

# Combined design and load shifting for distributed energy system

Wai Shin Ho · Haslenda Hashim · Jeng Shiun Lim ·  
Jiří Jaromír Klemeŝ

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**Abstract** Renewable distributed energy generation (DEG) system plays an important role in future power developments and is one of the options to reduce energy consumption. It is envisaged that energy efficiency of DEG systems can be improved via load shifting (LS). This study proposed a heuristic-based numerical approach to perform LS analysis on renewable stand-alone DEG systems. The technique is an extension from a method known as the Electric System Cascade Analysis (ESCA). The new technique, which focuses on efficient electricity utilisation is able to determine the optimal: (i) load profiles, (ii) capacity of power generator, (iii) capacity and power of energy storage (ES) and (iv) charging/discharging schedule of ES. The stage-wise technique allows user to compare and determine the optimal design in a flexible way while having a better understanding of the selection of options. The application of ESCA-LS on a case study revealed that after incorporation of direct LS (load manipulation) in addition to LS by ES (supply manipulation), the power generators and ES capacity can be further reduced. While reduction of 3.1 % for solar-PV installation area and 3.9 % for biomass power generator is recorded, ES power-related capacity and energy-related capacity managed a higher reduction of up to 19.0 and 13.2 % for the main case study

**Keywords** Distributed energy generation (DEG) · Load shifting · Renewable Energy (RE) · Power Pinch Analysis (PPA) · Energy storage (ES)

## Introduction

Distributed energy generation (DEG) system [small localised energy generation system (Ghosh et al. 2012)] is a pronounced platform to stimulate developments of renewable energy (RE) and is also one of the best options to combat issues of global energy sustainability and global warming worldwide (Topkaya 2012). Although large-scale integration of DEG system into the current power grid may yet be economically feasible, deployment of DEG especially stand-alone DEG in remote areas (Marsden 2011) and islands system (Cosentino et al. 2012) had been increasing. Increments of DEG system in these areas are mainly due to difficulty or non-viability of grid connection or simply due to unjustified cost of constructing a transmission lines from a centralised grid. Countries which provided DEG for rural electrification includes Kenya (Bernard 2012), China (Bhattacharyya and Ohiare 2012), India (Liming 2009) and Brazil (van Els et al. 2012), among many others.

Apart from DEG systems, load shifting (LS), a demand-side management (DSM) technique had been a matter of studies since 1980s (Iglesias et al. 2012). LS is a technique applicable to all utilities globally ‘whether large or small; cooperative, municipal, or investor-owned; and urban or rural’ (Gellings 1985). In a large-scale centralised grid network, LS is mainly practiced for curve flattening or peak shaving purposes. In cases of stand-alone DEG, depending on the system (type of operating units) itself,

W. S. Ho · H. Hashim (✉) · J. S. Lim  
Process Systems Engineering Centre (PROSPECT),  
Faculty of Chemical Engineering, Universiti Teknologi  
Malaysia, 81310 Skudai, Johor, Malaysia  
e-mail: haslenda@cheme.utm.my

J. J. Klemeŝ  
Centre for Process Integration and Intensification—CPI2,  
Research Institute of Chemical and Process Engineering—  
MÜKKI, Faculty of Information Technology, University  
of Pannonia, Egyetem utca 10, Veszprém 8200, Hungary

different constraints may be present. For instance, focusing on RE systems, shifting of load specifically to periods of high power generation can be advisable (Dietrich et al. 2012). This strategy is especially crucial for solar photovoltaic (PV) and wind turbine systems due to its intermittent nature. It is noted that in these systems, instead of peak shaving, new peaks are formed at periods of high power generation. For other RE systems such as biomass thermal and geothermal, the same strategy (peak shaving) as practiced by the current centralised grid can be applied due to both systems being analogous.

The LS is commonly accomplished via direct shifting of load or through energy storage (ES) devices, both with their own distinct advantages and limitations. Direct shifting of load usually refers to end users directly changing their energy consumption habits, for instance, rescheduling of daily routines such as washing clothes, cooking and washing dishes (via dish washer) to other time period than usually intended. While this technique is a simple form of LS, it still requires behaviour changes, which are rather difficult. LS via ES on the other hand does not require loads to be shifted directly but instead it manipulates the power supply timing (storing energy at time of high generation to supply during time of lower generation) providing flexibility to end users' energy consumption (Evans et al. 2012). Utilisation of ES devices usually involves higher investment cost and energy losses.

With pressing needs of sustainable energy systems (Gutiérrez-Arriaga et al. 2012) and difficulties of deciding optimal LS plan, several works related to LS had been studied and many relevant tools for system optimisation had also been developed. Shaw et al. (2009) provided a quantitative assessment on the impact of domestic LS on reduction in distribution network losses. In term of optimisation, most works are based on optimisation model-centric approaches. Dietrich et al. (2012) formulated LS procedures into a mathematical model and applied it on an isolated energy system that are powered by wind energy. These authors evaluated the impact of LS on operation cost. They also assessed the effects of increasing capacity of wind power system on the operation. Gudi et al. (2012) uses Particle Swarm Optimisation algorithm to perform LS for a set of household appliances that are powered by various sources of energy. Lujano-Rojas et al. (2012) proposed a novel load management strategy for the optimisation of a RE system that consists of wind turbine, ES system and a diesel generator, by prediction of wind speed and its corresponding power. These authors also considered the duty cycles of electrical appliances and user behaviours. In the case of load management for single electrical appliances, Finn et al. (2013) incorporated RE into the energy system and performs LS for dish washer in response to external factors such as wind availability and pricing.

