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ORIGINAL PAPER

Power Pinch Analysis supply side management: strategy on purchasing and selling of electricity

Wen Hui Liu[1,2] · Kabilen Kaliappan[1,2] · Sharifah Rafidah Wan Alwi[1,2] · Jeng Shiun Lim[1,2] · Wai Shin Ho[1,2]

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Abstract Pinch analysis concept has been recently stepped into the realm of design and optimisation of power systems. One well-established pinch analysis that has been used in power systems design and optimisation is called Power Pinch Analysis (PoPA). In PoPA, both graphical and numerical approaches have provided an insight on the systematic approach to target and design various power systems. By only visualising the minimum amount of outsource energy required by the power system, the graphical PoPA method as a whole does not show the purchasing of outsource energy based on the exact time intervals. Using graphical PoPA, the objective of this study is to determine a proper strategy to buy and sell outsource electricity to improve the overall performance of a hybrid power system comprising renewable power generators and energy storage system. The strategies are made based on three design parameters: energy-related capacity, power-related capacity of energy storage and maximum grid power rating between centralised grid and hybrid power system. While deciding on the best strategy and heuristics to be implemented, the effects on system operation and economy are indirectly analysed. It is experimented that the output can benefit electricity consumers or producers.

Keywords Power Pinch Analysis · Electricity · Hybrid power system · Optimisation

Abbreviations

AC	Alternating current
AEEND	Available excess electricity for next day
AF	Amortised factor
CPCC	Continuous power composite curve
DC	Direct current
DCC	Demand composite curve
EG	Total grid energy (purchased/sold)
ERC	Energy-related capacity
ES	Energy storage
ESCA	Electric system cascade analysis
FiT	Feed-in tariff
GCC	Grand composite curve
GPR	Maximum grid power rating
HPS	Hybrid power system
MOES	Minimum outsourced electricity supply
O&M	Operating and maintenance
PA	Pinch analysis
PCC	Power composite curve
PCT	Power Cascade Table
PoPA	Power Pinch Analysis
PP	Power pinch point
PRC	Power-related capacity
RE	Renewable energy
SAHPPA	Stand-alone hybrid system power pinch analysis
SCC	Source composite curve
SCT	Storage Cascade Table

✉ Wai Shin Ho
hwshin@utm.my; shasha@cheme.utm.my

[1] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia

[2] Process Systems Engineering Centre (PROSPECT), Research Institute of Sustainable Environment (RISE), Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia

Development of Power Pinch Analysis

Pinch analysis (PA) in the earliest stage was proposed to design an optimal heat exchange network for process industry. PA concept was first published in a Journal by Linnhoff and Flower (1978). The 'red' book of Heat Integration was later published by Linnhoff et al. (1982) which was referenced by many researchers. PA was subsequently emerged and adapted in different fields, including mass pinch (El-Halwagi and Manousiothakis 1989), water pinch (Wang and Smith 1994), total site heat integration (Klemeš et al. 1997), oxygen pinch (Zhelev and Ntlhakana 1999), hydrogen pinch (Alves and Towler 2002), production planning (Singhvi and Shenoy 2002), financial management (Zhelev 2005), energy analysis (Zhelev and Ridolfi 2006), carbon pinch (Tan and Foo 2007), biomass supply chain (Lam et al. 2010) and power pinch (Wan Alwi et al. 2012). Detailed work reporting on PA development can be found in Klemeš and Kravanja (2013). Another recent PA contribution has emerged as Waste Management Pinch Analysis (Ho et al. 2016). In short, PA has been widely used in synthesising a resource integration, recovery and conservation network.

The application of PA has also stepped into the realm of design and optimisation of power systems. Both graphical and numerical approaches provide a systematic approach to target and design power systems. Bandyopadhyay (2011) proposed a PA-based method to target and design an isolated energy system (coupling solar photovoltaic and battery system), by plotting the stored energy versus time in a grand composite curve (GCC). Wan Alwi and the team developed the graphical method known as power pinch analysis (PoPA) by introducing graphical tools like power composite curve (PCC), continuous PCC (CPCC) (Wan Alwi et al. 2012) and outsourced and storage electricity curves (Wan Alwi et al. 2013) that plot the time versus electricity for both power source and demand. The developed tool is able to target the minimum outsource electricity requirement for a readily designed Hybrid Power System (HPS) during the start-up and the 24-h continuous operation. However, efficiency losses were neglected. Ho et al. (2012) developed a numerical tool known as Electric System Cascade Analysis (ESCA) that determines the optimal capacity of power generators and energy storage (ES) system (energy-related capacity, ERC and power-related capacity, PRC), for a grass-root design of distributed energy generation system while taking into consideration on efficiency losses. ESCA generally focused on an off-grid system without energy outsourcing. The work by Ho et al. (2012) was initially done for a non-intermittent power system, but later ESCA was applied in a power system involving intermittent sources (Ho et al. 2014a).

By adapting the cascade table of ESCA (Ho et al. 2012), Mohammad Rozali et al. (2013a) then proposed a numerical method known as Power Cascade Table (PCT) and Storage Cascade Table (SCT) for a readily designed power system [similar to that by Wan Alwi et al. (2012)] as an extension of the previous studies, yet efficiency losses were again neglected. The method then included additional efficiency losses (self-discharge rate of ES) other than those previously discussed (inverter efficiency losses, charging and discharging efficiency losses) in Mohammad Rozali et al. (2013b). Mohammad Rozali (2013b) also included the coupling of alternating current (AC) and direct current (DC) in the HPS. Not only did PoPA improved in optimising power allocation and sizing of ES system, but the method itself also adapted the optimal design and sizing of renewable energy (RE) generators (Mohammad Rozali et al. 2014) which aimed to achieve a cost-effective HPS. The economy performance of HPS was again studied by introducing load-shifting method (Mohammad Rozali et al. 2015) which has the effect in reducing the maximum power demand of the HPS. In a recent work, Extended PoPA (Esfahani et al. 2015) was introduced to enhance the operability of HPS by storing excess hydrogen based energy in a hydrogen storage.

Ho et al. (2014b) introduced stand-alone hybrid system power pinch analysis (SAHPPA) as an enhancement to the graphical presentation (demand composite curve, DCC and source composite curve, SCC) by Wan Alwi et al. (2012). SAHPPA considers both intermittent and non-intermittent sources and all possible efficiency losses along the energy transmission system. Through graphical and mathematical formulation approaches, the capacities of power generators and ES involved in the designated grid HPS can be determined in SAHPPA. A summary of the aforementioned PA methods in power systems is tabulated in a chronological manner (Table 1).

Graphical presentation of PoPA (Wan Alwi et al. 2012) gives a macro-visualisation insights to the overall operation of the HPS but it cannot tell the exact flow of electricity between the units in a micro-scale, presented in the numerical method of PoPA (Mohammad Rozali et al. 2013a). From the numerical PoPA approach, it was suggested that electricity should be bought from the centralised grid or diesel generator; however, the exact timing for outsource electricity was not discussed. The choice of when to buy outsource electricity is an important factor to consider, as it will affect the overall design and costing of the power system. For example, buying electricity in a large sum requires larger power from the grid and generator which would increase the cost. As discussed by Ho et al. (2012) during the designing stage, it is also important to consider both the ERC and PRC of ES which are also affected by the trend of buying and selling of electricity.

Table 1 Summary for PA development in power systems' design and optimisation

Analysis tool	Graphical/ numerical	Grid connected	Type of renewable energy (intermittent/non-intermittent)	Inverter efficiency	Battery charging/ discharging efficiency	Self-discharge rate	Depth of discharge	AC–DC coupling	Maximum energy-related capacity for energy storage	Maximum power-related capacity for energy storage	Optimal power generator capacity	Optimal inverter capacity
Adapted GCC (Bandyopadhyay 2011)	Graphical	Off-grid	Intermittent	Yes	Yes	No	No	No	Yes	Yes	No	No
PCC and CPCC (Wan Alwi et al. 2012)	Graphical	Both	Both	No	No	No	No	No	Yes	No	No	No
ESCA (Ho et al. 2012)	Numerical	Off-grid	Non-intermittent	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No
PCT and SCT (Mohammad Rozali et al. 2013a)	Numerical	Both	Both	No	No	No	No	No	Yes	No	No	No
Modified SCT (Mohammad Rozali et al. 2013b)	Numerical	On-grid	Both	Yes	Yes	Yes	No	Yes	Yes	No	No	No
ESCA (Ho et al. 2014a)	Numerical	Off-grid	Intermittent	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes
SAHPPA (Ho et al. 2014b)	Both	Off-grid	Both	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No

Load shifting directly manipulates the demand side energy demand. It is expected that through supply side management (made possible with the integration of energy storage), substantial improvement can be achieved.

This paper aims to introduce strategies to buy and sell the electricity (supply side management) of an on-grid HPS at designated time intervals, which addresses the gap in the existing PoPA method by Wan Alwi et al. (2012) and Mohammad Rozali et al. (2013a). This study also aims to further improve on the grid management connecting to HPS, as well as the system design and economic performance. Taking into account medium-sized industry and a fixed tariff, different scenarios will be demonstrated to compare and suggest the best strategy to be implemented.

