**Cost-Screening Study for a Cost-Effective Hybrid Power System Using Power Pinch Analysis**

by

Siti Hawa Nabilah Binti Zahari

15571

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

SEPTEMBER 2015

Universiti Teknologi PETRONAS,

32610, Bandar Seri Iskandar,

Perak Darul Ridzuan.

# CERTIFICATION OF APPROVAL

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(CHEMICAL ENGINEERING)

Approved by,

__________________________________

(Dr. Nor Erniza Binti Mohammad Rozali)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

September 2015

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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SITI HAWA NABILAH BINTI ZAHARI

# ABSTRACT

The application of renewable energy (RE) for electricity generation is rapidly increasing due to the depletion of the conventional fossil as well as environmental issue. Hybrid Power System (HPS) comprises the combinations of RE that incorporate energy storage that could be the best solution to solve the problems of generating off-grid electricity network especially for rural areas. Power Pinch Analysis (PoPA) has been developed to identify the optimal allocation of power in HPS, thus producing an optimal system. In this research, a PoPA technique called the modified Storage Cascade Table (SCT) has been utilized to identify the actual storage capacity for specific energy storage. Afterwards, the Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) has been adapted in this research to screen four different types of energy storage namely lead-acid battery, superconducting magnetic energy storage (SMES), supercapacitor and flywheel energy storage (FES) in order to attain the most cost-effective HPS. Results show that SMES gives the best performance on the efficiency and the lowest payback period which lead to the most cost-effective HPS for household applications.

# ACKNOWLEDGEMENT

In The Name of Allah, The Most Gracious and The Most Merciful.

All praises go to Him for the accomplishment of this final year project. The success and the final outcome of the project require a lot of assistance and guidance from many people.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AC | - | Alternating Current |
| CAES | - | Compressed Air Energy Storage |
| DC | - | Direct Current |
| DoD | - | Depth of Discharge |
| EES | - | Electrical Energy Storage |
| FES | - | Flywheel Energy Storage |
| GHG | - | Greenhouse Gases |
| HPS | - | Hybrid Power System |
| HES | - | Hybrid Energy System |
| IAS | - | Investment vs Annual Saving |
| MOES | - | Minimum Outsourced Electricity Supply |
| PA | - | Pinch Analysis |
| PoPA | - | Power Pinch Analysis |
| PV | - | Photovoltaic |
| RE | - | Renewables Energy |
| SCT | - | Storage Cascade Table |
| SHARPS | - | Systematic Hierarchical Approach for Resilient Process Screening |
| SMES | - | Superconducting Magnetic Energy Storage |

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# CHAPTER 1

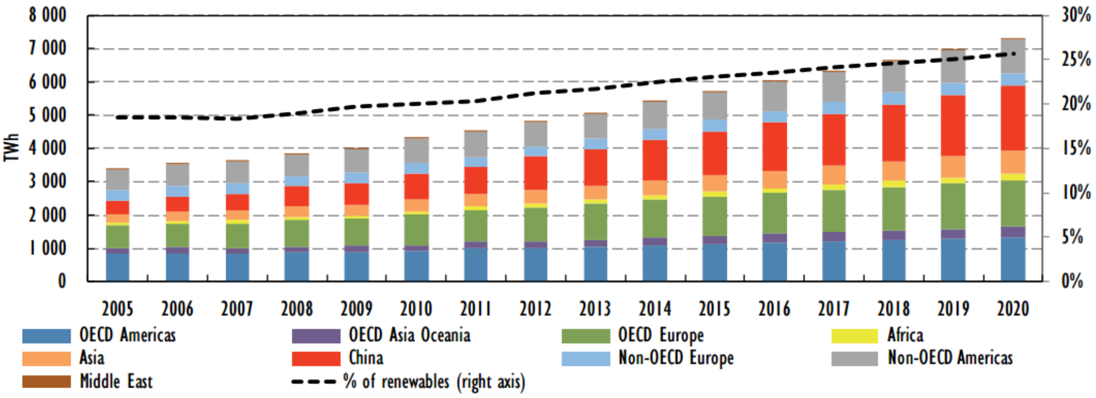
# INTRODUCTION

## 1.1 Background of Study

The fact that the energy cannot be created or be destroyed but it can be changed or transformed from one form to another has led to a vast exploration on the energy transformation via various modes. One of the essential energy that was discovered back in about 600 BC by the Ancient Greek is the electrical energy. As the global demand for electricity keep rising, there are multiple ways that primary energy can actually be transformed into electrical energy. The most common is the coal-fired power generation which is expected to have a major increased share as approaching 2020 (Bajpai *et al.*, 2012).

Recently, the application of Renewables Energy (RE) in power generation is growing and hydropower is expected to be in lead with 60% growth projection mainly in China and Asian countries (International Energy Agency, 2014). Other renewables such as wind and solar photovoltaic (PV) also follow the increasing growth trends but with percentages that slightly lower compared to the hydropower (Sims *et al.*, 2003). The intermittent renewable power sources such as wind and solar power were also predicted to act as the main role in global electricity production in the year of 2025 up to 2050 (Schoenung *et al.*, 2003). In addition, this renewables have been used as an alternative fuel as it is naturally replenished and can be categorized as inexhaustible sources.

Accordingly, it has been observed that the development of solar and wind energy technologies in some countries such as China and Europe for power generation purposes are continuously growing (International Energy Agency, 2014). China shows the highest production of renewable electricity approximately 1200 TW/h in 2015 and consequently projected an increasing forecast for its production up to 2020. Figure 1.1 represents the global renewable electricity production by region.




Notes: unless otherwise indicated, all material in figures and tables in this chapter derive from International Energy Agency (IEA) data and analysis. Hydropower includes pumped storage; the onshore and offshore wind split is estimated; total generation is gross power generation.

Figure 1.1 Global renewable electricity production by region (International Energy Agency, 2014)

Involvement of RE in electricity generation has brought to the development of Hybrid Power System (HPS) that can be seen as the new solution for solving the problems in rural areas or locations that are not accessible to the electricity supply. Besides, the interruptions of power supply that are usually one of the biggest challenges occur in industrial sectors also can be ended with the installation of this HPS.

HPS is a stand-alone power system that combined two or more power sources which comes from the renewables and non-renewables. The sources of the HPS come from the renewables which consist of controlled and uncontrolled RE while the example of sources from non-renewables are such as diesel generator and coal-fired steam generator.

Controlled sources refer to the primary energy sources such as hydro that can bring high possibility in controlling the electrical power production whereas uncontrolled sources are meant for the unpredictable and independent from human's action such as the wind and solar power plants (Paska *et al.*, 2009).

The typical major components of HPS may include the storage systems, renewable energy sources and power conditioning equipment (Mohammad Rozali, 2014). The storage technology for HPS is one of the important factors to be revised in utilizing the RE sources into power network as the electricity should be generated exactly as the time it is needed in order to satisfy the demand.

This research will focus on determining the most cost-effective HPS by using Power Pinch Analysis (PoPA). Pinch Analysis (PA) or also known as process integration is a method used in obtaining the optimum recovery system by using several techniques. Graphical and algebraic approaches are the two methods in PA that are being used for finding the 'pinch' that represents the bottleneck for the resource recovery (Mohammad Rozali, 2014). The main key for the successful PA is setting the energy targets (Kemp, 2006). In many industries and plant sectors, the main target is commonly related to energy reduction and cost-optimization of production.

## 1.2 Problem Statement

Environmental issue has been observed to be critical on the 20's era and expected to become worst if there is no precaution steps taken. The high demand of fossil fuels such as petroleum has contributed to the high emissions of carbon dioxide ($CO_2$) in the atmosphere. The effects of huge amount of greenhouse gases including the $CO_2$ are unimaginable, since it will lead to global warming and could give a severe impact towards the human's health.

Burning of fossil fuels in power stations for electricity generation purposes has been widely implemented all over the world. In any power generation steps, turbine is needed and prime mover is fixed according to the sources of energy available. For instance, coal is being burned to boil the water resulting in steam production to drive the turbine that attach to the generators to generate electricity. A solution must be figured to reduce the fossil fuel which issue since this major energy sources are non-renewables and are expected to be depleted someday in the future.

Accordingly, researchers and scientists have been trying to manipulate the renewables energy (e.g.: wind, solar, biomass) to function exactly like the non-renewables to produce the same output. One of the most practical alternatives for network planners in order to achieve targets set by the national and international Greenhouse Gas (GHG) emission reduction targets is by applying the electricity generation using renewable energy generation technologies (Abdullah *et al.*, 2015).

Therefore, application of RE in Hybrid Power System (HPS) is invented to meet the expected solutions by using the RE as an alternative for power generation. The existing HPS are to be said not economical due to the selection of equipment's types that are involved in the construction of the HPS itself. For instance, the component that gives a big impact on HPS's performance is the energy storage system. Various types of energy storage available with their respective cost and technical characteristics will surely contribute to the overall performance of the HPS. Thus, this research focuses on the cost-screening study targeting on the energy storage in order to obtain a cost-effective Hybrid Power Systems (HPS) by implementing a new technique named Systematic Hierarchical Approach for Resilient Process Screening (SHARPS).

Follow is the problem statement of this research:

*Given a set of power sources from renewable energy sources specifically the wind and solar energy, and a set of power demands required by industrial sectors, it is desired to execute a cost-screening study in order to achieve a cost-effective Hybrid Power System (HPS) by using a systematic method based on Power Pinch Analysis (PoPA). In this research, the economics of various types of storage for the HPS is being taken into consideration and an approach of cost-screening technique named Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) technique is being adapted. The problem involves determining the cost-effective HPS by performing cost-screening study for energy storage systems.*

## 1.3 Objectives and scope of study

The main objective of this research is to attain a cost-effective Hybrid Power Systems (HPS) by performing a cost-screening study for the energy storage systems.

This paper shall cover all of the aspects as listed:

i. Targeting and allocations of electricity using Power Pinch Analysis (PoPA) technique called the modified Storage Cascade Table (SCT).
ii. Cost-screening study on the cost-effective HPS by using the approach of Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) technique.
iii. Cost analysis comparison study on the four different types of power storage available for HPS such as lead-acid battery, superconducting magnetic energy storage (SMES), supercapacitor, and flywheel energy storage (FES).

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Hybrid Power Systems (HPS)

Hybrid Power Systems (HPS) can be defined with various definitions. According to (Paska *et al.*, 2009), HPS is a set of units with a number of primary energy consists of renewable and non-renewable energy that available for electricity generation or combined heat and power generation. This system is driven by the advanced power electronics system that co-ordinate the whole operation.

Referring to Mohammad Rozali (2014), HPS functioned to generate electricity from RE sources that available depending on the load required by using different types of generators. Most of the authors agreed that the HPS is commonly made up by different types of power generators which using the RE and non RE sources as the input. However, for the RE, the sources are not available all the time throughout the year. Therefore, this unavailability of RE have brought to a deeper research on the hybrid renewable energy systems with the objective to ensure an adequate supply of electricity can be prepared (Bajpai *et al.*, 2012).

