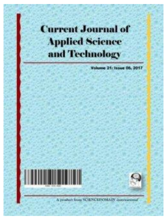

Current Journal of Applied Science and Technology

29(1): 1-15, 2018; Article no.CJAST.43842
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843,
NLM ID: 101664541)

Dimensioning of a Water Pumping System by the Systematic Scanning Method

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Authors' contributions

This work was carried out in collaboration between all authors. Author GCS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors VP and VC managed the analyses of the study. Authors ES and AV managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2018/43842
Editor(s):
(1) Dr. Singiresu S. Rao, Professor, Department of Mechanical and Aerospace Engineering, University of Miami, Coral Gables, USA.
Reviewers:
(1) Boussaibo André, University of Ngaoundéré, Cameroon.
(2) Essam El Shenawy, Egypt.
(3) Vimal Chand Sontake, Nagpur University, India.
Complete Peer review History: http://www.sciencedomain.org/review-history/26196

Original Research Article

Received 24 June 2018
Accepted 07 September 2018
Published 12 September 2018

ABSTRACT

This paper presents the design of a wind pumping system coupled to a reservoir of water storage. The objective functions used in the design process are the loss of power probability (LPSP) concept for the reliability, the life cycle cost (LCC) for the economic evaluation and the CO_2 emissions of life cycle regarding the processing of the various components of the system. The presented model, allows an optimised design of wind pumping system taking into account technical, economic and environmental criteria while ensuring the needs of the consumer without interruption. The optimisation is based on a systematic scanning approach that makes it possible to generate without restriction all the candidate solutions. The design variables considered are the wind turbines number (NW), the type of wind (TW), the tank number (N_{tank}), the type of tank (T_{tank}), type mast (T_{tower}) and the total head (T_{head}), that is to say, the type of well. A case study is conducted to analyse one wind turbine pumping project. The system is designed to supply drinking water in a rural community

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located at Sèmè-Kpodji, Benin (6°22’N, 2°37’E, 7m). The ten best solutions are presented and the one with the greatest desirability is a set of 11 wind turbines and 4 storage tanks (a 36.4% ratio) of type (1), with an initial investment cost of 27368 US dollars and a water shedding rate (LPSP) of 9.55%.

Keywords: Wind turbine; optimisation; motor-pump model; desirability; objective function.

1. INTRODUCTION

Water is a vital element and covers about 70% of the surface of the planet. It is used to supply drinking water for people, livestock, irrigation, etc. The alarming deterioration of the water quality and the growing inequality of water resources coupled with reduced rainfall in many arid countries engender serious problems in terms of health, urban planning, economics, brief development. Today, many African countries are experiencing a great crisis of drought. Faced with this situation, a question arises: How to power these water populations, whose absence is a factor of the underdevelopment? Groundwaters seem to be the only alternative to this dilemma, but all is not enough to have groundwater; it is indispensable to develop technology for pumping the water extraction. Pumping water has become a major issue for the improvement of living conditions and socio-economic development of rural communities nowadays. Several technologies provide a valid, and sustainable solution. Pumping systems can be classified according to their energy source: Manual - pedal - powered by animal traction - wind - a diesel generator respectively gasoline - photovoltaics. However, pumping systems supplied with the wind, or photovoltaic energy are getting more and more attractive and competitive from cost and performance viewpoints compared to water pumping equipment using conventional energy sources. Systems powered by renewable energy sources (solar and wind) are particularly appropriate in remote areas where fuel supply is problematic. Benin has in its southern part some wind corridors that are conducive to the development of windmills of pumping. In the literature, several studies have been achieved relating to water pumping to supply populations. Thus, some authors have developed different models of energy (hybrid and non-hybrid), while others have worked on a methodology to estimate the economic and energy cost of the life cycle of sub-components of such systems (Badescu [1]; Hamidat, Hagj Arab and Boukadoum [2]; Odeh, Yohanis and Norton, 2010; Borowy and Salameh, 1996; Ai et al. [3], Kaabeche et al. [4]; Markvart [5], Yang et al. [6]; Ekren and Ekren [7]; Bernal-Augustín et al. [8]; Dufo-López and Bernal-Augustín [9]; Yang et al. [10]; Kaabeche et al. [11]; Diaf et al.[12]; Deshmukh and Deshmukh [13]; Rajendra and Natarajan [14]; Khan and Iqbal [15]; Koutroulis et al. [16]; Borrowy and Salameh [17]; Ofry and Brauntein [18]). With most of the design methods encountered in the literature, the size of the tank is often only roughly estimated. Thus, in the case of the too small tank, there is a risk of overflow of water. But with an over-sized tank, the construction costs may become too high. In this paper, the optimisation of a wind system, with water storage tank (see Fig. 1) to supply the electrical demand for water pumping in a small town located near Cotonou (Benin) is investigated. The optimisation is based on the concepts of minimisation of LPSP (Loss of Power Supply Probability), the life-cycle cost (LCC) for the economic and CO_2 emissions for sustainable development. The systematic method of scanning is used in the context of identifying the set of solutions without restriction, which are ranked in descending order according to their desirability. The method implemented is divided in four steps. Firstly, the analysis of the water needs of the locality are determined, then draw up models of the various components of the system are achieved, followed by the determination of performance criteria and the different rates of satisfaction and finally the classification and selection of solutions are processed.

2. MATERIALS AND METHODS

2.1 Consumption Profile Adopted

Water requirements of the selected location are not negligible. The final water uses distribution obtained in this study is the following: faucets (39.20%), toilets (22.2%), showers (19.9%), clothes washers (9.7%) and finally leaks (8.9%) (See Fig. 1).

