Grid-interactive micro-hydrokinetic with pumped-hydro storage: The case study of three South African demand sectors

S.P. Koko, K. Kusakana, and H.J. Vermaak

Abstract— This paper investigates the operation of different demand sector such as residential, commercial and industrial load profiles when supplied with a grid tied micro-hydrokinetic pumped-hydro storage (MHK-PHS) hybrid system. The aim is to explore the demand sector which is more favorable to the proposed grid-tied MHK-PHS hybrid system under the time-of-use (TOU) tariff scheme. Hence, the optimum configuration of the proposed MHK-PHS hybrid system is determined in order to investigate the effect of each demand sector on sizing and operation of the hybrid system. HOMER Pro Version 3.6.1 has been used to perform the optimization under TOU tariff scheme. The results have shown that the industrial load sector incur the lowest cost of energy at the highest capital cost as opposed to the residential and commercial load sectors. However, from economic perspective, the residential demand sector proved to be more favorable to the proposed hybrid system due to the lowest net present cost (NPV). For each load demand sector, HOMER led to oversizing constraint of the hybrid system by not recharging the storage system after use.

***Index Terms*—Micro-hydrokinetic, Pumped hydro storage, demand sectors, Time of Use**

1 INTRODUCTION

The rapid depletion of fossil fuel resources and the need to reduce greenhouse gases (GHGs) emission level have resulted into worldwide concerns. Such concerns have necessitated an urgent exploration for alternative energy sources. More than 80% of world energy supply is still dominated by fossil fuels contributing to climate change [1]. This trend is expected to continue due to population growth leading to rapid growth in fossil fuel power generation. The use of renewable energy sources to meet the daily energy demand is a solution to address such challenges.

Allowing consumers to sell renewable energy to the utility grid can cope with the fast-growing electricity demand and thus boost the grid stability [2]. This can also help consumers to reduce their electricity bill costs. To ensure safe and reliable operation micro-grid system, it is necessary to incorporate an energy storage system (ESS) since many electrical utilities tend to allow their electricity prices to differ from time to time [3].

Time of use (TOU) electricity tariff is the common time-based pricing mechanism used by many utility companies. The price of electricity is raised during peak hours and then lowered during off-peak hours. Hence, according to the price variation, ESS can allow consumers to store energy during inexpensive period and use it during expensive peak period and/or sell it to the grid. If grid-connected hybrid system consisting of renewable energy sources and ESS is well managed, it will assist consumers to substantially reducing their electricity cost and also increase the reliability of the utility grid.

Renewable energy sources such as wind and solar have a drawback of not meeting the demand throughout the day due to their unpredictable nature and random variation [3]. To overcome such drawback, hydrokinetic technology is a promising solution than can be used in areas with flowing water resource. It is easily predictable since it does not vary rapidly within a very short period of time [4]. However, there are very few studies that have concentrated of modelling and size optimization of the hydrokinetic systems. These studies have revealed the technical and economic benefits offered by hydrokinetic technology [4 -7]. It has proved to offer the most economical and environmentally friendly solutions as compared to solar, wind and diesel generator (DG) systems. However, none of these studies have explored the effect of different load profiles on sizing and operation of hydrokinetic hybrid systems. Furthermore, none of them have considered using the TOU tariff mechanism since they have concentrated on off-grid hydrokinetic systems.

In order to efficiently and economically utilize the hydrokinetic technology, it needs to be integrated with a pumped hydro storage (PHS) system, instead of the battery storage system [8]. In this paper, residential, commercial, and industrial demand sectors are investigated to see the effect of each one on optimal configuration and operation of the proposed grid-connected micro-hydrokinetic pumped-hydro storage (MHK-PHS) hybrid system under the TOU electricity tariff scheme. This is done using the Hybrid Optimization Model for Electric Renewables (HOMER) software tool. HOMER has proved to be the most widely used software tool to carry out prefeasibility, optimization and sensitivity analysis [9]. Each load profile was allowed to have the daily energy consumption of 60 kWh to validate the comparison results.

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2 METHODOLOGY

The power flow layout of the proposed grid-connected MHK-PHS hybrid system is as shown in Fig. 1. The hybrid system consists of the micro-hydrokinetic system, PHS system and the demand sector (residential, commercial or industrial load). The load energy requirement can be provided by the MHK river system, utility grid and/or by the PHS system depending on the current tariff rate. The energy sales to the utility grid can be from the MHK river system and/or PHS system. In this study, the HOMER Pro Version 3.6.1 has been selected since it is equipped with a hydrokinetic module in its library. It also has TOU rate schedule computability. During simulations, an interest rate was assumed to be 7% for the project with a lifespan of 25 years. The simulations were carried with the aim of meeting each load demand at no capacity shortage.

