MULTI-OBJECTIVE DESIGN OPTIMIZATION OF A HYBRID PV-WIND-BATTERY SYSTEM

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Abstract - Stand alone hybrid renewable energy systems are more reliable than a system with a single source of energy. However, its design is a crucial issue. In this context, we propose a triple Multi-Objective design, minimizing, simultaneously, Life Cycle Cost (LCC), Embodied Energy (EE) and Loss of Power Supply Probability (LPSP). Optimization has been insured by a dynamic model of the system under Matlab/Simulink and using a controlled elitist genetic algorithm. Results indicate that proposed method, through its multitude Pareto front solutions, will help designers to take into consideration environmental impact of such systems.

Keywords – hybrid system, multi-objective design optimization, dynamic simulation, Cost minimization, Loss of Power Supply Probability, Embodied Energy.

1. INTRODUCTION

Energy from renewable sources is being considered as an important alternative in the electrical power systems around the world. Among renewable power sources, wind and solar have recognized a remarkably rapid growth in the past ten years. Additionally, they generate power close to local consumption; hence reducing impacts from high voltage transmission lines through rural and urban landscapes. However, neither a stand alone solar nor a wind energy system can provide a continuous supply of energy due to seasonal and periodical variations. Therefore, in order to satisfy the load demand, it is more reliable and efficient to install hybrid energy systems. Photovoltaic panels are often combined with wind turbines or diesel generators and storage batteries. Before developing such hybrid electric system, it is essential to find the optimal configuration of the different generators considering consumer energy demand and available resources on the site. In this context, simulation and optimization of stand-alone hybrid renewable energy systems has been carried out by a number of researchers and studies [1].

Borowy and Salameh [2] explicit a method to optimize the size of the PV generator and the capacity of the batteries in PV-Wind-Battery systems. They tried to achieve the desired unmet load by modifying the number of photovoltaic panels and batteries. Wind turbine, type of panel and battery technology are fixed. As there is more than one technically feasible solution, they select the one with the lowest cost.

Yang et al. [3, 4] present a method for the optimization of hybrid PV-wind-Battery systems that minimizes the Levelized Cost of Energy (LCE). The optimization is made by trying components' combinations changing number and orientation of PV modules, rated power and tower height of the wind turbine, and the battery bank capacity. Diaf et al. [5, 6] made the optimization of a hybrid PV-Wind-Battery system in different locations in Corsica in France. Their optimization procedure takes on consideration Loss of Power Supply Probability (LPSP) and Levelized Cost of Energy (LCE).

In 2007, Jun-hai SHI et Al. [7] proposed a robust design method for an autonomous PV-wind hybrid power system to obtain an optimum system configuration insensitive to design variable variations. It was based on a constraint multi-objective optimization problem, which is solved by a multi-objective genetic algorithm, NSGA-II.

Rodolfo Dufo-López, José L. and Bernal-Agustín [8] have applied, for the first time, the Strength Pareto Evolutionary Algorithm to the Multi-Objective design of PV-Wind-Diesel-Hydrogen-Battery systems, minimising, simultaneously, three objectives: cost, pollutant emissions and unmet load.

Our contribution log on this context. It deals with a multi-objective design methodology for a hybrid wind-PV-Battery system. It differs from other studies on:

- models and computational method as optimization has been carried out using a dynamic model of the system under Matlab/Simulink,
- Optimization objectives considering a new approach based on Embodied Energy (energy required by all of the activities associated to a production process) in addition with Life Cycle Cost (LCC) and Loss of Power Supply Probability (LPSP).

Thus, our paper starts by showing data: sources and load profiles. Then, system models are described. Next, optimization objectives and computational method are explained. Finally, results and conclusions are presented.

2. REQUİRED DATA : SOURCES AND LOAD PROFİLE

In this study, we use half-hourly data from 2002 to 2009 available on the National Wind Technology Center- Colorado (Latitude: 39° North, Longitude: 105° West, Elevation: 1855 meters) web site [9]. Renewable energy potentials are given for each year in the table below. They are calculated using numerical integration of the power [10].

