

SAHPPA: a novel power pinch analysis approach for the design of off-grid hybrid energy systems

Wai Shin Ho · Cheng Seong Khor ·
Haslenda Hashim · Sandro Macchietto ·
Jiří Jaromír Klemesš

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Abstract This work proposes a novel approach called stand-alone hybrid system power pinch analysis (SAHPPA), which is particularly applicable for the design of off-grid distributed energy generation systems. The enhanced graphical tool employs new ways of utilising the recently introduced demand composite curve and supply composite curve while honouring and adapting fundamental energy systems engineering concepts. The SAHPPA method is capable of optimising the capacity of both the power generators and energy storage for biomass (i.e. non-intermittent) and solar photovoltaic (i.e. intermittent) energy technologies, which is a contribution to the emerging area of power pinch analysis. In addition, the procedure considers all possible efficiency losses in the overall system encompassing the charging–discharging and current inversion processes.

Keywords Power pinch analysis · Demand composite curve · Supply composite curve · Distributed energy generation · Off-grid · Power generator · Energy storage · Losses

Abbreviations

DCC	Demand composite curve
ESCA	Electric system cascade analysis
O&M	Operating and maintenance
PPA	Power pinch analysis
SAHPPA	Stand-alone hybrid system power pinch analysis
SCC	Supply composite curve

Introduction

Growing concern over greenhouse gas emissions and its impact on climate change have increased significantly the role of renewable energy resources. In tandem with this development is the emergence of energy systems that are increasingly distributed with potentially more efficient generation technologies (Bouffard and Kirschen 2008), which are variably known as decentralised generation, embedded generation, small-scale generation or distributed generation (Pepermans et al. 2005). A hybrid energy system particularly for deployment in standalone or isolated community in remote areas has become especially important. Such a system produces power by a combination of renewable energy-based electricity generators with the assistance of a power conditioning system (e.g. converter) and a power storage system (e.g. battery bank and pumped hydro) with fossil fuels used as a backup only.

For a country like Malaysia, which is well endowed with sunshine (i.e. solar energy resource) and biomass

W. S. Ho · H. Hashim
Process Systems Engineering Centre (PROSPECT), Faculty of
Chemical Engineering, Universiti Teknologi Malaysia,
81310 Skudai, Johor, Malaysia

C. S. Khor (✉)
Chemical Engineering Department, Universiti Teknologi
PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak,
Malaysia
e-mail: khorchengseong@petronas.com.my

S. Macchietto
Centre for Process Systems Engineering, Imperial College
London, South Kensington Campus, London SW7 2AZ, UK

J. J. Klemesš
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

(Ong et al. 2011), there is considerable potential for distributed hybrid energy generation systems to provide low-carbon energy supply and consequently contribute to the sustainable development. Various methods have been proposed for the design of such systems including model-based optimisation or mathematical programming, e.g. Kaldellis and Vlachos (2005); Monte Carlo simulation, e.g. Karki and Billinton (2001); artificial intelligence-based techniques such as genetic algorithms, e.g. Koutroulis et al. (2006); and pinch analysis e.g. Nemet et al. (2012). A recent review on the related area can be found in Klemeš and Varbanov (2013). An overview of pinch analysis and mathematical programming for process integration is elaborated by Klemeš (2013). The presented paper focuses on the application of pinch analysis-based approaches for power generation systems design.

The pinch analysis technique (Linnhoff et al. 1982) originally found applications in heat exchanger network design for the process industry. It has been documented in several books from University of Manchester [then known as University of Manchester Institute of Science and Technology (UMIST)] and the second edition of Linnhoff's book (Kemp 2007). These works have been followed by Smith (1995), Smith et al. (2000) and Smith (2005). Pinch analysis has been adopted in a wide range of problems including water network synthesis (Ng et al. 2007), resource conservation (Foo 2013) and energy systems planning (Tan and Foo 2007). Recently, several important books on pinch analysis have been published, and they include Klemeš et al. (2010), El-Halwagi (2012), Foo (2012) and a newly edited "Process Integration Handbook" in which most of the leading process integration researchers contributed to (Klemeš 2013).

The classical Grand Composite Curve tool has recently been applied to design isolated solar photovoltaic (PV) energy system with battery storage (Bandyopadhyay 2011) that is used in conjunction with a design space methodology (Sreeraj et al. 2010). The extension presented in this paper is that time is considered as the quality parameter (as analogous to temperature in heat pinch analysis) to perform sizing of the energy storage devices.

Based on the aforementioned Grand Composite Curve technique, Wan Alwi et al. (2012) developed a power composite curve as a targeting method to determine the minimum outsourced electricity supply to be purchased (from the grid) and excess electricity available for the next day operation. An enhancement of this graphical tool called continuous power composite curve can assist in analysing the system from 1 day to another to further reduce power supply and demand.

In dealing with a similar issue, Ho et al. (2012) proposes a stepwise numerical heuristics called electric system cascade analysis (ESCA) for the design of standalone distributed

energy generation and storage systems involving both non-intermittent (mainly fossil fuels, biomass) and intermittent sources (solar). The suggested technique is applicable to determine the power capacity of back-up thermal generators and both power- and energy-related capacities of battery storage. This work also considers power losses in the charging and discharging process as well as efficiency losses in the inverter used for converting from direct current (DC) to alternating current (AC). A major drawback of disregarding losses is the possible under-sizing of the system capacity. This has been demonstrated in the presented work. It is noteworthy that a corresponding visualisation-based graphical tool is not developed for this purpose since it is potentially cumbersome to include power losses. This is because at different conditions, the system maybe charging, discharging or requires current inversion, thus causing more energy losses that result in varying net efficiency.

Ho et al. (2013) considers extending the ESCA method to incorporate load shifting to improve the energy efficiency of an off-grid distributed energy generation system. The improved technique serves to optimise its load profile, power generation capacity and energy storage capacity, power and charging–discharging schedule. A realistic case study involving a hybrid solar PV and biomass energy system with storage is used to demonstrate the new development. The consideration for wind energy is planned for the future work.

Wan Alwi et al. (2013) extend the power composite curve technique developed earlier to allow power allocation to determine the minimum outsourced electricity and current storage capacity at each time interval. This graphical tool called Outsourced and Storage Electricity Curves can be used in conjunction with load shifting to further reduce maximum storage capacity and maximum power demand. Two heuristics are postulated and demonstrated on a case study from the literature.