Commonly, HPS is equipped with the power conditioning system (e.g. converter) and power storage system (e.g. battery bank and pumped hydro) (Ho *et al.*, 2014). For a normal HPS to be operated, a storage system is needed to store the excess electricity when the electricity productions are higher than the load. The converter or regulator are necessary to convert the electricity produces according to the appliances (Mohammad Rozali, 2014). The stored electricity are being discharge when the current electricity production do not meet the demands at a particular time.

## 2.2 Electrical Energy Storage (EES)

Complications in electricity transmission and distribution that are commonly faced by power network systems applying HPS due to uncontrolled season and weather conditions have brought the researchers into a deeper searching on the storage technologies. Electrical Energy Storage (EES) is one of the alternative in storing the energy in a certain state and being discharge by converting them into electrical energy when the condition is necessary (Ho *et al.*, 2013). The storage technologies also important to solve the problems of unstable network load as well as can provide an immediate response to the demand when the electricity is needed (Ibrahim *et al.*, 2008).

Ho *et al.* (2013) describe the variations in EES which can be categorized into five; mechanical, electrochemical, electrical, chemical and thermal energy storage. Meanwhile, according to Mohammad Rozali (2014), there are several storage technologies for HPS that have been discovered such as pumped hydro storage, compressed air energy storage (CAES), superconducting magnetic energy storage (SMES), flywheel energy storage (FES), and lead-acid battery. Mohammad Rozali (2014) also mentioned that storage technology is very significant especially for the energy systems located in remote areas and are away from the electricity grid.

## 2.3 Power Pinch Analysis (PoPA)

Power Pinch Analysis (PoPA) was derived from the conventional Pinch Analysis (PA) in which the subject is the power systems instead of heat. The same concept and basic applied to PoPA as in PA, but the only difference is the driving force used is the time different as an analogy to the temperature. PoPA consists both the graphical and algebraic approaches in which the plotted time versus electricity variations, with the understanding that the electricity can only be cascaded to the future, but not to previous time (Mohammad Rozali, 2014).

Mohammad Rozali (2014) also stated that PoPA starts from the graphical and algebraic method that involves Power Composite Curve (PCC), Continuous Power Composite Curves (CPCC), Power Cascade Table (PCT), and Storage Cascade Table (SCT). The objective of these four techniques that consist both of graphical and algebraic is to develop targeting methods for first day and continuous 24h operations for designing development of an optimal HPS.

Targets for the Minimum Outsourced Electricity Supply (MOES) and Available Excess Electricity for the Next Day (AEEND) are the two outputs in algebraic and graphical PoPA method. In addition, algebraic approach such as the SCT can provide power allocations while modified SCT was then developed to integrate the HPS with the considerations of energy losses (Mohammad Rozali, 2014).

## 2.4 Systematic Hierarchical Approach for Resilient Process Screening (SHARPS)

SHARPS technique was previously being applied as a cost screening tool for design and retrofit of minimum water network for urban and industrial sectors. The current SHARPS technique that exists is only applicable to the water systems involving a single contaminant (Wan Alwi *et al.*, 2006). SHARPS provide a simple procedure shown as Figure 2.1.

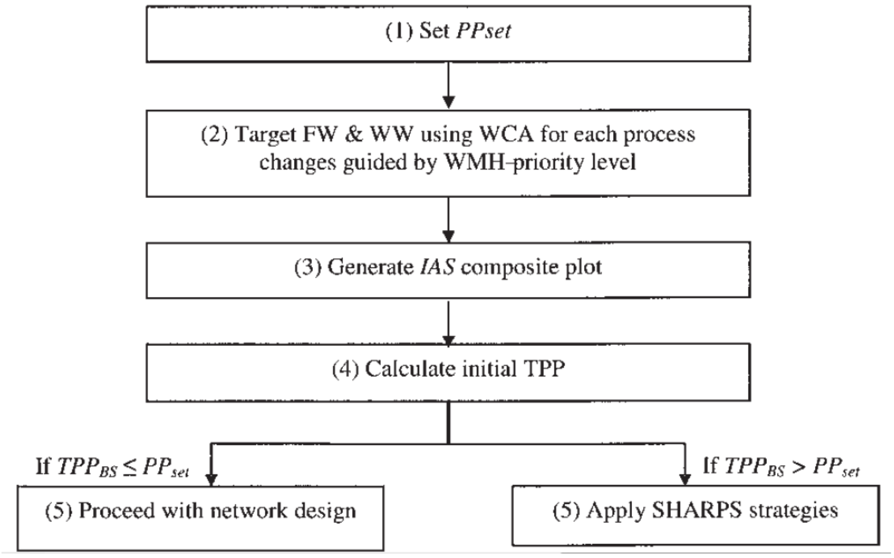



Figure 2.1 The overall SHARPS procedure (Wan Alwi *et al.*, 2006)

## 2.5 The State of the Art on Cost-Screening Study for a Cost-Effective Hybrid Power Systems (HPS) - Addressing the Research Gap

Systematic strategies are proposed in this research in order to address all of the research gaps related to the cost-screening studies on the available energy storage to attain the most cost-effective Hybrid Power Systems (HPS).

i. The available techniques and method of producing a cost-effective HPS were only focusing on the equipment sizing and cost for each component exist in HPS. None of them were found to apply the PoPA technique in their study. Detail analysis were done by analyzing the characteristics of each component and determine the most cost-effective to be placed in order to produce a cost-effective HPS in overall. Therefore, this research will concentrate on using PoPA as the technique in targeting power allocations to determine the storage capacity for a cost-effective HPS to be produced.

ii. Wan Alwi *et al.* (2006) mentioned that SHARPS only developed for water systems and limited to only for single contaminant. Therefore, this research is focusing on applying SHARPS technique for cost screening of power system. SHARPS are implemented in analyzing the most cost effective energy storage after some of the technical characteristics were obtained from PoPA.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter presents the overall framework of this research begins with the construction of the modified Storage Cascade Table (SCT) and ends with the application of a cost-screening technique named Systematic Hierarchical Approach for Resilient Process Screening (SHARPS). The cost-screening study was performed to four different types of power storage which are the lead-acid, superconducting magnetic energy storage (SMES), supercapacitor and flywheel energy storage (FES).

## 3.2 Modified Storage Cascade Table (SCT)

Modified Storage Cascade Table (SCT) was being use as one of the approaches for integrating the Hybrid Power System (HPS) with the considerations of energy losses occurring in the systems. This method which falls under the algebraic method of Power Pinch Analysis (PoPA) functioned to determine the allocations of charging/discharging electricity, storage capacity, shortage and outsource electricity considering losses occurring in HPS with battery storage. The main reason of applying this method is to obtain the storage capacity and the amount of minimum outsourced electricity in which this data will be used in the specific cost-screening technique. The summary in obtaining the results for modified SCT is shown in Figure 3.1.

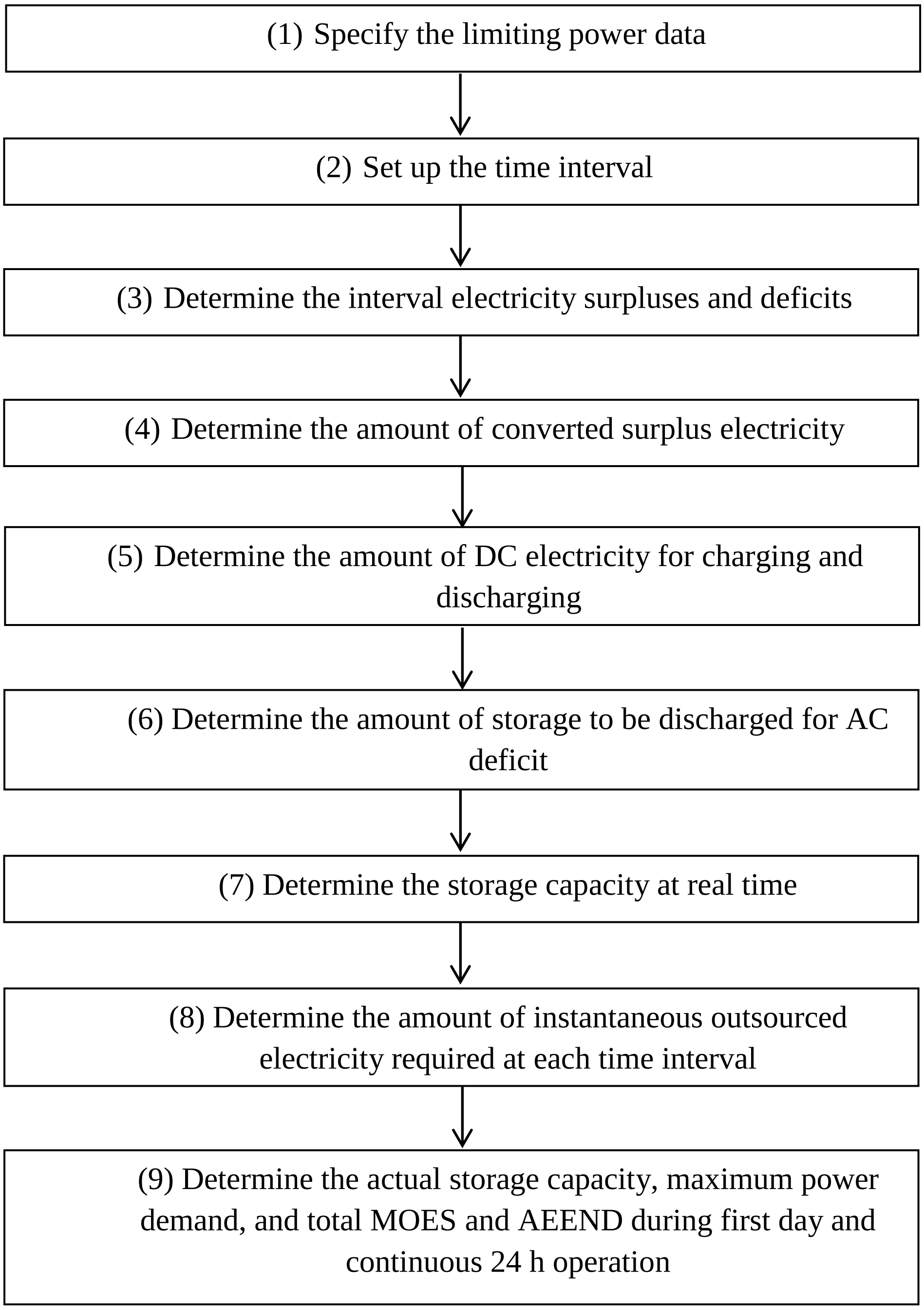



Figure 3.1 Modified SCT construction steps (Mohammad Rozali,

### 3.2.1 Specify the Limiting Power Data

Limiting power sources and limiting power demands are the two main components of limiting power data that needed for the analysis and these two components can be categorized into AC and DC electricity respectively. For the purpose of demonstrating the methodology, data from Mohammad Rozali (2014) was used and tabulated in Tables 3.10 and 3.11.

