



Optimization of renewable energy projects with Excel when professional software is not available

Optimización de proyectos de fuentes renovables de energía con Excel cuando no se dispone de software profesionales

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Abstract

Sometimes, for the realization of profitability analysis and projects with renewable energy sources, professional software is not available, or the input and output parameters do not correspond to those available or desired by the user, since the designer chooses the parameters with which his algorithm has to operate. Many projects such as the one presented in this document can be designed by professionals and students with modest computer knowledge and solved with the Excel application present in all Microsoft Office packages. The example shown is aimed at determining the main parameters of the preliminary project, performing the profitability calculations and the sensitivity analysis of a hybrid wind-electric system that must guarantee the base demand of an isolated grid. The results are compared with those obtained with the professional software HOMER Beta V.2.68.

Keyword: Macro project parameters; Hybrid systems; Project feasibility; Excel programming.

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Resumen

En ocasiones, para la realización de análisis de rentabilidad y proyectos con fuentes renovables de energía no se dispone de un software profesional, o no se corresponden los parámetros de entrada y de salida con los disponibles o deseados por el usuario pues el diseñador escoge los parámetros con los cuales ha de operar su algoritmo. Muchos proyectos como el que se presenta en este documento pueden ser diseñados por profesionales y estudiantes con un modesto conocimiento de computación y resueltos con la aplicación Excel presente en todos los paquetes de Microsoft Office. El ejemplo mostrado tiene como objetivo la determinación de los principales parámetros del anteproyecto, realizar los cálculos de rentabilidad y el análisis de sensibilidad de un sistema híbrido eólico-electrógeno que debe garantizar la demanda base de una red aislada. Se comparan los resultados con los obtenidos en el software profesional HOMER Beta V.2.68.

Palabra clave: Parámetros macro del proyecto; Sistemas híbridos; Factibilidad de proyectos; programación con Excel.

Introduction

In many cases there is a scenario given by the demand and availability of energy, but there are no tools to carry out a feasibility study, determine the fundamental parameters and analyze the profitability of the project. Many professional softwares require expensive licenses for their use, others, although they can be "free", need to be installed in the PC, which makes their transfer and demonstration difficult; however, the most difficult problem to solve is the non coincidence in many occasions of the input and output parameters with which the softwares operate and those available and desired by the user.

Taking a wind project as an example, the parameter that determines the energy that can be produced in a time t is the wind speed, which as it is known, has random behavior. The way in which this parameter is input differs depending on the software used; it can be the hourly average speed, monthly average, annual average, it can also be the distribution of two Weibull parameters, etc.), then from that information the software through its internal tools determines the probability distribution of each speed. The two-parameter Weibull distribution represents very accurately the probabilistic behavior of wind speeds at many locations around the globe. It is given by:

$$p(v_i) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

In which: k and c are the shape and scale parameters respectively, whose values can be determined by different ways: empirical methods from mean velocity, least squares and others (Khan et al., 2015).

For projects of some importance, average hourly velocities are normally taken throughout the year, i.e. 8760 measurements and classified by ranges, e.g.: for group v_1 , those between 0.5 and 1.4 m/s: for group v_2 , those between 1.5 and 2.4 m/s and so on.

If n velocity measurements are made, the probability of a velocity i is given by:

$$p(v_i) = \frac{m_i}{n} \quad (2)$$

In which, m_i is the number of measurements (or hours) corresponding to the speed i and n the number of total measurements made. It is evident that the sum of probabilities is 1 (100%). If wind speeds are measured for 8760 hours of the year, the time that each probability is fulfilled is given by:

$$t_i = 8760 \cdot p(v_i) \quad h \quad (3)$$

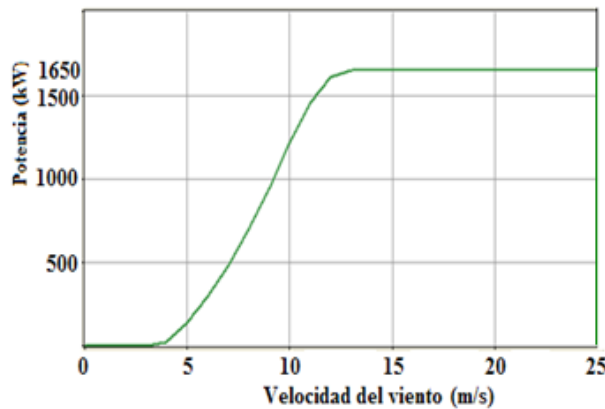
The energy developed by a wind generator during a time t_i can be determined by:

$$E_i = P_i \cdot t_i \quad kWh \quad (4)$$

In which: P_i is the useful power developed by the wind generator at wind speed v_i .