Mohammad Rozali et al. (2013b) employ the classical cascade analysis technique to develop numerical targeting tools with similar purpose and capabilities as its graphical counterparts. Their approach is applicable for the design of on- and off-grid hybrid energy systems for startup and normal operations. Consideration for the effects of power losses during conversion, transfer and storage is attempted in Mohammad Rozali et al. (2013a). This work also accounts for a combined AC–DC coupled system with self-discharge losses in a lead–acid battery storage system.

It is worthy to note other work employing pinch analysis in which time is used as a temperature-driving force analogue. Recent works include applications for production planning of biomass utilisation (Ludwig et al. 2009), batch scheduling of reactors in multipurpose plants (Foo et al. 2007) and scheduling of manpower resources (Foo et al. 2010).

The presented paper proposes an enhanced graphical tool based on power pinch analysis concepts for the design of an off-grid distributed hybrid energy generation system. Fundamental concepts and relations in energy systems engineering for the design can be applied as well. “Methodology: SAHPPA procedure” section presents methodology of the proposed approach for determining the capacity and other associated design parameters of the power generators and energy storage device. Implementation of the technique is then demonstrated on an illustrative example in “Capacity of energy storage” section. Discussion of the results and proposed design are provided in “Power losses” together with comparison to previous techniques. Concluding remarks point out the strengths and applicability of the approach.

Methodology: SAHPPA procedure

The proposed novel approach stand-alone hybrid system power pinch analysis (SAHPPA) is an extension of its predecessor, the ESCA approach developed by the same research group (Ho et al. 2012). SAHPPA offers a tool to determine and optimise the capacities of both power generators and energy storage for hybrid energy systems by considering various effects of efficiency losses incurred. Novel ways of utilising the demand composite curve (DCC) and supply composite curve (SCC) introduced by Wan Alwi et al. (2012) in conjunction with fundamental concepts in energy systems engineering are proposed.

The general assumptions in SAHPPA are as follows: power supply is loaded before being considered for energy storage; an initial amount of energy stored is equal to final amount of energy stored to prevent power accumulation in the battery system with consideration for efficiency losses; excess power is allocated for energy storage; stored energy is used as electricity supplement during high demand periods; intermittent power generators produce energy based on external factors such as solar intensity in the case of solar PV systems.

The SAHPPA procedure is demonstrated by an illustrative example—a case study for the design of a stand-alone distributed hybrid power system comprising biomass and solar PV technologies to supply electricity to a small-scale batch processing factory in Malaysia. Relevant data on time of use and power demand of the appliances for the system design are as shown in Table 1.

Demand composite curve

The construction of a DCC is similar to the principles of Wan Alwi et al. (2012), in which the vertical axis represents time (h), while the horizontal axis represents

Table 1 Data for the example

	Power rating (kW)	Operating time		Total operating time (h)	Power consumption (kWh)
		Start	End		
Appliance 1 (A1)	5	0:00	24:00	24	120
Appliance 2 (A2)	10	8:00	17:00	9	90
Appliance 3 (A3)	10	8:00	24:00	16	160
Appliance 4 (A4)	15	21:00	24:00	3	45
Appliance 5 (A5)	50	8:00	17:00	9	450
Appliance 6 (A6)	20	0:00	8:00	8	160

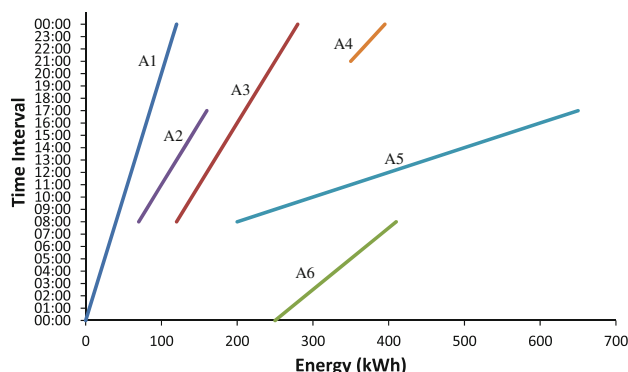


Fig. 1 Time of use and power demand of appliances for the example

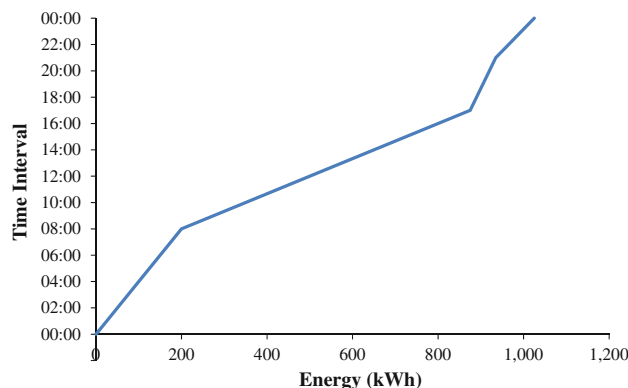


Fig. 2 Demand composite curve (DCC)

electricity generation or consumption (kWh). Each individual scaled demand line segment, which represents an electrical appliance, can be constructed as shown in Fig. 1. Note that gradient of the segment can be determined by taking the inverse of the corresponding power rating for a particular demand. Within each time interval, the Demand

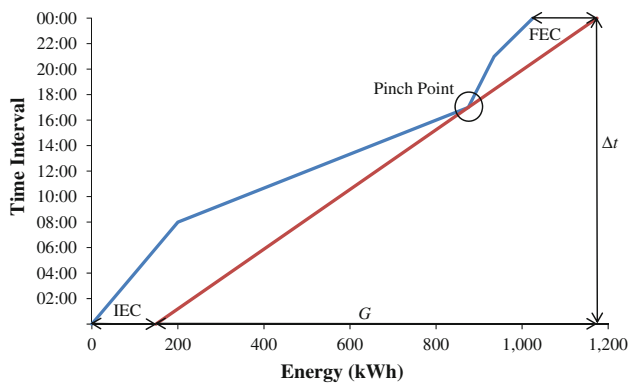


Fig. 3 Demand and supply composite curves for a biomass energy system

Line segments are combined to produce a DCC by summing the respective electricity demands. The procedure is repeated for the rest of the time intervals to yield the DCC for the entire system as shown in Fig. 2.

