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Feasibility analysis of river off-grid hydrokinetic systems with pumped hydro storage in rural applications

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ABSTRACT

Hydrokinetic power generation is currently gaining interest as a cost effective way of supplying isolated areas where reasonable water resource is available. However the seasonal characteristic of the water resource as well as the intermittent fluctuating load demand prevents this power generation system from being entirely reliable without appropriate energy storage system. Few researchers have recently analyzed the use of hydrokinetic systems as standalone or combined with other energy source, however the authors of these researches did not explore other means of storing energy except for traditional battery storage systems. In this study, the most conventional and established storage technology, pumped hydro storage, is proposed to be used in conjunction with a standalone hydrokinetic system in off-grid power supply. The techno-economic feasibility of such combination is analyzed and compared to the option where batteries are considered as storage system. The operation principle of the system is presented; the mathematical model and simulation model are also developed. Simulations are performed using two different types of loads in rural South Africa as case studies to demonstrate the technical cost advantages as well as the cost effectiveness of the proposed supply option. The results reveal that the novel micro-pumped hydro storage based hydrokinetic system is a cost-effective, reliable and environmentally friendly solution to achieve 100% energy autonomy in remote and isolated communities.
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1. Introduction

At this present time, conventional fossil fuels are being used as main sources of energy in the major part of the world; these sources are costly and release significant amounts of green house gases while they are converted into energy [1]. There is an urgent need for more sustainable energy sources which can be cost effective, reliable and environmental friendly. For a sustainable energy production, renewable energies (i.e. solar, wind, hydro, and biomass) are the most suitable supply options [2]. Apart from all being renewable and sustainable, each of the energy sources has its specific characteristics and advantages that make it well suited for specific applications [3].

Hydropower generation is an established clean technology and micro hydro schemes are being deployed worldwide especially in standalone power generation. For areas where adequate water resource is available, micro hydro has been proven to be the best supply option compared to other renewable resources in terms of cost of energy produced [4]. Apart from conventional hydropower generation, hydrokinetic (HKT) is a new category of hydropower energy that generates electricity by extracting kinetic energy of flowing water instead of potential energy of falling water, making the energy conversion process far less site specific and more competitive compared to traditional micro hydropower [5].

Very few techno-economic feasibility studies have been conducted on the use of standalone micro hydrokinetic power systems for rural power supply. Investigation on the possible use of micro hydrokinetic instead of conventional micro hydropower has been done in [6]. Based on the net present cost and the cost of energy produced, the results of this study show that hydrokinetic power is the best supply option compared to conventional micro hydropower, standalone photovoltaic (PV), wind and DG for a selected location in South Africa.

In Ref. [7], the author investigated the potential use of hydrokinetic-based hybrid systems for low cost and sustainable electrical energy supply. Different hybrid system configurations with PV, wind, diesel generator are modeled and simulated. The simulation results from two different case studies show that hybrid systems with hydrokinetic modules incorporated in their architectures have lower net present costs as well as lower costs of energy compared to all other supply options where the hydrokinetic modules are not included.

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Nomenclature

Abbreviations

AC	alternating current
BES	battery energy storage
BTS	Base Transceiver Station
CAES	compressed air energy storage
COE	Cost of Energy
DC	direct current
DHT	Darrieus hydrokinetic turbine
FBES	flow battery energy storage
FES	flywheel energy storage
HKT	hydrokinetic turbine
HOMER	Hybrid Optimization Model for Energy Renewables
PHS	pumped hydro storage
PV	photovoltaic
RES	renewable energy system
SCES	super capacitor energy storage
SMES	superconducting magnetic energy storage
SOC	state of charge

Symbols

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

Subscripts

A	turbine area
C_{Bat}	capacity of one battery
$C_{p,HKT}$	coefficient of the hydrokinetic turbine performance
E_{HKT}	energy from the hydrokinetic system
E_{Load}	load energy demand
E_{M-P}	charging power from the hydrokinetic system to the pump
E_R	potential energy of the water stored in the upper reservoir
E_{T-G}	energy generated from the turbine-generator
g	gravity
h	net pumping head
n	total number of batteries
Q_{M-P}	water flow rate from the pump
Q_{T-G}	water volumetric flow rate from the reservoir onto the turbine
t	time
V	storage capacity of the water reservoir
v	water current velocity
V_{DC}	output voltage of the battery storage system

It has to be highlighted that the main disadvantage of hydrokinetic technology, as for other renewable energy sources in general, is its resource-dependent output power and its reliance on weather and climatic conditions [8]. Therefore, it cannot always produce enough energy to continuously match the fluctuating load energy requirements without requiring the use of energy storage systems.

After a deeper analysis of the works cited in Refs. [6,7] above, it can be noted that energy storage systems were incorporated in all possible supply options proposed. However the authors of these papers did not explore other means of storing energy except for battery storage systems which have limitations such as high capital cost, short lifespan and environmental issues.

Energy storage is a research area of primary significance for the development of renewable sources, since it appears to be one of the few options to the problem of fluctuation in renewable energy production [9]. The energy storage system can reduce the fluctuating output from renewable energy sources, and guarantee that power can be produced and distributed reliably to better respond to the load energy requirements. Furthermore, it allows the energy generated to be stored when demand is low, ready to be used when demand is high. The storage system is consequently a significant component to ensure reliable and sustainable supply of renewable energy sources [10]. However, electricity storage is a complex process for the reason that electricity can only be stored after being converted into other forms of energy and this engages costly equipment and energy losses. Several energy storage technologies with distinct characteristics are currently available. These include compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro storage (PHS), battery energy storage (BES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), hydrogen energy storage (HES), and thermal energy storage (TES). The operation principles of these different energy storage system types are briefly explained below:

- CAES is a modification of the basic gas turbine technology, in which low-cost electricity is used for storing compressed air in a reservoir. The air is then heated and expanded in a gas turbine in order to produce electricity during peak demand hours [11].
- In the FES the energy is stored in kinetic energy form, which is proportional to the rotor inertia and the square of the rotational speed. Flywheel present advantages when they are used for supplying pulsed loads or in scenarios where high power is transferred to/from the storage system [12].
- In the PHS energy is stored by pumping water uphill using peak-off electricity and then letting the water move downhill and driving the generator to produce electricity for power grid when needed [13].
- The BES uses a chemical reaction to convert the stored chemical energy into electrical energy and produce voltage between terminals [14].
- Similar to a conventional battery, FBES converts chemical energy directly into electrical energy by chemical reactions. However, the electro-active material is stored externally in two tanks of electrolysis and produces the energy by reversible electro-chemical reaction between two electrolytes [15].
- SMES utilizes the magnetic field to store the energy which has been cryogenically cooled to a temperature below its superconducting critical temperature [16].
- SCES are electrochemical capacitors with relatively high energy density, approximately hundreds of times greater than conventional electrolytic capacitors. Super capacitors have great advantages over batteries such as the ability to be charged and discharged continuously without degrading [17].
- HES is receiving world attention due to its potential to replace petroleum products and reduce greenhouse gas emission significantly. The main components of a hydrogen storage system include an electrolyzer unit, the storage component and an energy conversion unit [18].
- TES is among of the most important forms of energy storage. (TES) can be stored as a change in internal energy of a material as thermochemical, latent heat and sensible heat or a combination of these [19].

