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Optimal design of a wind system for water pumping. Using a genetic algorithm

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This article presents the design of a wind pumping system coupled to a reservoir of water storage. This work has been done with the HOGA program (Hybrid Optimization by Genetic Algorithms). Different 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 CO_2 emissions of life cycle on the production of the various system components. With the presented model, the optimization of the design of wind pumping system can be realized technically, economically and environmentally, while ensuring the needs of the consumer without interruption. Design variables used are the wind turbines number N_W, the type of wind T_W, the tank number N_{tank}, the type of tank T_{tank}, type mast T_{tower} and total head T_{head}, that is to say the type of well. A case study is conducted to analyse one wind turbine pumping projet, which is designed to supply drinking water in a rural community located at Sèmè-Kpodji, Benin (6°22'N, 2°37'E, 7m).

Keywords: wind turbine; optimization; motor-pump model; desirability, objective function, genetic algorithm.

Оптимальное проектирование насоса с ветряным двигателем для откачки воды с использованием генетического алгоритма

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Статья рассматривает вопросы проектирования насоса с ветряным двигателем, соединенного с резервуаром для хранения воды. В процессе проектирования используются такие целевые функции как вероятность потери мощности, принцип надежности, экономические издержки жизненного цикла и уровень выбросов CO_2 различных компонентов системы. Представленная модель оптимизирует конструкцию насоса с ветряным двигателем с технической, экономической и экологической точки зрения, бесперебойно обеспечивая при этом потребности потребителя. Используются следующие переменные: количество ветровых турбин N_W, тип ветра T_W, число резервуаров N_{tank}, тип резервуара T_{tank}, тип мачты T_{tower} и суммарная высота напора T_{head} — т. е. тип колодца. Исследование проводится на примере анализа работы насоса с ветряным двигателем, предназначенного для обеспечения питьевой водой сельской общины Семе-Кпожи, Бенин (6°22'N, 2°37'E, 7 м).

Ключевые слова: ветровая турбина; оптимизация; модель насоса с двигателем; желательность, целевая функция, генетический алгоритм.

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 pose 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 in our days a major issue for the improvement of living conditions and socio-economic development of rural communities. Several technologies make it possible today to bring a valid, durable and clean solution. Pumping systems are distinguished according to their energy source: Manual — pedal — powered by animal traction — wind — a diesel generator respectively gasoline — photovoltaics. However, pumping systems for wind, photovoltaics are becoming more attractive and compete from cost perspective and performance with systems using conventional energy sources. Systems powered by renewable energy sources (solar and wind) are particularly useful in remote areas where fuel supply is problematic. Benin has in its southern part some wind corridors that are conducive to the development of wind mills of pumping. In the literature, several studies have been made in the field of water pumping for water supply of the population. Thus, some authors have developed physical models of various components of a hybrid energy system or not and others have developed a methodology for estimating the economic and energy cost over the life cycle of sub-components of these systems [10, 12, 17, 19]. With present design methods, the size of the tank is often coarsely estimated. Thus, in the case of too small a tank, there has been overflow of water. As against, over-sized with a reservoir, may be present in construction costs too high. In this paper the optimization 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 described. The optimization is based on the concepts of minimization of LPSP (the power supply loss probability), the life cycle cost (LCC) for the economic and CO2 emissions. The NSGA-II algorithm, evolutionary genetic type was used in order to determine the set of optimal compromise solutions, which are ranked in descending order according to their desirability. The method used is declined in four steps. Firstly we proceed to the analysis of the water needs of the locality, then draw up models of the various components of the system, then defines the performance criteria and the different rates of satisfaction and finally proceeds to the classification and selection of solutions.

Materials and methods

1. Consumption profile adopted and Wind Data

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. 1a).