Supply composite curve and power capacity

SAHPPA proposes an alternative technique to Wan Alwi et al. (2012) for constructing the SCC. The SAHPPA-based technique is customised for non-intermittent and intermittent energy systems, in which the need for such a distinction between the two types of renewable energy system is explained later in this section. The SCC is utilised to determine the required capacity of the power generators that is an extension of previous work as Wan Alwi et al. (2012), which assumes a fixed capacity.

Non-intermittent power generator

A non-intermittent system such as a biomass energy system is assumed to be at constant generation, and the SCC can be represented as a straight line segment. The SCC can be constructed by iteratively adjusting the SCC such that the initial energy content (IEC) of energy storage is equal to its final energy content (FEC) while touching the DCC at what is referred to as the pinch point (see Fig. 3). The pinch point is significant as there is no energy left in storage to supply to the system. In other words, energy storage is at its minimum level at the pinch point (but not at zero energy level due to effects of depth of discharge, as detailed later).

From Fig. 3, the capacity C_B for a biomass energy system is given by:

$$C_B = \frac{G}{\Delta t} \tag{1}$$

where G is the net energy required (as shown in Fig. 3) and Δt is the time duration considered (typically 24 h).

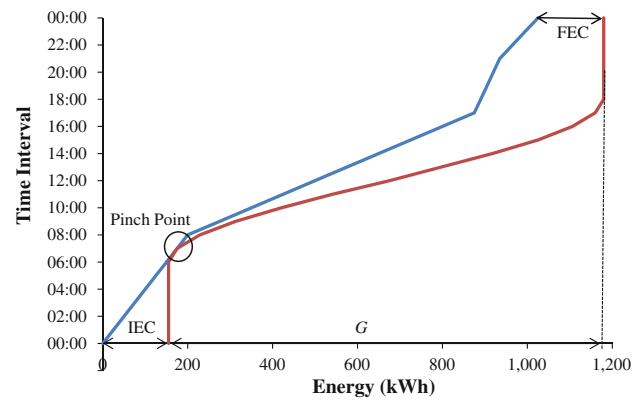


Fig. 4 Demand and supply composite curves for a solar PV energy system

This representation is mainly applicable for a non-intermittent power generator. For an intermittent system using solar PV or wind energy, external factors such as solar intensity and wind speed have to be taken into account. A case with such an energy system in SAHPPA is presented for solar PV technology in the next section.

Intermittent power generator

To construct SCC for a stand-alone intermittent power generator such as a solar PV system, an iterative stepwise procedure is proposed:

- (1) Construct a vertical line segment from the horizontal axis of energy, which is at the last time point, until it touches the DCC to give the initial pinch point. This line corresponds to zero generation before sunrise. The IEC can be determined at the pinch as shown in Fig. 4 (i.e. by taking the horizontal magnitude from the pinch to the DCC at the final time point).
- (2) Construct another vertical line segment from the first time point in such a way that the FEC equals to IEC (see Fig. 4). This line corresponds to zero generation after sunset.
- (3) Determine the distance between the two vertical lines—this gives the net energy required by the system G .
- (4) Determine the required solar PV capacity C_{PV} corresponding to total solar intensity $I(t)$ at time t as follows:

$$C_{PV} = \frac{G}{\sum_t I(t)} \tag{2}$$

- (5) Construct a solar generation supply curve (SGSC) based on energy generated by the solar PV system S_{PV} at each time point using the following relation in

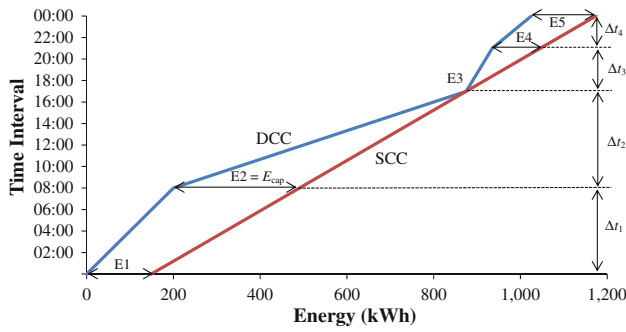


Fig. 5 Composite curves to determine energy-related capacity

such a way that the curve connects the endpoints of both vertical lines:

$$S_{PV}(t) = C_{PV}I(t), \quad \forall t. \tag{3}$$

The SGSC combined with the two vertical lines forms the SCC for the solar PV system.

- (6) If the SGSC lies above the DCC, shift the entire SCC to lie below the DCC while touching the DCC at a new pinch point.
- (7) The required area for installing the solar PV system A_{PV} can be calculated using:

$$A_{PV} = C_{PV}M \tag{4}$$

where M is the area for installing 1 kWp (kW peak) of solar PV system.

Capacity of energy storage

The energy and power-related capacity of an energy storage device can be determined from the DCC and SCC according to the SAHPPA procedure detailed in this section.

Energy-related capacity of energy storage

Energy-related capacity of storage is related to the maximum energy charged into the system. This parameter, denoted as E_{cap}^{max} , can be determined by identifying magnitude of energy (kWh) that corresponds to the maximum horizontal distance between a point on the DCC and a point on the SCC. To illustrate for the case of the biomass energy system presented earlier, the largest distance between any point on these curves is given by E_2 at approximately time 8:00 (see Fig. 5). Then, by accounting for effects of the depth of discharge DoD of energy storage, E_{cap}^{max} is determined as:

$$E_{cap}^{max} = \frac{E_2}{DoD} \tag{5}$$

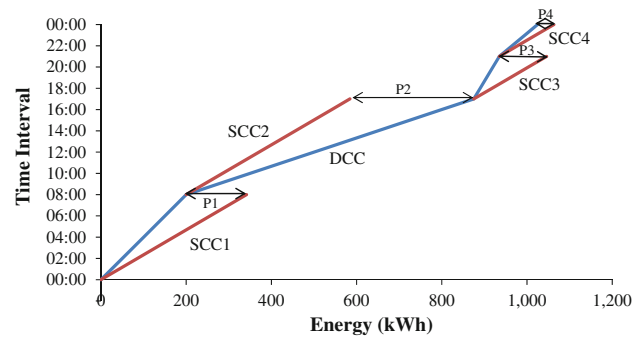


Fig. 6 Decomposed supply composite curves to determine power-related capacity

Power-related capacity of energy storage

Power-related capacity P_{cap}^{max} of an energy storage device can be determined by evaluating changes in energy capacity of storage at a particular time point. The changes show whether a storage device is in charging or discharging operating mode, and its corresponding maximum rate of energy change gives P_{cap}^{max} . Two techniques in SAHPPA to evaluate changes in the capacity of energy storage are proposed.

