Investigation of VRB-ESS integrated with hybrid power system for building

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***Abstract*—Beneficial in terms of improved reliability, energy services, operational life and energy efficiency, VRB-ESS and its integrated power system have brought forth the highest form of perfection in generation and distribution. This paper analyzes the interaction among components of hybrid power system (HPS), as well as the relative size of the components that is used efficiently at an optimum rate. Using developed Microsoft excel methodology, the different HPSs have been simulated for the building load profile and aim to optimize the averaged unit energy cost – US$ per kWh for each configuration of HPS.**

Keywords–Vanadium Redox Battery (VRB); Energy storage; Fuel Cell; Photovoltaic; Hybrid Power System; Optimal design

I. INTRODUCTION

The optimal HPS design depends on simulation software and factors. The present simulation software, genetic algorithm and developer mostly focus on overall present value [1], simple payback time (SPBT) and energy payback time (EPBT) [2, 3] of hybrid power system and base on the present value to evaluate HPS and its subsystems. The cost of components and subsystem used in the simulation software is based on linear function for each component [4] and provides the present value of HPS subsystems, but the cost of VRB-ESS is not linear to their kW capacity. Discussed in section III/E/2(k), VRB-ESS cost is combined with kW cost and kWh cost to represent their economical effects. In other hand, the simulation software takes long time to repeatedly simulate the system if the HPS configuration or parameters are changed. This paper gives a methodology that applies financial manner to simulate the averaged unit energy cost (US$/kWh) through life-cycle-time and optimize the design of the hybrid power system according to building load profile. The methodology is also suitable for micro-grid dispatch operation.

II. SYSTEM CONFIGURATION

The typical HPS is shown in Figure 1. It shows three energy sources, solar PV power, Fuel cell and national grid power system (NGP), are interacted with VRB-ESS to supply electricity to AC load (building loads).

The DC-BUS manages DC electricity generated by solar PV modul (PVM) and fuel cell, as well as DC energy stored in VRB-ESS. The voltage leveler shall be the indivadual DC-DC converter and let all sources work with DC-BUS in same voltage level.

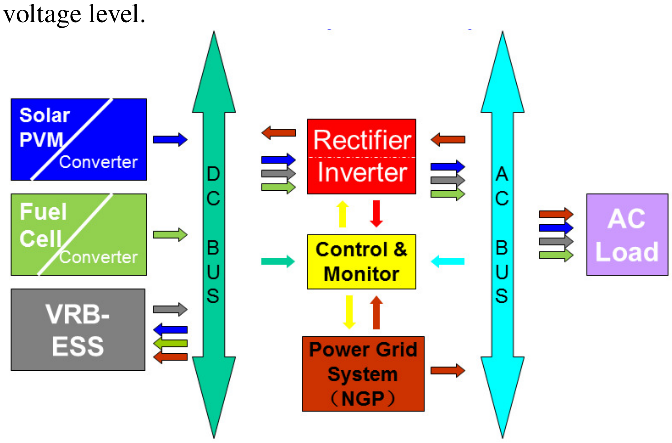

Figure 1 – Typical HPS with VRB-ESS

The AC-BUS manages AC electricity generated by NGP and supplied by DC-AC inverter and supply AC electricity to AC loads.

Simplly, DC-BUS and AC-BUS are connected and adjusted by bidirectional converter that allows DC and AC convert automatically to respond with demand. The VRB-ESS works together with the HPS to shave the peak load during the peak load time and lower NGP comsuption.

III. SIMULATION MODELLING

The models of subsystem shown in Figure 1 are descripted at below.

A. Solar PV model

In Figure 1, solar PVM output shall match DC-BUS, the series PVM number (N_s) and parallel number (N_p) will identify the voltage and current of solar PV power system. The solar PV power system model is given in equation (1).

$$E_{pv} = I_{ns}(t) * A_{pvm} * \eta_{pvm} * (N_s * N_p) * t * \eta_{con} * \eta_{inv} \quad (1)$$

Where,

E_{pv} – Total energy generated by solar PV power system (Wh)
I_{ns} – Site solar insolation (W/M²)
A_{pvm} – PVM effective area (M²)
η_{pvm} – PVM conversion efficiency (%)
N_s –PVM series number
N_p – PVM parallel number
t – working hours (h)
η_{con} – DC-DC converter efficiency (%)
η_{inv} – DC-AC inverter efficiency (%)

Equation (1) shows us that solar PVM's effective area and efficiency are key parameters to control solar PV power system output, and the site solar insolation limits whether the site is suitable to install solar PV power system, because it is not valuable or economical if the site solar insolation is too small during a year.

