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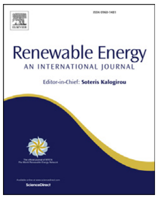

Energy management of a grid-connected hydrokinetic system under Time of Use tariff

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ABSTRACT

In this work, the optimal power scheduling for a grid-connected hydrokinetic-battery hybrid system is proposed to sufficiently explore hydrokinetic energy and to benefit customers at demand side. The developed model for the hybrid system's optimal power flow management aims to minimize electricity cost subject to the power balance, hydrokinetic and battery storage outputs as well as other operational constraints. With respect to demand side management, an optimal control method is developed to schedule the power flow of hybrid system over 24-h. Simulations are performed using MATLAB (R2016a), and the results demonstrate that operating the proposed hybrid system under the developed optimal energy management model can reduce the operation cost and allow consumers to generate substantial income by selling power to the grid.

1. Introduction

With the current increase in population all over the world; technological progress in the power generation sector is needed to sustainably respond to the electricity needs while reducing negative impacts on the environments.

Renewable energy (RE) technologies, such as wind, solar, hydropower and their combinations in hybrid systems, have become attractive alternatives of producing energy in comparison to traditional fossil fuels due to low cost, no pollutant emission, energy security as well as their modularity [1–3]. Renewable energy sources can be used as standalone to supply isolated load or as grid-connected for selling power to the utility company [4]. Because of the variable nature of their resources as well as for design and energy management purposes; renewable systems are often used in conjunction with storage systems [5]. Battery storage systems can reduce the risk of renewable systems' intermittent power supply, and always ensure that the load demand is continuously met [6].

In general, grid-connected renewable systems do not require battery storage therefore advanced energy management strategies are also not required [7]. Maximizing the use of the renewable power is the only strategy adopted when the generation is less than the instantaneous load demand [8]. On the contrary, battery storage makes the energy management more difficult, as more complicated operation strategies must be taken into account, such as charging the battery from the grid or renewable source and discharging into the grid or to the load when necessary [9]. As a result, controllers are required for hybrid renewable-battery systems, such that the use of the renewable system can be considerably improved and the grid regulation can be enhanced in terms of safety, reliability and efficiency [10].

For grid-connected hybrid renewable-battery systems, the varying electricity price imposed by the grid, the instant of power transaction, and the difference between renewable power generation and load demand are main challenges encountered [11]. From the demand side management (DSM) point of view, energy from the renewable source or from the grid can be stored when the generation is higher than the demand or when the electricity price from the grid is very low. The stored energy can then be used when the electricity price from the grid is high, during peak power demand, or when the renewable power is unavailable [12]. Well managed grid-connected hybrid system with DSM can assist customers in reducing their electricity cost, and also can assist utility companies to control the grid in terms of security and efficiency issues while increasing the reliability.

Several research works have reported on the benefit of applying energy management on hybrid solar photovoltaic (PV) and wind systems as standalone or connected to the grid. However very few works have been conducted on the use of standalone hydrokinetic system (HKT) combined with other energy sources. A model to

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optimize the daily operation of a hybrid energy system consisting of a hydrokinetic, a pumped hydro storage system and diesel generator has been developed in Ref. [13]. 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.

The modeling and performance analysis of a micro hydrokinetic system as compared to wind generation system using MATLAB/Simulink software has been presented in Ref. [14]. These performances are compared to generate the same amount of electrical power. The simulation results illustrate the ability of a hydrokinetic turbine driven permanent magnet synchronous generator to generate electricity markedly better and cheaper than a wind system within South Africa.

A model to optimize the operation of a hybrid energy system consisting of a hydrokinetic system, a battery bank and diesel generator has been developed in Ref. [15]. The optimization approach is aimed at minimizing the cost function subject to the availability of water resource, total load energy requirements as well as the diesel generator and the battery operational constraints. The obtained results demonstrate that a substantial reduction up to 71% in the daily operation cost can be achieved using the hybrid system compared to the case where the diesel generator is used alone.

A pumped hydro storage to be used in conjunction with a standalone hydrokinetic system in off-grid power supply was proposed in Ref. [16]. The techno-economic feasibility of such combination is analyzed and compared to the option where batteries are considered as storage system. The results reveal that the novel combination is a cost-effective, reliable and environmentally friendly solution to achieve 100% energy autonomy in remote and isolated communities. More details on the operation principle of the hydrokinetic used with pumped hydro storage are presented in Ref. [17]; 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 potential use of Hydrokinetic-Diesel generator hybrid systems for sustainable and cost-effective electricity generation in rural South Africa has been investigated in Ref. [18]. For this purpose, different potential supply options are simulated using HOMER and the results are analyzed based on the Net Present Cost and the Cost of Energy produced. The simulation results show that Hydrokinetic-Diesel generator hybrid systems have lower net present costs as well as lower costs of energy compared to other supply options such as standalone Photovoltaic, Hydrokinetic or diesel generator.

A survey of different innovative technologies that can be applied to the micro-hydropower system to make it cost effective for rural energy supply has been conducted in Ref. [19]. Electrical, mechanical, civil or electronic technologies that can increase the viability of micro-hydropower as a cost-effective energy source for remote and isolated communities are presented. Hydrokinetic has been discussed as one of the main innovative solution to be implemented in rural South Africa.

