Energy flow modeling between grid and micro-hydrokinetic-pumped hydro storage hybrid system

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

Abstract—This paper proposes an optimal energy management model for a grid-connected micro-hydrokinetic pumped hydro storage (MHK-PHS) hybrid system supplying the commercial load. The aim of the model is to minimize the energy costs through power-flow control variables and time-of-use (TOU) tariff scheme. The optimization problem will be solved through the use of the *linprog* solver in the MATLAB's optimization toolbox for 216 hours as a means of including the weekend as well. The simulation results show that the developed model can assist the onsite MHK-PHS hybrid system to optimally reduce the electricity consumption cost of the commercial load. Additionally, Sundays have proved to lead to concurrent use of all power sources for the entire business hours of the commercial load.

***Index Terms*—Commercial load, micro-hydrokinetic, pumped hydro storage, energy management, time-of-use**

1 INTRODUCTION

Electricity is the fastest growing form of energy due to population growth as well as the industrial and commercial business developments [1]. Globally, electricity generation grows by an annual average of almost 3%. Close to 80% of the world energy supply is mainly generated from fossil fuels resulting into a climatic change due to carbon emission. Due to the increasing energy demand, the need for reducing the peak energy demand is a challenge in many countries. It enforces utility companies to install new fossil fuel power plants which result into an increase in electricity price for end-users as well as an increase in greenhouse gases (GHGs) emission level [2].

Energy efficiency and demand side management (DSM) programs are the common approaches to minimize peak energy demand [3]. Energy management on the demand side helps the consumers to reduce their electricity bills while also boosting the supply side against the instability that might lead to load shedding. Hence, this reduces the need for additional supply capacity. Time-of-use (TOU) pricing scheme is a commonly used effective method to influence the consumer consumption behavior [4].

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Using the TOU scheme, electric utilities design a tariff rate structure that varies with time and season. During peak period, the price of electricity is high compared to standard and off-peak periods. Hence, consumers can save money by shifting their energy usage to standard or off-peak periods.

In addition to energy efficiency and DSM, an approach such as Renewable energy generation can also be used to reduce peak demand leading to an improved reliability of the grid supply [5], [6]. However, the unreliable nature of renewable energy sources such as solar and wind makes this approach less competitive. To mitigate such a drawback, it is necessary to use the hybrid system integrated with an energy storage system. Among different renewable technologies, hydrokinetic has proved to generate electricity markedly better and cheaper than solar and wind technologies [7], [8]. It has proved to generate electricity more economically if used in conjunction with a pumped hydro storage (PHS) system instead of battery storage system [9]. It generates electricity at low speeds (0.5 m/s or above) through zero hydraulic head by extracting the kinetic energy of the flowing water within river streams, tidal current or other artificial water channels [10], [11], [12].

Commercial businesses are one of the five dominating energy consuming sectors in South Africa, along with transportation, industrial, residential and mining sectors [13]. Hence, commercial businesses such as commercial farms situated in close proximity to the flowing water resource, can make use of the grid-connected hydrokinetic-PHS hybrid system to reap the energy savings benefit.

Optimization techniques are considered as fundamental computational tools for energy management within smart grids [14]. Several research studies have been carried on optimal energy management for hybrid renewable energy system under TOU electricity tariff scheme [14], [15], [16], [17], [18], [19], [20]. The main common purpose was to minimize the electricity consumption costs. However, these studies focused merely on a 24-hour load profile by assuming that the demand is constant throughout the week. Additionally, simply the weekdays TOU tariff rates were used to study the behavior of the optimization model. As a result, the behavior of the models under the weekend TOU tariff rates was ignored.

This study therefore works on developing an optimal energy management model for a grid-connected micro-hydrokinetic-pumped hydro storage (MHK-PHS) hybrid system to sufficiently benefit the commercial load at the demand side. The aim is to minimize the energy consumption cost by considering the TOU tariff scheme. Both the weekdays and weekend TOU tariffs for the high demand season (winter) will be used. The proposed model will manage the power flow for 216 hours (9 days) in order to analyze the behavior of the model during the weekend and weekdays.

2 SYSTEM LAYOUT AND MATHEMATICAL MODEL

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 MHK river system, PHS system as well as the primary commercial load. The arrows represent the directions of the power flows.

