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Optimization of the daily operation of a hydrokinetic–diesel hybrid system with pumped hydro storage

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ABSTRACT

The present paper develops a model to optimize the daily operation of a hybrid energy system consisting of a hydrokinetic, a pumped hydro storage system and diesel generator. The optimization approach is aimed at minimizing the cost function subject to the availability of water resource, the variable load requirements, and operational constraints of the hybrid system's components. The main purpose of the developed model is to minimize the daily amount of diesel fuel consumed to supply the load while maximizing the use of the hydrokinetic operating in conjunction with the pumped hydro storage. For simulation purposes, the hourly load demand, resource data for a selected rural area in South Africa have been collected and used as an input to the developed model. The economic analysis has resulted in the calculation of optimized daily operation cost of the proposed hybrid system in summer and winter conditions. The obtained results demonstrate that a substantial reduction in the daily operation cost can be achieved (88% in summer and 97% in winter) using the hybrid system compare to the case where the diesel generator is used alone.

1. Introduction

Nowadays, fossil fuels constitute the principal sources of energy in the many parts of the planet. In some cases these fossil fuel can be depleted and usually have negative impacts on the environment while they are being converted into usable energy forms [1]. There is an imperative necessity for more sustainable energy sources which can be cost competitive, reliable and have less or no environmental impacts. Renewable energy sources (i.e. solar, wind, hydropower, etc.) are the most appropriate candidates for power generation especially in small-scale and remote locations [2]. Apart from renewable character of the resources (sunlight, wind, water), each of the renewable energy sources has its specific operation principle that make it suitable for specific locations and applications [3].

Solar photovoltaic (PV) is an established clean way of generating energy. PV systems are currently gaining consideration all over the world, due to their low operation and maintenance costs, and easy deployment to meet growing energy needs [4]. However, apart from its high capital cost, the other major weakness of PV generation is the fact that the power generated depends on the fluctuating solar resources. Therefore the PV cannot always match the load power demand.

Wind turbines (WT) are mainly in the coastal region where the wind potential is very good. However, as explained from the PV, the output power from wind systems also varies with the fluctuation in wind resources [5].

For inland regions where sufficient water resource is available, micro-hydro is a well suited option for rural electrification compared to other renewable resources in terms of cost of energy produced [6]. Unlike traditional hydropower schemes, hydrokinetic (HKT) is an emerging technology that uses kinetic energy from moving water to generate electricity. Unlike traditional hydropower schemes, hydrokinetic systems have more potential sites for implementation which make them more competitive compared to traditional micro hydropower [7]. However the main disadvantage of the above cited renewable energy technologies is their strong reliance on weather and climatic conditions which influence the availability of the renewable resources; therefore, they cannot always generate required power to constantly match the fluctuating load demand.

Few feasibility studies have been performed on isolated micro hydrokinetic plants for rural electrification. Comparisons between micro hydrokinetic and other supply options for rural power supply have been conducted in Ref. [8]. Based on the net present cost and the cost of energy produced, the results of this investigation have demonstrated that HKT power is the best supply option compared to conventional micro hydropower, PV, WT and DG for a selected location in South Africa.

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Nomenclature

Abbreviations

DG	diesel generator
HKT	hydrokinetic turbine
HOMER	hybrid optimization model for energy renewables
PHS	pumped hydro storage
PV	photovoltaic
WT	wind turbine

Symbols

δ	evaporation and leakage loss
η_{DG}	diesel generator efficiency
η_{HKT}	combined efficiency of the hydrokinetic turbine and the generator
η_{M-P}	overall pumping efficiency
η_{T-G}	overall efficiency of the turbine-generator set
ρ_W	water density (kg/m^3)

Subscripts

A	turbine area (m^2)
$C_{p,HKT}$	coefficient of the hydrokinetic turbine performance
E_D	energy dissipated by the dummy load (kW h)
E_{DG}	energy from the diesel generator (kW h)
E_{HKT}	energy from the hydrokinetic system (kW h)
E_{Load}	load energy demand (kW h)
E_{M-P}	charging energy from the hydrokinetic system to the pump (kW h)
E_R	potential energy of the water stored in the upper reservoir (kW h)
E_{T-G}	energy generated from the turbine-generator (kW h)
g	gravity (m/s^2)
h	net pumping head (m)
j	sampling interval considered (s)
N	number of sampling intervals
P_{DG}	power from the diesel generator (kW)
P_{HKT}	energy from the hydrokinetic system (kW)
P_{Load}	load energy demand (kW)
P_{M-P}	charging power from the hydrokinetic system to the pump (kW)
P_{T-G}	power generated from the turbine-generator (kW)
Q_{M-P}	water flow rate from the pump (m^3/s)
Q_{T-G}	water volumetric flow rate from the reservoir onto the turbine (m^3/s)
t	Time (s)
V	storage capacity of the water reservoir (m^3)
v	water current velocity (m/s)
V_{DC}	output voltage of the battery storage system (V)

In Ref. [9] the author investigated the potential use of hydrokinetic-based hybrid systems for low cost and sustainable electrical energy supply to isolated load in rural South Africa where adequate water resource is available. Different hybrid system configurations are modeled and simulated using the hybrid optimization model for electric renewable (HOMER) and the results are analyzed to select the best supply option based on the net present cost and the cost of energy produced. In Ref. [10] the author examined the possible use of HKT-based hybrid systems for low cost energy production in South Africa. Different hybrid system combinations with PV, WT, and DG are simulated. The results showed that hybrid systems with HKT modules integrated have better net present costs as well as costs of energy compared to all other supply options where the HKT modules are not incorporated.

After a deeper analysis of Refs. [8–10], it has been revealed that energy storage systems were included in all simulated supply options. However the authors of these papers have only considered the battery storage system, not analyzing the potential benefits of other energy storage options.

Energy storages are one of the few responses to the integration with variable energy production due to the fluctuation of their resources [11]. Storage system can decrease the effects of variable output power from renewable sources, and assure that power can be reliably dispatched in response to the fluctuating load requirements [12]. However, storing electrical energy is a complex operation because electricity can only be stored after being converted into other forms of energy; this engages expensive conversion equipments and induces energy losses. A number of energy storage systems are currently available; these include compressed air energy storage, flywheel energy storage, battery energy storage, flow battery energy storage, superconducting magnetic energy storage, super capacitor energy storage, hydrogen energy storage, thermal energy storage and pumped hydro storage (PHS). The different characteristics of these different energy storage system types are explained in Ref. [13].