Pina et al. (2012) modelled a wind and hydro-based electricity generation system in TIMES software to optimise economic decisions and operation.

Molderink et al. (2010) on the other hand proposed a three-step optimisation strategy that includes offline local prediction, offline global planning and online local scheduling. First step of the procedures develops a neural network system predicting energy profiles of household for upcoming day by considering historical energy usage patterns and external factor such as weather conditions (Bakker et al. 2010). The energy supply plan is then formulated into an integer linear programming (ILP) and finally the results are obtained (Bosman et al. 2010). In another extension, a local controlling algorithm is developed to control domestic power and heat demand as well as generation and storage of heat and power (Molderink et al. 2009). Tan et al. (2010) proposed a Monte Carlo-based stochastic model to determine optimal battery sizes and load profile for solar-PV system in a commercial building.

The state-of-the art analysis indicates that previous studies related to DSM have been focused on 'black-box' mathematical modelling approaches. In terms of application, these optimisation/simulation models are usually presented in a form of software and require additional cost above the investment cost of the DEG system itself. It might be beyond the budget available for users, especially for those from rural areas in developing countries. As these analyses are performed in a 'black-box' condition, it would restraint users to have full control over the decision-making process and understand the mechanism behind the analysis.

This study therefore proposed a stage-wise heuristic-based numerical approach with LS for optimisation of a stand-alone renewable DEG system. The method which is capable to provide optimal design and schedule of a DEG system is an extension from an established method known as the Electric System Cascade Analysis (ESCA) (Ho et al. 2012). ESCA is a numerical technique based on power pinch analysis (PPA) demonstrated by Bandyopadhyay (2011) in his work to design an isolated RE system using the Grand Composite Curve to determine the optimal capacity of ES. Another work related to utilisation of numerical technique for optimisation of a renewable-based system are that by Nemet et al. (2012) which focuses on solar thermal energy. The advantages of these approaches include omittance of sophisticated software while granting users with full decision-making options and understandings.

## Methodology

ESCA-LS procedures are performed based on several heuristics. Terminologies applied in LS analysis are defined below:

Time slice (TS)—Set of time intervals from a specific time horizon (Nemet et al. 2011).

Shiftable load—A load which can be rescheduled within its allowable TS.

Fixed load—A non-shiftable load.

Allowable TS—TS which are suitable for assigning a shiftable load.

The overall flow of ESCA-LS is shown in Fig. 1.

Prior to direct LS, users are required to first (Step 1) perform ESCA based on the original load profile to determine the pinch point, the peak-point (point where the energy content in the ES is at peak) and capacities of each operating units (for comparison purposes). Flow of ESCA is shown in Fig. 2. Compared to the previous ESCA methodology (Ho et al. 2012), several revisions were made to suit LS analysis. These revisions are as below:

- Determine number of TS in addition to the required data for analysis. Lower number of TS would reduce the accuracy of the analysis while larger number of TS would increase the complexity and tediousness of the analysis. For a moderate approach, 24 TS is advisable for an analysis with time horizon of 24 h (1 day).

- Identification of shiftable and fixed loads.
- Capacity estimation of power generators is calculated based on formulation shown in Eqs. 1 and 4 instead of wild guesses; allowing users to begin the analysis at a closer estimation thus reducing number of iterations. Equation 1 for thermal system (non-intermittent) and Eq. 4 for solar-PV system.
- Energy for charging of ES are calculated without losses during charging (Eqs. 3, 6) thus indicating the amount of energy to be charged into an ES as opposed to the previous formulation which takes into account charging losses (net energy charged into an ES).
- Losses during charging are now accounted for during the calculations of cumulative energy in ES shown in Eq. 8.

The specific equations required to complete the Cascade table are shown below with Eqs. 1–3 for biomass power system (also representing all other thermal power systems), Eqs. 4–6 for solar-PV systems, and Eqs. 7, 8 for both systems. A general cascade table of ESCA is shown in Tables 1, 2, and 3.

Formulation of biomass power system analysis:  
Estimation of capacity:

$$S_B = \frac{\sum_t L_t}{T} \tag{1}$$

where  $S_B$  is capacity of biomass generator;  $L_t$  is energy demand in each TS,  $t$ ; and  $T$  is total number of specified TS.

Net energy surplus/deficit:

$$N_t = G_t - L_t \forall t \tag{2}$$

where  $N$  is net energy demand (deficit/surplus); and  $G$  is power generated.