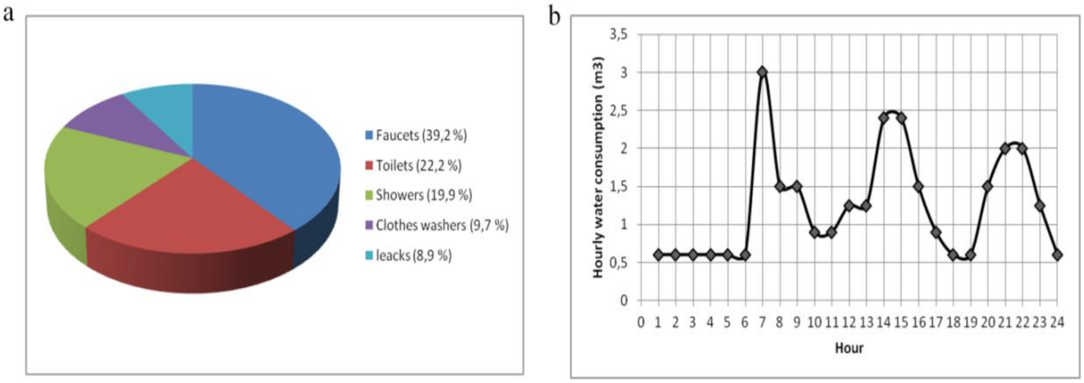


Fig. 1. Water use: (a) Water uses distribution (b) Hourly water consumption profile through the day

Consumption is not constant every day of the year; it fluctuates according to the months of the year, according to the weeks of the month, the days of the week and different times of the day. This variation reflects in the time the rhythm of human activities. The daily water consumption of the town is 30 m^3/day (this daily consumption is assumed constant along the year), and the hourly water consumption profile through the day is shown in Fig. 1.

2.2 Description of the Pumping System

To meet these needs, wind turbines can be used as an energy source for pumping water. The system used herein comprises a turbine, a water source; a water tank and a subsystem pumping (pump and motor) (see Fig. 2). For wind-driven pumping systems, storage of water in tanks is the most popular solution compared to electrochemical energy storage in batteries. Instead of storing surplus energy produced inexpensive batteries, the exceeding wind energy is utilised to store water in tanks. This approach shows excellent performance under real operating conditions. The wind pumping system permits the conversion of mechanical energy into electrical energy through a rotor coupled to a generator, which powers the AC pump. The nominal power of the pump concerned in this study is 1000 W.

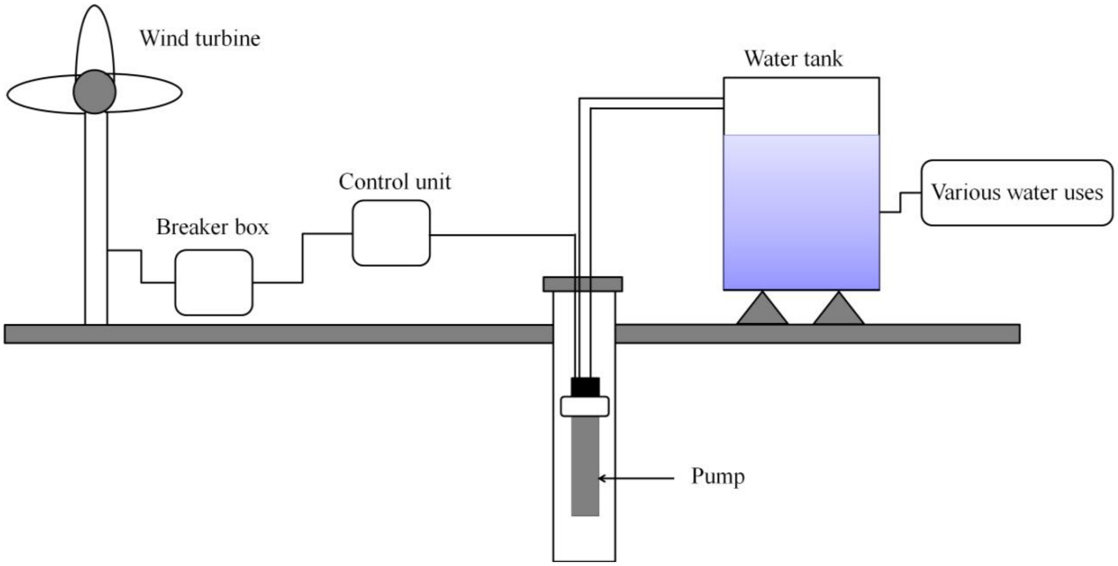


Fig. 2. Configuration of a wind turbine powered pumping system

2.3 Mathematical Model of Wind Turbine Production

The power output of the wind turbine generator at a specific site depends on wind speed at hub height and speed characteristics of the turbine. Wind speed at hub height can be calculated by using the power-law equation according to Yang and Burnett [19] .

$$V_2 = V_1 \left(\frac{Z_2}{Z_1} \right)^{\alpha} \tag{1}$$

Where V_1 and V_2 represent the wind speed at hub and Z_1 and Z_2 reference height, and α is roughness coefficient whose value generally varies between 0.1 and 0.25 depending on the site. The one-seventh power law (0.14) is a good reference number for relatively flat surfaces such as the open terrain of grasslands away from tall trees or buildings. The power generated by the turbine is calculated as follows, after Fogelman and Montloin [20].

$$P_W = \begin{cases} 0 & ; \quad V_c \le V_W , V_W \le V_c \\ P_{W\max} * \left(\dfrac{V_W - V_c}{V_r - V_c} \right)^3 & ; \quad V_c < V_W \le V_r \\ P_{W\max} + \dfrac{P_f - P_{W\max}}{V_o - V_r} * \left(V_W - V_r \right) & ; \quad V_r \le V_W \le V_o \end{cases} \tag{2}$$

Where, V_c, V_o and V_r represent respectively the cut-in, cut-out, and rated speeds of the turbine (m/s). Also, $P_{W\max}$ is the maximum output power of the turbine and P_f is the power when $V_W = V_o$. The two turbines used in this study are of IMEX-Blade using Maglev technology. Their characteristics are summarised in Table 9.