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

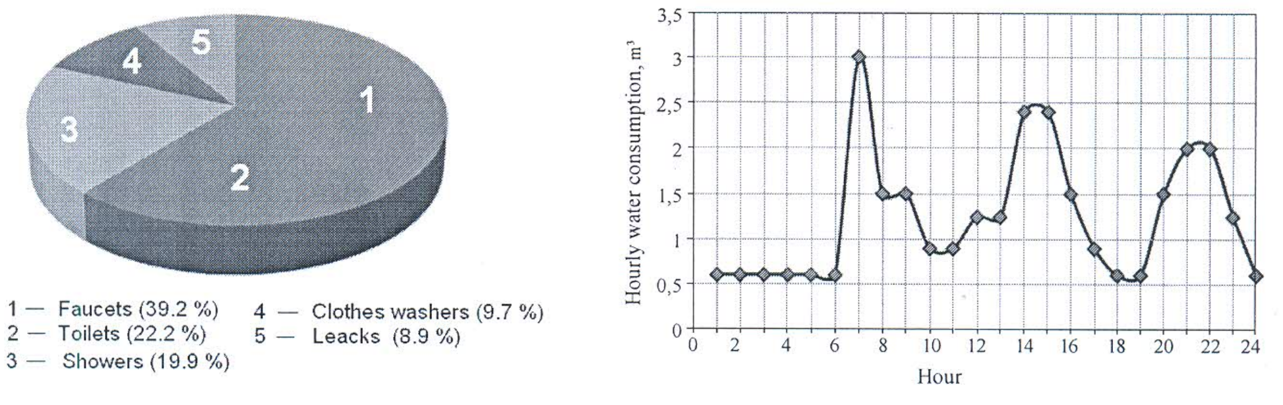

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Fig. 1. Water use: (a) Water uses distribution; (b) Hourly water consumption profile through the day

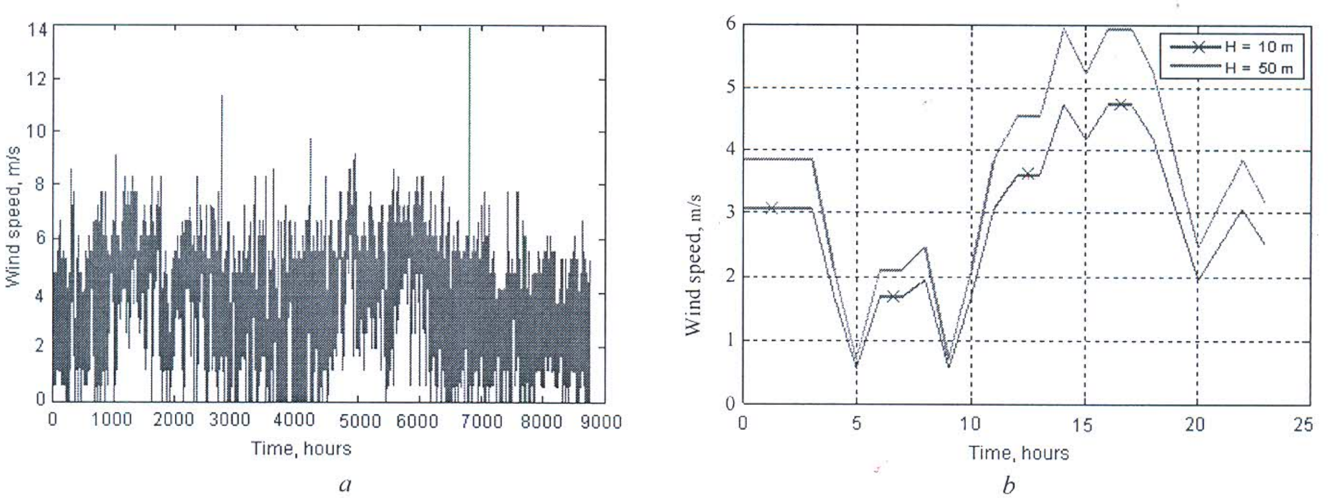

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Table 1

Design variables

Design variables	Nomenclature	Range	Component type considered
Wind turbine number	N_W	1–20	—
Tank number	N_{tank}	1–10	—
Type of wind turbine	T_W	1–2	600 W – 1300 W
Type of tank	T_{tank}	1–2	20 m³–50 m³
Type of tower	T_{tower}	1–3	50 m – 60 m – 70 m
Type of well	T_{head}	1–3	30 m – 50 m – 70 m