From the available literature, it appears that the grid-connected hydrokinetic with battery storage system has not yet been investigated. Therefore, the focus of this paper will be on analyzing a grid-connected HKT-battery system under the Time of Use (TOU) program with contracted selling as an example. An optimal power flow management algorithm of the proposed hybrid system is developed, aiming to minimize the electricity cost within the DSM framework. It will be shown how consumers can optimally schedule the hybrid system's operation to earn cost savings with changing prices in the TOU program, and how they can manage their generation, consumption and storage to sell surplus power to the grid over peak period.

2. Related works

The hybrid renewable energy system research field has been investigated in areas, such as system design [19], installation [20], operation and maintenance [21], modeling [22], control and optimization [23]. These studies have mostly been conducted for standalone systems.

For grid-connected hybrid renewable energy systems research works are conducted on the design and implementation of smart energy management system to coordinate the utility, storage, and load with the aim of optimizing the operation cost of the systems.

The optimization of a grid-connected PV-based power plant have been analyzed by Zebarjadi and Askarzadeh [24]. In this cited study, the portion of the purchased power from the utility grid and the area of the installed PV system are optimized in order to have a cost-effective and reliable energy system.

Adaramola [25] has examined the feasibility of solar PV-grid tied energy system for electricity generation in a selected location in the northern part of Nigeria using HOMER energy optimization software. Based on the findings from this study, the development of grid-connected solar PV system in the north-eastern part of Nigeria could be economically viable.

Tarigan et al. [26] have simulated the feasibility of installing a grid-connected photovoltaic (PV) system in a typical residential in Surabaya, Indonesia. The work was conducted to evaluate the technical, economic and environmental aspects of PV system supplying household electric energy needs. The simulation expected to help in demonstrating the advantages and challenges of installing of a grid-connected PV system for residential in Surabaya.

For the grid-connected use considering DSM, energy management approaches from both the demand side and supply side were developed to respond to the electricity demand while minimizing the considered system's operating and environmental costs [27].

Khan et al. [28] have presented a comprehensive and comparative review of the load forecasting and dynamic pricing schemes in smart grid environment. Real Time Pricing, Time of Use and Critical Peak Pricing are discussed in detail.

Sichilalu and Xia [29] have developed an optimal scheduling strategy model for a grid-tied photovoltaic (PV) system to power a heat pump water heater (HPWH). The system is composed of PV modules that are grid-tied and a backup battery. The PV is capable of supplying power simultaneously to the HPWH and domestic load, whilst the grid and the battery are complementary sources. The objective function of this model is energy cost. The time-of-use (TOU) electricity tariff is taken into account in the optimal scheduling model. The control variables are the power flows within the branches of the system. This model has shown to have more economic benefits than solar thermal heaters, because of the possibility to turn the dwelling into net-zero energy or positive-energy buildings with the attractiveness of the feed-in tariff.

Wolisz et al. [30] have analyzed the feasibility and the resulting potential of coupling the electricity grid with the thermal supply of residential buildings. In this work the technical and economical key impact factors for such thermal DSM approach are elaborated. The practicability and possible magnitude of the intended DSM is then analyzed based on the identified scenarios. It is found that especially the strong dissemination of smart metering and smart control infrastructure is crucial to incorporate these capacities into DSM activities.

Dufo-Lopez and Bernal-Agustin [31] have presented a methodology to evaluate the technical and economic performance of a grid-connected system with storage under a time-of-use electricity tariff. The storage can help smooth demand, reducing peak demand from the grid and, in some cases, also reducing the electricity bill for the consumer.

Dufo-Lopez [32] has considered a storage system to be added to a private electricity facility in order to reduce the electricity bill. This kind of system could make sense with a time-of-use tariff (with two or three periods of different electricity price) or a real-time pricing tariff, where each day, electricity is bought from the AC grid during off-peak hours to store energy, and during on-peak hours, the storage supplies the whole load or a part, avoiding the purchase of expensive electricity from the AC grid.

3. Description of the grid connected HKT-battery hybrid system

The hybrid system analyzed in this work is composed of a HKT system and battery bank that are both connected to the grid. The output power of the HKT feeds the load demand directly. If the demand is less than the HKT's output, the surplus HKT power will be charged into the battery bank or sold to the grid depending on the state of charge of the battery as well as on the pricing period. If the load power requirement is larger than the HKT's output, the deficit of power will be supplied by the battery or the grid. The grid plays a major function in the hybrid system for charging the battery and directly supplying the load demand. The battery can also be charged by the grid in the off-peak period, and then discharged in the peak period to save electricity cost. The grid provides electricity directly when the load cannot be entirely met by the HKT and the battery. The schematic of this hybrid system is shown in Fig. 1, in which arrows represent directions of power flows in the hybrid system. P_{HKT-B} is the HKT power used for charging the battery; P_{B-L} is the discharging power of battery for load demand; P_{G-B} is the grid power for charging the battery; P_{G-L} is the grid power for load demand; P_{HKT-L} is the HKT power directly supplying load demand; P_{SOLD} is the battery discharge for selling power to the grid.