A direct approach involves utilising the composite curves (as shown in Fig. 5) to determine these energy capacity changes at each time point, in which the power-related capacity can be computed as:

$$P_{cap}(t) = \frac{E_{cap}(t + 1) - E_{cap}(t)}{\Delta t}, \quad \forall t \tag{6}$$

where for duration Δt of a time interval, $E_{cap}(t)$ and $E_{cap}(t + 1)$ are the storage energy capacities at the start and at the end. A positive value of P_{cap} indicates that energy is charged into storage (i.e. $E_{cap}(t + 1) > E_{cap}(t)$), while a negative value indicates storage is discharging energy (i.e., $E_{cap}(t + 1) < E_{cap}(t)$).

An alternative approach involves decomposing the SCC at suitable time intervals corresponding to kinks of the DCC. This is followed by shifting each decomposed part of SCC towards DCC such that each part touches DCC at the start of the time interval, as shown in Fig. 6. An energy storage is charged if SCC is on right side of DCC (i.e. gradient of DCC is greater than SCC). Conversely, storage is discharged if SCC is on left side of DCC (i.e. gradient of DCC is less than SCC). Power-related capacity of energy storage is given by the overall net change in the energy rate:

$$P_{cap}^{max} = \sum_t \frac{E(t)}{\Delta t}. \tag{7}$$

Power losses

Compared to previous work presented by Mohammad Rozali et al. (2013a), this approach accounts for all possible efficiency losses in a distributed energy generation system for both power generators and energy storage. The consideration encompasses the charging–discharging process as well as during AC–DC inversion and vice versa. It is noteworthy that such losses could lead to changes in the design parameters computed at each of the iterations in the calculations involved.

Losses in power generators

To estimate the associated losses of the system, total energy storage discharged $E^d(t)$ at a time point t , round-trip efficiency η_R and inverter efficiency η_I are considered. The value of η_R represents the ratio of total energy discharged (i.e. storage output) to total energy charged (i.e. storage input). $E^d(t)$ can be determined from the SCC. Energy due to losses E_B^l for a non-intermittent biomass system can be estimated as:

$$E_B^l = \frac{E_B^d}{\eta_R \eta_I^2} - E_B^d \tag{8}$$

Note that η_I is applied twice (hence the squared term) for a biomass-based system, which generates AC electricity, since current inversion is required prior to charging (i.e. from AC to DC) and during supply to the load (DC to AC).

Similarly losses for an intermittent solar PV system are given by:

$$E_{PV}^l = \frac{E_{PV}^d}{\eta_R} - E_{PV}^d \tag{9}$$

No inversion is involved for solar PV technology since conversion from DC to AC during energy supply to the load is accounted for in the generator capacity—see Eq. (13).

Since the losses correspond to additional energy required to support the system, actual capacities \tilde{C} of power generators incorporating losses, which are higher, can then be determined as follows:

$$\tilde{C}_B = \frac{G_B + E_B^l}{\Delta t}, \tag{10}$$

$$\tilde{C}_{PV} = \frac{G_{PV} + E_{PV}^l}{\eta_I \sum_t I(t)}. \tag{11}$$

Losses in energy-related capacity of energy storage

Similar to the foregoing approach for power generators, the actual energy-related capacity $\tilde{E}_{cap,B}^{max}$ of storage as corrected

for efficiency losses for a non-intermittent biomass-based system can be estimated as:

$$\tilde{E}_{cap,B}^{max} = \frac{E_{cap,B}^{max}}{\eta_I \sqrt{\eta_R}} - (\tilde{C}_B - C_B)t_{\theta}. \tag{12}$$

A square root of η_R is taken since only losses due to discharging are involved. The second expression on right-hand side of Eq. (12) represents additional energy supplied to system due to increase in generator capacity at a specific time point t_{θ} when discharging occurs (because maximum energy charged corresponds to total energy discharged).

For an intermittent solar PV system, the actual energy-related capacity of energy storage can be determined in the same fashion using the Eq. (13):

$$\tilde{E}_{cap,PV}^{max} = \frac{E_{cap,PV}^{max}}{\eta_I \sqrt{\eta_R}} - \eta_I (C_{PV}^{actual} - C_{PV}) \sum_{t \in \{t_{\theta}\}} I(t). \tag{13}$$

The effects of DoD can be incorporated in a similar manner to Eq. (5) for both types of energy systems.

Losses in power-related capacity of energy storage

Effects of losses on power-related capacity of energy storage can be considered based on the largest requirement of either charging or discharging. In a charging mode, the actual power-related capacity \tilde{P}_{cap}^{max} increases as given by Eqs. (14) and (15) for a biomass- and solar PV-based system:

$$\tilde{P}_{cap,B}^{max} = P_{cap,B}^{max} + \eta_I (\tilde{C}_B - C_B), \tag{14}$$

$$\tilde{P}_{cap,PV}^{max} = P_{cap,PV}^{max} + I^{max} (\tilde{C}_{PV} - C_{PV}), \tag{15}$$

where η_I accounts for energy lost during inversion prior to charging into storage for a biomass-based system, but which is not applicable to a solar PV-based system (as explained earlier) while I^{max} represents maximum solar radiation under sunny weather.

On the other hand, \tilde{P}_{cap}^{max} in a discharging mode decreases according to the following relations for the respective system:

$$\tilde{P}_{cap,B}^{max} = P_{cap,B}^{max} - \frac{1}{\eta_I} (\tilde{C}_B - C_B), \tag{16}$$

$$\tilde{P}_{cap,PV}^{max} = P_{cap,PV}^{max} - \frac{1}{\eta_I} (\tilde{C}_{PV} - C_{PV}), \tag{17}$$

where η_I represents losses during discharging before supply to load. Note that if \tilde{P}_{cap}^{max} is determined based on discharging mode, it may be worthy to revisit Eqs. (14) and (15), because reduced power-related capacity might in turn decrease the discharging magnitude to such an extent that energy storage is in a charging mode.

