IMPACT OF DIFFERENT LOAD PROFILES ON SIZING AND PERFORMANCE OF A MICRO-HYDROKINETIC-BATTERY BASED HYBRID SYSTEM.

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Abstract: Hydrokinetic hybrid systems are gaining more interest since hydrokinetic technology has proved to offer a cost-effective electrification solution. Very few research studies on sizing and optimization of micro-hydrokinetic-battery (MHK-B) based hybrid systems have been done. However, the authors did not explore the impact of different load profiles on optimal sizing and performance of the MHK-B hybrid system. In this study, the impact brought by different load profiles such as residential, commercial and industrial sectors on sizing and operation of a river based MHK-B hybrid system is investigated using Hybrid Optimization Model for Electric Renewable (HOMER) software. HOMER Pro version 3.6.1 has been selected since it is equipped with hydrokinetic turbine module. The flowing water resource data obtained from a typical river of South Africa has been used as an input. Sample of load profile curves for residential, commercial, industrial have been used to estimate the daily load demands. The optimum configuration results indicated that for the same daily energy consumption, the type of a load profile affects the battery storage capacity, hydrokinetic turbine size, inverter and rectifier operational hours as well as the annual excess energy for the MHK-B hybrid system.

Keywords: Micro-hydrokinetic, battery storage, load demand profiles, optimal sizing, HOMER Pro Version 3.6.1

I. INTRODUCTION

Growing awareness on environmental protection and depletion of fossil fuels encourages the use of renewable energy sources (RESs). However, the use of a single technology based renewable energy (RE) system leads to high investment costs and low reliability due to the intermittent and uncertain nature of RESs [1]. It does not guarantee a continuous uninterrupted power supply and may lead to over-sizing of the system. Hybrid renewable energy system (HRES) is a solution to enhance the reliability of the supply at a low maintenance cost [2]. By incorporating energy storage system (ESS) to store excess energy can offset the operational uncertainties of RESs in a HRES [3]. This offers a solution to address the mismatch between the demand and the RE output; and also a possibility to reduce the size of the renewable energy systems [4].

When planning to construct a HRES, it is important for a designer to select the optimum system configuration satisfying the primary load demand. Each component of the HRES needs to be correctly sized to ensure the design of an efficient, reliable and economic hybrid system. Under-sizing a HRES may often unmatch the energy supply and the load demand whereas over-sizing may result into higher capital costs and inefficient use of the HRES [5]. Several software tools are available for designing and evaluating the performance of the HRES as shown in [6]. Hybrid optimization model for electric renewable (HOMER) software is one of the commonly used tools for optimal sizing of a HRES [7]. It determines the optimal size for off-grid and grid-connected systems and can also generate optimization results for variable inputs in order to enable sensitivity analysis with the aim of finding the best configuration based on the given site conditions (load, resources and components sizes and costs).

Among different renewable energy technologies, hydrokinetic technology is currently gaining more considerable attention. Studies have exposed the potential benefits of using micro-hydrokinetic technology in rural electrification. It has proved to offer a reliable and cost-effective electrification solution when compared to solar and wind in areas with flowing water resource [8, 9]. Very few sizing and energy optimization research studies have been conducted on hydrokinetic hybrid system comprising of battery storage system [9-14]. However, none of these studies have analyzed the impact of different load demand profiles from different types of users on optimal sizing and operation of a HRES. Hence, this study focuses on analyzing the impact brought by different load types (residential, commercial, and industrial) on sizing and operation of a river-based micro-hydrokinetic-battery based (MHK-B) hybrid system using the latest HOMER PRO Version 3.6.1. To achieve this objective, the residential load profile curve of a typical high-consumption South African consumer [15] and the commercial and industrial daily load curves found in [16] have been used to estimate the load demands. For proper comparison purpose, the three load profiles have been allowed to have the same daily energy consumption level with different consumption patterns/curves. The results have shown that for the same daily energy consumption, the type of a load profile affects the battery storage capacity, inverter and rectifier operational hours as well as the annual excess energy.

II. MATHEMATICAL MODEL OF THE PROPOSED HYBRID SYSTEM

A. Operation principle of the proposed hybrid system

The layout of the proposed off-grid MHK-B hybrid system is shown in Fig. 1 below. The system consists of an off-grid micro-hydrokinetic river system, battery storage system and end-user (residential, commercial or industrial load). Micro-hydrokinetic river system is used to supply electricity to the load while the battery system is used to store excess energy from the micro-hydrokinetic river system. The storage mode will take place only when the load demand is less than the power generated by a micro-hydrokinetic river system. If a load demands more than the generated capacity, the battery will then supplement the imbalance by supplying the deficit. To ensure a reliable and sustainable energy supply at no shortage, the battery storage capacity and micro-hydrokinetic river system must be adequately sized.

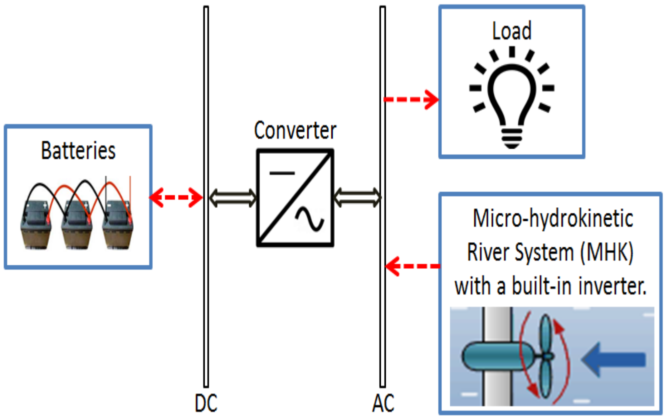

Fig. 1: Proposed MHK-Battery hybrid system layout

B. Hydrokinetic system

Hydrokinetic river systems extract the kinetic energy of the flowing water in a river by making use of the swept area of a turbine rotor blade. Its output power depends on the speed of the flowing water. It can be installed in rivers with a minimum velocity of 0.5 m/s and above [17]. Its operation principle is similar to the one of a wind turbine system [18]. However, unlike the wind resource, the main advantage is that the flowing water resource does not suddenly fluctuate within a very short period of time [9]. Since the water density is 800 times greater than the air density, hydrokinetic turbines can extract enough power even at low speeds [19-21]. This simply implies that the amount of energy generated by a hydrokinetic turbine is much greater than the one generated by a wind turbine of equal diameter and performance under equal wind and water speeds [17]. The energy generated by the hydrokinetic system is expressed as follows [10, 14]:

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

Where: ρ_W is the water density (1000 Kg/m3), A is the hydrokinetic turbine swept area (m^2), v is the water speed (m/s), C_p is the power coefficient of a hydrokinetic turbine performance, η_{HKT-G} is the overall efficiency of a hydrokinetic turbine-generator unit and t is the time (s).