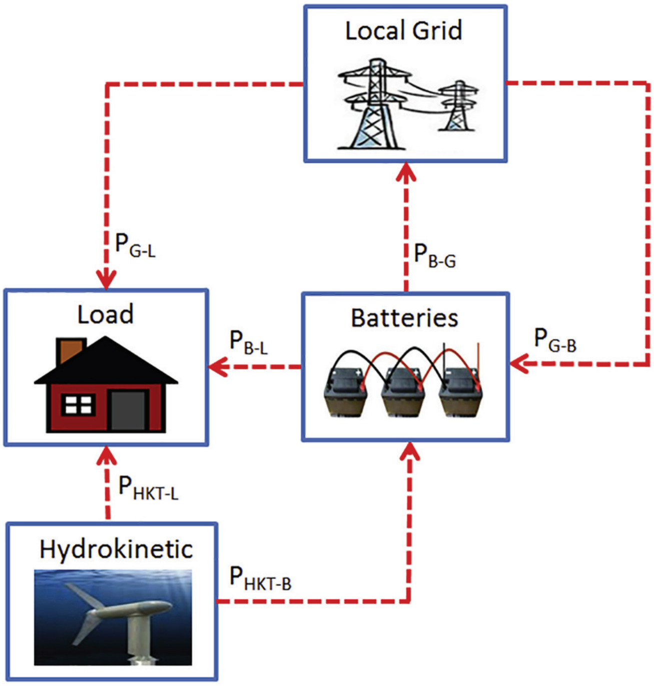

Fig. 1. Hybrid system layout (power flow).

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 [33].

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, 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 as the wind does.

The power generated by the hydrokinetic system is expressed as:

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

where: ρ_W is the density of water (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), ρ_W the water density (1000 kg/m^3), v is the water current velocity (m/s).

3.2. Battery storage system

The power flows from the HKT, the grid and the load demand at any given sampling interval j, determine whether the battery is charging or discharging. The dynamics of the battery state of charge (SOC) can be expressed in discrete-time domain by a first order differential equation as follows [34,35]:

$$\begin{aligned} SOC_{(j+1)} = {} & (1 - d_b) \times SOC_{(j)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times (P_{HKT-B(j)} + P_{G-B(j)} \\ & - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{SOLD(j)}) \end{aligned} \tag{2}$$

where: SOC is the state of charge of the battery; d_b is the self-discharging rate of the battery storage system; η_C is the battery charging efficiency; η_D is the battery discharging efficiency and E_{nom} is the battery system nominal energy.

By induction reasoning, the dynamics of the battery state of charge at j^{th} sampling interval can be expressed in terms of its initial value, $SOC_{(0)}$ of a day as follows:

$$\begin{aligned} SOC_{(j)} = {} & (1 - d_b) \times SOC_{(0)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times \sum_{i=0}^{j-1} \left(P_{HKT-B(j)} + P_{G-B(j)} \right) \\ & - \frac{\Delta t}{E_{nom}\eta_D} \times \sum_{i=0}^{j-1} \left(P_{B-L(j)} + P_{SOLD(j)} \right) \end{aligned} \tag{3}$$

4. Optimization model and proposed optimal control method

4.1. DSM model of the grid connected HKT-Battery hybrid system

As stated in the introduction, the optimization problem addressed in this work aims to minimize the electricity cost within the framework of TOU in which the electricity price changes over different time intervals according to cost imposed by the utility company, for instance a high price for peak load periods, medium price for standard periods and low price for off-peak periods. In this study, the daily electricity price at the selected region of South Africa can be given as [36]:

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [7,10) \cup [18,20) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,24) \\ \rho_s; t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \tag{4}$$

where.

$\rho_k = 0.20538$ \$/kWh is the price for the peak pricing period;
$\rho_0 = 0.03558$ \$/kWh is the price for the off-peak period;
$\rho_s = 0.05948$ \$/kWh is the price for the standard period.

4.2. Objective function

The proposed cost function has three main components. The first component is the cost of purchasing electricity from the grid, which is used to supply the load demand and charge the battery. The second component is the revenue generated from electricity sales to the grid. The third part is the wearing cost of hybrid system. The total function can be expressed as:

$$f = \sum_{j=1}^{N} \rho_j \left(P_{G-B(j)} + P_{G-L(j)} \right) \Delta t - r_k \rho_k \sum_{j=1}^{N} P_{B-G(j)} \Delta t + \sum_{j=1}^{N} a \left(P_{B-L(j)} + P_{B-G(j)} \right) \Delta t + 24b \tag{5}$$

where: $r_k = 0.65$ is the contracted ratio of the peak price; ρ_k for selling power during the peak pricing period; a is the coefficient of battery wearing cost and b is the hourly wearing cost of other components [36].

4.3. Constraints

The control variables in the objective function above have to satisfy the following constraints:

- HKT's output constraints:

The sum of instantaneous HKT's power for charging the battery and for supplying the load must be less than the HKT's output power generated.

$$P_{HKT-B(j)+P_{HKT-L(j)}} \leq P_{HKT(j)} \tag{6}$$

- Power balance constraint:

The required load demand must be exactly satisfied by the total power of HKT, the grid and the battery. This can be expressed as:

$$P_{B-L(j)} + P_{G-L(j)} + P_{HKT-L(j)} = P_{L(j)} \tag{7}$$

Each power source is modeled to be controllable in the range of zero to their rated power for the 24-h period. Therefore, the variable limits are the output limits of these different power sources at any sampling interval j. These can be expressed as:

- Control variables limits

$$0 \leq P_{HKT-B(j)} \leq P_{HKT-B}^{\max} \quad (1 \leq j \leq N) \tag{8}$$

$$0 \leq P_{B-L(j)} \leq P_{B-L}^{\max} \quad (1 \leq j \leq N) \tag{9}$$

$$0 \leq P_{G-B(j)} \leq P_{G-B}^{\max} \quad (1 \leq j \leq N) \tag{10}$$

$$0 \leq P_{G-L(j)} \leq P_{G-L}^{\max} \quad (1 \leq j \leq N) \tag{11}$$

$$0 \leq P_{HKT-L(j)} \leq P_{HKT-L}^{\max} \quad (1 \leq j \leq N) \tag{12}$$

$$0 \leq P_{B-G(j)} \leq P_{B-G}^{\max} \quad (1 \leq j \leq N) \tag{13}$$

The available battery bank state of charge in any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable state of charge. This can be expressed as:

$$SOC^{\min} \leq SOC_{(j)} \leq SOC^{\max} \tag{14}$$

5. Methodology

Case study 1 and 2 are designed to validate the grid connected system supplying different loads under the time-of-use tariff. The system consists of HKT, a battery storage system and a load. A scheduling interval of 24 h is considered. The decision variables are $P_{G\text{-}L}$, $P_{B\text{-}L}$, $P_{HKT\text{-}L}$, $P_{G\text{-}B}$, $P_{HKT\text{-}B}$ and P_{SOLD}.

The HKT and battery storage system have maximum output power ratings of 4 kW each and the maximum power that can be transferred between the main grid and proposed system is given as 4 kW.

In this work, measured load and water velocity have been used as input data to evaluate the performance of the system submitted to the developed optimal energy management system. These hourly data are available from Ref. [34]. 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.

The sizing of HKT and battery bank is based on a sizing model in Ref. [38]. The parameters of this hybrid system are given in Table 1. The maximum power delivered by each source is given as 4 kW. Therefore, the selected HKT system is sized in such a way to give a rated power of 4 kW at 1.4 m/s water velocity.

An optimal control method is used to manage the power flows in all the sampling periods over a 24-h period to minimize the daily electricity cost in Eq. (5), subjected to constraints shown from Eqs. (6)–(14). Because the objective function and constraints are linear, this power flow control problem can be expressed as a linear programming problem as [37]:

$$\min\ f(x), s.t. \begin{cases} Ax \leq b \\ A_{eq}X = b_{eq} \\ lb \leq x \leq ub \end{cases} \tag{15}$$

where: $f(x)$ represents the objective function; A_{eq} and b_{eq} are the coefficients associated with equality constraints; A and b are the coefficients associated with inequality constraints; l_b and u_b are the lower and upper bounds of variables.

This optimization problem is solved using the "linprog" function from MATLAB (R2016a) optimization toolbox running on a computer with Intel (R) core processor and 8 GB of RAM.

The simulation results will be discussed and categorized according to the behavior of the proposed grid-connected hybrid system under the different pricing periods.

6. Case study

6.1. Household's optimal control results

A daily detailed load data is obtained from a typical household and the hybrid system is designed in such a way to provide electricity for low consumption electrical appliances. When scrutinizing this load profile, one can notice a general pattern arising from the daily activities of the users which changes depending on different seasons of the year. The selected load demand from Ref. [34] reaches a peak demand of 8 kW in winter. Therefore, the hybrid system must be able to adequately respond to this demand.

6.1.1. Power flow under off-peak pricing period [0, 6)

Fig. 2(A) 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.

The power provided to the load includes the battery $P_{B\text{-}L}$, grid $P_{G\text{-}L}$ and $P_{HKT\text{-}L}$. During the off-peak period, only the HKT system provides power to the load as illustrated in Fig. 2(B); the battery and the grid do not supply the load during that period as shown in Fig. 2(C) and (D) respectively.

The $P_{HKT\text{-}B}$ is the part of the hydrokinetic power not consumed by the load since it is used to recharge the battery as shown in Fig. 3(B) and (C). There is enough power from the HKT to recharge the battery and to be sold to the grid to generate revenue. Even if the price is low during this period, excess power not used to supply the load or to recharge the battery is sold to the grid as shown in Fig. 2(D).

6.1.2. Power flow under standard pricing period [6, 7) U [20, 22)

During the standard price period, although the HKT system can fully satisfy the load demand, the grid power has been used. To store enough power for sale, the battery is not discharged during the standard period.

6.1.3. Power flow under peak pricing period [7, 10)

During the peak pricing period, the power from the HKT as well as the one stored in the battery are used to satisfy the load demand (Fig. 2(B) and (C)) while there is no power flow from or to the grid. It can be seen from Fig. 3(B) how the state of charge decreases when the battery is giving its maximum power to the load. The power stored in the battery could have been sold to the grid during this period but because of the proposed hybrid system's size and the priority given to the load demand, there is no excess power to be sold during this peak power demand. Therefore, it can be seen for Fig. 3(D) that the power sold to the grid is very small.

Table 1
Simulation parameters.

Item	Household
Battery nominal capacity	5.6 kWh
Battery maximum SOC	95%
Battery minimum SOC	20%
Battery charging efficiency	95%
Battery discharging efficiency	85%
HKT power	4 kW

6.1.4. Power flow under standard pricing period [10, 18)

During this off-peak pricing period, both the load demand and the price of electricity are low. Therefore, the power from the grid is used to principally supply the load and to recharge the battery at the same time. This can be seen when looking at Figs. 2(D) and 3(C) respectively. Fig. 2(B) and (C) confirm that no power from the HKT or the battery is used to supply the load; this power is sold to the grid as illustrated from Fig. 3(D).

6.1.5. Power flow under peak pricing period [18, 20)

During this second peak pricing period, all the power generated by the HKT system is used to supply the load with a small contribution from the battery as shown in Fig. 2(B) and (C). The remainder of the power available from the battery is then sold to the grid to generate profit during this high demand pricing period as illustrated from Fig. 3(D). Even if the amount of power sold to the grid is lower compared to the one sold during off-peak period, the profit is high due to the high price of electricity during peak period.