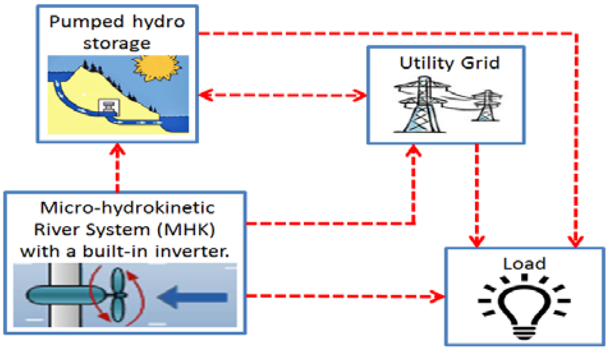

Fig. 1: Proposed hybrid system layout (power flow)

2.1 Hydrokinetic resource data

Hydrokinetic resource data is necessary to define the flowing water speeds that a hydrokinetic turbine would experience in a typical river. The monthly average water velocity of a typical river situated in Kwazulu Natal Province (South Africa) has been used as input to the hydrokinetic module as illustrated in Fig. 2.

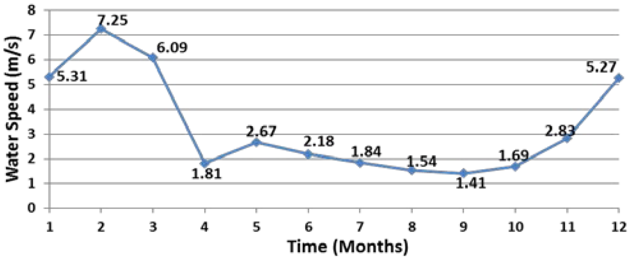

Fig. 2: Monthly Average Water Velocity [4-7]

2.2 Load description

Each demand sector is modelled separately as a primary load type. For residential load, the load profile of a typical South African residential consumer was considered during simulation [10]. For commercial and industrial loads, the typical load curves from a study conducted by Jardini et al. [11] were considered. For better comparison purpose, the three load profiles were allowed to have the same daily energy consumption of 60 kWh per day as shown in Fig. 3. This is denoted by the area under each curve.

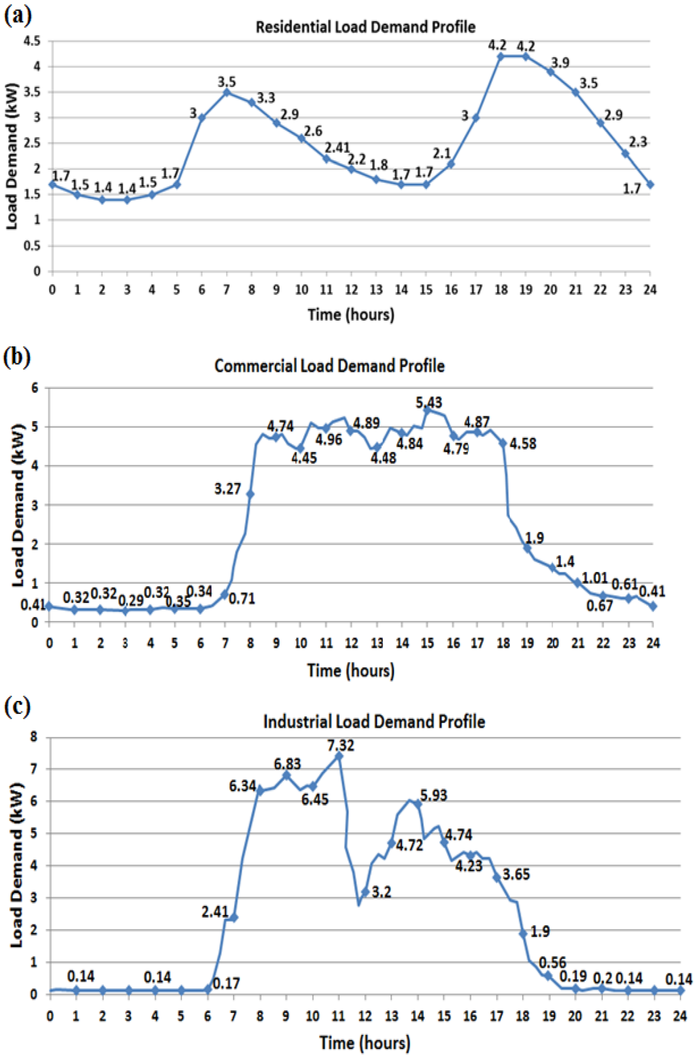

Fig. 3: Daily load profile for (a) residential, (b) commercial, and (c) industrial