III. SIMULATION DATA

To determine the impact of different load profiles on MHK-B hybrid system operation, three different load profiles having the same energy consumptions have been used during simulations. The simulation where carried used the same flowing water data from a typical river of South Africa and the same system components as inputs to HOMER Pro Version 3.6.1. During simulation the interest rate of 7% has been considered and the project was assumed have a 25 years lifespan. The simulations have been carried out with the intention of meeting the load demand at no capacity shortage.

A. Load profiles description

As mentioned earlier, this study is conducted with the intention of using MHK-B hybrid system to meet the demand of residential, commercial and industrial consumer load types, separately. The main objective is to see the impact of each load profile on the hybrid system sizing and operation. Hence, each load type is modelled separately as a primary load type. Jardini et al. [16] conducted a field measurement study to determine and validate the average daily load profile curve for residential, commercial and industrial low voltage alternating current (AC) load types. The commercial and industrial load profile curves have been used to estimate daily power demand for commercial and industrial loads. For residential load, a typical South African high-consumption residential consumer load profile curve was considered [15]. It can be noticed that the South African daily peak demand usually occurs in the morning when people get ready to go to work and in the evening when people get home and turn on the appliance simultaneously.

To fulfil the objectives of the study, the three load profiles were allowed to have the same daily energy consumptions without changing their shapes or curves. The area under each curve represents the daily energy consumption. Fig. 2 illustrates the resulting load profiles for the residential, commercial and industrial load types as used in the simulations. Each load profile has been set to have the same energy consumption of 60 kWh/day for a better comparison purpose. After enabling the same energy consumption for each load type, the residential load resulted into a peak power demand of 4.42 kW at a small base load of 1.4 kW. The commercial load resulted into a peak power demand of 5.43 kW at a small base load of 0.29 kW while the industrial load resulted into a peak power demand of 7.32 kW at a small base load of 0.14 kW.

It can be seen that both the commercial and industrial loads demand more energy during the day as compared to the residential load. At around 12h00, the industrial load demand drops at a high rate when compared to other working or peak hours. The reason is because unlike the commercial businesses, most industrial businesses allow their employees to simultaneously take a lunch break instead of allowing different break shifts to take place. Hence, this allows the production process to delay a bit.

B. 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 Table 1 [9]. It can be seen that the maximum and minimum water-flow velocities take place in February and September, respectively. However, the proposed MHK-B hybrid system must be designed to meet the load demand throughout the year.

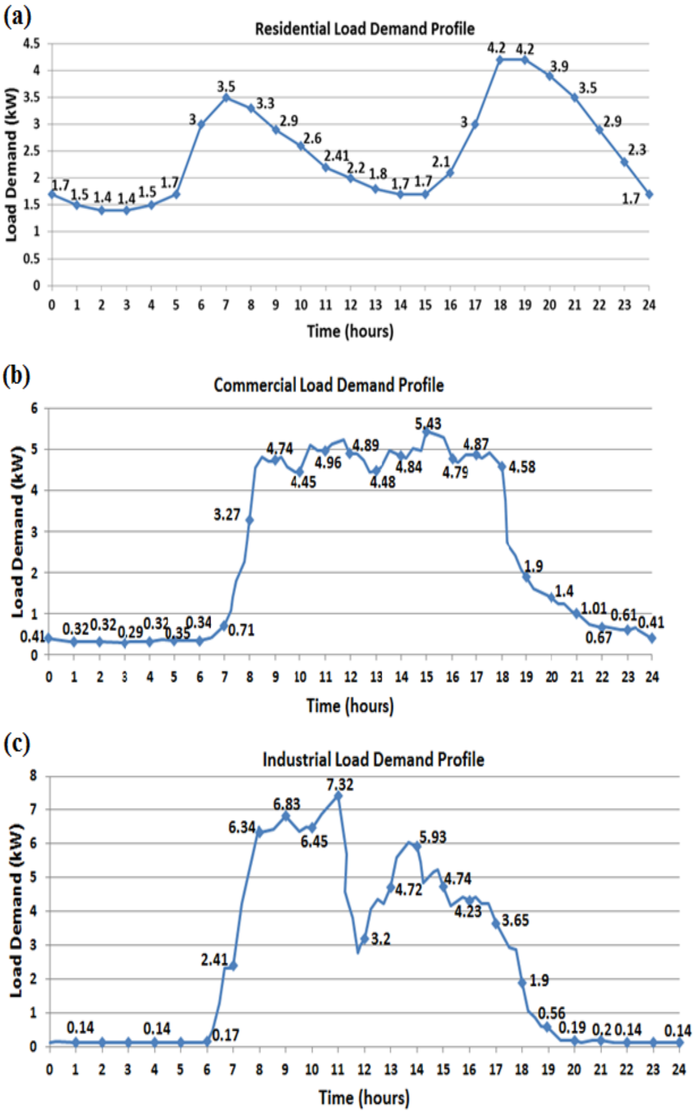

Fig. 2: Daily load demand profile for (a) residential, (b) commercial, (c) industrial

IV. Components Costs and Specifications

The proposed MHK-B hybrid system consists of hydrokinetic river system to generate electricity and battery system to store energy for usage during deficit time. The performance and costs for each component of the proposed hybrid system are critical since they are the contributing factors leading to an 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 2. All components are assumed to have the replacement costs being equal to the capital cost.

A. Hydrokinetic system

River based hydrokinetic turbines are available in a range of 1-10 kW [17]. In this study a generic 1.5 kW Darrius hydrokinetic turbine (DHK) system with the swept area of 1.56 m^2 has been selected [14]. It generates its rated output power at water-flow speed of 2 m/s or above. One unit requires a capital cost of US$15,000 with operation and maintenance (O&M) costs considered to be 2% (US$300) per year. Similar to the wind turbines, its life span is estimated to be 25 years [22]. The output power curve of the turbine is shown in Fig. 3. When the water speed exceeds 2 m/s it is assumed that the output power remains constant at 1.5 kW.