6.1.6. Power flow under off-peak pricing period (22, 24]

During this second off-peak pricing period, the load is supplied by the power from the grid as shown in Fig. 2(D). All the power from the HKT is sold to the grid via the battery as shown in Figs. 2(B) and 3(D).

6.1.7. Daily income generated

On the selected day, if the load demand is supplied by the grid only without the HKT and battery storage system, the daily electricity cost would be $4.32. When optimally operating the grid-connected HKT hybrid system, the daily income generated by selling electricity to the grid is $9.39. In other words, when making the balance between what is purchased from the grind and what is sold to the grid, the customer can earn $5.07. This income is a function of the size of the hybrid system's components, the battery initial state of charge as well as of the load profile.

6.2. Base transceiver Station's results of optimal control

The base transceiver station (BTS) selected for this study needs energy for the communications equipment and the cooling system used to remove heat from the cabin as given by Ref. [34]. This load has been selected because of its pattern which is different than the one from the household; this will induce a different response of the hybrid system operation energy scheduling.

6.2.1. Power flow under off-peak pricing period [0,6)

Fig. 4(A) shows the BTS load profile for the selected winter day. It is noticeable from this figure that except for the auxiliary equipment such as air-conditioning which is running during the day for only 6 h (11:00 h–17:00 h), and the security lights for 11 h throughout the night (19:00 h–6:00 h), the rest of the BTS communication equipment is running for 24 h non-stop. Therefore, the total daily profile is a combination of three linear demands resulting in a step (staircase) function.

During this off-peak pricing period, only the HKT system provides power to the load as illustrated in Fig. 4(B). In this case, $P_{HKT\text{-}B}$ matches exactly the demand; therefore, there is no excess of energy from the HKT system to recharge the battery or to be sold to the grid

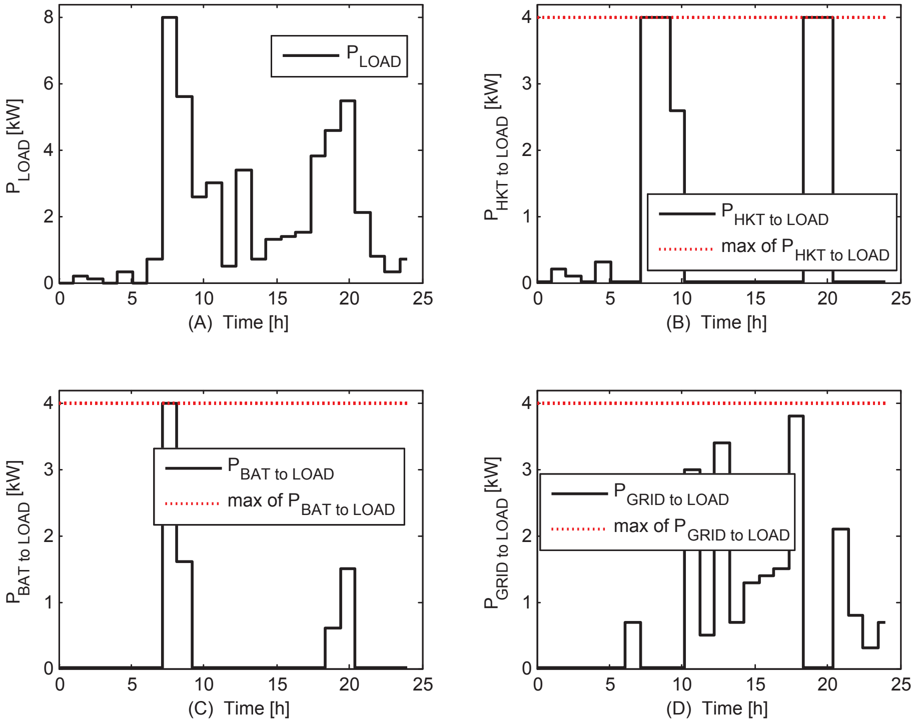

Fig. 2. Load side power flow (Household case).