2.3 Electricity TOU tariffs

TOU pricing tariffs used by South African electrical utility (Eskom) have been applied as a case study during simulation [12]. Genflex TOU tariff scheme has been considered in this study. This scheme is used for customers who consume energy (from Eskom) and also generate energy for sale (to Eskom). Table I shows the Eskom Genflex TOU tariffs for high-demand and low-demand seasons. During the study, 1 US$ = 13.51 ZAR. In this study, the contracted ratio assuming that the selling price is 65% of the utility price was used.

Table I - Eskom Genflex TOU Tariffs and Seasonal Periods [12]

TOU Periods	High-demand season (Jun to Aug)	Period range	Low-demand season (Sep to May)	Period range
Peak periods	US$0.21/kWh	06:00- 09:00, 17:00- 19:00	US$0.07/kWh	07:00- 10:00, 18:00- 20:00
Standard periods	US$0.06/kWh	09:00- 17:00, 19:00- 22:00	US$0.05/kWh	06:00- 07:00, 10:00- 18:00, 20:00- 22:00
Off-peak periods	US$0.035/kWh	22:00- 06:00	US$0.03/kWh	22:00- 06:00

3 MAIN SIMULATION INPUT PARAMETERS

The proposed MHK-PHS hybrid system consists of the hydrokinetic river system to generate electricity and a PHS system to store energy. The performance and costs for each component of the proposed hybrid system are critical for optimum design configuration. The cost of each component is broken down into capital, replacement, and operation and maintenance (O&M) costs as illustrated in Table II. All components are assumed to have the replacement costs being equal to the capital cost.

Table II - Eskom Genflex TOU Tariffs and Seasonal Periods [12]

Components	Capital Cost (US$)	O&M (US$)	Replacement Cost (US$)	Life Time (years)
1.5 kW Hydrokinetic Turbine + an 8 kW Inverter	15,000 + 5,509 = 20,509	300 + 55.09 = 355.09	20,509	25
1 kW Pumped-Hydro Storage	3,000/kW	180/kW	3,000/kW	30

3.1 Hydrokinetic system and the inverter

River based hydrokinetic turbines are available in a range of 1-10 kW [13]. In this study a generic 1.5 kW direct current (DC) Darrius hydrokinetic turbine (DHK) system with the swept area of 1.56 m^2 has been selected [5].

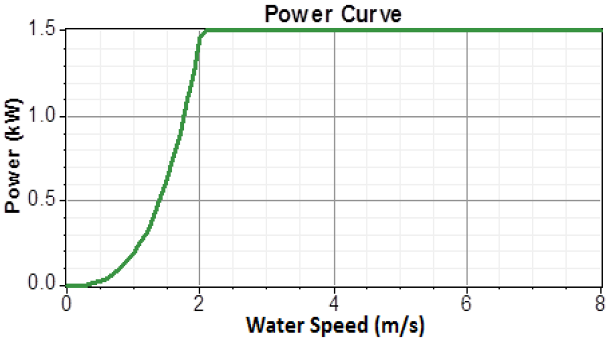

Fig. 4: Darius hydrokinetic (DHK) turbine power curve [5]

One unit requires a capital cost of US$15,000. The operation and maintenance (O&M) costs are considered to be 2% of the capital cost (US$300) per year. Similar to the wind turbines, the lifespan of a hydrokinetic turbine is estimated to be 25 years [14]. The output power curve of the turbine is shown in Fig. 4.

An 8 kW, 50 Hz, 230 Vac Victron inverter has been considered in this study to convert DC output power of a hydrokinetic generator into AC power. The cost price of this converter is US$5,509 with the O&M cost assumed to be US$55.09 [5]. Since the battery is the only component to be connected to the DC bus when modelling a PHS system, the inverter costs were added to the costs of the hydrokinetic turbine to represent the overall cost of the hydrokinetic system as shown in Table II. The aim is to enables the hydrokinetic system to be directly connected to the AC bus.