2.4 Pumping Subsystems Model

To determine the power of a pump immersed in a well or borehole or that of a surface pump, it is necessary to know the total head and the nominal flow rate. Thus, considering a wind pumping system, the required electrical power output to the motor-pump combination can be expressed as (Clarck et al. [21]; Bouzidi et al. [22]; Arab et al. [23]):

$$P_L(t) = \frac{\rho g Q H_t}{3600 \eta} \tag{3}$$

Where Q is the output water flow rate (m^3 / h), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), H_t is total head (m) and η is the power efficiency of the motor-pump combination.

The hourly consumption corresponding energy (Wh) of the pump is given by:

$$E_L(t) = P_L(t)\, \Delta T \tag{4}$$

Where ΔT symbolises the simulation time step which is equal to 1 hour. With such assumptions, power and energy are equal in value.

2.5 Water Storage Tank Model

The state of charge of a tank depends on wind production and water needs of users. Thus, the energy stored in the tank at a time t can be expressed as follows:
Water storage charging,

$$E_{\tan k}(t) = E_{\tan k}(t-1) + \left(E_W(t) - \frac{E_L(t)}{\eta_{conv}} \right) \times \eta_{\tan k} \tag{5}$$

Water storage discharging,

$$E_{\tan k}(t) = E_{\tan k}(t-1) + \left(\frac{E_L(t)}{\eta_{conv}} - E_W(t) \right) \tag{6}$$

Where $E_{\tan k}(t)$ and $E_{\tan k}(t-1)$ the energy stored in the tank (Wh) at the time *t* and *t-1*, respectively; $E_W(t)$ is the total energy generated by wind turbines after energy loss of controller (Wh); $E_L(t)$ is the energy hydraulic demand at the time (Wh); η_{conv} and $\eta_{\tan k}$ are the conversion efficiency and charge efficiency of water storage tank, respectively, is taken equal to 1. At any time *t*, the charged quantity of the water storage tank is subject to the following two constraints:

$$0 \le E_{\tan k}(t) \le E_{\tan k, \max} \tag{7}$$

Where $E_{\tan k, \max}$ is the maximum storage capacity of the tank.

The functioning of the tank is similar to that of a battery in an ordinary wind system. Thus, when the production of wind energy is sufficient, water needs are satisfied and the energy is used to fill the storage tank. The water capacity of the tank is determined from equation (5). In the case where the production of wind is not enough, then water is drawn from the tank, so its capacity must be predetermined from equation (6) in order that the reservoir could correctly ensure that function.

2.6 Criteria for Evaluating System Performance

2.6.1 Definition of criteria

The choice of criteria is a crucial step in the formulation of an optimisation problem. Here the necessary criteria to evaluate the performance of the system are related to economic, environmental and reliability standards.

2.6.2 Models criteria

The randomness that characterises the production system requires an analysis that takes into account its whole life cycle. Thus, the costs of energy and the economic life cycle of the system are studied.

2.6.2.1 The economic model based on the LCC concept

Life cycle cost (LCC) includes the value of the initial investment, the cost of replacing the component, the cost of maintenance and repair and the cost of downtime. For a component of the system I, the economic cost of the life cycle (during 25 years) can be expressed by the following equation (Navaeefard et al. [24]; Dehghan et al. [25]; Khan et al. [15]):

$$LCC_i = N_i\left(CI_i + CR_i.K_i + CMR_i.PWA\left(ir, R_v\right)\right) \tag{8}$$

With:

$$K_i = \sum_{n=1}^{y_i} \frac{1}{\left(1+ir\right)^{nL_i}} \tag{9}$$

$$y_i = \left(\frac{R_v}{L_i}\right) - 1, \text{ If } R_v \text{ is dividable to } L_i \tag{10}$$

$$y_i = \frac{R_v}{L_i}, \text{ If } R_v \text{ is not dividable to } L_i \tag{11}$$

$$PWA\left(ir, R_v\right) = \frac{\left(1+ir\right)^{R_v} - 1}{ir\left(1+ir\right)^{R_v}} \tag{12}$$

Where N_i is the number of component i s, CI_i is the initial investment cost, CR_i is the replacement cost, CMR_i is the cost of maintenance and repair of component i. PWA and K_i are annual and single payment present worth factors, respectively. y_i and L_i are the numbers of replacements of component i and its lifetime. ir is the real interest rate, R_v is the project's lifetime.