Hybrid power system model

As illustrated in Fig. 1, an on-grid HPS system supported with ES system is the model considered in this study. The installation of ES (using lithium-ion battery) ensures consistent power supply to demand. Two RE generators are considered: solar photovoltaic module and biomass generator. The energy demand comes from machinery power consumption in a typical medium-sized Malaysian industry.

In the planning and scheduling of the HPS electricity flow, a few heuristics are obeyed. Power generated from RE sources will be transferred firstly to demand, before going to the ES. When the power supply exceeds the demand (system surplus) at a certain point of time, the excess power will be charged into ES. When the demand exceeds the supply (system deficit), the instantaneous excess power required will be discharged from ES. The grid power is considered next. The purchasing or selling of electricity between the grid network and HPS is dependent on scenarios (system surplus or deficit) that the strategies introduced in this paper will decide when and how much kilowatts of electricity should be bought or sold. Finally, when the system demand is met from three sources (RE generator, ES and grid), the excess content in ES will be sold to the grid or vice versa, excess grid power will be stored into ES. The symbols shown in Fig. 1 are the parameters to be identified when performing the methodology and they will be explained in "PoPA methodology" section.

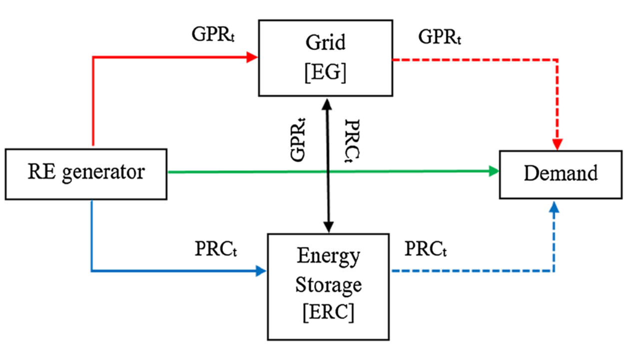


Fig. 1 The HPS model used for demonstrating strategies proposed in this paper

The assumptions made in demonstrating this model include the following:

(i) The current type involved in the overall HPS is the same, i.e. AC. No conversion is needed.
(ii) There is no efficiency loss when energy is transferred from one point to another.
(iii) The energy consumption and supply repeat the same pattern every 24 h.

Methodology

To optimise a HPS, one must first know how to perform the conventional PoPA method in order to determine the variables: energy-related capacity (ERC) and power-related capacity (PRC) of the ES system before determining the timely outsource energy from the grid, namely grid power rating (GPR). This is demonstrated in "PoPA methodology" section. "Strategies to purchase grid electricity" section explains the strategies to be applied to obtain optimal ERC, PRC and GPR. "Calculation for system costing" section shows the calculation to analyse the economic performance of the HPS based on the three decision variables (ERC, PRC and GPR) determined. The results from three strategies are compared and the best strategy is selected.

PoPA methodology

In order to perform PoPA, two sets of data defining the power system's operation namely the power source and power demand including their respective power rating and operational time are required. Both power source and demand are plotted into a cluster of time–energy curves as shown in Fig. 2. The SCC and DCC are constructed by summing up the respective electricity source and demand including its power rating. With the DCC begins at the origin of the axis, the SCC is adjusted to the right such that it would touch the DCC (with DCC being on the left side) at a point called the Power Pinch Point (PP), forming a PCC as illustrated in Fig. 3. A more detailed description on the graphical PoPA method can be found in the original work of Wan Alwi et al. (2012).

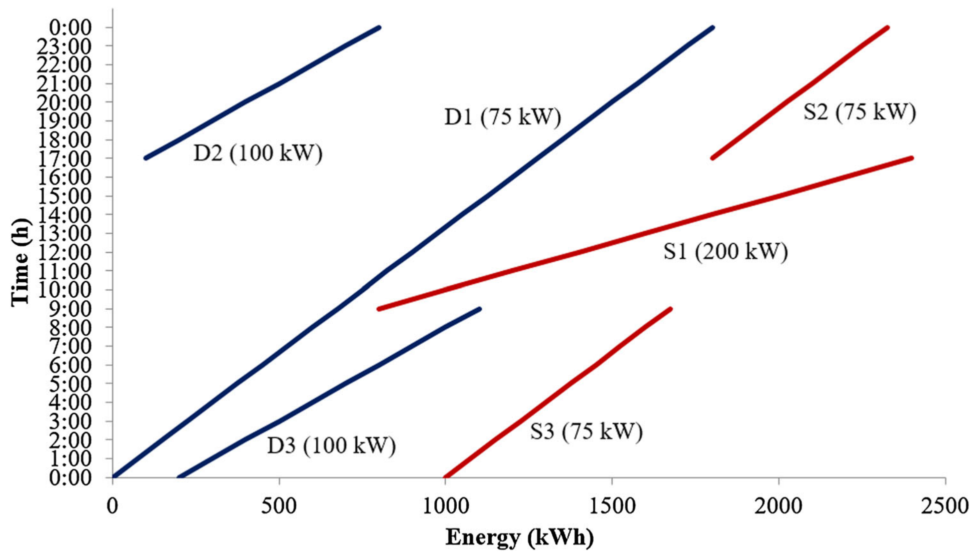


Fig. 2 Examples of individual supply and demand curves and their respective power ratings

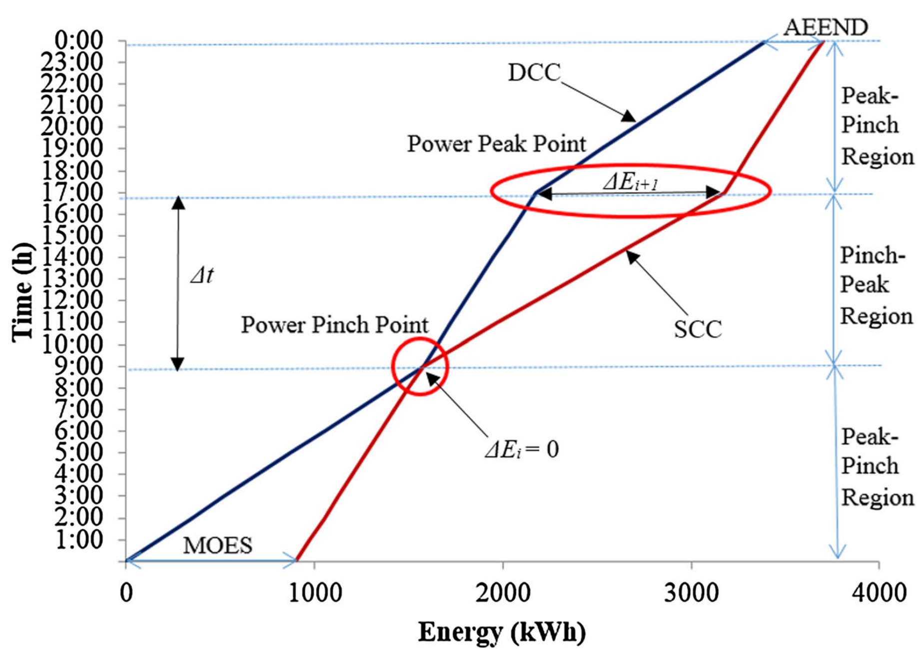


Fig. 3 Example of PCC

From Fig. 3, the design parameters can thus be extracted:

(i) Minimum outsourced electricity supply (MOES)

The energy difference at time 00:00 indicates the amount of start-up energy required at the beginning of the day to ensure the stability of the system.

(ii) Available excess electricity for next day (AEEND)

The energy difference at time 24:00 indicates the excess energy of the system at the end of the day. This excess electricity can be used to supply for the system's energy insufficiency indicated by the MOES of the following day. However, if the excess exceeds the requirement of the MOES, these energy are either sold or dumped to prevent accumulation in storage (Mohammad Rozali et al. 2013a).

(iii) Total grid energy (EG)—the sum of net outsource energy being bought from or sold to the grid

$$\mathrm{EG} = \mathrm{MOES} - \mathrm{AEEND}, \tag{1}$$

where positive value is the amount of electricity to be bought (MOES > AEEND), while negative value is the amount to be sold (AEEND > MOES).

(iv) Power pinch point (PP)—indicates the time when the ES contains minimal amount of energy

(v) Energy-related capacity of the energy storage (ERC)

Difference between DCC and SCC is the largest at one point of time, indicating the energy level of the ES at that time is the maximal. ERC is also known as power peak point as shown in Fig. 3.

(vi) Power-related capacity of the energy storage (PRC)

Operating power of ES can be calculated by identifying the changes in energy level of ES from one time interval to another. Equation (2) shows the formulation to calculate the power of charging/discharging, P. The change in energy level of the ES, ΔE and the time duration of the corresponding time interval, Δt can be extracted from the graph (Fig. 3).

$$P = \frac{\Delta E_{i+1} - \Delta E_i}{\Delta t} \quad (2)$$

It is noted that negative P indicates discharging, while positive P indicates charging. PRC is the largest magnitude of P.