Table 3.1 Limiting power sources for Illustrative Case Study 1

| **Power source** | | **Time, h** | | **Time interval, h** | **Power source rating, kW** | **Electricity generation, kWh** |
|---|---|---|---|---|---|---|
| AC | DC | From | To | | | |
| Wind | | 2 | 10 | 8 | 50 | 400 |
| Biomass | | 0 | 24 | 24 | 70 | 1680 |
| | Solar | 8 | 18 | 10 | 60 | 600 |

Table 3.2 Limiting power sources for Illustrative Case Study 1

| **Power demand** | | **Time, h** | | **Time interval, h** | **Power demand rating, kW** | **Electricity consumption, kWh** |
|---|---|---|---|---|---|---|
| **AC** | **DC** | **From** | **To** | | | |
| | Appliance 1 | 0 | 24 | 24 | 30 | 720 |
| Appliance 2 | | 8 | 18 | 10 | 50 | 500 |
| | Appliance 3 | 0 | 24 | 24 | 20 | 480 |
| Appliance 4 | | 8 | 18 | 10 | 50 | 500 |
| Appliance 5 | | 8 | 20 | 12 | 40 | 480 |

### 3.2.2 Set up the Time Intervals

Initially, the time interval for each occurrence was determined and any duplicates were removed. The time interval for power sources and power demands are listed in Column 1 in ascending order. Column 2 lists are the values for the duration between two adjacent-time intervals. Based on Illustrative Case Study 1, the constructed modified SCT is shown in Tables 3.3a and 3.3b.

Table 3.3a Modified SCT for Illustrative Case Study 1

| 1 8 | 2 | 9 | 3 10 | 11 4 | | 15 2 | | 6 13 | | 7 14 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **Time interval, h** | **∑ Power source rating, kW** | | **∑ Power demand rating, kW** | | **∑Electricity Source, kWh** | | **∑ Electricity Demand, kWh** | | **Electricity surplus/deficit, kWh** | |
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** |
| **0** | | | | | | | | | | | |
| | 2 | 70 | 0 | 0 | 50 | 140 | 0 | 0 | 100 | 140 | -100 |
| **2** | | | | | | | | | | | |
| | 6 | 120 | 0 | 0 | 50 | 720 | 0 | 0 | 300 | 720 | -300 |
| **8** | | | | | | | | | | | |
| | 2 | 120 | 60 | 140 | 50 | 240 | 120 | 280 | 100 | -40 | 20 |
| **10** | | | | | | | | | | | |
| | 8 | 70 | 60 | 140 | 50 | 560 | 480 | 1120 | 400 | -560 | 80 |
| **18** | | | | | | | | | | | |
| | 2 | 70 | 0 | 40 | 50 | 140 | 0 | 80 | 100 | 60 | -100 |
| **20** | | | | | | | | | | | |
| | 4 | 70 | 0 | 0 | 50 | 280 | 0 | 0 | 200 | 280 | -200 |
| **24** | | | | | | | | | | | |

| Converted surplus, kWh | | Charging/ Discharging quantity (DC), kWh | Discharge for AC deficit, kWh | Start up | | | Operation | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Battery capacity (kWh) | Outsourced electricity, kWh | | Battery capacity (kWh) | Outsourced electricity, kWh | |
| AC-DC | DC-AC | | | | AC | DC | | AC | DC |
| | | | | 0 | | | 59.4 | | |
| 133 | 0 | 33 | 0 | 29.70 | 0 | 0 | 89.10 | 0 | 0 |
| 684 | 0 | 384 | 0 | 375.29 | 0 | 0 | 434.67 | 0 | 0 |
| 0 | 19 | 0 | -22.11 | 350.70 | 0 | 0 | 410.08 | 0 | 0 |
| 0 | 76 | 0 | -299.75 | 0 | 184.25 | 0 | 0 | 133.50 | 0 |
| 57 | 0 | -43 | 0 | 0 | 0 | 43 | 0 | 0 | 43 |
| 266 | 0 | 66 | 0 | 59.4 | 0 | 0 | 59.40 | 0 | 0 |

Table 3.4b Modified SCT for Illustrative Case Study 1

### 3.2.3 Determine the Electricity Surplus/Deficit

Product of time interval and the power source rating resulted on the values for the electricity source (Column 5) while the electricity demand values (Column 6) is the results for the multiplication of time interval with the power demand rating (Equation 3.1). The electricity surplus/deficit values were obtained by the difference of electricity source with the electricity demand (Equation 3.2). Electricity surplus is represented by a positive value while the electricity deficit is represented by a negative value (see Column 7). These can be easily translated by the equations below. These equations shall be applied separately for AC and DC electricity calculation.

$$\sum \text{Electricity Source/ Demand} = \sum \text{Power Rating} \times \text{Time interval duration} \quad (3.1)$$

$$\text{Electricity surplus/deficit} = \sum \text{Electricity Source} - \sum \text{Electricity Demand} \quad (3.2)$$

### 3.2.4 Determine the Amount of Converted Electricity Surplus

Converting the electricity surplus would satisfy the deficit experienced previously in Column 7. The amount of converted electricity surplus can be obtained using several methods. For AC to DC electricity conversion, the amount of converted electricity surplus can be obtained from the equation (3.3).

$$\text{Amount of converted AC electricity to DC electricity} = \text{AC electricity surplus} \times \text{Rectifier efficiency} \quad (3.3)$$

Meanwhile, for DC to AC electricity conversion, equation (3.3) is only applicable if the DC electricity surplus is less than the AC electricity deficit.

Consequently, converting all DC electricity to AC electricity will lead to a high loss because all AC electricity needed to be converted to DC electricity back for storing purposes. Therefore, only certain amount of required AC electricity is converted from the available DC surplus. The amount of converted DC electricity to AC electricity in this specific case can be obtained from the equation (3.4).

Amount of converted DC electricity to AC electricity =

$$\text{Amount of AC deficit / Inverter efficiency} \tag{3.4}$$

### 3.2.5 Determine the Amount of DC Electricity for Charging/Discharging

The amount of DC electricity available for storage after load utilisation is listed in Column 9. The positive value indicates the charging quantity while the negative value represents the discharge quantity for the DC deficit. Firstly, value of converted AC electricity from the equation (3.5) must be calculated and if the value is less than or equal to the amount of DC electricity converted, then the amount of DC electricity for charging/discharging can be obtained from equation (3.6). If the value of converted AC electricity is more than the amount of DC electricity converted, then the amount of DC electricity for charging/discharging is zero.

$$\text{Converted AC} = AC_{s/d} \text{ / Inverter efficiency} \tag{3.5}$$

$$\text{Charging/Discharging quantity (DC)} = DC_{s/d} + AC_{converted} - DC_{converted} \tag{3.6}$$

Where

$AC_{s/d}$ = AC electricity surplus/deficit;

$DC_{s/d}$ = DC electricity surplus/deficit;

$AC_{converted}$ = amount of DC converted from AC electricity surplus;

$DC_{converted}$ = amount of DC electricity surplus that will be converted to AC to satisfy AC load demand.

### 3.2.6 Determine the Storage Amount Discharge for AC Deficit

The amount of the electricity from the energy storage needed to be discharge to satisfy the AC deficit previously is listed in Column 10 and calculated using equation (3.7).

DC Electricity to be discharged =

$$\text{(Converted DC surplus + AC deficit) / Rectifier efficiency} \qquad (3.7)$$

However, equation (3.7) is only applicable if the storage capacity is greater than the DC discharge requirement to meet the AC deficit. Generally, the energy storage will be discharged to its depth of discharge (DoD) when the available amount is not enough to satisfy the AC deficit experienced and the DoD of lead-acid battery used is normally about 80% of its maximum capacity (Komor *et al.*, 2012). The same value of DoD was used in the calculation involving different types of energy storage. In calculating the amount of the available DC electricity from the energy storage to meet the AC deficit, equation (3.8) was used.

$$\text{DC electricity available from the energy storage} = B_{t-1}\,(1-\sigma\times T) \times \eta_I \times \eta_d \qquad (3.8)$$

Where

$B_{t-1}$ = battery capacity at previous time interval [kWh];

$\sigma$ = hourly self-discharge rate = 0.00004/h; t = time [h];

T = time interval [h];

$\eta_I$ = inverter efficiency = 0.95;

$\eta_d$ = discharging efficiency = 0.9.

### 3.2.7 Determine the Amount of Energy Storage Capacity at Real Time

The amount of available electricity inside the energy storage depends on the values listed in Column 9 and Column 10. By considering the technical characteristics of each types of energy storage such as the self-discharge rate as well as charging and discharging efficiency, the cumulative energy storage capacity at real time can be calculated using equation (3.9). It is important to include in the calculation that once the energy storage has been discharged to its DoD, the electricity cascade for the next time interval will begin at zero. The energy storage capacity at t=0 for the next day (continuous 24 h operation) was taken from the electricity stored during first day operation at t=24.

$$B_t = B_{t-1} (1- \sigma \times T) + (C_t \times \eta_c) + D_t / \eta_d \qquad (3.9)$$

Where

$B_t$ = battery capacity [kWh];

$C_t$ = charging quantity [kWh];

$D_t$ = discharging quantity [kWh];

$\sigma$ = hourly self-discharge rate = 0.00004/h (for lead-acid battery);

t = time [h]; T = time interval [h];

$\eta_c$ = charging efficiency = 0.9 (for lead-acid battery);

$\eta_d$ = discharging efficiency = 0.9 (for lead-acid battery).

### 3.2.7 Determine the Amount of Instantaneous Outsourced Electricity Required at Each Time Interval

When the amount of electricity stored in the energy storage is still not sufficient to satisfy the electricity deficit, external electricity may be purchased from the grid. As the grid supplies AC electricity, the amount of DC electricity listed in Column 12 and Column 14 are divided with the rectifier efficiency to give the exact amount of outsourced electricity that needed to be purchased.

### 3.2.7 Determine the Amount of Maximum Energy Storage Capacity, Amount of Outsourced Electricity, and Total Minimum Outsourced Electricity Supply (MOES)

The amount of maximum energy storage capacity was taken from the largest value in Column 11 and Column 13 during first day operation and continuous 24 h operation respectively. Meanwhile, the actual energy storage capacity was calculated by dividing the targeted capacities with the DoD value. This can be illustrated by equation (3.10).

$$B_{t(actual)} = B_t / DoD \quad (3.10)$$

The amount of outsourced electricity is obtained from equation (3.11).

$$\text{Amount of outsourced electricity} = \sum (\text{AC Power demand rating} \times \text{Time interval}) + \sum (\text{DC Power demand rating} \times \text{Time interval} / \text{Rectifier efficiency}) \quad (3.11)$$

The sum of outsourced AC and DC electricity amount listed in Column 12 give the MOES for the first day operation while the sum of outsourced AC and DC electricity amount listed in Column 14 give the MOES for the 24 h operation. The total MOES value assuming a year operation (365 days) was gained from equation (3.12).

$$\text{Total MOES} = \text{MOES}_{\text{start-up}} + (\text{MOES}_{\text{operation}} \times 364 \text{ days}) \quad (3.12)$$

## 3.3 Economic Analysis

A cost-effective Hybrid Power System (HPS) can be evaluated based on the payback period. The shorter the time taken for the payback period, it can be said that the system produce is a cost-effective system. The payback period value can be calculated by using equation (3.13).

$$\text{Payback period} = \text{Net Capital Investment} / \text{Net Annual Saving} \quad (3.13)$$

The net capital investment is the product of capital cost of the energy storage (USD/kWh) with the amount of storage capacity (kWh) used in respective system (Equation 3.14). Meanwhile, the amount of net annual saving was obtained from the difference of the tariff rate of the required outsourced electricity with the cost of the reduced MOES and the cost of the storage systems maintenance (Equation 3.15). In the calculation, the residential tariff was assumed to be 0.16 USD.kWh (0.516 RM/kWh).

