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Optimal size of hybrid photovoltaic/diesel water pumping system with tank storage

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Abstract - *In this paper, an optimal sizing model has been performed to optimize the different configurations of hybrid PV/diesel water pumping system, (HPDWPS) employing water tank storage. The suggested model involves the sub models of the hybrid system, the Loss of Power Supply Probability, (LPSP) and the Life Cycle Cost, (LCC). Thus, through the application of the studied model, the techno-economic optimization of such system can be easily realized. The adopted methodology suggests different procedures based on the water consumption profiles, total head, tank capacity, diesel generator backup system and photovoltaic array peak power. In the aim to highlight the reliability of the developed model, a case study is conducted to investigate one hybrid system project, which is designed to supply the drinking water to secluded and scattered small villages of Ghardaïa region (South Algeria). Moreover, the optimized hybrid system is compared to other energy source options, namely PV/TANK system and Diesel/TANK.*

Résumé - *Dans cet article, un modèle de dimensionnement optimal a été réalisé pour optimiser les différentes configurations du système de pompage d'eau hybride PV/diesel, (HPDWPS) utilisant le stockage dans des réservoirs d'eau. Le modèle proposé implique les sous-modèles du système hybride, la probabilité de perte d'alimentation, (LPSP) et le coût du cycle de vie, (LCC). Ainsi, grâce à l'application du modèle étudié, l'optimisation technico-économique d'un tel système peut être facilement réalisée. La méthodologie adoptée suggère différentes procédures en fonction des profils de consommation d'eau, de la charge totale, de la capacité de la citerne, du système de secours du générateur diesel et de la puissance de pointe des panneaux photovoltaïques. Dans le but de mettre en évidence la fiabilité du modèle développé, une étude de cas est menée pour étudier un projet de système hybride, conçu pour fournir de l'eau potable à de petits villages isolés et dispersés de la région de Ghardaïa (sud de l'Algérie). De plus, le système hybride optimisé est comparé à d'autres sources d'énergie, notamment les systèmes PV/TANK et Diesel/TANK.*

Keywords: Sizing hybrid PV/diesel water pumping system - Life cycle cost (LCC) - Loss of power supply probability (LPSP) - Standalone systems - Motor-pump set model.

1. INTRODUCTION

Traditionally, diesel water pumping systems have been used to pump water, especially in remote areas. However, the price lessening of the photovoltaic module has led to a decrease in the price of the photovoltaic pumping system, which makes it very viable and it can compete with diesel pumping. Solar and wind energy systems are omnipresent, freely available, respectful of the environment.

The remoteness of many arid zones of the electricity network penalises the use of conventional energies and favours the supply of renewable energies which are abundant allowing local use [1] (Zhou *et al.*, 2010), [2] (Kaabeche *et al.*, 2011). The secluded areas are endowed with great insulation, which justifies the use of renewable energies. Photovoltaic pumping systems have a low maintenance cost compared to diesel which causes enormous CO_2 emissions and consequently the provocation of the greenhouse effect [2] (Bakelli *et al.*, 2011). In this context, various water-pumping systems have been reported in the literature.

Thus, studies in relationship with irrigation applications were reported in [3, 4] (Al-Ali *et al.*, 2001; Pande *et al.*, 2003; [5] Mahmoud *et al.*, 2003; [6] Glasnovic *et al.*, 2007; [7] Hamidat *et al.*, 2009; [8] Yu *et al.*, 2011; [9] Mokeddem *et al.*, 2011; [10] Benghanem *et al.*, 2013). Their results confirmed that these systems could be suitable in arid and semi-arid regions, due to their low and medium head irrigation systems. Moreover, their use for micro-irrigation systems proved very interesting.

Reference to the sizing optimization of PV water pumping systems, Cuadros *et al.*, presented a methodology for the optimal sizing of the photovoltaic generator feeding a drip irrigation system. The sizing has been optimized by following three steps.

Firstly, estimating the water requirements followed by a hydraulic analysis considering the pumping head, the last step was the estimation of the power required for irrigation. Lately, [2] Bakelli *et al.*, (2011). developed an optimal sizing model to optimize the size of various components of PV water pumping system with water storage tank. They used Loss of Power Supply Probability (LPSP) as a technical criterion and the Life Cycle Cost (LCC) as the economic one.