This study introduced the maximum grid power rating, GPR as one important parameter to be applied in the strategies proposed in the next section. GPR is defined as the maximum power demand that a system outsources from the grid utility at one time interval. Unlike total grid energy, EG is a constant value for a particular case study of fixed supply and demand data, GPR on the other hand is a user-defined parameter. This means the value changes according to the range of time interval used to distribute the amount of electricity bought from the grid. The relationship between GPR and the distribution time range is inversely proportional. Hence GPR becomes a critical parameter in a system design and optimisation.

Strategies to purchase grid electricity

Strategy 1: To achieve minimal centralised grid power rating, GPR

In order to achieve minimal centralised GPR, energy should be bought equally throughout the day. For example, a system is in need of an additional 240 kWh of energy at a certain point of time, if the energy is bought in an instant, power rating of 240 kW is required. If it is distributed over a period of 24 h, only a power rating of 10 kW is required, which shows a significant reduction in power rating. The new SCC as an effect of this strategy is shown in Fig. 4.

As observed from Fig. 4, due to equal distribution of the net system energy over the operation period, the new MOES has similar value with the new AEEND. This will smoothen the system operation from 1 day to the following day. Yet the reduction of GPR might cause increment in ERC and PRC that would indirectly affect the system's economy performance. However, in a long run, the cost saving from GPR reduction effect is still able to make this strategy cost-effective.

Strategy 2: To achieve minimal energy-related capacity, ERC

As previously discussed, the ERC is determined where the difference between the DCC and SCC is the largest, mainly as a result of net energy charged in the pinch-peak region. If electricity has to be bought, it should be done in the peak-pinch region as that is the region with net energy deficit. Depending on the location of the ERC (either above or below Pinch), different strategies of buying are applied.

(i) Purchasing of electricity with ERC below Pinch

In cases where electricity has to be bought where the ERC is below Pinch, it should be done closest to and below the PP as it will have a continuous domino effect down to the MOES thus reducing the ERC. From the pre-determined EG, grid power is purchased at the exact amount with the system demand at the time intervals right below PP, in a consecutive manner. Take Fig. 5 for instance, the purchase of electricity is done firstly at time interval between 11:00 and 12:00, then 10:00 and 11:00, 9:00 and 10:00 and so on, until the last net energy is being bought from the grid to the system demand. It can be observed that DCC touches SCC at multiple continuous PPs at a range of time intervals and ERC below PP is reduced. In Fig. 5, new ERC equals to new MOES.

(ii) Purchasing of electricity with ERC above Pinch

In cases where electricity has to be bought where the ERC is above Pinch, there are no specific rules on how the electricity should be bought as there is no possible way to further reduce the ERC.

Strategy 3: To achieve minimal power-related capacity, PRC

Minimisation of PRC requires users to firstly determine the charging and discharging power of the system at each time interval. Grid electricity then should be bought within the time interval where the discharging power magnitude is the largest. Once the power has been reduced to the magnitude equal to the second largest discharging power of the system, the remaining of net system electricity should then be bought equally in all the discharging zones (including PP) and this will simultaneously reduce the GPR. A GCC as shown in Fig. 6 is used as Strategy 3 illustration. Positive

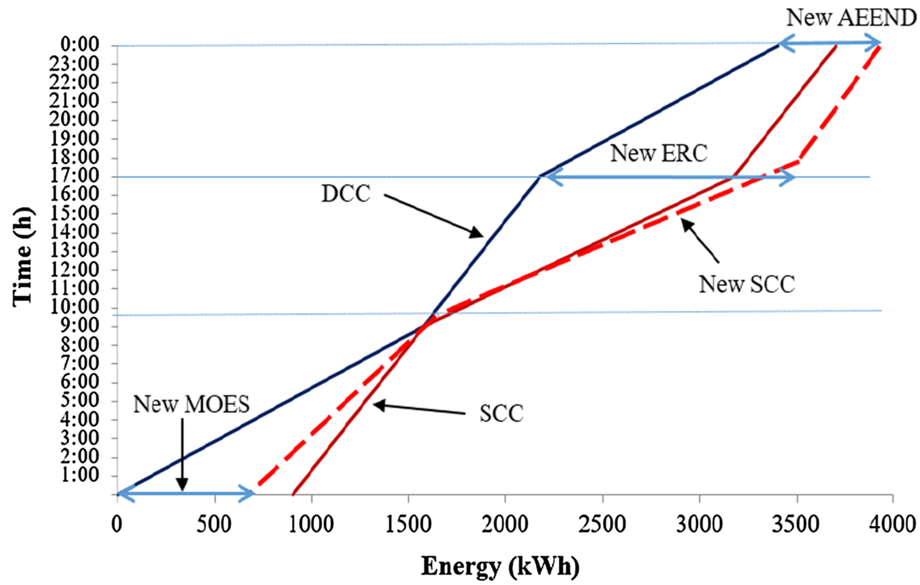


Fig. 4 New SCC after Strategy 1 is implemented to achieve minimal GPR in an electricity buying case scenario

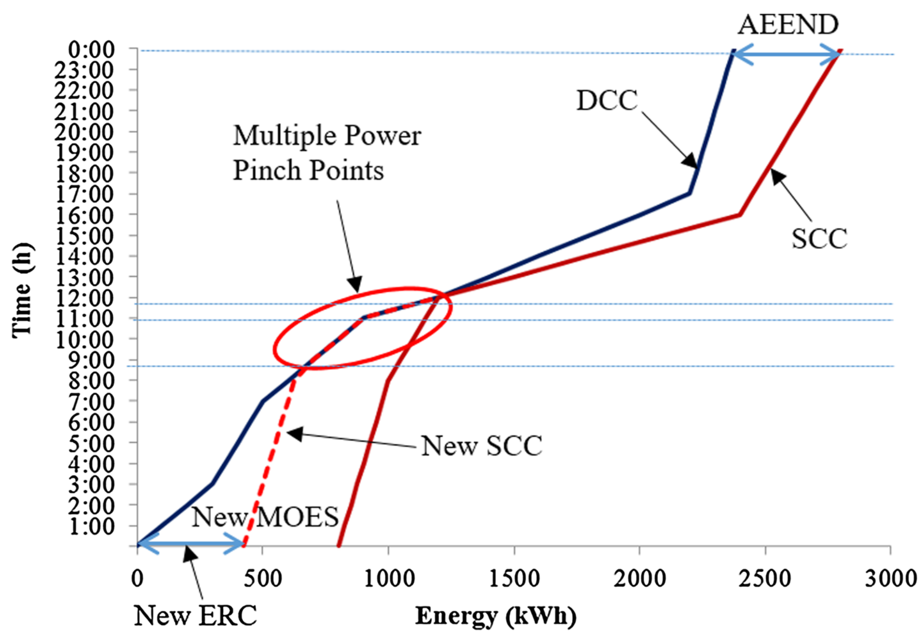


Fig. 5 New SCC after Strategy 2 is implemented to the case of purchasing electricity with ERC below *Pinch*

slope in the GCC indicates charging state of ES, whereas negative slope indicates discharging state of ES. The steeper the slope at one time interval means the larger power rating at that charging or discharging period. The strategy of minimising PRC will alter the steepness of the slopes and the range of the electricity in the ES (y-axis of GCC).

Corresponding to that, electricity should be bought only at time of discharging (difference between DCC and SCC decreases with time). If electricity has to be bought but the PRC is that of charging, no reduction is then possible.

Calculation for system costing

One objective of the study is to minimise cost for the overall HPS power management via the strategies proposed. Costing is presented as the annualised cost of the system. In order to compare how the three strategies affect the economy performance of the HPS, the generator's cost is ignored here. The costing in this study is only analysed based on the extension of outsource energy and ES whereby the following two factors are considered:

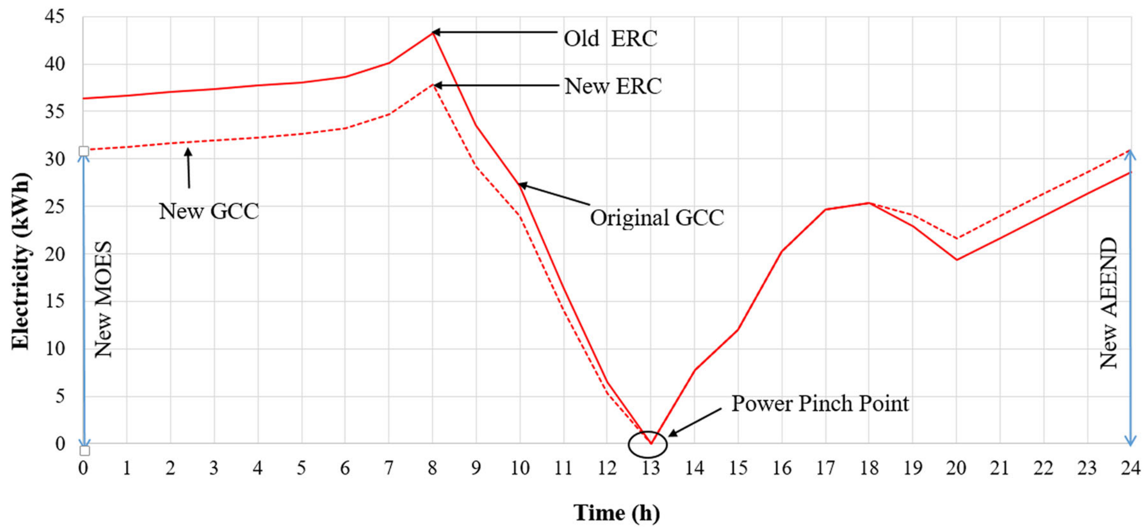


Fig. 6 GCC showcasing the operating state in an ES system

(i) Energy from grid and grid power rating

$$\text{Cost of billing, } C_1 = [(\text{EG} \times \text{PEG} \times 30\text{ day}) + (\text{GPR} \times \text{PGPR})] \times 12\text{ months}, \quad (3)$$

where

EG is the total grid energy purchased per day (kWh/day) calculated from Eq. (1);

PEG is the rate charged for each kWh purchased (RM/kWh);

GPR is the maximum power rating supplied from the grid (kW) and

PGPR is the rate charged for each kW of GPR per month (RM/kW month).