of human activities. The daily water consumption of the tow is 30 m³/day (we have considered that it is the same for all the day in the year), and the hourly water consumption profile through the day is show in Figure1b. The proposed method is applied to a wind system designed to meet the daily water consumption needs of rural household. Data on wind speed from the meteorological station in Cotonou, located around thirty kilometers of the site selected in this work. In addition, these data are measured at 10 m from the ground and made an extrapolation using empirical models in the literature (Equation 1) to obtain the wind speed at 50 m above the ground. In Figure 2a are represented Hourly data of the wind speed at 10 m from the ground on one year and Figure 2b are represented Hourly data of the wind speed at 10 m and 50 m from the ground over one day.

The design variables needed to determine solutions are summarized in Table 1.

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. 3). For the systems of wind pumping operating over wind, the storage of water in the tanks is the solution most adopted compared to electrochemical storage in the batteries. Instead of storing the surplus of energy produced in expensive accumulators, this is the surpluses of pumped water which are stocked in a tank. Wind pumping system allows the conversion of mechanical energy into electrical energy through a rotor coupled to a generator, which controls the pump AC rated power 1000 W.

Wind turbine system model

Power output of 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 power-law equation [15]:

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

Where V_1 and V_2 are the wind speed at hub and reference height Z_2 and Z_1 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. Choosing a suitable model is very important for wind turbine power output simulations. The most simplified model to simulate the power output of a wind turbine [10] can be described by:

$$P_W = \begin{cases} P_r \cdot \dfrac{V - V_c}{V_r - V_c} & ; \quad V_c \le V \le V_r \\ P_r & ; \quad V_r < V \le V_f \\ 0 & ; \quad V \le V_c \text{ and } V \ge V_f \end{cases} \tag{2}$$

where P_r is the rated electrical power; V_c is the cut-in wind speed; V_r is the rated wind speed; and V_f is the cut-off wind speed. The two turbines used in this study are of IMEX-Blade using Maglev technology. Their characteristics are summarized in Table 2.