At this present time, PHS is the most widespread energy storage system not dealing with the conversion of chemical energy to electricity. This technology can be implemented with a roundtrip efficiency of 70–80%, and its capacity is not influenced by the seasonal variation of the water flow [14].

Currently, a number of studies are available, dealing with micro-PHS for integration of isolated renewable energy sources.

Anagnostopoulos and Papantonis [15] presented a numerical study of the optimum sizing and design of a PHS unit in a hybrid wind–hydro plant. Aihara et al. [16] presented a method to determine the optimal operation sequence of a PHS which improved both reliability and economy power systems with a large integration of PV. Ruisheng et al. [17] investigated a WT–PV with PHS to minimize the unbalances between the generation and the demand. Ma et al. [18] compared the economical aspect of the PHS and battery storage for a renewable energy supplying an island. Additionally, some case studies have been conducted on the use of PHS to enhance the penetration level of wind power in standalone micro-grid. The mains findings from these studies are summarized in Ref. [19].

Inspired by the potential benefits of pumped hydro storage, hydrokinetic and diesel generator in rural electrification, this paper presents a novel PHS-based HKT-DG power generation system for a remote island. In our previous study reported in Ref. [13], a micro-PHS used in conjunction with a standalone hydrokinetic system in off-grid power generation has been proposed. The techno-economic feasibility of this combination is analyzed and compared to the option where batteries are considered as storage system. The results reveal that the novel micro HKT with PHS system is a cost-effective, reliable and environmentally friendly solution to achieve 100% energy autonomy in remote and isolated communities where water resource is available.

However, while analyzing the above mentioned papers dealing particularly with the combination of HKT with DG or HKT with HPS; the following shortfalls can be pointed out:

- The relation between the diesel generator fuel consumption and load demand used in HOMER is represented as a linear function.
- Fixed load demand and constant daily operational cost, which can be extrapolated to obtain monthly or yearly costs, are used as input data.
- HOMER does not include hydrokinetic modules in its list of available components; therefore the authors have modeled this system as a wind turbine because of their similar operation principle. A new wind turbine model has been created with the power curve of the hydrokinetic turbine.
- HOMER does not include hydro pumped storage modules in its list of available components Therefore a new battery have been built and the capacity have been specified as a fixed value in Ah, the lifetime in terms of years, and the maximum charge and discharge current have also been specified separately. However the problem is that the battery must still be linked to the DC bus, but provided that no other component is linked to the DC bus, the authors have tried to overcome by specifying a large, cost free, and 100% efficient converter making the connection between the DC and AC bus where the load is connected.
- These were just case studies and thus they might not be the optimal system in terms of technical and economic performance.

Based on the shortfalls revealed above; the present paper reports on the development of a mathematical programming model to optimize the daily operation of the proposed HKT-DG with PHS systems. The optimization approach is aimed at minimizing the operation cost function subject to the load energy requirements as well as to the DG and the PHS operational constraints. Considering a short time horizon, the PHS and hydrokinetic's daily operation costs are not taken into account, thus only the cost of the diesel fuel consumed is considered. Therefore, the main purpose of the developed control algorithm is to minimize the DG's operation cost while maximizing the use of HKT and PHS in the electricity generation process. The non-linearity in the fluctuation of the load demand, the non-linearity of the DG fuel consumption curve as well as the PHS operation limits have been considered in the developed model. The simulations of have been performed using "fmincon" interior point implemented in MATLAB; the results have been compared with the case where the DG is used alone to supply the load.

2. Hybrid system components description and operation

The schematic of the proposed hybrid system's power flow is shown in Fig. 1 and the operation principle of the system's component is discussed in the subsections below.

The load energy requirement is principally covered by the hydrokinetic system. When there is more than enough energy to supply the load directly from the HKT, no supplementary energy is needed; consequently the surplus of generated energy is used to drive the motor–pump set to fill in the reservoir. However, when there is an insufficient energy to supply the load directly by the HKT, extra energy is provided from water flowing from the reservoir and driving the turbine-generator set. If the HKT and the turbine-generator set from the PHS cannot respond to the load energy requirement, the DG is turned on, as last resort, to balance the shortage on energy needed by the load. The flowchart illustrating the simulation and optimization procedure is presented of Fig. 2.

2.1. Diesel generator

A DG is normal diesel engine coupled to an electrical generator. DG's are the most common way of providing electrical power to isolated areas not connected to the grid and are currently available in different sizes ranging from less than one kW to over MW. The energy generated (E_{DG}) by a DG with rated power output (P_{DG}) is expressed as [20]:

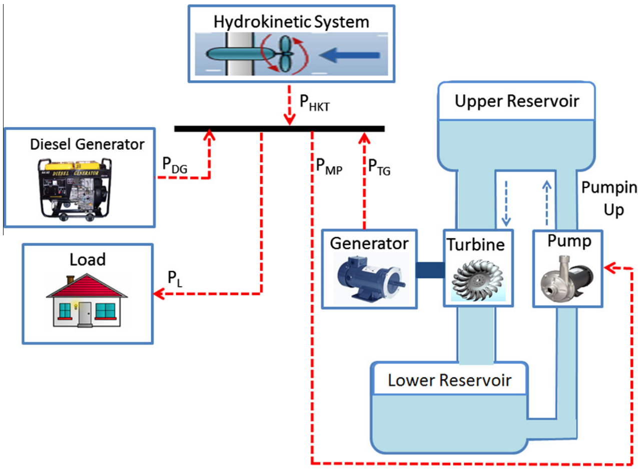

Fig. 1. Proposed hybrid system layout.

$$E_{DG} = P_{DG} \times \eta_{DG} \times t \tag{1}$$

where η_{DG} is the efficiency of the DG and t is the time.

2.2. Hydrokinetic system

Hydrokinetic energy systems convert kinetic energy from flowing water without using a dam, barrage or penstock. Hydrokinetic systems can produce energy from water flowing at very low velocities with nearly no environmental impact, over a larger range of potential sites than those offered by traditional hydropower systems [21].

The energy extraction principle used by hydrokinetic systems is similar to the one used in wind conversion systems. However, given that water is approximately 800 times denser than air [22], the corresponding energy produced by a hydrokinetic system is much higher than the one produced by a wind system of equal diameter under equal water and wind velocity. The other advantages of hydrokinetic system are that the water resource does not vary randomly as the wind resource does, and the direction of the flowing water does not change direction as the wind does.