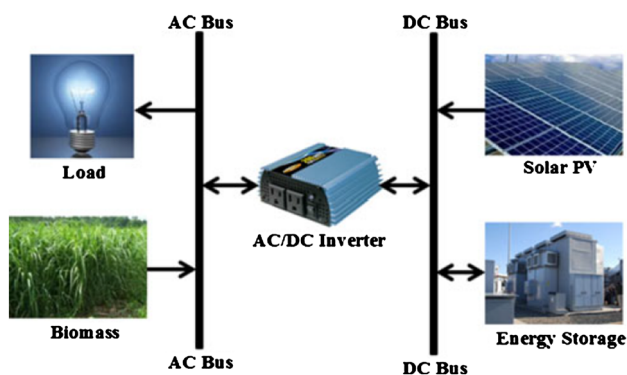


Fig. 7 Configuration of the hybrid power system for the case study

Table 2 Design parameters for the Illustrative example

Parameter	Value
Installation area for 1 kWp of monocrystalline silicon solar PV module M	8 m ² (Rashid et al. 2011)
Depth of discharge DoD	80 % (Komor and Glassmire 2012)
Battery round-trip efficiency η_R	56.2 5% (Haidar et al. 2011)
Inverter efficiency η_I	90 % (Zhou et al. 2008)

The next section presents an illustrative example that demonstrates the implementation of the SAHPPA approach.

Illustrative example

Problem description

In this section, we demonstrate an implementation of the SAHPPA procedure by revisiting the illustrative example presented earlier. Configuration of the system for the example is shown in Fig. 7, which employs a direct-fired biomass technology and solar PV power generators with a sodium sulphur battery for energy storage. As indicated earlier, in this system, DC electricity generated by solar PV system is inverted to AC electricity before it is fed to the load, while no inversion is required for storage as the battery stores and produces DC electricity. On the other hand, the biomass-based system generates AC electricity (so, does not need inversion) but requires inversion from AC to DC for storage. Table 2 lists the associated design parameters for the Illustrative example.

Implementation of SAHPPA procedure

A complete flow of the general procedure to implement SAHPPA is described in the following seven-step sequence as summarised in the flow chart in Fig. 8.

Step 1 The first step involves constructing DCC for the power load given in Table 1, as outlined in “Demand composite curve” section.

Step 2 The SCC is constructed, one for a biomass energy system and another for a solar PV system, according to the approach presented in “Supply composite curve and power capacity” section.

Step 3 The resultant composite curves (see Figs. 9, 10) allow the system capacity C_B and C_{PV} to be obtained for the biomass and solar PV systems. In addition, the area A_{PV} for installing the solar PV generator can be determined. Correction for losses for both power generator types can be incorporated as explained in “Losses in power generators” section.

Step 4 Now the SAHPPA procedure can be applied for the design of energy storage. As elucidated by the two separate branches in Fig. 8, depending on weather conditions, the system is designed such that the biomass system acts as a back-up power generator to the solar PV system during low sunshine situations (i.e. rainy or cloudy weather).

Step 5.1 Under a best-case scenario of sunny weather with daily solar intensity as shown in Fig. 11, only solar PV storage is used to provide energy to the system.

Step 5.2 On the other hand, only biomass energy is used when no solar energy storage is available under a worst-case scenario of rainy or cloudy weather.

Therefore, two separate SAHPPA executions are conducted to design energy storage for a biomass power subsystem and a solar PV subsystem to ensure overall system reliability under all types of weather conditions. It can be demonstrated that since the SAHPPA implementation as shown in Fig. 8 encompasses a worst-case scenario, the design is robust and caters for variability in the load demands as detailed in a sensitivity analysis study in “Sensitivity analysis” section later.

Based on “Capacity of energy storage” section, the energy-related capacity $E_{cap,PV}^{max}$ and $E_{cap,B}^{max}$ for the two systems can be calculated by utilising Eq. (5), which accounts for the effects of DoD. Following this, the power-related capacity $P_{cap,PV}^{max}$ and $P_{cap,B}^{max}$ is determined using either of the two approaches proposed in “Power-related capacity of energy storage”. The second approach, which involves using decomposed SCC, is shown in Figs. 12 and 13 for the biomass and solar PV systems, respectively. Efficiency losses are considered by utilising the relations developed in “Losses in energy-related capacity of energy storage” and “Losses in power-related capacity of energy storage” sections to obtain $\tilde{E}_{cap,PV}^{max}$, $\tilde{E}_{cap,B}^{max}$, $\tilde{P}_{cap,PV}^{max}$ and $\tilde{P}_{cap,B}^{max}$.

Step 6. Since the overall system design has to accommodate all weather conditions, corresponding larger magnitudes in terms of \tilde{E}_{cap}^{max} and \tilde{P}_{cap}^{max} are adopted to ensure a