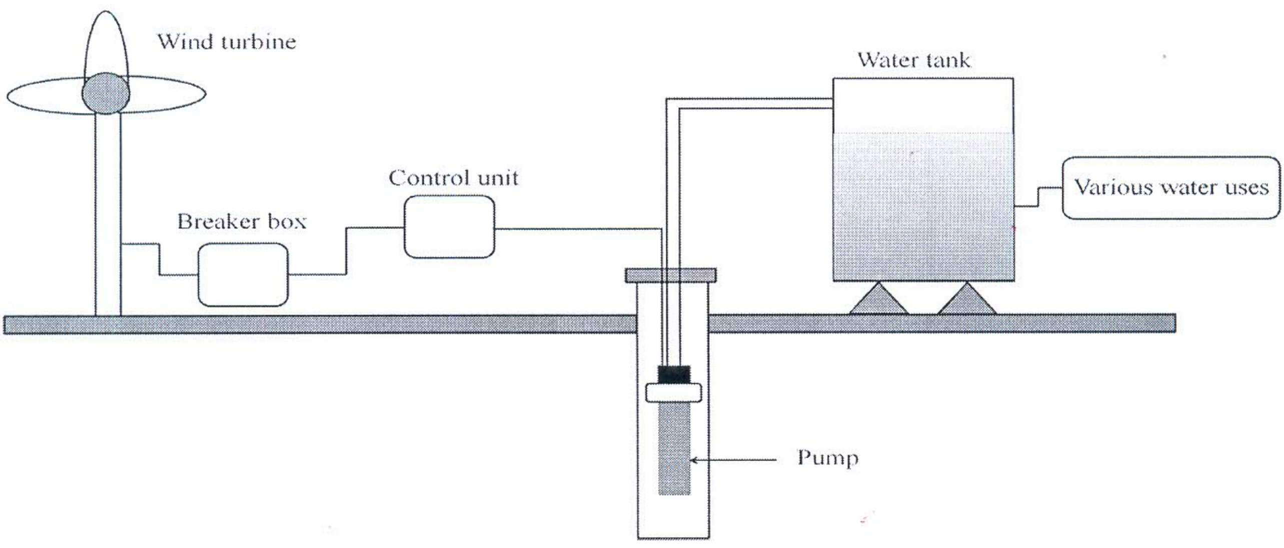


Fig. 3. Configuration of a wind turbine powered pumping system

Table 2

Characteristics of the two wind turbine

Parameters	Wind turbine 1	Wind turbine 2
P_r	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_f	65 m/s	60 m/s

Pumping subsystems model

To determine the power of a submerged wells or drilling pump or surface pump, it is necessary to know the total head well as flow that we would like to tap. Thus, whereas in a wind pumping system, the required electrical power output to the motor-pump combination can be expressed as [4, 5, 9]:

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

where Q is the output water rate (m^3/h), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), 3600 is the number of second per hour, 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:

$$E_L(t) = P_L(t)\,\Delta T \quad (4)$$

Where ΔT is the simulation step that we take equal to 1 hour. Under these conditions, we equate power and energy.

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 by the following equation:

Water storage charging,

$$E_{tank}(t) = E_{tank}(t-1) + \left(E_W(t) - \frac{E_L(t)}{\eta_{conv}}\right)\cdot\eta_{tank} \quad (5)$$

Water storage discharging,

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

Where $E_{tank}(t)$ and $E_{tank}(t-1)$ the energy stored in the tank (Wh) at the time t and t–1, are 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 t (Wh); η_{conv} and η_{tank} are the conversion efficiency and charge efficiency of water storage tank, respectively, η_{tank} is taken equal to 1. At any time t, the charged quantity of the water storage tank is subject to the following two constraints:

$$0 \le E_{tank}(t) \le E_{tank,\max} \quad (7)$$

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

The functioning of tank is similar to that of a battery in an ordinary wind system. Thus, when the production of wind is sufficient water needs are satisfied and the rest of the energy is used to fill the tank. The water capacity of the tank is determined from the equation (5). In the case where the production of wind is not enough, the tank is loaded and its capacity is determined from equation (6).

Criteria for evaluating system performance

1. The economic model based on the LCC concept

Life cycle cost (LCC) includes the cost of 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 [7, 12, 14]:

$$\mathrm{LCC}_i = N_i\left(\mathrm{CI}_i + \mathrm{CR}_i K_i + \mathrm{CMR}_i \mathrm{PWA}(ir, R_v)\right), \quad (8)$$

With:

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

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

$$y_i = \frac{R_v}{L_i} \text{ If } R_v \text{ is not dividable to } L_i \quad (11)$$

$$\mathrm{PWA}(ir, R_v) = \frac{(1+ir)^{R_v} - 1}{ir(1+ir)^{R_v}} \quad (12)$$

Where N_i is number of component i, 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 number of replacements of component i and its life time; ir is real interest rate, R_v is project's lifetime.

We then deduce the total economic cost of the life cycle of the system:

$$C_{total} = \sum_i \mathrm{LCC}_i. \quad (13)$$

In this study, we chose ir = 6% and R_v = 25 years. The economic costs of the different components of the system are summarized in Table 3 [2, 12, 14, 18–21].