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 applied where the quantity of water available for power generation with a roundtrip efficiency of 70–80%. Furthermore PHS capacity is not limited by the seasonal variation of the flow. [20].

Currently, few studies have reported the micro-PHS for standalone renewable energy systems. In Ref. [21] a new method for the effective operating pattern for a PV–PHS taking into consideration the fuel cost and the impact of excess power on the reliability of system operation is presented. A method for determining an optimal PHS operation pattern which makes it possible to improve both reliability and economy in the power systems with a large integration of PV is presented in Ref. [22]. To minimize the mismatch between the generation and load energy consumption, a wind–solar with PHS power supply system was investigated in Ref. [23]. The economic character of the PHS and battery storage for a renewable energy supplying an island has been analyzed in Ref. [24].

In addition, several case studies have been conducted on the PHS to increase the penetration level of wind power in isolated micro-grid. In Ref. [25], the authors presented a method for analyzing the effects of installing a properly managed wind-powered PHS to increase the penetration level of renewable energy sources in an isolated electric power system of the Canary Islands. The economic feasibility of small scale wind powered PHSs, not taking into account the undoubted environmental benefits, have been proven using the isolated insular power system of Karpathos–Kasos as case study [26]. In Ref. [27], the authors have examined the operation of the Irish power system with very high levels of wind energy, with and without PHS; and the results showed that the uncertainty of wind makes the option of storage more attractive. In Ref. [28], the ability of the Greek power system to absorb renewable power and the necessity of pumped storage systems is studied; the results show that for the gradual increase of variable output RES, pumped storage systems are required. The authors of Ref. [29] have conducted a technical feasibility study on a standalone hybrid solar–wind system with pumped hydro storage for a remote island in Hong Kong; the results have demonstrated that technically the PHS based renewable energy system is an ideal solution to achieve 100% energy autonomy in remote communities. Moreover, the authors of Ref. [30] have suggested that the potential of the PHS in off-grid electricity generation is even more significant if the renewable energy system power generation capacities are below 300 kW.

Based on the specific benefits of both micro-hydrokinetic and PHS as exposed in the different research discussed in the sections above, the combination of these two technologies is proposed in the present study. This combination can represent an attractive and interesting option for off-grid energy generation and storage problems which can be expected to decrease the cost of energy produced, decrease the environmental impacts and increase the reliability and availability of the electrical power supply. Therefore, in the present study, the techno-economic feasibility of such a system is analyzed and compared to the option where batteries are considered as storage system. The system working principle is presented; the model and simulation model are also developed. Simulations are performed using two different types of loads in rural South Africa as case study to demonstrate the technical advantages as well as the cost effectiveness of the proposed supply option.

2. Proposed system description and operation principle

The schematic diagram representing the operation principle is shown in Fig. 1; the system under consideration is composed of standalone hydrokinetic system used in conjunction with a PHS supplying an isolated load not connected to the grid. The micro-PHS plays a significant role in shifting energy surpluses from the hydrokinetic generation system, minimizing the fluctuation of water sources, and matching the fluctuating energy production and fluctuating load energy requirements as well.

The operating principle of the proposed system can be briefly explained as follows: The pump up-rises the water from the river or a stream, to the upper reservoir using excess hydrokinetic output when the generation exceeds the demand. The stored water is then allowed to fall down through a turbine driving a generator producing enough energy to complement the difference during times when the electrical demand is higher than the hydrokinetic production. Like this, a reliable and sustainable energy generation system would be continuously assured if the charging and discharging rates as well as the reservoir capacity are adequate.

Another potential advantage of the micro-PHS is that it can be fully incorporated within the local natural environments because it can use the streams and collect rain water in the reservoir. The stored water can also be used for household and agricultural purposes [31].

3. Proposed system mathematical

3.1. 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 [32].

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 [33], 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 [34]:

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

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.

3.2. Pumped hydro system

3.2.1. 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. (2) [35]. This energy is directly supplied by the hydrokinetic system.

$$E_{M-P} = \frac{\rho_W \times g \times h \times Q_{M-P}}{\eta_{M-P}} \tag{2}$$

where E_{M-P} is the charging power from the hydrokinetic system to the pump (W); Q_{M-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 η_{M-P} is the overall pumping efficiency.

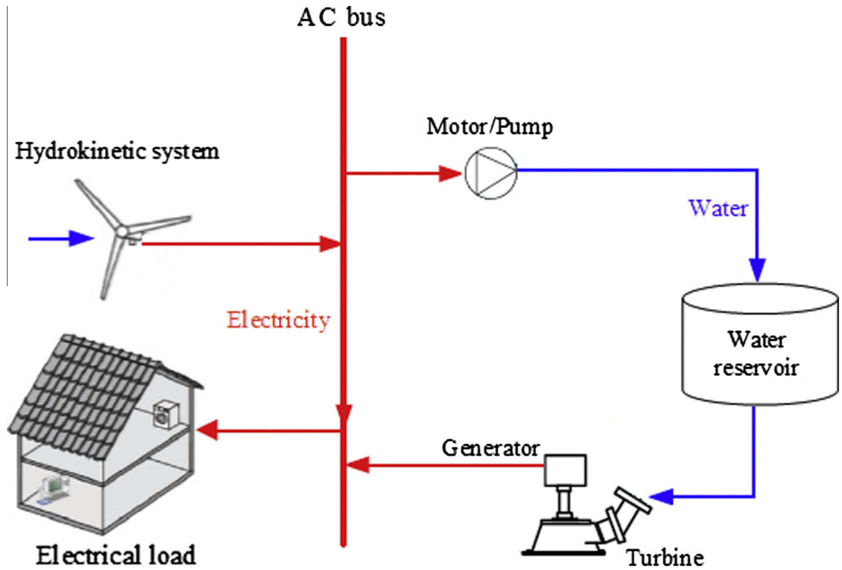

Fig. 1. Proposed system layout (with electricity flow and water flow).

