cost of operation and maintenance of the Diesel generator throughout the life of the system.

$C_{FUEL}$ is the cost of the fuel consumed throughout the life of the system.

We assume that the system life of the PV panels which are the elements that have a greater lifetime.

The fitness function of the combination *i* of the secondary algorithm is:

$$fitness_{SEC_i} = \frac{(N_{SEC} + 1) - i}{\sum_j [(N_{SEC} + 1) - j]}; \; j = 1 \ldots\ldots N_{SEC}$$

## 4. CASE STUDY

The information on the case study is based on electrification of rural communities in countries of the thirty world [6].

This community is located in southern of Oaxaca, at 96 deg 30 min longitud oeste and 16 deg 13 min north latitude at a distance 110 km from the Oaxaca City [5]. At presents, there are about 100 residents living in about 40 houses, The increase in the resident population is expected to be 5% per annum. The electrical load demand is assumed to be approximately 4.094 kWh/day. His charge is constituted for 40 houses, one school ,one rural health center and a little store of basic products.

In this study, the electrical appliances on the communities is assumed to consist of the basic electrical load equipments such as 10 W, 20 W fluorescents lamps, 40 W – 200 W television sets, 10 W radio, 4 kW frigorific domestic and fan [6]. Furthermore, the load profile for a whole day is shown in Fig 1.

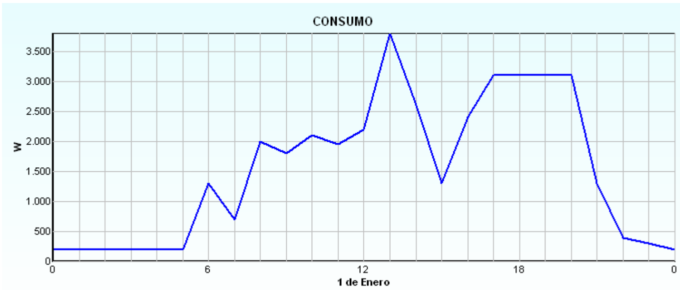

Fig 1.Electrical load demand for a whole year.

According studies makes for NREL in southern Oaxaca, high resource areas are located approximately 80-110 km south of Oaxaca City near the town of Miahuatlán. The northeast winds appear to accelerate over the relatively low ridges to the south and west of Miahuatlán as they are diverted around the western end of high mountains in the Sierra Madre del Sur, and de average wind speed is roughly 7.0 m/s, fig 1. [7].

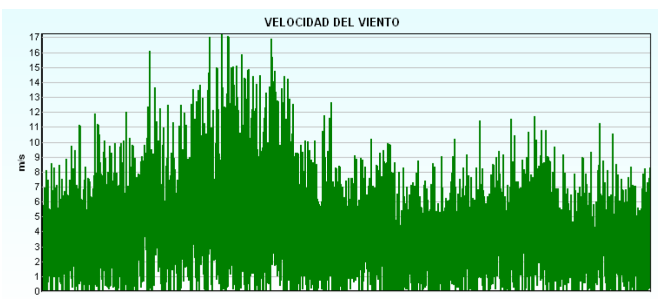

Fig 2. annual average wind speed

The simulation on the economic aspects of the proposed hybrid systems is based on a simulation software called HOGA [6], this program using Genetic Algorithms. This program calculates the optimal configuration of the system. This optimal configuration is describe very precisely: the number of PV panels and the type of panels, the number of batteries and the type of battery, the inverter power, the Diesel generator power, the optimal control strategy of the system with its parameters, the Total Net Present Value[1] of the system and the different relative costs such as the fuel cost, and finally, the number of running hours for the Diesel generator per year. The program also optimizes the dispatch strategy, as does HOMER, but it also optimizes the SOC set point, that is an important variable [5].

The architecture of the software is divided in to three parts as shown in the fig. 3. Inputs to be provided to the systems are:

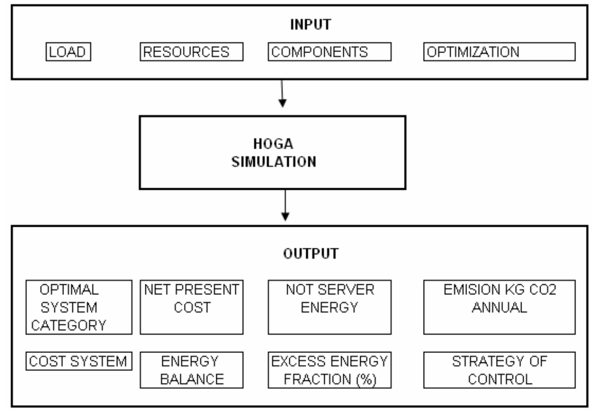

Fig 3. Architecture of the Simulation and Optimization modules.

In this study, the model has considered all the possible energy resources for the purpose of optimization. In terms of the component cost for the PV, Wind turbine, Diesel, Battery and Inverted, they are based on a study from the International Centre for application of solar Energy (CASE) made in 2001 [8].