The total economic cost of the life cycle of the system can then be deduced:

$$C_{total} = \sum_i LCC_i \tag{13}$$

Table 1. Components specifications (Thiaux, [26]; Khan et al. [15] ; Navaeefard et al. [24]; Yang et al. [10]; Yang et al. [6]; Bakelli et al. [27])

Component	CI	CR	CMR	Efficiency (%)	Life (yr)
Wind turbine	2 US$/W	2 US$/W	0.02 US$/W/yr	-	25
Water tank	0.55 US$/$m^3$	0.55 US$/$m^3$	0.0055 US$/$m^3$/yr	100	25
Motor pump	2.73 US$/W	2.73 US$/W	0.08 US$/W/yr	45	10
Converter	0.7 US$/VA	0.7 US$/VA	0.007 US$/yr	90	15
Tower	250 US$/m	250 US$/m	6.5 US$/m/yr	-	25
Water drilling	0.27 US$/m	0.27 US$/m	0 US$/m	-	25

Table 2. Energy consumption and CO_2 emissions in the system equipment manufacturing (Thiaux [26]; Madam [28])

Components	Facility energy	CO_2 emissions
Wind turbine	0.215 kWh/W.yr	69 g CO_2/W.yr
Water tank	445 kWh/m^3.yr	34000 g CO_2/m^3.yr
Converter	0,4 kWh/VA.yr	12,5 g CO_2/VA.yr
Tower	7.2 kWh/m	5.9 g CO_2/m

Table 3. Levels of criteria

Criteria	Aim	USL	AUC
CI	Minimize	100	50000
CR	Minimize	100	50000
CMR	Minimize	418	800
LPSP	Minimize	0	60 %
GER	Minimize	957766085	$1.0246*10^9$
GES	Minimize	723597795	$5.8365*10^9$

In this study, the following assumption are made: *ir* = 6% and R_v = 25 years. The economic costs of the different components of the system are summarised in Table 1.

2.6.2.2 Gross energy requirement

The life cycle analysis is a tool for decision support in eco-design for evaluating the environmental impact of the system, from raw material extraction to end of life system. The indicator chosen in this study is the Gross energy requirement (GER). This cost represents the total primary energy required for the manufacture, maintenance, recycling and transport to the place of use of the system. For an autonomous wind system, the overall energy cost can be computed as follows:

$$GER_{Total} = N_W.P_n.GER_W.DV_W + N_{\tan k}.E_{\tan k,\max}.GER_{\tan k}.y_{\tan k}.DV_{\tan k} + P_{n,conv}.GER_{conv}.y_{conv}.DV_{conv} + GER_{tower}.H \tag{14}$$

Where GER_{Total} the primary energy cost of the system, GER_W is the primary energy cost of the wind, P_n is rated power, DV_w is the lifetime of the wind. $GER_{\tan k}$ is the primary energy cost DV_{tank} is the lifetime, y_{tank} is the number of replacements, of the water tank. GER_{conv} is the primary energy cost, DV_{conv} is the life cycle, y_{conv} is the number of replacements, of the converter. GER_{tower} is the primary energy cost of the wind turbine mast and *H* is the height of the wind turbine mast.

In relation (14), the primary energy relative to the manufacture of the motor pump is assumed to be negligible compared to the other terms for reasons of simplification (this is a first approach hypothesis).

2.6.3 Lifecycle CO_2 emissions

Energy consumption during the implementation of the system generates CO_2 emissions can also be evaluated as follows:

$$GES_{Total} = N_W.P_n.GES_W.DV_W + N_{\text{tank}}.E_{\text{tank},\max}.GES_{\text{tank}}.y_{\text{tank}} + P_{n,conv}.GES_{conv}.y_{conv}.DV_{conv} + GES_{tower}.H \tag{15}$$

Where GES_{Total} is a total CO_2 emission of the system, GES_W is CO_2 emission from wind $GES_{\tan k}$ is CO_2 emission from the water tank, GES_{conv} is CO_2 emission from the converter, GES_{tower} is CO_2 emission from the tower.

In relation (15), for reasons of simplification, the CO_2 emission relating to the manufacture of the motor pump is assumed to be negligible compared to other terms (a first approach hypothesis).

Table 2 shows the calculation results for the energy consumption and CO_2 emissions during system equipment manufacturer. These are the numerical values per unit capacity per year.

2.6.3.1 Loss power supply probability

Because of the intermittent wind speed characteristics, which highly influence the energy production from the system, power reliability analysis is usually considered as an important step in any such system design process. There are a number of methods used to calculate the reliability of the systems. The most popular method is the loss of power supply probability (LPSP) method. The LPSP is the probability that an insufficient power supply results when the system (wind power and energy storage) is not able to satisfy the load demand. The design of a reliable stand-alone wind system can be pursued by using the LPSP as the key design parameter. For an analysis period T (1 year in this study), the LPSP is the ratio of the sum of all values of energy loss LPS for the same period of the energy required.

The loss of energy is expressed by (Bogdan and Salameh [29]:

$$LPS(t) = E_L(t) - \left(E_W(t) + E_{\tan k}(t-1)\right)\eta_{conv} \tag{16}$$

LPSP is expressed by

$$LPSP = \sum_{t=1}^{T} LPS(t) / \sum_{t=1}^{T} E_L(t) \tag{17}$$

2.7 Models of the Rates of Satisfaction

The different criteria used in this study do not have the same weight. To solve that problem of scaling, desirability functions are processed to obtain dimensionless criteria. But the choice of a desirability function depends on the requirements of the investigated problem. In our case, all criteria are to be minimised as displayed in Table 5. For the purpose, the function of the desirability of Harrington is applied (Sebastian et al. [30]):

$$d(Y_m) = \exp\left(-\exp\left(\beta + \alpha . Y_m\right)\right) \quad , \quad \text{avec}$$

$$\alpha = \frac{\ln\left(\ln(0{,}01) / \ln(0{,}99)\right)}{AUC - USL}, \tag{18}$$

$$\beta = \ln\left(-\ln(0{,}99)\right) - \alpha . USL$$

Where *d* is the desirability associated with the criterion Y_m, AUC is the absolute upper cutoff, *USL* is the upper soft limit for the criterion. Levels of criteria are summarised in Table 3.