3.2.2. 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 [35]. The energy generated from the turbine-generator E_{T-G} set can be expressed as:

$$E_{T-G} = \rho \times g \times h \times Q_{T-G} \times \eta_{T-G} \tag{3}$$

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

3.2.3. 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 [36]. The potential energy E_R of the water stored in the reservoir can be expressed as:

$$E_R = \rho \times V \times g \times h \tag{4}$$

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

3.2.4. Energy balance

The load energy demand 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:

$$E_{Load} = E_{HKT} - E_{M-P} + E_{T-G} \tag{5}$$

When there is more than enough energy to supply the load directly by the hydrokinetic system, no supplementary energy is needed, consequently E_{T-G} is zero and the surplus of generated energy E_{M-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, both E_{T-G} and E_{M-P} are zero. However, when there is an insufficient energy to supply the load directly by the hydrokinetic system, extra energy E_{T-G} is provided from water flowing from the reservoir and driving the turbine-generator set, E_{M-P} is zero.

4. Simulation model

HOMER (Hybrid Optimization Model for Electric Renewable) [37] is selected as a simulation tool to develop a model that minimizes the sizing and operation costs of different realistic hydrokinetic systems with the two selected storage options for the project duration.

4.1. Hydrokinetic module

The hydrokinetic module has been modeled using a wind turbine unit because they are having identical working principle. A new wind turbine can be modeled with the speed-power characteristic curve of the desired hydrokinetic turbine (which is entered as wind data). The anemometer height has to be set equal to the turbine hub height so that HOMER does not scale the wind speed data [7].

4.2. Pumped hydro storage module

Knowing that the PHS operates as storage mechanism with a certain capacity and a certain round-trip efficiency, it can be built in HOMER as an electrical deferrable storage device. The following analogies with a battery can be made:

- The flow rate from the motor-pump set can be compared to the charging rate of a battery.
- The volume of the tank can be compared to the capacity of a battery.
- The water level in the reservoir at a specific time can be compared to the battery state of charge (SOC).
- The water flow rate from the reservoir to the turbine-generator set can be compared to the discharging rate of a battery.

Therefore a new battery can be built and the capacity can be specified as a fixed value in Ah, the lifetime in terms of years, and the maximum charge and discharge current can also be 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, this problem can be 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.

In traditional micro hydro power generation, potential energy of the falling water is initially converted to equivalent kinetic energy. The potential energy from the water stored in the reservoir is taken as equals to the energy stored in the batteries recommended by HOMER. This can be expresses as [38]:

$$E_R = n \times C_{Bat} \times V_{DC} \tag{6}$$

where n is the total number of batteries, C_{Bat} the capacity of one battery (Ah), V_{DC} the output voltage of the battery storage system.

For design purposes, Eq. (6) can be rearranged to find the required capacity (volume) of the water reservoir.

$$V = \frac{n \times C_{Bat} \times V_{DC}}{\rho \times g \times h \times \eta_{T-G}} \tag{7}$$

However, if the corresponding potential energy in the battery system is known, the volume of the reservoir will only depend on the desired water head h. It can be noticed from Eq. (7) that the volume is inversely proportional to the water head, therefore a trade-off between these two variables needs to be found to minimize the reservoir construction cost.

5. Simulation data

A rural household as well as a Base Transceiver Station (BTS) load patterns are selected on two different sites as case studies to analyze the techno-economic characteristic of the hydrokinetic system used with the two different storage options. The water velocity data, the daily load profiles as well as the costs of the different components described in Sections 5.1 and 5.2 are used as input to HOMER. Section 5.3 emphasizes on the different assumptions made while modeling the different system's components as well as the ones to be used in the simulations of the different options.

5.1. Case 1: Rural household

5.1.1. Load description

Based on the need to supply the basic electrical appliances for typical low income rural communities in South Africa, a daily load profile is generated from an average household located in the KwaZulu Natal province as shown on Fig. 2. The household peak power demand is 5.6 kW and the daily energy consumption 35 kW h. It is assumed that an average household needs electricity for lighting, television, radio, fridge, kettle, cell phone chargers, iron, etc. [39].

5.1.2. Water resource assessment

The yearly water resource profile according to its velocity is given of Fig. 3 [7]. From this profile it can noticed that the minimum water velocity is reached in September; for that reason the hydrokinetic system has to be sized to operate at its rated capacity even during that month.

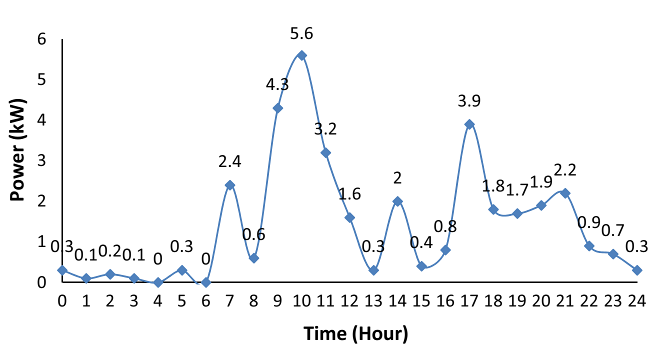

Fig. 2. Rural household load profile.

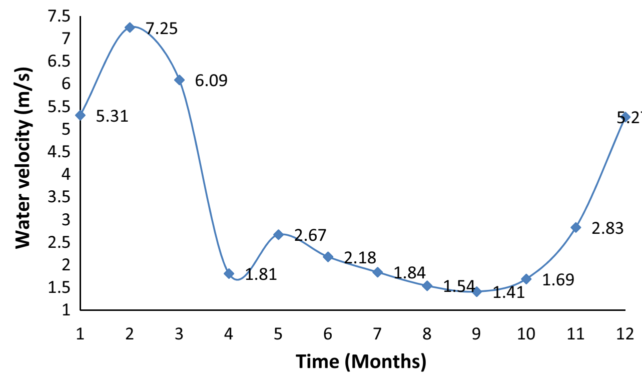

Fig. 3. Monthly average water velocity (Case 1).