## 5. SIMULATION RESULTS AN DISCUSSION

The results for HOGA have been obtained with the following values: Main algorithm Generations are 100. Main algorithm population is 50. Secondary Algorithm generation is 5 and population is 20. So the number of combinations examined is: 100*50*5*20=500.000. The total cases evaluated are 94.104. The optimisation has taken 1 hour 47 minutes and 350 seconds, the simulation results are shown in Table 1.

Six cases of hybrid systems have been considered. The first case is shown in the first row of table has the lowest Net Present Cost (NPC). A comparison is made between the five types of hybrid system based on NPC, fuel consumption, battery life and generator life. It is observed that PV/Wind/Diesel/Battery/Inverter combination is the most economical approach. This is illustrated in the first in the first row. According to the study, the first case also shows a longer battery and generator life span. An example of PV/ Wind/ Diesel/ Battery/ Inverter configuration is shown in Fig.4.

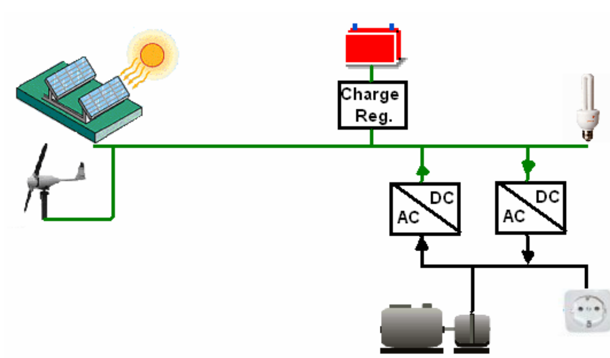

Fig 4. PV/Wind/Diesel hybrid systems.

[1] Cost f the investments plus the discounted present values of all future cost.

In terms of fuel saving, again, the first system as shown in the first row of Table 1 is the most economical. Since the renewable energy resources (PV and Wind) are meeting the load demands almost constantly, the smallest size (3 kWA) diesel generator will be sufficient. This leads to a substantial saving in the maintenance requirements. The least economical system is the stand-alone Diesel generator system as it has to be run all the time in order to meet the load demand constantly. As the generators are not loaded to their optimal operational conditions, they consumes higher fuel consumption than the others. The generator life- span of the system is also much shorter.

Consequently, the PV/W/D hybrid system having emission of 175 kgCO2/year. According to the system has enough power to supply electrical load demand on daytime by using PV, wind energy while on the night time load consumption can reach the power from diesel generator and battery. We can see that it has three resources of energy to supply the load demand; therefore, battery has not to supply the high load for a long period of time so it makes extension of the battery life.

On the other hand, the mot expensive system is the stand-alone diesel generator because it has the highest replacement and fuel cost. It need to replace the generator once every three years while the hybrid renewable energy needs to replace the generator only once every six years. So, the stand alone system will cost more than it is necessary.

Fig 5 shows the cost of the different elements of the system optimised by HOGA, for this load configuration as a percentage of the Total Net Present Cost. The auxiliary elements (Charge Regulator, Inverter, Battery Charge and Other) only cost 13.37 % of the Total Net Present Cost of the system. Although the PV, Wind generator and Batteries (acquisition and replacing) is a 15,76 %, 40,52%, 23,09 %. Cost Diesel generator and fuel plus the operation and maintenance is only 4,86% of the Total Cost System.

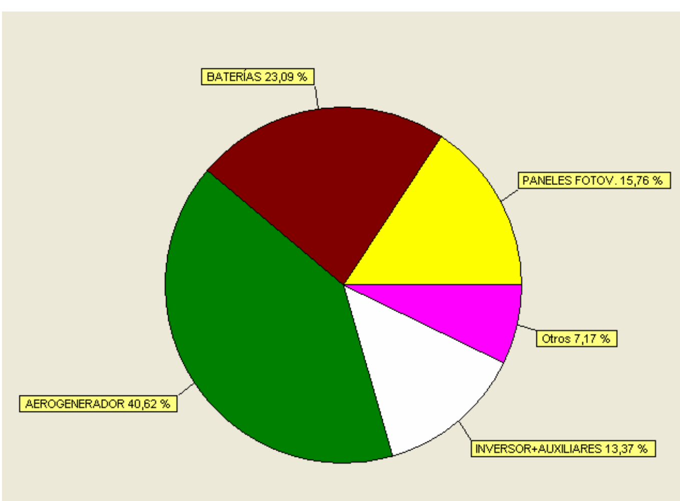


Fig 5. Cost of the different elements, in percentage of the Total Net Present Cost.

In fig 6. shows the evolution of the Emissions CO2 of the best combination found versus of Total Net Present Cost found with HOGA as a function of the main algorithm generations in a optimisation (multi objective optimization) , where the number of generations in the main algorithm is 100 with a 94.104 total evaluated cases.