3.2 Pumped-hydro storage system

Since HOMER is not equipped with PHS system, usually a battery which is equivalent to an upper reservoir needs to be created and used to model the PHS plant [8, 15-16]. Trojan T-105 battery settings were set to 230 V and 26 Ah respectively to allow each battery to store up to a maximum of 6 kWh when supplying a 1 kW power for a maximum of 6 hours of discharge. The power delivered by the battery increases with an increase in discharge current [17]. Hence, a maximum discharge current was set to 4.35 A which is equivalent to 0.0926 m^3/sec of volumetric discharge rate for a minimum volume of 200 m^3 at a head height and roundtrip efficiency taken to be 18.35 m and 60% respectively for small scale installation. The costs of the PHS have been entered into the battery model with a life span taken to be 30 years. The installation cost of a PHS system per kW varies from US$2000 to US$4000 [8]. In this study, the average installation cost of US$3000/kW has been considered. The O&M costs are assumed to be 6% of the initial capital cost [15].

A PHS plant has a round trip efficiency of 70-85% depending on the size, design and technical arrangements [18-19]. Hence, in this study the round trip efficiency is estimated to be 60% due to the small-scale PHS plant. For large-scale installation it has been proved that a minimum waterfall height must be at least 100 m to ensure the efficient operation of a PHS system [20]. In this study, the volume of the upper reservoir is based on the waterfall height of 18.35 m since this is a small-scale installation. After determining the optimal number of storage batteries needed for each load demand profile, the total stored energy (kWh) in all batteries will be determined by multiplying the number of batteries by nominal capacity of each battery. HOMER suggests that the energy stored in the batteries is equivalent to the potential energy stored in the upper reservoir. Hence, the total energy storage capacity of the upper reservoir is proportional to the optimal number of batteries as determined by HOMER and is expressed using Eq. 1 as:

$$E_S = n \times C_{Bat} \times V_{DC} \quad (1)$$

Where: n is the optimum number of batteries, C_{Bat} is the nominal capacity of one battery (Ah), and V_{DC} is the selected battery voltage. Results and discussion

In this section, the optimum configuration results obtained using HOMER Pro Version 3.6.1 are discussed. To ensure validity of the results, the three load profiles were allowed to have the same daily energy consumption (60 kWh/day) without changing the shapes of their curves. Table III illustrate the optimal configuration results for each load profile. The annual energy sales and generated income for each load profile are as shown in Table IV.

Table III - HOMER Optimal configuration results

	Residential load	Commercial load	Industrial load
Optimum Size	13.5 kW hydrokinetic turbine system + 5.98 kWh (26 Ah) Upper reservoir	16.5 kW hydrokinetic turbine system + 5.98 kWh (26 Ah) Upper reservoir	22.5 kW hydrokinetic turbine system + 5.98 kWh (26 Ah) Upper reservoir
Capital cost ($)	187,581	228,599	310,635
Operating cost ($/y)	743.45	688.44	573.54
Net present cost ($)	196,245	236,622	317,319
Levelized cost of energy ($/y)	0.173	0.170	0.168
Total energy production (kWh/y)	97,475	119,135	162,455
Grid energy sales (kWh/y)	75,576	97,250	140,569
Purchased grid energy (kWh/y)	0	0	0

3.3 Result discussion

3.3.1 Residential load type: case 1

Table IV - Energy sales and generated revenue

	Residential		Commercial		Industrial	
	Energy sold (kWh)	Revenue ($)	Energy sold (kWh)	Revenue ($)	Energy sold (kWh)	Revenue ($)
Jan	8,190	248.28	10,424	313.94	14,887	449.74
Feb	7,392	224.15	9,409	283.45	13,441	406.11
Mar	8,184	248.17	10,418	313.82	14,881	449.62
Apr	5,330	160.18	6,915	205.94	10,084	301.81
May	8,184	248.17	10,418	313.82	14,881	449.62
Jun	7,920	410.96	10,076	531.47	14,401	761.18
Jul	5,885	300.76	7,608	397.75	11,050	580.06
Aug	2,685	128.29	3,697	186.96	5,716	292.61
Sep	1,573	44.20	2,324	64.19	3,823	108.51
Oct	4,128	122.95	5,461	160.78	8,122	240.93
Nov	7,921	240.16	10,082	303.70	14,401	435.12
Dec	8,184	248.17	10,418	313.82	14,881	449.62
Total	75,576	2,624.45	97,250	3,389.65	140,569	4,924.91

Based on the optimum configuration results, the residential load type requires 13.5 kW hydrokinetic turbine size (9 DHK turbines) to ensure 0% unmet demand.

