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Conference paper

Multi-objective optimization of a photovoltaic/wind/diesel pumping system with water tank in the Adrar region

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ABSTRACT

Irrigating the remote regions of southern Algeria, which generally use diesel generators, with clean, environmentally-friendly energy is a challenge. Taking into account the solar and wind potential of the Adrar region, a renewable system using both sources seems more cost-effective. The realization of hybrid renewable energy systems takes into account several technical, economic and environmental aspects. This study consists in finding an efficient and adequate energy supply for the irrigation of one hectare of date palm in the Adrar region. It proposes a mathematical modelling for the given problem in different possible models, for this, we used the basic concepts of multi-objective optimization (bi-objective), and the adaptation of the concept of genetic algorithms to find solutions. The theoretical foundations discussed in this research have enabled us to design and implement a software that optimizes the hybrid pumping system used for the irrigation of date palms by minimizing the total cost and reducing CO2 emissions produced by the diesel group.

1. INTRODUCTION

It is well known that the optimal sizing methods of Hybrid systems can be classified into four categories: Intuitive method, analytical method, numerical method and intelligent method (Hontoria, Aguilera, and Zufiria 2005; Rawat, Kaushik, and Lamba 2016; Muhsen, Khatib, and Nagi 2017; Nekkache et al. 2018). Intuitive methods are the simplest, but they are less accurate and provide a rough estimation of the system component size. This method is based on the designer experience to determine the size of the

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PV system components according to "worst month" or yearly average values, including a certain safety margin. In this method, simple mathematical equations are used and the estimate is generally oversized.

Analytical methods are simple and more accurate, relying on empirical relationships to calculate the sizing of the PV system components. These methods employ developed mathematical modelling for sizing a reliable and/or cost effective PV system. With these methods, the calculation of system's size is very simple and accurate, but their main drawback is the complexity of equation coefficient calculation ("coefficient" depends heavily on the location and technical specifications of the system components).

Numerical methods use a system simulation for each time and calculate the system's energy balance and the storage unit's State Of Charge (SOC). In general, the drawback of these methods is that they require long-term meteorological data and heavy calculations to best simulate system performance over a wide range of configurations. These long-term meteorological data are often used in many simulation software packages (PVSYST, HOMER, Retscreen, etc.) or in simulation environments such as MATLAB, TRANSYS, LABVIEW, etc.(M. Khattab et al. 2020; Yahyaoui et al. 2017; Sharma, Sharma, and Tiwari 2020; Al-Badi et al. 2018; Elkholy and Fathy 2016)

Intelligent methods use artificial intelligence (AI) techniques such as artificial neural networks, fuzzy logic and nature-inspired metaheuristics.

Metaheuristics are a class of intelligent self-learning algorithms for finding near-optimum solutions to hard optimization problems, mimicking intelligent processes and behaviors observed from nature, sociology, thinking, and other disciplines. Recently, a large class of metaheuristics has been used in many fields to solve complex optimization problems, due to their advantages over traditional optimization techniques. These methods are very accurate, reliable and can process incomplete data, but they require high computations.(Mazloumi et al. 2023; Nekkache et al. 2023; Ahmed and Demirci 2022; Monís et al. 2020)

The review of PV systems sizing methods highlighted above, reveals the growing interest in the use of AI-based methods, particularly Metaheuristics. For this purposes, several recent metaheuristics have been applied in our study, some of them have been used for the first time in the PV pumping systems design.

This study uses a genetic algorithm to solve the economic and environmental multi-objective sizing problem. The main novelty of this paper is that it considers different types of renewable energy combined with one non-renewable energy while taking environmental impacts and all life-cycle costs of the equipment into account.

This paper is organized as follows: Section 2 presents the materials and methods where the optimization algorithm is described. Followed by the results and discussion of the algorithm in Section 3. Conclusions are drawn in Section 4.

2. MATERIALS AND METHODS

2.1 Hybrid PV/wind/diesel pumping system description

The pumping system consists of a motor, a pump and a tank for the water storage. The interaction between the components allows the engine to convert the electrical energy provided by the hybrid system (PV-Wind-Diesel generator) into mechanical energy. The mechanical energy at the output of the engine makes it possible to run the pump, which will itself convert the mechanical energy received into hydraulic energy.

Thereafter, the water at the pump outlet will be stored in an adequate tank that depends on the water demand of the site to be irrigated.