Likewise, work established by [11] Abu-Aligah (2011) scrutinize necessary steps and key components needed to design a small photovoltaic water pumping system and compare it with diesel powered pumping system. One of the significant conclusions of his work is that the output of a solar pumping system is affected by the system sizing derived from the correct site and required data.

Kelley *et al.* (2010), [12] studied the photovoltaic pumping system and demonstrated the gainfulness of the use of PV technology for pumping water. They also compared the PV pumping system to the diesel one and after this study, he proved that PV is technically and economically more interesting.

They used the maximum power required as a technical criterion and the present value cost of the two studied systems for the economic criterion. Besides the initial capital cost, the evolution of diesel and photovoltaic costs during the period of analysis greatly influences the results.

An optimal sizing of hybrid power systems (HPS) supplied by different renewable generators was presented; Power Pinch Analysis (PoPA) method has been applied for appropriate HPS sizing. The scenario considered the reduction of the size of the most expensive renewable energy generator was chosen for its lowest payback period [13] (Rozali *et al.*, 2014). Nevertheless, different procedures to provide an efficient design of such system are necessary for developing the optimal operating system performance with low cost erection [14] (Deveci *et al.*, 2015).

Other PVWPS management studies focused on water mining control or on seawater pumped electricity storage as well as on hybrid systems [15] (Paredes-Sánchez *et al.*, 2015). Throughout the current work, an optimal sizing model, to optimize the capacity sizes of different components of hybrid PV/diesel water pumping system, (HPDWPS) using water tank storage has been developed. The recommended model takes into consideration the sub models of the pumping system, the Loss of Power Supply Probability, ($LPSP = 0$, total system autonomy) and the Life Cycle Cost, (LCC).

With accordance to the requirements of system reliability, the proposed model can complete the hybrid system optimal sizing, according to techno-economic criteria. The methodology offers many procedures based on the consumption profiles of water, total head, tank capacity and photovoltaic array peak power. The optimized system is compared to other energy source option.

A case study is conducted to scrutinize one hybrid project, which is designed to provide drinking water to isolated and dispersed tiny villages located at Ghardaïa region, Algeria (32°29'N, 3°40'E, 450 m).

2. MATERIALS AND METHODS

2.1 Hybrid PV/diesel pumping system description

Provision of drinking water for human consumption in remote areas represent an interesting area of an off grid hybrid PV/diesel water pumping systems. Generally, these systems gathered a PV array, diesel generator (DG), water source; a water storage tank and an AC pump. In this configuration of hybrid power generation of water pumping systems, the water storage tank plays the same role of batteries in the classical hybrid systems and the electric power load demand is replaced by water demand.

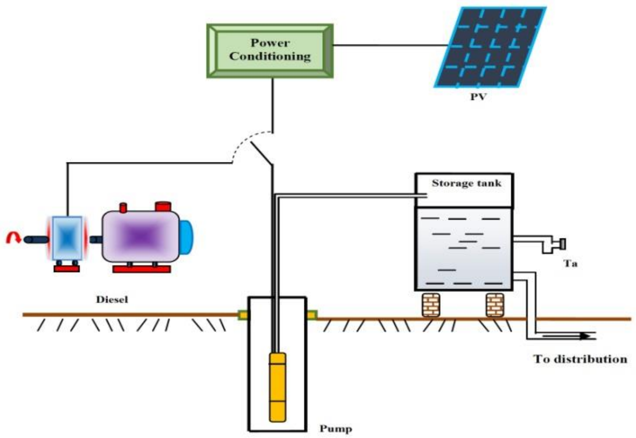

Fig. 1: Schematic diagram of a standalone hybrid PV/DG water pumping system with tank

2.2 Hybrid PV/diesel pumping system general model

2.2.1 Photovoltaic system model

The hourly output power of the PV generator in the maximum power point condition (MPP) is given by [17] (Chow *et al.*, 2006):

$$P_{PV} = I_{G,tilt} \times \tau_g \times P \times \eta_e \left(1 - \varphi_c (T_c - 25)\right) \quad (1)$$

Where P_{PV}, the electrical power output, T_c, temperature of the PV module, P, the packing factor of the PV module, τ_g, the effective transmissivity of the glazing, and η_e, the electrical conversion efficiency at the reference temperature 25 °C as well as the temperature coefficient φ_c of the solar cell.