The energy generated by the hydrokinetic system (E_{HKT}) is expressed as [23]:

$$E_{HKT} = \frac{1}{2} \times \rho_W \times A \times v^3 \times C_{p,HKT} \times \eta_{HKT} \times t \tag{2}$$

where ρ_W is the density of water (1000 kg/m^3), $C_{p,HKT}$ is the coefficient of the hydrokinetic turbine performance, η_{HKT} is the combined efficiency of the hydrokinetic turbine and the generator, A is the turbine area (m^2), v is the water current velocity (m/s) and t is the time.

The energy balance model of the HKT generator at time t is expressed as:

$$E_{HKT} = E_{HKT,Load} + E_{M-P} + E_D \tag{3}$$

where $E_{HKT,Load}$ is the energy directly delivered to the load; $E_{M\text{-}P}$ is the energy transferred to the water pump; and E_D is the excess/dissipated energy sent to the dump load.

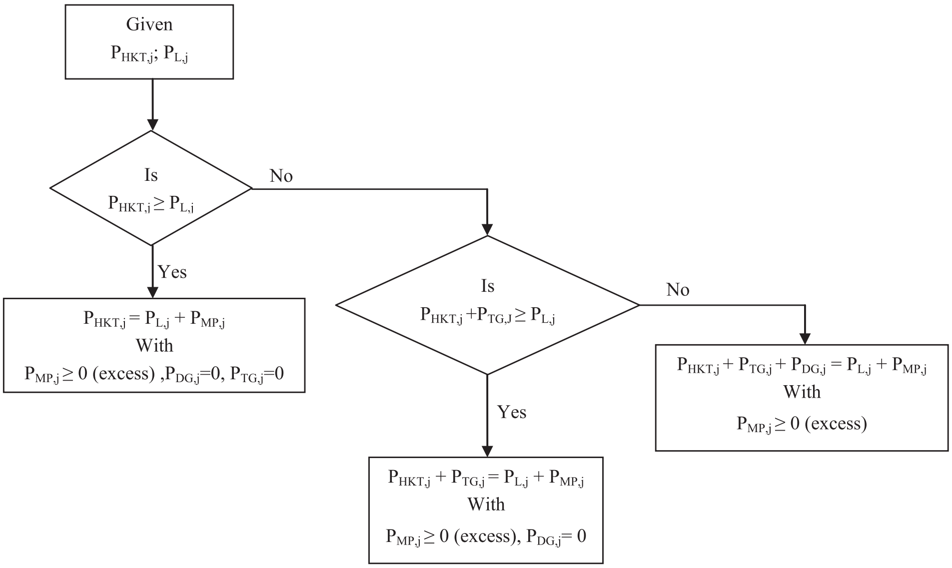

Fig. 2. Simulation and optimization procedure flowchart.

2.3. Pumped hydro system

2.3.1. Motor–pump set

The energy required by the motor–pump set to suck water from the river up to the reservoir can be expressed in Eq. (4) [24]. This energy is directly supplied by the hydrokinetic system.

$$E_{M-P} = \frac{\rho_W \times g \times h \times Q_{M-P}}{\eta_{M-P}} \tag{4}$$

where $E_{M\text{-}P}$ is the charging power from the hydrokinetic system to the pump (W); $Q_{M\text{-}P}$ is the water flow rate from the pump (m^3/s); h is the net pumping head (m); g is the acceleration due to gravity ($9.8\ m/s^2$) and $\eta_{M\text{-}P}$ is the overall pumping efficiency.

2.3.2. Turbine-generator set

In the situation where there is a shortage of energy, water from reservoir is used to operate the turbine driving the micro hydro generator [25]. The energy generated from the turbine-generator $E_{T\text{-}G}$ set can be expressed as:

$$E_{T\text{-}G} = \rho \times g \times h \times Q_{T-G} \times \eta_{T\text{-}G} \tag{5}$$

where $\eta_{T\text{-}G}$ is the overall efficiency of the turbine-generator set; $Q_{T\text{-}G}$ is the water volumetric flow rate from the reservoir onto the turbine (m^3/s).

2.3.3. Upper reservoir

The volume of water stored in the reservoir should be sufficient to meet the load power demand in a situation whereby there is an insufficient power from the hydrokinetic [26]. The potential energy E_R of the water stored in the reservoir can be expressed as:

$$E_R = \rho \times V \times g \times h \tag{6}$$

where E_R is potential energy in the reservoir (kW h); V is the storage capacity of the water reservoir (m^3).

2.4. Energy balance

The load energy requirement E_{Load} is principally covered by the hydrokinetic system, so the system's energy balance of generation and load demand at each and every time can be expressed as:

$$E_{Load} = E_{HKT} - E_{M-P} + E_{T-G} + E_{DG} \tag{7}$$

Table 1
Water resource and load data.

Time (h)	Summer		Winter	
	Water speed (m/s)	Load (kW)	Water speed (m/s)	Load (kW)
00:00	1.41	0.3	1.2	0.3
01:00	1.41	0.2	1.2	0.2
02:00	1.41	0.1	1.2	0.1
03:00	1.41	0.0	1.2	0.0
04:00	1.41	0.3	1.2	0.3
05:00	1.41	0.0	1.2	0.0
06:00	1.41	2.4	1.2	3.0
07:00	1.41	0.6	1.2	0.7
08:00	1.41	4.3	1.2	8.0
09:00	1.41	5.6	1.2	5.6
10:00	1.41	3.2	1.2	2.6
11:00	1.41	1.6	1.2	3.0
12:00	1.41	0.3	1.2	0.5
13:00	1.41	2.0	1.2	3.4
14:00	1.41	0.4	1.2	0.7
15:00	1.41	0.8	1.2	1.3
16:00	1.41	3.9	1.2	1.4
17:00	1.41	1.8	1.2	1.5
18:00	1.41	1.7	1.2	3.8
19:00	1.41	1.9	1.2	4.6
20:00	1.41	2.2	1.2	5.9
21:00	1.41	0.9	1.2	2.1
22:00	1.41	0.7	1.2	0.8
23:00	1.41	0.3	1.2	0.3

Table 2
Simulation parameters.