Then, the criteria are gathered according to the aggregation method based on the weighted geometric mean of the functions of desirability (Derringer et al. [31]):

$$DOI_k = \prod_{r=1}^{q} d_r^{\vartheta_r} \tag{19}$$

Where DOI_k are the indices of desirability and ϑ_r the weights relating to the criteria

DOI_1 is the index relating to the economic shutter, DOI_2 is related to the reliability of the system, DOI_3 is related to the environmental aspects.

Desirability indices obtained are aggregated according to the same principle to lead to the global objective function:

$$OF = \prod_{k=1}^{3} DOI_k^{w_k} \tag{20}$$

Where w_k symbolises the weighting coefficients concerning the index of desirability.

The weights used are essential because they represent the wishes of the user in the implementation of the wind system. The values of these weights are summarised in Tables 4, 5 and 6. The different weights used in Tables 4, 5 and 6 are chosen in harmony with the importance of each criterion in the design of the system.

2.8 Optimization Method Used

In this study, ten criteria are considered. It's about:

- → the minimisation of all the criteria defined under FC1 (CI, CR, CMR);
- → the minimisation of the criteria defined for FS (LPSP);
- → the minimisation of all the criteria defined with regard to FC2 (GER, GES).

Next, to the presentation of the modelling, the optimization of the multi-criteria approach can be summarised as follow.

Table 4. Weight of the indices of desirabilities

	DOI_1	DOI_2	DOI_3
Weight (%)	22.55	67.38	10.07

Table 5. Weight-related criteria DOI_1

Criteria	**CI**	**CR**	**CMR**
Weight (%)	43.41	34.54	22.05

Table 6. Weight-related criteria DOI_3

Criteria	**GER**	**GES**
Weight (%)	60.99	39.01

To search the solutions of the so elaborated model systematic scan of the design variables is performed. Thus, for different combinations of design variables, all the corresponding global objective functions are determined.

Thus, a total of 7,200 candidate solutions are obtained and sorted in descending order according to their corresponding satisfaction rate.

Fig. 7 summarises the various steps of the optimisation method.

In the study, seven criteria are considered. These are:

Minimisation of all criteria under DOI_1 (CI, CR, CMR);
Minimisation of the criteria under DOI_2 (LPSP);
Minimisation of all criteria under DOI_3 (GER, GES).

The optimisation of the multi-objective approach can be achieved through the following algorithm:

Find $x=\left[N_W, N_{\tan k}, T_W, T_{\tan k}, T_{tower,} T_{WD}\right]^T$

Which minimises

$$OF(x)=\{CI(x), CR(x), \ldots, GES(x)\}$$

Subject to $100 \leq CI(x) \leq 50000$

$$100 \leq CR(x) \leq 50000$$

$$723597795 \leq GES(x) \leq 5.8365*109 \quad (21)$$

$$1 \leq N_W \leq 20$$
$$1 \leq N_{\tan k} \leq 10$$
$$1 \leq T_W, T_{\tan k} \leq 2$$
$$1 \leq T_{tower} \leq 3$$
$$1 \leq T_{head} \leq 3$$

Thus, for different sets of combination of design variables, the corresponding global objective functions are determined. The candidate solutions obtained are ranked in descending order according to their corresponding satisfaction.

3. RESULTS AND DISCUSSION

The proposed method is applied to a wind system designed to meet the daily water consumption needs of a rural household. Fig. 3a shows the hourly data of the wind speed at 10 m of the ground over a year and in Fig. 3b is shown the hourly data of the wind speed at 10 m and at 50 m of the ground over a day.

To check the status of operation of wind pumping system designed from models of the various constituent components, a simulation was achieved over three days. For this purpose, a wind pumping system consisting of 20 wind turbines of nominal power 1300 W each, coupled with 10 tanks of nominal capacity 50 m^3/tank is considered. The height of the mast is 70 m and the total head is 70 m. In Fig. 4 (a), are superimposed curves representing respectively the power demand and that produced by all wind turbines. From the observation of this figure, it appears that the power produced by wind turbines is not regular and is adjustable at will according to the needs of the user. For example, the maximum instantaneous power demand is 1272 W at 7 hours while the production of wind turbines is only 26 W at this precise moment. So the phase shift between wind power and water consumption does not favour the optimisation of wind nor water autonomy. As shown in Fig. 4 (a), a significant proportion of wind power is not in line with the consumption. It is, therefore, necessary to add a wind system storage tanks in this case so that they can the stored energy when the wind cannot cover the needs of the user. In Fig. 4 (b), the variation of the capacity of the tanks is a function of time, as well as the load and the power produced by wind turbines, were simulated. The simulation was started with initially empty tanks. When strong wind occurs (between 12h and 19h simulation time for example), wind turbines can supply completely the consumer's water request and fill the tanks, using extra energy. But during periods of low wind (between 20 and 30 hours of simulation time for example), wind power is insufficient, the tanks have to ensure the water demand.

Fig. 5 shows the 3-D representation for various combinations of wind turbines and tanks for different values of IC and GER. For this purpose, a wind turbine rated power 1300 W and a tank nominal capacity of 50 m^3 are chosen. The height of the mast and the total head are fixed at 70 m. It is found that the greater the number of wind turbines and tank increases, the greater IC value increases (Fig. 5 (a)). It is the same for GER (Fig. 5 (b)).

Fig. 6 shows the curves of desirability relating to IC and LPSP. In Fig. 6 (a), the request was to design a wind pumping system as much as possible by minimising the CI (U.S.$ 100). But systems with CI going so far to U.S.$ 50.000 are also accepted. But beyond this cost, the solutions are to be rejected (zero desirability). On Fig. 6 (b), it is desired to design a wind turbine system while minimising as much as possible the LPSP (1%). But systems which offer LPSP up to 60% are assumed correctly. Beyond this rate, the proposed solutions are rejected.