B. Fuel cell model

In figure 1, fuel cell output shall match DC-BUS through a DC/DC converter. Its model is given in equation (2).

$E_{fc} = [N_p * i(t)] * (N_s * V_{cell}) * t$ (2)

Where,
E_{fc} – fuel cell total generated energy (Wh)
N_s – fuel cell series number
N_p – fuel cell parallel number
i(t) – cell output current (A)
V_{cell} – cell output voltage (V)

From equation (2), fuel cell's performance is controlled by its cell's current and voltage. If the fuel cell generates more electricity with same fuel quantity, the fuel cell's performance is better.

C. VRB-ESS model

The Vanadium Redox (or redox flow) Battery (VRB) is a type of rechargeable flow battery that employs vanadium ions in different oxidation states to store chemical potential energy. [5] Since first-vanadium redox flow cell is invented by Professor Maria Skyllas-Kazacos form University of New South Wales (UNSW) in Sydney, Australia in 1985, the developers have focused on the vanadium / vanadium redox couple, electrolyte stability at high concentrations, and production of electrolyte from raw materials and built several VRBs for various applications. [6, 7] VRB technology is a proven, economically attractive and low-maintenance solution for energy storage. When a group of VRBs are used for energy storage, the whole system becomes VRB-ESS.

The VRB-ESS work principle is descripted as: when HPS total energy output (E_{hps}) is greater than total energy consumed by load (E_L), the excess energy (E_{hps} - E_L) will charge up VRB and store the amount energy in VRB-ESS; when HPS total energy output (E_{hps}) is less than total energy desired by load (E_L), the insufficient energy (E_{hps} - E_L) will take from VRB-ESS and VRB-ESS will be discharged. The VRB-ESS model is given in equation (3) [1]:

$SOC(t) = SOC(t-1) + (E_{hps} - E_L)$ (3)

Where,
SOC(t) – state of charge of VRB-ESS at hour t
SOC(t-1) – state of charge of VRB-ESS at previous hour (t-1)

D. Hybrid power system model

In figure 1, the energy of the HPS shall be balance anytime. It is given in equation (3) and (4).

$E_{hps} = E_{pv} + E_{fc} + E_g = SOC(t) - SOC(t-1) + E_L$ (4)

Where,
E_g – energy supplied by NGP

Equation (4) shows us that VRB-ESS works with HPS to dynamically respond with demand.

E. Economical model

Having the HPS energy model given as equation (4), we can get economic model for the HPS to optimize the HPS.

1. Finical formula and averaged cost [8]

This paper analyzes the cost that bases on life cycle cost. Some formulas and equations are listed as following.

Equivalent discount rate, $d' = \frac{d-e}{1+e}$ (5)

Levelizing Factor: $LF = \frac{(1+d')^n - 1}{d' * (1+d')^n} \times \frac{d * (1+d)^n}{(1+d)^n - 1}$ (6)

Capital Recovery Factor: $CRF(d,n) = \frac{d * (1+d)^n}{(1+d)^n - 1}$ (7)

Annual capital payment: $C_{ac} = C_{ic} * CRF(i,n)$ (8)
Averaged variable cost: $C_v = C_{iv} * LF$ (9)
The total averaged annual cost: $C_{at} = C_{ac} + C_v$ (10)
The averaged electricity tariff (unit price of electricity):
$C_{kwh} = C_{at} / E_{hps}$ (US$/kWh) (11)

Where,
d – annual discount rate (%)
e – annual escalation rate (%)
C_{ic} – the total initial capital cost
C_{ac} – the annual capital payment for C_{ic}
C_{iv} – total initial variable cost
C_v – the averaged variable cost
C_{at} – total averaged annual cost

2. Conditions and assumptions for simulation

The building load profile is given in figure 2. This is a base line for HPS optimal design. Any designed HPS shall fully meet the load need with optimal performance.