Item	Household
Sampling time (Δt)	30 min
PHS nominal capacity	5.6 kW h
PHS maximum Volume	100%
PHS minimum Volume	0%
PHS overall efficiency	50%
HKT power	2 kW
DG rated power	8 kW
Diesel fuel price	1.4 $/l
a	0.246
b	0.0815
c	0.4333

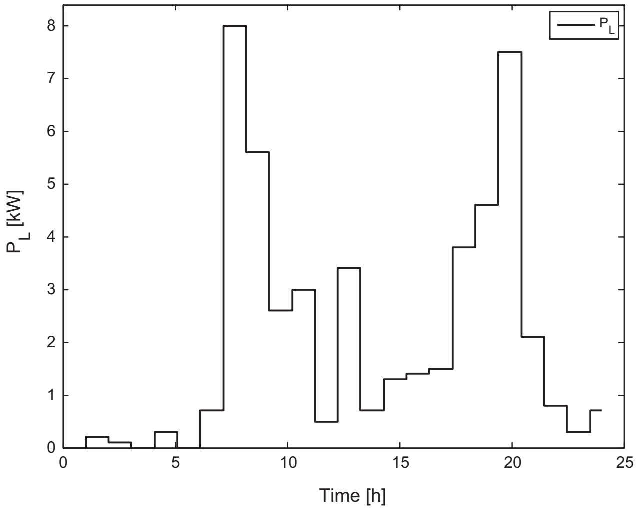

Fig. 3. Daily load profile in winter.

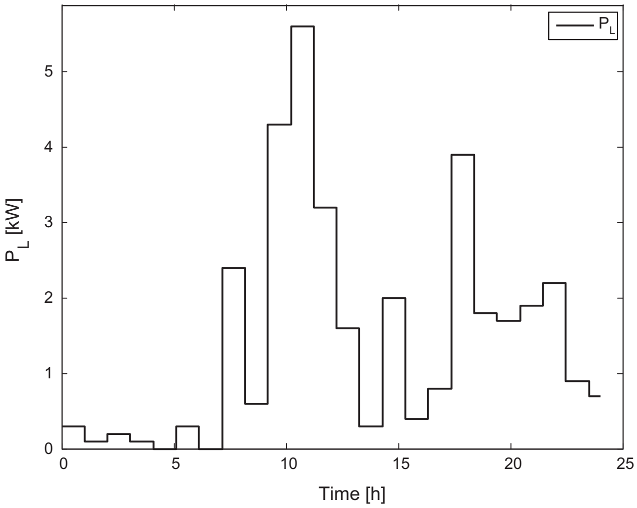

Fig. 5. Daily load profile in summer.

When there is more than enough energy to supply the load directly by the hydrokinetic system, no supplementary energy is needed, consequently $E_{T\text{-}G}$ is zero and the surplus of generated energy $E_{M\text{-}P}$ is used to drive the motor–pump set and fill in the reservoir. When the energy generated by the hydrokinetic turbine equals the load demand, $E_{T\text{-}G}$, E_{DG} and $E_{M\text{-}P}$ are zero. However, when there is an insufficient energy to supply the load directly by the hydrokinetic system, extra energy $E_{T\text{-}G}$ is provided from water flowing from the reservoir and driving the turbine-generator set, $E_{M\text{-}P}$ is zero. If E_{HKT} and $E_{T\text{-}G}$ cannot respond to the load energy requirement, the DG is turned on to provide E_{DG}, balancing the shortage on energy needed by the load.

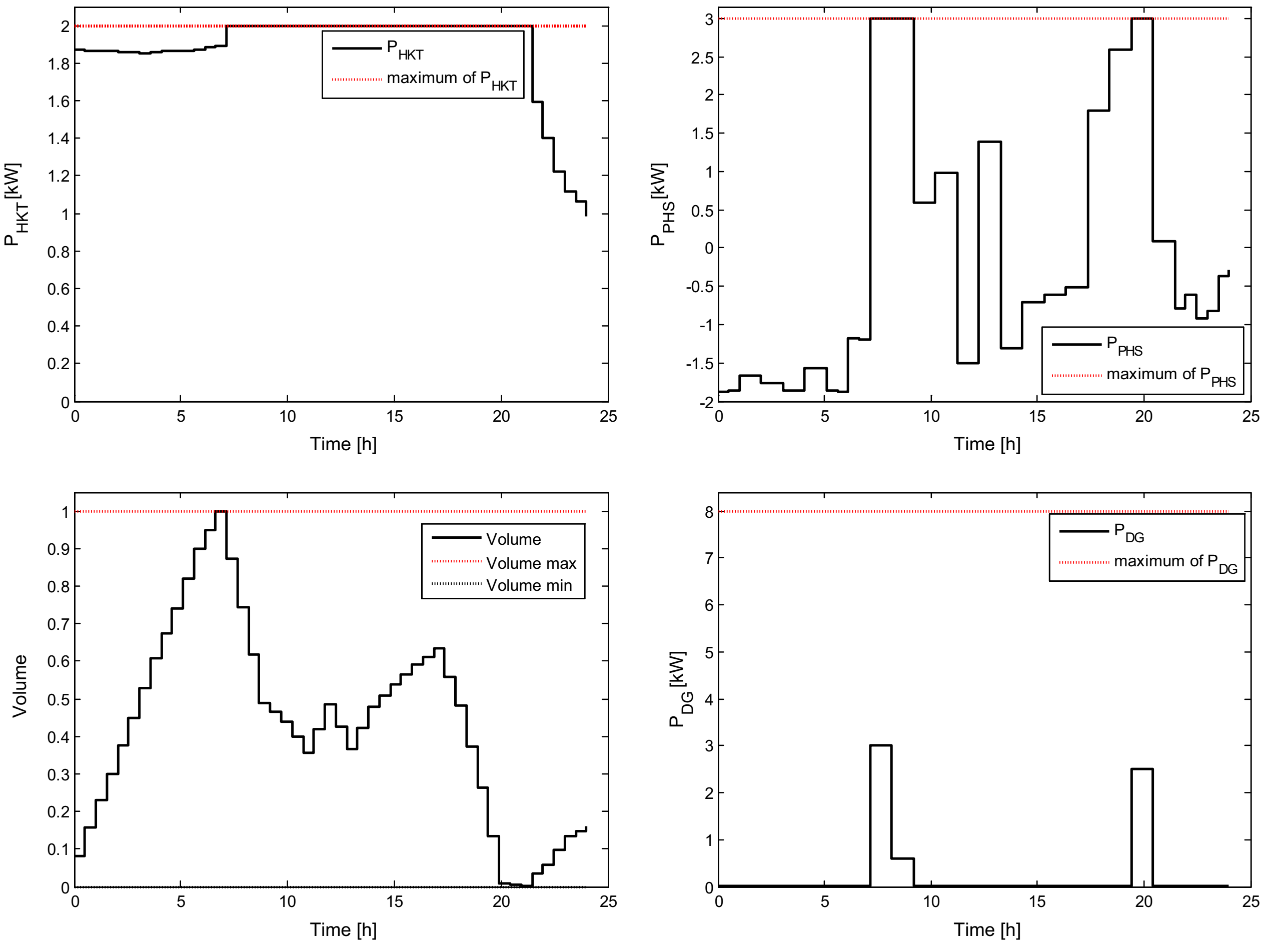

Fig. 4. Daily optimized power flow (P_{HKT}, P_{PHS}, and P_{DG}) and reservoir dynamics (winter case 1).