These turbines generate the maximum output power of 13.5 kW when the water speed is above 2 m/s. Hence, generating a total annual energy of 97,475 kWh, of which only 22.5% is used to supply the load while 77.5% is sold to the grid. This optimal configuration resulted into the highest operating cost and levelized cost of energy when compared to the commercial and industrial cases. When considering the ratio between the total annual energy sales and the total generated revenue shown in Table 4, it shows that the energy was sold at an average selling price US$0.035/kWh.

Large amount of energy is sold into the grid during the months with water speed of 2 m/s or above. During these months, the energy sold into the grid ranges from 10 kWh to a maximum of 12.1 kWh during off-peak period (22h01- 05h59) as shown in Fig. 5 (a). During both the morning and evening peak hours of the load profile, the energy sales dropped. Therefore, based on the TOU peak periods (Table I), the large amount of energy was not sold during peak periods. Hence, the chances of yielding the maximum income/revenue are minimal. The storage reservoir is only functional during the beginning of the year as shown in Fig. 5 (b). No energy is purchased from the grid throughout the year as shown in Table III.

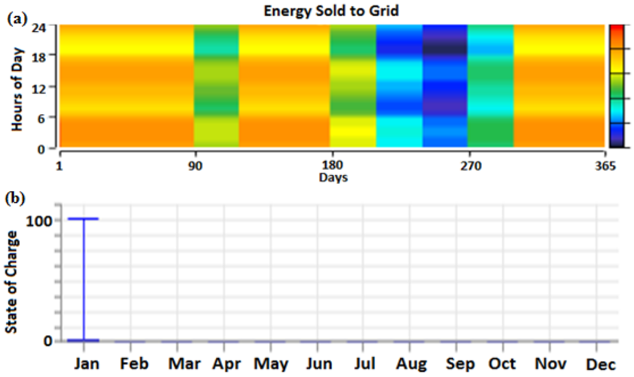

Fig. 5: Residential load (a) energy sales to the grid & (b) PHS state of charge.

3.3.2 Commercial load type: case 2

The optimum configuration results for the commercial load profile requires 16.5 kW hydrokinetic turbine size (11 DHK turbines) to ensure 0% unmet demand. The total annual energy of 119,135 kWh is generated, of which only 18.4% is used to supply the load while 81.6% is sold to the grid. When considering the ratio between the total annual energy sales and the total generated revenue as shown in Table 4, it shows that the energy was also sold at an average selling price US$0.035/kWh.

Large amount of energy was sold into the grid during the months with water speed of 2 m/s or above. During these months, the energy sold into the grid ranges from a minimum of 14.6 kWh to a maximum of 16.21 kWh for 12 hour period (20h00-08h00) as shown in Fig. 6 (a). Therefore, based on the TOU tariff periods, only 2 hours (06h00-08h00) of the costly peak periods have been used to sell large amount of energy. This is better compared to the residential load case. However, an improvement is still needed to optimally utilize most of the TOU peak periods for energy sales into the grid.

During business operational hours, energy sales drop to an average of 11.5 kWh. During the worst month of September, up to a maximum of 5.4 kWh can be sold into the grid between 20h00-08h00. Similar to the residential load case, it can be seen that no energy was purchased from the grid throughout the year as shown in Table III. Fig. 6 (b) shows that the storage reservoir is discharged during the beginning of January without being recharged throughout the year. Hence, no energy storage is taking place throughout the year.

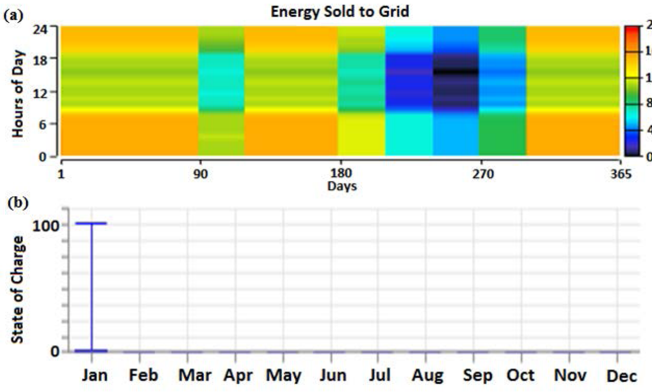

Fig. 6: Commercial load (a) energy sales to the grid & (b) PHS state of charge.

