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Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation

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ABSTRACT

In this paper we show a multi-objective evolutionary algorithm (MOEA) for the optimisation of stand-alone (off-grid) hybrid systems (photovoltaic-wind-diesel-battery) to minimise total net present cost (NPC) and maximise human development index (HDI) and job creation (JC). Optimisation of this kind of system is usually performed considering only the minimisation of cost (NPC or the levelised cost of energy), as well as the emissions and the unmet load in some cases. In this paper, for the first time, we consider the maximisation of HDI and JC as part of optimisation. HDI depends on the consumption of electricity, so the extra energy that can supply the hybrid system can improve the HDI index. JC is different for each technology, obtaining different values for each combination of components in the system. The three objectives are often opposed, so a Pareto-optimisation MOEA is a good option to obtain a set of possible solutions in which no solution is better than another one for all three objectives (optimal Pareto set). We provide an example in the optimisation of a hybrid system to supply electricity to a small community in the Sahrawi refugee camps of Tindouf.

1. Introduction

In off-grid stand-alone systems (far from the electrical grid), the electrical supply is usually provided by diesel generator (with or without battery storage), photovoltaic generator (PV) with battery storage, wind turbines with batteries or hybrid systems. Previous studies show drivers and barriers to rural electrification by off-grid renewable energy systems [1–4]. Other works show the optimisation of stand-alone hybrid systems by minimising the NPC of the system or the levelised cost of energy (LCE) [5–11]. In some previous works, the authors apply heuristic techniques as genetic algorithms (GA) [12,13] in order to reduce the computation time of the optimisation. Most of these studies only optimise the cost (NPC or LCE), but some previous works also consider other objectives, such as the minimisation of CO_2 emissions and/or unmet load by applying Pareto-optimisation MOEA [14–20].

In this paper we present, for the first time, a methodology for the optimisation of a hybrid system (Fig. 1) to supply the electrical load of a rural off-grid area without electricity access while minimising NPC and also maximising HDI and JC. As each component (PV generator, wind turbines, diesel generator, battery bank and inverter/charger) can present different sizes or technologies, the number of possible combinations of components and control strategies could be too high, and the evaluation of all of them could imply inadmissible computation time, so heuristic techniques are applied to perform the optimisations within an acceptable computation time. In this paper we use an MOEA combined with a GA.

In the literature review, we found no previous work which has considered the three objectives (NPC, HDI and JC) using an optimisation methodology. Rojas-Zerpa and Yusta [21,22] proposed a combined application of two multi-criteria decision-making methods (Analytical Hierarchy Process and Compromise Ranking method) to facilitate the selection of the best solution for electrical supply of remote rural locations, considering technical, economic, environmental and social criteria (including HDI and JC). Their work uses weights for each criterion, which are selected based on the opinions of experts, and uses multi-criteria methods, not multi-objective optimisation methodologies.

The system with all possible components is shown in Fig. 1. It is

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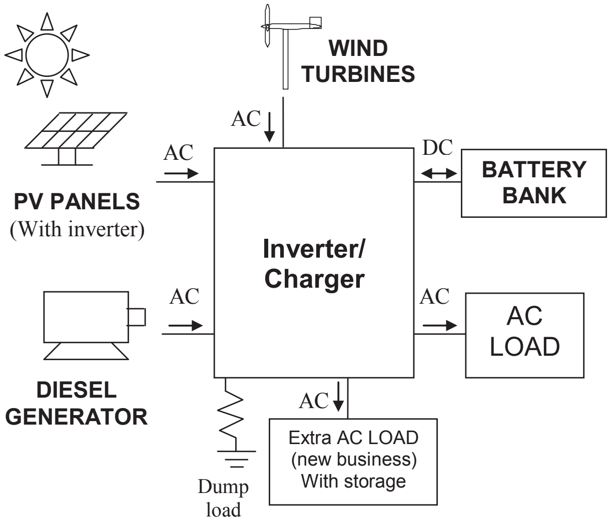

Fig. 1. AC coupled PV-wind-diesel-battery system.

an AC coupled system; different possible configurations are shown by Salas et al. [23]. In Fig. 1, the AC load is the load that must be covered by the hybrid system; that is, the expected load that is mandatory to cover. The excess energy produced by the PV and the wind turbines (when the AC load is fully covered and the battery bank is at full charge) can be used by new extra business or services (extra AC load, with their own battery storage), incrementing the total load consumed by the community and then increasing the HDI. A dump load is used to consume electricity produced by the wind turbines when the AC load and the extra AC load are covered and the batteries are full.