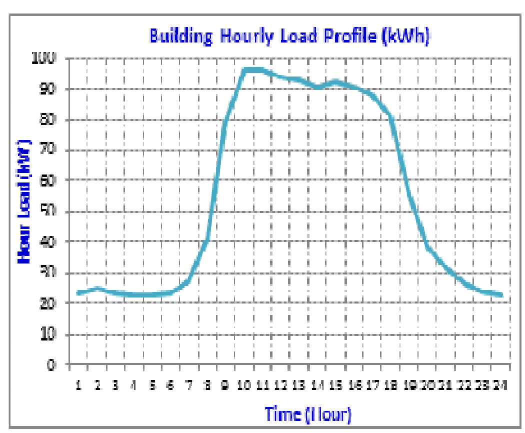

Figure 2 – Building Load profile

The Singapore insolation data is shown in figure 3. It is an hourly average global horizontal insolation (GHI) based in Singapore and measured in 2011.

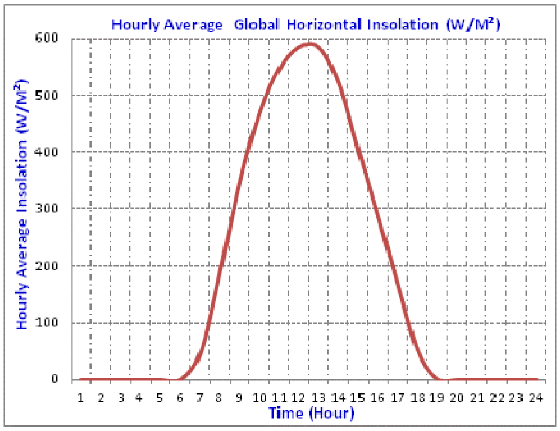

Figure 3 – Singapore hourly average GHI (2011)

From figure 2 and 3, we know the two trends' patterns are very similar. The peak happens at noon time. This lets solar PV power be more attractive to building.

The general assumptions and conditions used in this paper are as followings:

(a) The general annual discount rate is 10% (d=10%)
(b) The general annual escalation rate is 5% (e=5%), except the specially noted escalation rate.
(c) The equipment lifespan is 20 years (n=20)
(d) O&M cost is not counted the replacement cost of major components in the equipment lifespan
(e) Maximum PV installation capacity is 43kWpp (limited to effective installation area); PVM peak power is 250Wpp; PVM overall conversion efficiency is about 15.41%; Solar PVM decaying efficiency is not considered
(f) It is not considered that the efficiency of VRB-ESS is affected by SOC
(g) The efficiency of power conditioning system (PCS) including DC-DC converter and / or DC-AC inverter is about 94% for PVM, VRB-ESS and fuel cell
(h) DC-AC inverter capital cost is about US$0.711 per watt [10] for PVM and fuel cell; the bi-inverter capital cost is about US$1.022 per watt for VRB-ESS.
(i) The sources of electricity tariff are from Energy Market Authority, Singapore in July 2012. The peak usage charge is 26.65 S₵/kWh, the low peak usage charge is 16.2765 S₵/kWh, and Contracted capacity charge is 6.9665 S$/kW. Considering currency exchange rate at 1.2419 S$/US$ and the electricity average escalation rate at 9.57% (e=9.57%), the contracted capacity charge is 5.6043 US$/kW, the averaged peak usage charge is 48.3926 US₵/kWh, the averaged low peak usage charge is 29.544 US₵/kWh. Substituting data to below formula and some administrative charges are not considered in the computation as they will take very small portion of total electricity cost. *Cg = Peak usage (kWh) * 0.483926 US$/kWh + Lower Peak usage (kWh) * 0.29544 US$/kWh + Peak demand (kW) * 5.6043 US$/kW* we can obtain the NGP averaged tariff at US$ 0.47394/kWh for 20 years.
(j) The fuel cell cost is about US$1.5 per watt and its overall efficiency is 75% (η_{fc} = 75%), annual O&M cost is 3% of total initial capital cost. H_2 consumption is about 29.78 g/kWh
(k) According to current market VRB cost structure, VRB cell capital cost model [6] is given in equation (12). The annual O&M cost is 2.5% of total initial capital cost