I. RENEWABLE ENERGY POTENTIALS OF THE NATIONAL WIND TECHNOLOGY CENTER, COLORADO

Year	Photovoltaic Potential (Kwh/year/m²)	Exploitable* wind Potential (Kwh/year/m²)	Total Renewable energy potential (Kwh/year/m²)
2009	1608	1077	2685
2008	1682	1336	3018
2007	1644	1111	2755
2006	1694	1306	3000
2005	1650	948.1	2598.1
2004	1629	906.5	2535.5
2003	1636	1109	2745
2002	1702	922.7	2624.7

* Calculated using wind data speed between 3.5 m/s and 25 m/s

According to this table, photovoltaic potential is prevailing wind potential. Therefore, for the optimization procedure, data of the year 2009 with the lowest photovoltaic potential will be used. Experiments have shown that this choice will increase the probability that design meets optimization criteria for all years, especially in terms of unmet load.
Concerning electricity needs, we use real consumption data which were acquired in a typical home of 4 occupants, outside cooking, heating and hot water. Averaging acquisition period is half an hour to be in adequacy with energy resources. Data correspond to a weekday and a weekend day. These days are reproduced for the whole year.

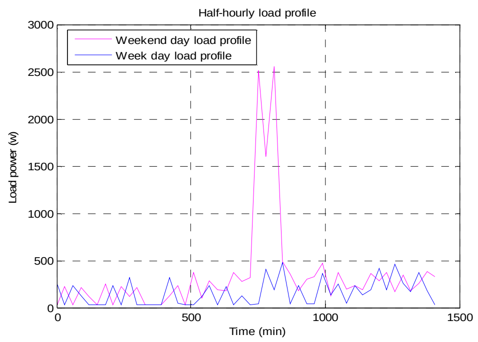

Fig.1. Half-hourly load profile

During a week day, the family consumes 3.787 kWh/day with a maximum detected power of 478.6 W. During a weekend day, electricity needs increase due to household tasks (washing machine, dishwasher, etc.). The daily consumption then reaches 8.32Kwh/day with a maximum power up to 2560 W.
By reproducing these profiles over the year, annual consumption of the residence is estimated at 1898 Kwh/year.

3. HYBRİD SYSTEM MODELS

3.1. WİND TURBİNE MODEL

Since most home-sized wind turbines tend to operate towards same efficiency, rotor diameter or swept area rather than generator size makes far better criteria for comparing various models offered by different manufacturers. For this reason, we have chosen the swept area (*Awt*) as decision variable for wind turbine sizing. Consequently, electrical power output of a wind generator is given as follows [11]:

$$Pwg = Cp \cdot \eta gb \cdot \eta g \cdot \frac{1}{2} \cdot \rho A V^3 = \eta t . \frac{1}{2} \cdot \rho .(Awt).V^3 \quad (1)$$

With: ρ [Kg/m3] = Air density $= \dfrac{353.049}{T} e^{(-0.034\frac{Z}{T})}$

Z [m] represents elevation and T [°C] temperature,

V [m/s] : Wind speed,
Awt [m²] : Wind turbine swept area,

$Cp = \dfrac{Pex}{Pw}$: Turbine efficiency,

$\eta gb = \dfrac{Pg}{Pex}$: Gearbox efficiency,

$\eta g = \dfrac{Pe}{Pg}$: Generator efficiency,

As most wind turbines available today are three-bladed horizontal axis, we have considered for our study this type with an overall efficiency factor $\eta t = 35$ %.