T_c in {Eq. (1)} is usually determined via the NOCT, (Normal Operating Cell Temperature) given by the PV module manufacturer [17] (Markwart *et al.*, 2003).

$$T_c = T_a + \left(\frac{(NOCT - 20)}{800}\right) I_{G,tilt} \quad (2)$$

Where T_a is the ambient temperature (°C).

2.2.2 Diesel system model

The hourly fuel consumption of the diesel generator $F_{cons}(t)$ can be modelled by linear law based on the output power required by the load [19] (Dufo-Lopez *et al.*, 2008).

$$F_{cons}(t) = A \times P(t)_{DG,\,gen} + B \times P_{DG,\,rat} \tag{3}$$

Where A and B are parameters of the consumption curve provided by the manufacturer while $P(t)_{DG,gen}$ and $P_{DG,rat}$ are the generated and rated power of the DG respectively. The values allocated to A and B are 0.246 and 0.08145 l/kWh, respectively.

The DG efficiency (kWh/l) is expressed as,

$$\eta_{DG} = \left(P(t)_{DG,gen} \;/\; F_{cons}(t)\right) = \left(1 \Big/ \left(A + B \times \frac{P_{DG,rat}}{P(t)_{DG,gen}}\right)\right) \tag{4}$$

The lower heating value of Gas-oil efficiency (LHV) in percentage (%) can be defined as follows,

$$\eta_{DG}\,(\%) = \frac{P(t)_{DG,gen}\ (kW)}{F_{cons}(t)\ (l/h) \times LHV_{Gas-oil}\ (kWh/l)} \times 100 \tag{5}$$

$LHV_{Gas-oil}$ range between 10 and 11.6 kWh/l.

2.2.3 Pumping sub systems model

In this paper, the mathematical model used linked the output water flow rate (Q) versus the input operating electric power (P_a) and total head (h).

This empirical model was developed based on the experimental results of pumping subsystem tests elaborated at the PV pumping laboratory of URAER / Ghardaïa (Unité de Recherche Appliquée en Energies Renouvelables). The developed model is given as follows: [19, 20] (Bakelli, 2012a; Bakelli *et al.*, 2012b).

$$Q(P_a, h) = a(h) \times \exp\left(b(h) / P_a \right) \tag{6}$$

Where $a(h)$ and $b(h)$ depend on the total head and can be described by the following equations,

$$a(h) = a_0 + a_1 h + a_2 h^2 + a_3 h^3 \tag{7}$$

$$b(h) = b_0 + b_1 h + b_2 h^2 + b_3 h^3 \tag{8}$$

Where a_i and b_i, the model parameters, which depend on the pumping subsystem characteristics.

2.2.4.Water storage tank model

The size of the water storage tank is usually taken referred to number days of autonomy, which is 2 or 3 days. However, by using a diesel engine as the backup, a fraction of one day is also considered.

According to the PV production and the load requirements, the state of charge of water storage tank can be estimated from the following equations,

Water storage tank charging is presented by the {Eq. (9)}, in below,

$$SOC(t) = SOC(t-1) + \left(Q_{PV}(t) - Q_L(t)\right) \times \eta_{tank} \tag{9}$$

Water storage tank discharging is shown by the {Eq. (10)}, as below

$$SOC(t) = SOC(t-1) - \left(Q_L(t) - Q_{PV}(t)\right) \tag{10}$$

Where $SOC(t)$ and $SOC(t-1)$ are, the states of charge of water storage tank (m^3) at the time t and $t-1$ respectively. $Q_{PV}(t)$, the water quantity pumped by PV array at a given heat; $Q_L(t)$, is load demand at the time t; η_{tank}, the charge efficiency of water storage tank; η_{tank} is taken equal to 1. At any time t. The quantity of water charged into the storage tank is submitted to the following constraints.

$$0 \le SOC(t) \le SOC_{max} \tag{11}$$

SOC_{max}, is the maximum charge of water storage tank, it corresponds to the daily water demand (m^3) multiply by the number of storage days.