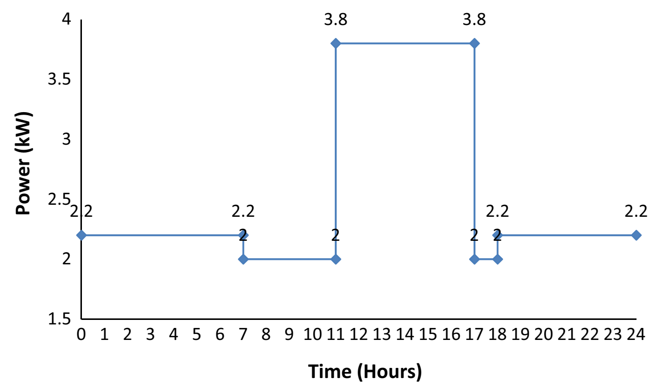

Fig. 4. BTS load profile.

5.2. Case 2: Base Transceiver Station (BTS)

5.2.1. Load description

A BTS used for cellular network has been selected as load for a second case study. This load situated in the Western Cape has a very different profile compared to a household as shown on Fig. 4. The BTS peak power demand is 3.8 kW and the daily energy consumption 59 kW h. Electricity is needed to supply the telecommunication apparatus, cooling system as well as security lights on the BTS site [40].

5.2.2. Water resource assessment

The BTS site is situated at almost 1500 km in different climatic region from the rural household in the first case study. For this site, the yearly water velocity profile is given of Fig. 5 [7]. From this profile it can noticed that the minimum water velocity is reached in August; therefore the hydrokinetic system has to be sized to operate at its rated capacity even during that month.

5.3. Component costs and assumption

The sizes and prices of power modules considered in this study are shown in Table 1 which gives estimations based on quotations from local South African manufacturers as well as suppliers of power generation equipment [41,42].

The followings components design assumptions need to be taken into account for simulation purposes:

- The Darrieus hydrokinetic turbine (DHT) has been chosen due to the possibility of generating high power at very low velocity [43]. The considered DHT turbine gives a rated power of 1 kW at 1.4 m/s water velocity. Thus, it is assumed that the produced

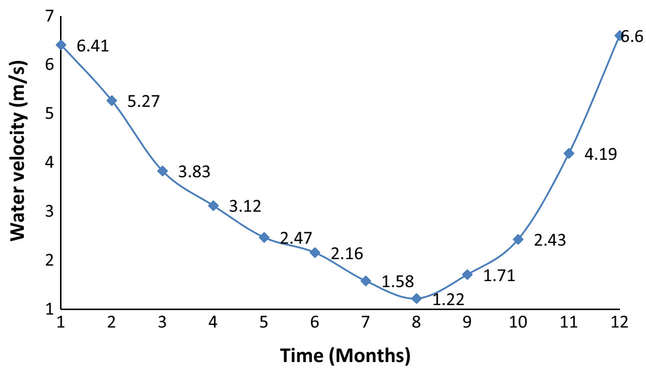

Fig. 5. Average water velocity (Case 2).

Table 1
Component data and prices.

Modules	Price ($)	O&M ($/y)	Replacement ($)	Lifetime (y)	Energy cost ($/kW h)
HK (1 kW)	7500	20	7500	25	–
Converter (7 kW)	3730	10	3730	15	–
Battery (6 V, 360 Ah)	215	5	215		–
PHS (1 kW)	4000		4000	30	
Grid (km)	9000	180	–	–	0.144

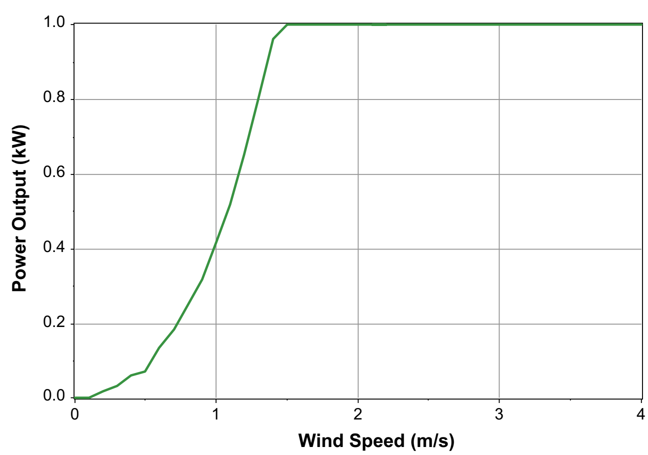

Fig. 6. Hydrokinetic power curve.

power remains constant for water velocities above 1.5 m/s. Fig. 6 shows the corresponding turbine's power curve. The hydrokinetic turbine losses are assumed to be 35%, combined losses of the hydrokinetic turbine and the generator is assumed to be 40%, and the coefficient of power of the whole system is taken as 30%.

- The roundtrip efficiency PHSs (i.e. energy output to energy absorbed for pumping) is between 70% and 80%. This takes into account typical pump and turbine losses of 8%, motor and generator losses of 2% and energy losses of typically 7% in pumping and turbine operation [44]. However, this efficiency can be taken as low as 50% due to the small size of the installation. Therefore the two border operation conditions with a worst efficiency of 50% and a best efficiency of 70% will be subject of a sensitivity analysis.
- Costs for PHS are very site specific and also depends on the capacity of the installation with some quoted costs ranging from $2000 to 4000/kW [45]. Therefore, for this study, the two costs will be considered for sensitivity analysis.
- It is assumed for illustration purposes, that the topographical location of the two sites offer the possibility to build man-made concrete based covered pool type hydro storage reservoir at the height "*h*" of 20 m. In reality, the available heights from the sites can be higher based on the mountainous nature of the KwaZulu Natal and Western Cape provinces.
- The investment, operation and maintenance as well as replacement cost of the different components used in the simulation are shown on Table 1.

6. Results and discussion

HOMER simulates the different combinations and then rejects all combinations that are not feasible from the potential results. The simulation results obtained from the hydrokinetic system with the different energy storage options will be analyzed and then compared on the basis of their respective Cost of Energy (COE) while supplying the same load pattern; this realized under 0% capacity shortage factor of the peak hourly demand (i.e. the percentage of time when the supply option is not able to respond to the load energy requirements including the reserves). For the PHS, two border cases will be considered for each site:

- The worst case scenario with a capital cost of $4000/kW and an efficiency of 50%.
- The best case scenario with a capital cost of $2000/kW and an efficiency of 70%.

