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Technical Communication

Simulation and optimization of a stand-alone power plant based on renewable energy sources

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ABSTRACT

By using the optimization software tool HOMER, this project aims at the energetic and economical optimization of a RES-based stand-alone system, already installed at Leicestershire, UK. Based on local meteorological data, an optimization strategy has been developed to identify the most economical and efficient scenarios for the generation of electricity to cover the desirable load in annual basis. Furthermore, the environmental-friendly character of the system was highly concerned in terms of emissions reduction, therefore the capability of an off-grid system was also investigated. The simulations show that an off-grid project with zero emissions is feasible, presenting the additional advantage of minimal capital investment costs. Finally, it is found that grid connection corresponds to very high operational costs in a long term.

1. Introduction

Since the environmental pollution is of worrying level and the carbon fuel reserves decrease, the Renewable Energy Sources (RES) seem to be a significant alternative towards a sustainable and environmental-friendly solution for the energy problem in global scale. Their use is rather essential because they are environmental-friendly and inexhaustible. The major problem which comes up by the combined use of RES for the coverage of a given load is the selection and the adjustment of the parameters related both with energy and economy, to obtain the best result on the energy coverage and on the economical performance of the established technologies. Several attempts have been made on that issue and not only to promote their ecological character [1,2] but also to run off-grid, like this which gets under way at West Beacon Farm, Leicestershire, UK and constructed within the framework of HaRI project, being the case study of the present work [3]. The design and the establishment of the plant has been published in this journal [4]. It is obvious that the whole plant has not been optimized, thus the connection with grid is essential for the coverage of the electric load, some technologies like hydrogen, hydroelectric and photovoltaics are of low efficiency and the initial and operational costs are quite high [4].

All these drawbacks, as it has been shown previously, is possible to be overcome indicating that an autonomous system can be economically feasible whereas the selection of the appropriate technologies has to become in accordance with the climatic conditions [5]. The present study aims at the presentation of the combined use of RES in a power plant designed in an optional way. Apart from the optimization of the established unit, it is essential for other combinations of

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RES to be proposed through simulations. It is rather obvious that the characteristics of the renewable resources influence the behavior and economics of renewable power systems [6]. Towards such a solution, all the different scenarios presented here, utilize different renewable sources, i.e. solar energy, wind energy, hydropower and hydrogen, produced mainly by electrolysis.

2. Theory

2.1. Technological issues

Technologies which take advantage of solar energy transform the solar radiation into DC load through photovoltaic panels. The electric power produced by a typical photovoltaic panel is given as [7]:

$$P_{solar} = \eta_{PV} \cdot \eta_{inv} \cdot G \cdot OR \cdot A_{PV} \cdot K_{PV} \quad (1)$$

The critical parameter for the conversion of solar energy to electricity is the amount of solar radiation available during the day (solar potential) and it depends on the location of photovoltaic arrangement and the local environmental conditions.

The kinetic energy of the wind that can be captured from the wind turbines and converted to electrical power depends on the wind speed (wind potential) and the height of the wind turbine since the wind speed varies with the height, following the Weibull distribution [6]. The power produced by a turbine at a given height can be expressed as [8]:

$$P_{wind} = 0.5 \cdot A^2 \cdot 1.23 \cdot u^3 \quad (2)$$

It must be stressed out that only the 30–40% approximately (actually a coefficient up to Betz limit of 59%) can be transformed to electrical energy at the horizontal axis wind turbines because of the mechanical losses of the turbines [8].

Hydroelectricity is one of the most mature forms of renewable energy, providing more than 19% of the global electricity consumption [9]. The electrical energy which can be produced by a hydroelectric unit depends on the control of the flow of the water. This factor is the most important because the spin of the turbine depends on that (water potential) [6], so the kinetic energy of water is transformed into mechanical and finally, into electricity through the capacitors. The expression which represents the above procedure is [10]:

$$P_{hydro} = \eta_{turb} \cdot \eta_{gen} \cdot \rho \cdot g \cdot h_{eff} \cdot Q \quad (3)$$

Fuel cell systems are energy devices that directly convert the chemical energy of the feeding fuel into electricity without Carnot limitation, being suitable for stationary and mobile applications. Due to the high conversion efficiencies and the negligible environmental impact, fuel cell technology is considered as one of the most promising to contribute essentially to generation of electrical power in the near future [11]. Among several types of fuel cells, Polymer Electrolyte Membrane fuel cells (PEM FCs) have high power densities, quick start-up and load characteristics while their normal operational temperature is quite low, thus they gain significant interest among the researchers [12].