B. Converter

An 8 kW, 50 Hz, 230 Vac Victron converter has been considered in this study to recharge the batteries and to convert DC output power from the batteries into AC power needed by the load. The cost price of this converter is US$5,509 with the O&M cost assumed to be US$55.09 [14]. This converter has an efficiency of 96% and its lifespan is assumed to be 10 years. This implies that it can supply a load demanding up to a maximum of 7.68 kW.

TABLE I:
MONTHLY AVERAGE WATER VELOCITY [9]

Months	**Water speed (m/s)**
January	5.31
February	7.25
March	6.09
April	1.81
May	2.67
June	2.18
July	1.84
August	1.54
September	1.41
October	1.69
November	2.83
December	5.27

TABLE II: COMPONENT SIZES AND COSTS

Components	Capital Cost (US$)	O&M (US$)	Replacement Cost (US$)	Life Time (years)
1.5 kW Hydrokinetic turbine (DHK)	15,000/unit	300/year	15,000/unit	25
8 kW, 50 Hz, 230 Vac Victron converter	5,509/unit	300/year	5,509/unit	10
225 AH, Trojan T-105 battery	200/battery	40/year	200/battery	5

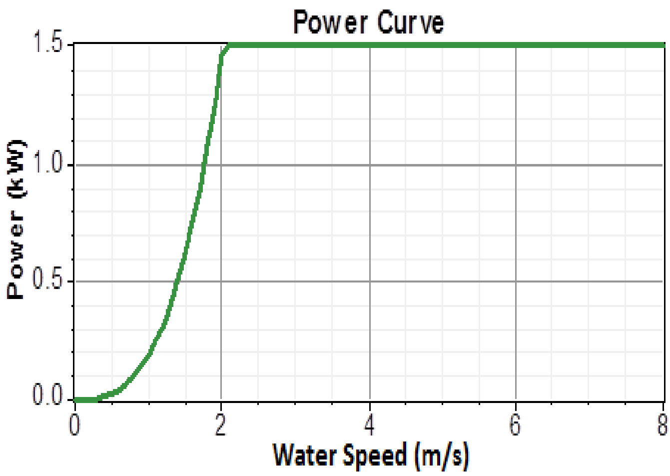

Fig. 3: Darius hydrokinetic (DHK) turbine power curve [14]

C. *Battery storage system*

A 6 V, 225 Ah deep cycle Trojan T-105 battery was considered as storage when simulating each load type in this study. The per unit purchasing price (based on current South African market) is US$200 with O&M cost assumed to be 2% of the purchasing price per year. The battery has a life-time throughput of 845 kWh with a lifespan assumed to be 5 year.

V. SIMULATION RESULTS AND DISCUSSION

As stated in the introduction, the objective of the study is to analyzing the impact of residential, commercial and industrial load profile respectively on sizing and operation of an MHK-B hybrid system. This objective has been achieved using the optimum configuration results obtained in HOMER Pro Version 3.6.1. To ensure the validity of the impact analysis, the three load profiles were allowed to have the same daily energy consumption without changing the shapes of their curves. Table 3 illustrates the optimal configuration results for each load profile.

A. *Impact of load profiles on optimal sizing and operation*

The optimum hybrid configuration of the MHK-B hybrid system using a built-in hydrokinetic turbine module available in HOMER Pro Version 3.6.1 was determined in this study. Each load profile demands 60 kWh per day. Based on the optimal configuration results, it can be seen that the residential load type demands less hydrokinetic turbine size (7.5 kW) as compared to the size (9 kW) required for commercial and industrial load types. The reason is because the residential load demands peak energy for fewer hours as compared to the commercial and residential loads. The optimal configuration results also reveal that for the same daily energy consumption, the residential load type demand least storage capacity (2925 Ah) while the industrial load type demand the most (6525 Ah). Fig. 4 shows the monthly generated output power of the hydrokinetic turbine system for the residential load type while Fig.5 shows the monthly generated output power for the commercial or industrial load types. It can be noticed that the monthly output power generated by the hydrokinetic turbines yields the maximum power production only when the water velocity is 2 m/s or above (during January, February, March, May, June, November and December).

B. *Residential load type: Case 1*

To supply the residential load profile, the optimal configuration of the MHK-B hybrid system consists of 5 hydrokinetic turbine modules, 13 batteries and an 8 kW converter as calculated by HOMER to ensure 0% unmet residential load demand throughout the year. Fig. 6 and 7 shows the inverter and rectifier output power throughout the year, respectively. The inverter output power indicates that the battery bank discharges to supply electrical power to the unmet load demand and the converter output power indicate that the batteries are recharged.

Based in Fig. 6, it can be seen that the battery bank supports the hydrokinetic system by supplying the unmet load demand only during August and September due to insufficient water speed. Hence, the battery bank state of charge (SOC) drops as shown in Fig. 8 and will start recharging after 22h00 in August and after 23h00 in September as shown in Fig. 7. The longer discharge hours take place in September between 17h00-22h00 when the load demands above 2.6 kW.

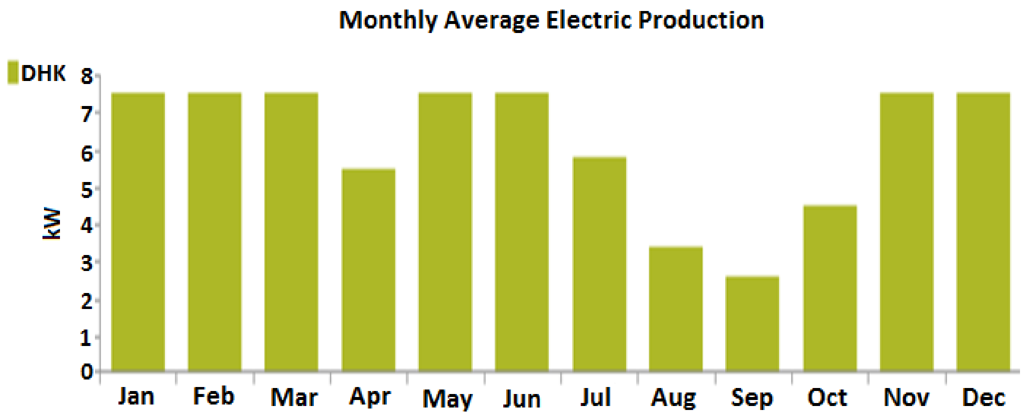

Fig. 4: Monthly generated output power from a hydrokinetic system for residential load