6.1. Household case

6.1.1. Option 1: Hydrokinetic + battery storage system

For the rural household case study, the optimal combination is composed of 5 hydrokinetic modules, 8 batteries and a 7 kW converter.

Fig. 7 shows the average monthly hydrokinetic output power. During the month of September, due to insufficient water resource the hydrokinetic plan gives an average of 1 kW which is its minimum output.

From Fig. 8, it can also be seen that the inverter is contributing to supply the load all trough the year during the peak load demand occurring just before noon (9h00–11h00). This daily contribution becomes more frequent between August and October where it occurs in the morning around 7h00, in the evening around 17h00; the one occurring before noon becomes more important forcing the inverter close to its maximum capacity. From Fig. 9, it can be seen that the rectifier is used throughout the year just after the peak demand occurring before noon with the aim of recharging the battery system. However, it can be seen that from August to October, the rectifier is forced to give its maximum output power during off-peak times occurring after the morning, noon as well as evening peak load demands; this is done in a attempt to recharge the battery system at its maximum capacity.

The battery state of charge can also be seen from Figs. 10 and 11. It can be noticed in April, as well as from August to October the load is also relying on the battery system to balance the deficit of generation from the hydrokinetic system. This situation is worse during September where the load is heavily relying on the battery; therefore the average state of charge (SOC) in that month is around 65%.

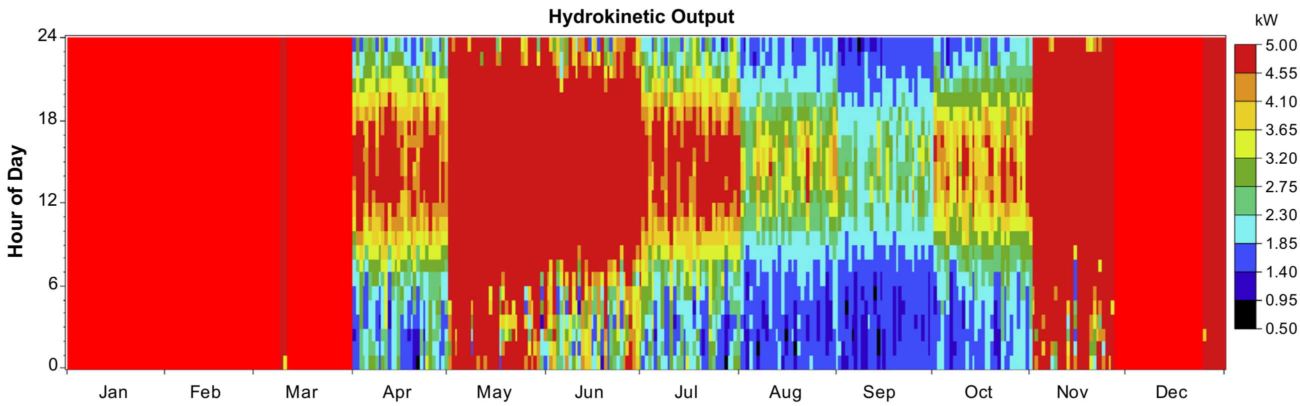

Fig. 7. Hydrokinetic yearly power output (Case 1).

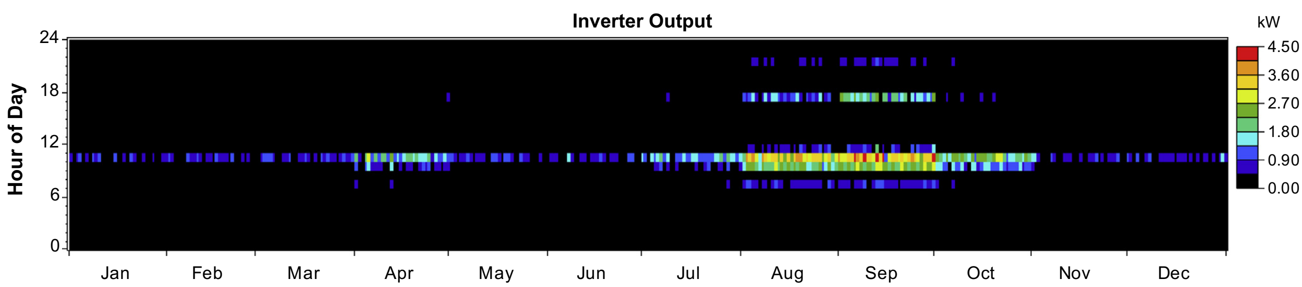

Fig. 8. Inverter output power (Case 1).

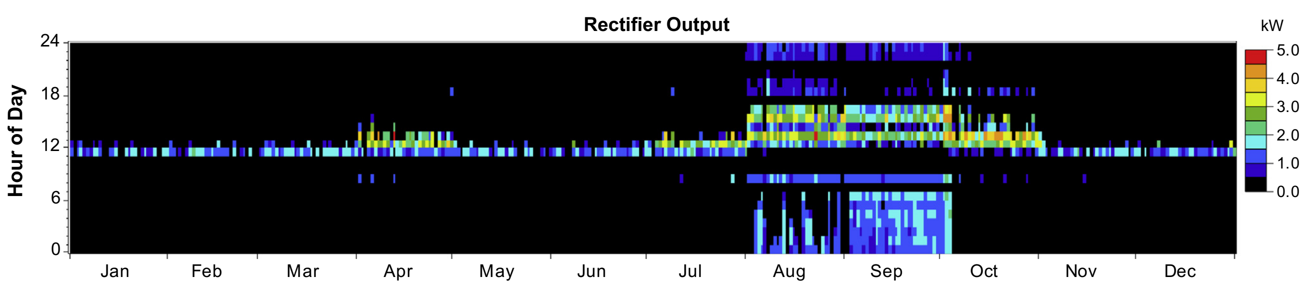

Fig. 9. Rectifier output power (Case 1).