3.2. PHOTOVOLTAİC GENERATOR MODEL

Output power of the photovoltaic generator is given by the following equation [12]:

$$Ppv = \eta g \cdot Apv \cdot Ir \quad (2)$$

Where
ηg: power conversion efficiency of the module (power output from system divided by power input from sun)
Apv [m²]: surface area of PV panels
Ir [W/m²]: solar radiance.
PV generator efficiency is given by [13]:

$$\eta g = \eta r \cdot \eta pc \cdot [1 - \beta (Tc - TNOCT)] \quad (3)$$

with:
ηr: reference module efficiency; it depends on cell material. For our study, we have chosen polycrystalline silicon technology with 13% of efficiency.
ηpc: power conditioning efficiency which takes into account weather uncertainty, uncorrected modules' inclination depending on season, and operating point of the modules which is rarely optimal and can be aggravated by lower module characteristics or loss of module efficiency over time (aging and dust deposit). ηpc is equal to 0.9,
β: generator efficiency temperature coefficient,

ranging from 0.004 to 0.006 per °C.
Tc: cell temperature (°C). For a PV module of polycrystalline silicon solar cells, it can be estimated from the ambient temperature Ta (°C) and the solar irradiation Ir as follows [14]:

Tc=30+0.0175(Ir-300)+1.14(Ta-25) (4)

TNOCT is the normal operating cell temperature (°C) at which cells operate under standard operating conditions: irradiance of 800 W/m2, 20ºC ambient temperature, average wind speed of 1 m/s, module in an electrically open circuit state, wind oriented parallel to array's plane, and all sides of the array fully exposed to wind.
After consulting data of several different polycrystalline silicon modules (such as Evergreen ES-A210 or Trina Solar TSM-PA05), we have considered a typical value of TNOC equal to 45°C and a typical value of β approximated to 0.0045 per °C .

3.3. BATTERY STORAGE MODEL

Most batteries used are lead-acid type in hybrid systems. A simple model is shown in figure 2. It consists of an ideal battery with open-circuit Voltage Vo, a constant equivalent internal resistance Rbat and terminal voltage Vbat.

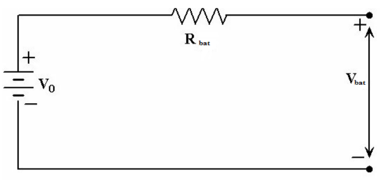

Fig.2. Ideal Lead-acid battery model

SOC of the battery bank is subject to the following constraints:

SOCmin=<SOC(t)<=SOCmax (5)

where SOCmax and SOCmin are the maximum and minimum allowable storage capacities.
SOCmax corresponds to the nominal capacity of the battery bank, Cn:

$$Cn=(\frac{Nbat}{Nbats})\cdot Cbat \qquad (6)$$

where
Nbat = total number of batteries
Nbats = number of batteries connected in series
Cbat [Ah] = nominal capacity of each battery.
SOCmin corresponds to the lower limit that battery bank does not have to exceed when discharging. It is determined by the maximum allowable battery Depth of Discharge (DOD) as follows:

$$SOC\min=(1-DOD)\cdot SOC\max \qquad (7)$$

Batteries are connected in series to reach the DC nominal required voltage (48V) and are connected in parallel to obtain the desired Ah system storage capacity. Equation (8) presents how to calculate the number of batteries to be connected in series using the DC bus nominal voltage and the nominal voltage of each individual battery Vbat:

Nbats = Ubus/Vbat (8)

Batteries' charging or discharging is controlled considering the difference between resources production (Pres) and load consumption (Pload). A switcher manages electrical energy so that the battery bank is connected only in two cases:
* If batteries' state of charge is below SOCmax (100 %) and Pload <Pres, the excess of energy [(Pres-Pload).Δt] is stored in batteries. Δt corresponds to the period of this excess state.
* If batteries' state of charge is above SOCmin (20%) and Pload> Pres, energy previously stored is used to support lack of energy [(Pload-Pres).Δt]. In this case, Δt corresponds to the period of this unmet load situation.
In our study, the design variable that needs optimization is total storage capacity of the battery bank Cn (Ah).