2.2. Economical issues

For a unit based on RES is essential not only to optimize the energy efficiency but also to be economically feasible. Thus, it is necessary to calculate the Net Present Cost (NPC), which roughly estimates the amount of money which must be spent throughout the years, given as [13]:

$$C_{NPC} = C_{tot}/CRF \quad (4)$$

However, the capital recovery factor is given by [13]

$$CRF = \frac{i \cdot (1+i)^N}{(1+i)^N - 1} \quad (5)$$

where the real interest rate is [13]

$$i = \frac{i' - f}{1 + f} \quad (6)$$

3. Simulation

The already installed unit is as in [3] and uses (a) two Carter 25 kW wind turbines, (b) a fixed array of photovoltaic panels, consisting of 3 kW monocrystalline modules and 3 kW polycrystalline ones, (c) approx. 3 kW hydroturbines, run from water flowing by storage engine, (d) a 15 kW LPG internal combustion engine and (e) a 7 kW PEM fuel cell stack, which utilizes pure hydrogen, stored at high pressure storage tank. All the above sources are supported by one 20 kW Zebra battery and the system supplies electrical power to a residential house and a set of offices. Instead of using a constant 34 kW load for our simulations, as in [4], a more realistic

Table 1 – The desirable load.

Hours	Load (kW)
00:00–01:00	6.000
01:00–02:00	6.000
02:00–03:00	6.000
03:00–04:00	6.000
04:00–05:00	7.000
05:00–06:00	7.000
06:00–07:00	16.500
07:00–08:00	16.500
08:00–09:00	18.000
09:00–10:00	18.000
10:00–11:00	18.000
11:00–12:00	20.000
12:00–13:00	20.000
13:00–14:00	25.000
14:00–15:00	34.000
15:00–16:00	34.000
16:00–17:00	34.000
17:00–18:00	20.000
18:00–19:00	20.000
19:00–20:00	20.000
20:00–21:00	20.000
21:00–22:00	7.000
22:00–23:00	7.000
23:00–24:00	6.000

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Table 2 – Description of different scenarios.

Scenario	Wind (kW)	PV (kW)	Hydro (kW)	Int Comb Eng (kW)	F.C. (kW)	Battery (Zebra, 20 kW each)	Grid
1a	Carter 2 × 25	6	3	15	7	1	Yes
1b	Carter 2 × 25	13				246	No
2	PGE 2 × 25					13	No
3a	PGE 1 × 25			34			No
3b	PGE 1 × 25			34		1	No

distribution of the load needs on daily basis has been selected for the purposes of the present work. As far as HARI installation is used to cover a house and small office needs, the desirable load presented in detail in Table 1 has been estimated for typical installations of such type.

Further to the installed plant, several alternative systems of different topologies and devices, are also examined. These topologies build up the different scenarios for the load coverage and are analytically presented in Table 2. It is worth noticing that all the scenarios must cover the desirable load and the peak demand of electricity while the unmet load should be minimized. All the scenarios in this project are set up on the software optimization tool HOMER (Hybrid Optimization Model for Electric Renewables) being capable of simulating systems of different RES, by using hourly data for the load [14].

For the needs of simulation of this project, the nominal interest rate and the annual inflation rate are considered as standard and equal to 7.5% and 3% respectively. The elements of the photovoltaic arrays, which are used in simulations, are known through the study of the m-Si technology, their orientation and their instrumentation [7]. For the wind turbines [15] and the Zebra batteries, the manufacturer's manuals are used. For the internal combustion engine, the emissions are added separately [16] while for the economical issues the costs are these which are used at the already established unit [3]. In addition, the solar radiation data are collected by the local meteorological station in the same region with the established unit (Leicestershire, UK) while the wind data are from the annually published wind chart for UK. Finally the gravity, g, is considered as standard (9.81 m/s^2).

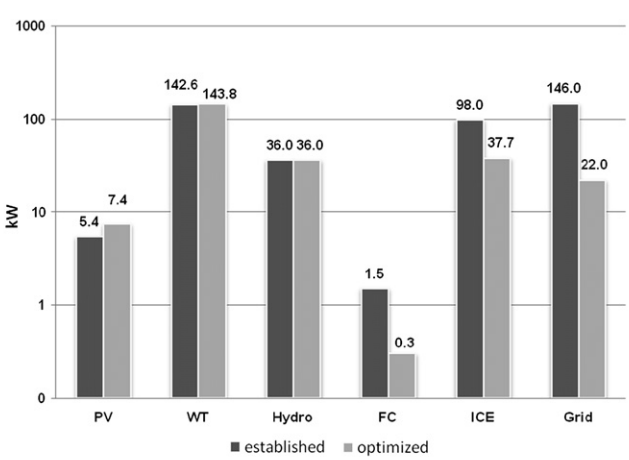

Fig. 1 – Electricity production per RES/device of the already established unit for the coverage of the peak demands (solid lines) and for a more realistic load (dashed lines).