3. The optimization problem

In this work, the optimization of the 24-h operational cost of the proposed hybrid power plant is desired. For this purpose, an optimization problem was formulated, through the minimization of the operation cost that results from the energy supplied to the load, considering the main operational restrictions of each of the hybrid system's components. The solution of this problem provides an operational strategy to be followed by the DG, HKH and hydro generator/pumping units during the 24 h.

The following optimization problem is solved:

$$\text{Minimize}: C_f \times \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c) \tag{8}$$

$$\text{Subject to}: P_{Load(j)} = P_{HKT,Load(j)} + P_{T-G(j)} + P_{DG(j)} \tag{9}$$

$$P_{HKT(j)} = P_{HKT,Load(j)} + P_{M-P(j)} \tag{10}$$

$$P_{PHS(j)} = P_{T-G(j)} - P_{M-P(j)} \tag{11}$$

$$E_{R(j)} = E_{R(0)} \times (1-\delta) + t_s \times \left(\eta_{M-P} \times \sum_{i=1}^{j} P_{M-P(j)} - \frac{\sum_{i=1}^{j} P_{T-G(j)}}{\eta_{T-G}} \right) \tag{12}$$

$$0 \le P_{DG(j)} \le P_{DG}^{\max} \quad (1 \le j \le N) \tag{13}$$

$$0 \le P_{HKT(j)} \le P_{HKT(j)}^{\max} \quad (1 \le j \le N) \tag{14}$$

$$0 \le P_{M-P(j)} \le P_{M-P}^{\max} \quad (1 \le j \le N) \tag{15}$$

$$0 \le P_{T-G(j)} \le P_{T-G}^{\max} \quad (1 \le j \le N) \tag{16}$$

$$-P_{PHS}^{rated} \le P_{T-G(j)} - P_{M-P(j)} \le P_{PHS}^{rated} \quad (1 \le j \le N) \tag{17}$$

$$E_R^{\min} \le E_{R(j)} \le E_R^{\max} \tag{18}$$

From the observation of the objective function (8), one can see that the main aim is to minimize the operation resulting from the use of the DG.

As shown in (9), the load can be supplied by the available portion of HKT, by the output power of the PHS and well as by the DG.

From (10), a fraction of the available HKT power is directly supplied to the load during the considered interval. Another portion of this can be stored in the reservoir (by using the pump component of the PHS) and delivered in subsequent intervals. In some particular cases, it may happen that a part of the available HKT energy could not be used; therefore it is dissipated by the dump load.

From (11), the PHS can either store water in the reservoir using the pump or produce energy from the stored water using the turbine and generator set; not both at the same time. Therefore, the power flow link to the PHS is assumed to be negative when the system is in the operating as a pump ($E_{M\text{-}P}$) and positive when the system is operating in generator mode ($E_{T\text{-}G}$).

Eq. (12) describes the energy dynamics in the upper reservoir. At the beginning of any sampling interval, the energy in the reservoir is the initial level plus the pumped energy, minus the energy supplied to the load by the turbine-generator set during that same interval. As explained above, the PHS can either pump or generate, not both at the same time. In this equation δ is the evaporation and leakage loss.

Eqs. (13)–(18) describe the operational restrictions of the HKT and DG generators, PHS units and storage capacity.

In the presented formulation, Eqs. (8)–(18) represent a non-linear optimization problem. The non-linear optimization problem can be solved using the "fmincon" interior point method in