4. MULTİ-OBJECTİVE OPTİMİZATİON PROCEDURE

4.1. OBJECTİVES :DESİGN AND EVALUATİON CRİTERİA

We wish to design a stand alone hybrid system that meets demand with a low Life Cycle Cost (LCC) and environmental impact in terms of Embodied Energy (EE). Therefore, design and evaluation criteria are as follows:

a. Reliability : minimizing Loss of Power Supply Probability (LPSP)

Due to intermittent nature of renewable sources, power system reliability has been considered as an important step in hybrid system design process. In our case, reliability has been expressed in terms of Loss of Power Supply Probability (LPSP). It is equal to the ratio of all energy deficits divided by the total load demand during considered period. It can be defined as [15]:

$$LPSP(t)=\frac{\sum_{t=1}^{T}DE(t)}{\sum_{t=1}^{T}Pload(t)\Delta t} \qquad (9)$$

Where DE (t) corresponds to the deficit energy at time t. Such a consideration is required when total energy available in an interval time [(t-1), t] and energy stored at (t-1) are insufficient to satisfy the load demand.
One of the objectives of the optimization procedure is to find combinations between elements that give a LPSP lower than the maximum allowed by the user.

b. Cost considerations : minimizing system Life Cycle Cost (LCC)

Another optimization objective is total Life Cycle Cost (LCC) minimization. LCC is calculated knowing components' value at present moment.
Present worth of an item, is calculated as follows [16]: $PW=(\Pr)\cdot Co$ (10)

where Co is component cost and Pr represents present value factor of an item that will be purchased n years later, and is given by equation (11):

$$\Pr(n)=(\frac{1+i}{1+d})^{n}=x^{n} \qquad (11)$$

where i and d represent respectively inflation and discount rate.

The life cycle cost is then given by:

$$LCC = Co + Cinst + PWmaintenance + PWreplacement \quad (12)$$

with : Cinst is the installation cost; PWmaintenance is the present value of maintenance cost determined as follows:

$$PWmaintenance = (maintenance cost) \cdot x \cdot \frac{1-x^n}{1-x} \quad (13)$$

and PWreplacement is the present value of the component taking in consideration periodical replacement.

In our case, we assume that price of the turbine relative to the area swept by its rotor is a good measure. This consideration is helpful because not subject to vagaries from power rating or size of wind turbine's generator. That is why, based on different references [17] [18], we have approximated LCC of wind turbines by a function of their swept area (*Awt*):

$$WT\_LCC\ (\$/m^2) = 1877.5 * Awt + 4712 \quad (14)$$

Calculations assume that total wind turbine initial cost is composed of about 55 percent for turbine and tower purchasing, 25% for installation and 20% for "Balance-of-system (BOS)" costs [19]. Current costs just concern yearly maintenance and represent about 2.5% of the whole initial investment cost.

For photovoltaic panels, according to a specialized website [20], we have assumed a purchasing price of 352$/m² that represents 50 percent of initial investment cost. The remaining 50 percent is divided between BOS (30%) and installation (20%). Moreover, yearly photovoltaic panels' maintenance represents about 2% of the whole initial investment cost. Thus, the LCC of one m² of solar panels is estimated at **942 $/m².**

About batteries, we have chosen lead acid technology for cost and performance reasons. Its purchase price is estimated at 175$/kWh [21]. Thus, considering replacement every five years, a LCC of **729 $ / kWh** is evaluated.

All LCCs estimations are based on a discount rate of 5%, an inflation rate of 3% and a lifetime of 25 years.

c. Environmental impact considerations : minimizing system Embodied Energy (EE)

In order to reduce environmental impact, embodied energy (energy required by all of the activities associated to a production process, expressed in MJ or Kwh) must be minimized. For photovoltaic panels, batteries, and additional components (BOS), data and assumptions are based on Tom Markvart and Luis Castañer book [22]. There are summarized in table II.

For wind turbines, data are not available in the literature, particularly for small ones; for this reason, we have conducted our own analysis [23]. In fact, Results are presented in table III.