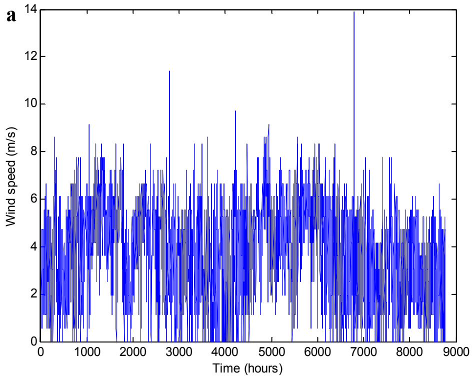


Fig. 3. Variation of wind speed: (a) Speed on a year. (b) Speed on a day to 10 m and 50 m above the ground

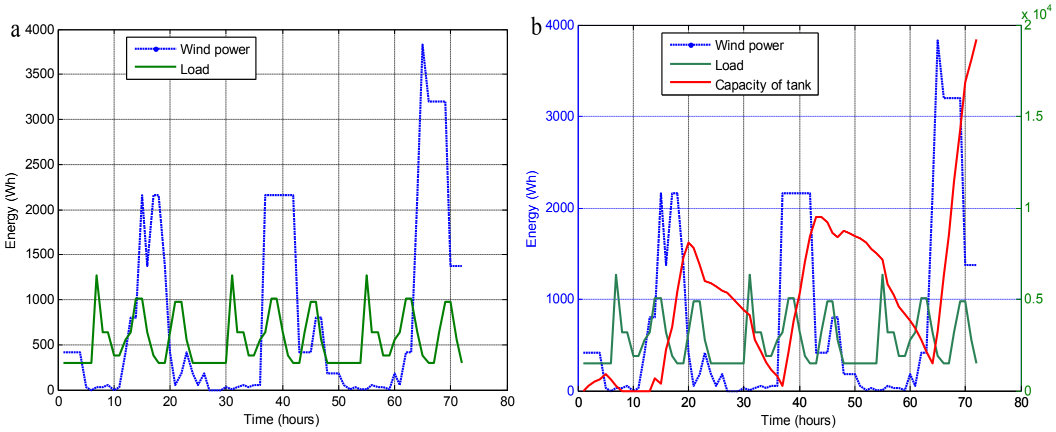


Fig. 4. Evolution of energy: (a) Called energy and energy produced by all the wind. (b) Simulation of the charge status of the tanks, the power demand and production of wind turbines versus time

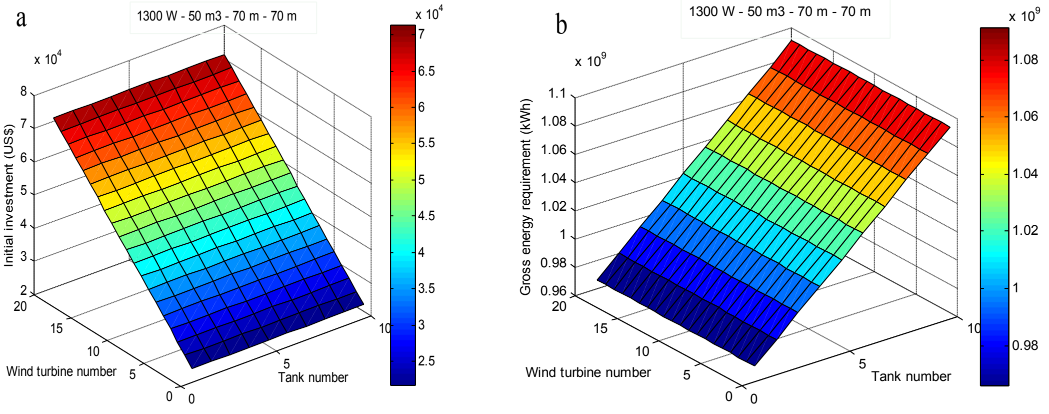


Fig. 5. 3D representation: (a) Different combinations of wind and tanks for different values of IC. (b) Different combinations of wind and tanks for different values of LPSP

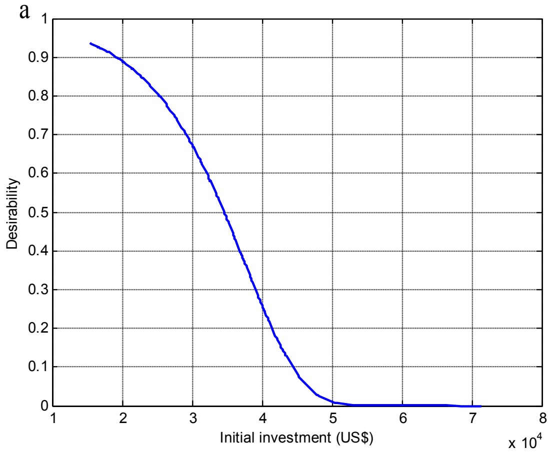


Fig. 6. Satisfaction rate: (a) Desirability relating to IC. (b) Desirability relating to LPSP

Fig. 7 (a) is an illustration of the evolution of the global objective function according to different possible configurations. The desirability of the optimal configuration is 0.9477. In Fig.7 (b) the level lines for which values are to be displayed have been selected. At this optimal configuration correspond 11 wind turbines rated power 600 W, 4 tanks of 20 m^3 capacity, a mast height of 50 m and a total head 30 m. Fig. 8 shows the relationship between the values of LPSP and different system configurations for the different total head. At each value of LPSP a set of combination of design variables corresponds. In this part, the types of wind turbines, tank, and mast are set. From the analysis of the figure, it appears that the higher the total load, the more it requires a large number of wind turbines and tanks. In addition, the lower the value of LPSP, the higher the number of wind turbines and tanks.