2.3 System operation strategies

The water quantity pumped by the PV generator and the amount of water stored are time dependent. So, the input/output of the tank is controlled by the following equation,

$$\Delta Q(t) = Q_{PV}(t) - Q_L(t) \tag{12}$$

(a) If $\Delta Q \ge 0$, the remaining quantity of water will be used to fill the tank. If the tank is entirely filled, the excess is dumped.

(b) If $\Delta Q \le 0$, the remaining quantity of water will be given by the tank or by the backup diesel/pump subsystem, depending on the dispatch strategy,

(i) If the tank is able to provide ΔQ, then the tank empties and diesel generator turns off

$$Q_{tank}(t) = \Delta Q(t) \tag{13}$$

(ii) If the tank is unable to provide ΔQ, then the diesel generator runs at his rated power.

Therefore, a part of water pumped by diesel generator will be used to meet the demand deficit and the remaining will be used to fill the tank. Thus, the remaining quantity of water is given by:

$$Q_{tank}(t) = \left(Q_{PV}(t) + Q_{Diesel}(t)\right) - Q_L(t) \tag{14}$$

Where $Q_{Diesel}(t)$, the quantity of water pumped by diesel/pump at time t.

2.4 Criteria for optimal sizing optimization of the studied system

In order to select an optimal combination of an HPDWPS to satisfy the daily water demand, an evaluation may be carried based on reliability and economy of the power supply. The proposed methodology for evaluation of the hybrid PV/diesel water pumping system, 'HPDWPS' is based on the two following concepts:

- LPSP concept for the reliability criteria
- LCC the economic valuation.

2.4.1 Reliability criteria based on LPSP technique

To achieve a zero load rejection, the loss of power supply probability (LPSP) of the designed system must be equal to zero (0). The $LPSP$ is given by [22] (Semaoui *et al.*, 2013),

$$LSP = \frac{\sum_{t=1}^{8760} LPS(t)}{\sum_{t=1}^{8760} Q_L(t)} \tag{15}$$

Where $LPS(t)$ is the loss power supply (LPS) at hour t, it can be expressed as,

$$LPS(t) = Q_L(t) - \left(Q_{PV}(t) + SOC(t-1)\right) \tag{16}$$

Where $Q_L(t)$, load demand at the time t $Q_{PV}(t)$ is the amount of water pumped by PV array; $SOC(t-1)$, the state of charge of water storage tank (m^3) at the time $(t-1)$.

All configurations which satisfy '$LPSP = 0$' are kept: next, the optimal configuration is predicted with accordance to the minimum LCC.

2.4.2 Economic criteria based on LCC concept

In this study, the Life Cycle Cost (LCC), is used as an indicator of the economic profitability of the presented hybrid system. The LCC is defined as the total cost of the whole HPDWPS. Five principal parts are considered: PV generator, the motor-pump set, the water tank, diesel engine and the converter.

According to the studied system, the life cycle cost (LCC) takes into consideration the initial investment cost (IC_{cap}), the present value of replacement cost (C_{rep}) and the present value of maintenance and operating cost (C_{rep}).

Thus, LCC may be expressed as follows [20, 21] (Bakelli, 2012),

$$LCC(DA) = IC_{cap} + C_{rep} + C_{main} \tag{17}$$

<u>Initial investment cost</u>

The initial investment cost of the system components (including costs of civil work, installation and connections) is given by,

$$\begin{aligned} IC_{cap}(DA) = {} & C_{PV} \times C_{Unit,PV} + C_{Diesel} \times C_{Unit,Diesel} + C_{conv} \times C_{Unit,conv} \\ & + C_{motpump} \times C_{Unit,motpump} + C_{tank} \times C_{unit,tank} + C_0 \end{aligned} \tag{18}$$

Where C_{PV}, $C_{Unit,PV}$, the total capacity (W) and the unit cost (DA/W) of PV array respectively. C_{Diesel}, $C_{Unit,Diesel}$, the total capacity (W) and the unit cost (DA/W) of the DG. C_{conv}, $C_{Unit,conv}$, the nominal capacity (W) and unit cost (DA/W) of the converter respectively. $C_{motpump}$, $C_{Unit,motpump}$, the total capacity (W) and the unit cost (DA/W) of the motor pump set respectively. C_{tank}, $C_{Unit,tank}$, the total capacity (m^3) and unit cost (DA/m^3) of the tank respectively. C_0, the total constant cost including the cost of civil work and installation (the civil work and installation costs are taken as 40 % of PV generator price for PV part and 20 % pf the set motor pump price for motor pump part).