*US$1,750 * (kW rating) + US$560 * (kWh rating) + US$6,170* (12)

3. Optimal system design model

The optimal HPS shall provide lowest averaged electricity tariff, the optimal system design model is given as following.

$$(C_{kwh})_{lowest} = \underset{J=1}{\overset{N}{MIN}}\left\{ C_{kwhj} \right\} \qquad (13)$$

where,
N – Configuration number of simulated HPS
C_{kwhj} – the minimum cost of configuration j

In each HPS configuration, any changes in different energy will occur the change of final energy cost - C_{kwhj}, we can obtain the lowest energy cost through the numerical simulation by selecting different energy quantity. This is given in equation (14) below:

$$C_{kwhj}=(C_{at_1} + C_{at_2} + \cdots + C_{atn})/E_{hps} \qquad (14)$$

C_{ati} – total cost of energy generation i contributed in E_{hps}

IV. Results and Analysis

Using equation 1 and 3 to 12, we can simulate the HPS to optimally size for PVM, NGP, fuel cell and VRB-ESS. We adjust PVM, fuel cell and NGP, and use energy balance equation to calculate VRB capacity. Consequently, we obtain kW ration of VRB/NGP, FC/NGP and averaged tariff.

Table 1 to 4 and Figure 4 to 10 show the simulation results under different conditions that effect on averaged electricity tariff for HPS shown in figure 1.

Table 1 - Simulation result of HPS at Pg = 0kW

S/No.	Max Load (kW)	Peak PVM (kW)	Peak NGP (kW)	Fuel Cell (kW)	VRB (kW)	VRB (kWh)	Levelized tariff (US$/kWh)
1	96.14	43.0	0	115.69	0.00	0.00	0.19160
2	96.14	37.5	0	116.83	0.00	0.00	0.19044
3	96.14	32.5	0	117.87	0.00	0.00	0.18939
4	96.14	30.5	0	118.29	0.00	0.00	0.18897
5	96.14	27.5	0	120.02	0.00	0.00	0.18917
6	96.14	22.5	0	122.97	0.00	0.00	0.18955
7	96.14	17.5	0	125.92	0.00	0.00	0.18994
8	96.14	12.5	0	128.87	0.00	0.00	0.19032
9	96.14	7.5	0	131.83	0.00	0.00	0.19070
10	96.14	2.5	0	134.78	0.00	0.00	0.19109
11	96.14	0.0	0	136.37	0.00	0.00	0.19136

Table 2- Simulation result of HPS at Pg = 20kW

S/No.	Max Load (kW)	Peak PVM (kW)	Peak NGP (kW)	Fuel Cell (kW)	VRB (kW)	VRB (kWh)	Levelized tariff (US$/kWh)
1	96.14	43.0	20	87.32	0.00	0.00	0.24879
2	96.14	37.5	20	88.46	0.00	0.00	0.24763
3	96.14	32.5	20	89.50	0.00	0.00	0.24658
4	96.14	30.5	20	89.92	0.00	0.00	0.24616
5	96.14	27.5	20	91.65	0.00	0.00	0.24636
6	96.14	22.5	20	94.60	0.00	0.00	0.24674
7	96.14	17.5	20	97.55	0.00	0.00	0.24712
8	96.14	12.5	20	100.51	0.00	0.00	0.24751
9	96.14	7.5	20	103.46	0.00	0.00	0.24789
10	96.14	2.5	20	106.41	0.00	0.00	0.24828
11	96.14	0.0	20	108.00	0.00	0.00	0.24855