Table 7 presents the ten best solutions of the study as well as their characteristics. They satisfy the requirements of the problem and give results that minimise all the objectives defined in terms of three criteria while remaining within the scope of each decision variable. The first solution introduces a LPSP of 9.55%. If it is decided to cover all water needs (LPSP = 0%), then more wind turbines and tanks will be needed.

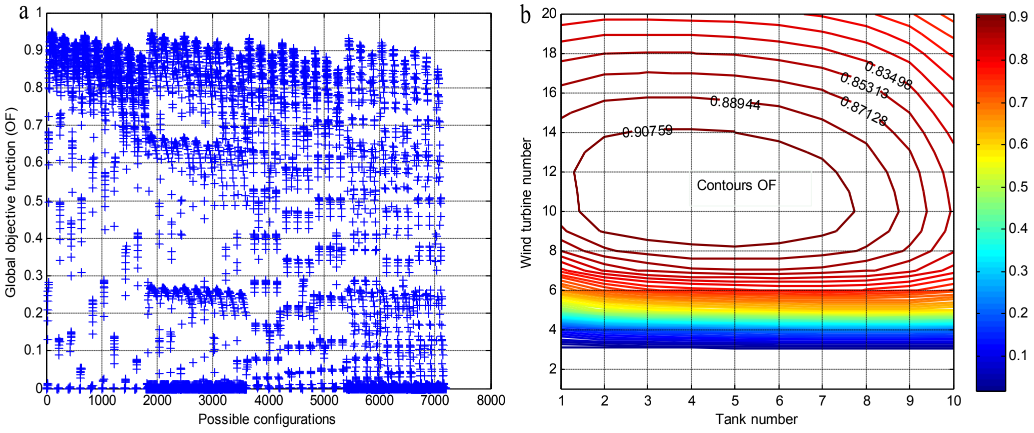
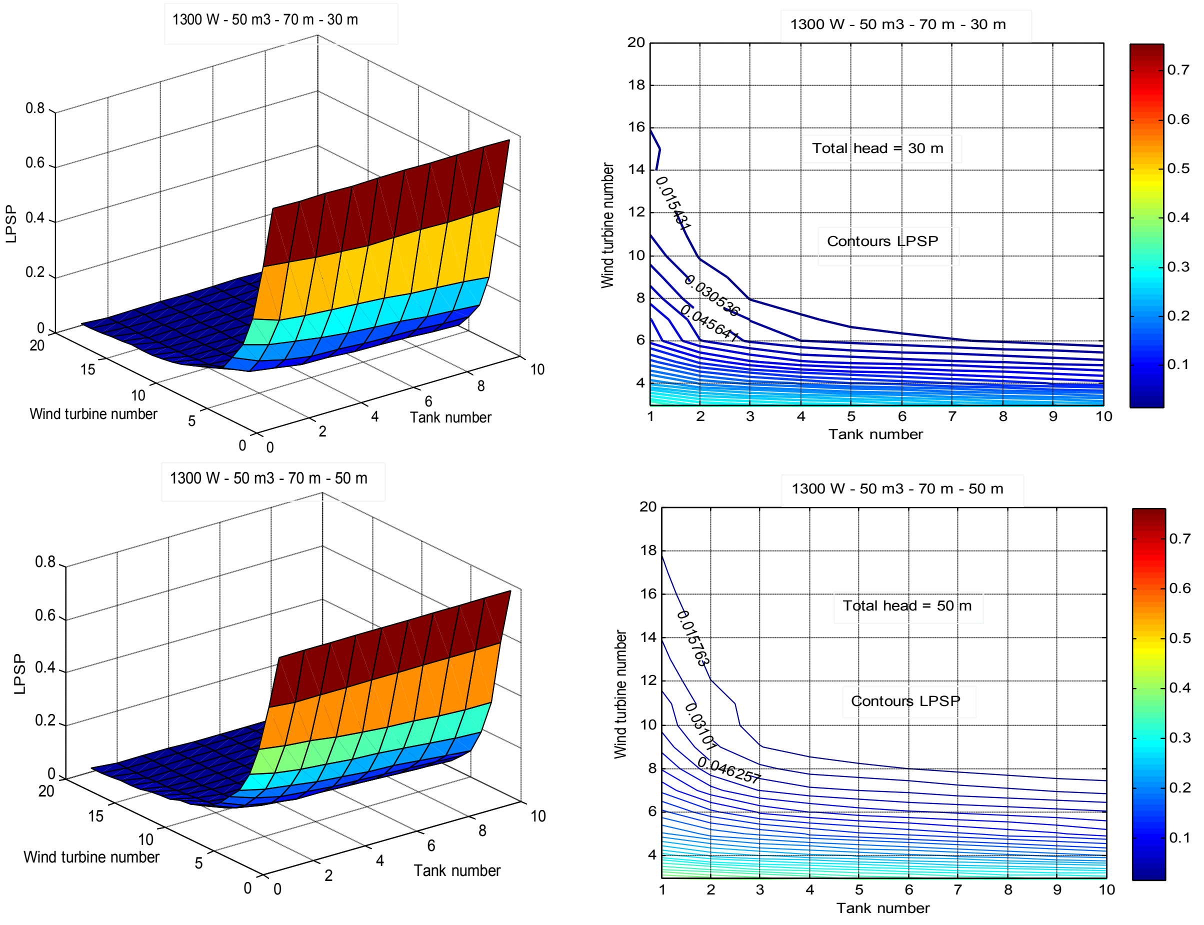