Generally, wind machines operate within a speed range from the starting speed v_a to the maximum or cut-off speed v_c . Within that speed range, each machine has a characteristic power curve, which may be as shown in Figure 1.

Figure 1. Vestas V-82 wind turbine features



Source: Authors

Knowing the probabilities of occurrence of each speed and the power curve of the turbine, it is possible to accurately determine the total energy that the turbine can develop in the year:

$$E_T = 8760 \int_{v_a}^{v_m} P(v_i) \cdot p(v_i) \quad kWh/a \quad (5)$$

Since discrete values of v are generally taken, then the energy can be approximately determined by:

$$E_T = 8760 \cdot \sum_{v_a}^{v_m} P(v_i) \cdot p(v_i) \text{ kWh/a} \quad (6)$$

The energy produced by the machine is used to obtain other project parameters.

It can be seen how important it is to know precisely the probability distribution of velocities, which can be obtained in different ways depending on the input data.

Materials and methods

For the individualized solution of the programs on renewable energy sources it is proposed to use the Microsoft Excel application for different reasons:

- It is present in all Office packages.
- It is easy to implement, correct, display.
- Unlike other programs, it is not necessary to know the programming instructions by heart because they are written by making references to cells.
- It has virtually all the plug-ins needed to design any software.
- With a little skill you can give the program a professional feel.

The proposed example has been developed for the interactive solution of a wind-electric hybrid power generation project connected to an isolated grid in order to determine the macro parameters that guarantee the energy demand and the profitability of the project.

The main source of energy is wind power, backed up by a generator set of several machines whose number is a parameter to be optimized. The maximum power of the generator set must be able to support the maximum hourly demand of the system so that there are no voltage dips due to a lack of wind power. Depending on the available wind energy, the wind farm contributes to the system and the genset reduces its production with the consequent fuel savings; the system can support all the energy produced by the wind farm. The power of the genset, the power and number of machines in the wind farm, the wind parameters at the reference (measurement) height k and c and the average air density at the height of the turbine shaft are given as variable data.

For the calculations of the capital cost of the wind farm and the genset it is convenient to use some method of cost estimation, such as those of the six-tenths theory or others, in this case the parametric equation developed for Latin American countries as a

function of the power, number, and hub height of the machines by Enriquez and Garcia (Enriquez and Garcia et al., 2016) is used for the wind farm.

$$C_{EO} = 18,02 \cdot P^{0,675} \cdot N^{0,924} \cdot Z^{1,73} \quad \$ \quad (7)$$

A fraction of the annual capital cost, typically between 5%-10%, is taken for the operation and maintenance cost.

For the genset, the capital cost is estimated as a function of power using the six-tenths theory with exponent 0.72 (Randall & Whitesides, 2012).

$$C_{GE} = 1\,000 \cdot N \cdot P^{0,72} \quad (\$) \quad (8)$$

For the operation and maintenance cost, a fraction of the annual cost of the genset is taken, generally between 5%-10% plus the cost of fuel consumed, for which the specific consumption (kg/MWh) and the price (\$/kg) are given. These costs can then be analyzed as sensitivity parameters (Roqueñí et al., 2008).

With this information it is possible to determine:

- Total energy produced by the wind farm and the generator set.
- Wind farm and genset capacity factor.
- Generating set working hours per year.
- Genset fuel consumption.
- Cost of fuel consumed.
- Net present value of the project.
- Levelized cost of energy (COE) (\$/kWh).
- Kg of CO₂ , SO₂ , NO_x , CO going into the atmosphere.
- Perform sensitivity analyses on the influence of different factors on profitability.

The main calculations are performed in two linked Excel sheets. The first one is divided into three main blocks, figure (2):

- Data entry of wind parameters.
- Turbine and genset data input.
- Results block.

In the wind data block, the parameters k , c and p are entered at the measurement height (reference height Z_{ref}) and the terrain roughness height (Burton et al., 2002).