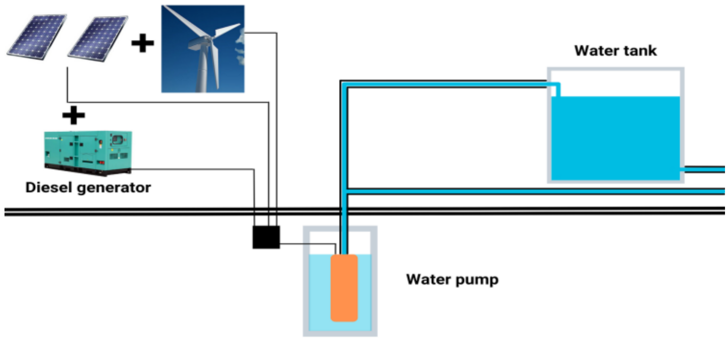

Fig 1. Schematic diagram of a hybrid PV/Wind/DG water pumping system with tank

2.2 Hybrid PV/wind/DG pumping system mathematical model

2.2.1 PV module modelling

PV modules often operate at maximum power. This explains why the maximum power of the PV module/generator becomes an important point in PV module/generator modelling, and its estimation represents the main part of system component modelling. It can be modelled as follows: (Khenfous et al. 2018; Skoplaki and Palyvos 2009).

$$P_m = P_{max,ref} * \left(\frac{G}{G_{ref}}\right)[1 - \gamma(T_c - 25)] \tag{1}$$

Where: $P_{max,ref}$: Reference power under STC (1000 W/m^2, 25°C), T_c: Module temperature (°C) and γ temperature coefficient of the power.

2.2.2 Wind turbine model

The most simplified model to simulate the power of a wind turbine can be described by:(Roy et al. 2022)

$$P_W(v) = \begin{cases} P_r * \left(\frac{V^2 - v_S^2}{V^2 - v_n^2}\right), & (v_S < v < v_n) \\ P_r, & (v_n < v < v_c) \\ 0, & (v > v_c) \end{cases} \tag{2}$$

With: v_S starting speed of the wind turbine, v_n rated speed, v_c Cut-off wind speed and P_r is the rated power.

2.2.3 Diesel generator modelling

Diesel generator modelling is based primarily on fuel consumption, which is linked to electrical power using the following model: (Dufo-López and Bernal-Agustín 2008; Khirennas et al. 2021).

$$q_{GD}(t) = a.P_{GD}(t) + b.P_{GD.nom} \tag{3}$$

q_{GD} (t) hourly fuel consumption. a and b [l/kWh] characteristic constants of the diesel generator. P_{GD} (t) power generated at time t. $P_{GD.nom}$ nominal power.

2.2.4 Modelling the motor-pump unit

Pumps are generally selected according to their operation, which depends on wellhead and flow rate. The motor-pump unit can be modelled using the following exponential model: (Bakelli, Hadj Arab, and Azoui 2012)

$$Q_{pump}(P,h) = \propto (h) exp^{\left(\beta(h)/P_{pump}\right)} \tag{4}$$

The coefficients α(h) and β(h) depend on the total head of the pump.h.
With:

$$\alpha (h) = a_0 + a_1.h + a_2.h^2 + a_3.h^3$$
$$\beta(h) = b_0 + b_1.h + b_2.h^2 + b_3.h^3$$

2.2.5 System operation strategy

To find the best configuration for your pumping system, it's important to define its operating strategy. *This* strategy takes into account the size of the tank, the amount of water pumped and the amount of water stored in the tank, which must meet load requirements at all times. The capacity and size of the water storage tank are generally taken in reference to autonomy days, which is often taken to be between 1 and 3 days, depending on the availability of renewable resources.

The tank's fill state depends on the hybrid energy system's output and load (demand) requirements. The following equation expresses the state of water tank storage:

$$\Delta Q = Q_{pump} + SOC - Q_L \tag{5}$$

- If ΔQ> 0: the remaining water is used to refill the reservoir. If the tank is completely full, the excess is discharged and SOC = SOC_{max}.
- If ΔQ< 0: the total quantity of water cannot satisfy the load and SOC = SOC_{min}. In this case, the diesel unit is switched on at maximum power to fill the tank and satisfy the load.

Thus, the power supplied to the pump becomes, $P_{pump} = P_{PV} + P_{wind} + P_{diesel}$

Notations: Q_L: Water load demand. Q_{pump}: Pumped water quantity. Q_{max}: Maximum water quantity. SOC: Tank State Of Charge. P_{PV}: Photovoltaic array power. P_{wind}: Wind turbine power. P_{diesel}: Diesel power. P_{pump}: Power supplying the pump. P_{nom}: Pump rated power.

2.3 Multi-objective optimization

Most real-life optimization problems are described in terms of several objectives or criteria, often contradictory and sometimes complementary, which must be optimized simultaneously. (Heydari et al. 2023).