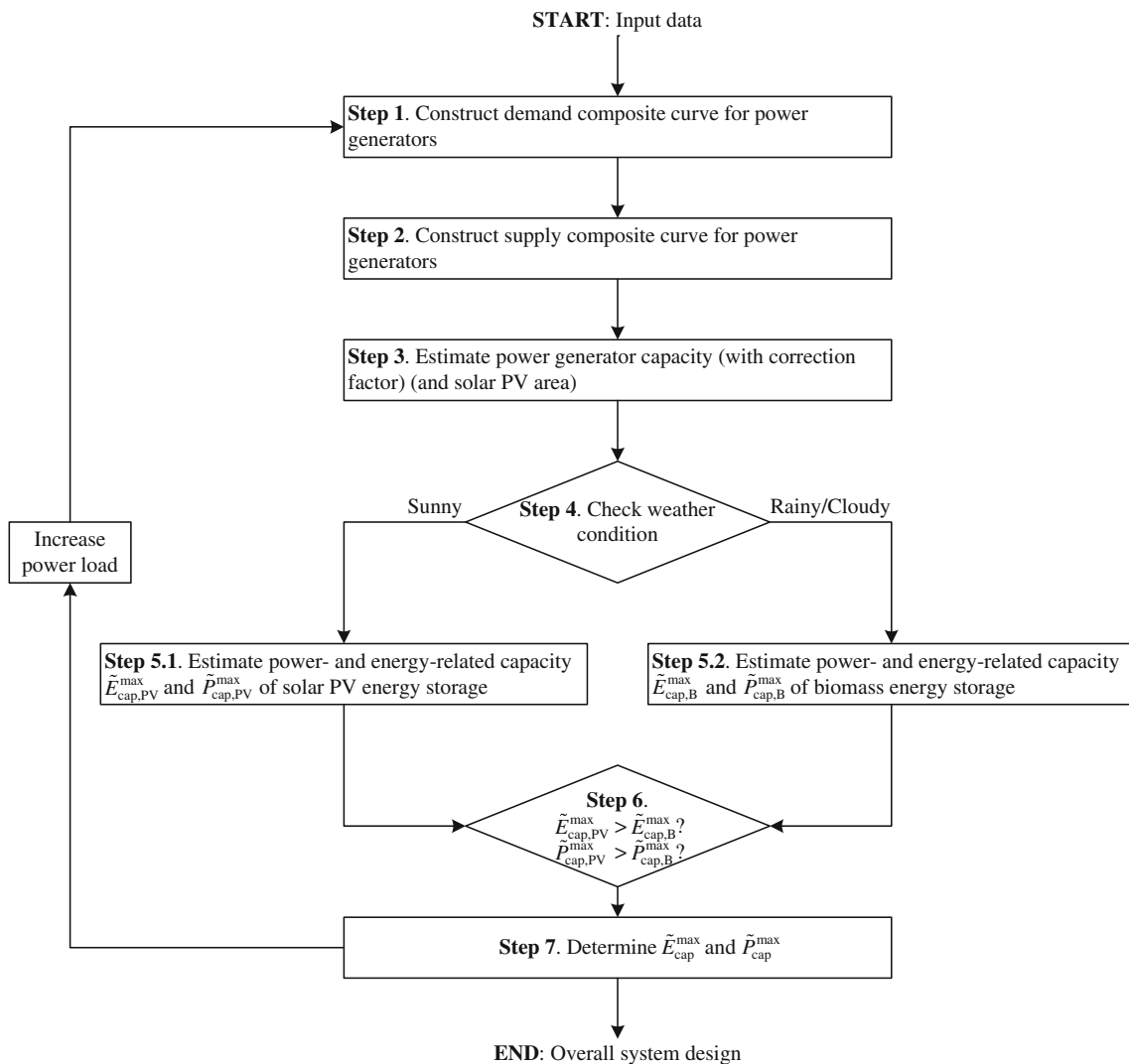


Fig. 8 General procedure to implement the stand-alone hybrid system power pinch analysis (SAHPPA) approach

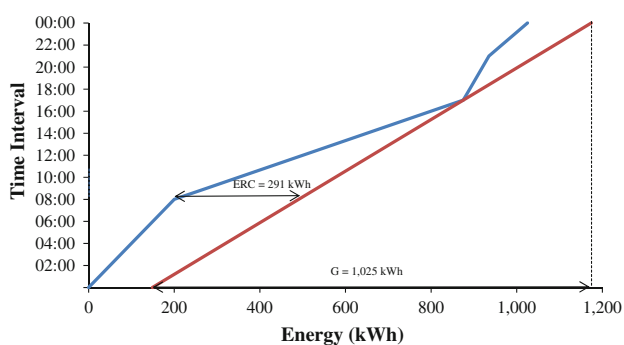


Fig. 9 Composite curves for the biomass energy system

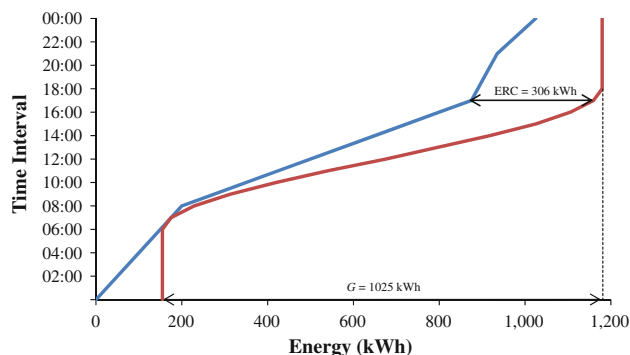


Fig. 10 Composite curves for the solar PV energy system

feasible system design by comparing the resultant design for the two individual subsystems (as based on general design principles).

Step 7 Finally, variables for the overall system design are obtained. However, in practical operation, actual load demands of the appliances (in terms of power

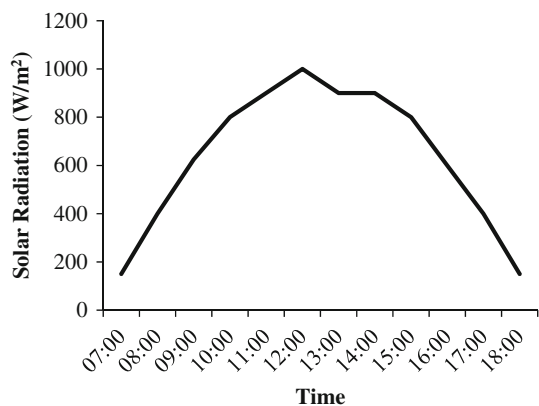


Fig. 11 Daily solar intensity under sunny weather condition for the case study

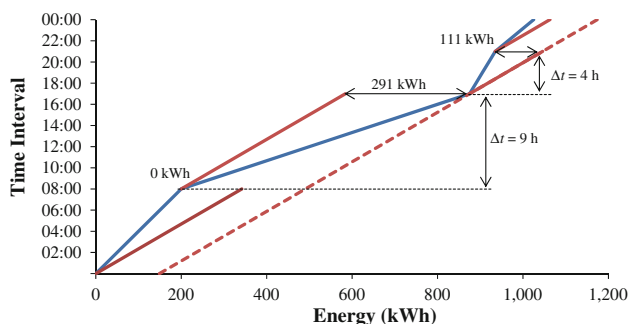


Fig. 12 Decomposed supply composite curves for the biomass energy system

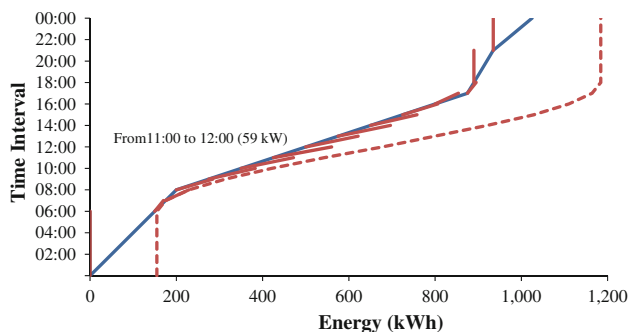


Fig. 13 Decomposed supply composite curves for the solar PV energy system

consumption) may fluctuate, while the SAHPPA approach is mainly amenable to deterministic demands. Hence, to assess the applicability of SAHPPA under variable load, sensitivity analysis is conducted by repeating the whole procedure with increased power consumption of the appliances on a case-wise basis.