Cost of billing is calculated based on TNB Tariff E1 (as shown in Table 5).

(ii) Energy storage

$$\begin{aligned}\text{Cost of ES, } C_2 &= \text{ERC cost} + \text{PRC cost} + \text{O\&M cost} \\ &= (\text{ERC} \times \text{PERC} + |\text{PRC}| \times \text{PPRC}) \\ &\quad \times \text{AF} \times 12\text{ months} + |\text{PRC}| \times \text{PO\&M}\end{aligned} \quad (4)$$

Cost of ES is the sum of three variable costs which are ERC cost, PRC cost and O&M cost, where

ERC is the energy-related capacity of an ES system (kWh);

PRC is the power-related capacity of an ES system (kW);

PERC is the cost of each kWh storage capacity of an ES system (RM/kWh);

PPRC is the cost of each kW power flow capacity of an ES system (RM/kW);

PO&M is the fixed cost of operation and maintenance of an ES system (RM/kW) and

AF is the amortised factor based on the number of years of instalment and interest rate charged.

The total annualised cost used to compare the three strategies proposed in this study is

$$\text{Total cost, } C = C_1 + C_2. \quad (5)$$

Case study demonstration

Two illustrative case studies are used to demonstrate the strategies of purchasing electricity proposed in this study. The strategies target to enhance technicality of grid power connecting to HPS as well as to minimise the overall system costing. The case studies are designated so that each represents a different case scenario to perform the strategies in a holistic way.

Case Study 1: Purchasing of electricity from grid with ERC below Pinch

Case Study 2: Purchasing of electricity from grid with ERC above Pinch

As mentioned earlier, two types of intermittent and non-intermittent sources, which are solar and biomass energy, are chosen for this study. Also the power demand comes from the equipment consumptions from a medium-sized industry in Malaysia. The power source data for both case studies are shown in Table 2, and the demand data for both case studies are shown, respectively, in Tables 3 and 4. Electricity consumed is calculated using Eq. (6).

$$\text{Electricity consumption (kWh)} = \text{Power rating (kW)} \times \text{Time interval (h)} \quad (6)$$

In this study, Malaysian grid utility rates are applied to the HPS model and are listed in Table 5. A Lithium-ion

Table 2 Electricity generation data in hourly basis

Time, h	Electricity generation, kWh	
	Biomass	Solar
00:00–01:00	13.33	0
01:00–02:00	13.33	0
02:00–03:00	13.33	0
03:00–04:00	13.33	0
04:00–05:00	13.33	0
05:00–06:00	13.33	0.26
06:00–07:00	13.33	1.17
07:00–08:00	13.33	2.82
08:00–09:00	13.33	3.90
09:00–10:00	13.33	7.27
10:00–11:00	13.33	6.99
11:00–12:00	13.33	7.77
12:00–13:00	13.33	11.17
13:00–14:00	13.33	11.40
14:00–15:00	13.33	7.94
15:00–16:00	13.33	11.96
16:00–17:00	13.33	8.08
17:00–18:00	13.33	4.29
18:00–19:00	13.33	1.26
19:00–20:00	13.33	0.09
20:00–21:00	13.33	0
21:00–22:00	13.33	0
22:00–23:00	13.33	0
23:00–24:00	13.33	0

(Li-ion) battery which has a 5-year lifecycle is used and the price for each parameter is also listed in Table 5. An amortised factor (AF) of 2.13×10^{-2} is taken based on a 10 % interest rate.

Results and discussion

Extracted from both PCC and GCC, the determined parameters for Case Study 1 are tabulated in Table 6, while Case Study 2 in Table 7. For all three strategies, the resultant MOES and AEEND are observed to have the same final value after each strategy is implemented. For instance in Case Study 1, the MOES and AEEND resulted from conventional PoPA methodology before the strategies are implemented are 36.38 and 28.65 kWh (Table 6). After Strategy 1, the new MOES has the equivalent 32.19 kWh with the new AEEND. For Strategy 2, the new MOES and AEEND are the same, which is 28.65 kWh, while for Strategy 3, the new MOES and AEEND are both recorded as 30.97 kWh.

Determination of optimal parameters from strategies of purchasing of electricity

Case Study 1: Purchasing of electricity from grid with ERC below Pinch

The net energy of Case Study 1 has an insufficiency of 7.73 kWh (MOES − AEEND); therefore, this amount of electricity has to be purchased from the grid. When the PCC of original PoPA is plotted (Fig. 7a), the PP occurs at 13:00 and the ERC is positioned below the Pinch (peak-pinch region). The extracted data from Fig. 7a (conventional PoPA) are (a) EG = 7.73 kWh; (b) ERC = 43.27 kWh (at 8:00) and (c) PRC = 10.68 kW (discharging at 11:00). In this case study, all the three strategies proposed in “PoPA methodology” section can be applied. The results are shown in Fig. 7b (Strategy 1), Fig. 7c

Table 3 Electricity demand from four different machineries for Case Study 1

Machinery	Time, h		Time interval, h	Power rating, kW	Electricity consumption, kWh
	From	To			
D1	00:00	10:00	10	13	130
D2	08:00	13:00	5	14	70
D3	10:00	20:00	10	17	170
D4	20:00	24:00	4	11	44

Table 4 Electricity demand from four different machineries for Case Study 2

Machinery	Time, h		Time interval, h	Power rating, kW	Electricity consumption, kWh
	From	To			
D1	00:00	10:00	10	15	150
D2	08:00	20:00	12	12	144
D3	12:00	16:00	4	12.5	50
D4	20:00	24:00	4	17	68

Table 5 Price list of grid utility and ES used in this study

	Unit	Price
Grid utility[a]		
Total grid energy, PEG	RM/kWh	0.337
Maximum grid power rating in a month, PGPR	RM/kW	29.60
Energy storage (Li-ion battery)[b]		
Energy-related capacity, PERC	RM/kWh	3794.74
Power-related capacity, PPRC	RM/kW	2210.02
Operating and maintenance, PO&M	RM/kW.y	32.94

[a] Tariff E1: medium voltage general industrial tariff (TNB Malaysia 2016)

[b] Source: Zakeri and Syri (2015)

Table 6 Results of Case Study 1

Parameter	PoPA	Strategy 1	Strategy 2	Strategy 3
Minimum outsourced electricity supply, MOES (kWh)	36.38	32.19	28.65	30.97
Available excess electricity for next day, AEEND (kWh)	28.65	32.19	28.65	30.97
Total grid energy (purchase), EG (kWh)	7.73	7.73	7.73	7.73
Grid power rating, GPR (kW)	–	0.32	7.73	1.16
Energy-related capacity, ERC (kWh)	43.27	41.66	35.54	37.85
Power-related capacity, PRC (kW)	−10.68	−10.36	−10.68	−9.90

Table 7 Results of Case Study 2

Parameter	PoPA	Strategy 1	Strategy 2	Strategy 3
Minimum outsourced electricity supply, MOES (kWh)	25.29	22.90		21.86
Available excess electricity for next day, AEEND (kWh)	19.56	22.90	N/A	21.86
Total grid energy (purchase), EG (kWh)	5.73	5.73		5.73
Grid power rating, GPR (kW)	–	0.24		0.38
Energy-related capacity, ERC (kWh)	34.24	36.63		35.01
Power-related capacity, PRC (kW)	−9.77	9.65		−9.41

(Strategy 2) and Fig. 7d (Strategy 3). All the related parameters and their values are reported in Table 6.

For Strategy 1 (minimal GPR), 7.73 kWh of energy is bought equally and consistently in 24 h that reduces the GPR to 0.32 kWh. The strategy has also minimised the size of ERC to 41.66 kWh and PRC to 10.36 kW.

For Strategy 2 (minimal ERC), all the net energy (7.73 kWh) has been bought at one interval time (12:00) below the Pinch to achieve minimal ERC. The domino effect of this strategy has successfully decreased the size of ERC to 35.54 kWh. However, the PRC value remains unchanged.

For Strategy 3 (minimal PRC), the largest ES power (PRC) happens at 10:00–11:00 time interval with a discharging capacity of 10.68 kW. Based on the second largest magnitude of ES power in the system, it has been reduced to 9.90 kW, with 0.78 kW purchased at time interval 10:00–11:00. The rest of the net energy of the system (excluding the 0.78 kW bought) has been bought in an equal amount of 1.16 kW among all the discharging zones. The strategy has simultaneously reduced the GPR to be 1.16 kW and ERC to be 37.85 kWh.