Net capital investment =

$$\text{Capital cost of energy storage} \times \text{Amount of storage capacity} \quad (3.14)$$

$$\text{Net annual saving} = (O \times D \times T_E) - (O_{HPS} \times D \times T_E) - (S \times OM) \quad (3.15)$$

Where

O = total daily outsourced electricity without HPS [kWh];

D = total days for a year operation [d];

TE = tariff rate for electricity [USD/kWh];

OHPS = total daily outsourced electricity with HPS [kWh];

S = storage capacity [kW];

OM = annualised operating and maintenance cost of the storage [USD/kWy].

## 3.4 Systematic Hierarchical Approach for Resilient Process Screening (SHARPS)

The strategy that is being applied in Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) is to identify the steepest gradient in the Investment versus Annual Saving (IAS) plot and adjust the process or replace the equipment in order to achieve the most cost-effective electricity network. Screening process is being applied in which different storage technologies applicable in HPS are being screened and one with the steepest gradient indicates the highest payback period which is less attractive to the plant owners.

In this research, the IAS plots were constructed for four different types of energy storage which is the lead-acid battery, superconducting magnetic energy storage (SMES), supercapacitor and flywheel energy storage (FES). The procedure of applying the SHARPS method is summarized in Figure 3.2.

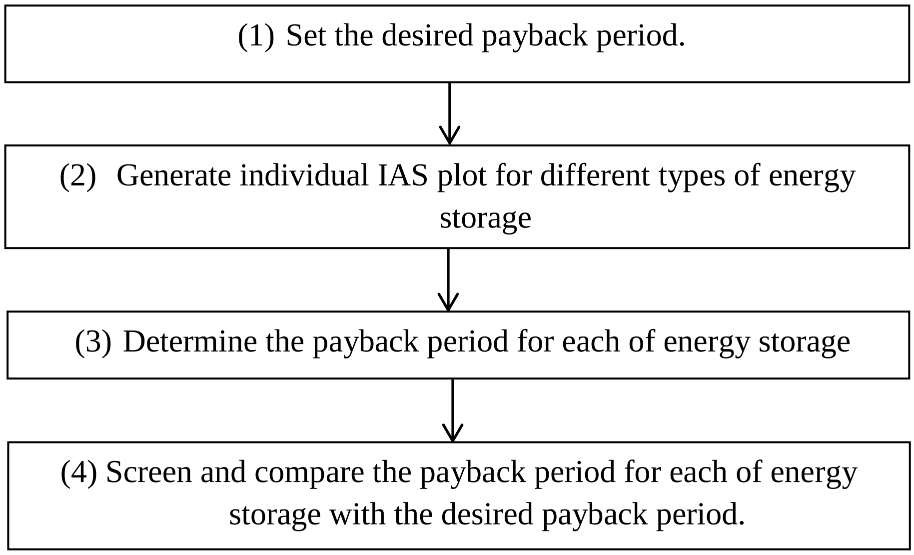



Figure 3.2 Summary of cost-screening technique

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Introduction

This chapter presents the application of the modified storage cascade table (SCT) and implementation of SHARPS based on the modified SCT results. In addition, comprehensive explanation and discussion regarding the findings completed with significant justifications are also provided in order to validate the proposed methodology.

## 4.2 Application of Modified Storage Cascade Table (SCT)

The modified SCT is constructed based on a case study by Ho *et al.* (2013). Table 4.1a and 4.1b shows the data consisting of the limiting power sources and demands for a residential area in Malaysia obtained from Ho *et al.* (2013). The household applications comprise of both AC and DC appliances, and DC electricity supply comes from the solar energy as the only power source system.

Table 4.1a Limiting power data for case study between time intervals 0 and 13 h (Ho *et al.*, 2013)

| **Time, h** | **Source rating, kW** | **Demand rating, kW** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **DC** | **AC** | | **DC** | | | | | | | |
| | Solar | Washing machine | Refrigerator | Rice cooker | Light | Air Conditioner | Television | Laptop | Iron | Kettle | Toaster |
| **0-1** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **1-2** | 0 | 0 | 0.500 | 0.300 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **2-3** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **3-4** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **4-5** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **5-6** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0 | 0 | 0 | 0 |
| **6-7** | 0 | 0.240 | 0.500 | 0 | 0 | 0 | 0 | 0 | 0 | 0.500 | 0 |
| **7-8** | 0.600 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.175 |
| **8-9** | 3.000 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0.065 | 0 | 0 | 0 |
| **9-10** | 3.500 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0.065 | 0 | 0 | 0 |
| **10-11** | 4.100 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0.065 | 0 | 0 | 0 |
| **11-12** | 4.300 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **12-13** | 4.300 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 4.1b Limiting power data for case study between time intervals 13 and 24 h (Ho *et al.*, 2013)

| **Time, h** | **Source rating, kW** | **Demand rating, kW** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **DC** | **AC** | | | | | **DC** | | | | |
| | Solar | Washing machine | Refrigerator | Rice cooker | Light | Air Conditioner | Television | Laptop | Iron | Kettle | Toaster |
| **13-14** | 4.300 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **14-15** | 2.000 | 0 | 0.500 | 0 | 0 | 1.200 | 0.075 | 0 | 0 | 0 | 0 |
| **15-16** | 2.100 | 0 | 0.500 | 0 | 0 | 1.200 | 0.075 | 0 | 0 | 0 | 0 |
| **16-17** | 1.000 | 0 | 0.500 | 0 | 0 | 0 | 0.075 | 0 | 0 | 0 | 0 |
| **17-18** | 0.500 | 0 | 0.500 | 0 | 0 | 0 | 0.075 | 0 | 0 | 0 | 0 |
| **18-19** | 0.200 | 0 | 0.500 | 0 | 0 | 0 | 0 | 0.065 | 0 | 0 | 0 |
| **19-20** | 0 | 0 | 0.500 | 0 | 0.030 | 0 | 0.075 | 0.065 | 0 | 0 | 0 |
| **20-21** | 0 | 0 | 0.500 | 0.300 | 0.030 | 1.200 | 0.075 | 0.065 | 0 | 0.500 | 0 |
| **21-22** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0.075 | 0.065 | 0.600 | 0 | 0 |
| **22-23** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0.075 | 0.065 | 0 | 0 | 0 |
| **23-24** | 0 | 0 | 0.500 | 0 | 0.030 | 1.200 | 0 | 0.000 | 0 | 0 | 0 |

The technical characteristics for four different types of energy storage are obtained and tabulated in Table 4.2.

Table 4.2 Technical Characteristics of Energy Storage Technologies

| **Technology** | **Charging/ Discharging (%)** | **Self-discharge rate (%/h)** |
|---|---|---|
| Lead-acid battery | 90[a] | 0.004[b] |
| SMES | 95[c] | 0.542[d] |
| Supercapacitor | 95[c] | 1.25[d] |
| FES | 92[c] | 4.17[d] |

[a]Bell *et al.* (1994), [b]Burger *et al.* (2005), [c]Shoenung SM. (2001) [d]Chen *et al.* (2009)

Based on the limiting power data from case study by (Ho *et al.*, 2013), modified SCT was constructed and tabulated in Table 4.3 for lead-acid battery. The modified SCT for superconducting magnetic energy storage (SMES), supercapacitor, and flywheel energy storage (FES) are available in Appendix A. The inverter and rectifier efficiency are assumed to be 95% efficient in all modified SCT calculations (Burger *et al.*, 2005). The four energy storage listed are presumed to store DC electrical energy, thus act as the DC storage.

Table 4.3a Modified SCT for HPS-Lead-Acid Battery between intervals 0 and 11 h

| **Time** | **Time interval** | **∑ Power source rating, W** | | **∑ Power demand rating, W** | | **Electricity Source, Wh** | | **Electricity Demand, Wh** | | **Electricity surplus/deficit, Wh** | | **Converted surplus, Wh** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC-DC** | **DC-AC** |
| **0** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| **1** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1230 | 0 | 0 | 800 | 1230 | -800 | -1230 | 0 | 0 |
| **2** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| **3** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| **4** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| **5** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| **6** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 740 | 500 | 0 | 0 | 740 | 500 | -740 | -500 | 0 | 0 |
| **7** | | | | | | | | | | | | | |
| | 1 | 0 | 600 | 500 | 175 | 0 | 600 | 500 | 175 | -500 | 425 | 0 | 403.75 |
| **8** | | | | | | | | | | | | | |
| | 1 | 0 | 3000 | 500 | 65 | 0 | 3000 | 500 | 65 | -500 | 2935 | 0 | 526.32 |
| **9** | | | | | | | | | | | | | |
| | 1 | 0 | 3500 | 500 | 65 | 0 | 3500 | 500 | 65 | -500 | 3435 | 0 | 526.32 |
| **10** | | | | | | | | | | | | | |
| | 1 | 0 | 4100 | 500 | 65 | 0 | 4100 | 500 | 65 | -500 | 4035 | 0 | 526.32 |
| **11** | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| **12** | | | | | | | | | | | | | |

Table 4.3b Modified SCT for HPS-Lead-Acid Battery between intervals 12 and 24 h

| **Time** | **Time interval** | **∑ Power source rating, W** | | **∑ Power demand rating, W** | | **Electricity Source, Wh** | | **Electricity Demand, Wh** | | **Electricity surplus/deficit, Wh** | | **Converted surplus, Wh** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC-DC** | **DC-AC** |
| **12** | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0.00 | 526.32 |
| **13** | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0.00 | 526.32 |
| **14** | | | | | | | | | | | | | |
| | 1 | 0 | 2000 | 500 | 1275 | 0 | 2000 | 500 | 1275 | -500 | 725 | 0.00 | 526.32 |
| **15** | | | | | | | | | | | | | |
| | 1 | 0 | 2100 | 500 | 1275 | 0 | 2100 | 500 | 1275 | -500 | 825 | 0.00 | 526.32 |
| **16** | | | | | | | | | | | | | |
| | 1 | 0 | 1000 | 500 | 75 | 0 | 1000 | 500 | 75 | -500 | 925 | 0.00 | 526.32 |
| **17** | | | | | | | | | | | | | |
| | 1 | 0 | 500 | 500 | 75 | 0 | 500 | 500 | 75 | -500 | 425 | 0.00 | 403.75 |
| **18** | | | | | | | | | | | | | |
| | 1 | 0 | 200 | 500 | 65 | 0 | 200 | 500 | 65 | -500 | 135 | 0.00 | 128.25 |
| **19** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 170 | 0 | 0 | 500 | 170 | -500 | -170 | 0.00 | 0.00 |
| **20** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1870 | 0 | 0 | 800 | 1870 | -800 | -1870 | 0.00 | 0.00 |
| **21** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1970 | 0 | 0 | 500 | 1970 | -500 | -1970 | 0.00 | 0.00 |
| **22** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1370 | 0 | 0 | 500 | 1370 | -500 | -1370 | 0.00 | 0.00 |
| **23** | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0.00 | 0.00 |
| **24** | | | | | | | | | | | | | |