The present value of replacement cost

The replacement cost depends principally on the replacement of some installation components.

Since the PV generator and the water storage tank have the life span of the system (its replacement cost can be considered as zero), while the motor pump set, DG and converter must be replaced. The present value of replacement cost (C_{rep}) can be determined using the following formula [23]: (Soras *et al.*, 1988).

$$C_{rep} = C_{Unit} C_{nom} \sum_{i=1}^{N_{rep}} \left(\frac{(1 + f_0)}{(1 + k_d)} \right)^{\frac{N_i}{N_{rep}+1}} \quad ......(19)$$

Where C_{conv}, the nominal capacity of the replacement system component {motor-pump set in (W), the diesel generator in (W) and the converter in (W)}. C_{Unit}, the unit component cost {motor-pump set (DA/W), the diesel generator and converter (DA/W)}. N_{rep}, the number of component replacements over the system life period. f_0, the inflation rate of component replacements and k_d, the real interest rate.

The present value of operation and maintenance cost

The present value of operation and maintenance cost of the pumping system $C_{O\&M}$ can be given by [24] (Boutelhig *et al.*, 2011):

$$C_{O\&M} = \begin{cases} C_{(O\&M)_0} \left(\frac{1 + f_1}{k_d - f_1} \right) \left(1 - \frac{1 + f_1}{1 + k_d} \right)^{L_p} & , \text{ for } k_d \neq f_1 \\ C_{(O\&M)_0} \times L_p & , \text{ for } k_d = f_1 \end{cases} \quad (20)$$

Where, f_1, the inflation rate for operations; L_P, the system life period in years; $C_{(O\&M)_0}$, the operation and maintenance cost in the first year. It can be given as a fraction (k_i) of the component initial capital cost (C_{IC}). $C_{(O\&M)_0}$ is expressed as,

$$C_{(O\&M)_0} = k_i \times C_{IC} \quad 21$$

In this survey, we suppose the escalade rate is constant for all components.

The following unit price, maintenance cost and lifetime of each component (PV array, diesel generator, converter, motor pump set and water storage tank) are assembled in **Table 1**. The configuration, which ensured the desired reliability of power supply with the lowest LCC, is taken as the optimal configuration.

Table 1: The costs and lifetime aspect for the system components

Component	Unit Price (DA/W)	Maintenance cost in the first year %	Lifetime (year)	Real interest rate k_d (%)	Inflation rate f (%)
PV array[a]	183.2	1% of price	25	8	4
Motor pump[a]	240	3% of price	10		
Water tank	42000 (DA/m^3)	1% of price	25		
Converter[a]	56.88	0% of price	10		
Diesel engine[a]	32000 (DA/kVA)	19.2 (DA/h)	7000 h		
Diesel fuel cost[a]	112 (DA/l)	-	-		

[a]Mean value of the literature data.

3. RESULTS AND DISCUSSION

3.1 Case study

After developing the mathematical model related to the optimal sizing of HPDWPS, it has been applied to analyse one hybrid project, which is designed to supply water for drinking and irrigation in Ghardaïa region, (South Algeria).

The technical characteristics of the PV module, motor pump and Diesel engine used in the studied project are listed in **Tables 2**, **3** and **4**. The diesel fuel cost is taken about 112 DA/liter (unsubsidized).

Table 2: Specifications of the PV module

Type	Motor	I_{sc} (A)	V_{max} (V)	I_{max} (A)	P_{max} (W)
Shell-SM55	21.7	3.45	17.4		

Table 3: Specifications of the motor pump

Type	Motor	Nominal power (W)	Range voltage (V)	Maximum current (A)
Submersible centrifugal	DC/AC	900	30-300/ 1x90-240	7

Table 4: Specifications of the diesel generator

Type	Voc (V)	Max Power (kVA)	Rated Power kVA	Fuel tank (l)	DC Output
KG 1500A	230	1.2	1.0	5.5	12V/8.3A

Data of solar irradiation on the horizontal surface as well as ambient temperatures recorded at Ghardaïa (Algeria) for the year 2005 are shown in figures 2 and 3. These data are used in system unit sizing and the generation is assumed to be constant in each hour interval.