II. ASSUMPTIONS AND DATA USED FOR ENERGY REQUIREMENTS ASSESSEMENT FOR A TYPICAL INSTALLED MULTICRYSTALLINE SILICON MODULE AND BATTERIES

Assumptions		
1-Data concerns a typical multicrystalline silicon PV module with aluminium frame. 2- We assume an optimistic 90% recycling rate for scrap batteries. 3-BOS components like cables and charge controllers contribute relatively little to the energy requirement of a Solar Home System (< 10%). 4-We assume an annual efficiency improvement of 1% for materials processing and manufacturing.		
Data		
PV module		
Process	**Energy requirements (MJ/m² module)**	**Energy requirements (KWh*/m²)**
Silicon winning and purification	**2200**	**611.6**
Silicon wafer production	**1000**	**278**
Cell /module processing	**300**	**83.4**
Module encapsulation materials	**200**	**55.6**
Overhead operations and equipment manufacture	**500**	**139**
Total module without frame	**4200**	**1167.6**
Module frame (aluminium)	**400**	**111.2**
Total module (framed)	**4600**	**1278.8**
BOS	**700**	**194.6**
Total module (installed)	**5300**	**1473.4**
Batteries		
State	**Energy requirements (MJ/Ah storage)**	**Energy requirements (KWh/Ah storage)**
Battery (initial)	**11**	**3.058**
Battery (after 5 years)	**10.46**	**2.907**
Battery (after 10 years)	**9.95**	**2.766**
Battery (after 15 years)	**9.46**	**2.63**
Battery (after 20 years)	**9**	**2.5**
Total Battery **	**50**	**14**

* 1KWh=3.6 MJ or 1MJ=0.278 KWh
** Round number

III. ASSUMPTIONS AND DATA USED FOR ENERGY REQUIREMENTS ASSESSMENT FOR SMALL WIND TURBINES

Assumptions		
1-Rotor blades are either glass reinforced plastic, wood-epoxy or injection molded plastic with carbon fibers. For calculations' standardization, we have considered molded fiber glass as we know its embodied energy. 2-Due to lack of data, an assumption was made to include the permanent magnets in the category of aluminum because of its high embodied energy.		
Wind Turbine Component weight		
Turbine		
Component	**% by turbine weight**	**Materials' repartition**
Rotor		
Hub	**4%**	**95% Steel, 5% Aluminium**
Blades (1)	**10%**	**100% Molded fibre glass**
Nacelle		
Gearbox	**6%**	**100% Steel**
Generator	**15%**	**50% Magnets, 20% Steel, 30% Copper**
Others		
Frame, Machinery& Shell	**35%**	**30% Aluminium, 12 % Copper, 5% Glass Reinforced Plastic, 53% Steel**
Cables, internal supports, electronic components	**30 %**	**80% Steel, 20%Copper**
Tower		
Tower	**30Kg/m² swept area***	**98% Steel, 2 % Aluminium**
Foundations		
Pile and platform	**65 Kg/m² Swept area***	**97% Concrete, 3% Steel**
Materials' embodied energy		
Material	**Embodied energy (MJ/kg)**	**Embodied energy (Kwh/kg)**
Steel	**24.4**	**6.783**
Aluminium&Magnets (2)	**155**	**43.09**
Copper	**48**	**13.344**
Molded fiber Glass	**28**	**7.784**
Glass Reinforced Plastic	**100**	**27.8**
Concrete**	**0.9**	**0.25**
Required energy for wind turbine manufacturing		
Manufacturing process	**100 MJ/m² swept area***	**27.8Kwh/m² Swept area**

*Approximation based on different studies
** Concrete type RC30 adequate for foundations (25 % cement replacement flyash)

Our methodology has been applied for different small wind turbines as shown in table IV.