Table 4.3c Modified SCT for HPS-Lead-Acid Battery between intervals 0 and 12 h

| Time | Charging/ Discharging quantity (DC), Wh | Discharge for AC deficit, Wh | Start up | | | Operation | | |
|---|---|---|---|---|---|---|---|---|
| | | | Storage capacity (Wh) | Outsourced electricity, Wh | | Storage capacity (Wh) | Outsourced electricity, Wh | |
| | | | | AC | DC | | AC | DC |
| **0** | | | 0.00 | | | 8033.82 | | |
| **1** | 0.00 | 0.00 | 0.00 | 500.00 | 1230.00 | 6082.04 | 0.00 | 0.00 |
| **2** | 0.00 | 0.00 | 0.00 | 800.00 | 1230.00 | 3779.46 | 0.00 | 0.00 |
| **3** | 0.00 | 0.00 | 0.00 | 500.00 | 1230.00 | 1827.84 | 0.00 | 0.00 |
| **4** | 0.00 | 0.00 | 0.00 | 500.00 | 1230.00 | 0.00 | 105.76 | 0.00 |
| **5** | 0.00 | 0.00 | 0.00 | 500.00 | 1230.00 | 0.00 | 500.00 | 1230.00 |
| **6** | 0.00 | 0.00 | 0.00 | 500.00 | 1230.00 | 0.00 | 500.00 | 1230.00 |
| **7** | 0.00 | 0.00 | 0.00 | 740.00 | 500.00 | 0.00 | 740.00 | 500.00 |
| **8** | 0.00 | 0.00 | 0.00 | 96.25 | 0.00 | 0.00 | 96.25 | 0.00 |
| **9** | 2408.68 | 0.00 | 2167.82 | 0.00 | 0.00 | 2167.82 | 0.00 | 0.00 |
| **10** | 2908.68 | 0.00 | 4785.54 | 0.00 | 0.00 | 4785.54 | 0.00 | 0.00 |
| **11** | 3508.68 | 0.00 | 7943.17 | 0.00 | 0.00 | 7943.17 | 0.00 | 0.00 |
| **12** | 3873.68 | 0.00 | 11429.17 | 0.00 | 0.00 | 11429.17 | 0.00 | 0.00 |

Table 4.3d  Modified SCT for HPS-Lead-Acid Battery between intervals 12 and 24 h

| **Time** | **Charging/ Discharging quantity (DC), Wh** | **Discharge for AC deficit, Wh** | **Start up** | | | **Operation** | | |
|---|---|---|---|---|---|---|---|---|
| | | | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | |
| | | | | **AC** | **DC** | | **AC** | **DC** |
| 12 | | | | | | | | |
| | 3873.68 | 0.00 | 14915.03 | 0.00 | 0.00 | 14915.03 | 0.00 | 0.00 |
| 13 | | | | | | | | |
| | 3873.68 | 0.00 | 18400.75 | 0.00 | 0.00 | 18400.75 | 0.00 | 0.00 |
| 14 | | | | | | | | |
| | 198.68 | 0.00 | 18578.82 | 0.00 | 0.00 | 18578.82 | 0.00 | 0.00 |
| 15 | | | | | | | | |
| | 298.68 | 0.00 | 18846.90 | 0.00 | 0.00 | 18846.90 | 0.00 | 0.00 |
| 16 | | | | | | | | |
| | 398.68 | 0.00 | 19204.96 | 0.00 | 0.00 | 19204.96 | 0.00 | 0.00 |
| 17 | | | | | | | | |
| | 0.00 | -101.32 | 19091.62 | 0.00 | 0.00 | 19091.62 | 0.00 | 0.00 |
| 18 | | | | | | | | |
| | 0.00 | -391.32 | 18656.06 | 0.00 | 0.00 | 18656.06 | 0.00 | 0.00 |
| 19 | | | | | | | | |
| | -170.00 | -526.32 | 17881.63 | 0.00 | 0.00 | 17881.63 | 0.00 | 0.00 |
| 20 | | | | | | | | |
| | -1870.00 | -842.11 | 14867.46 | 0.00 | 0.00 | 14867.46 | 0.00 | 0.00 |
| 21 | | | | | | | | |
| | -1970.00 | -526.32 | 12093.18 | 0.00 | 0.00 | 12093.18 | 0.00 | 0.00 |
| 22 | | | | | | | | |
| | -1370.00 | -526.32 | 9985.68 | 0.00 | 0.00 | 9985.68 | 0.00 | 0.00 |
| 23 | | | | | | | | |
| | -1230.00 | -526.32 | 8033.82 | 0.00 | 0.00 | 8033.82 | 0.00 | 0.00 |
| 24 | | | | | | | | |

Referring to the constructed modified SCT, the amount of maximum power demand, maximum storage capacity and minimum outsourced electricity supply (MOES) can be determined. The maximum power demand for all energy storage involved is calculated using equation (3.11). It is observed that the amount of outsourced electricity is 31.3926 kWh in which this value is identical for all energy storage that involved.

The significant of the identical value for the amount of outsourced electricity is that the electricity demands from the household appliances are the same without considering the types of energy storage that being applied in HPS. The daily amount of outsourced electricity is being calculated as follows.

Amount of outsourced electricity = $\sum$ (AC Power demand rating × Time interval)

+ $\sum$ (DC Power demand rating × Time interval / Rectifier efficiency)

Time interval = 1

Accordingly, the data for the maximum storage capacity was calculated using equation (3.10). The actual storage capacity for the lead-acid battery is obtained from the highest value in storage capacity for 24 h operation column which is 19.205 kWh and the maximum storage capacity can be calculated as follows.

Maximum storage capacity for lead-acid battery = (19.205 /0.8) = 24.006 kWh

The total MOES indicates the minimum annual amount of electricity that needs to be supplied to the system when the system experienced electricity deficit. Total MOES for the lead-acid was calculated as follows.

Total MOES = $MOES_{start\text{-}up}$ + ($MOES_{operation}$ × 364 days)

Total MOES = 12430.99 Wh + (5057.80 × 364) Wh = 1853.469 kWh

The results of calculations for the maximum storage capacity and total MOES for all storage were tabulated in Table 4.4.

Table 4.4 Maximum Storage Capacity and Total MOES

| Energy storage | Maximum storage capacity (kWh) | Total MOES (kWh) |
|---|---|---|
| **Lead-Acid Battery** | 24.006 | 1853.469 |
| **SMES** | 24.660 | 1591.380 |
| **Supercapacitor** | 23.790 | 2083.288 |
| **FES** | 21.425 | 4382.586 |

From Table 4.1, SMES shows the highest amount of electrical energy compared to the other three energy storage. FES shows the lowest value for its storage capacity, while lead-acid battery and supercapacitor displays a close amount of storage capacity between each other. In the meantime, the usage of FES requires the highest total annual outsourced of electricity supply. SMES once again shows the best performance in maintaining the lowest value for the annual outsourced electricity supply by approximately 63.9% lower compared to FES.

Another storage that listed among the lowest value of the annual outsourced electricity goes to lead-acid battery and followed by supercapacitor. It can be said that supercapacitor gives an optimum performance both on the storage capacity and amount of annual outsourced electricity. The poor performance of FES in this system compared to other storage is mainly caused by the high value of self-discharge rate of FES listed in Table 4.2. On the other hand, high efficiency of the charging/discharging process and low self-discharging rate has led to an excellence performance for SMES in the maximum amount of storage capacity.

Subsequently, the cost-screening technique can be applied since the amount of maximum storage capacity, the amount of outsourced electricity and the annual outsourced electricity with HPS (total MOES) has been established from the constructed modified SCT. Data needed for the cost-screening are being presented in Table 4.5.

Table 4.5 Cost of Storage Technologies (Schoenung *et al.*, 2003)

| **Technology** | **Capital cost, USD/kW** | **Operation & maintenance cost, USD/kWy** |
|---|---|---|
| Lead-acid | 250 | 10 |
| SMES | 200 | 10 |
| Supercapacitor | 300 | 5 |
| Flywheel | 300 | 5 |

The value of net capital investment and net annual savings were obtained from equations (3.14) and (3.15) respectively and presented in Table 4.6. Individual Investment versus Annual Savings (IAS) plot was constructed based on the data in Table 4.6 and shown in Figures 4.2 to 4.5 for lead-acid battery, SMES, supercapacitor and FES respectively.

Table 4.6 Economic Evaluation

| Energy Storage | Net Annual Investment (USD/kW) | Net Annual Savings (USD/kWy) |
|---|---|---|
| **Lead-acid battery** | 6001.55 | 1296.71 |
| **SMES** | 4931.92 | 1332.11 |
| **Supercapacitor** | 7137.12 | 1381.05 |
| **FES** | 6427.58 | 1024.99 |