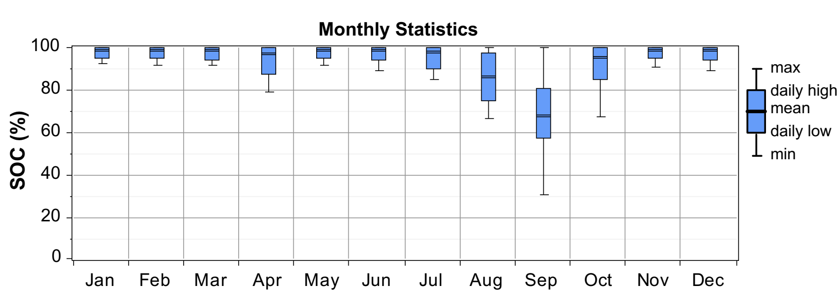

Fig. 10. Battery monthly state of charge statistics (Case 1).

6.1.2. Option 2: Hydrokinetic + pumped hydro storage

In Section 4.2, it has been assumed that the potential energy from the water stored in the reservoir is taken as equal to the energy stored in the batteries recommended by HOMER. Therefore, using the simulation results obtained in Section 6.1.2, the potential energy in the reservoir must be equal to the one stored in 8 batteries; this can be calculated using Eq. (6) and then used in the model developed in Section 4.2.

The simulation results show that the optimal combination is composed of 5 hydrokinetic modules, with a reservoir capacity of 17.28 kW h corresponding to a water reservoir of 317 m^3 at 20 m height.

The results in Figs. 12 and 13 show the hourly energy stored (considered as SOC) in the reservoir for a year period. It can be noticed that the SOC is relatively high all through the year indicating the reservoir is full or nearly fully charged

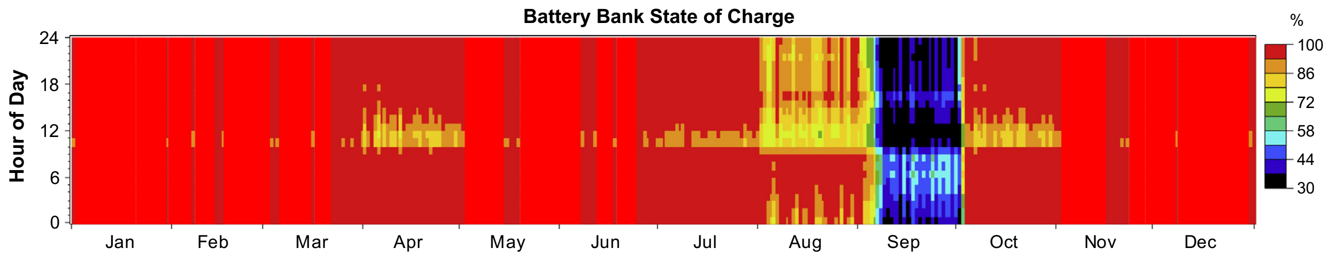

Fig. 11. Battery state of charge (Case 1).

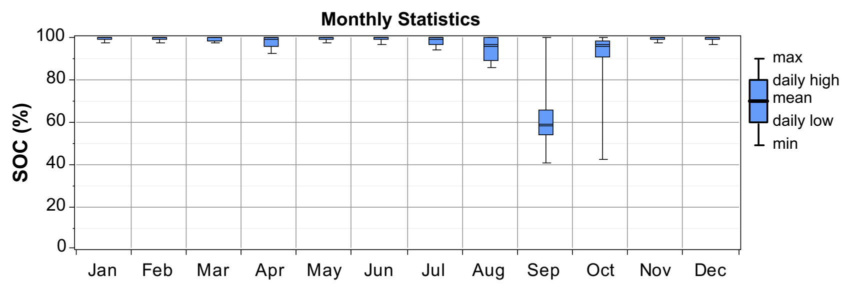

Fig. 12. PHS monthly reservoir state of charge statistics (Case 1).

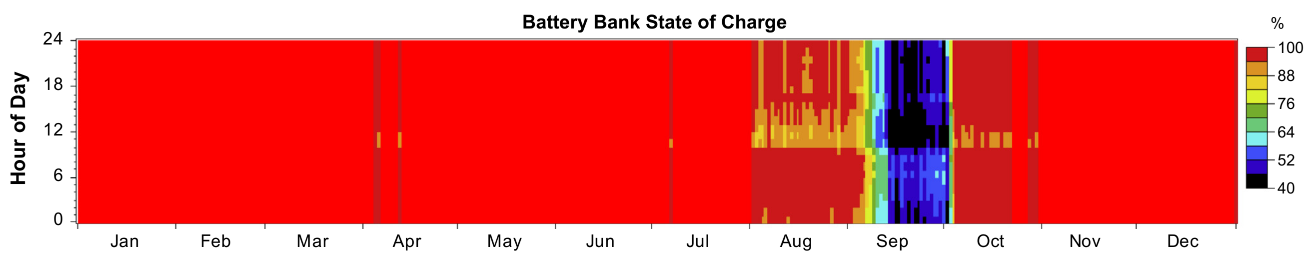

Fig. 13. Water reservoir state of charge (Case 1).

for a pretty long period. However, from this figure, it can be seen that high depth of discharge occurs during September with minimum water stored in the reservoir of approximately 60% or 190 m^3; this is due to insufficient water resource resulting in poor performance of the hydrokinetic system as main source of energy.

It has to be highlighted that the motor-pump and the turbine-generator sets will have almost the same profiles as the ones from the inverter and rectifier respectively presented in Figs. 8 and 9 respectively.

Table 2
Summary of the different supply options simulation results (household case).

Item	HKT + battery	HKT + PHS	
Scenario	–	Worst scenario	Best scenario
Capital ($)	42,951	41,500	39,500
NPC ($)	47,891	42,687	40,892
COE ($/kW h)	0.291	***0.259***	***0.248***
Operation ($)	1918	1342	1470
Replacement ($)	3694	0	0
Salvage ($)	−672	−155	−78
Grid extension (km)	2.14	1.68	1.52
Electricity excess	21,764	21,674	21,774
Storage autonomy (h)	8.22	35.2	35.2
Storage depletion (kW h/y)	−1.43	0	0
Storage expected life (y)	8.23	30	30

The bold-italicized values are the cost of energy produced (selection criteria) of the selected supply option.

6.1.3. Technical and economical results summary of the two supply options

Table 2 summarizes and compares the simulation results of the two supply options, it can be easily seen that using the costs as well as the electrical outputs, the PSH is a better option compared to the battery storage system. Meanwhile, in both cases, a considerable part of energy generated is wasted due to the limited storage capacity.

6.2. Case 2: Base Transceiver Station (BTS)

6.2.1. Option 1: Hydrokinetic + battery storage system

For the BTS case study, the optimal combination is composed of 9 hydrokinetic modules, 5 batteries and a 5 kW converter.