4. Results and discussion

The established unit was simulated in HOMER, resulting to what is depicted in Fig. 1. As far as the solar potential of the specific location is low, the energy produced by photovoltaic panels is quite low thus the higher portion of electrical energy comes from the grid and the established wind turbines which take advantage of the high local wind potential. On the other hand, hydrogen seems to have a small influence on the coverage of the desirable load because of the low power of the fuel cells used. It is important to also note that the energy which is necessary for the hydrogen production and storage is not based on RES supply but comes from the grid connection, increasing therefore the influence of the grid connections and its cost, as well. Finally, the use of such a small hydroturbine diminishes the role of the hydropower on the whole system. All the above underline the necessity of the whole system to be optimized. On top of that, the original design intends to cover a constant load at the peak value of consumption [4] without taking into account a normal daily variation. The real necessary load is assumed to be much smaller, thus the next simulation concerns the same unit with different more feasible load of Table 1, thus the reduction of the load is more than 50%. Indeed, the approach presented in [4] corresponds to a continuous demand of 34 kW which corresponds to 816 kWh per day, while the realistic load used in the present simulation correspond to

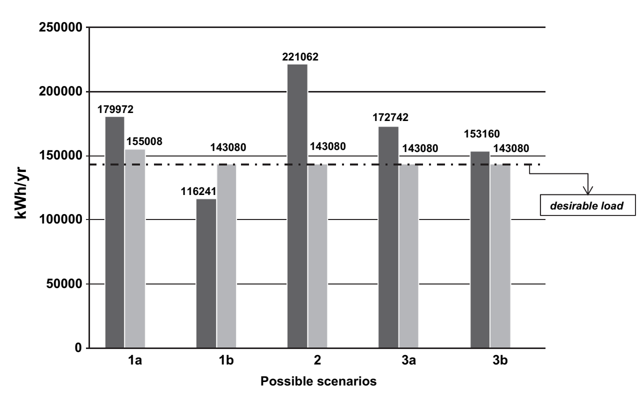

Fig. 2 – Comparison of different scenarios in terms of electricity production.

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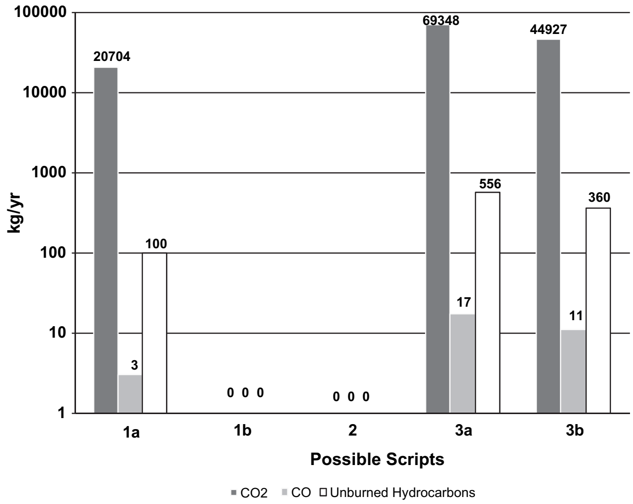

Fig. 3 – Comparison of the emissions per scenario.

only 392 kWh per day. Furthermore Fig. 1 shows that the contribution of grid supply to the whole consumption becomes small with the alteration of the load but it remains significant enough for an optimization procedure to be necessary.

The results of simulations are shown that the final choice upon the measures of loads must be Scenario 2, as Fig. 2 shows. The new wind turbines take high advantage of the wind power so the production of electricity is in a very high level and the excess can be used for the coverage of the thermal load or can be sold to grid if there is a connection. It is important to also note that all the scenarios present null unmet load values thus underlining the success of energetic optimization. The comparison among the different scenarios for the lowest emissions is presented in Fig. 3, where Scenario 2 seems to be the most preferable. Although Scenario 1b seems to have equivalently interesting results in terms of emissions, Scenario 2 is preferable because of the very large amount (246) of Zebra batteries being necessary for the implementation of

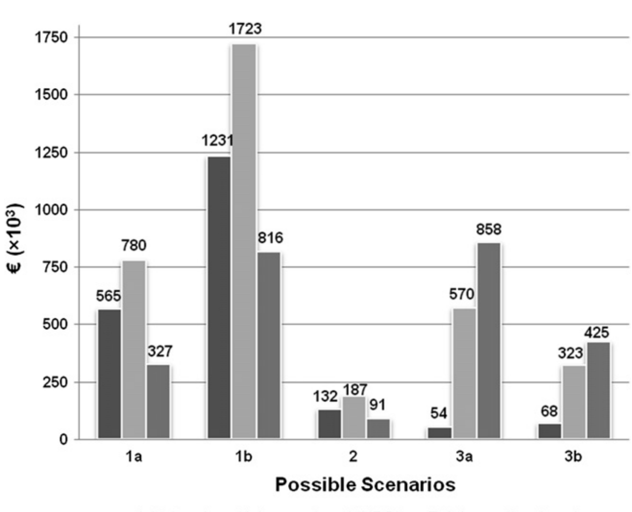

Fig. 4 – Economical results for each scenario.