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 is as follows:

$$\mathrm{GER}_{Total} = N_W P_n \mathrm{GER}_W DV_W + N_{tank} E_{tank,\max} \mathrm{GER}_{tank} y_{tank} DV_{tank} + P_{n,conv} \mathrm{GER}_{conv} y_{conv} DV_{conv} + \mathrm{GER}_{tower} H. \quad (14)$$

Table 3

Components specification

Component	CI	CR	CMR	Efficiency (%)	Life (yr)
Wind turbine	2 US$/W	2 US$/W	0.02 US$/W/yr	—	25
Water tank	0.55 US$/m³	0.55 US$/m³	0.0055 US$/m³/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

Where GER_{Total} is primary energy cost of the system, GER_W is primary energy cost, P_n is rated power, DVW is the life, of the wind. GER_{tank} is primary energy cost, DV_{tank} is the life, Y_{tank} is number of replacements, of the water tank. GER_{conv} is primary energy cost, DV_{conv} is the life, Y_{conv} is number of replacements, of the converter. GER_{tower} and H are primary energy cost and height of the mast, of the wind, respectively.

In relation (14) for lack of data, we have not considered the primary energy of the pump motor.

3. Life cycle CO_2 emissions

Energy consumption during the implementation of the system generates CO2 emissions can also be evaluated as follows:

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

Where GES_{Total} is total CO_2 emissions of system, GES_W is CO_2 emission from wind, GES_{tank} is CO_2 emission from water tank, GES_{conv} is CO_2 emission from converter, GES_{tower} is CO_2 emission from tower.

In relation (15) for lack of data, we did not take into account the CO_2 emissions on the manufacture of motor pump.

Table 4 shows the calculation results for the energy consumption and CO_2 emissions during system equipment manufacture. These are the numerical values per unit capacity per year [1, 11, 13, 18].

Table 4

Energy consumption and CO_2 emissions in the system equipment manufacturing

Components	Facility energy	CO_2 emissions
Wind turbine	0.215 kWh/W.yr	69 g CO_2/W.yr
Water tank	445 kWh/m³.yr	34000 g CO_2/m³.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

4. 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 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 [3]:

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

LPS is expressed by:

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

Models of the rates of satisfaction

The different criteria used in this study are not the same size. To solve this problem of scaling, desirability functions for transforming the variables dimensionless criteria are tapped. But the choice of a desirability function depends on the requirements of the study to be conducted in our case, all criteria are to minimize as shown in Table 6. For this purpose, the function of desirability of Harrington is used [16]:

$$d(Y_m) = \exp\left(-\exp(\beta + \alpha Y_m)\right) \text{ avec } \alpha = \frac{\ln\left(\ln(0,01)/\ln(0,99)\right)}{AUC - USL},$$

$$\beta = \ln\left(-\ln(0,99)\right) - \alpha\, USL \quad (18)$$

Where d is the desirability associated with the criterion Ym, AUC is the absolute upper cutoff, USL is the upper soft limit for the criterion. Levels of criteria are summarized in Table 5.

Table 5

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	$1.0246 \cdot 10^9$
GES	Minimize	723597795	$5.8365 \cdot 10^9$

Then, the criteria are aggregated according the aggregation method based on weighted geometric mean of the functions of desirabilities [8]:

$$ù_k = \prod_{r=1}^{q} d_r^{v_r} \quad (19)$$

Where DOI_k denote the indices of desirability and B the weights relating to the criteria. DOI1 is the index relating to the economic shutter, DOI2 is related to the reliability of the system, DOI3 is related to the environmental aspects.

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

$$\mathrm{OF} = \prod_{k=1}^{3} \mathrm{DOI}_k^{w_k} \qquad (20)$$

Where w_k denote the weighting coefficients concerning 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 summarized in Table 6.

Table 6

Indices of desirabilities	DOI_1	DOI_2	DOI_3
Weight, %	22.55	67.38	10.07
Criteria DOI_1	CI	CR	CMR
Weight, %	43.41	34.54	22.05
Criteria DOI_3	GER	GES	—
Weight, %	60.99	39.01	—

Optimization method used

The optimization of the dimensioning of wind turbine system is a multi-objective optimization. Indeed, the cost of the system should be minimal while providing consumers with quality electricity supply the best possible. The number of variables is important, our choice fell on a genetic algorithm called NSGA-II («Nondominated Sorting Genetic Algorithm II») [6]. The main parameters of this algorithm are:

- Number of generations $N_G = 50$;
- Number of individuals per generation $N_{ind} = 100$;
- Design variables (Table 1);
- Probability of crossover $P_c = 0.80$;
- Mutation probability $P_m = 0.05$;

The algorithm used to evaluate the performance of each individual by calculating the objectives, constraints specific to this individual and the global objective function after taking into account all the steps of the algorithm (crossover and mutation). In this study, six criteria are considered. These are:

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

Thus, for different sets of combination of design variables, we determine all the corresponding objective functions overall. 100 solutions candidates in total are obtained that we classify by decreasing order according to their corresponding rate of satisfaction. After modeling the problem in our approach to optimize multi-objective can be summarized as follows:

$$\text{Find } x = \left[N_W, N_{tank}, T_W, T_{tank}, T_{tower,} T_{head}\right]^T;$$
$$\text{Which minimizes } \mathrm{OF}(x) = \{\mathrm{CI}(x), \mathrm{CR}(x), \ldots, \mathrm{GES}(x)\};$$
$$\text{Subject to } 100 \le \mathrm{CI}(x) \le 50000;$$
$$100 \le \mathrm{CR}(x) \le 50000;$$
$$723597795 \le \mathrm{GES}(x) \le 5.8365 \cdot 10^9. \qquad (21)$$
$$1 \le N_W \le 20 \quad 1 \le N_{tank} \le 10$$
$$1 \le T_W,\ T_{tank} \le 2,\ 1 \le T_{tower} \le 3$$
$$1 \le T_{head} \le 3$$

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.

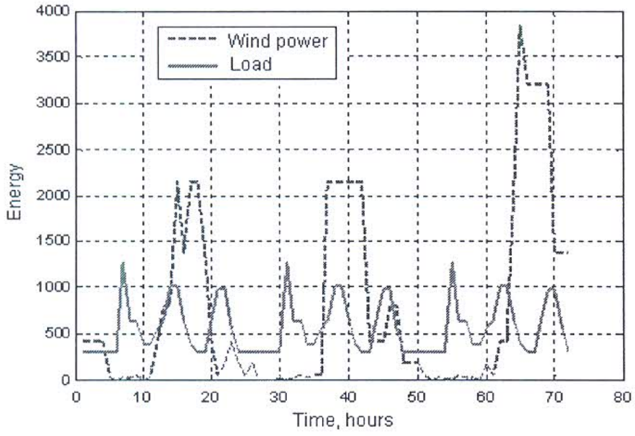
Results and Discussion

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 turbines each rated power 1300 W, coupled to 10 tanks of rated capacity 50 m^3 each is considered. The mast height is 70 m and the total head is 70 m. On Figure 4 (a), are superimposed the curves representing the load and the power produced by the entire wind turbine, respectively. From the observation of this figure, we see that the power produced by wind turbines is not regular and 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 favor the optimization of wind nor water autonomy.

As shown in Figure 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 return the stored energy when the wind will not be able to cover the needs of the user. On Figure 4 (b), the variation of the charge state of the tanks a function of time well as the load and the power produced by wind turbines were simulated. The simulation was started with initially empty tanks. In times of strong wind (12:00 h to 19:00), wind turbines it possible to supply the consumer and fill the tanks. During periods of low wind (20:00 h to 30:00), wind power is insufficient and these are the tanks ensure the cover of the needs.

Figure 5, we selected the contours for which you want to display the value. At this optimal configuration corresponds 17 wind turbines rated power 600 W, 2 tanks of 20 m^3 capacity, a mast height of 50 m and a total head 30 m ie a ratio of 255 W/m^3. Figure 6 shows the relationship between the values of LPSP and different system configurations for different total head. At each value of LPSP a game of combination of design variables corresponds. In this part, the types of wind turbines, tank, and mast are set. Analysis of this figure reveals that more total head is greater, more it requires a large number of wind turbines and tanks. In addition, more the value of LPSP is low, more the number of wind turbines and of tanks is high.