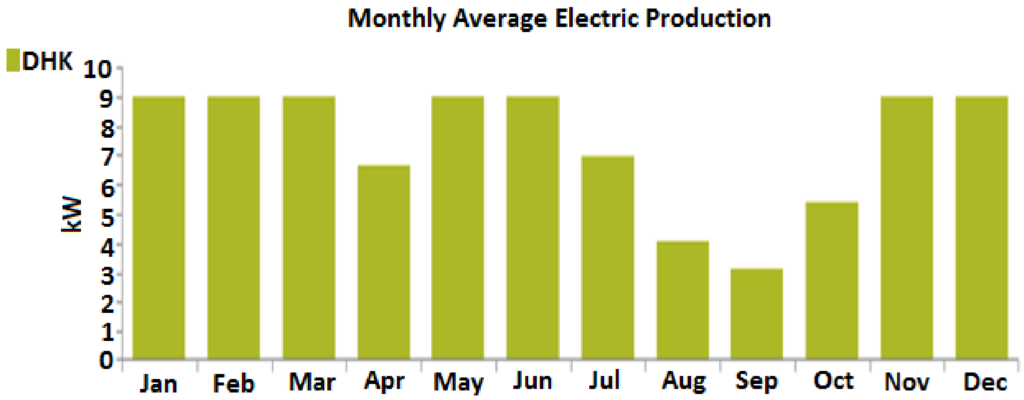

Fig. 5: Monthly generated output power from a hydrokinetic system for commercial or industrial load

TABLE III: HOMER PRO VERSION 3.6.1 OPTIMAL CONFIGURATION RESULTS

	Residential load	**Commercial load**	**Industrial load**
Optimization results	7.5 kW hydrokinetic turbine system + 13 Trojan batteries (2925 Ah) + 8 kW converter	9 kW hydrokinetic turbine system + 23 Trojan batteries (5175 Ah) + 8 kW converter	9 kW hydrokinetic turbine system + 29 Trojan batteries (6525 Ah) + 8 kW converter
Capital cost ($)	83,109	100,109	101,309
Operating cost ($/y)	2,805	3,360	3,670
Net present cost ($)	115,798	139,269	144,075
Levelized cost of energy ($/y)	0.454	0.546	0.565
Total energy production (kWh/y)	54,150	64,985	64,985
Excess electricity (kWh/y)	32,171	42,898	42,741
Storage autonomy (h)	5.02	8.70	10.97
Inverter hours of operation (h/y)	437	671	794
Peak Inverter P_{OUT} (kW)	1.6	2.31	4.2
Rectifier hours of operation (h/y)	3,210	2,992	5,797
Peak Rectifier P_{OUT} (kW)	0.93	1.65	2.08
Storage throughput (kWh/y)	355.86	831.81	1,488.70

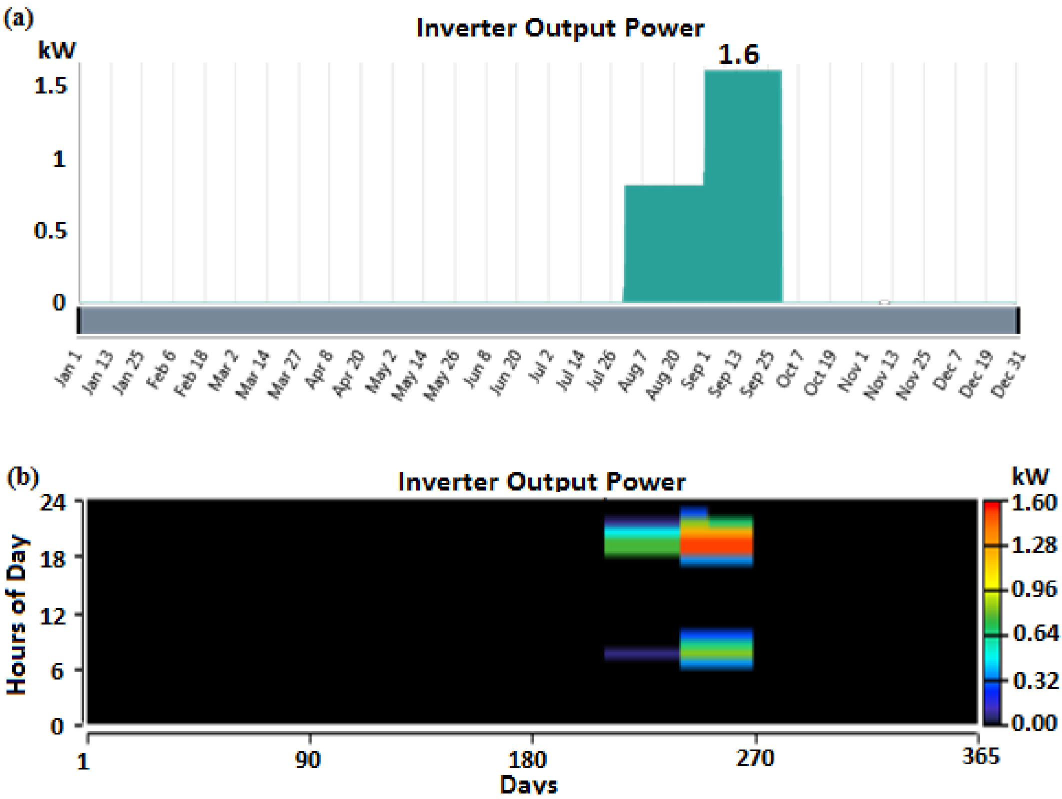

Fig. 6: Inverter output power (a) maximum power (b) hourly power (Case 1).