2.3.1 Decision variables

Defining the decision variables for our model, we have:

N_{PV} and $N_W \in \mathbb{N}^+$: integer variables that determines the number of photovoltaic modules and wind turbines respectively, needed to supply the electrical energy. The PV module used is SYP-50M-175 and the wind turbine is Whisper H80 1000W.

- $D_t \in \{0, 1\}$: A binary variable worth 1 if the diesel unit is on at time t, 0 otherwise.
- $R \in \mathbb{R}^+$: A positive real variable that determines the water tank capacity

2.3.2 Constraints

- Total water volume must meet the load demand
- The power supplied to the pump must not exceed the pump's rated power
- Tank capacity between a quarter and 3 times the maximum water quantity

2.3.3 Objective functions

Objective function of cost.

The economic calculation of the pumping system is based on the costs of maintenance C_m, replacement C_{rep}, operating C_{oper} and initial investment IC_{cap} of each system component (total life-cycle cost). Interest and inflation rates are considered in this study. Costs are given in Dollars. Its expression is given by the following equation: (Agajie et al. 2024)

$$LCC = IC_{cap} + C_m + C_{rep} + C_{oper} \tag{6}$$

The initial capital cost is the sum of the initial costs of all system components

Table 1. Costs of each system component in Dollars

Equipment	Unit cost (US$/W)	Maintenance cost (% of cost)	Lifetime (years)
PV module	1.5	1	25
Wind turbine	3	3	20
Diesel generator	700 $	0	30 000 hours
Motor-Pump	0.7	3	10
Inverter	0.711	0	10
Tank	130 $/m^3	1	25
Total installation cost	30% of PV, wind and diesel + 10% motor-pump unit		

Objective function of CO_2 emissions.

The total amount of CO_2 produced by the diesel generator over 1 year is the correct measure of pollutant emissions and can therefore be used as a target to minimize. The CO_2 emission function is written as follows: (Suryoatmojo 2014)

$$E_{CO2} = \sum_{1}^{8760} \delta_{diesel} * q_{DG}(t) \tag{7}$$

δ_{diesel} CO_2 emissions per liter of diesel consumed

Problem complexity.

To measure the difficulty of a problem, we can calculate its algorithmic complexity by calculating its size: In terms of variables, our model (Strategy) comprises: 8760 binary, 2 integer and 1 continuous variables. Moreover, in terms of constraints, it contains 8670 constraints of type (1), 8760 constraints of type (2) and 1 constraint of type (3).

Given the large problem size and mixed variables, and the fact that some non-linear constraints (type 1) are difficult to relax, this leads to NP-hard complexity. This model cannot be tested using solvers (exact methods), so we are turning to evolutionary solution methods. We are going to use evolutionary algorithms that exploit the principle of Darwinian genetics to solve NP-hard problems in general, and multi-objective optimization problems in particular.

3. RESULTS AND DISCUSSION

In what follows, we will describe the development environment for the resolution, and then adapt the method described in the previous section to our problem. Finally, we will present the application developed and how it works with the data provided by our center.

3.1 Application presentation

In this study, there are two objective functions to be minimized: lifetime cost and CO_2 emission with three decision variables, namely: the number of PV modules, the number of wind turbines and the capacity of the water storage tank. Lower and upper limits are given for each variable. The input data for the simulation program are the meteorological data and the annual demand profile illustrated in the following figure