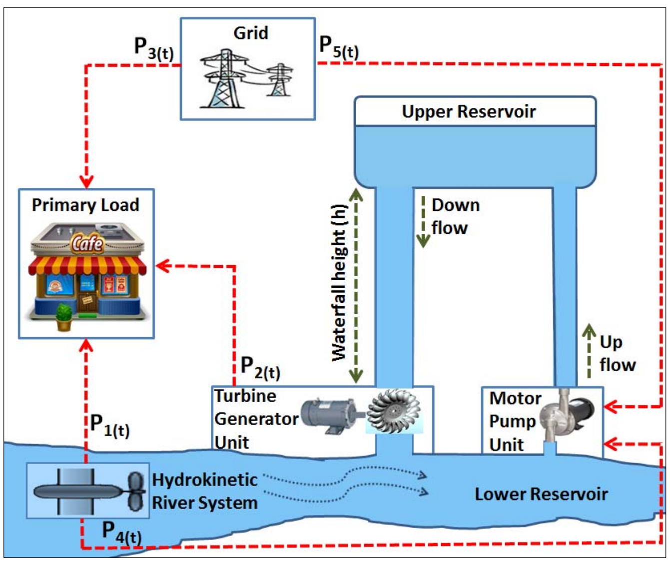

Fig. 1: Power flow layout of the proposed grid-connected MHK-PHS hybrid system

2.1 Hydrokinetic system

Hydrokinetic turbines are designed to extract the kinetic energy of the flowing water instead of the potential energy of the falling water. These turbines operate similar to wind turbines. Unlike the wind energy resource, hydrokinetic resources are easily predictable and can generate more electricity even at low speeds since the water is 800 times denser than air [21], [22], [23]. The energy generated by a hydrokinetic system is expressed as follows [8], [9]:

$$E_{HK} = 0.5 \times \rho_W \times A \times v^3 \times C_p \times \eta_{HKT-G} \times t \tag{1}$$

Where: ρ_W is the water density (1000 kg/m^3), A is the turbine swept area (m^2), v is the water speed (m/s), C_p is the power coefficient of a turbine performance, $\eta_{HKT\text{-}G}$ is the overall efficiency of a hydrokinetic turbine-generator unit and t is the time (s).

2.2 Conversional pumped-hydro storage (PHS) system

In this study, a PHS system is used to store excess energy from the MHK river system and/or the energy from the grid. PHS system has proved to be the most durable, cost-effective and efficient energy storage system since its required capital cost is less than 100 US$ per kWh [24]. It stores energy in the form of potential energy. The power supplied to the motor-pump unit for refilling the upper reservoir is expressed as follows [25]:

$$P_{M:P} = \frac{\rho_W \times g \times H \times Q_{M:P}}{\eta_{M:P}} \tag{2}$$

Where, g is the gravitational acceleration (9.81 m/s^2), H is the water-head height (m), $Q_{M:P}$ is volumetric flow rate of the water sucked from the lower reservoir by the motor-pump unit (m^3/s) and $\eta_{M:P}$ is the overall efficiency of the motor-pump unit.

The power generated by the turbine-generator unit is expressed as follows [25]:

$$P_{T:G} = \rho_W \times g \times H \times Q_{T:G} \times \eta_{T:G} \tag{3}$$

Where, $Q_{T:G}$ is the water volumetric flow rate into the turbine (m^3/s) and $\eta_{T:G}$ is the overall efficiency of the turbine-generator unit.

The amount of stored energy (kWh) in the upper reservoir is expressed as follows [25], [26]:

$$E_S = \frac{V \times \rho_W \times g \times H \times \eta_{T:G}}{3.6 \times 10^6} \tag{4}$$

Where, V is the volumetric storage capacity of the upper reservoir (m^3).

3 DISCRETE MODEL FORMULATION AND THE PROPOSED ALGORITHM

The optimization outline of this study comprises the objective function as well as the constraints based on the TOU tariffs.

3.1 Objective function

As stated in the introduction, the optimization problem in this study is addressed to minimize the energy consumption costs. Hence, based on the power flow layout the discrete cost objective function (F) at any sampling interval (j) is expressed as follow:

$$F = \sum_{j=1}^{N} C_j \cdot (P_{3(j)} + P_{5(j)}) \cdot \Delta t \quad (5)$$

Where, N is the total number of sample intervals, Δt is the sampling time (i.e. the time between the sampling points), C_j is the TOU electricity price at the j^{th} sampling time (R/kWh), $P_{3(j)}$ is the power flow from the utility grid to the primary load (kW), and $P_{5(j)}$ is power flow from the utility grid to the motor-pump unit (kW).