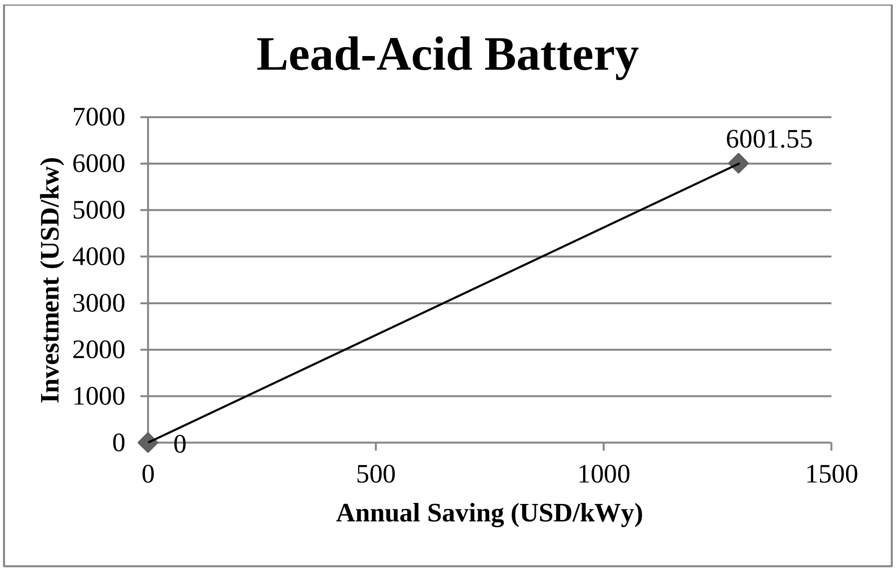



Figure 4.1 IAS plot-Lead-acid battery

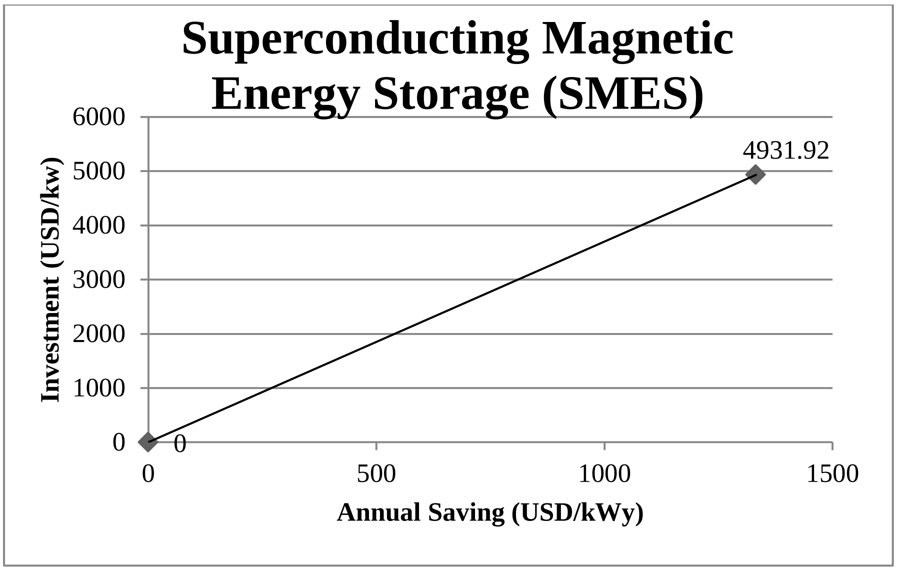



Figure 4.2 IAS plot-SMES

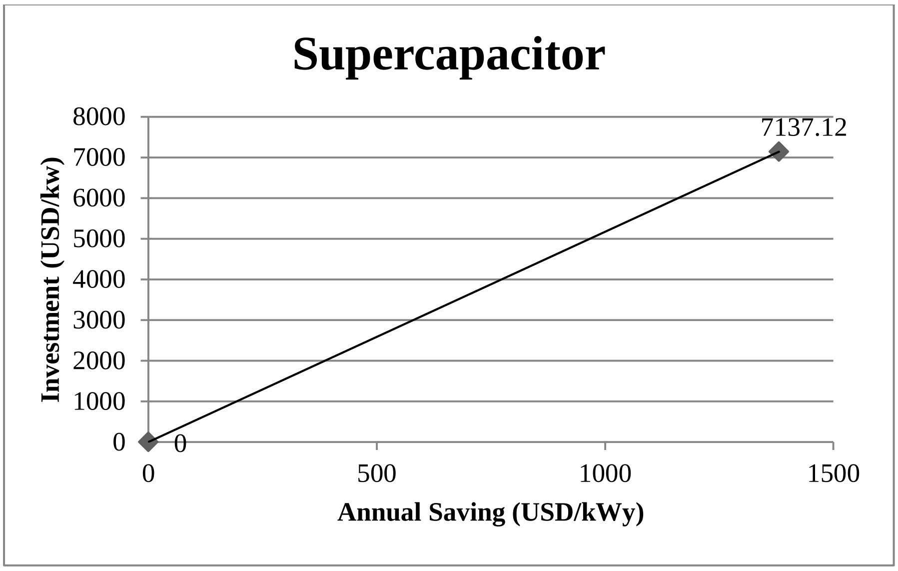



Figure 4.3 IAS plot-Supercapacitor

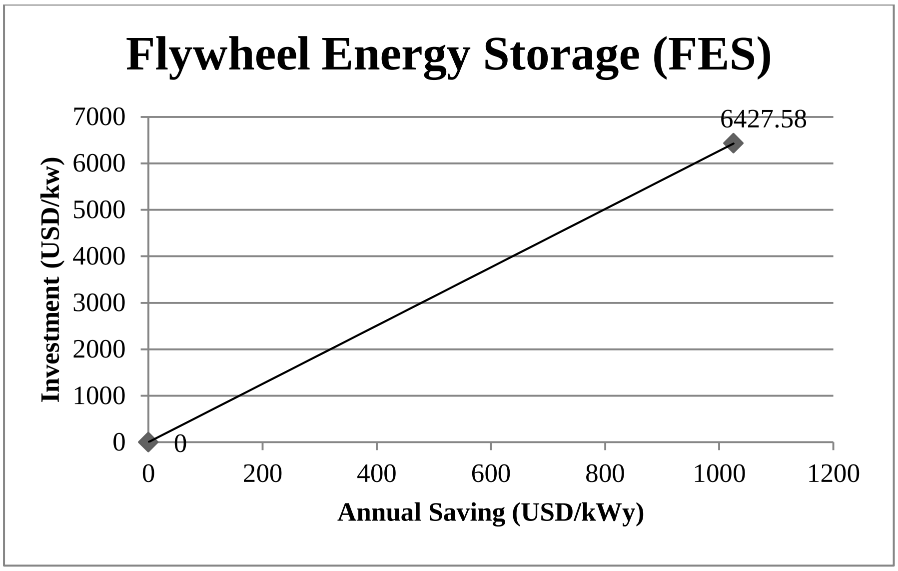



Figure 4.4 IAS plot-FES

Proceeding to the cost analysis, the first step in implementing SHARPS is by plotting the desired payback period. Referring to Wan Alwi *et al.* (2006), the example of desired payback period that can be set is two years. Therefore, it has been decided that desired payback period in this case will be three years (considering a slight longer of time for the payback period).

For the cost-screening purposes, individual plots were combined in the same graph as given in Figure 4.6. All of the considered storage technologies were screened by comparing the attained payback period of each with the desired payback period. This was done by focusing on the steepest gradient formed by each of the energy storage. Desired payback period line was plotted in the same graph in order to guide the cost-screening and the decision making for the most cost-effective storage of the studied HPS.

Based on Figure 4.6, it can be observed that the less steep gradient which indicates the shortest payback period compared to the other energy storage. It can be said that SMES is the most cost-effective energy storage since the line graph gradient is the nearest to the desired payback period. The key factors affecting the decision of SMES as the most cost-effective energy storage are the net annual saving and the investment. Net annual investment for SMES is the lowest compared to the rest whereas the net annual savings is ranked at second highest after supercapacitor. Instead of that, highest value for maximum storage capacity is also represented by SMES.

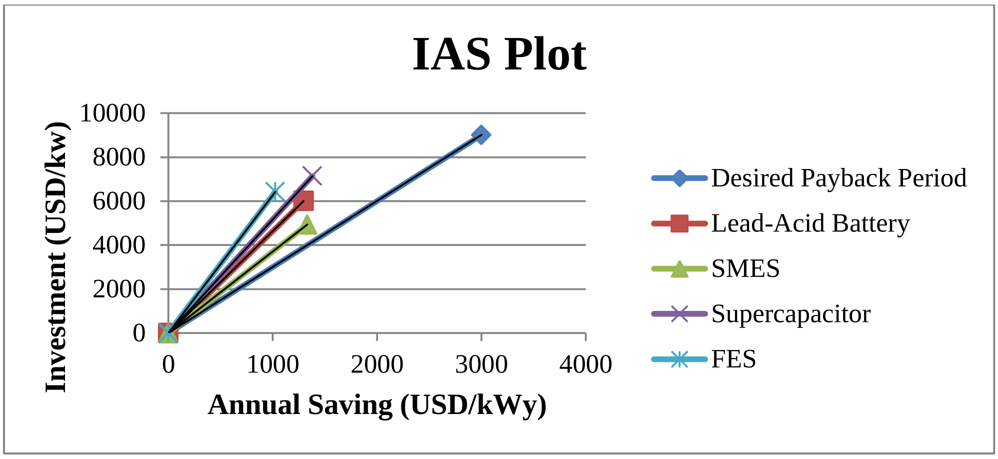



Figure 4.5 Application of Cost-Screening Technique

# CHAPTER 5

# CONCLUSION

## 5.1 Conclusion

This research is beneficial for studies related to the cost optimization in designing Hybrid Power Systems (HPS) equipped with energy storage system. The various energy storage technologies available should be analyzed in terms of the effectiveness of the respective energy storage in contributing the most cost-effective HPS.

One of the method falls under the Power Pinch Analysis (PoPA) named Modified Storage Cascade Table (SCT) has been used in the beginning as the method in determining the maximum storage capacity, the maximum power demand and total minimum outsourced electricity (MOES). These parameters are crucial to be obtained in order to guide the cost-screening process.

Meanwhile, Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) method was proven effective in determining the cost-effective HPS based on the comparison of the payback period with the desired payback period. Therefore, selection of the lowest steep gradient that illustrated as the payback period of the plot will definitely leads to the attainment of the most effective HPS that would lead to the cost-effective HPS.

It has been identified in overall that SMES shows the best performance in obtaining the lowest payback period compared to the lead-acid battery, supercapacitor and flywheel energy storage (FES). Therefore, a cost-effective HPS is to be said can be achieved by implementing SMES as the energy storage system for the household applications. SHARPS as the cost-screening method enables the designer to customize HPS design in terms of types of energy storage selection in which leading to a construction of a cost-effective HPS in overall.

## 5.2 Recommendations

Several future works that can be explored in finding the cost-effective Hybrid Power System (HPS) are being identified. The suggested recommendations are as follows:

i. Performing a cost-screening study based on Systematic Hierarchical Approach for Resilient Process Screening (SHARPS) method on major component exist in HPS such as the generator, the wind turbine systems, and the power conditioning equipment.
ii. Cost comparison for equipment that is being used for the power generated by using the Renewable Energy (RE) sources such as the types of the photovoltaic solar panel.