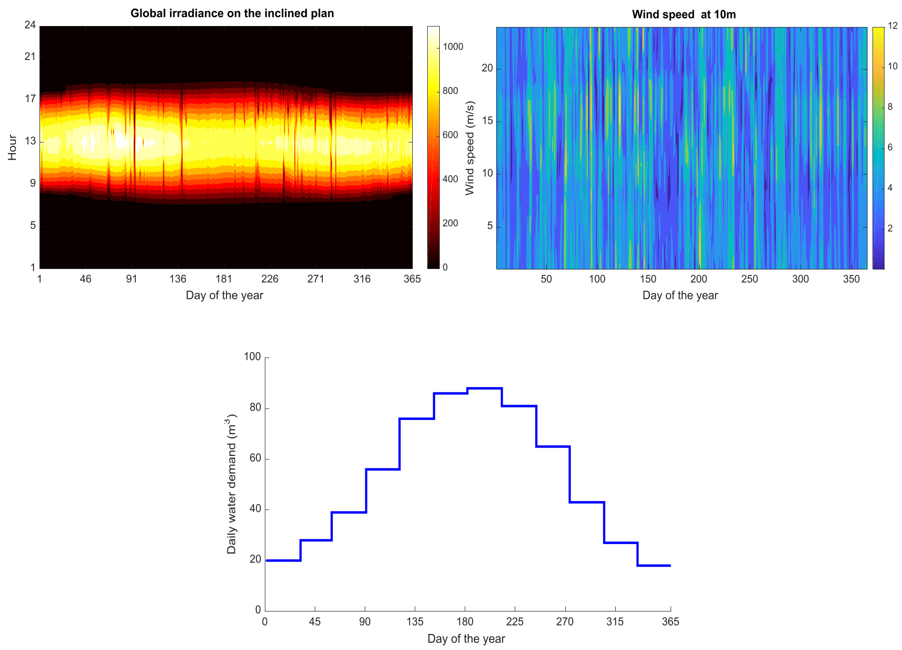

Fig 2. Input Data of the simulation program

3.2 Algorithm adaptation

In this section, we present our adaptation of the NSGA II algorithm to solve our problem. To solve our problem, we have taken into account criteria concerning the state of the system at each initial population generation: every time the sum of the power supplied by the PV and wind generators exceeds the power of the pump, a reduction in the number of wind generators is affected. In our case, the first objective function is the sum of the unit, replacement and maintenance costs of each system component, the aim being to minimize this function, and similarly for the second function, which is defined by the sum of the quantity of fuel used, multiplied by a constant.

Minimizing these functions will therefore give a good balance between energy uses. To achieve this, we created a function that randomly activates the diesel generator instead of the wind generator.

This algorithm is based on the principle of genetic algorithms: a population of individuals (solutions) evolving at the same time, each solution represented in the form of a chromosome. An artificial chromosome (usually in the form of a chain) represents each possible solution to the problem. In our case, an artificial chromosome represents the number of PV panels, wind turbines, fuel tanks and diesel consumption.

3.3 Process and results

The program was tested on real data for 2019 provided by the CDER center.

The program generates a number of efficient solutions, and it is up to the decision-maker to choose the most suitable solution from these.

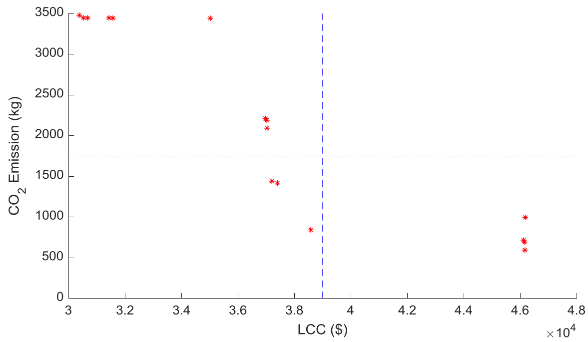

Fig. 3. Graph of efficient solutions after several iterations

We have taken results from several compilations of our method to compare with the results of the method used from CDER.

Table 2. The results of the NSGA-II algorithm

	Number of PV modules	Number of wind turbines	Tank capacity m^3	Number of operating hours of Diesel generator	LCC ($)	CO_2 Emissions (kg)
Solution 1	12	0	34	577 h	37202,037	1440,154
Solution 2	10	0	28	626 h	37033,984	2091,593
Solution 3	12	0	36	568 h	37401,408	1417,691
Solution 4	15	1	41	238 h	46166.667	594.032

3.4 The results of the algorithm

The time taken to run the entire application for a size of 8760 hours over the twelve months of the year was 520,642 seconds, which is a fairly reasonable time considering the large size of the problem and its usefulness.

The results obtained are therefore satisfactory and meet the desired objective. They demonstrate the performance and efficiency of the NSGA II algorithm.

The results show that a PV/Diesel/tank system is the best solution based on LCC, offering the lowest cost 37033,984 $ and the for the lowest CO_2 emissions with 594.032 kg for a PV/Wind/Diesel/tank system.

4. CONCLUSION

For the optimal dimensioning of a hybrid water pumping system, consisting of photovoltaic (PV) modules, a wind generator, a motor-pump unit and a diesel unit with a tank, whose objective is to satisfy water needs while minimizing the total cost of the system and reducing CO_2 emissions.

After defining the system's operating strategy, we formulated the mathematical model that takes into account the problem's objective functions, constraints and set of decision variables.

We chose a multi-objective evolutionary method to solve this bi-objective optimization problem. NSGA II enabled us to give the Pareto front, which contains the set of non-dominated solutions.

The present work can be improved by adding: forecasting studies on meteorological conditions (wind speed, sunshine, temperature); adding another reliability objective, which will be maximized. As well as a comparative study between a system with and without water tank storage.

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