The grid electricity purchasing pattern for each strategy is illustrated in Fig. 8.

Case Study 2: Purchasing of electricity from grid with ERC above Pinch

In Case Study 2, since MOES is larger than AEEND, that means there is a deficit of 5.73 kWh of energy in the system which has to be purchased from the grid. According to the original PCC plotted in Fig. 9a, the PP occurs at 10:00 and the ERC is positioned above the Pinch (Pinch-Peak Region). The extracted data from Fig. 9a (conventional PoPA) are (a) EG = 5.73 kWh; (b) ERC = 34.24 kWh (at 20:00) and (c) PRC = 9.77 kW (discharging at 9:00). In this case study, only Strategy 1 and 3 are

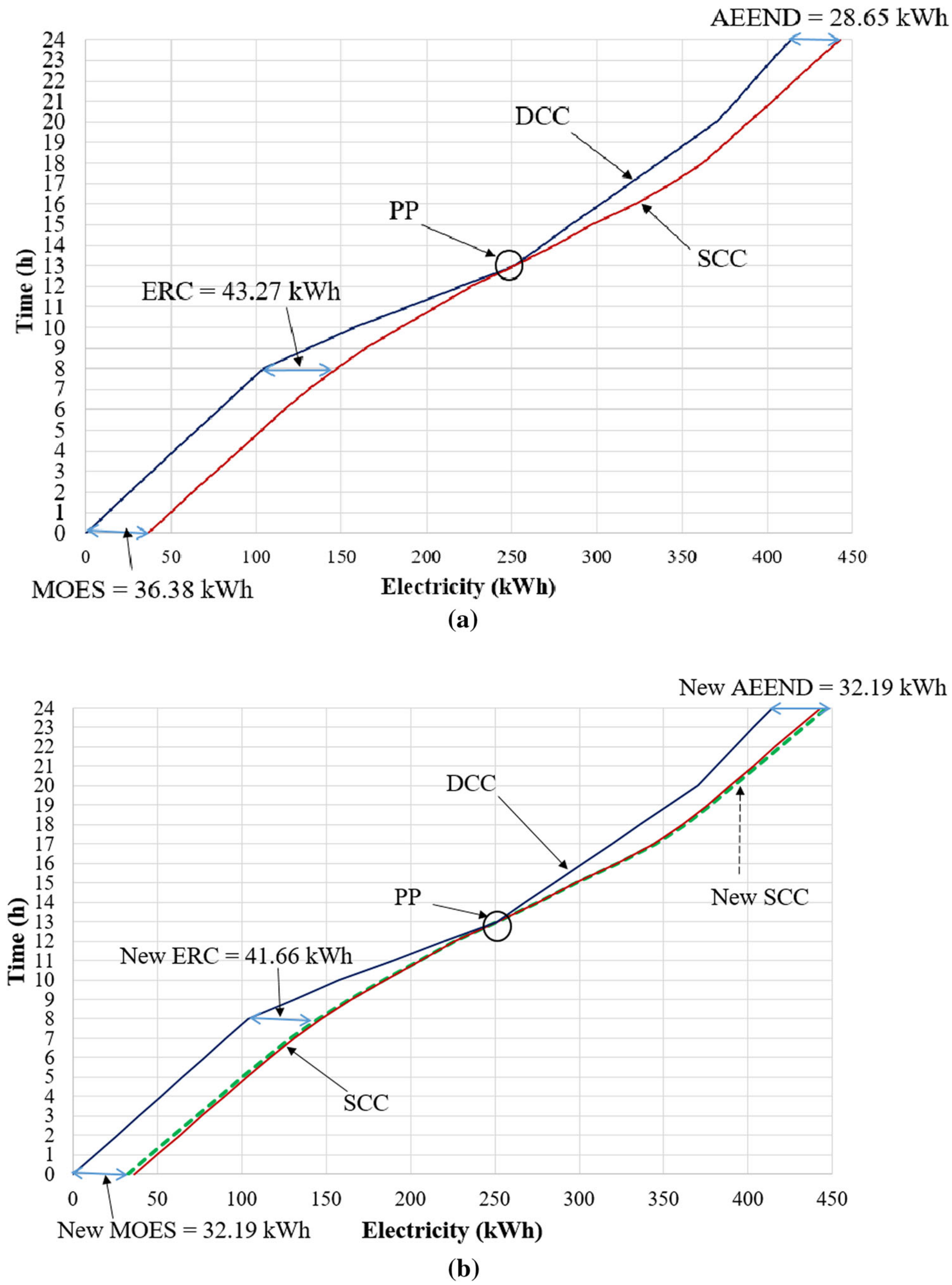


Fig. 7 Graphical output for Case Study 1: **a** PCC from PoPA method; **b** New SCC in PCC after Strategy 1; **c** New SCC 2 in PCC after Strategy 2; **d** GCC comparison after Strategy 3

applicable. The results are shown in Fig. 9b (Strategy 1), Fig. 9c (Strategy 3). The values of all the related parameters are recorded in Table 7.

After the implementation of Strategy 1 (minimal GPR), the new GPR is determined as 0.24 kWh. Unlike Case Study 1, the ERC has been increased to 36.63 kWh. There is a slight decrease for PRC and it happens at charging state at 17:00.

Strategy 2 (minimal ERC) cannot be applied in Case Study 2 as ERC is above Pinch, the purchase of electricity to the system will enlarge the resultant ERC.

For Strategy 3 (minimal PRC), the largest ES power (PRC) happens at 8:00–9:00 time interval with a discharging capacity of 9.77 kW. This value has been reduced to 9.41 kW, which is the second largest magnitude of ES power in the system, by purchasing a total power of 0.36 kWh at time interval 8:00–9:00. The remaining of the net energy of the system (excluding the 0.36 kW bought) has been bought in an equal amount of 0.38 kW in all the discharging zones. The strategy has simultaneously reduced the GPR to be 0.38 kW and increased ERC to be 35.01 kWh.

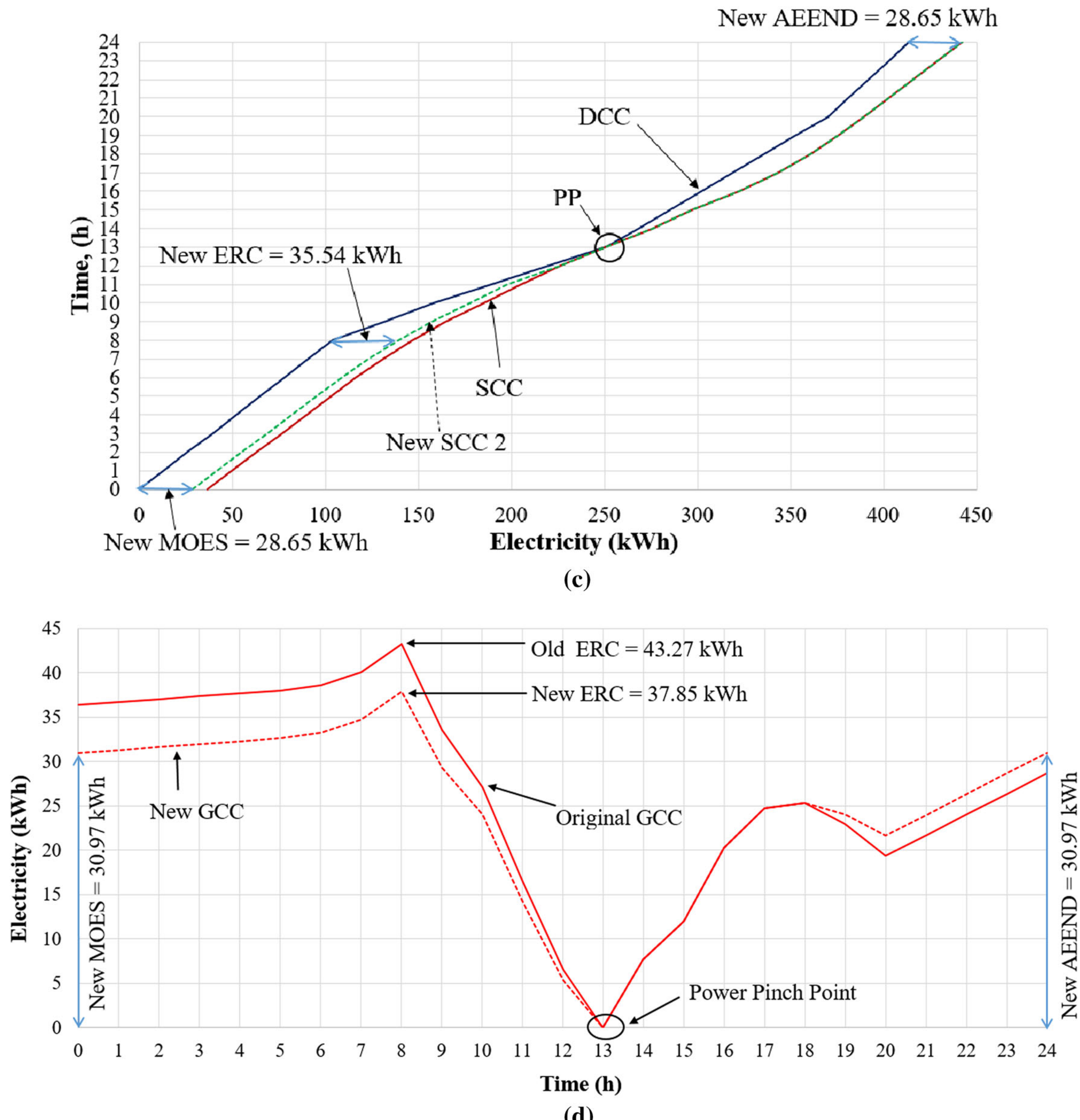


Fig. 7 continued

The grid electricity purchasing pattern for each strategy is illustrated in Fig. 10.