3.1.1 Power balance constraint

Based on the power flow layout, the load demand must be satisfied by the MHK river system, PHS system and the grid at any time during the control horizon. Therefore, the power balancing constraint can be discretised as follows:

$$P_{Load(j)} = P_{1(j)} + P_{2(j)} + P_{3(j)} \quad (1 \le j \le N) \quad (6)$$

Where, $P_{1(j)}$ is the power flow from the MHK river system to the primary load (kW) and $P_{2(j)}$ is the power flow from the turbine-generator unit to the primary load (kW).

3.1.2 Hydrokinetic output power constraint

The sum of the instantaneous output powers consumed from the MHK river system by the motor-pump units and the commercial load must not be more than the MHK's generated output power. This constraint can then be expressed as follows:

$$P_{1(j)} + P_{4(j)} \le P_{MHK(j)}^{\max} \quad (1 \le j \le N) \quad (7)$$

Where, $P_{4(j)}$ is the power flow from the MHK river system to the motor-pump unit (kW).

3.1.3 Control variable limits constraints

The five power sources are controllable from zero minimum limits to a maximum limit of their rated or available instantaneous power. Therefore, they are expressed as follows:

$$0 \le P_{1(j)} \le P_{1(j)}^{\max} \quad (1 \le j \le N) \quad (8)$$

$$0 \le P_{2(j)} \le P_{2}^{rated} \quad (1 \le j \le N) \quad (9)$$

$$0 \le P_{3(j)} \le P_{3}^{rated} \quad (1 \le j \le N) \quad (10)$$

$$0 \le P_{4(j)} \le P_{4(j)}^{\max} \quad (1 \le j \le N) \quad (11)$$

$$0 \le P_{5(j)} \le P_{5}^{rated} \quad (1 \le j \le N) \quad (12)$$

3.1.4 Storage constraints

The state of the upper reservoir water level, $Cap(j)$ will be used as a decision variable for preventing the upper reservoir from overcharging. In cases whereby the upper reservoir is completely full, the maximum capacity = 1. Therefore, the storage limit level constraint for the upper reservoir is expressed as follows:

$$Cap^{\min} \le Cap_{(j)} \le Cap^{\max} \quad (13)$$

Where, Cap^{min} is the minimum allowable capacity of the upper reservoir and Cap^{max} is the maximum allowable capacity of the upper reservoir.

The dynamics of the upper reservoir water level state at any j^{th} sampling interval is expressed in terms of the initial water level, $Cap_{(0)}$ as shown by Eq.(14).

$$Cap_{(j)} = Cap_{(0)} + \sum_{j=1}^{N} [(P_{4(j)} + P_{5(j)}) \cdot \frac{\eta_{M:P}}{E_{pot}} \cdot \Delta t] - \sum_{j=1}^{N} P_{2(j)} \cdot \frac{\Delta t}{\eta_{T:G} \cdot E_{pot}} \quad (14)$$

Where, E_{Pot} is the nominal potential energy of the upper reservoir (kWh).

3.1.5 TOU Tariffs

Fig. 2 shows that the Weekdays and Weekend have different TOU period. The daily Eskom (Ruraflex Gen) electricity cost prices (C) to be used under the TOU tariff scheme (for high demand season) are given as follows [27]:

$$C(t) = \begin{Bmatrix} C_p = ZAR3.29/kWh \\ C_s = ZAR0.99/kWh \\ C_o = ZAR0.54/kWh \end{Bmatrix} \quad (15)$$

Where, C_P is the tariff price during peak period; C_S is the tariff price during standard period, C_O is the tariff price during off-peak period and ZAR being the South African currency.

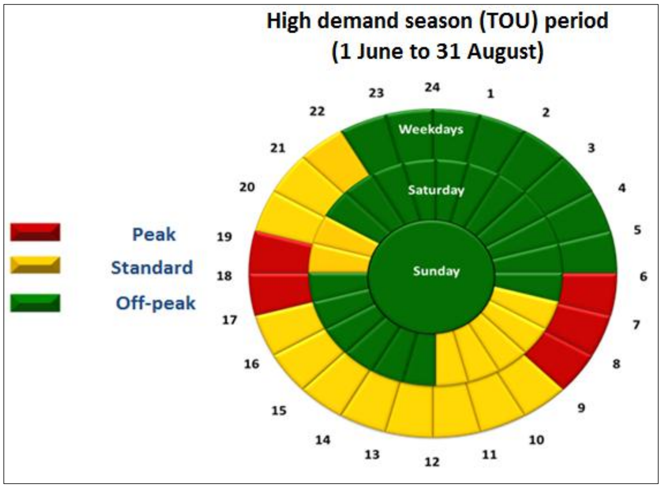

Fig. 2: TOU period for high demand season [27]