Fig. 7 (a). Evolution of the objective function based on combinations of design variables. (b) Contours of the global objective function


1300 W - 50 m3 - 70 m - 30 m
LPSP
0.8
0.6
0.4
0.2
0
Wind turbine number
20
15
10
5
0
Tank number
0
2
4
6
8
10
1300 W - 50 m3 - 70 m - 30 m
Total head = 30 m
Contours LPSP
0.015431
0.030536
0.045641
Wind turbine number
Tank number
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1300 W - 50 m3 - 70 m - 50 m
LPSP
Wind turbine number
Tank number
1300 W - 50 m3 - 70 m - 50 m
Total head = 50 m
Contours LPSP
0.015763
0.03101
0.046257
Wind turbine number
Tank number

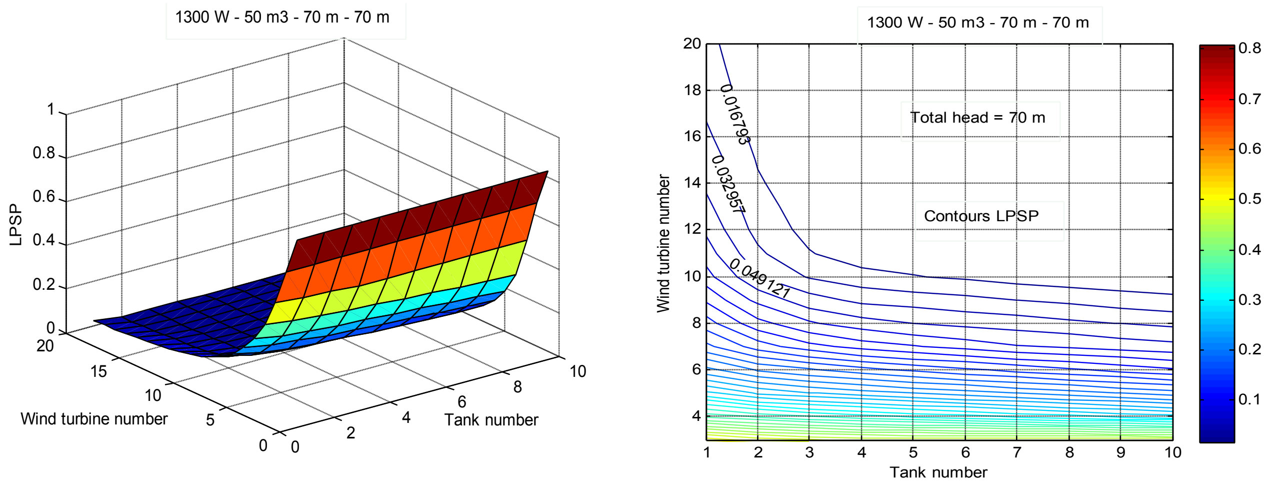


Fig. 8. Visualization of LPSP: (a) 3 D representation of LPSP. (b) Contours LPSP

Table 7. Characteristics of the ten best solutions

N°	N_W	N_{tank}	T_W	T_{tank}	T_{tower}	T_{head}	CI	RC	MRC	GER	GES	LPSP (%)	OF
1	11	4	1	1	1	1	27368	38031	537.54	974485835	2.009×10^9	9.55	0.9477
2	11	5	1	1	1	1	27379	38031	537.65	980048335	2.434×10^9	8.38	0.9465
3	11	3	1	1	1	1	27357	38031	537.43	968923335	1.584×10^9	11.31	0.9463
4	12	4	1	1	1	1	28568	38031	549.54	974489060	2.01×10^9	7.29	0.9460
5	12	3	1	1	1	1	28557	38031	549.43	968926560	1.585×10^9	8.95	0.9455
6	10	4	1	1	1	1	26168	38031	525.54	974482610	2.008×10^9	12.87	0.9451
7	10	5	1	1	1	1	26179	38031	525.65	980045110	2.433×10^9	11.63	0.9445
8	12	5	1	1	1	1	28579	38031	549.65	980051560	2.435×10^9	6.04	0.9438
9	11	1	1	2	1	1	27351	38031	537.38	966142085	1.371×10^9	12.52	0.9431
10	12	1	1	2	1	1	28551	38031	549.38	966145310	1.372×10^9	10.08	0.9429

4. CONCLUSION

In this paper, an optimisation method to find the optimal configuration of a wind pumping system coupled to tanks was investigated. This system is designed to cover the water needs of a small city of Benin Republic, Africa. The performance criteria have taken into account the economic and energy costs of the system life cycle and reliability. The systematic scanning method allowed to generate a set of candidate solutions that are ranked according to their global objective function. These solutions offer the user a number of choices in accordance with their needs and their purchasing power. For example, a user who decides to meet his or her water needs without interruption (LPSP = 0%), must pay a lot more than a customer who chooses the solution N°1 of Table 8. The advantage of this method is that it makes it possible to generate all the solutions without restriction. But the main drawback is that it is greedy in computing time, unlike the genetic algorithm methods.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Annex: Characteristics of the two turbines

Table 9. Characteristics of the two wind turbine

	Wind turbine 1	Wind turbine 2
P_{Wmax}	600 W	1300 W
Diameter	1.06 m	2 m
height	1.20 m	2.1 m
V_c	1 m/s	1 m/s
V_r	12 m/s	13 m/s
V_o	65 m/s	60 m/s
P_f	580 W	1200 W

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/26196