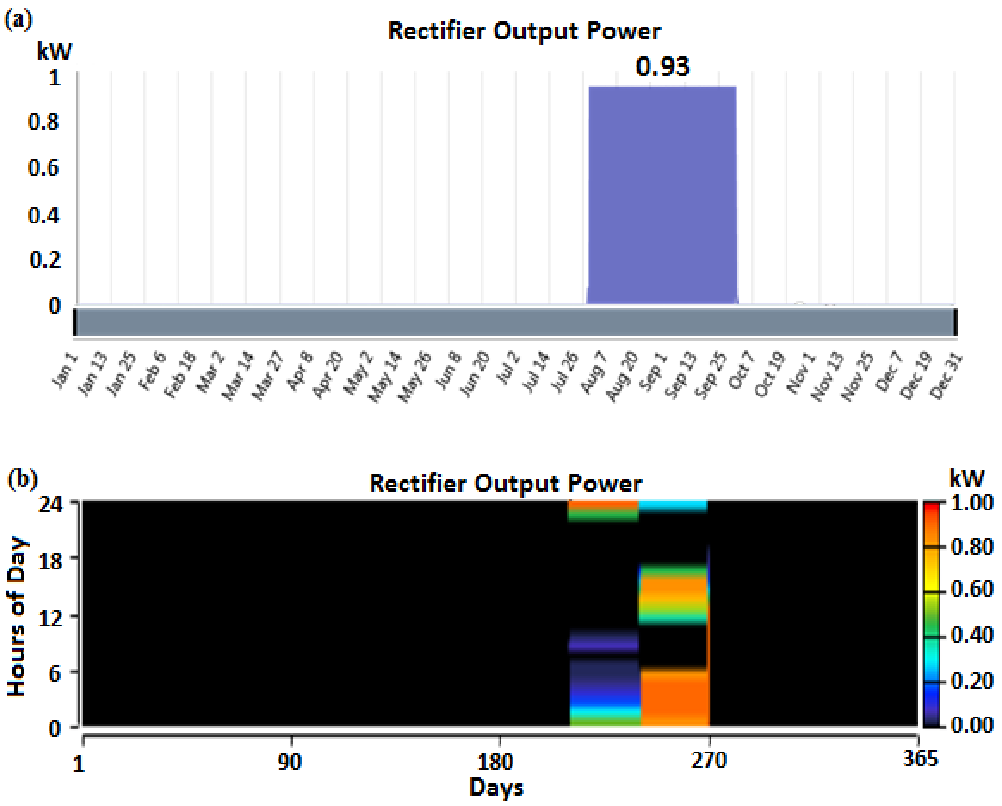

Fig. 7: Rectifier output power (a) maximum power (b) hourly power (Case 1)

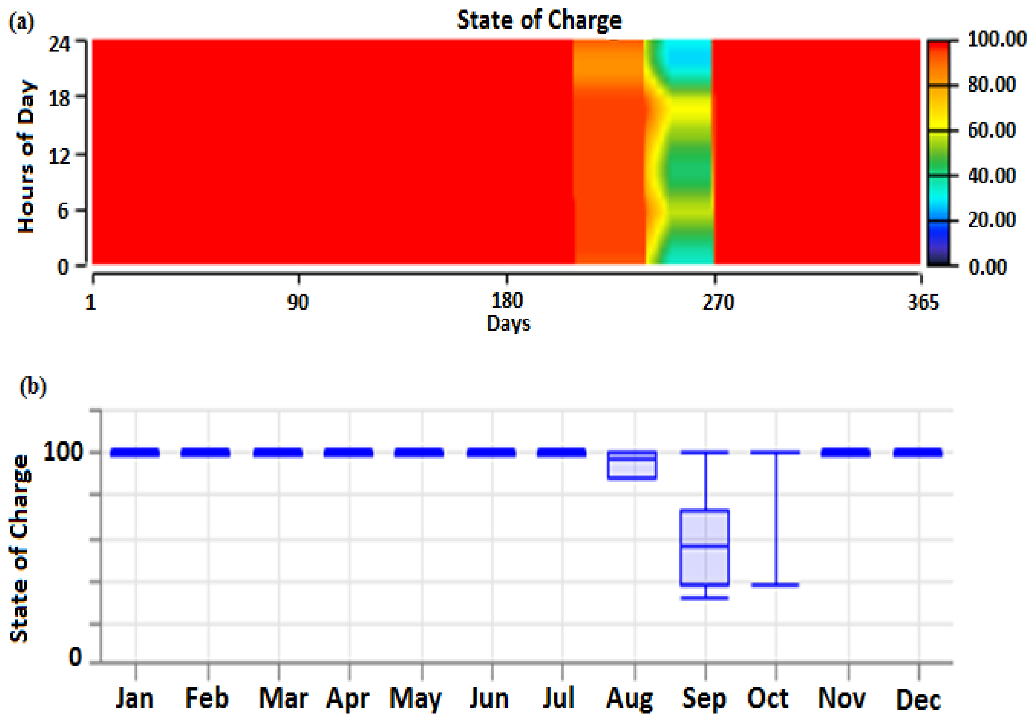

Fig. 8: Batteries state of charge (a) hourly (b) monthly statistic (Case 1)

This reveals that there are more inverter operational hours as compared to August month. During the month of April, the hydrokinetic turbine generates 5.5 kW which is sufficient to meet the residential peak demand as shown in Fig. 4. Hence, the battery bank does not discharge and does not charge since it is in 100% state of charge.

The worst batteries SOC is reached in September since the load is heavily relying on the battery bank. This worst SOC allows the battery bank level to drop to almost 30% as shown in Fig. 8. During this month, the maximum output power of 1.6 kW is demanded by the load from the batteries as shown in Fig. 6. During the months of August and September, the power required to refill the batteries reaches the maximum value of 0.93 kW as shown in Fig. 7.

C. Commercial load type: Case 2

The optimal configuration of the MHK-B hybrid system to satisfy the commercial load profile consists of 6 hydrokinetic turbine modules, 23 batteries (5175 Ah) and an 8 kW converter as calculated by HOMER. The required hydrokinetic generation capacity and storage capacity are higher than the ones required for residential load. Hence, this leads to a higher capital cost and also results into higher net present cost (NPC), cost of energy (COE) as well as the operating costs. Fig. 9 and 10 shows the inverter and rectifier output power throughout the year, respectively. The inverter output power indicates the discharging process of the battery bank when supplying electrical power to the unmet load demand while the converter output power indicates the recharging process of the battery.

From Fig. 9, it can be seen that the battery bank support the hydrokinetic system by supplying the unmet load demand during August and September due to insufficient water speed. Hence, the battery bank discharges between 08h00 and 19h00 as shown in Fig. 11a and will start recharging after 19h00 as revealed by the rectifier output. During the months of October, the low water speed of 1.69 m/s allows the five hydrokinetic turbines to generate 5.45 kW which is sufficient to meet the peak demand of a commercial load. Hence, the battery does not discharge.

The worst batteries SOC is reached in September since the load is heavily relying on the battery bank. This worst SOC allows the battery bank level to drop to almost 37.5% during commercial working hour as shown in Fig. 11. The SOC does not reach 100% during September. During this month, the highest output power demanded by the load from the batteries is 2.31 kW as shown in Fig. 9. This is lower than in the case of the residential load. During the months of August and September, the power required to refill the batteries reaches the maximum value of 1.65 kW as shown in Fig. 10. This is higher than in the case of the residential load.