3.2 Proposed algorithm

The optimization problem will be solved using the "linprog" syntax from the MATLAB optimization toolbox. This solver is for linear constraints and objective function and it is expressed in its canonical form as follows:

$$\min_{x}\left\{f^{T}x\right\} \quad \text{subject to} \quad \left\{\begin{matrix} A\cdot x\leq b \\ A_{eq}\cdot x\leq b_{eq} \\ lb\leq x\leq ub \end{matrix}\right\} \tag{16}$$

Where, A and b are the coefficients associated with inequality constraints, A_{eq} and b_{eq} are the coefficients associated with equality constraints, and lb and ub are the lower and upper bounds of the variables, respectively.

4 RESULTS AND DISCUSSION

The optimization model of the proposed grid-connected MHK-PHS hybrid system for the purpose of minimizing consumption costs is analysed through the use of the linprog solver for 216 hours. Based on the TOU tariff periods shown in Fig. 2, it can be noticed that the peak periods do not exist on Saturdays and Sundays. Hence, in this study the simulations have been carried out for both weekdays and weekend using the high demand season tariff rates.

A typical commercial load profile consuming an average of 60 kWh has been used in this study [12]. To create a more reasonable load profile, HOMER software was used to synthesize the load profile by adding 10% randomness for different days as shown in Fig. 3A.

The flowing water resource (June month) from a typical river situated in Kwazulu Natal has been used during simulations [7], [9], [12]. The standard deviation of 0.2% was used to generate the hourly variable water velocity profile for June month as shown in Fig. 4A. Two of 1.5 kW hydrokinetic turbines have been selected to generate up to a maximum output power of 3 kW when the speed is 2 m/s or above [7], [12]. Fig. 3B shows that the selected turbine generates a maximum of 3 kW throughout since the water speed varies around 2.18 m/s as shown in Fig. 4A.

The overall simulation parameters on the proposed grid-connected MHK-PHS hybrid system are as shown in Table 1. Fig. 3 shows the system power flow on the load side while Fig. 4 shows the power flow on the storage side. In all subfigures of Fig. 3 and Fig. 4, the simulations were run for 216 hours (from Sundays to Monday) as shown by the load profile (Fig. 3A). From 0 to the end of 24^{th} hour represents Sunday, from 25^{th} hour till the end of 144^{th} hour represents weekdays. From the 145^{th} hour until the end of 168^{th} represents Saturday while from 193^{th} hour to 216^{th} hour represents another Sunday.

Table 1: Simulation parameters

Item	Figure
Sampling time (Δt)	30 minutes
PHS nominal capacity	2.6 kWh
PHS maximum volume	100%
PHS minimum volume	5%
Initial upper reservoir capacity	50%
Overall efficiency of the Turbine-generator unit.	70%
Overall efficiency of the Motor-pump unit.	85%
MHK system rating	3 kW

4.1 Power flow during weekdays

Fig. 3B and Fig. 3C show that during weekdays, the load demand is entirely met by the MHK system and the turbine-generator unit (PHS). Only a small fraction is met by the grid during night off-peak hour (22:00-05:59) of Wednesday and Thursday as shown in Fig. 3D. The reason is because during off-peak hour, MHK system uses most of the power to refill the upper reservoir (Fig. 4B) since the state of the storage reservoir has approached the minimum allowable capacity as shown in Fig. 4D. In addition to supplying the unmet load demand, the grid is still used during off-peak hours for refilling the upper reservoir as a way of minimizing the costs as shown in Fig. 4C. Therefore, the power from the grid is not utilized during standard and peak hours. It is utilized only during off-peak hours, when it is necessary due to minimum capacity reached by the upper reservoir.

During off-peak period, the turbine-generator unit is not allowed to generate electricity at all, due to three reasons. The first reason is because the electricity price is cheap during off-peak hours; hence it is not costly to utilize the grid. The second reason is because it is economical to recharge the upper reservoir for the next day. Lastly, the load demand is low.