Scenario 1b. Moreover, for the last two scenarios, the emissions are increased, because of the use of the internal combustion engine and the grid connection (if any).

Finally, the best scenario will be judged by using the economical criteria, where the preferable unit will be that with the lowest capital and operational costs as well as the lowest NPC through 25 years. From Fig. 4, the scenarios with the internal combustion engines have low initial costs but through the years the total amount of money which must be spent is very high because of the fuel's price. On the other hand, the units which use exclusively RES (Scenarios 1b & 2) have high initial costs but low operational ones. Furthermore, albeit hydrogen is a promised technology, it seems to be too expensive to be used instead of other, more mature, RES. Conclusively Scenario 2, is still the best option because it satisfies the economical criteria, as well.

5. Conclusions

By using the software tool HOMER, different scenarios are studied for the coverage of the desirable electric load in a unit which is already established in Leicestershire, UK. In the present work, several different feasible ways for the coverage of an electric load with a combined usage of different "green" technologies have been investigated. The grid connection is found to be inessential and at the same time the total costs can be significantly decreased. Specifically, the best-proposed Scenario 2 presents 22.8% better load coverage (without grid connection), 100% lower emissions level (zero emissions) and 76% lower total cost (76.6% decrease for the initial and 72.2% for operational costs). These results indicate a potential solution for the global energy problem in the direction of an environmental-friendly financially efficient solution based only on RES.

REFERENCES

[1] Clúa JGG, Mantz RJ, De Battista H. Hybrid control of a photovoltaic-hydrogen energy system. Int J Hydrogen Energy 2008;33:3455–9.
[2] Shakya BD, Aye L, Musgrave P. Technical feasibility and financial analysis of hybrid wind-photovoltaic system with hydrogen storage for Cooma. Int J Hydrogen Energy 2005;30:9–20.
[3] Gammon R, Roy A, Barton J, Little M. Hydrogen and renewable integration (HARI); 2006.
[4] Little M, Muray T, David I. Electrical integration of renewable energy into stand-alone power supplies incorporating hydrogen storage. Int J Hydrogen Energy 2007;32:1582–8.
[5] Muselli M, Notton G, Louche A. Design of hybrid-photovoltaic power generator with optimization of energy management. Sol Energy 1999;65:143–57.
[6] Tsikis I, Coutelieris FA. A mathematical model for the estimation of the energetic potential for several renewable energy sources: application on the design of a modern power plant. Defect Diffus Forum 2009;297–301:1414–9.
[7] Duffie JA, Beckman WA. Solar engineering of thermal processes. John Wiley & Sons, Inc; 1980.
[8] Manwell FJ, McGouan GJ, Rogers LA. Wind energy explained theory design and application. USA: John Wiley & Sons, Ltd; 2002.

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[9] Paish O. Small hydro power: technology and current status. Renew Sust Energy Rev 2002;6:537–56.
[10] Foss FJ. Basic engineering fluid mechanics. In: Johnson WR, editor. The handbook of fluid dynamics. CRC Press LLC; 1998.
[11] Appleby AJ, Foulkes FR. Fuel cell handbook. New York, USA: Van Norstand Reinhold; 1989.
[12] Hamelin J, Agbossou K, Laperrieve A, Laurencelle F, Bose T. Dynamic behavior of PEM fuel cel stack for stationary appplicationas. Int J Hydrogen Energy 2001;26:625–9.
[13] Brealy AR, Myers CS. Principles of corporate finance. USA: McGraw-Hill; 1991.
[14] Bernal-Agustin JL, Dufo-Lopez R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sust Energy Rev; 2009:2111–8.
[15] Carter Wind Systems, Maintenance manual model 25, Carter Wind Systems, Inc. 569–2238.
[16] Murillo S, Miguez JL, Porteiro J, Gonzalez LML, Granada E, Moran JC. LPG: pollutant emission and performance enhancement for spark-ignition four stroke outboard engines. Appl Therm Eng 2005;25:1882–93.

Latin symbols

A: surface area, m^2
C: cost, €
CRF: capital recovery factor
f: annual inflation rate
G: mean annual solar radiation, W/m^2
g: gravity, m/s^2
h: head, m
i: real interest rate
i': nominal interest rate
K: number of devices
N: number of years
OR: orientation factor
P: power, W
Q: volumetric flow rate, m^3/s
u: velocity (m/s)Greek symbols
ρ: density, kg/m^3
η: efficiency factor, %Subscripts
eff: effective
gen: generator
hydro: hydro potential
inv: inverter
NPC: net present cost
PV: photovoltaic
solar: solar potential
tot: total
turb: turbine
wind: wind potential