The second block provides the parameters of the turbines: type, maximum power and number, hub height and the average value of the expected total efficiency due to wind farm arrangement losses (Manwell & McGowan, 2009); the nominal power of the genset, which is the firm or base power to be guaranteed and the number of generators that make up the genset; the specific consumption and the price of each kg of fuel are also given.

The Weibull shape parameter k does not vary practically when passing from the reference height to the turbine hub height because the velocity frequency is the same at both heights, but the scale parameter c is very sensitive to the height variation and the surface roughness of the terrain Z_0 , so its value must be corrected for the turbine hub height (Villarrubia, 2007). It is shown to be given by:

$$c_Z = c_{ref} \cdot const = c_{ref} \cdot \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{ref}}{Z_0}\right)} \quad (9)$$

In which:

Z - Turbine hub height (m)

Z_0 - Roughness height

The energy correction factor (equation 6) is also determined for the effect of density change due to the altitude of the site (Streeter et al., 2000). It is given by:

$$F_\rho = \frac{\rho_Z}{1,225} \quad (10)$$

Being:

ρ_Z - Density of on site

1.225 - Density of air at normal standard conditions

Then, in the third block in column (A) the wind speeds from 1 to 25 m/s are placed, which is normally the limit or cut-off speed of the turbines work; in column (B) the Weibull equation (1) is applied with the value of c corrected in (8) to determine the probability of each speed, but if the information that is available is the number of hours that each speed m is fulfilled, then the probabilities are determined by equation (2);

In column (C), the values of the turbine power corresponding to each wind speed are entered, and then, in column (D), the energy generated by the wind farm for each wind speed is determined. The number of turbines, the wind density correction factor and the total efficiency of the wind farm must be taken into account:

$$E_{EOi} = N \cdot E_{ti} \cdot F_\rho \cdot \eta = 8760 \cdot N \cdot F_\rho \cdot \eta \cdot P(v_i) \cdot p(v_i) \quad kWh \quad (11)$$

The wind energy captured by the farm during the year is determined by adding the values of the energies corresponding to each speed (sum of column D):

$$E_{EO} = \sum_{i=1}^{i=25} E_{EOi} \quad kWh / a \quad (11)$$

The park capacity factor is given by:

$$FC_{EO} = \frac{E_{EO}}{N \cdot P_t \cdot 8760} \quad (12)$$

In column (E) the energy demanded in each time interval is determined (in a similar way as it was done with the energy produced by the turbines), the total sum of the column equals the total energy demanded during the year. The differences between the cells in column E and D give in column F, the deficit of wind energy in each interval to be supplied by the genset. If the opposite occurs, i.e., when wind power exceeds demand, then it is counted as excess energy produced, which if the system is an interconnected grid can be absorbed. With this information it is possible to estimate if there is a deficit or excess with respect to the base power and increase or decrease the number of turbines, this can be another sensitivity parameter.

$$P_{EOi} = N \cdot \eta \cdot P_{ti} \quad (13)$$

Excel provides the necessary logic functions to determine whether there is a deficit or excess of energy. In column (F) the energy demand is compared to the wind potential energy with the function "Si". That is:

$$=SI(\text{Demand} > E_{EO}, (\text{Demand} - E_{EO}), (0)) : (14)$$

In column (H) the hours that the genset works when there is a wind energy deficit are determined, this allows then to calculate the energy produced and the fuel consumed. A function similar to the one given above can be used.

$$=SI(E_{GEi} > 0, (8760 \cdot p(v_i), (0))) \quad (15)$$

These equations, like all the previous ones, are written by making references to the cells where the variables are located.

The energy developed by the genset when there is a deficit of wind energy is determined in column (I).

$$E_{GEi} = P_{GEi} \cdot t_i / 1000 \quad MWh \quad (16)$$

The total energy generated in the year by the genset is obtained by adding column (I)

The capacity factor of the genset is determined by:

$$FC_{GE} = \frac{E_{GE}}{P_{GE} \cdot 8760} \quad (17)$$

The fuel consumption of the genset is given in column (J) by:

$$G_i = E_{GEi} \cdot t_i \quad kg/h \quad (18)$$

The sum of column (J) gives the annual fuel consumed.

The second sheet is composed of four blocks, figure (3), in the first one the data from sheet 1 are imported following the Excel data import procedure; in the second block other data are entered that can be variables in the problem: % allocated for operation and maintenance, annual interest rate, electricity sales rate, years of project life, specific fuel consumption and unit cost of fuel.