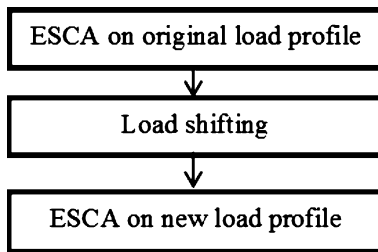
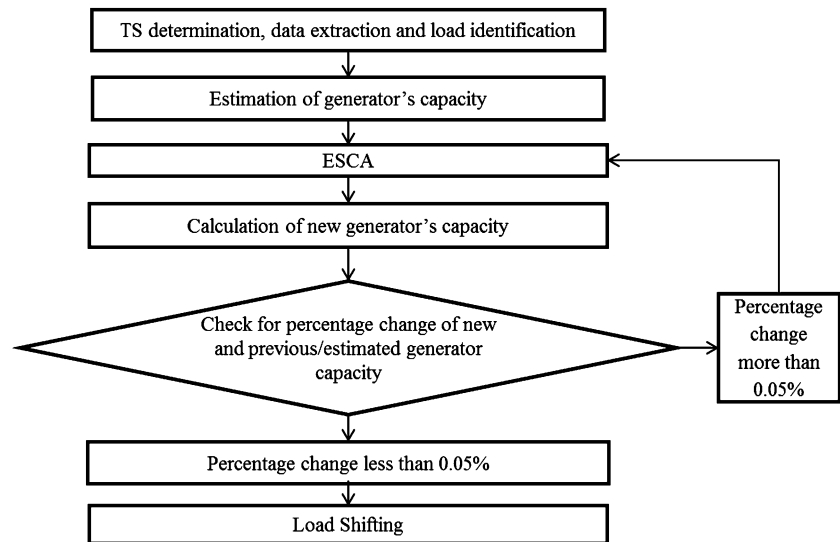


Fig. 1 Flow of ESCA-LS

Fig. 2 Flow of ESCA



**Table 1** General cascade table for ESCA

Time slice	Demand load	Power generation	Net energy surplus/deficit	Charging	Discharging	Cumulative energy	New cumulative energy Initial energy content of ES
TS1	$L_{TS1}$	$G_{TS1}$	$N_{TS1}$	$C_{TS1}$	$D_{TS1}$	$E_{TS1}$	$E_{TS1(new)}$
TS2	$L_{TS2}$	$G_{TS2}$	$N_{TS2}$	$C_{TS2}$	$D_{TS2}$	$E_{TS2}$	$E_{TS2(new)}$

**Table 2** Charging/discharging schedule for example 1

TS	Net energy surplus/deficit (W)	Charging/ discharging (W)	Shiftable load (W)	New charging (W)	New discharging (W)
Set-up 1					
A	1,000	900	400	540	
B	700	630	800		-121
Set-up 2					
A	1,000	900	800	180	
B	700	630	400	270	
Set-up 3					
A	1,000	900	1,200	-242	
B	700	630		630	

Based on the three set-ups, for set-up 1, the total charging/discharging requirements add up to 661 W and the maximum charging/discharging requirements is 540 W. 450 W (total charging/discharging) and 270 W (maximum charging/discharging) for set-up 2 and 872 W (total charging/discharging) and 630 W (maximum charging/discharging) for set-up 3. By comparison of both factors (total and maximum charging/discharging), set-up 2 is the best choice

**Table 3** Charging/discharging schedule for example 2

TS	Net energy surplus/deficit (W)	Charging/ discharging (W)	Shiftable load (W)	New charging (W)	New discharging (W)
Set-up 1					
A	50	45		45	
B	750	675	400	315	
C	300	270	450		-181
Set-up 2					
A	50	45	400		-423
B	750	675	450	270	
C	300	270		270	
Set-up 3					
A	50	45		45	
B	750	675	850		-121
C	300	270		270	

The best solution in this case would be that of set-up 3 which is to place both shiftable loads into the same TS

Charging:

$$C_t = N_t f_1 \tag{3}$$

where  $C_t$  is energy for charging of ES; and  $f_1$  is inverter efficiency.

Formulation of solar-PV analysis:

Estimation of area:

$$A_S = \frac{\sum_t L_t}{\sum_t f_s \times R_t} \tag{4}$$

where  $A_S$  is area of installed solar-PV;  $f_s$  is efficiency of solar modules; and  $R_t$  is solar radiation in each TS, t.

Net energy surplus/deficit:

$$N_t = G_t f_1 - L_t \quad \forall t \tag{5}$$

Charging:

$$C_t = \frac{N_t}{f_1} \tag{6}$$

It is noted that inversion is not required during the charging of solar-PV. The energy losses accounted for in Eq. (5) is recovered through division of  $f_1$ .

Other formulations (applicable for both systems):

Discharging:

$$D_t = \frac{N_t}{f_D f_l} \tag{7}$$

where  $D_t$ , is net energy for discharging of ES; and  $f_D$  is ES discharging efficiency.

Cumulative energy in ES (for both biomass power system and solar-PV):

$$E_{t+1} = E_t + C_i f_C + D_t \tag{8}$$

where  $E_t$  is cumulative energy in ES; and  $f_C$  is ES charging efficiency.