HDI is a country development indicator that takes into account life expectancy at birth, expected years of schooling and gross national income per capita [24]. In 2014, 17.8% of the world's population did not have access to electricity; i.e. 1285 million people [24,25].

Access to electricity can improve all of these indicators and then increase HDI. For example, life expectancy can be increased by the supply of potable water (which can be easily extracted by electrical pumps) and food conservation can be improved by means of electrical refrigerators, among other factors. Education can be improved with electricity, as it enables the use of computers and electric lighting. Gross national income per capita is also improved with electricity access, as new services and business can be developed.

The United Nations [24] classifies countries as having a low, medium, high or very high human development index. HDI depends on the electricity use per capita in a logarithmic dependency introduced by Pasternak [26] with data for 60 countries from the United Nations Human Development Report 1999 [27] (Eq. (1)).

$$\mathrm{HDI} = 0.091\ \ln\left(E_{\mathrm{load\_annual\_per\_capita}}\right) + 0.0724 \tag{1}$$

where $E_{\mathrm{load\_annual\_per\_capita}}$ (kWh/yr/person) is the annual electricity consumption per capita.

Later Rojas-Zerpa [28] showed also a logarithmic dependence (with different fit parameters) with data for 128 countries [29] (Eq. (2)).

$$HDI = 0.0978\ \ln\left(E_{\mathrm{load\_annual\_per\_capita}}\right) - 0.0319 \tag{2}$$

The JC of various electricity generation technologies has been studied by different researchers [30–36]. Ramanathan and Gadesh [30] studied the number of employees per GWh/yr (energy supplied during one year) by the different technologies in India. The unit jobs/(GWh/yr) are adequate for fossil fuel technologies like diesel generators, as the lifetime of a generator (and also the operation and maintenance cost) depends on the number of hours of operation (and therefore on the energy supplied). Fuel consumption also depends on the amount of energy supplied, so the jobs related to this kind of technology are correctly measured in jobs/(GWh/yr) of energy supplied. These researchers [30] reported 0.17 jobs/(GWh/yr) for electricity generated by diesel in India in 1984–85. This value has fallen since then due to technological advances and improved labour productivity; Rojas-Zerpa [28] proposes a value of 0.14 jobs/(GWh/yr) for diesel or gasoline electricity generation.

For other technologies, such as PV generators or wind turbines, different units are used for job creation. Many studies use units for jobs in manufacturing and installation (non-continuous activities) of PV and wind power plants in terms of job·years per MW (where MW means peak power for PV and maximum output power for wind turbines), denoted in many cases as job-years/MW or person-years/MW. One job·year means a full-time job for one person for a duration of 1 year. However, operation and maintenance (O&M) jobs (continuous activities whose duration is the whole lifetime of the system) are usually measured in jobs/MW. For example, in a power plant of 20 MW that requires 50 persons for 1 year for the manufacturing of its components and 25 persons for 6 months for the installation, the number of job·year/MW is calculated as (50 job·1 year + 25 job·0.5 year)/20 MW = 3.125 job·year/MW. If the power plant's expected lifetime is 25 years, we could normalize to the average jobs during its lifetime, so we can consider that it has created an equivalent number of full-time permanent jobs (i.e. jobs during its lifetime) of 3.125 job·year/MW/25 years = 0.125 jobs/MW. In the same example, if for O&M the power plant of 20 MW needs 5 persons, then 5 job/20 MW = 0.25 jobs/MW in O&M during its lifetime. So, during its lifetime, the equivalent total number of permanent full-time jobs is 0.125 + 0.25 = 0.375 jobs/MW.

Wei et al. [31] compare three previous studies of PV generators obtaining a great range between 0.41 and 2.48 jobs/MW (including manufacturing, installation and O&M), and compares five studies of wind turbines obtaining a range between 0.39 and 0.8 jobs/MW. Many other studies obtain different values using different units, including or excluding indirect jobs. Cameron and Van der Zwaan [36] compare different studies, including all the phases (manufacturing, installation and O&M) and considering both direct and indirect jobs, normalized to the units of jobs/MW, obtaining the results shown in Table 1.

2. Methodology

In this section the mathematical models of the components used in the simulation and evaluation of each combination of components and control strategy are shown. After that, we describe the multi-objective optimisation techniques using MOEA and GA. Finally, in this section we show the calculation of the variables to be optimised (NPC, HDI and JC).

Table 1
Total job creation including all phases, direct and indirect jobs [36].

	Total job creation (jobs/MW)		
	Minimum	Mean	Maximum
PV	0.5	2.7	7.6
Wind	0.2	1.1	2.9