Table 7 presents the five best solutions of the study well as their characteristics. These solutions satisfy the constraints of the problem and give results that minimize all the objectives defined in terms of three criteria while remaining within the scope of each decision variable. The first solution introduces a LPSP 7.52%. If we decide to cover all water needs (LPSP = 0%), it will use more wind turbines and tanks.



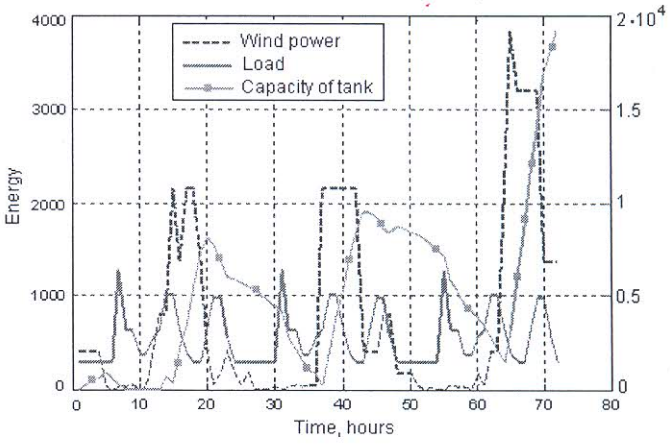


Fig. 4: Evolution of energy: (a) Called energy and energy produced by all the wind; (b) Variation of the charge state of the tank

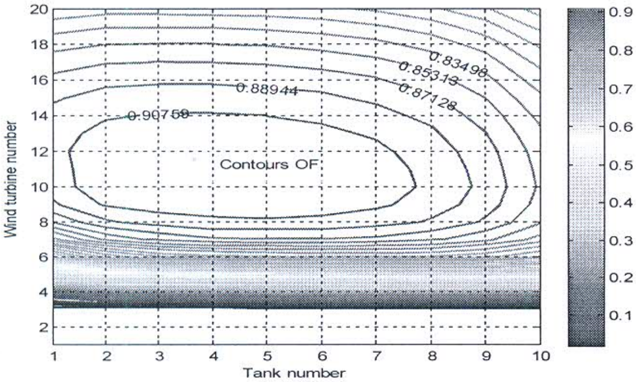


Fig. 5. Contours of the global objective function

Conclusion

In this paper, we presented an optimization method to find the configuration optimal of a wind pumping system coupled to tanks. This system is designed to cover the water needs of a city of Benin. The components of the pumping subsystem are modeled and validated by simulation that it is not the most appropriate method. The genetic algorithm is used to make system optimization. The design of the pumping system is made according to the concept of the loss power supply probability (LPSP), the concept of the life cycle cost (LCC) and the concept of the life cycle energy of the system (primary energy and CO2 emissions). Different selected criteria are not the same size, the desirability functions are put to use to solve the problem of scaling.

At the end of this study, different candidate solutions are generated and made available to the design. The best solution obtained i.e. that which with the total objective function highest, consists of 17 wind turbines, 2 tanks, all type 1 (see table 1) a 50 m mast and a well pump head 30 m. This solution requires an LCC 38958 dollars, a primary energy of 963380185 kWh and a CO2 emission 1.165.109 with LPSP 7.52%; which corresponds to a ratio of 255 W/m^3.

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Table 7

Characteristics of the ten best solutions

No	N_W	N_{tank}	T_W	T_{tank}	T_{tower}	T_{head}	CI	RC	MRC	GER	GES	LPSP,%	OF
1	17	2	1	1	1	1	34546	3803	609.32	963380185	1.165×10^9	7.52	0.9512
2	6	2	2	1	1	1	29746	3803	561.32	963367285	1.161×10^9	16.38	0.9424
3	15	3	1	1	3	2	37159	3803	715.43	968936379	1.588×10^9	6.27	0.9419
4	13	1	1	1	2	1	32235	3803	626.21	957804857	736017854	16.11	0.9403
5	14	7	1	1	2	2	33503	3803	638.87	991183082	3.2871×10^9	4.43	0.9390