Results and discussion

Proposed design using SAHPPA

The resultant design variables for the hybrid power systems by implementing SAHPPA are summarised in Tables 3 and 4 for the biomass- and solar PV technologies. For comparison, the variables computed for the cases of not including the correction factors for efficiency losses and DoD are tabulated. Analysis of the results reveals an increase by more than 25 % in the capacity of both power generators and energy storage, particularly in the power-related capacity of battery for the solar PV system. By this means, it can be deduced that there is significance in taking the losses and DoD into consideration with implication for the design as well as the associated cost and eventual operation.

By considering resultant design for the two individual subsystems, the larger magnitudes as given by $\tilde{E}_{cap,PV}^{max}$ and $\tilde{P}_{cap,PV}^{max}$ are employed to provide variables for the overall system design as tabulated in Table 5.

Sensitivity analysis

Sensitivity analysis is performed by considering three cases of increased power consumption of 10, 20 and 30 %, respectively, for each of the appliances. Resulting effects on the design variables of the hybrid energy system are tabulated in Table 6 in terms of the magnitude and relative difference (in percentage as stated in parentheses) to the nominal design summarised in the foregoing Table 5. It can be observed that there is resultant nonlinear increase in the major design parameters with increased load demands. The largest magnitude increase involves system capacity particularly for the biomass generator at 17.1 % higher than the nominal in the 30 % increment case. Energy-related capacity and power-related capacity also increase considerably by as much as 12.8 and 11.4 %. It can, therefore, be deduced that increasing the biomass power generator capacity and the energy storage sizing after performing SAHPPA is a viable consideration to provide additional safety margins.

Comparison with other methods

A comparison with the ESCA numerical tool (Ho et al. 2012) is conducted for a quantitative validation of the design obtained using the SAHPPA approach (see relevant data in Appendix A). Table 7 tabulates the design suggested by the ESCA method alongside that of SAHPPA (as obtained earlier in the previous section) for the same illustrative example—the full cascade analysis results

Table 3 Design variables for the biomass energy system

Design variable	Value	Difference with correction factors (%)
Net energy required G	1,025 kWh	–
System capacity (C_B, \tilde{C}_B)	42.7 kW (without losses) 57.2 kW (with losses)	34.0%
Energy-related capacity ($E_{cap,B}^{max}, \tilde{E}_{cap,B}^{max}$)	[1] 291.0 kWh (without DoD or losses) [2] 300.6 kWh (without DoD, but with losses) [3] 375.8 kWh (with DoD and losses at $t_0 = 8:00-17:00$)	[1 vs. 2] 3.3 %; [1 vs. 3] 29.1 %; [2 vs. 3] 25.0 %
Power-related capacity ($P_{cap,B}^{max}, \tilde{P}_{cap,B}^{max}$)	32.3 kW (without losses) 40.8 kW (with losses in charging mode)	26.3 %

Table 4 Design variables for the solar PV energy system

Design variable	Value	Difference with correction factors (%)
Net energy required G	1,025 kWh	–
System capacity (C_{PV}, \tilde{C}_{PV})	134.0 kWp (without losses) 184.0 kWp (with losses)	37.3 %
Energy-related capacity ($E_{cap,PV}^{max}, \tilde{E}_{cap,PV}^{max}$)	[1] 306.0 kWh (without DoD or losses) [2] 428.6 kWh (without DoD, but with losses) [3] 535.8 kWh (with DoD and losses)	[1 vs. 2] 40.1 % [1 vs. 3] 75.1 % [2 vs. 3] 25.0 %
Power-related capacity ($P_{cap,PV}^{max}, \tilde{P}_{cap,PV}^{max}$)	52.0 kW (without losses) 102.0 kW (with losses in charging mode)	96.2 %
Installation area required A_{PV}	1,072 m ² (without losses) 1,472 m ² (with losses)	37.3 %

Table 5 Variables for the overall system design

Design variable	Value
Net energy required G	1,025 kWh
System capacity	57.2 kW for biomass system; 184.0 kWp for solar PV system
Energy-related capacity \tilde{E}_{cap}^{max}	535.8 kWh
Power-related capacity \tilde{P}_{cap}^{max}	102.0 kW
Installation area required	1,472 m ² for solar PV system

Table 6 Sensitivity analysis results for the overall system design

design variable	Value for 10 % increase		Value for 20 % increase		Value for 30 % increase	
Net energy G (kWh)	1128	(10.0%)	1230	(20.0%)	1333	(30.0%)
System capacity (kW) for biomass	60.5	(5.8%)	63.7	(11.4%)	67.0	(17.1%)
System capacity (kW) for solar PV	189.2	(2.8%)	196.1	(6.6%)	203.0	(10.3%)
$\tilde{E}_{cap,PV}^{max}$ (kWh)	559.6	(4.4%)	582.0	(8.6%)	582.0	(12.8%)
$\tilde{P}_{cap,PV}^{max}$ (kW)	107.0	(4.9%)	110.3	(8.1%)	110.3	(11.4%)
Installation area (solar PV) (m ²)	1514	(2.8%)	1569	(6.6%)	1569	(10.3%)

Table 7 Comparison between SAHPPA and previous work (ESCA)

	Biomass system		Solar PV system	
	ESCA	SAHPPA	ESCA	SAHPPA
System capacity (kW)	52.7	57.2	182.2	184.0
Energy-related capacity (kWh)	371.6	375.8	528.5	535.8
Power-related capacity (kW)	33.0	40.8	98.8	102
Total annualised cost (RM/y)	95,773	101,955	336,248	339,901

using ESCA are presented in Appendix B. It can be concluded that use of the design procedure proposed by the SAHPPA methodology is justified as there is no order of magnitude difference in the design compared to that of ESCA. Design capacities of both power generators and energy storage registered increments with use of the more representative SAHPPA tool incorporating correction factors for efficiency losses. As is also shown, such increments have consequence towards the estimated total annualised cost of the system. Furthermore, SAHPPA is relatively simpler to implement than ESCA on top of its graphically oriented approach that is intuitive and visually appealing to engineers in the industry who demand readily interpreted solution particularly under time pressure.