D. Industrial load type: Case 3

Similar to the commercial load profiles, the optimal configuration results for supplying the industrial load profile also consists of 6 hydrokinetic turbine modules and 8 kW converter. However, the difference is that the industrial load requires the largest minimal storage capacity of 29 batteries (6525 Ah). Hence, an optimal configuration for the industrial load profile bids for the highest capital cost of US$101,309 as compared to the residential and commercial load cases. This results into the highest COE and NPC since the power consumptions of the three load profiles are the same.

Fig. 12 and Fig. 13 show the behavior of the inverter unit and rectifier unit output power throughout the year, respectively. It can be noticed that unlike in the residential and commercial load cases, the battery bank discharges many times (in April, July, August, September and October) as shown in Fig. 12. Hence, this leads to the highest operational hours of the inverter (794/year). The battery bank approaches the lowest SOC of 32% in September as shown in Fig. 14. During this month, the unmet industrial load demands a maximum output power of 4.2 kW power from the batteries as shown in Fig. 12. The industrial load allows the rectifier unit to operate for the longest duration by refilling the upper reservoir during non-working hours (18h00-08h00) and during lunch break (at 12h00) as shown in Fig. 13. The maximum power used to recharge the batteries reaches 2.08 kW which is the highest compared to both residential and commercials load cases.

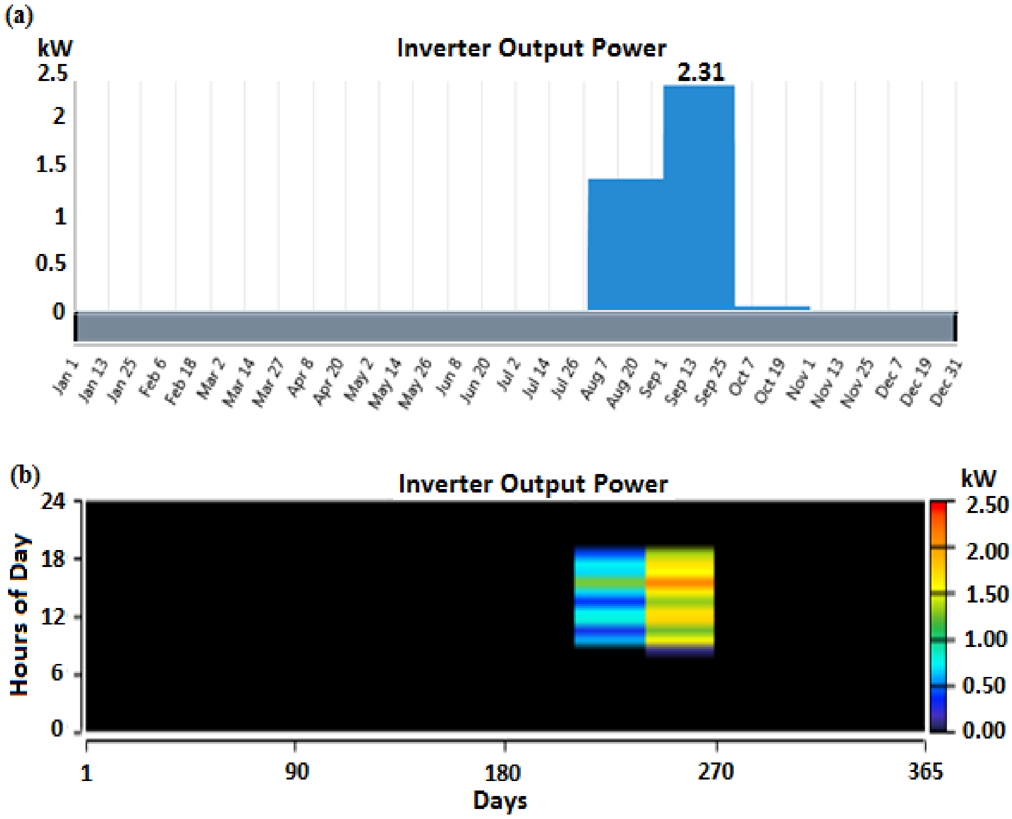

Fig. 9: Inverter output power (a) maximum power (b) hourly power (Case 2)

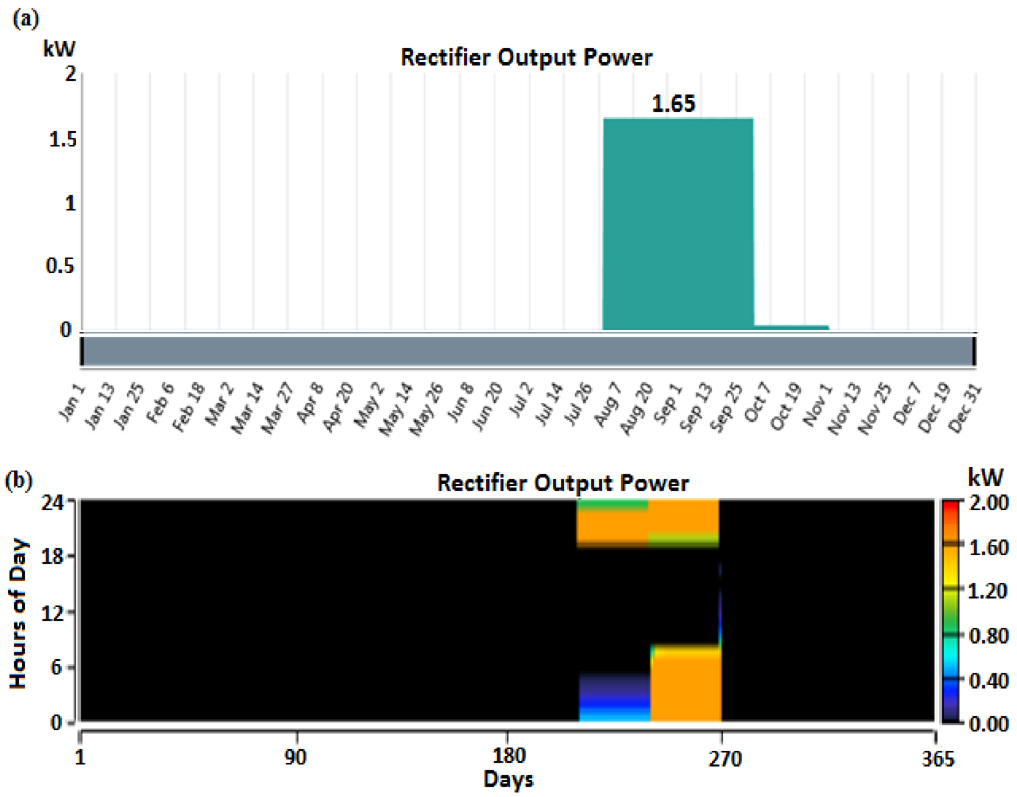

Fig. 10: Rectifier output power (a) maximum power (b) hourly power (Case 2)