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# APPENDIX A

Modified SCT for HPS-SMES between intervals 0 and 12 h

| Time | Time interval | ∑ Power source rating, W | | ∑ Power demand rating, W | | Electricity Source, Wh | | Electricity Demand, Wh | | Electricity surplus/deficit, Wh | | Converted surplus, Wh | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AC | DC | AC | DC | AC | DC | AC | DC | AC | DC | AC-DC | DC-AC |
| | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 1 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1230 | 0 | 0 | 800 | 1230 | -800 | -1230 | 0 | 0 |
| 2 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 3 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 4 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 5 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 6 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 740 | 500 | 0 | 0 | 740 | 500 | -740 | -500 | 0 | 0 |
| 7 | | | | | | | | | | | | | |
| | 1 | 0 | 600 | 500 | 175 | 0 | 600 | 500 | 175 | -500 | 425 | 0 | 403.75 |
| 8 | | | | | | | | | | | | | |
| | 1 | 0 | 3000 | 500 | 65 | 0 | 3000 | 500 | 65 | -500 | 2935 | 0 | 526.32 |
| 9 | | | | | | | | | | | | | |
| | 1 | 0 | 3500 | 500 | 65 | 0 | 3500 | 500 | 65 | -500 | 3435 | 0 | 526.32 |
| 10 | | | | | | | | | | | | | |
| | 1 | 0 | 4100 | 500 | 65 | 0 | 4100 | 500 | 65 | -500 | 4035 | 0 | 526.32 |
| 11 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 12 | | | | | | | | | | | | | |

Modified SCT for HPS-SMES between intervals 12 and 24 h

| Time | Time interval | ∑ Power source rating, W | | ∑ Power demand rating, W | | Electricity Source, Wh | | Electricity Demand, Wh | | Electricity surplus/deficit, Wh | | Converted surplus, Wh | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AC | DC | AC | DC | AC | DC | AC | DC | AC | DC | AC-DC | DC-AC |
| 12 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 13 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 14 | | | | | | | | | | | | | |
| | 1 | 0 | 2000 | 500 | 1275 | 0 | 2000 | 500 | 1275 | -500 | 725 | 0 | 526.32 |
| 15 | | | | | | | | | | | | | |
| | 1 | 0 | 2100 | 500 | 1275 | 0 | 2100 | 500 | 1275 | -500 | 825 | 0 | 526.32 |
| 16 | | | | | | | | | | | | | |
| | 1 | 0 | 1000 | 500 | 75 | 0 | 1000 | 500 | 75 | -500 | 925 | 0 | 526.32 |
| 17 | | | | | | | | | | | | | |
| | 1 | 0 | 500 | 500 | 75 | 0 | 500 | 500 | 75 | -500 | 425 | 0 | 403.75 |
| 18 | | | | | | | | | | | | | |
| | 1 | 0 | 200 | 500 | 65 | 0 | 200 | 500 | 65 | -500 | 135 | 0 | 128.25 |
| 19 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 170 | 0 | 0 | 500 | 170 | -500 | -170 | 0 | 0 |
| 20 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1870 | 0 | 0 | 800 | 1870 | -800 | -1870 | 0 | 0 |
| 21 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1970 | 0 | 0 | 500 | 1970 | -500 | -1970 | 0 | 0 |
| 22 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1370 | 0 | 0 | 500 | 1370 | -500 | -1370 | 0 | 0 |
| 23 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 24 | | | | | | | | | | | | | |

Modified SCT for HPS-SMES between intervals 0 and 12 h

| | | | Start up | | | | Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Charging/ Discharging quantity (DC), Wh | Discharge for AC deficit, Wh | Storage capacity (Wh) | Outsourced electricity, Wh | | | Storage capacity (Wh) | Outsourced electricity, Wh | | |
| | | | | AC | DC | DC-AC | | AC | DC | DC-AC |
| | | | 0 | | | | 8527.94 | | | |
| 0 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 6632.97 | 0 | 0 | 0 |
| 1 | | | | | | | | | | |
| | 0 | 0 | 0 | 800 | 1230 | 1294.74 | 4415.85 | 0 | 0 | 0 |
| 2 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 2543.17 | 0 | 0 | 0 |
| 3 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | -614.27 | 0 | 0 |
| 4 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 5 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 6 | | | | | | | | | | |
| | 0 | 0 | 0 | 740 | 500 | 526.32 | 0 | 740 | 500 | 526.32 |
| 7 | | | | | | | | | | |
| | 0 | 0 | 0 | 96.25 | 0 | 0 | 0 | 96.25 | 0 | 0 |
| 8 | | | | | | | | | | |
| | 2408.68 | 0 | 2288.25 | 0 | 0 | 0 | 2288.25 | 0 | 0 | 0 |
| 9 | | | | | | | | | | |
| | 2908.68 | 0 | 5039.10 | 0 | 0 | 0 | 5039.10 | 0 | 0 | 0 |
| 10 | | | | | | | | | | |
| | 3508.68 | 0 | 8345.04 | 0 | 0 | 0 | 8345.04 | 0 | 0 | 0 |
| 11 | | | | | | | | | | |
| | 3873.68 | 0 | 11979.81 | 0 | 0 | 0 | 11979.81 | 0 | 0 | 0 |
| 12 | | | | | | | | | | |

Modified SCT for HPS-SMES between intervals 12 and 24 h

| Time | Charging/ Discharging quantity (DC), Wh | Discharge for AC deficit, Wh | Start up | | | | Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Storage capacity (Wh) | Outsourced electricity, Wh | | | Storage capacity (Wh) | Outsourced electricity, Wh | | |
| | | | | AC | DC | DC-AC | | AC | DC | DC-AC |
| 12 | | | | | | | | | | |
| | 3873.68 | 0 | 15594.88 | 0 | 0 | 0 | 15594.88 | 0 | 0 | 0 |
| 13 | | | | | | | | | | |
| | 3873.68 | 0 | 19190.35 | 0 | 0 | 0 | 19190.35 | 0 | 0 | 0 |
| 14 | | | | | | | | | | |
| | 198.68 | 0 | 19275.09 | 0 | 0 | 0 | 19275.09 | 0 | 0 | 0 |
| 15 | | | | | | | | | | |
| | 298.68 | 0 | 19454.37 | 0 | 0 | 0 | 19454.37 | 0 | 0 | 0 |
| 16 | | | | | | | | | | |
| | 398.68 | 0 | 19727.68 | 0 | 0 | 0 | 19727.68 | 0 | 0 | 0 |
| 17 | | | | | | | | | | |
| | 0 | -101.32 | 19514.10 | 0 | 0 | 0 | 19514.10 | 0 | 0 | 0 |
| 18 | | | | | | | | | | |
| | 0 | -391.32 | 18996.43 | 0 | 0 | 0 | 18996.43 | 0 | 0 | 0 |
| 19 | | | | | | | | | | |
| | -170 | -526.32 | 18160.50 | 0 | 0 | 0 | 18160.50 | 0 | 0 | 0 |
| 20 | | | | | | | | | | |
| | -1870 | -842.11 | 15207.22 | 0 | 0 | 0 | 15207.22 | 0 | 0 | 0 |
| 21 | | | | | | | | | | |
| | -1970 | -526.32 | 12497.10 | 0 | 0 | 0 | 12497.10 | 0 | 0 | 0 |
| 22 | | | | | | | | | | |
| | -1370 | -526.32 | 10433.24 | 0 | 0 | 0 | 10433.24 | 0 | 0 | 0 |
| 23 | | | | | | | | | | |
| | -1230 | -526.32 | 8527.94 | 0 | 0 | 0 | 8527.94 | 0 | 0 | 0 |
| 24 | | | | | | | | | | |

Modified SCT for HPS-Supercapacitor between intervals 0 and 12 h

| **Time** | **Time interval** | **∑ Power source rating, W** | | **∑ Power demand rating, W** | | **Electricity Source, Wh** | | **Electricity Demand, Wh** | | **Electricity surplus/deficit, Wh** | | **Converted surplus, Wh** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC-DC** | **DC-AC** |
| | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 1 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1230 | 0 | 0 | 800 | 1230 | -800 | -1230 | 0 | 0 |
| 2 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 3 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 4 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 5 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 6 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 740 | 500 | 0 | 0 | 740 | 500 | -740 | -500 | 0 | 0 |
| 7 | | | | | | | | | | | | | |
| | 1 | 0 | 600 | 500 | 175 | 0 | 600 | 500 | 175 | -500 | 425 | 0 | 403.75 |
| 8 | | | | | | | | | | | | | |
| | 1 | 0 | 3000 | 500 | 65 | 0 | 3000 | 500 | 65 | -500 | 2935 | 0 | 526.32 |
| 9 | | | | | | | | | | | | | |
| | 1 | 0 | 3500 | 500 | 65 | 0 | 3500 | 500 | 65 | -500 | 3435 | 0 | 526.32 |
| 10 | | | | | | | | | | | | | |
| | 1 | 0 | 4100 | 500 | 65 | 0 | 4100 | 500 | 65 | -500 | 4035 | 0 | 526.32 |
| 11 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 12 | | | | | | | | | | | | | |

Modified SCT for HPS-Supercapacitor between intervals 12 and 24 h

| **Time** | **Time interval** | **∑ Power source rating, W** | | **∑ Power demand rating, W** | | **Electricity Source, Wh** | | **Electricity Demand, Wh** | | **Electricity surplus/deficit, Wh** | | **Converted surplus, Wh** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC-DC** | **DC-AC** |
| 12 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 13 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 14 | | | | | | | | | | | | | |
| | 1 | 0 | 2000 | 500 | 1275 | 0 | 2000 | 500 | 1275 | -500 | 725 | 0 | 526.32 |
| 15 | | | | | | | | | | | | | |
| | 1 | 0 | 2100 | 500 | 1275 | 0 | 2100 | 500 | 1275 | -500 | 825 | 0 | 526.32 |
| 16 | | | | | | | | | | | | | |
| | 1 | 0 | 1000 | 500 | 75 | 0 | 1000 | 500 | 75 | -500 | 925 | 0 | 526.32 |
| 17 | | | | | | | | | | | | | |
| | 1 | 0 | 500 | 500 | 75 | 0 | 500 | 500 | 75 | -500 | 425 | 0 | 403.75 |
| 18 | | | | | | | | | | | | | |
| | 1 | 0 | 200 | 500 | 65 | 0 | 200 | 500 | 65 | -500 | 135 | 0 | 128.25 |
| 19 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 170 | 0 | 0 | 500 | 170 | -500 | -170 | 0 | 0 |
| 20 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1870 | 0 | 0 | 800 | 1870 | -800 | -1870 | 0 | 0 |
| 21 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1970 | 0 | 0 | 500 | 1970 | -500 | -1970 | 0 | 0 |
| 22 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1370 | 0 | 0 | 500 | 1370 | -500 | -1370 | 0 | 0 |
| 23 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 24 | | | | | | | | | | | | | |

Modified SCT for HPS-Supercapacitor between intervals 0 and 12 h

| | | | **Start up** | | | | **Operation** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **Charging/ Discharging quantity (DC), Wh** | **Discharge for AC deficit, Wh** | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | | | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | | |
| | | | | **AC** | **DC** | **DC-AC** | | **AC** | **DC** | **DC-AC** |
| | | | 0 | | | | 7113.98 | | | |
| 0 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 5176.31 | 0 | 0 | 0 |
| 1 | | | | | | | | | | |
| | 0 | 0 | 0 | 800 | 1230 | 1294.74 | 2930.44 | 0 | 0 | 0 |
| 2 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 1045.05 | 0 | 0 | 0 |
| 3 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 737.13 | 0 | 0 |
| 4 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 5 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 6 | | | | | | | | | | |
| | 0 | 0 | 0 | 740 | 500 | 526.32 | 0 | 740 | 500 | 526.32 |
| 7 | | | | | | | | | | |
| | 0 | 0 | 0 | 96.25 | 0 | 0 | 0 | 96.25 | 0 | 0 |
| 8 | | | | | | | | | | |
| | 2408.68 | 0 | 2288.25 | 0 | 0 | 0 | 2288.25 | 0 | 0 | 0 |
| 9 | | | | | | | | | | |
| | 2908.68 | 0 | 5022.90 | 0 | 0 | 0 | 5022.90 | 0 | 0 | 0 |
| 10 | | | | | | | | | | |
| | 3508.68 | 0 | 8293.36 | 0 | 0 | 0 | 8293.36 | 0 | 0 | 0 |
| 11 | | | | | | | | | | |
| | 3873.68 | 0 | 11869.69 | 0 | 0 | 0 | 11869.69 | 0 | 0 | 0 |
| 12 | | | | | | | | | | |