Next, in the third block, preliminary calculations of capital costs, maintenance and operating costs, and residual values of the wind farm and the genset are made (Blank & Tarquin, 2006):

Annual cost of operation and maintenance of the wind farm

$$C_{omEO} = \frac{C_{EO} \cdot FC_{EO}}{N} \quad (\$/a) \quad (19)$$

FC_{EO} - Fraction of park cost (2-4 %)

N - Years of project life

Cost of operation and maintenance of the generator set

$$C_{omGE} = FC_{GE} \cdot E_{GE} \cdot T_e \quad \$/a \quad (20)$$

FC_{GE} - Fraction of the value of the energy produced by the genset (4-6%)

E_{GE} - Annual energy produced by the generator set

T_e - Electricity tariff

In addition to the cost of operation and maintenance, the cost of fuel must be taken into account in generator sets.

To estimate the amount of fuel consumed, the specific consumption and the energy generated are used as data:

$$G = g(kg/kWh) \cdot E_{GE}(kWh/a) \quad kg/a \quad (21)$$

To determine the cost of fuel, the unit cost is used:

$$C_c = C_e(\$/kg) \cdot G(kg/a) \quad \$/a \quad (22)$$

To determine the profitability of the project, economic-financial evaluation criteria are suggested that use asset flows discounted over time. Since the necessary information is available to determine all costs, energy produced and income, any of the most commonly used criteria can be applied: Net Present Value, Life Cycle Cost, Levelized Cost of Energy and others. (Fernández, 2012). In this example the NPV is applied, it is given by:

$$VPN = (C_{EO} + C_{GE}) - (V_{rEO} + V_{rGE}) + \sum_{n=1}^n \frac{FC_n}{(1+i)^n} \quad (23)$$

Where:

C_{EO} and C_{GE} - represent the capital costs of the wind farm and generator set.

V_{rEO} and V_{rGE} - represent the residual value of the fleet and genset after the useful life period has expired. This is usually 10-25% of the initial cost.

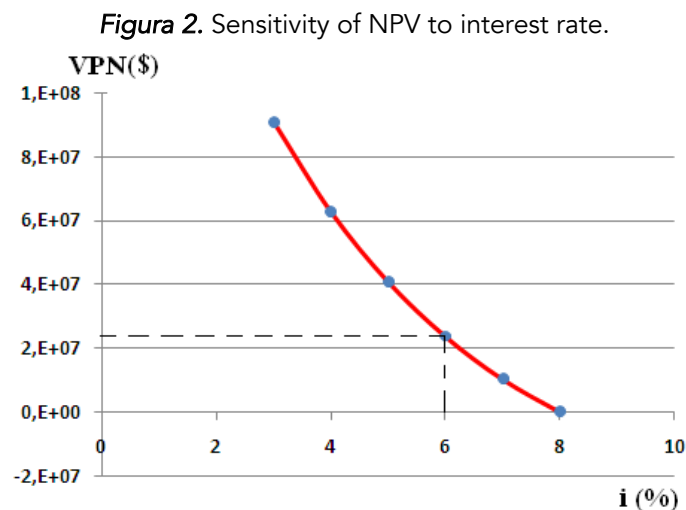
CF - Cash Flows. It is the result of the income from electricity sales and the expenses (operating, maintenance and fuel costs) during the years (n) of the project's life. For this case, all cash flows are considered to be equal.

i - Interest rate to be paid annually for the project financing, normally between 6%-10%.

The professional software HOMER uses in its software the Net Present Cost (NPC). (Beiter et al., 2016); (Oyarzo, 2008).

In the spreadsheet, after having the NPV result with the initial values assigned to each variable, sensitivity analyses are performed with the selected variables, keeping the other variables constant. You can have separate graphs, which can then be merged into a single graph, called a spider graph. (Watson, 1995).

Figure 2 shows the behavior of the NPV when varying the interest rate in the range of 3% to 8% for a given project, the initial (equilibrium) value was 6% with the rest of the variables, which yielded an NPV of \$25.3.10⁶. Note the marked influence of this factor on profitability.



Source: Authors

To determine the amount of gases that pollute the atmosphere, it is necessary to have as information the amount of fuel consumed per year and its chemical composition, then by analyzing the combustion residues, the remaining fraction of each component per kg of fuel combusted is determined (Unnasch et al., 2001).