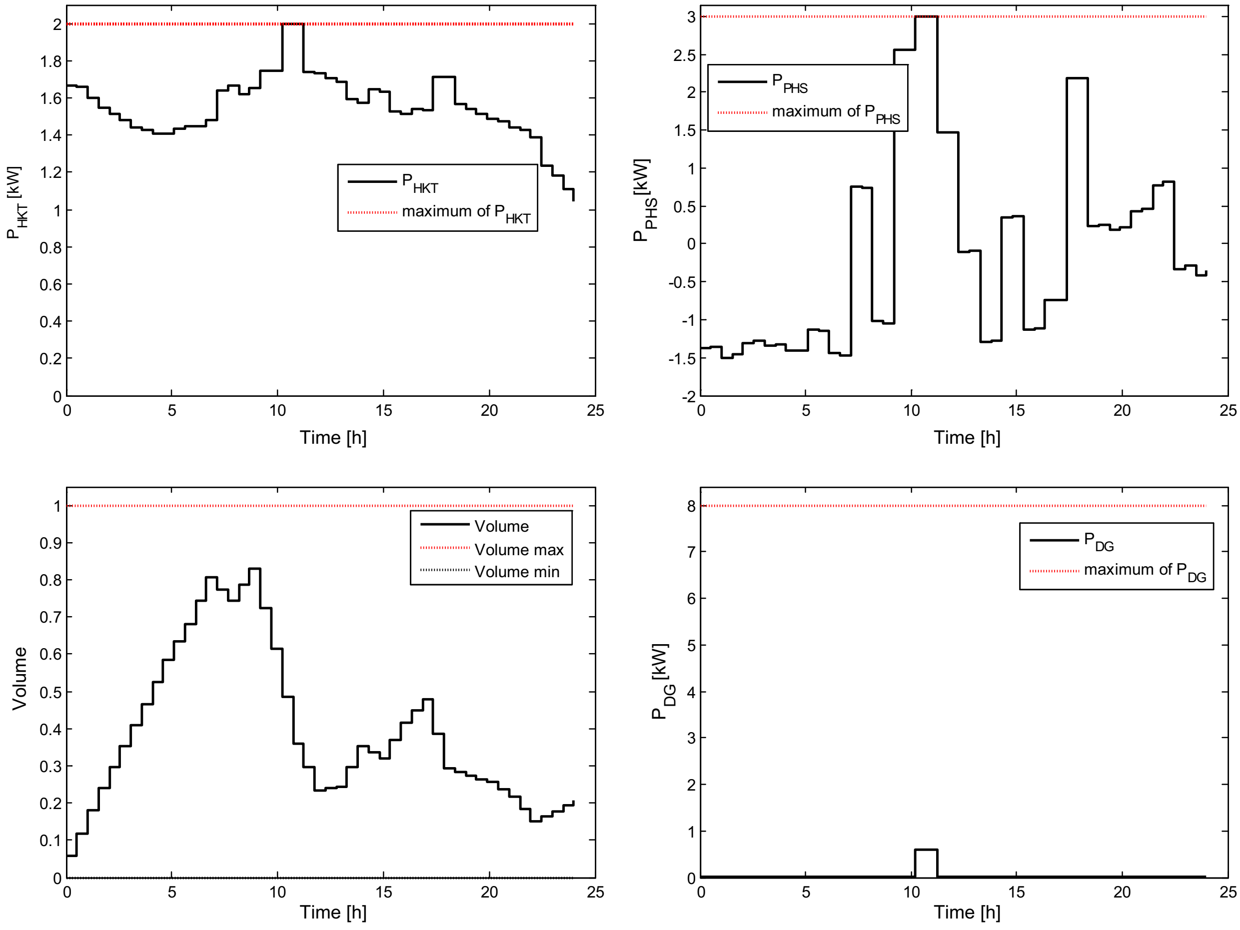

Fig. 6. Daily optimized power flow (P_{HKT}, P_{PHS}, and P_{DG}) and reservoir dynamics (summer).

MATLAB [27]. However, any other non-linear optimization methods could also be used. Fmincon solves problems in the form:

$$\min_x f(x) \text{ Subject to : } \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ A \cdot x \le b \\ A_{eq} \cdot x = b_{eq} \\ l_b \le x \le u_b \end{cases} \tag{19}$$

where x, b, b_{eq}, l_b, and u_b are vectors; A and A_{eq} are matrices; $c(x)$ and $c_{eq}(x)$ are functions that return vectors and $f(x)$ are function that returns a scalar. $f(x)$, $c(x)$, and $c_{eq}(x)$ can be nonlinear functions.

4. Case study

4.1. Resource and load data

A rural area in South Africa, with real load and water resource data, is selected as a case study to analyze the behavior of the hybrid system. This system has to be optimally sized in such a way that the demand is always met at any given time. The hourly water velocity as well as load demand for a 24 h period are shown in Table 1 for the selected summer and winter day, respectively. These data are available from Ref. [28]; they are used as input to the optimal operation control model developed in Section 3 above.

It has to be highlighted that the HKT resource data have been collected for a day in September where the velocity is the lowest compared to the other days of year. Therefore the selected HKT turbine is sized in such a way to give a rated power of 1 kW at 1.4 m/s water velocity. It can also be seen from Table 1 that the load reaches a peak demand of 8 kW in winter; therefore any supply option must be sized to respond to this demand without any difficulty.

4.2. Component sizes and model parameters

The sizes of the hybrid system's components as well as the different parameters used in the simulations are given in Table 2 below.

5. Simulation results and discussions

In this section, the simulation results of the hybrid system operating in summer as well as in winter conditions are presented and compared to the case where the DG is used alone to supply the load under the same conditions. The solution of the optimization problem expressed by Eqs. (8)–(18) provides the hourly optimal power flow from the HKT and DG during each of the 24 h. Storage levels and the PHS operational scheduling in the period are also determined, assuming that HKT power is supposed constant during each sampling interval.

5.1. Hybrid system behavior

5.1.1. Winter case

Fig. 3 shows the load profile for the selected winter day. It can be observed that the demand is highly nonlinear; low during the night with high peaks in the morning and in the evening.