In determination of pinch (point where cumulative energy in ES is at minimum) and peak-points (point where cumulative energy in ES is at maximum), (Step 2) all shiftable loads are removed from the Cascade table and LS can then be performed based on heuristics described in the next subsection. After reallocating the shiftable loads, (Step 3) ESCA is repeated based on the new load profile to obtain final results. It is noted that the energy-related and power-related capacities of the ES are extracted from the cascade table.

### Load shifting

The principle of LS in this analysis revolves around the objectives to minimise capacity of power generators, energy-related capacity of ES and power-related capacity of ES. Detailed optimisation of these operating units usually faces many trade-offs and could be too complex for manual numerical analysis such as this. In order to provide a straight forward analysis with satisfactory results, minimisation of power generators is prioritised over ES.

Minimising capacity of power generators can be achieved through reduction of energy losses within the DEG system. These losses occur during conversion of current from AC to DC and vice versa and during charging/discharging of ES. The strategy to reduce energy losses is by avoiding charging and discharging of energy into and out of ES through placing shiftable loads at TS with energy surplus.

Energy-related capacity of ES on the other hand, is defined by the pinch and peak-points of a grand composite curve, as illustrated in Fig. 3. In the pinch-peak region, energy is generally charged into the ES while in the peak-pinch region, energy are generally discharged from the ES. By placing shiftable loads in the pinch-peak region, the peak of a grand composite curve will thus decrease. Nevertheless, it should also be noted that placing a shiftable load close to the pinch point within the pinch-peak region might result in the appearance of a new pinch point. A new pinch point appears when a shiftable load with magnitude exceeding the cumulative energy in an ES at a specific TS is placed. The load can instead be placed at later TS (before peak-point) allowing sufficient energy to be accumulated thus preventing the appearance of a new pinch point.

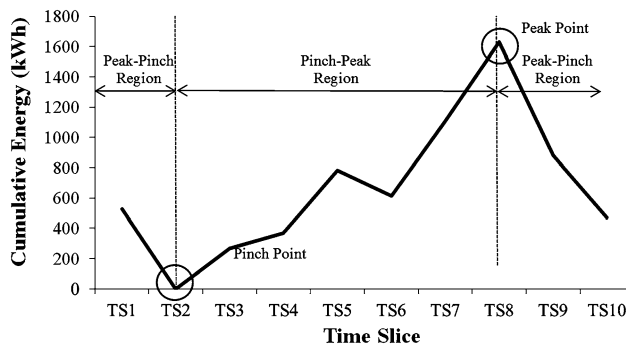


Fig. 3 Points and regions of ESCA Grand Composite Curve

Power-related capacity of ES on the other hand is defined by the largest magnitude of charging/discharging of energy. It can therefore be minimised by placing shiftable loads at TS with the largest energy surplus and avoid placement of shiftable load at TS with the largest energy deficit.

With consideration over these objectives, four heuristics based on TS were identified. These heuristics are as shown below:

- i) Placement of shiftable load at TS with largest energy surplus within its allowable TS (reduces charging/discharging requirements and reduces magnitude for charging).
- ii) Placement of shiftable loads at TS with least energy deficit within its allowable TS in cases where no surpluses were present (reduces magnitude for discharging).
- iii) Placement of shiftable loads at TS within the pinch-peak region in cases where more than one of the same magnitude of largest surpluses or least deficit were present (reduces magnitude of peak)
- iv) Placement of shiftable loads at later TS of the same magnitude within the pinch-peak region, allowing for more energy to accumulate in ES to prevent occurrence of a new pinch point

To be reminded that as the analysis prioritised the minimisation of power generator capacity, load will still be first placed at TS with largest surpluses or least deficit even if it is not within the pinch-peak region.

Lastly, in any instance during a placement of a shiftable load at TS with an existing shiftable load, an additional evaluation by comparing the amount of energy for charging/discharging is performed. Examples of the comparison are shown in the examples below. Choices are either to replace the TS with the latter shiftable load and transfer the former shiftable load to the second largest surplus TS or least deficit TS (conforming to the heuristics above) within its allowable TS; or to allocate both shiftable loads into the same TS. If the second largest TS were also occupied, the evaluation will be repeated in the same manner. It is advisable to begin LS in descending order of shiftable load magnitude.

### Example 1: priority based on magnitude

Example 1 involves shifting of two loads, 400 W (allowable TS from TS A to TS B) and 800 W loads (allowable TS from TS A to TS B). Charging and discharging is calculated based on inverter efficiency of 90 % and charging and discharging efficiency of 92 %.

### Example 2

Example 2 involves shifting of two loads, 400 W (allowable TS from TS A to TS B) and 800 W loads (allowable TS from TS B to TS C).

## Case study, results and discussion

This research work has been targeted to design a hybrid solar-biomass stand-alone DEG system for a single residential house. The DEG system is shown in Fig. 4. This system is designed to operate mainly on solar-PV system while biomass thermal power generator functions as a back-up generator.