Fig. 14 shows the average monthly hydrokinetic output power. During the month of August, due to insufficient water resource the hydrokinetic plan gives an average of 1 kW which is its minimum output.

Fig. 15 also shows the inverter output power and the rectifier daily output profiles, respectively. From this figure it can be seen that the inverter is mostly used during August during the peak load demand occurring from 11h00 to 17h00. From Fig. 16, it can be seen that the rectifier is mostly used in August during off-peak time just after 17h00 to recharge the battery storage system. It can also be noticed from Figs. 17 and 18 that the battery is in average almost fully charged all through the year except during August where the demand from the load requires greater contribution from the battery; therefore the daily average state of charge (SOC) in that month is around 75%.

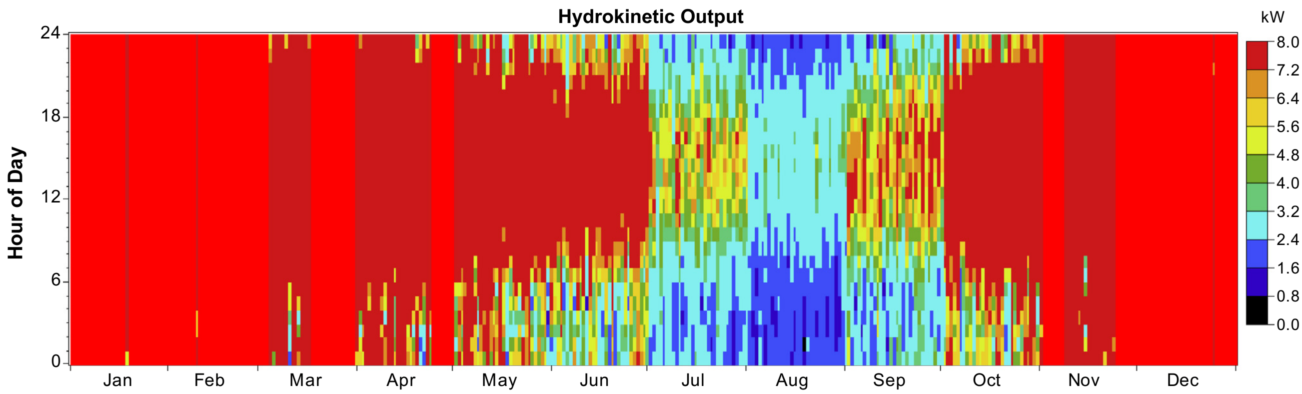

Fig. 14. Hydrokinetic yearly power output (Case 2).

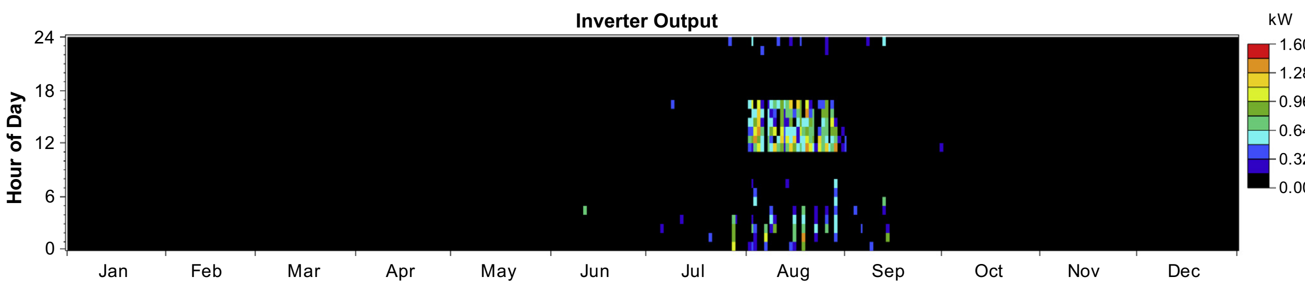

Fig. 15. Inverter output power (Case 2).

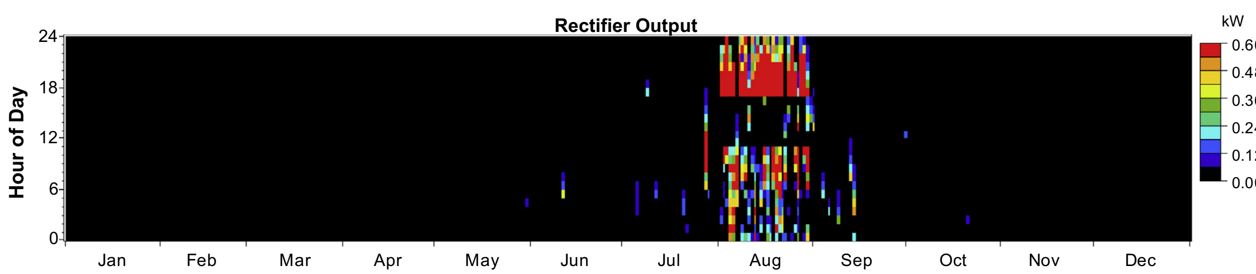

Fig. 16. Rectifier output power (Case 2).

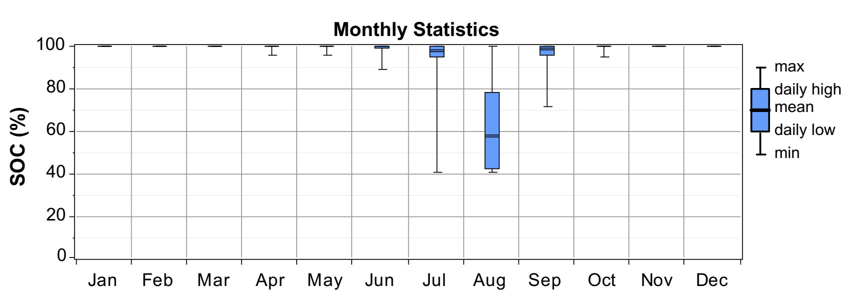

Fig. 17. Battery monthly state of charge statistics (Case 2).

6.2.2. Option 2: Hydrokinetic + pumped hydro storage

The simulation results show that the optimal combination of 9 hydrokinetic modules, with a reservoir capacity of 10.8 kW h corresponding to a water reservoir of 198 m^3 at 20 m height.