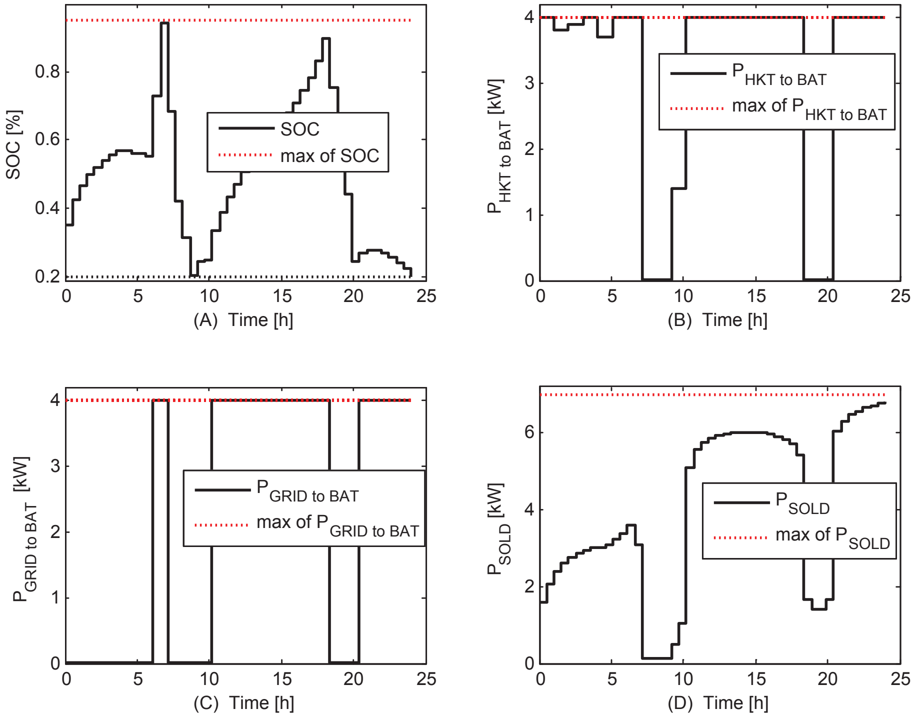

Fig. 3. Battery side power flow (Household case).

during this period. The power from the battery is sold to the grid and the battery is discharged within its operation limits as presented in Figs. 4(C) and 5(D) respectively.

There is no grid power used to either recharge the battery or supply the load as shown in Figs. 4(D) and 5(C).

6.2.2. *Power flow under standard pricing period [6, 7) U [20, 22)*

During the standard price period, all the power from the HKT and the grid are used to recharge the battery as shown in Fig. 5(C) and (D). This is done so that there can be enough power stored for sale during the peak period. The load is exclusively supplied by the grid as shown in Fig. 4(D).

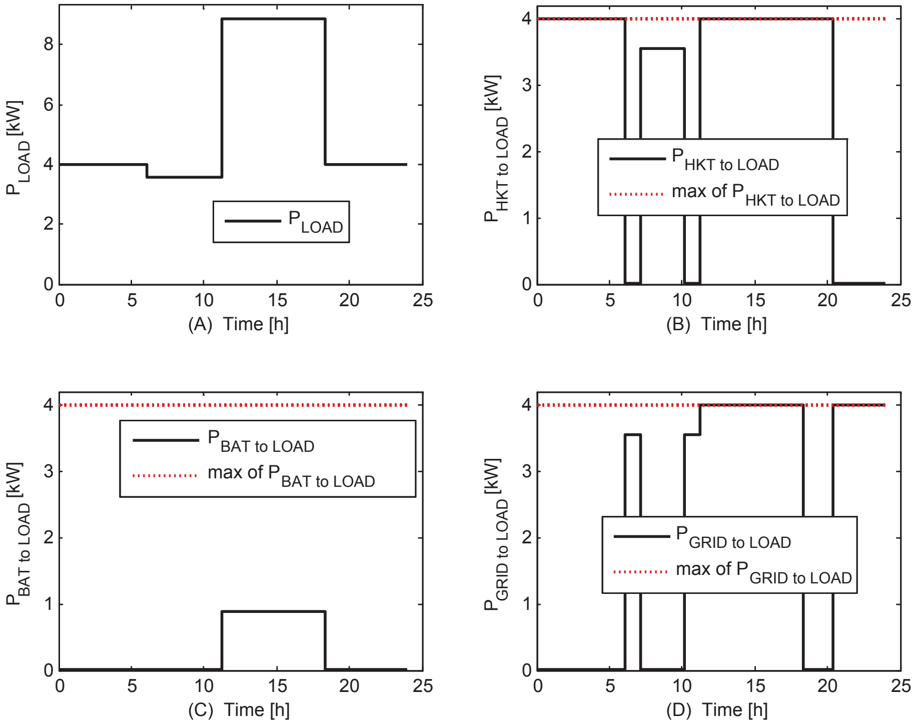

Fig. 4. Load side power flow (BTS case).

6.2.3. *Power flow under peak pricing period [7, 10)*

During the peak pricing period, the demand is exclusively satisfied by the HKT as shown in Fig. 4(B). The whole power available from the battery is sold to the grid together with the excess power from the HKT not used by the load as shown in Fig. 5(B) and (D). This results in a decrease of the battery's SOC as represented in Fig. 5(A).

6.2.4. *Power flow under standard pricing period [10, 18)*

During this period the demand is high but the cost of electricity from the grid is low; therefore, both the HKT and the grid are used to supply the load demand supplemented by a small contribution from the battery, as shown in Fig. 4(A)–(D), respectively. The power from the battery not used by the load is sold to the grid; this can be seen in Fig. 5(D).