Modified SCT for HPS-Supercapacitor between intervals 12 and 24 h

| | | | Start up | | | | Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **Charging/ Discharging quantity (DC), Wh** | **Discharge for AC deficit, Wh** | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | | | **Storage capacity (Wh)** | **Outsourced electricity, Wh** | | |
| | | | | **AC** | **DC** | **DC-AC** | | **AC** | **DC** | **DC-AC** |
| 12 | | | | | | | | | | |
| | 3873.68 | 0 | 15401.32 | 0 | 0 | 0 | 15401.32 | 0 | 0 | 0 |
| 13 | | | | | | | | | | |
| | 3873.68 | 0 | 18888.81 | 0 | 0 | 0 | 18888.81 | 0 | 0 | 0 |
| 14 | | | | | | | | | | |
| | 198.68 | 0 | 18841.45 | 0 | 0 | 0 | 18841.45 | 0 | 0 | 0 |
| 15 | | | | | | | | | | |
| | 298.68 | 0 | 18889.68 | 0 | 0 | 0 | 18889.68 | 0 | 0 | 0 |
| 16 | | | | | | | | | | |
| | 398.68 | 0 | 19032.31 | 0 | 0 | 0 | 19032.31 | 0 | 0 | 0 |
| 17 | | | | | | | | | | |
| | 0 | -101.32 | 18687.75 | 0 | 0 | 0 | 18687.75 | 0 | 0 | 0 |
| 18 | | | | | | | | | | |
| | 0 | -391.32 | 18042.25 | 0 | 0 | 0 | 18042.25 | 0 | 0 | 0 |
| 19 | | | | | | | | | | |
| | -170 | -526.32 | 17083.75 | 0 | 0 | 0 | 17083.75 | 0 | 0 | 0 |
| 20 | | | | | | | | | | |
| | -1870 | -842.11 | 14015.36 | 0 | 0 | 0 | 14015.36 | 0 | 0 | 0 |
| 21 | | | | | | | | | | |
| | -1970 | -526.32 | 11212.47 | 0 | 0 | 0 | 11212.47 | 0 | 0 | 0 |
| 22 | | | | | | | | | | |
| | -1370 | -526.32 | 9076.19 | 0 | 0 | 0 | 9076.19 | 0 | 0 | 0 |
| 23 | | | | | | | | | | |
| | -1230 | -526.32 | 7113.98 | 0 | 0 | 0 | 7113.98 | 0 | 0 | 0 |
| 24 | | | | | | | | | | |

Modified SCT for HPS-FES between intervals 0 and 12 h

| Time | Time interval | ∑ Power source rating, W | | ∑ Power demand rating, W | | Electricity Source, Wh | | Electricity Demand, Wh | | Electricity surplus/deficit, Wh | | Converted surplus, Wh | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC** | **DC** | **AC-DC** | **DC-AC** |
| | | | | | | | | | | | | | |
| 0 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 1 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1230 | 0 | 0 | 800 | 1230 | -800 | -1230 | 0 | 0 |
| 2 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 3 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 4 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 5 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 6 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 740 | 500 | 0 | 0 | 740 | 500 | -740 | -500 | 0 | 0 |
| 7 | | | | | | | | | | | | | |
| | 1 | 0 | 600 | 500 | 175 | 0 | 600 | 500 | 175 | -500 | 425 | 0 | 403.75 |
| 8 | | | | | | | | | | | | | |
| | 1 | 0 | 3000 | 500 | 65 | 0 | 3000 | 500 | 65 | -500 | 2935 | 0 | 526.32 |
| 9 | | | | | | | | | | | | | |
| | 1 | 0 | 3500 | 500 | 65 | 0 | 3500 | 500 | 65 | -500 | 3435 | 0 | 526.32 |
| 10 | | | | | | | | | | | | | |
| | 1 | 0 | 4100 | 500 | 65 | 0 | 4100 | 500 | 65 | -500 | 4035 | 0 | 526.32 |
| 11 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 12 | | | | | | | | | | | | | |

Modified SCT for HPS-FES between intervals 12 and 24 h

| Time | Time interval | ∑ Power source rating, W | | ∑ Power demand rating, W | | Electricity Source, Wh | | Electricity Demand, Wh | | Electricity surplus/deficit, Wh | | Converted surplus, Wh | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AC | DC | AC | DC | AC | DC | AC | DC | AC | DC | AC-DC | DC-AC |
| 12 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 13 | | | | | | | | | | | | | |
| | 1 | 0 | 4400 | 500 | 0 | 0 | 4400 | 500 | 0 | -500 | 4400 | 0 | 526.32 |
| 14 | | | | | | | | | | | | | |
| | 1 | 0 | 2000 | 500 | 1275 | 0 | 2000 | 500 | 1275 | -500 | 725 | 0 | 526.32 |
| 15 | | | | | | | | | | | | | |
| | 1 | 0 | 2100 | 500 | 1275 | 0 | 2100 | 500 | 1275 | -500 | 825 | 0 | 526.32 |
| 16 | | | | | | | | | | | | | |
| | 1 | 0 | 1000 | 500 | 75 | 0 | 1000 | 500 | 75 | -500 | 925 | 0 | 526.32 |
| 17 | | | | | | | | | | | | | |
| | 1 | 0 | 500 | 500 | 75 | 0 | 500 | 500 | 75 | -500 | 425 | 0 | 403.75 |
| 18 | | | | | | | | | | | | | |
| | 1 | 0 | 200 | 500 | 65 | 0 | 200 | 500 | 65 | -500 | 135 | 0 | 128.25 |
| 19 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 170 | 0 | 0 | 500 | 170 | -500 | -170 | 0 | 0 |
| 20 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 800 | 1870 | 0 | 0 | 800 | 1870 | -800 | -1870 | 0 | 0 |
| 21 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1970 | 0 | 0 | 500 | 1970 | -500 | -1970 | 0 | 0 |
| 22 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1370 | 0 | 0 | 500 | 1370 | -500 | -1370 | 0 | 0 |
| 23 | | | | | | | | | | | | | |
| | 1 | 0 | 0 | 500 | 1230 | 0 | 0 | 500 | 1230 | -500 | -1230 | 0 | 0 |
| 24 | | | | | | | | | | | | | |

Modified SCT for HPS-FES between intervals 0 and 12 h

| | | | Start up | | | | Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | Charging/ Discharging quantity (DC), Wh | Discharge for AC deficit, Wh | Storage capacity (Wh) | Outsourced electricity, Wh | | | Storage capacity (Wh) | Outsourced electricity, Wh | | |
| | | | | AC | DC | DC-AC | | AC | DC | DC-AC |
| | | | 0 | | | | 1749.66 | | | |
| 0 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | -232.34 | 500 | 0 | 0 |
| 1 | | | | | | | | | | |
| | 0 | 0 | 0 | 800 | 1230 | 1294.74 | -2474.94 | 800 | 0 | 0 |
| 2 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | -4280.77 | 500 | 0 | 0 |
| 3 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 5253.88 | 0 | 0 |
| 4 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 5 | | | | | | | | | | |
| | 0 | 0 | 0 | 500 | 1230 | 1294.74 | 0 | 500 | 1230 | 1294.74 |
| 6 | | | | | | | | | | |
| | 0 | 0 | 0 | 740 | 500 | 526.32 | 0 | 740 | 500 | 526.32 |
| 7 | | | | | | | | | | |
| | 0 | 0 | 0 | 96.25 | 0 | 0 | 0 | 96.25 | 0 | 0 |
| 8 | | | | | | | | | | |
| | 2408.68 | 0 | 2215.99 | 0 | 0 | 0 | 2215.99 | 0 | 0 | 0 |
| 9 | | | | | | | | | | |
| | 2908.68 | 0 | 4799.57 | 0 | 0 | 0 | 4799.57 | 0 | 0 | 0 |
| 10 | | | | | | | | | | |
| | 3508.68 | 0 | 7827.42 | 0 | 0 | 0 | 7827.42 | 0 | 0 | 0 |
| 11 | | | | | | | | | | |
| | 3873.68 | 0 | 11064.81 | 0 | 0 | 0 | 11064.81 | 0 | 0 | 0 |
| 12 | | | | | | | | | | |

Modified SCT for HPS-FES between intervals 12 and 24 h

| Time | Charging/ Discharging quantity (DC), Wh | Discharge for AC deficit, Wh | Start up | | | | Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Storage capacity (Wh) | Outsourced electricity, Wh | | | Storage capacity (Wh) | Outsourced electricity, Wh | | |
| | | | | AC | DC | DC-AC | | AC | DC | DC-AC |
| 12 | | | | | | | | | | |
| | 3873.68 | 0 | 14167.19 | 0 | 0 | 0 | 14167.19 | 0 | 0 | 0 |
| 13 | | | | | | | | | | |
| | 3873.68 | 0 | 17140.21 | 0 | 0 | 0 | 17140.21 | 0 | 0 | 0 |
| 14 | | | | | | | | | | |
| | 198.68 | 0 | 16608.25 | 0 | 0 | 0 | 16608.25 | 0 | 0 | 0 |
| 15 | | | | | | | | | | |
| | 298.68 | 0 | 16190.48 | 0 | 0 | 0 | 16190.48 | 0 | 0 | 0 |
| 16 | | | | | | | | | | |
| | 398.68 | 0 | 15882.12 | 0 | 0 | 0 | 15882.12 | 0 | 0 | 0 |
| 17 | | | | | | | | | | |
| | 0 | -101.32 | 15109.71 | 0 | 0 | 0 | 15109.71 | 0 | 0 | 0 |
| 18 | | | | | | | | | | |
| | 0 | -391.32 | 14054.30 | 0 | 0 | 0 | 14054.30 | 0 | 0 | 0 |
| 19 | | | | | | | | | | |
| | -170 | -526.32 | 12711.37 | 0 | 0 | 0 | 12711.37 | 0 | 0 | 0 |
| 20 | | | | | | | | | | |
| | -1870 | -842.11 | 9233.36 | 0 | 0 | 0 | 9233.36 | 0 | 0 | 0 |
| 21 | | | | | | | | | | |
| | -1970 | -526.32 | 6134.94 | 0 | 0 | 0 | 6134.94 | 0 | 0 | 0 |
| 22 | | | | | | | | | | |
| | -1370 | -526.32 | 3817.90 | 0 | 0 | 0 | 3817.90 | 0 | 0 | 0 |
| 23 | | | | | | | | | | |
| | -1230 | -526.32 | 1749.66 | 0 | 0 | 0 | 1749.66 | 0 | 0 | 0 |
| 24 | | | | | | | | | | |