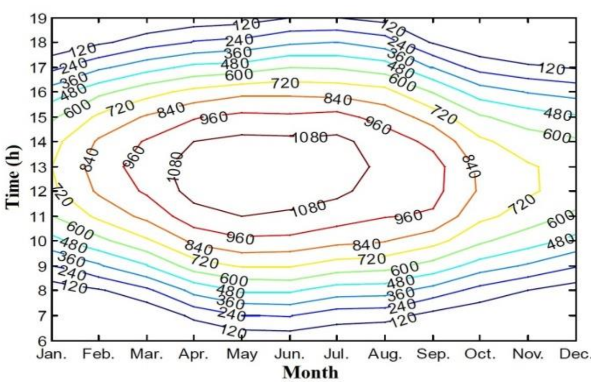

Fig. 2: Hourly distribution of global solar radiation on horizontal surface [25]

3.2 Impact of heads and storage capacity on system configurations

The relationships between various heads, storage capacity and system configurations are studied. Figure 5 demonstrate the results of the relationship between storage capacity and system configurations for different heads and zero load rejection ($LPSP = 0$).

In this figure, the curves are hyperbolic. Each point of them represents a couple (Number of PV modules and number of storage days) that ensures the desired water request. It also showed that from one day of storage capacity, the PV size increases with the increase of the heads.

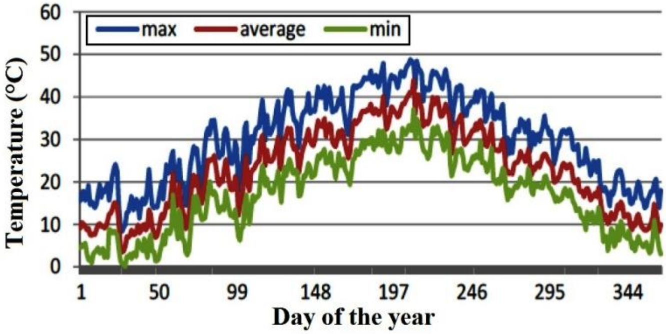

Fig. 3: Daily average, minimum and maximum ambient temperature during the year [26]

Figure 4 shows the load profile adopted in this study. This profile is supposed to be the same for all the days of the year with a total daily requirement of 27 m^3 of water.

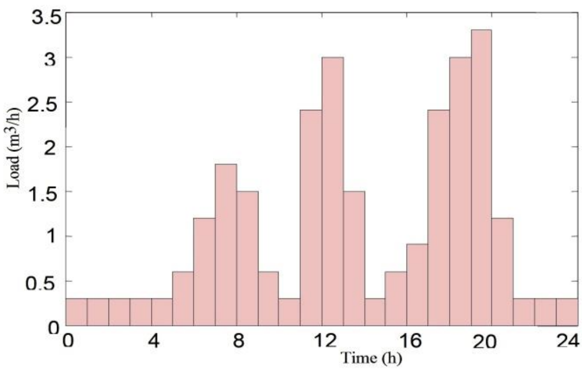

Fig. 4: Daily distribution of water consumption

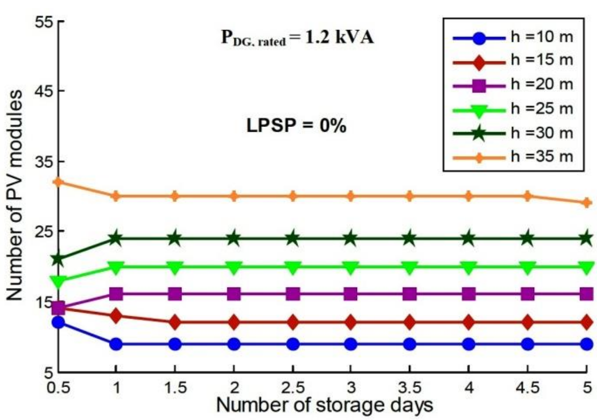

Fig. 5: Optimal system configurations vs. various number of storage days for different heads and $LPSP = 0\%$

3.3 Impact of heads and storage capacity on the number of operating hours of DG

Figure 6 shows the variation in the number of operating hours of DG and storage capacity for various heads. It is also shown that the number of operating hours of DG is variable. It depends on the heads and the number of autonomy days. Thus, if the heads increase the number of operating hours of DG increases and the number of autonomy days decreases.