Table 3- Simulation result of HPS at Pg = 40kW

S/No.	Max Load (kW)	Peak PVM (kW)	Peak NGP (kW)	Fuel Cell (kW)	VRB (kW)	VRB (kWh)	Levelized tariff (US$/kWh)
1	96.14	43.0	40	58.95	0.00	0.00	0.30598
2	96.14	37.5	40	60.09	0.00	0.00	0.30482
3	96.14	32.5	40	61.13	0.00	0.00	0.30377
4	96.14	30.5	40	61.55	0.00	0.00	0.30335
5	96.14	27.5	40	63.28	0.00	0.00	0.30355
6	96.14	22.5	40	66.23	0.00	0.00	0.30393
7	96.14	17.5	40	69.18	0.00	0.00	0.30431
8	96.14	12.5	40	72.14	0.00	0.00	0.30470
9	96.14	7.5	40	75.09	0.00	0.00	0.30508
10	96.14	2.5	40	78.04	0.00	0.00	0.30546
11	96.14	0.0	40	79.63	0.00	0.00	0.30574

Table 4- Simulation result of HPS at Pg = 60kW

S/No.	Max Load (kW)	Peak PVM (kW)	Peak NGP (kW)	Fuel Cell (kW)	VRB (kW)	VRB (kWh)	Levelized tariff (US$/kWh)
1	96.14	43.0	60	30.58	0.00	0.00	0.36317
2	96.14	37.5	60	31.73	0.00	0.00	0.36201
3	96.14	32.5	60	32.76	0.00	0.00	0.36096
4	96.14	30.5	60	33.18	0.00	0.00	0.36054
5	96.14	27.5	60	34.91	0.00	0.00	0.36074
6	96.14	22.5	60	37.86	0.00	0.00	0.36112
7	96.14	17.5	60	40.82	0.00	0.00	0.36150
8	96.14	12.5	60	43.77	0.00	0.00	0.36189
9	96.14	7.5	60	46.72	0.00	0.00	0.36227
10	96.14	2.5	60	49.67	0.00	0.00	0.36265
11	96.14	0.0	60	51.26	0.00	0.00	0.36293

A. The averaged tariff is decreasing following fuel cell increasing. (Shown in Figure 4, 5 and 6).
B. All lowest averaged tariffs are obtained when VRB-ESS capacity is zero. This means that the VRB-ESS cost is major factor to affect its application in hybrid power system. (Shown in Table 1, 2, 3 and 4)
C. All lowest averaged tariffs are obtained when PVM power is 30.5kW. This means that the PVM cost is major factor to affect its application in hybrid power system and balance the averaged tariff (Shown in Table 1, 2, 3 and 4).
D. The NGP power affects significantly averaged tariff.
E. When Pg = 0kW, the averaged tariff is lowest, this is due to without peak demand. (Shown in table 1 and figure 7). This means that the peak demand shaving affects the averaged tariff is significant.
F. The averaged tariff is highest when NGP powers are 70kW (Shown in figure 7). This is due to minimum demand shaving benefit.
G. The averaged tariffs are increasing following NGP increasing (Shown in figure 7 and figure 10). This is because of that fuel cell cost is competitive and peak demand shaving.
H. Fuel cell affects significantly averaged tariff (Shown in Figure 4, 5, 6 and 7).

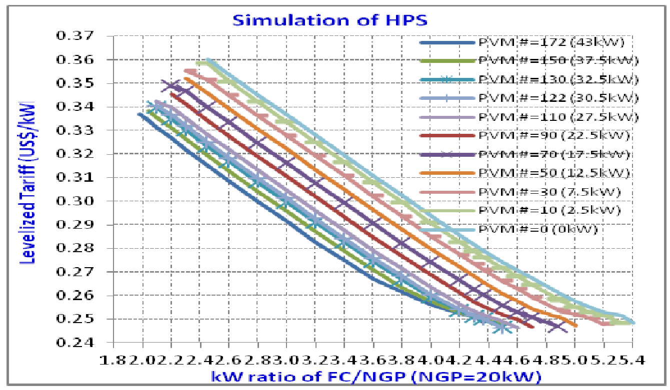

Figure 4 – Simulation result of HPS (Pg = 20kW) on averaged tariff (US$/kWh) vs kW ratio of FC/NGP