3.3.3 *Industrial load type: case 3*

The optimum configuration results for the industrial load type requires 22.5 kW hydrokinetic turbine size (15 DHK turbines) to ensure 0% unmet demand. This results into highest capital and net present costs as compared to both the residential and commercial load cases. However, this offers the lowest operating and levelized energy costs. The total annual energy of 162,455 kWh is generated, of which only 13.5% is used to supply the load while 86.5% is sold to the grid. Similar to both the residential and commercial load cases, an average energy selling price of US$0.035/kWh is achieved.

Fig. 7 (a) shows that more energy was sold into the grid during the months with water speed ranging from 2 m/s and above. During these months, the daily energy sold into the grid ranges from a minimum of 14.18 kWh to a maximum of 22.36 kWh. The large amount of energy sales is achieved between 19h00-08h00 while the minimum energy sales is achieved during business hours. Therefore, based on the TOU periods, only 2 hours of the costly peak periods has been used to sell the large amount of energy. This is similar to the commercial load profile and still needs an improvement. Similar to other two cases, no energy was purchased from the grid throughout the year. Similar to other two cases, Fig. 7 (b) shows that no energy storage process took place after discharging the reservoir.

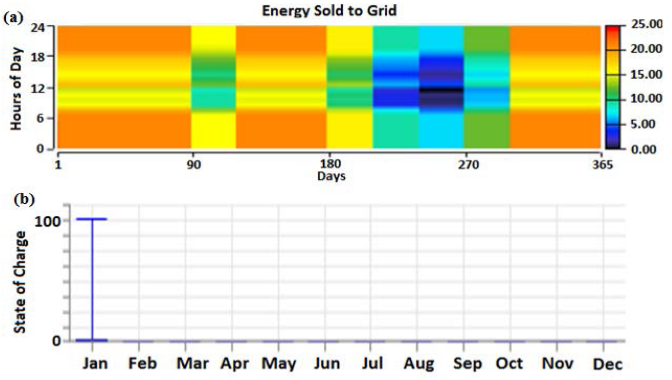

Fig. 7: Industrial load (a) energy sales to the grid & (b) PHS state of charge.

4 CONCLUSION

This paper explored the demand sector which is more favorable to the proposed grid-tied MHK-PHS hybrid system under the time-of-use (TOU) tariff scheme. The impact brought by different load profile on optimal sizing of the proposed grid-connected MHK-PHS hybrid system is investigated. Eskom's TOU tariff schedule and pricing was used during the simulation. The flowing water resource data obtained from a typical river of South Africa was used and entered into HOMER Pro version 3.6.1 simulation tool. Residential, commercial, and industrial load curves having the same daily energy consumption were considered and supplied with the grid-connected MHK-PHS hybrid system at no capacity shortage.

Based on the optimum configuration results obtained using HOMER, the residential load requires the lowest capital cost when compared to the commercial and industrial loads. It also proved to offer the lowest NPC even though the levelized COE is slightly higher than the commercial and industrial one. Hence, from economic perspective, the proposed hybrid system proved to be more superior for the residential load sector as compared to other sectors.

Based on energy production and sales results, the results proved that the large amount of energy sales for the residential load sector did not take place during critical peak hours of the utility TOU tariff schedule. If the maximum or large amount of energy sales took place during peak hours, this would have added more revenue due to the highest selling price. In cases of the commercial and industrial load profiles, HOMER made use of at least 2 peak hours to sell the large amount of energy to the utility grid. However, an improvement is still needed to optimally utilize most of the TOU peak periods in order to generate more revenue.

HOMER results also indicated that the excess energy was sold into the grid for 24 hours without reserving other energy for later use or sale during peak hours. As a result, HOMER did not make use of the available energy storage system to store energy during low priced off-peak hours. Hence, this has led to oversizing of the hydrokinetic system since less than 25% of the total energy production was used to supply the primary load. The process of not purchasing electricity from the grid especially during off-peak hours also resulted into oversizing of the hydrokinetic system.

To overcome the oversizing constraint created by HOMER, the results of this study have led to the following recommendations that would ensure minimal investment cost for the maximum energy sales revenue:

- To design an optimal energy management system for the proposed grid-connected HKT-PHS hybrid system that would maximize the energy sales to the grid when the energy price is high and also enable purchasing from the grid when the energy price is low under TOU tariff scheme.
- The energy management system must also be able to allow the energy storage system to absorb energy from the grid and/or hydrokinetic system and to release energy to the primary load and/or grid depending on the TOU tariff schedule.

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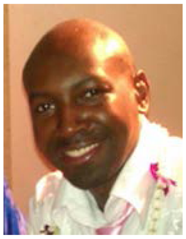

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