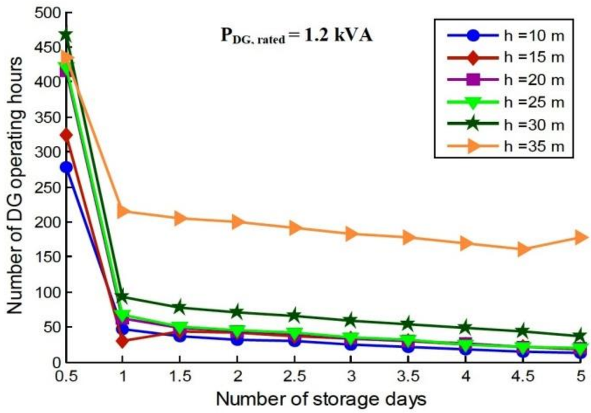

Fig. 6: Number of operating hours of DG for different heads

3.4 Impact of heads and storage capacity on the DG fuel consumption

The variation in the fuel consumption and storage capacity for various heads is shown in figure 7. Since the diesel generator always run at its rated power, the fuel consumption depends on the number of operating hours. It also depends on the heads and the number of autonomy days. Thus, when the heads increase the fuel consumption of DG increases and the number of the days of autonomy decreases.

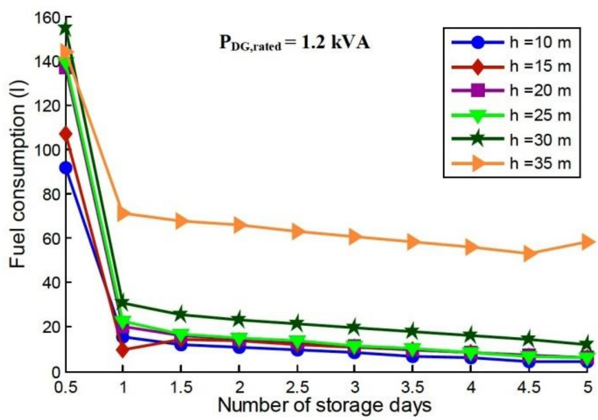

Fig. 7: Fuel consumption of DG for different heads

3.5 Impact of system configurations on the LCC

The relationships between the LCC and water reliabilities as well as the system configurations are presented in figure 8. In this figure, the full symbol curves illustrate the outcomes of the relationship between storage capacity and system configurations for several heads. Whereas the curves given by the hollow symbols represent life cycle cost

(LCC) under different configurations. Clearly, one point with the minimum LCC value occurs in each curve which means the best configuration.

This configuration was considered as the optimal one. On the other hand, a careful examination of figure 8 showed that the lowest LCC was when the water tank and the number of PV modules were both moderate.

It was also shown that the LCC for $h = 10$ m is lower than 15 m, 20 m, 25 m, 30 m and 35 m for zero load rejection ($LPSP = 0$) because the number of PV modules and number of operating hours were more moderate.

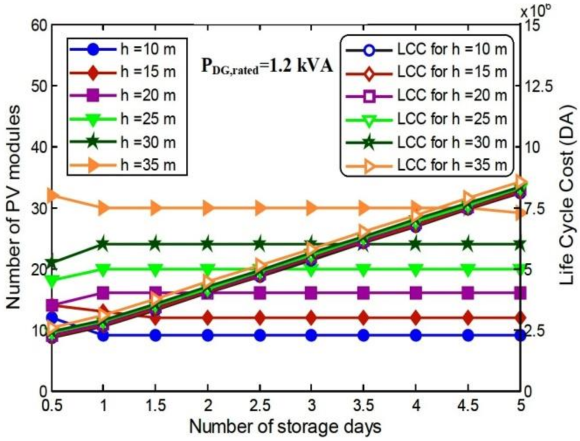

Fig. 8: System configurations and Life Cycle Cost for different heads

3.6 System configurations and storage capacities of various renewable energy systems

Figure 9 illustrates the relationships between system configurations and storage capacities for two hybrid energy systems namely: PV/DG/TANK and PV/TANK. It is clear that the PV generator power is more moderate for the hybrid PV/DG/TANK compared to the standalone PV/TANK system.