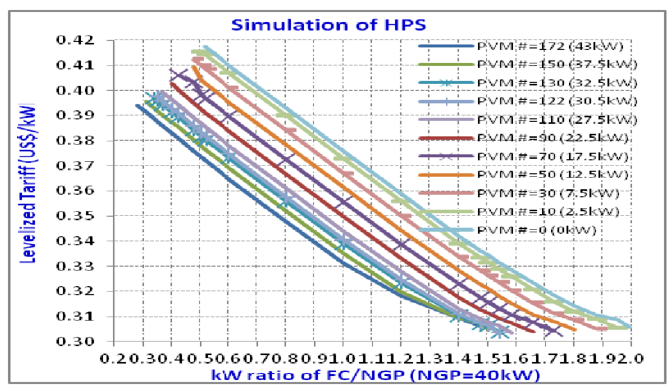

Figure 5 – Simulation result of HPS (Pg = 40kW) on averaged tariff (US$/kWh) vs kW ratio of FC/NGP

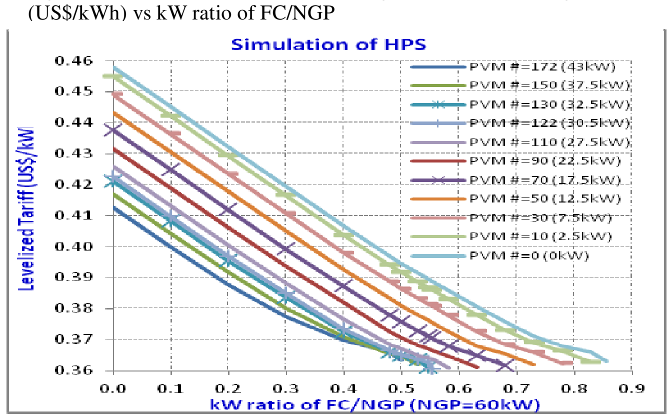

Figure 6 – Simulation result of HPS (Pg = 60kW) on averaged tariff (US$/kWh) vs kW ratio of FC/NGP

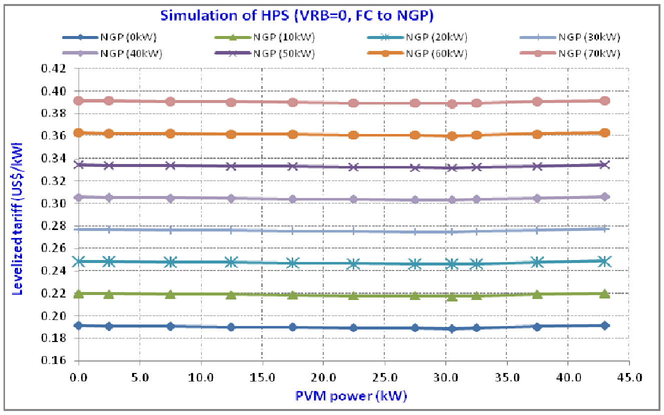

Figure 7 – Simulation result of HPS Averaged tariff vs PVM power

The figure 8 shows us that when kW ratio of VRB/Fuel cell is great 0.05, the averaged electricity tariff will increase following Fuel cell output decreasing (VRB/Fuel cell ratio is increasing), as well as the averaged electricity tariff will increase following solar PVM power decreasing, this means the solar PVM cost is reasonable to HPS; when kW ratio of VRB/Fuel cell is less 0.05, the averaged electricity tariff will increase following Fuel cell output decreasing (VRB/Fuel cell ratio is increasing), but the averaged electricity tariff will be bigger than others when solar PVM power is bigger. The 0.05 of the kW ration of VRB/Fuel cell is the kneed point of optimal cost. This result is shown in the figure 9.

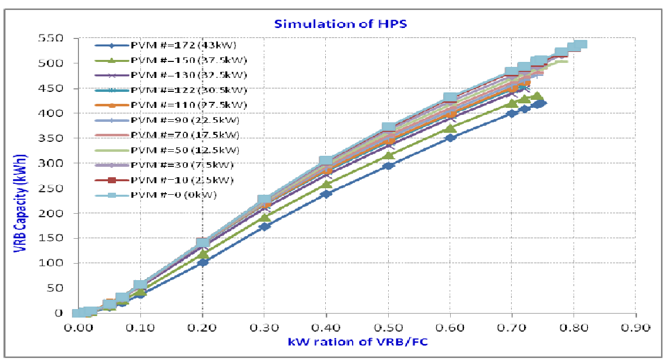

Figure 8 – Simulation result of HPS on averaged tariff (US$/kWh) vs kW ratio of VRB/Fuel cell (Pg=0kW)