Economical analysis

As described in "Calculation for system costing" section, the costing calculations for outsourced energy and ES as to reflect on the entire operation costing of HPS in this study are performed. The result is reported in Table 8.

In Table 8, the billing cost, C_1 for case studies using conventional PoPA method cannot be determined by Eq. (3) and thus it cannot be compared and analysed with the other three strategies. This is because the time and amount for the purchasing of outsourced electricity are not known. In accordance to that, the value of GPR is undetermined (refer to Tables 6, 7).

For Case Study 1, Strategy 1 is reported to cause the lowest billing cost, C_1, compared to the other two strategies. This is due to the fact that the strategy itself has directly and significantly optimised the GPR to its minimal value, by distributing the system net energy in 24 h equally. Strategy 3 has also contributed in the GPR minimisation; however, the distribution of net outsourced energy from the grid is only at the time intervals when discharging of ES is occurring. Hence Strategy 3 has a higher C_1 value than Strategy 1. Strategy 2 does not have much impact in minimising C_1 value as the strategy focuses on minimisation of ES system instead of

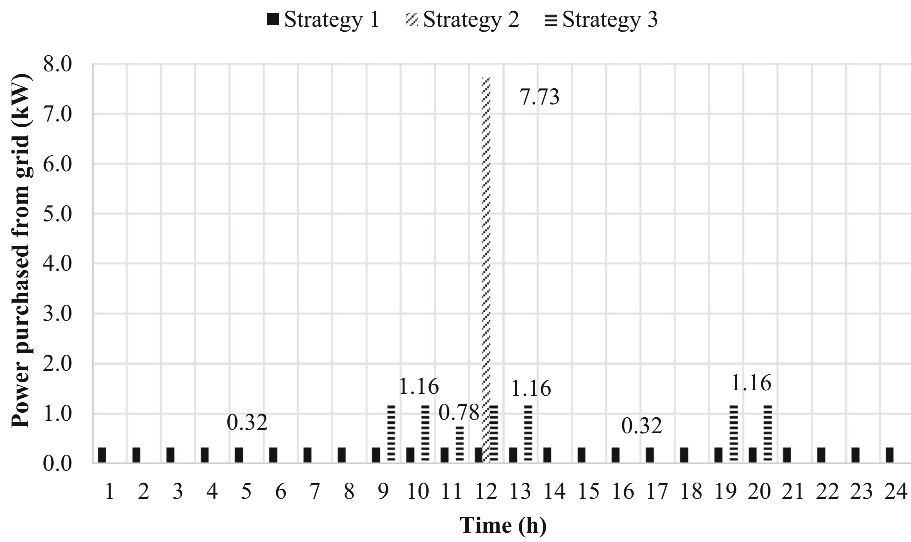


Fig. 8 Comparison on the purchasing trend of grid electricity with respect to time (hourly) for the three strategies in Case Study 1

outsourced power from the grid. As a result, Strategy 2 has the highest C_1 value.

As for the ES cost, C_2, Strategy 2 and 3 in Case Study 1 have achieved lower optimal values compared to the original PoPA and Strategy 1. Both Strategy 2 and 3's implementation have direct impact on the ES system of the HPS. Nevertheless, Strategy 2 focuses on reducing the decision parameter of ERC, whereas Strategy 3 is inclined towards PRC reduction. Based on the price data used in this study (Table 5), the price of ERC is relatively higher than PRC. The more the ERC value is reduced, the cheaper the ES cost is. The result in Table 8 indicates that Strategy 2 is able to reduce ERC value the most, hence reduces C_2 value to its minimum.

In term of overall cost, Strategy 3 has the net lowest value among the others because the strategy has a combination influence from all the decision parameters (GPR, ERC and PRC).

For Case Study 2, the same trend and justification are discussed as in Case Study 1 to compare the C_1 value between Strategy 1 and 3. But for C_2, both Strategy 1 and 3 have slightly increased the ES cost from the original PoPA. Overall, since the total cost for original PoPA is undetermined, Strategy 3 is still able to target the lowest total cost in operating the HPS.

To sum up from the above analysis, Strategy 3 is the best strategy to be implemented in electricity purchasing scenario.

Sensitivity analysis

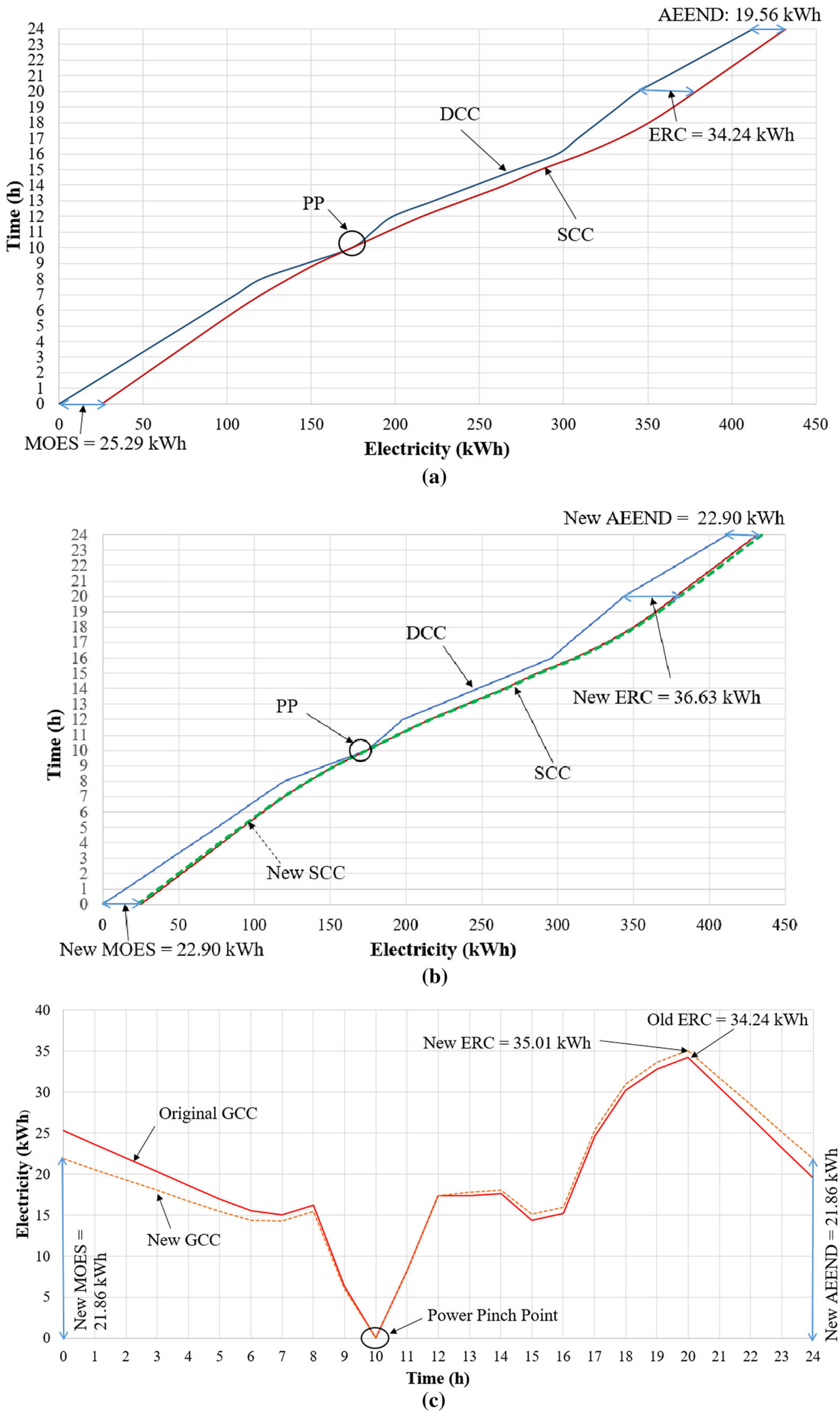
In this section, sensitivity analysis is carried out to study the effect of AF for adding ES in the HPS on the best strategy to be implemented in grid management. The AF is based on the number of years of instalment of ES system. Case Study 1 is chosen to carry out the sensitivity analysis.