The results in Figs. 19 and 20 show the energy stored (considered as SOC) in the reservoir for a year period. It can be noticed that the SOC is relatively high all through the year indicating the reservoir is full or nearly fully charged for a pretty long period. However, high depth of discharge occurs in August, with an average reservoir state of charge of approximately 80% or 158 m^3; this is due to insufficient water resource resulting in poor performance of the hydrokinetic system as main source of energy.

Here also, it has to be highlighted that the motor-pump and the turbine-generator sets will have almost the same profiles as the ones from the inverter and rectifier respectively.

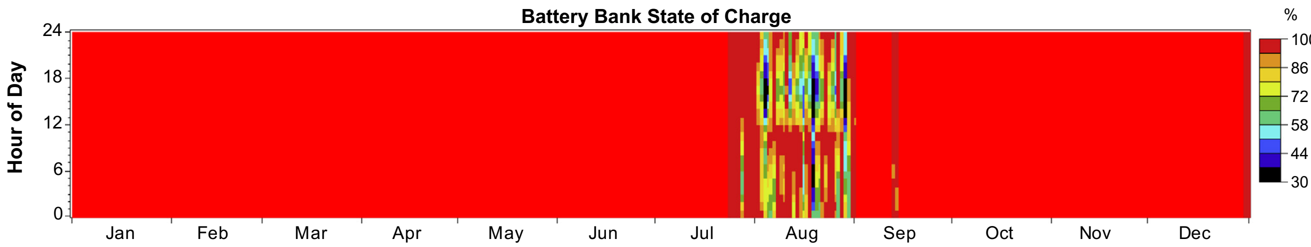

Fig. 18. Battery state of charge (Case 2).

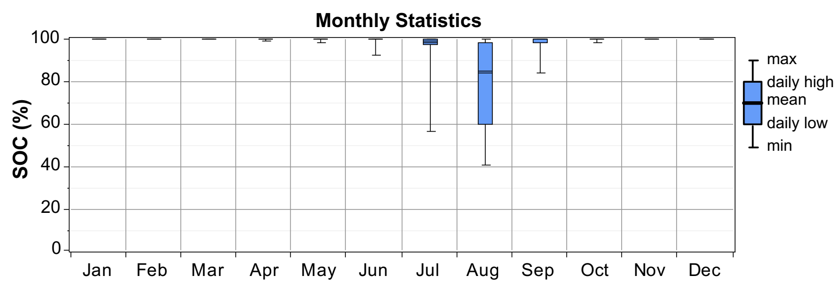

Fig. 19. PHS monthly reservoir state of charge statistics (Case 2).

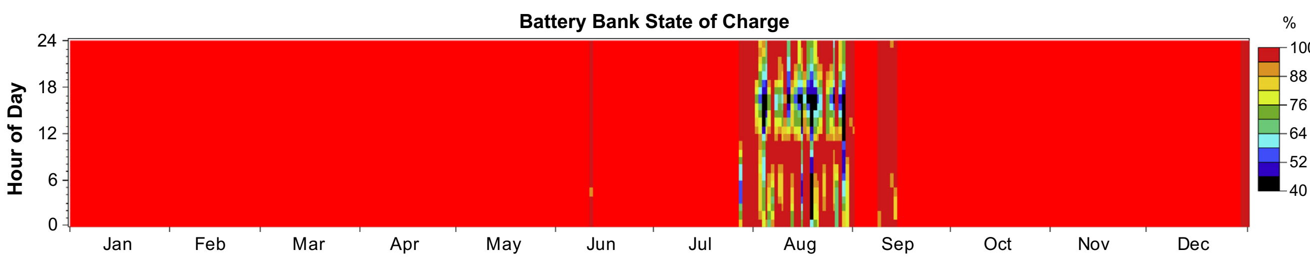

Fig. 20. Water reservoir state of charge (Case2).

Table 3
Summary of the different supply options simulation results (BTS case).

Item	HKT + Battery	HKT + PHS	
Scenario	–	Worst scenario	Best scenario
Capital ($)	71,684	71,500	69,500
NPC ($)	76,277	73,710	71,787
COE ($/kW h)	0.278	***0.269***	***0.262***
Operation ($)	2727	2365	2365
Replacement ($)	2233	0	0
Salvage ($)	−367	−155	−78
Grid extension (km)	3.25	3.03	2.86
Electricity excess	43,605	43,565	43,613
Storage autonomy (h)	3.09	2.64	2.64
Storage depletion (kW h/y)	−0.897	0	0
Storage expected life (y)	10	30	30

The bold-italicized values are the cost of energy produced (selection criteria) of the selected supply option.

Table 3 summarizes and compares the simulation results of the two supply options, as for the household case, it can be easily noticed that the PSH is a better option compared to the battery storage system in terms of COE. It can also be noticed that in both cases, a considerable part of energy generated is wasted due to the restricted battery or PHS capacity.

7. Conclusions and suggestions

This paper investigated the use of PHS based hydrokinetic system to supply electricity to remote rural areas not connected to the grid. From the review of few literatures currently available, it has been revealed that hydrokinetic is the best supply option where adequate water resource is available; and small scale pumped hydro storage can guarantee the reliable, sustainable and nonstop power supply. However no work has been published yet analyzing the use of hydrokinetic technology operating in conjunction with micro-PHS. Therefore the techno-economic feasibility of such combination has analyzed and compared to the option where batteries are considered as storage system. The system working principle has been presented; the mathematical model and simulation model have also been developed and applied to two case studies in South Africa.

Simulations of two different options (hydrokinetic/battery and hydrokinetic/PHS) have been performed using HOMER software, and the results have been analyzed to select the best supply option based on the COE produced. Despite the fact that even the worst case scenario on the micro-PHS initial capital cost as well as the efficiency have been considered for simulation purposes, the results have demonstrated that for both the household and BTS case studies the combination of hydrokinetic and micro-PHS system is the most cost-effective, reliable and environmentally friendly solution compared to the option where the battery storage system is considered.

The results of this investigation have led to the following recommendations:

- Further studies must be conducted to find a trade-off between the height and the reservoir volume with the aim of minimizing the costs while maximizing the system's energy output.

- In view of the significant ongoing progress in the batteries technology, their life-cycle cost is expected to be reduced in the future whereas the PHS costs are rather fixed. Therefore further studies on the optimal sizing or operation control of the micro-PHS should be conducted to strengthen the techno-economic superiority of this technology over the battery based one.

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