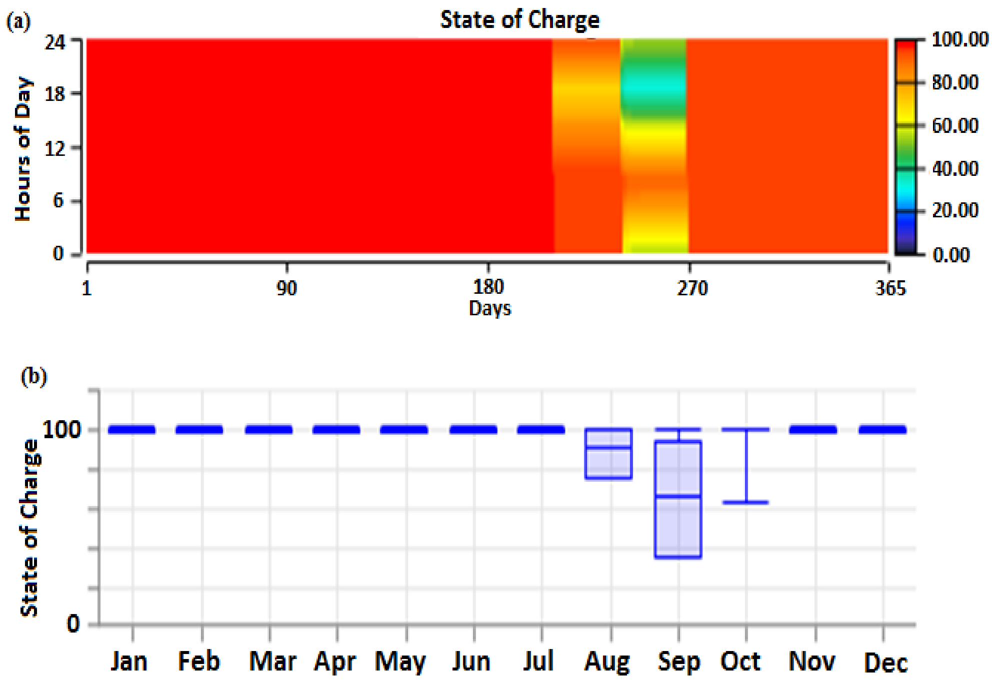

Fig. 11: Batteries state of charge (a) hourly (b) monthly statistic (case 2)

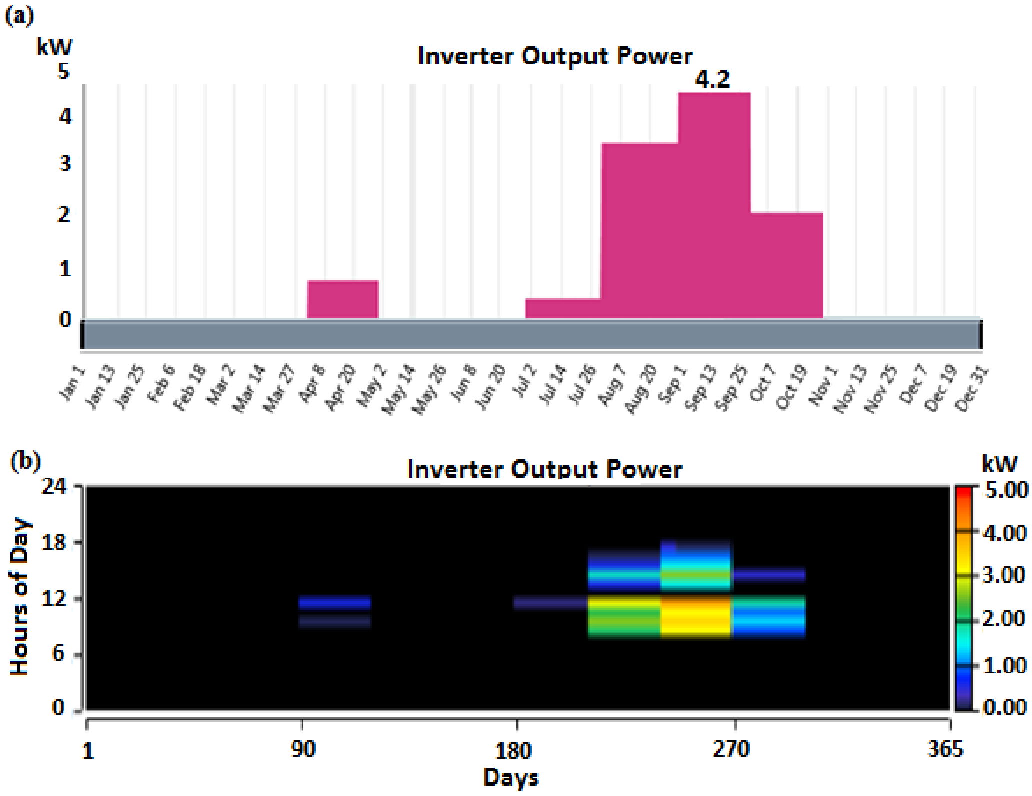

Fig. 12: Inverter output power (a) maximum power (b) hourly power (Case 3)