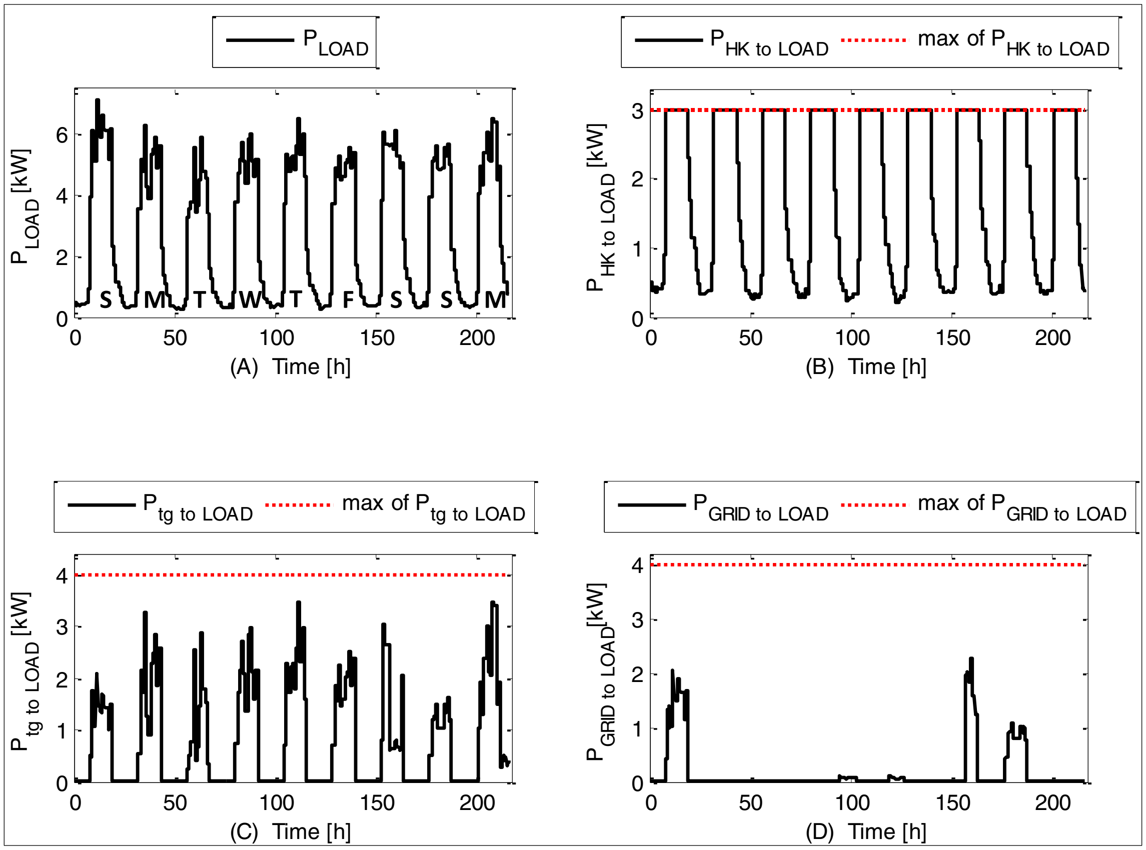

Fig. 3: Load profile and load side power flow

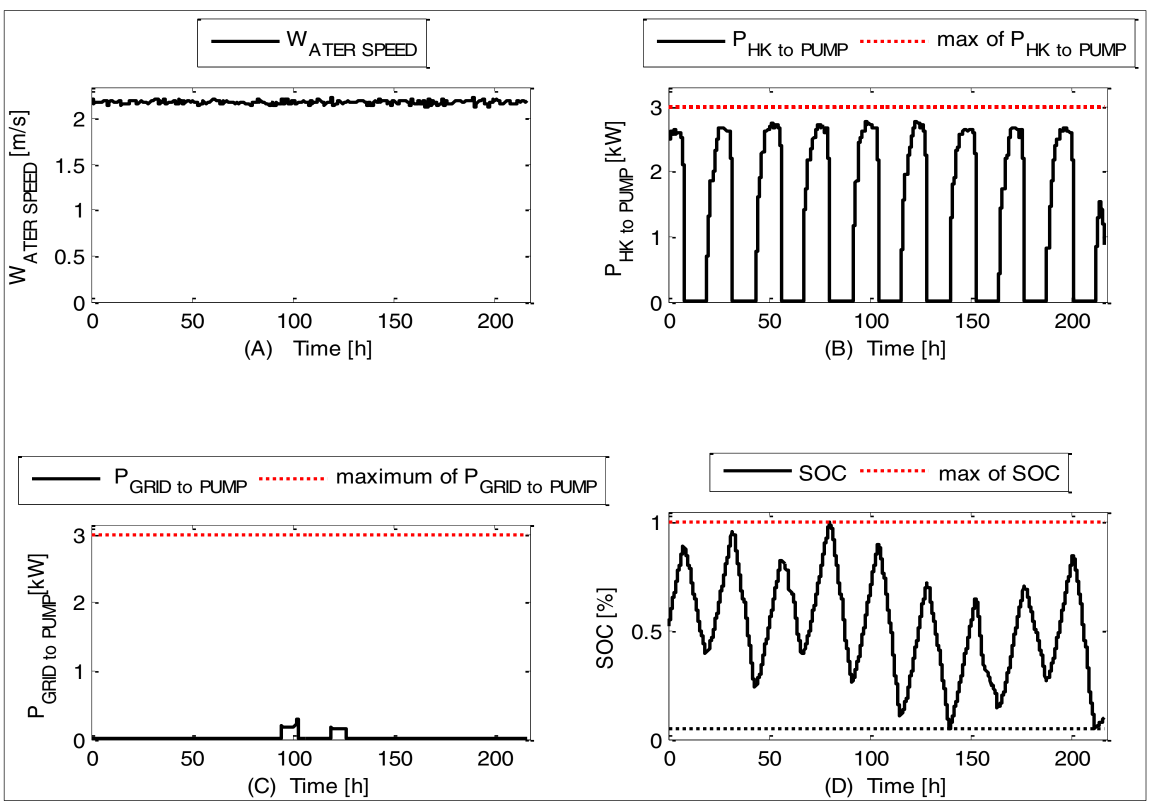

Fig. 4: Water speed and PHS side power flow

It has being noticed that for each weekday, the model allows the MHK power to refill the upper reservoir after 18:00 since the load demand is low after working hours as shown by Fig. 4B. The refilling process stops after 08:00 in the mornings due to high commercial load demand. Consequently, the reservoir water level will start decreasing since the turbine generator unit generates electricity to compensate the unmet load demand.

4.2 Power flow during the weekend

Fig. 2 has highlighted that during early Saturday morning hours, the standard TOU tariff rates are charged instead of the peak TOU tariff rates charged during weekdays. Fig. 3A shows that from early Saturday working hours of the morning when the commercial business is about to start, the load is demanding more than 3 kW. As a result, both the hydrokinetic system and the turbine-generator unit are used to meet the load demand as shown in Fig. 3B and Fig. 3C. As soon as Saturday off-peak hours are approached (12:00-17h59), the model allows the power demanded from the turbine-generator unit to drop to from 2.64 kW to 0.6 kW. Hence, the utility grid is also allowed to supply electricity to the load since electricity is cheap. Hence, the storage reservoir is discharging at a lower rate as shown in Fig. 4D. Fig. 3D shows that the total energy consumed from the grid during the weekend (Saturday & Sundays) is more than the one consumed during weekdays. The reason is because the load demand is high during the inexpensive off-peak period scheduled during the business hours.