### Step 1: ESCA on original load profile

Following the flow presented in Fig. 1, first step of the procedure (Step 1) is to perform ESCA which requires determination of number of TS, extraction of data and identification of load type. The data for a stand-alone DEG are listed below:

- Hourly energy demand by appliances
- Inverter efficiency—90 % (Shin and Hashim 2012)
- Battery charging and discharging efficiency—92 % (Steward et al. 2009)
- Depth of discharge of battery—80 % (Steward et al. 2009)
- Hourly solar intensity (for solar-PV system)—Fig. 5 (Othman et al. 1993)

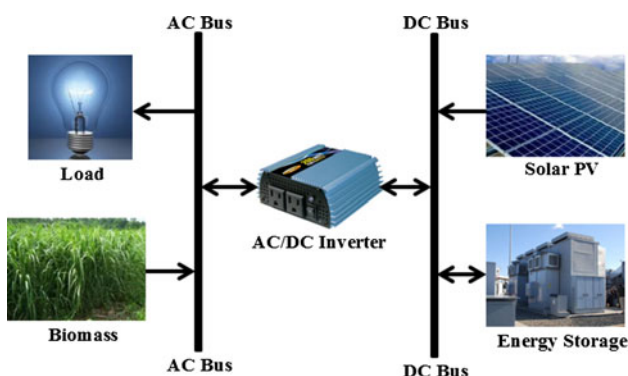


Fig. 4 Schematic of DEG system

- Solar-PV efficiency (for stand-alone PV system)—15 % (Updated Capital Cost Estimates for Electricity Generation Plants 2010)

This study applies a typical load profile of a residential unit—a family house of three individuals in Malaysia. It is assumed that with advance DEG system, the lifestyle of those in remote areas could be upgraded comparable to those in urban areas. Type of appliances with its corresponding power rating, original operation hours and duration for the house are shown in Table 4. Shiftable loads instead are shown in Table 5 and the original energy profile is shown in Fig. 6. Allowable TS of shiftable loads are defined within a certain time horizon to prevent major behaviour changes assuming that all appliances are manually operated. As for determination of TS, 24 TS are defined to represent each hour in a day

In order to ensure the robustness of the system, two separate ESCA analyses were carried out for a best case scenario where solar-PV can fully meet all energy demand without back-up (sunny day), and a worst case scenario where the system have to fully rely on back-up (rainy day) to remain stable and reliable.

Based on the original load profile, requirement of solar-PV and biomass power generator and its respective ES are shown in Table 6. The pinch and peak-point for solar-PV analysis were identified at TS 6 ad TS 18 and TS 6 and TS 19 for biomass power generator system.

### Step 2: load shifting

#### Solar-PV: best case scenario

In the procedure of performing LS, the first shiftable load (Shower Heater 1) was placed at TS 7 based on Heuristic I, followed by ‘Shower Heater 2’ at TS 12 (Heuristic I) and ‘Shower Heater 3’ at TS 17 (Heuristic I). During the placement of ‘Iron’, further evaluation was made between ‘Shower Heater 2’ and ‘Iron’ at TS 12 (Heuristic I). The evaluation is shown in Table 7.

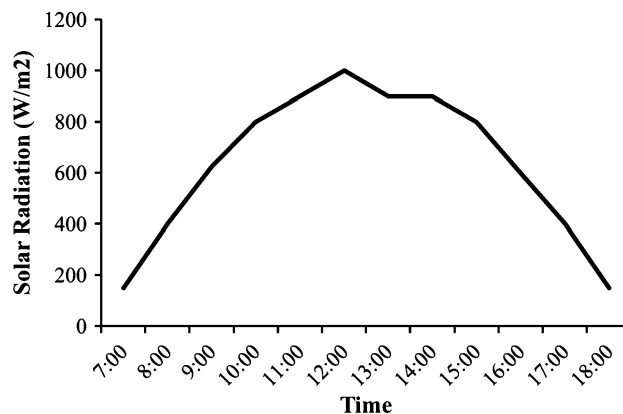


Fig. 5 Daily solar radiation (best case scenario—sunny day)

**Table 4** Household electrical appliances data

Appliances	Power (W)	Operation time		Duration (h)	Power consumption (Wh)
		Begin	End		
Refrigerator (220 L)	500	0:00	0:00	24	12,000
Lighting	30	19:00	6:00	11	330
Air conditioner	1,200	20:00	6:00	10	12,000
Television	75	14:00	16:00	2	2,400
		19:00	23:00	4	300
Laptop	65	8:00	11:00	3	195
		18:00	23:00	5	325
Shower heater	3,600	6:00	6:30	0.5	1,800
		2:00	2:30	0.5	1,800
		21:30	22:00	0.5	1,800
Iron	1,200	21:00	21:30	0.5	600
Washing machine	240	6:00	7:00	1	240
Electric kettle	2,000	6:00	6:15	0.25	500
		20:00	20:15	0.25	500
Rice cooker	600	1:00	1:30	0.5	300
		20:00	20:30	0.5	300
Toaster	700	7:00	7:15	0.25	175

**Table 5** Allowable TS for shiftable loads

Shiftable loads	Time slices		Power consumption (Wh)
	Begin from TS (h)	End at TS (h)	
Shower heater 1	6:00	7:00	1,800
Shower heater 2	11:00	15:00	1,800
Shower heater 3	17:00	22:00	1,800
Iron	9:00	22:00	600
Electric kettle 1	6:00	7:00	500
Electric kettle 2	18:00	20:00	500
Rice cooker 1	12:00	14:00	300
Rice cooker 2	18:00	20:00	300
Washing machine <sup>a</sup>	6:00	10:00	240
	22:00	23:00	
Toaster	6:00	7:00	175