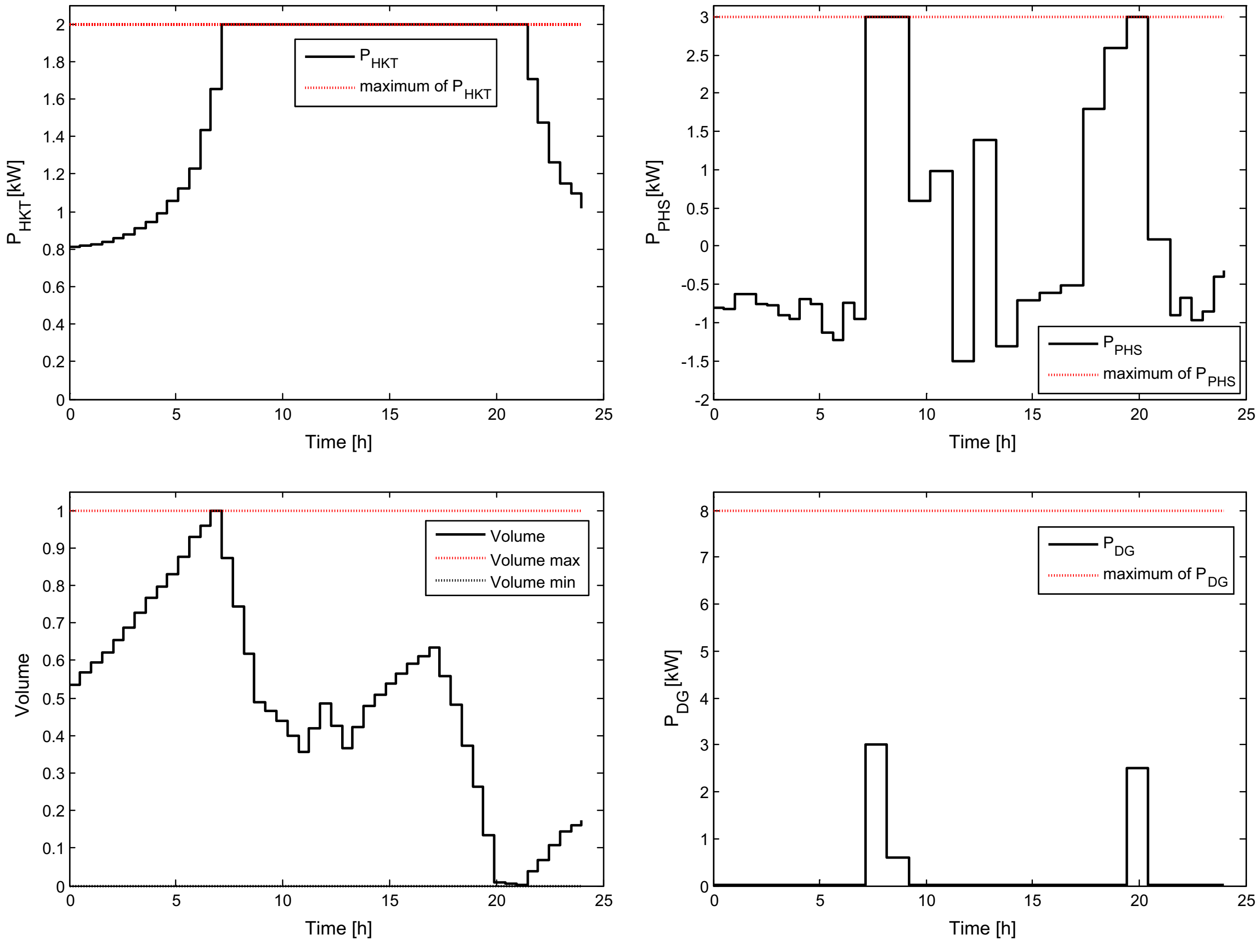

Fig. 7. Daily optimized power flow (P_{HKT}, P_{PHS}, and P_{DG}) and reservoir dynamics (winter case 2).

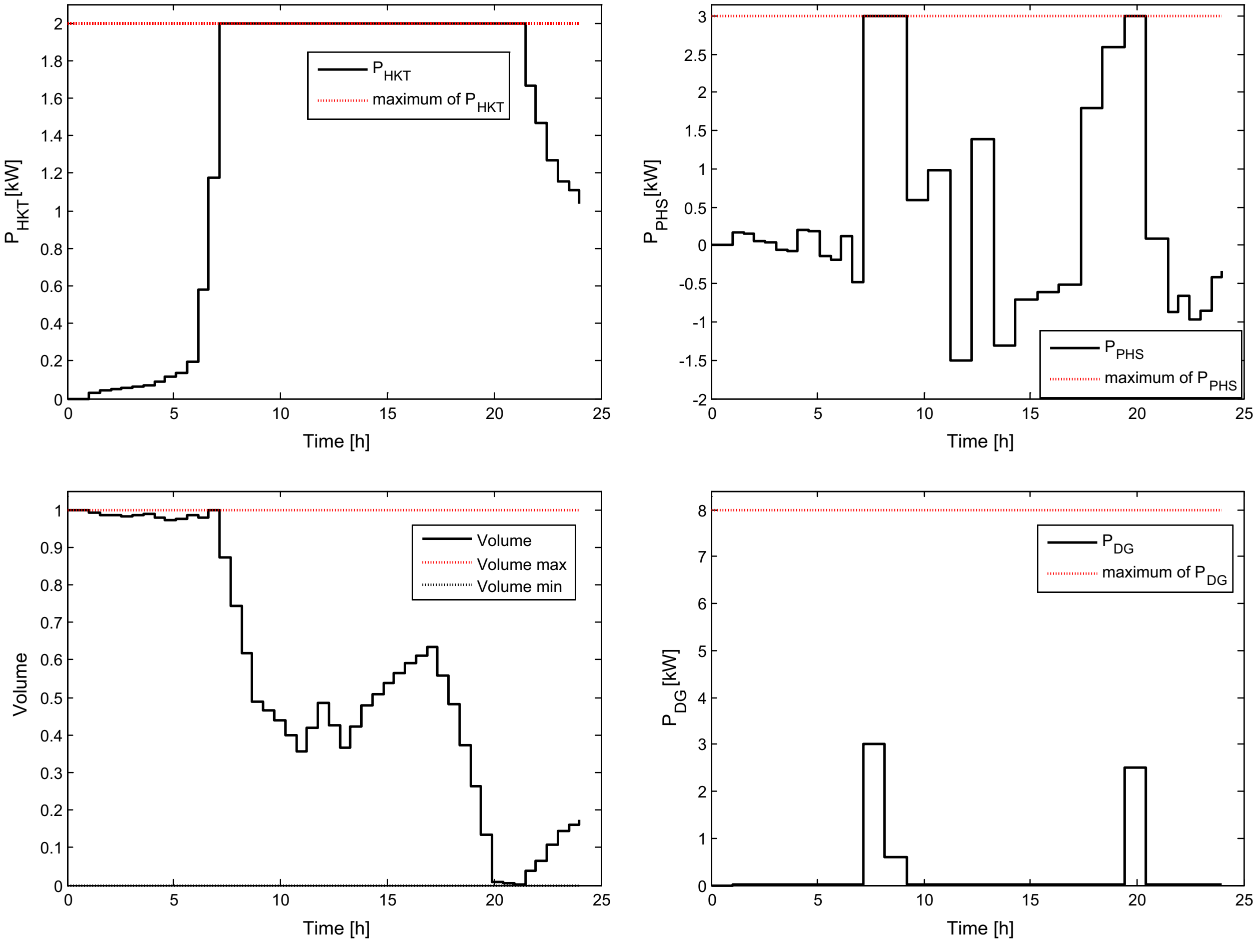

Fig. 8. Daily optimized power flow (P_{HKT}, P_{PHS}, and P_{DG}) and reservoir dynamics (winter case 3).

Fig. 4 represents the HKT output power, the PHS output power, the variation of water volume (potential energy) in the reservoir as well as the DG output power in the hybrid system, respectively. The following observation can be made:

- From 00h00 to 07h00: It can be noticed that during the night and early morning the load demand is low and the water reservoir is almost empty, thus the HKT system producing enough power to supply the motor–pump set as well as to supply the load at the same time. Therefore, the volume of water in reservoir increases to reach its maximum capacity at around 06h30. During that time, the power from PHS is negative, representing its pumping operation mode. The DG is kept of because there is enough power from the HKT to supply the load.
- From 07h00 to 09h00: The morning peak load demand occurs between 07h00 and 09h00, therefore the HKT is used at its maximum in conjunction with the Turbine-Generator power represented by the positive power flow from the PHS. The DG also switches ON, only to balance the energy needed, then switches OFF as soon as there is enough power from the HKT and the PHS.
- From 09h00 to 17h00: After the morning peak, the volume of water in the PHS is at 35% of its maximum capacity; therefore the HKT power stays at its maximum to produce more power than the load requirement. This surplus is used to pump water in the reservoir which a level of 60% at the end of the afternoon.
- From 17h00 to 21h00: In the evening, the power demand increases gradually from 17h00 and then reaches the peak between 19h00 and 20h00, and finally decreases at 21h00. Therefore the HKT and the Turbine-Generator set of the PHS are used at their maximum power during the peak in conjunction with a small contribution of the DG. It can be noticed that toward the end of this peak power demand, the volume of water in the reservoir is at its lower limit.
- From 21h00 to 00h00: After the evening peak demand, the load decreases and there is enough power from the HKT to supply the load. Therefore the excess of energy is used to supply the motor–pump of the PHS to store eater in the reservoir. During this period, the DG is kept OFF.