Results

The system is composed of 5 VESTAS generators of 1650 kW power and a generator set composed of five generators of 800 kW power, for a total of 4 MW which is the maximum load of the system. Figure 1 shows the input data and the calculations of wind energy produced, energy supplied by the genset, excess energy, which is the energy produced by the wind generators above the demand; the annual fuel consumption is also determined.

In the second sheet, based on the previous results, the factors that determine the profitability and the combustion gases that have an impact on the environment are determined.

The above results were compared with those obtained by the HOMER professional software when supplied with the same data in an isolated system. Table 1. The results are shown. It is observed that in the energy parameters the difference is very small; in the case of the generator set working hours there is apparently a very large difference, this is because HOMER performs the calculation by dividing the annual energy developed by the generator set (11 108 MWh/y) by the power of the set (4MW), resulting in 2777 hours. In the proposed method, the number of hours is obtained by adding the times that the genset contributes to the grid, i.e.:

$$h_{GE} = 8760 \cdot \sum_{i=1}^{i=25} p(v_i) \quad \text{para } E_{GE} > 0$$

The polluting gases are calculated by conventional methods based on the elemental composition of the fuel, the coefficient of excess air and the fraction of carbon involved in the formation of CO₂ and CO. The divergence in these results can be given by the coefficient of excess air, which in this case was taken as 30%, or in the criterion for fixing the fraction of carbon in the formation of CO.

Table 1: Comparison of results with those obtained by HOMER Beta V2.68

	Gener Wind MWh/a	F.C. E.O. %	Gener Elect. MWh/a	F.C GE. %	Excess Energy MWh/a	Hours Gener. Elect.	Consumption Combust. (Kg/y)
HOMER	30 971	42,9	11 108	31.7	7 132	2 777	3 152 450
V2.68 Beta							
HYBRID	30 752	42,6	11 337	32.4	7 049	5 230	3 287 777
UO V-1.							
Difference	0,7%	0,7%	2%	2,2%	1,2%	*	4,1%

Products of combustion (kg/a)

Financial
evaluation

	CO2	SO2	NO2	CO	LCC	VPN	COE
							\$/kWh
HOMER	9 652	19385	212607	23827	65 719	---	0,08
V2.68 Beta	837				736		
HYBRID	10 078	21 699	229 380	67 509	---	16 816	0,09
UO V-1.	132					650	
Difference	4%	11%	5%	*			11%

Source: Authors

Figure 3. Preliminary data sheet and calculations

PROGRAMA PARA EL ESTUDIO DE FACTIBILIDAD DE UN SISTEMA HÍBRIDO EÓLICO-DIESEL										
HOJA 1 CONECTADO A UNA RED ELECTRICA AISLADA										
DATOS VARIABLES DEL PROBLEMA										
PARAMETROS DEL VIENTO					POTENCIA BASE QUE DEBE SER GARANTIZADA (MW) 4					
Parámetro de forma k a la altura de referencia Z (m)	4									
Parámetro de escala c a la altura de referencia Z (m)	8.55									
Densidad del aire kg/m3	1.2									
Altura de rugosidad Zo	0.03									
Altura de referencia Zref (m)	30									
DATOS DE LAS TURBINAS					DATOS DEL GRUPO ELECTRÓGENO					
Tipo de turbina eólica	VESTAS V82				Número de generadores				5	
Potencia nominal /turbina (kW)	1650				Potencia por generador (kW)				800	
Cantidad de turbinas	5				Consumo específico kg/MWh				290	
Altura del buje Z	78				Costo del combustible \$/kWh				0.9	
Eficiencia del parque por arreglo de las turbinas (%)	100%									
BLOQUE DE CÁLCULOS										
Parámetro C corregido a la altura a la altura del buje z	9.73									
Factor de corrección de la densidad aire	0.98									
ENERGÍA PRODUCIDA EN EL PARQUE EÓLICO					ENERGÍA DEL GRUPO ELECTRÓGENO					
v (m/s)	p(v) buje	P(v) KW	E (MWh/a)	DEMANDA	MWh/a GE	MWh/a Exc.	Horas/a GE	PGE (MW)	Efic. GE	G (kg)
1	0.000	0	0	16	16	0	3.9	4.00	0.39	4,529
2	0.004	0	0	125	125	0	31.2	4.00	0.39	36,175
3	0.012	0	0	418	418	0	104.5	4.00	0.39	121,210
4	0.028	0	0	972	972	0	242.9	4.00	0.39	281,762
5	0.052	18	40	1,821	1,781	0	455.3	3.91	0.39	516,505
6	0.083	140	501	2,920	2,420	0	730.1	3.31	0.37	701,699
7	0.117	289	1,451	4,100	2,649	0	1025.0	2.58	0.38	768,236
8	0.145	477	2,959	5,067	2,107	0	1266.7	1.66	0.38	611,120
9	0.156	690	4,631	5,481	850	0	1370.3	0.62	0.33	246,540
10	0.146	941	5,905	5,125	0	780	0.0	0.00	0.00	0
11	0.116	1,210	6,026	4,067	0	1,959	0.0	0.00	0.00	0
12	0.076	1,453	4,763	2,677	0	2,086	0.0	0.00	0.00	0
13	0.041	1,607	2,800	1,423	0	1,377	0.0	0.00	0.00	0
14	0.017	1,650	1,197	593	0	605	0.0	0.00	0.00	0
15	0.005	1,650	378	187	0	191	0.0	0.00	0.00	0
16	0.001	1,650	87	43	0	44	0.0	0.00	0.00	0
17	0.000	1,650	14	7	0	7	0.0	0.00	0.00	0
18	0.000	1,650	2	1	0	1	0.0	0.00	0.00	0
19	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
20	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
21	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
22	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
23	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
24	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
25	0.000	1,650	0	0	0	0	0.0	0.00	0.00	0
		MWh/a	30,753.125	35,041	MWh/a	11,337.161	7,049.101	5230		3,287,777
		FAC. CAP	0.426		FAC. CAP.	0.324				