IV. DIFFERENT SMALL WIND TURBINES EMBODIED ENERGY

Product	Swept area (m²)	Wind Turbine Weight (Kg)	Global embodied energy (MJ)	Global embodied energy (MJ)/m²
SouthWest (Air X)	1.020	5.850	1346.909	1320.499
SouthWest (Whisper 100)	3.460	21.000	4630.560	1338.312
SouthWest (Whisper 200)	7.070	70.000	10906.321	1542.620
Southwest (Skystream 3,7)	10.870	77.000	15135.374	1392.399
Aeromax Engineering (Lacota S, SC)	3.430	16.000	4333.512	1263.415
Bergey (BWC 1500)	7.070	76.000	11226.249	1587.871
Bergey (BWC XL,1))	4.910	34.000	6795.031	1383.917
Bergey (BWC Excel-R)	35.260	477.000	61212.101	1736.021
Bornay (Inclin 6000)	12.570	107.000	18459.980	1468.574
Abundent Renewable Energy (ARE110)	10.180	143.000	17954.454	1763.699
Abundent Renewable Energy (ARE442)	40.720	612.000	73950.670	1816.077
Kestrel Wind (800)	3.460	45.000	5910.273	1708.171
Kestrel Wind (1000)	7.070	75.000	11172.928	1580.329
Kestrel Wind (3000)	11.340	150.000	19504.738	1719.995
Proven WT 0,6	5.100	70.000	8907.392	1746.547
Proven WT 2,5	9.000	190.000	19263.231	2140.359
Proven WT 6	23.600	500.000	50607.266	2144.376
Proven WT 15	63.500	1100.000	123086.038	1938.363
Mean				1643.975

Our final conclusion is that **1644 MJ/m²** (swept area) is an appropriate assessment of energy requirements for small wind turbines.
These results show that batteries are the most demanding in terms of primary energy because of their regular replacement every five years and wind turbines are more energy efficient than photovoltaic panels.

4.2. COMPUTATİONNAL METHOD AND ALGORİTHM

All mathematical models of the hybrid wind-PV system have been implemented in Matlab/simulink environment. Sizing has been obtained by dynamic simulation and using the" Matlab Optimization toolbox". A controlled elitist genetic algorithm (a variant of NSGA-II) is used for the implementation. This one always favors individuals with better fitness value (rank) that can help to increase the diversity of the population even if they have a lower fitness value. It is important to maintain the diversity of population for convergence to an optimal Pareto front. It consists of controlling the elite members of the population as the algorithm progresses. Two options, Pareto Fraction and Distance Function, control the elitism. Pareto Fraction limits the number of individuals on the Pareto front (elite members). The distance function, selected by "DistanceFcn", helps to maintain diversity on a front by favoring individuals that are relatively far away on the front [24]. Parameters used in our case are the following:
maximum number of generations: 600, population size: 45, crossing fraction: 0.9, mutation rate: 0.01 and Pareto front fraction: 0.6.

5. RESULTS AND DİSCUSSİON

Multi-objective Optimization (MOP) seeks to minimize the three objective functions: LPSP, LCC and EE. Contrary to single-objective optimization, the solution of a MOP is not a single solution but a set of solutions known as a Pareto optimal set, named a Pareto border or Pareto front. Any solution of this set is optimal in the sense that no improvement can be made on one of the three objective functions without worsening at least one of them. Figure 3 shows the 3D Pareto front obtained in our case.

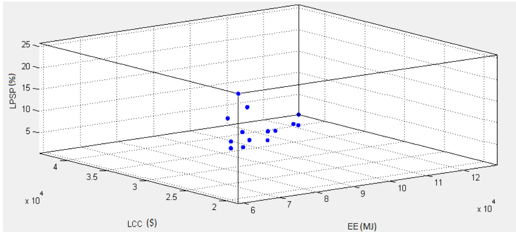

Fig.3. 3D Pareto front

Pareto Set is composed of fourteen solutions. These solutions are detailed in table V. They show that, the more the consumer tolerates load shedding, the greater the hybrid system is undersized and therefore cheaper in terms of both Life Cycle Cost and primary energy requirements. Indeed, there is a considerable costs increase between sizing the system to provide 95% of system electrical needs vs. providing 100% of system needs.