Concluding remarks

In the presented paper, it is shown that implementing SAHPPA on an illustrative example results in an increase of more than 25 % in the design capacities of power

generators and energy storage when considering the effects of efficiency losses and depth of discharge (in the latter). Comparison with the ESCA tool developed previously also demonstrates that SAHPPA generates a more representative estimate of the system's total annualised cost. The SAHPPA tool is, therefore, a suitable power pinch analysis tool to assist in the design of off-grid distributed standalone hybrid power generation systems, which offers the capability of optimising the capacity of both power generators and energy storage for both intermittent and non-intermittent energy technologies. Future work will involve applying SAHPPA for a medium-to-large scale industrial processing facility such as a palm oil mill at a remote location in Malaysia with restricted connection to the national electricity grid. The SAHPPA procedure is also going to be expanded to consider wind energy technology in the systems design.

Appendix

Appendix A: Cost data

Power generator	Capital cost (RM ^a /kW)	Fixed O&M ^b cost (RM/kW)	Variable O&M cost (RM/kWh)
Biomass (direct-fired)	12,120	316	0.02
Solar PV	16,414.62	122.9	–
<i>Source</i> DECC (2010), EIA (2010)			
Energy storage	Energy-related cost (RM/kWh)	Power-related cost (RM/kWh)	Fixed O&M cost (RM/kW)
Sodium sulphur battery	901.44	735.55	184.67
<i>Source</i> Steward et al. (2009)			
System life: 20 years			
Fractional interest rate/year: 7 %			

^a RM stands for the Ringgit Malaysian currency (RM1.00 = EUR as based on November 2013 currency exchange rate)

^b O&M: operating and maintenance

Appendix B: Results using ESCA

Time (h:min)	Demand (kWh)	Biomass energy generation (kWh)	Net energy demand (kWh)	Charging of energy (kWh)	Discharging of energy (kWh)	Cumulative energy (kWh)	Adjusted cumulative energy (kWh)
						0.00	147.76
00:00	25	52.70	27.70	18.70	0.00	18.70	166.45
01:00	25	52.70	27.70	18.70	0.00	37.39	185.15
02:00	25	52.70	27.70	18.70	0.00	56.09	203.85
03:00	25	52.70	27.70	18.70	0.00	74.79	222.55
04:00	25	52.70	27.70	18.70	0.00	93.49	241.24
05:00	25	52.70	27.70	18.70	0.00	112.18	259.94
06:00	25	52.70	27.70	18.70	0.00	130.88	278.64
07:00	25	52.70	27.70	18.70	0.00	149.58	297.34
08:00	75	52.70	-22.30	0.00	-33.04	116.54	264.30
09:00	75	52.70	-22.30	0.00	-33.04	83.50	231.26
10:00	75	52.70	-22.30	0.00	-33.04	50.47	198.22
11:00	75	52.70	-22.30	0.00	-33.04	17.43	165.19
12:00	75	52.70	-22.30	0.00	-33.04	-15.61	132.15
13:00	75	52.70	-22.30	0.00	-33.04	-48.64	99.11
14:00	75	52.70	-22.30	0.00	-33.04	-81.68	66.07
15:00	75	52.70	-22.30	0.00	-33.04	-114.72	33.04
16:00	75	52.70	-22.30	0.00	-33.04	-147.76	0.00
17:00	15	52.70	37.70	25.45	0.00	-122.31	25.45
18:00	15	52.70	37.70	25.45	0.00	-96.86	50.90
19:00	15	52.70	37.70	25.45	0.00	-71.41	76.34
20:00	15	52.70	37.70	25.45	0.00	-45.97	101.79
21:00	30	52.70	22.70	15.32	0.00	-30.64	117.11
22:00	30	52.70	22.70	15.32	0.00	-15.32	132.43
23:00	30	52.70	22.70	15.32	0.00	0.00	147.76

Time (h:min)	Demand (kWh)	Solar radiation (W/m ²)	Solar energy generation (kWh)	Net energy demand (kWh)	Charging of energy (kWh)	Discharging of energy (kWh)	Cumulative energy (kWh)	Adjusted cumulative energy (kWh)
							0.00	185.19
00:00	25	0.00	0.00	-25.00	0.00	-37.04	-37.04	148.15
01:00	25	0.00	0.00	-25.00	0.00	-37.04	-74.07	111.11
02:00	25	0.00	0.00	-25.00	0.00	-37.04	-111.11	74.07
03:00	25	0.00	0.00	-25.00	0.00	-37.04	-148.15	37.04
04:00	25	0.00	0.00	-25.00	0.00	-37.04	-185.19	0.00
05:00	25	0.15	27.97	0.17	0.14	0.00	-185.04	0.14
06:00	25	0.40	74.58	42.13	35.10	0.00	-149.94	35.25
07:00	25	0.63	116.54	79.88	66.57	0.00	-83.37	101.82
08:00	75	0.80	149.17	59.25	49.38	0.00	-33.99	151.19
09:00	75	0.93	172.47	80.23	66.86	0.00	32.86	218.05
10:00	75	1.00	186.46	92.81	77.34	0.00	110.21	295.39
11:00	75	0.90	167.81	76.03	63.36	0.00	173.57	358.75
12:00	75	0.90	167.81	76.03	63.36	0.00	236.93	422.11

continued

Time (h:min)	Demand (kWh)	Solar radiation (W/m ²)	Solar energy generation (kWh)	Net energy demand (kWh)	Charging of energy (kWh)	Discharging of energy (kWh)	Cumulative energy (kWh)	Adjusted cumulative energy (kWh)
13:00	75	0.80	149.17	59.25	49.38	0.00	286.30	471.49
14:00	75	0.60	111.88	25.69	21.41	0.00	307.71	492.89
15:00	75	0.40	74.58	-7.87	0.00	-11.67	296.04	481.23
16:00	75	0.15	27.97	-49.83	0.00	-73.82	222.22	407.41
17:00	15	0.00	0.00	-15.00	0.00	-22.22	200.00	385.19
18:00	15	0.00	0.00	-15.00	0.00	-22.22	177.78	362.96
19:00	15	0.00	0.00	-15.00	0.00	-22.22	155.56	340.74
20:00	15	0.00	0.00	-15.00	0.00	-22.22	133.33	318.52
21:00	30	0.00	0.00	-30.00	0.00	-44.44	88.89	274.07
22:00	30	0.00	0.00	-30.00	0.00	-44.44	44.44	229.63
23:00	30	0.00	0.00	-30.00	0.00	-44.44	0.00	185.19

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