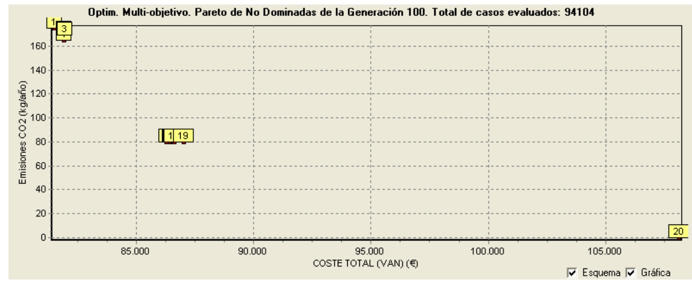


fig 6. Emissions CO2 versus Total Net Present Cost.

## 6. CONCLUSION

In this paper, the economic aspects of the use of a hybrid energy system on remote Mexican communities is investigated. In this study, Six types of configuration of hybrid systems have been simulated. It was found that the most economical systems to meet the load demand in a whole day, is Wind/Diesel/Battery/Inverted system. It is found that the system is managed to supply a total load of 14.946 kWh/day. The cost of energy at 0.55 $/kWh is the lowest among the cases simulated. However, the optimum power system is the PV/Wind/Diesel/Battery/Inverter combination. The sizes of the components are recommended to be at size 2,88 kW, 19.5 kW, 3 kWA 56,6 kWh and 4.500 kA respectively. This configuration has the lowest capital cost, fuel cost and the components replacement cost. The results from the simulation exercise will be a useful tool to aid decision in the capital investment for the communities of Mexico.

HOGA gives the best solution of all possible combinations, finding the best solution with the help of GA. The Adventage of HOGA is the precision: it gives the number of PV panels and its type, and the number of batteries in parallel and their type.

In Mexico, the promotion of renewable energies is top priority. Reaching the mentioned set of incentives and modifications to the legal and regulatory framework, aim to assure the economic viability of projects currently in the construction stage, or already in operation, and foster the development of new projects to increase the use of renewable energy resources.

The aforementioned actions form part of a national strategy which will allow us to advance the pursuance of the compromise acquired by the Government of Mexico, of granting to the future generations, a country with economic growth that accounts for the long-term social and environmental variables, and allows to continue its path towards a sustainable development.

| N° | C. total (VAN) (€) | Emissions (kgCO2/año) | PV (kWp) | Batt (kWh) | Gen (kW) | Die (kWA) | Inv (kA) | Batt_Regulator (A) | Conversor AC/CD (W) | Excess energy kWh/año | worker¨s hours Die (hr/year) | Batt Life (years) | Cost of energy (€/kWh) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 81533 | 175 | 2,88 | 56,6 | 19,5 | 3 | 4500 | 403,6 | 2300 | 19315 | 88 | 10,27 | 0,55 |
| 2 | 81947 | 170 | 2,88 | 36,8 | 19,5 | 3 | 4500 | 403,6 | 2160 | 19319 | 72 | 10,11 | 0,55 |
| 3 | 81956 | 169 | 2,88 | 36,8 | 19,5 | 3 | 4500 | 403,6 | 2256 | 19317 | 72 | 10,11 | 0,55 |
| 4 | 81952 | 165 | 2,88 | 36,8 | 19,5 | 3 | 4500 | 403,6 | 2300 | 19317 | 68 | 10,06 | 0,55 |
| 5 | 87016 | 80 | 2,88 | 57,6 | 19,5 | 3 | 4500 | 403,6 | 2300 | 19194 | 33 | 12 | 0,58 |
| 6 | 108113 | 0 | 2,88 | 64,5 | 32,5 | 1,9 | 4500 | 671,8 | 92 | 41475 | 1 | 12 | 0,72 |

Table 1. System size for 24 hours load profile

**REFERENCES**


[ 1 ]Department of Energy Mexico, Renewable Energies in Mexico, Mexico 2003.

[ 2 ]Chun Che FUNG, A simulation study on the economic aspects of hybrid energy systems for remote islands in Thailand, report in investigation in Renewable Energy 2002 IEEE.

[ 3 ] ASME Wind Energy Symposium, California USA, 2000.

[ 4 ] "First-Year Monitoring Results of the Wind/PV Hybrid Power System in Xcalak, Quintana Roo, Mexico" Proceedings, Wind Power 1994, p. 716.

[ 5 ]Rodolfo Dufo -Lopez , Design and Control Strategies of PV-Diesel Systems Using Genetic Algorithms, Department of Electrical Engineering, University of Zaragoza, Spain. 2004

[ 6 ]Ruiz Guillen, Javier, Renewable energies for rural electrification in countries on way developed. EHN, Chile. 2004

[ 7 ]D. Ellliott, Wind Energy Resource Atlas of Oaxaca, National Renewable Energy Laboratory NREL. USA 2003.

[ 8 ]The International Centre for Application of Solar Energy (CASE), The feasibility study on renewable energy systems for island electrification in Thailand. May 2001