V. OBTAINED PARETO SET SOLUTIONS

Photovoltaic module area Apv (m²)	Wind turbine swept area Awt (m²)	Nominal storage capacity Cn(Ah)	LCC ($)	Required energy EE (MJ)	LPSP (%)
20.000	5.000	300.000	43437.100	129220.000	0.296
18.802	4.063	291.698	40259.226	120915.064	0.669
18.980	4.245	244.655	39122.480	119805.100	1.071
17.248	4.381	255.625	38131.008	111400.684	1.307
16.777	4.874	229.686	37704.143	108415.905	1.760
15.766	3.225	259.045	34682.684	101812.186	1.929
13.693	3.000	275.150	32870.677	91261.166	2.513
12.282	3.015	225.591	29836.344	81331.777	4.943
12.743	2.420	143.735	26290.101	78705.070	8.802
11.571	2.707	163.768	26425.944	73967.537	9.025
11.727	2.122	117.716	23861.930	71526.315	12.719
10.719	2,798	81.793	22924.584	65498.223	17.045
11.018	1.150	68.340	19641.102	63702.644	21.389
10.181	1.134	58.344	18472.604	58741.874	25.693

Despite the existence of multiple Pareto optimal solutions, only one of them can be chosen. In our case, the user will choose the solution that satisfies a 5 % LPSP criterion:
- Photovoltaic modules' installed area Apv =12.282m², (8 sharp 170 W panels for instance),
- Wind turbine swept area Awt=3.015m², an Aeromax Engineering (Lakota S, SC) wind turbine has a close swept area of 3.43m² with a low LCC,
- Battery bank storage capacity gives Cn = 225.591Ah, 4 US 185 Deep Cycle Monobloc Battery 12V 200Ah in series can be installed.

With this hybrid system configuration (8 sharp 170 W panels, Lakota wind turbine and 4 US 185 Batteries), we verify in table V, for all years, that our hybrid system provides more than 95% of the electric needs (LPSP<5%). Consequently, user does not have to incorporate another source of electricity into the system. In addition, a reasonable LCC near 30000$ is obtained and 81332 MJ or 22610 kWh embodied energy is required to reach the sum total of the energy necessary for an entire product life cycle.

VI. CHOSEN SOLUTION EVALUATION

Year	Load Kwh	PV Kwh	Wind kwh	Excess kwh	Unmet load kwh	%Unmet Load (LPSP)
2002	1903	2864	1109	1619	55.32	2.907
2003	1903	2751	1332	1740	71.03	3.732
2004	1893	2752	1098	1517	70.86	3.743
2005	1894	2772	1139	1581	66.34	3.503
2006	1903	2846	1569	2040	45.63	2.398
2007	1898	2762	1334	1751	70.67	3.723
2008	1907	2832	1604	2057	54.69	2.868
2009	1898	2722	1294	1693	89.93	4.738

Table VI validates the adequacy of the proposed sizing method. For all the years, lack of production does not exceed 5 % of the total yearly electric load of the hybrid residence. However, we have a considerable excess that needs somewhere to go. It can be used in cooking or in water heating supply.

6. CONCLUSİON

In this paper, we have applied a controlled elitist genetic algorithm to the Multi-Objective design of a hybrid PV-wind-battery system, minimizing, simultaneously, three objectives: life cycle cost (LCC), system embodied energy (EE) and Loss of power supply probability (LPSP). Optimization has been insured by a dynamic model of the system under Matlab/Simulink. Contrary to single-objective optimization, we have found a set of solutions (14) known as a Pareto optimal set.
In addition, the inclusion of the embodied energy as a criterion is also one innovative aspect of our work. To integrate it, we have made the analysis of primary energy requirements of each component. This analysis has shown that batteries are greedy on primary energy requirements. It is important to improve their manufacturing process and lifespan, for example by better energy management techniques. Besides, it has provided a primary energy assessment of small wind turbines infrequently discussed in the literature due to scale overhead, showing that small wind turbines are more energy efficient than photovoltaic panels.
Finally, it is important to stress that the proposed method will help designers of hybrid Wind-PV-Batteries systems to make their decisions more consciously about environmental impact.

7. ACKNOWLEDGMENT

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