5.1.2. Summer case

The difference between the hybrid system operation scheduling in winter and summer are also analyzed using the developed model. This difference is mainly due to the change of water velocity with the climate and the change of load requirements which have significant effects on the hybrid system's dispatch strategy. Using the data from Section 4 above, the simulation results reveals that the DG contribution is less required in summer compared to winter due to lower load demand in summer compared to winter at the specified location of the study.

The load profile is given on Fig. 5 while the HKT output power, the PHS output power, the variation of the reservoir's water volume as well as the DG output power during the selected summer day are presented in Fig. 6. From this figure, it can be seen that the load mostly relies on the HKT and the PSH storage system, even during high peak demands; the water level in the reservoir is not reduced to its minimum as it is the case in winter. The DG contribution is lower compared to the one from the selected winter day because it is only switched ON for a short period of time to cater the deficit of energy from the HKT and the PHS during the peak demand occurring around 10h00.

5.2. Sensitivity analysis

The PHS initial water level can have a significant impact on the hybrid system's daily power flow. Here a sensitivity analysis is done on PHS's reservoir initial water level to see how it affects the daily operation scheduling of the hybrid system's different components. Data from the hybrid system supplying the rural household in winter are used here for illustration purposes.

Figs. 4, 7 and 8 show the simulation results from the cases where the initial water level is respectively 0%, 50% and 100% of the reservoir's total capacity. It can be noticed from these three figures that one of the constraints in the hybrid system's operation strategy is to use the HKT power to supply the motor–pump set to fill in the reservoir when the load is low. Therefore, in these three cases, the DG is kept OFF early in the morning when the load is low.

However, it has to be noticed that if ever a peak demand above the HKT rating occurs while the reservoir is empty, the DG will switch ON to compensate the deficit of power. Therefore the initial water level in the reservoir can play a significant role in the hybrid system's optimal scheduling as well as on the system's daily operation cost, depending on when the peak demand is occurring.

5.3. Cost savings

Figs. 9 and 10 respectively illustrate the winter and summer output power from the DG for the 24 h period where it is used as the only option to supply the fluctuating load demand. It can be seen that the DG continuously adjusts its power output, using the load following principle, to respond to the demand. It can be seen that in summer, the DG output power is following the load pattern but it does not reach its rated power.

Table 3 shows how much operation fuel can be saved by using the proposed hybrid system instead of the DG "alone" in the selected winter or summer day. These results demonstrate that it is very important to take into account the variations of the load and with seasons when calculating the system's daily operation cost.

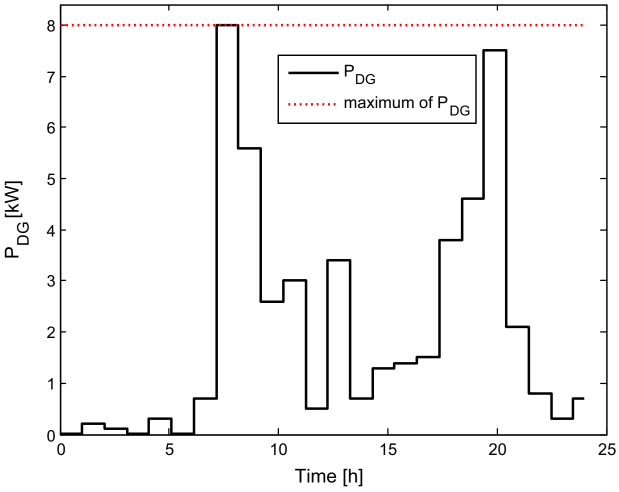

Fig. 9. DG optimal scheduling and output power in winter.

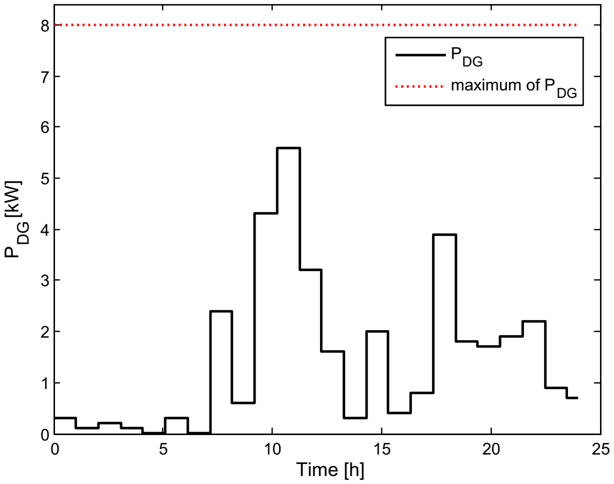

Fig. 10. DG optimal scheduling and output power in summer.

Table 3
Costs comparison.

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	26.25	36.75	18	25.2
Hybrid system	3.13	4.38	0.3	0.42
Savings	23.12	32.37	17.7	24.78

6. Conclusion

In this paper, a model was developed to find the optimal daily operation scheduling to be implemented in a hybrid system composed of hydrokinetic and diesel generator with pumped hydro storage. This model aims to minimize the use of the diesel generator while maximizing the use of the hydrokinetic and the pumped hydro storage system. As already mentioned, this work considers the non-linearity of the daily load demand as well as diesel fuel consumption resulting in non-uniform daily operational costs.

The simulation results show that using the pumped hydro storage ability, it is possible to deal with any load operational constraints that usually require a rapid response from the power generation or storage system. For the two case studies, it has been demonstrated that using the proposed hybrid system and taking into account the non-linearity in daily and seasonal variations of the load demand, substantial reduction in the daily operation cost can be achieved. The difference in daily operation cost achieved highlight the potential of the proposed optimization model to reduce fuel consumptions for the proposed hybrid system compared to the diesel generator only scenario.

Pumped hydro storage also increases the penetration of the generation form hydrokinetic systems, aiming to improve the participation of hydrokinetic generation in electricity markets. A decrease in the needs on diesel generator can be also obtained, since there will be an increase of the availability and reliability of power supply.

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