Based on the two costing elements C_1 and C_2 involved in determining the economy performance of the HPS, it is identified that the C_2 has major contribution to the total cost. This analysis is done to determine if there is a change in strategy trend when C_2 is affected due to the increment of years of instalment. At an interest rate of 10 %, different AFs according to number of instalment years are charged to C_2 (inclusive of ERC cost, PRC cost and O&M cost). The sensitivity result is illustrated in Fig. 11.

From Fig. 11, it can be concluded that Strategy 3 has been the best strategy to be implemented to the HPS. The reduction in PRC integrated with equally distributed net grid energy along the operation hours leads to the cheapest system expenditure compared to the other two strategies. It is noteworthy that there is switching in trend between Strategy 1 and 2 at the 20th instalment year and above. From the 5th year, the difference of total costing between Strategy 1 and 2 is getting closer until the 20th year, the costing for Strategy 1 implementation turned to be lower than that of Strategy 2. This is due to the nature of strategy itself. The implementation of Strategy 1 (minimal GPR) tends to reduce ERC and PRC value simultaneously, whereas Strategy 2 only targets for ERC reduction without or has less effect on the other two parameters. At a longer instalment year (smaller AF), the system that applies Strategy 1 saves more than Strategy 2.

Selling of electricity to the grid: strategies and case study

For the case scenarios which excess energy of the system is to be sold to the grid, it is charged based on feed-in tariff


AEEND: 19.56 kWh
DCC
ERC = 34.24 kWh
PP
SCC
Time (h)
MOES = 25.29 kWh
Electricity (kWh)
(a)
New AEEND = 22.90 kWh
DCC
New ERC = 36.63 kWh
PP
SCC
New SCC
Time (h)
New MOES = 22.90 kWh
Electricity (kWh)
(b)
Old ERC = 34.24 kWh
New ERC = 35.01 kWh
Original GCC
New GCC
Electricity (kWh)
New MOES = 21.86 kWh
Power Pinch Point
New AEEND = 21.86 kWh
Time (h)
(c)

◀**Fig. 9** Graphical output for Case Study 2: **a** PCC from PoPA method; **b** New SCC in PCC after Strategy 1; **c** GCC comparison after Strategy 3

(FiT) scheme, depending on the type of RE that has been used to generate electricity. In this paper, both biomass and solar energy are eligible for FiT. However, there is a maximum capacity quota for the payment of RE-based

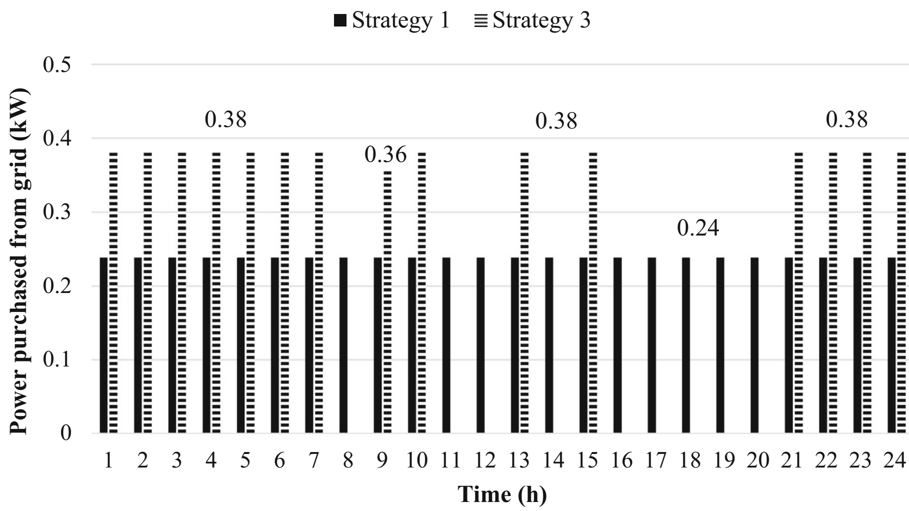


Fig. 10 Comparison on the purchasing trend of grid electricity with respect to time (hourly) for the three strategies in Case Study 2

Table 8 Annualised costing result for Case Study 1 and 2

Item	PoPA	Strategy 1	Strategy 2	Strategy 3
Case Study 1: purchasing of electricity from grid with ERC below Pinch				
Billing cost, C_1 (RM)	–	1051.94	3682.55	1348.82
ES cost, C_2 (RM)	48,231.44	46,481.68	40,754.42	42,529.08
Total cost, C (RM)	–	47,533.62	44,436.96	43,877.90
Case Study 2: purchasing of electricity from grid with ERC above Pinch				
Billing cost, C_1 (RM)	–	779.70	N/A	831.14
ES cost, C_2 (RM)	38,958.73	41,196.10	N/A	39,486.71
Total cost (RM)	–	41,975.82	–	40,317.85

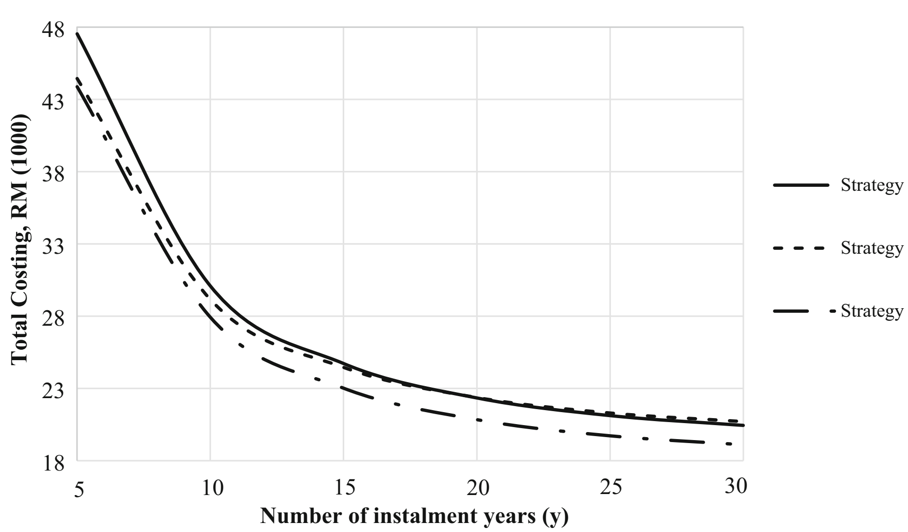


Fig. 11 Total HPS costing at each grid management strategy with increasing of years of instalment (different AFs)

electricity from SEDA Malaysia to the power producers (SEDA Malaysia 2016). The limited FiT rate cannot best demonstrate the strategies proposed in this paper because one concern of the strategies is to maximise the saving for HPS.

However, if electricity is allowed to be sold at any amount and at any time being, the strategy of selling of electricity to the grid is still applicable. The strategies based on the three decision parameters are of opposite to the above electricity purchasing strategies. An illustrative case study is presented along with the demonstration for these strategies.

Case Study 3: Selling of electricity to grid with ERC above Pinch

Given a surplus of 34.35 kWh in the system (AEEND > MOES) that the excess energy has to be sold to the grid. After performing PoPA, the following data can be extracted from the DCC and SCC in Fig. 12.

(i) PP at 10:00,
(ii) EG = 34.35 kWh (to be sold),
(iii) ERC = 50.94 kWh (at 20:00) and
(iv) PRC = 11.08 kW (charging state at 17:00).

Strategy 1: To achieve minimal centralised grid power rating, GPR

In order to achieve minimal centralised GPR, energy should be sold equally throughout the day. In Case Study 3, Strategy 1 has resulted a new GPR of 1.43 kWh of electricity to be sold equally and consistently in 24 h. Both ERC and PRC have been reduced their capacities to 36.63 and 9.65 kW (Fig. 12).

Strategy 2: To achieve minimal energy-related capacity, ERC

In cases where electricity has to be sold where the ERC is above Pinch, it should be done closest to and above the PP as it will have a continuous domino effect up to the AEEND thus reducing the ERC capacity. From the predetermined EG, energy is sold to the grid at the exact amount with the net system surplus (after generation meets demand) at the time intervals right above PP in a consecutive manner. Taking Case Study 3 as example, a consecutive selling of electricity is done above the PP (wherever there is a surplus at the instantaneous time) until the last electricity is being sold (at 17:00). This avoids the surplus electricity to be accumulated into the ES and also the increment the resultant ERC. As a result, multiple pinch points can be observed from Fig. 13, i.e. at the time interval 14:00–16:00. ERC has been reduced largely from 50.94 to 18.16 kWh. A new reduced PRC is reported to be 8.10 kW, occurring at a discharging state at 9:00. The consecutive selling of electricity above Pinch has brought the new GPR down to 10.77 kWh.

If in cases where electricity has to be sold where the ERC is below Pinch, there is no specific rules on how the electricity should be sold as there is no possible way to further reduce the ERC.