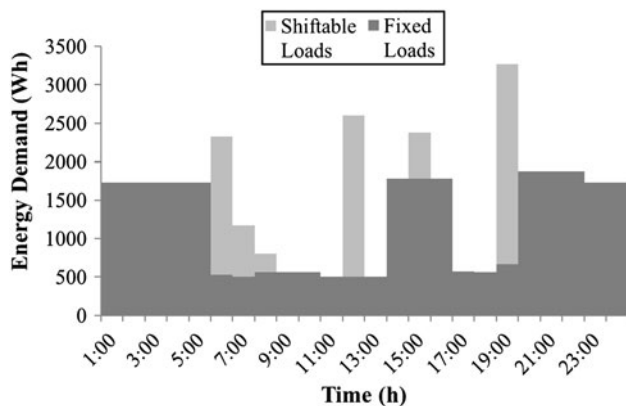
<sup>a</sup> Washing machine can be operated from 6:00 to 10:00 or from 22:00 to 23:00

Based on the results, set-up 2 resulted in the lowest charging magnitude, ‘Shower Heater 2’ was therefore maintained at TS 12 and ‘Iron’ was placed at TS 11. Another evaluation was made at TS 7 for ‘Shower Heater 1’ and ‘Electric Kettle 1’ (Heuristic I). Through similar procedures, ‘Shower Heater 1’ was maintained at TS 7 and ‘Electric Kettle 1’ was placed at TS 6. ‘Electric Kettle 2’ was then placed at TS 18 (Heuristic I). ‘Rice Cooker 1’ at TS 13 after further evaluation between ‘Rice Cooker 1’ and ‘Shower Heater 2’ at TS 12 (Heuristic I). ‘Rice Cooker 2’ was placed at TS 18 (Heuristic I) with ‘Electric Kettle 2’. The evaluation between ‘Rice Cooker 2’ and ‘Electric Kettle 2’ is shown in Table 8. ‘Washing Machine’ is placed at TS 10 (Heuristic I) and lastly ‘Toaster’ is placed at TS 6 (Heuristic I) after

evaluation between ‘Toaster’ and ‘Shower Heater 1’ and between ‘Toaster’ and ‘Electric Kettle 1’ were conducted.

*Biomass power generator: worst case scenario*

For biomass power generator LS procedure, ‘Shower Heater 1’ was first placed at TS 7 (Heuristic I and Heuristic III), followed by ‘Shower Heater 2’ at TS 13 (Heuristic I and heuristic IV), ‘Shower Heater 3’ at TS 18 (Heuristic i), and ‘Iron’ at TS 12 (Heuristic I and Heuristic IV). It is noted that TS 12 and TS 13 has the same amount of surplus and evaluation between ‘Shower Heater 2’ and ‘Iron’ is therefore omitted. ‘Electric Kettle 1’ was placed at TS 6 (Heuristic I and Heuristic III) after further evaluation (with



**Fig. 6** Household energy profile

‘Shower Heater 1’), ‘Electric Kettle 2’ at TS 19 (Heuristic I) after further evaluation (with ‘Shower Heater 3’), ‘Rice Cooker 1’ at TS 13 (Heuristic I and Heuristic IV) after further evaluation with ‘Shower Heater 2’, ‘Shower Heater 2’ were then evaluated with ‘Iron’ at TS 12 with the outcome of ‘Shower Heater 2’ being placed at TS 12 and ‘Iron’ at TS 11. ‘Rice Cooker 2’ was placed at TS19 (Heuristic I) with ‘Electric Kettle 2’ after further evaluation (with ‘Shower Heater 3’ and ‘Electric Kettle 2’), ‘Washing Machine’ at TS 8 (Heuristic I) after further evaluation (with ‘Shower Heater 1’ and ‘Electric Kettle 1’), and finally ‘Toaster’ at TS 6 (Heuristic I and Heuristic III) after further evaluation (with ‘Shower Heater 1’ and ‘Electric Kettle 1’).

### Step 3: ESCA on new load profile

#### Solar-PV

With newly determined load profile, ESCA is repeated. Table 9 shows the ESCA cascade table for solar-PV. Shiftable loads are placed in column 6 of ESCA table. It is noted that there is an additional column for solar radiation (column 3) in solar-PV ESCA. Solar-PV area was identified as 40.98 m<sup>2</sup>.

**Table 6** Required capacity of operating units before load shifting

	Best case scenario	Worst case scenario
Solar-PV area (m <sup>2</sup> )	40.1	–
Biomass power generator (kW)	–	1,687
ES power capacity (kW)	4,960	3,120
ES energy capacity (kWh)	27,657	6,525

**Table 7** Evaluation between ‘Shower Heater 2’ and ‘Iron’ at TS 12

TS	Net energy surplus/deficit (W)	Shiftable load (W)	New charging (W)
Set-up 1			
TS11	5,410	1,800	3,249
TS12	6,011	600	4,867
Set-up 2			
TS11	5,410	600	4,329
TS12	6,011	1,800	3,790
Set-up 3			
TS11	5,410		4,869
TS12	6,011	2,400	3,250

#### Biomass power generator

Table 10 shows the ESCA table for biomass power generator.