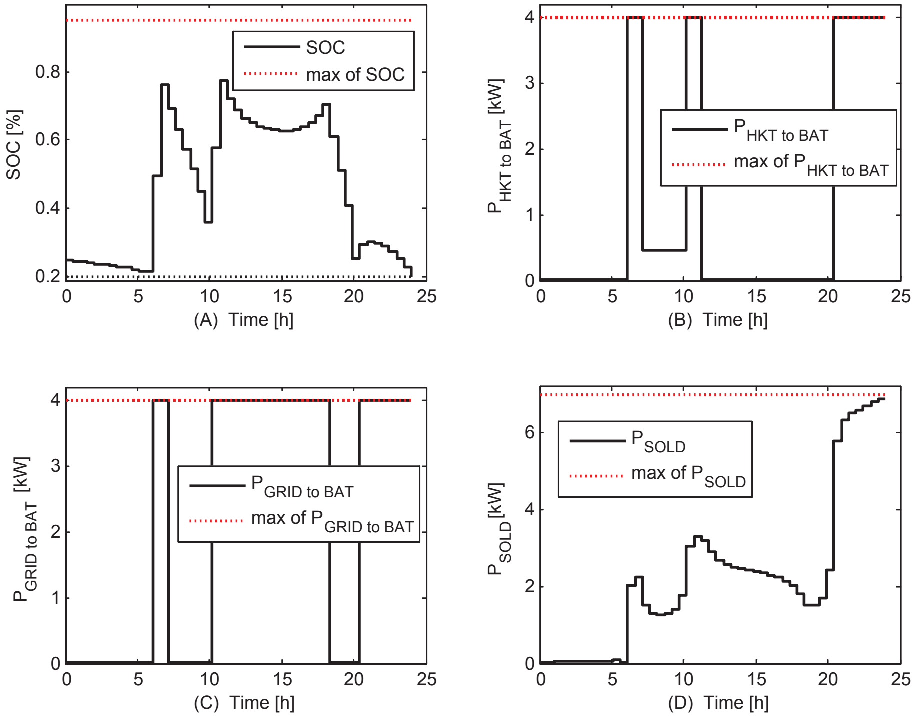

Fig. 5. Battery side power flow (BTS case).

6.2.5. *Power flow under peak pricing period [18, 20)*

During this second peak price period, all the power generated by the HKT system is used to supply the load as shown in Fig. 4(B). There is no grid power used to either recharge the battery or supply the load as shown in Figs. 4(D) and 5(C). Similarly, even if the amount of power sold to the grid is lower compared to the one sold during off-peak period, the profit is high due to the high price of electricity during peak period.

6.2.6. *Power flow under off-peak price period (22, 24]*

During this second off-peak price period, the load is supplied by the power from the grid as shown in Fig. 4(D). All the power from the HKT is sold to the grid through the battery as shown in Fig. 4(B) and (D).

6.2.7. *Daily income generated*

If the BTS demand is supplied by the grid only without the HKT and battery storage system, the daily electricity cost would be $10.34. When optimally operating the grid-connected HKT hybrid system, the daily income generated by selling electricity to the grid is $12.46. In other words, when making the balance between what is purchased from the grid and what is sold to the grid, the customer can earn $2.12. This income is a function of the size of the hybrid system's components, the battery initial state of charge as well as of the load profile.

7. Conclusion

Demand side management has been applied in the optimal energy management of grid-connected HKT-battery hybrid system. The Time of Use operating tariff with power selling to the grid has been studied for energy management in this work. A model for decreasing electricity charges at the consumer's side has been developed. The simulation results have demonstrated that the developed optimal operation model for the hybrid system results in the maximal use of HKT and battery storage system. The simulation results highlight the important role played by the battery in storing power from the utility grid during off-peak periods and in providing power to the load during peak periods. Consequently, by optimally operating the hybrid system, the load consumes nominal amount of power from the utility grid and the consumers can generate income by selling electricity to the grid. It has been demonstrated that optimal control is a powerful control method for power flow management in DSM.

For future work, Model Predictive Control will be developed to handle the control when the hybrid system experiences disturbances in HKT output and load demand. Also different load patterns as well as different renewable energy sources will be considered for experimental purposes with the aim of validating the simulation results.

References

[1] M. Goedeckeb, S. Therdthianwong, S.H. Gheewala, Life cycle cost analysis of alternative vehicles and fuels in Thailand, Energy Policy 35 (6) (2007) 3236–3246.

[2] K. Kusakana, H.J. Vermaak, Hydrokinetic power generation for rural electricity supply: case of South Africa, Renew. Energy 55 (2013) 467–473.

[3] S. Ashok, Optimised model for community-based hybrid energy system, Renew. Energy 32 (2007) 1155–1164.

[4] K. Kusakana, H.J. Vermaak, Hybrid renewable power systems for mobile telephony base station in developing countries, Elsevier Renew. Energy 51 (2013) 419–425.

[5] K. Kusakana, Optimal Operation Control of Hybrid Renewable Energy Systems, D.Tech thesis, Electrical Engineering, Central University of Technology, 2014.

[6] S. Jain, V. Agarwal, An integrated hybrid power supply for distributed generation applications fed by nonconventional energy sources, IEEE Trans. Energy Convers. 23 (2) (2008) 622–631.

[7] P. García-Triviño, A. José Gil-Mena, F. Llorens-Iborra, C.A. García-Vázquez, L.M. Fernández-Ramírez, F. Jurado, Power control based on particle swarm optimization of grid-connected inverter for hybrid renewable energy system, Energy Convers. Manag. 91 (2015) 83–92.

[8] G.R. Aghajani, H.A. Shayanfar, H. Shayeghi, Presenting a multi-objective generation scheduling model for pricing demand response rate in micro-grid energy management, Energy Convers. Manag. 106 (2015) 308–321.

[9] H. Kanchev, D. Lu, F. Colas, V. Lazarov, B. Francois, Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications, IEEE Trans. Ind. Electron 58 (10) (2011) 4583–4592.

[10] C. Chen, S. Duan, T. Cai, B. Liu, G. Hu, Smart energy management system for optimal microgrid economic operation, IET Renew. Power Gener. 5 (3) (2011) 258–267.

[11] Y. Riffonneau, S. Bacha, F. Barruel, S. Ploix, Optimal power flow management for grid connected PV systems with batteries, IEEE Trans. Sustain. Energy 2 (3) (2011) 309–320.