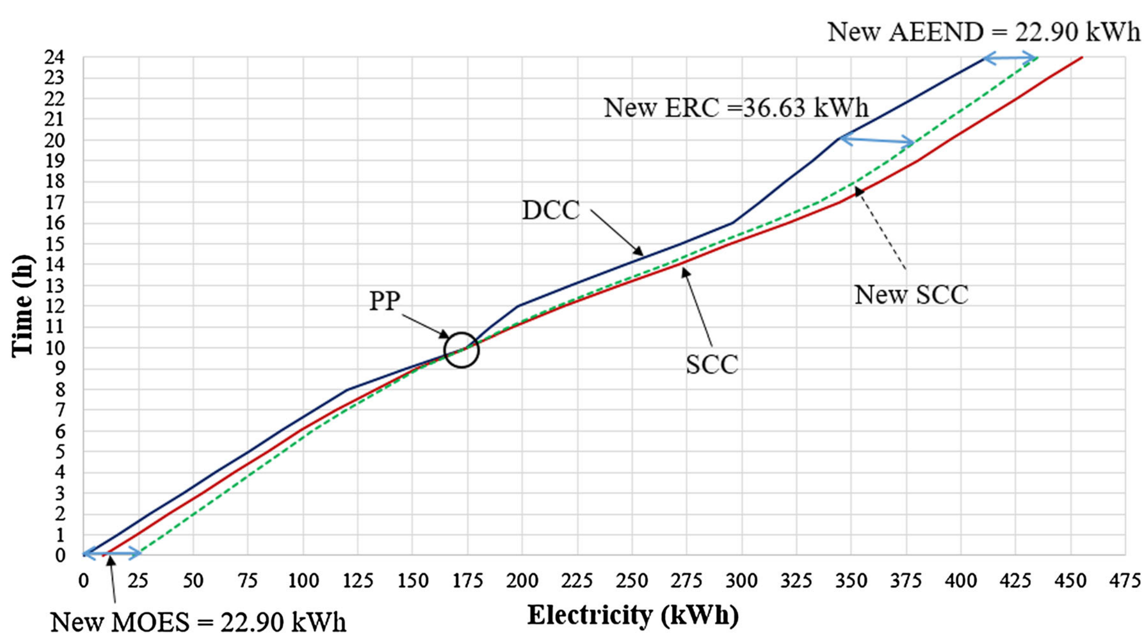


Fig. 12 New SCC as an effect of Strategy 1 application in Case Study 3

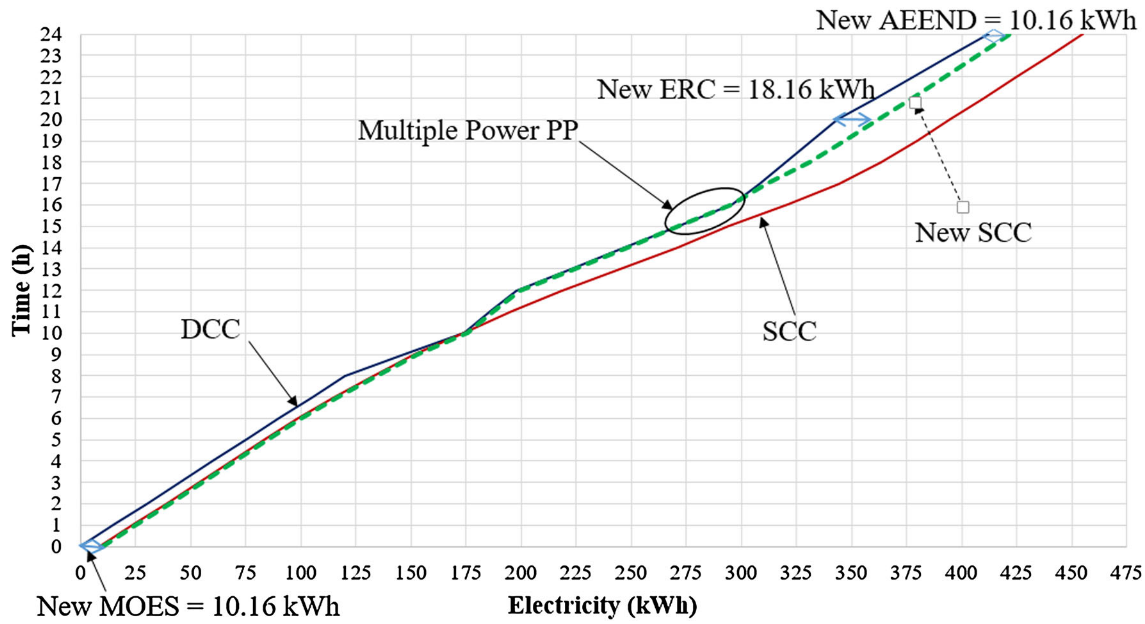


Fig. 13 New SCC after implementing Strategy 2 to Case Study 3

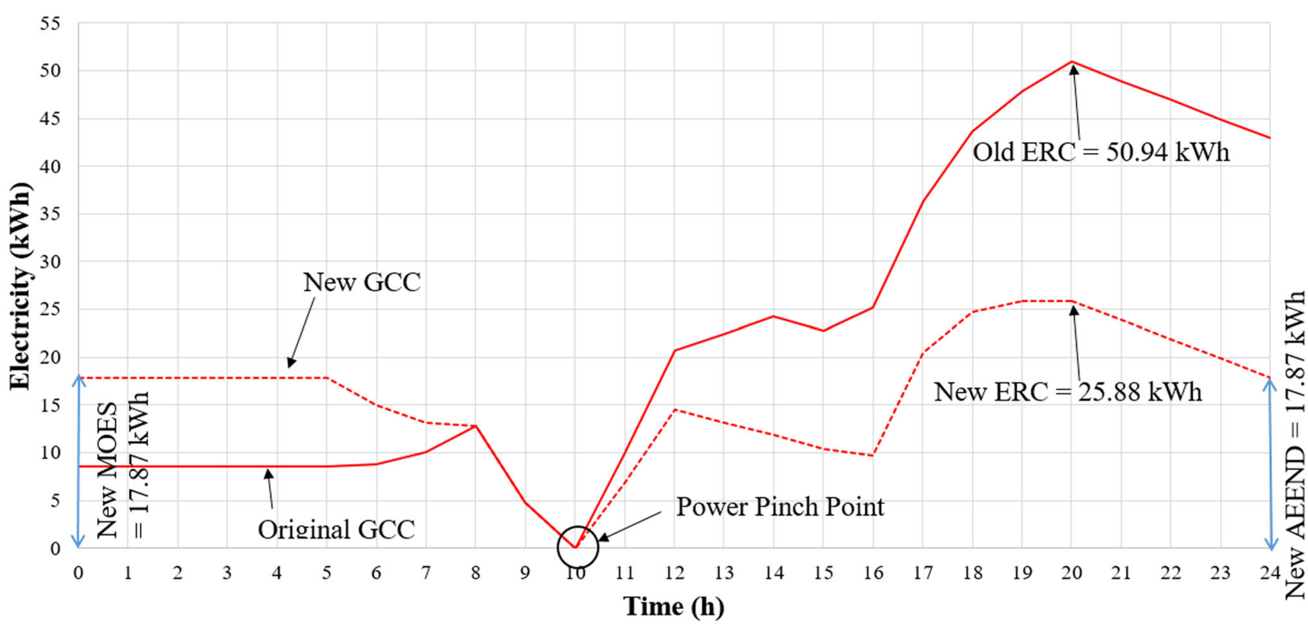


Fig. 14 GCC before and after Strategy 3 is applied

Strategy 3: To achieve minimal power-related capacity, PRC

After identifying the charging and discharging zones of the power system in a GCC, electricity should be sold within the time interval where the charging power magnitude is the largest. When the largest charging power is reduced to the magnitude equals to the second largest charging power, the remaining of net system electricity should then be sold equally within the charging zones (including PP). Electricity should be sold at time of charging but this strategy is not applicable for selling electricity when the PRC is of discharging.

For Case Study 3, the largest PRC (occurred in 16:00–17:00 with 11.08 kW charging capacity) has been reduced to 10.77 kW, by selling off 0.32 kW. The rest of the net energy of the system has been sold in an equal amount of 3.09 kW among all the charging zones. The strategy has also simultaneously reduced the GPR to be 3.90 kW (switched to 19:00) and ERC to be 25.88 kWh.

Figure 14 shows the illustration of Case Study 3 after applying Strategy 3.

All the three strategies proposed targeting on three decision parameters are effective in improving the design and economic aspect of an on-grid HPS. Depending on the type of case scenarios (buying or selling electricity) and the location of ERC in the PCC curve, the best strategy to be implemented can be identified via the sizing and economic analysis presented in this paper. From the result obtained from the implementation of each individual strategy to one particular case, it is inferred that the best strategy that can achieve optimum HPS design and costing is when all the three strategies are integrated.

Conclusion

Study on energy system especially those which consists of several types of energy sources has become essential to consider the sustainability of the system in terms of reliability and economics. Through this study, it can be seen that as the opposite of load shifting (manipulating demand side consumption), supply side energy manipulation can result in substantial benefit to the design and operation of a HPS as demonstrated.

In this paper, the analysis considers a fixed rate tariff, while the analysis is valid for all fixed rate cases, most of the industrial electricity tariff is based on an on–off peak tariff structure. Taking the result and analysis presented in this paper as basis, a future work on variation in tariff pricing will be presented in the future.

At the current finding combined with previous discussion of PoPA (especially on load shifting), it is expected that many power engineers, decision maker and policy makers on energy-related matters will gain a better and clearer insight on the role of load shifting and supply side management in improving the operational efficiency of the HPS.

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