#### Discussion

The result summary of ESCA analysis before and after LS is shown in Table 11. Based on the results, there is indeed an improvement to the system after LS. All three of operating units of the DEG system reduces in capacity. The new load profile for both cases is shown in Figs. 7 and 8.

#### System reliability

As previously mentioned, the analysis was performed separately for solar-PV and biomass power generator to ensure robustness of the system. Although both systems provide the optimal capacity of ES power and energy, the larger capacity will represent the capacity of ES required by the DEG system. The selection is done to ensure reliability of DEG systems, that regardless of any external factor, the DEG systems will be deemed operable.

**Table 8** Evaluation between ‘Rice Cooker 2’ and ‘Electric Heater 2’ at TS 18

TS	Net energy surplus/deficit (W)	Shiftable load (W)	New discharging (W)
Set-up 1			
TS18	337	500	–197
TS19	–670	300	–1,171
Set-up 2			
TS18	337	300	33
TS19	–670	500	–1,413
Set-up 3			
TS18	337	800	–559
TS19	–670		–809



**Table 9** Solar-PV ESCA on new load profile

Time slice	Fixed load (Wh)	Solar radiation (W/m <sup>2</sup> )	Solar-PV generation (Wh)	Net surplus/deficit (Wh)	Shiftable load (Wh)	New charging (Wh)	New discharging (Wh)	Cumulative energy (Wh)	New cumulative energy (Wh)
TS1	1,730		0	-1,730			-2,089	-2,089	13,530
TS2	1,730		0	-1,730			-2,089	-4,179	11,441
TS3	1,730		0	-1,730			-2,089	-6,268	9,351
TS4	1,730		0	-1,730			-2,089	-8,357	7,262
TS5	1,730		0	-1,730			-2,089	-10,447	5,173
TS6	500		0	-500	675		-1,419	-11,866	3,083
TS7	500	150	922	422	1,800		-1,664	-13,530	1,664
TS8	565	400	2,459	1,894		1,705		-11,962	0
TS9	565	625	3,842	3,277		2,949		-9,249	1,568
TS10	565	800	4,918	4,353	240	3,702		-5,843	4,282
TS11	500	900	5,533	5,033	600	3,989		-2,173	7,687
TS12	500	1,000	6,147	5,647	1,800	3,463		1,012	11,357
TS13	500	900	5,533	5,033	300	4,259		4,931	14,543
TS14	1,775	900	5,533	3,758		3,382		8,042	18,461
TS15	1,775	800	4,918	3,143		2,829		10,644	21,572
TS16	1,775	600	3,688	1,913		1,722		12,229	24,175
TS17	575	400	2,459	1,884	1,800	76		12,298	25,759
TS18	565	150	922	357	800		-535	11,763	25,828
TS19	670		0	-670			-809	10,954	25,293
TS20	1,870		0	-1,870			-2,258	8,696	24,484
TS21	1,870		0	-1,870			-2,258	6,437	22,226
TS22	1,870		0	-1,870			-2,258	4,179	19,967
TS23	1,730		0	-1,730			-2,089	2,089	17,709
TS24	1,730		0	-1,730			-2,089	0	15,619

In this scenario, solar-PV area of at least 42.28 m<sup>2</sup>, biomass power generator of at least 1,622 W, ES power-related capacity of at least 4,259 W, and ES energy-related capacity of at least 32,285 Wh. Users may also choose to implement only the biomass power generator system which requires less ES power-related capacity of at least 951 W, and ES energy-related capacity of at least 3,791 Wh. Reminded that depending on market availability, higher capacity of each operating unit may be installed.

*Behaviour changes*

In term of behaviour changes due to LS, the analysis is performed to prevent major changes by setting a range of allowable TS for each shiftable load. However, users might be uncomfortable with the fact that every activity had to be done within each specified TS. If users decided to build the system based on the minimal results (result from Step 3), they will lose the flexibility to perform activities at other TS except for the specified TS. To allow some flexibility to the system, the users can instead build the system

according to the result from Step 1. LS results (results for Step 2) can then be applied as a guideline for users to follow to reduce the energy intensity of the system. For example, a biomass power generator with capacity of 1,687 W will only have to operate at 1,622 W if LS recommendations were followed.

In this scenario, solar-PV area of at least 42.28 m<sup>2</sup>, biomass power generator of at least 1,687 W, ES power-related capacity of at least 5,258 W, and ES energy-related capacity of at least 37,183 Wh are required. If biomass power generator were solely selected, ES energy-related capacity and ES power-related capacity of 3,120 W and 8,156 Wh is required.

Sole operation of solar-PV is not considered in this study due to long rainy seasons in Malaysia which would render solar-PV only systems to be infeasible.