Hoja 2						
ANÁLISIS DE FACTIBILIDAD DEL PROYECTO HÍBRIDO EÓLICO-DIESEL						
TIPO DE TURBINAS EÓLICAS			VESTAS V82			
POTENCIA nominal DE LAS TURBINAS (kW)			1650			
NUMERO DE TURBINAS			5			
ALTURA DEL BUJE (EJE) DE LAS TURBINAS (m)			78			
POTENCIA TOTAL DEL GRUPO ELECTRÓGENO (MW)			4			
NUMERO DE UNIDADES DEL G.E			5			
POTENCIA DE CADA UNIDAD DEL G.E. (MW)			0.8			
PRODUCCIÓN DEL PARQUE EÓLICO (MWh/a)			30,753			
PRODUCCIÓN DEL GRUPO ELECTRÓGENO			11,337			
FACTOR DE CAPACIDAD DEL PARQUE EÓLICO			0.43			
FACTOR DE CAPACIDAD DEL GRUPO ELECTRÓGENO			0.32			
HORAS DE TRABAJO REAL DEL GRUPO ELECTRÓGENO			2,834.3			
CONSUMO DE COMBUSTIBLE DEL GRUPO ELECTRÓGENO (kg/a)			3,287,777			
Composición elemental del combustible			C	H	O	S
			0.88	0.113	0.004	0.0033
OTROS DATOS NECESARIOS						
F. Com EO (%)	F. Com GE (%)	T. interés (%)	T. Elect (\$/kWh)	A. vida/proyecto	g Comb kg/MWh	Cu comb. (\$/kg)
10%	20%	6%	0.20	25	220	0.9
CÁLCULOS PRELIMINARES						
Costo EO (\$)	Costo GE (\$)	Com EO (\$/a)	Com GE (\$/a)	Ccomb. (\$/a)	VrEO (\$)	VrGE (\$)
22,219,199	1,230,906	88,877	453,486	2,244,758	5,554,800	307,726
RESULTADOS ECONÓMICO Y DE IMPACTO AMBIENTAL						
Venta E. (\$/a)	VPN (\$)	COE (\$/KWh)	CO2 (kg/a)	So2 (kg/a)	Nox (kg/a)	CO (kg/a)
8,418,057	15,212,431	0.09	10,078,132	21699	229,380	67509

Source: Authors

Conclusions

This example demonstrates that with a modest knowledge of Microsoft's Excel application, it is possible to design important programs for the study of renewable energy projects. In this case a wind-diesel hybrid system was taken as an example, but it could have been wind-hydro or any other. Comparison of the results with the well-known HOMER software indicates that the accuracy and therefore the confidence level is high. By simply varying some input data to the program (Sheet 1), all values change automatically, which facilitates sensitivity analyses.

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