Fig. 2 has also highlighted that both standard and peak period do not exist on Sunday. From early Sunday morning business hours (08:00), the load demand is met by all the three power sources up until the end of the business hours (18:00). After 18:00, the small base load demand is then met by the MHK system only. The excess power from the MHK system is used to refill the upper reservoir for the next day.

5 CONCLUSION

This study has presented a TOU based optimal energy management model for the grid-connected MHK-PHS hybrid system. This was meant for minimizing the grid electricity cost for the commercial consumer without selling energy to the grid. The developed optimization model has revealed the cost saving benefit by maximizing the renewable energy usage (from the MHK and PHS systems) and by minimizing the grid energy usage especially during the costly standard and peak periods.

The results have shown that the model allowed the PHS system to generate electricity mostly during standard and peak period to compensate the unmet commercial load demand since the 3 kW MHK system was unable to meet the entire demand. In addition to 3 kW power generated by the MHK system, the grid power was used merely during low-cost off-peak period to refill the upper reservoir and to supply a fraction of power to the load for the entire 9 days.

Additionally, the results have revealed that during the weekend the grid is allowed to supply more energy to the load as compared to during weekdays. On Saturday, the grid is used for few hours as compared to Sundays. Finally, Sundays have proved to lead to the concurrent use of all power sources to meet the load demand for the entire business hours.

The results of the study have led to the following recommendations:

- To investigate the economic performance of the hybrid system if the motor-pump unit is isolated from the grid.
- To develop an optimal energy management model for the hybrid system when allowed to sell the energy to the grid under TOU tariff scheme.

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