[12] T. Logenthiran, D. Srinivasan, T.Z. Shun, Demand side management in smart grid using heuristic optimization, IEEE Trans. Smart Grid 3 (3) (2012) 1244–1252.

[13] K. Kusakana, Optimization of the daily operation of a hydrokinetic–diesel hybrid system with pumped hydro storage, Energy Convers. Manag. 106 (2015) 901–910.

[14] S.P. Koko, K. Kusakana, H.J. Vermaak, Micro-hydrokinetic river system modelling and analysis as compared to wind system for remote rural electrification, Electr. Power Syst. Res. 126 (2015) 38–44.

[15] K. Kusakana, Optimisation of the daily operation of a hydrokinetic-Diesel generator power plant, in: International Conference on the Industrial and Commercial Use of Energy, ICUE, 2015, pp. 367–372.

[16] K. Kusakana, Pumped storage-based standalone hydrokinetic system: feasibility and techno-economic study, in: International Conference on the Industrial and Commercial Use of Energy, ICUE, 2015, pp. 373–378.

[17] K. Kusakana, Feasibility analysis of river off-grid hydrokinetic systems with pumped hydro storage in rural applications, Energy Convers. Manag. 96 (2015) 352–362.

[18] K. Kusakana, H. Vermaak, Cost and performance evaluation of hydrokinetic-diesel hybrid systems, Energy Procedia 61 (2014) 2439–2442.

[19] K. Kusakana, A survey of innovative technologies increasing the viability of micro-hydropower as a cost effective rural electrification option in South Africa, Renew. Sustain. Energy Rev. 37 (2014) 370–379.

[20] A. Maleki, F. Pourfayaz, M.A. Rosen, A novel framework for optimal design of hybrid renewable energy based autonomous energy systems: a case study for Namin, Iran, Energy 98 (2016) 168–180.

[21] S.N. Kamenopoulos, T. Tsoutsos, Assessment of the safe operation and maintenance of photovoltaic systems, Energy 93 (2015) 1633–1638.

[22] K. Kusakana, H. Vermaak, Hybrid diesel generator/renewable energy system performance modeling, Renew. Energy 67 (2014) 97–102.

[23] K. Kusakana, H.J. Vermaak, B.P. Numbi, Optimal operation control of hydrokinetic-based hybrid systems, Renew. Energy Serv. Mank. 1 (2015) 291–303.

[24] M. Zebarjadi, A. Askarzadeh, Optimization of a reliable grid-connected PV-based power plant with/without energy storage system by a heuristic approach, Sol. Energy 125 (2016) 12–21.

[25] M.S. Adaramola, Viability of grid-connected solar PV energy system in Jos, Nigeria, Electr. Power Energy Syst. 61 (2014) 64–69.

[26] E. Tarigan, Djuwari, F.D. Kartikasari, Techno-economic simulation of a grid-connected PV system design as specifically applied to residential in Surabaya, Indonesia, Energy Procedia 65 (2015) 90–99.

[27] X. Wang, A. Palazoglu, N.H. El-Farra, Operational optimization and demand response of hybrid renewable energy systems, Appl. Energy 143 (2015) 324–335.

[28] A.R. Khan, A. Mahmood, A. Safdar, Z.A. Khan, N.A. Khan, Load forecasting, dynamic pricing and DSM in smart grid: a review, Renew. Sustain. Energy Rev. 54 (2016) 131–1322.

[29] S.M. Sichilalu, X. Xia, Optimal power dispatch of a grid tied-battery-photovoltaic system supplying heat pump water heaters, Energy Convers. Manag. 102 (2015) 81–91.

[30] H. Wolisz, C. Punkenburg, R. Streblow, D. Müller, Feasibility and potential of thermal demand side management in residential buildings considering different developments in the German energy market, Energy Convers. Manag. 107 (2016) 86–95.

[31] R. Dufo-Lopez, J.L. Bernal-Agustin, Techno-economic analysis of grid-connected battery storage, Energy Convers. Manag. 91 (2015) 394–404.

[32] R. Dufo-Lopez, Optimization of size and control of grid-connected storage under real time electricity pricing conditions, Appl. Energy 140 (2015) 395–408.

[33] K. Kusakana, Optimal operation scheduling of a hydrokinetic-diesel hybrid system with pumped hydro storage, in: 4th International Conference on Electric Power and Energy Conversion Systems (EPECS), 24-26 November 2015, pp. 1–6.

[34] K. Kusakana, Optimisation of battery-integrated diesel generator hybrid systems using an ON/OFF operating strategy. International Conference on the Domestic Use of Energy (DUE 2015), 30 March-1 April 2016. 187–192.

[35] L. Bokopane, K. Kusakana, H.J. Vermaak, Optimal energy management of an isolated electric Tuk-Tuk charging station powered by hybrid renewable systems. International Conference on the Domestic Use of Energy (DUE 2015),

30 March – 1 April 2016. 193–201.
[36] Z. Wu, H. Tazvinga, X. Xia, Demand side management of photovoltaic-battery hybrid system, Appl. Energy 148 (2015) 294–304.
[37] K. Kusakana, H.J. Vermaak, B.P. Numbi, Optimal sizing of a hybrid renewable energy plant using linear programming, in: IEEE Power Engineering Society Conference and Exposition in Africa, PowerAfrica, 2012, pp. 1–5.
[38] K. Kusakana, H.J. Vermaak, B.P. Numbi, Optimal operation control of hydrokinetic based hybrid systems, Renew. Energy Serv. Mank. 1 (2015) 291–303.