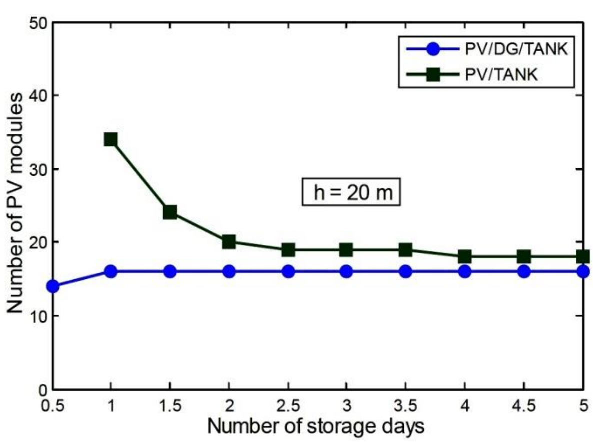

Fig. 9: Optimal number of PV modules vs. various number of storage days for PV/DG/TANK and PV/TANK systems configurations

3.7 LCC and storage capacity of various renewable energy systems

The Life Cycle Cost (LCC) of various hybrid energy systems and different autonomy days was exhibited in figure 10. It can be seen from this figure that the LCC for hybrid PV/DG/TANK system is lower than PV/TANK and DG/TANK systems for the desired LPSP of 0% for the studied case.

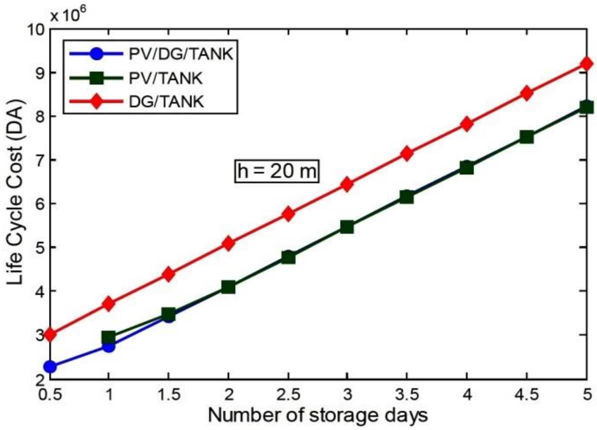

Fig. 10: Life Cycle Cost vs. various number of storage days for PV/DG/TANK, PV/TANK

4. CONCLUSIONS

In order to exploit efficiently and economically the solar energy source, an optimal sizing model has been developed, based on an iterative approach, which has the ability to optimize the capacity sizes of diverse components of hybrid PV/diesel water pumping system, HPDWPS using a water tank storage.

The proposed model was composed of three sub models, namely: the sub model of the hybrid PV/diesel water pumping system. The technical sub model developed according to the Loss of Power Supply Probability ($LPSP$) technique for system reliability evaluation and the economic sub model developed based on the concept of the Life Cycle Cost (LCC), which is considered as a good gauge of economic viability in renewable energy engineering field.

A set of configurations meeting the desired LPSP ($LPSP = 0$) can be obtained by using the technical sub model. The configuration with the lowermost LCC gave the optimal one.

In the purpose to highlight the methodology, a case study was conducted to examine one hybrid water pumping system, which is intended to provide water for drinking and irrigation near Ghardaïa, Algeria.

The algorithm input data set involves the hourly measured irradiances on the horizontal plan as well as ambient temperature recorded at Ghardaïa for the year 2005, the desired LPSP, water load requirements during the year and technical data of the system components.

Hybrid PV/diesel water-pumping system with water tank storage has been simulated by running the developed program and the relationships between diverse heads, storage capacity and system configurations have been studied.

The optimal configurations of the hybrid pumping system are determined in terms of zero load rejection and the Life Cycle Cost (LCC). The results of the optimization illustrate that a PV/DG/TANK alternative is more economically viable compared to PV/TANK system or DG/TANK only.

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