**Conclusion**

ESCA methodology has been further developed to incorporate direct LS which are performed based on heuristic-

**Table 10** Biomass power generator ESCA on new load profile

Time slice	Fixed load (Wh)	Biomass power generation (Wh)	Net surplus/deficit (Wh)	Shiftable load (Wh)	New charging (Wh)	New discharging (Wh)	Cumulative energy (Wh)	New cumulative energy (Wh)
								1,101
TS1	1,730	1,622	-108			-131	-131	971
TS2	1,730	1,622	-108			-131	-261	840
TS3	1,730	1,622	-108			-131	-392	710
TS4	1,730	1,622	-108			-131	-522	579
TS5	1,730	1,622	-108		402	-131	-653	449
TS6	500	1,622	1,122	675			-282	819
TS7	500	1,622	1,122	1,800	735	-819	-1,101	0
TS8	565	1,622	1,057	240	951		-425	676
TS9	565	1,622	1,057		951		450	1,552
TS10	565	1,622	1,057		470		1,325	2,427
TS11	500	1,622	1,122	600			1,757	2,859
TS12	500	1,622	1,122	1,800	740	-819	939	2,040
TS13	500	1,622	1,122	300			1,619	2,721
TS14	1,775	1,622	-153			-185	1,434	2,536
TS15	1,775	1,622	-153			-185	1,249	2,351
TS16	1,775	1,622	-153		942	-185	1,065	2,166
TS17	575	1,622	1,047				1,931	3,033
TS18	565	1,622	1,057	1,800	137	-897	1,034	2,135
TS19	670	1,622	952	800			1,160	2,261
TS20	1,870	1,622	-248			-300	860	1,962
TS21	1,870	1,622	-248			-300	561	1,662
TS22	1,870	1,622	-248			-300	261	1,362
TS23	1,730	1,622	-108			-131	131	1,232
TS24	1,730	1,622	-108			-131	0	1,101

**Table 11** Result summary

	Generator		ES	
	Biomass (W)	Solar PV (m <sup>2</sup> )	ES power-related capacity (W)	ES energy-related capacity (depth of discharge of 80 %) (Wh)
<b>Biomass power generator system</b>				
Without load shifting	1,687	-	3,120	8,156
With load shifting	1,622	-	951	3,791
Reduction (%)	3.9		69.5	53.5
<b>Solar-PV system</b>				
Without load shifting	-	42.28	5,258	37,183
With load shifting	-	40.98	4,259	32,285
Reduction (%)		3.1	19.0	13.2

numerical procedures. The demonstrations case studies on a residential household electricity profile in Malaysia found that in addition to the LS by ES (supply manipulation), direct LS (load manipulation) further reduces the capacity of operating units, achieving both technical and economic benefits.

The novel technique is intended for designing an off-grid DEG system. It could however also be used by users as a tool for analysing trade-offs in DEG systems if loads

were shifted to other TS than intended. The analysable trade-offs are such as between flexible lifestyle and system performance, and between capacities of operating units.

The study presented in this paper is suitable for off-grid power system. Further studies are required to extend ESCA-LS to a grid connected system or to consider more than one type of utility, such as heat and power. In addition, cost analysis could also be incorporated so that it may provide a holistic analysis.

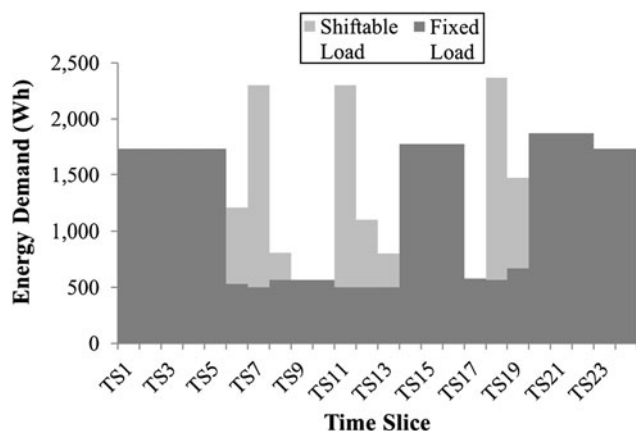


Fig. 7 New load profile for solar-PV

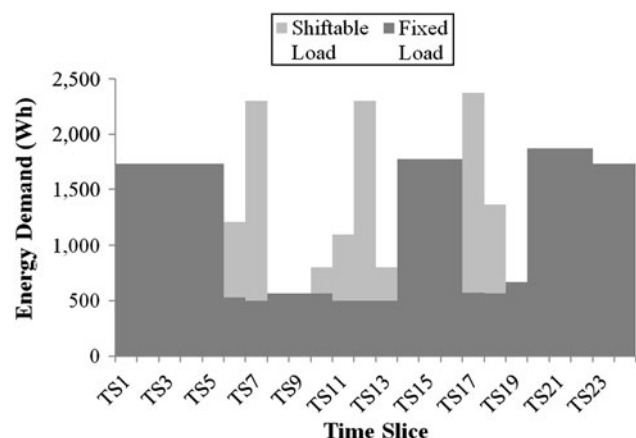


Fig. 8 New load profile for biomass power generator

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