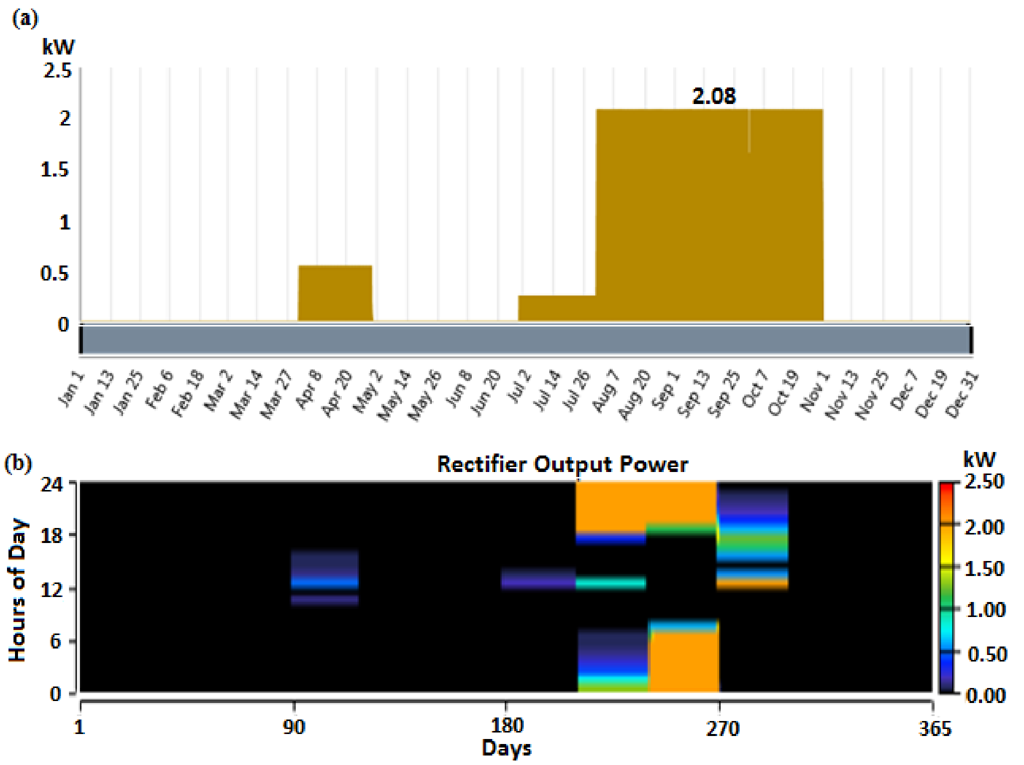

Fig. 13: Rectifier output power (a) maximum power (b) hourly power (Case 3)

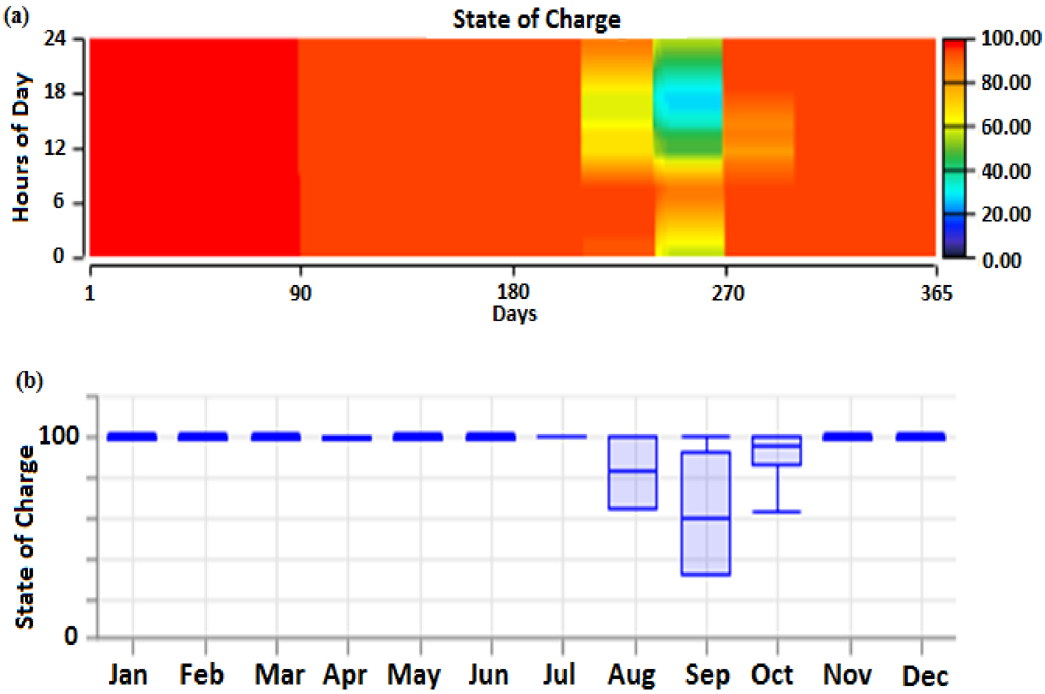

Fig. 14; Batteries state of charge (a) hourly (b) monthly statistic (Case 3)

VI. CONCLUSION

This paper analyzed the impact brought by different load profiles on optimal sizing and performance of the MHK-B hybrid power supply system. The flowing water resource data obtained from a typical river of South Africa was used as an input to obtain the optimal configuration of the MHK-B hybrid system using HOMER Pro version 3.6.1 simulation tool. Different daily load profile curves such as residential, commercial, and industrial loads having the same daily energy consumption of 60 kWh were considered and supplied by the MHK-B hybrid system at 0% capacity shortage. Comparison analysis has been carried out using overall optimum configuration results of both the generation and storage units of the MHK-B hybrid system.

According to the economic figures of each load profile, HOMER results have shown that the MHK-B hybrid system is more superior when supplying the residential load profiles due to the lowest COE and NPC. The commercial load profile incurs higher initial capital cost leading to higher COE and NPC and then followed by the industrial load profile. The optimum configuration results have shown that the type of a load profile to be supplied affects the size of the battery storage capacity as well as the operational hours of discharging and recharging the batteries.

Based on the peak output power results of the inverter and rectifier units, it has been noticed that under the same daily energy consumption, the industrial load profile requires the highest power to recharge the batteries and also demands highest power to supply the unmet load demand as compared to both the residential and commercial loads. This led to the highest operational hours of both the inverter and rectifier units. The commercial load profile was found to lead to the lowest rectifier operational hours per year as compared to both the residential and industrial loads. The residential load profile was found to lead to the lowest inverter operational hours and excess energy per year as compared to both the commercial and industrial loads.

All three load profiles were found to yield large amount of excess energy per year (exceeding 50% of the generation capacity). This shows that there is a room to sell this excess energy to the grid or use it to supply power to the deferrable loads such as thermal storage, heating, air conditioning, etc.

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

- To determine the impact level of the three load profiles on a MHK-B hybrid system configuration when considering uncertainties due to external disturbances.

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