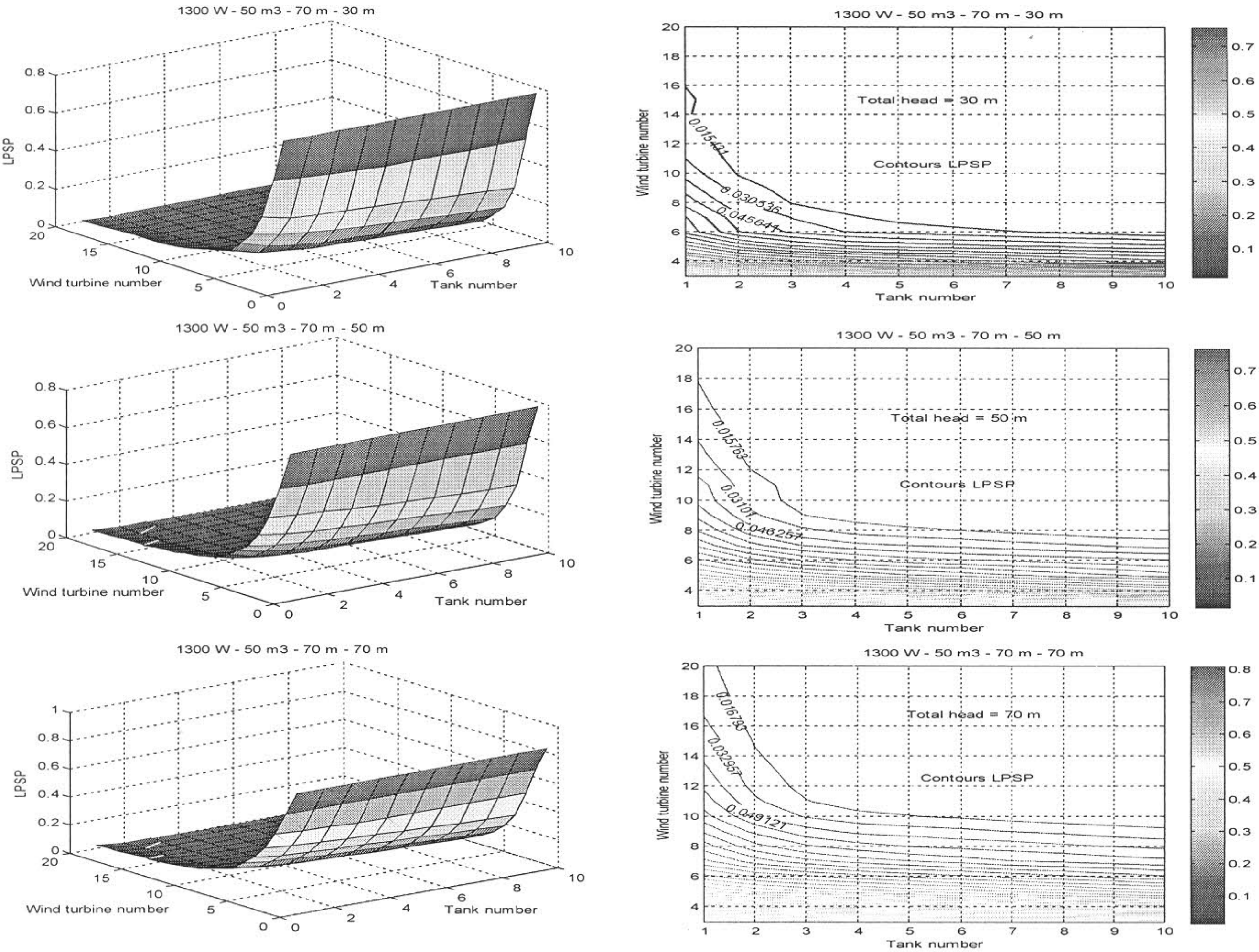

Fig. 6: Visualization of LPSP: (a) 3 D representation of LPSP; (b) Contours LPSP

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