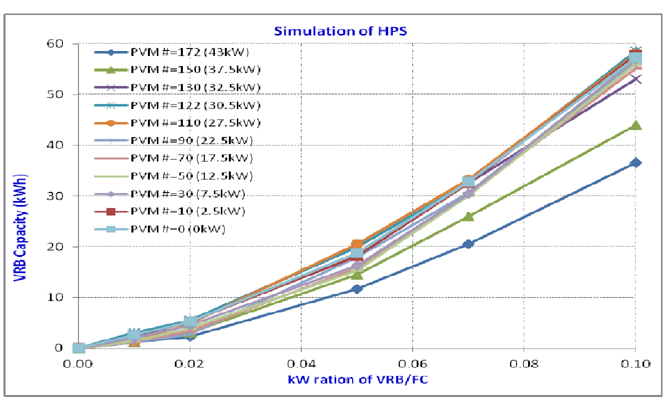

Figure 9 – Kneed point for HPS on averaged tariff (US$/kWh) vs kW ratio of VRB/Fuel cell (Pg=0kW)

The figure 10 shows that the averaged traffic is increasing with national grid power increasing. This result is due to competitive cost of fuel cell and maximum shaving of peak demand.

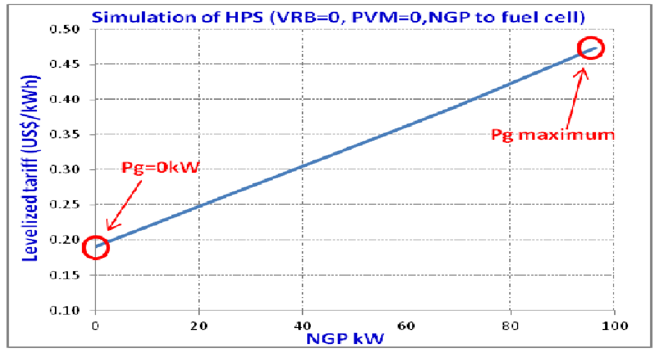

Figure 10 – Simulation result of HPS Averaged tariff vs NGP

From above ratiocination and demonstration, the HPSs have their own characteristics and each device can work together with each other in optimal way. The table 5 shows results for few different configurations of HPS. The numerical estimation results prove that the fuel cell has maximum economic performance contributing to those HPSs and is more economic competitive to other energy sources that are discussed in this paper, such as solar PVM and NGP.

Table 5 – Numerical simulation results

		NGP	VRB+NGP	HPS1	HPS2	HPS3	Building Load demand (kW)
NGP (kW)		96.14	95.50	81.02	X	0.00	96.14
VRB-ESS	kW	X	0.97	0.81	0.00	0.00	
	kWh	X	1.81	0.81	0.00	0.00	
PVM (kW)		X	X	43.00	0.00	30.50	
Fuel cell (kW)		X	X	X	136.37	118.29	
Levelized Tariff (US$/kWh)		0.47394	0.47150	0.44205	0.19136	0.18897	

For the building profile and present market information of VRB-ESS, Fuel cell, solar PVM and NGP, the optimal HPS consists of below specific components.

a) Solar PVM
   a. Quantity: 122
   b. Model: 250Wpp
   c. Total solar PVM installation: 30.5kW
b) NGP: 0 kW peak
c) Fuel cell: 118.29 kW
d) VRB-ESS: 0 kW / 0 kWh
e) Averaged tariff of the HPS: US$0.18897/kWh for 20 years

V. CONCLUSIONS

The hybrid power system can operate in optimal way through economical dispatch. In this paper conditions, the fuel cell has maximum economic performance contributing to the HPS and is more competitive to other energy sources that discussed in this paper, such as solar PVM and NGP.

The VRB-ESS can shave the peak demand and lower down the NGP averaged electricity tariff. The VRB-ESS can backup supply for critical loads when power generation systems are totally outage. Its cost shall be lowered down to increase its competitiveness.

VI. ACKNOWLEDGMENT

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