

A process integration approach for design of hybrid power systems with energy storage

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Abstract Selection of energy storage technology in hybrid power systems (HPS) is vital due to the unique advantages and capabilities offered by different storage technologies. For an optimal operation, the efficient and economical storage system for an HPS should be selected. This work introduces a new systematic generic framework to determine the most cost-effective storage technology for an HPS. A Power Pinch Analysis tool called the AC/DC modified storage cascade table has been developed to optimise the HPS by considering various storage technologies. The economics of the various types of storage modes was analysed, taking into account the associated energy losses, among others. The method was applied to two case studies with different power trends to evaluate the effect of storage efficiencies and storage form on the performance of HPS. A superconducting magnetic storage system of 26.12 kWh capacity, that gives an investment payback period of 3.6 years, is the most cost-effective storage technology for the small-scale household system in Case Study 1. For the large-scale industrial application presented in Case Study 2, the Lead–Acid battery with a capacity of 15.38 MWh gives the lowest payback period (1.43 years).

Keywords Power Pinch Analysis (PoPA) · Hybrid power systems (HPS) · Renewable energy · Energy losses · Energy storage systems · Storage efficiencies

Abbreviations

AC	Alternating current
AEEND	Available excess electricity for the next day
CAES	Compressed air energy storage
CHP	Combined heat and power
DC	Direct current
DoD	Depth of discharge
DRP	Demand response programs
ESS	Energy storage systems
FES	Flywheel energy storage
HPS	Hybrid power systems
MOES	Minimum outsourced electricity supply
PCT	Power cascade table
PoPA	Power Pinch Analysis
PSO	Particle swarm optimisation
PV	Photovoltaic
RE	Renewable energy
SCT	Storage cascade table
SMES	Superconducting magnetic energy storage

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Introduction

Energy storage technology has been a key element for hybrid renewable energy systems located in isolated areas, where connection to the electricity grid is very limited. Due to the stochastic nature of RE, dealing with fluctuating energy supply and demand is a key challenge in managing an HPS. Installation of energy storage technology can be an

effective solution in overcoming this challenge. Application of the storage system ensures real-time load levelling and allows for better RE utilisation by avoiding load shedding in times of overproduction (Ibrahim et al. 2008). In addition, long-term market potential of wind and solar resources can be sustained with the incorporation of cost-effective energy storage (Loughlin et al. 2013).

Various types of storage systems are already in use, while others are still being developed. The various forms of storage are differentiated as the potential (pumped hydro and compressed air), power superconducting magnetic energy storage (SMES), mechanical flywheel energy storage (FES), thermochemical (solar thermal system) and electrochemical (battery) energy. In order to satisfy the demands, the stored energy can be converted to electricity as needed.

The energy storage system can also be used to link different networks i.e. the power and gas systems. Jentsch et al. (2014) reported the case where electricity from RE is stored in the natural gas infrastructure. Apart from storing the surplus RE electricity and reducing CO₂ emissions, the Power-to-Gas (PtG) storage can also be used for heating and cooling, as well as for the transport sector. Even though the conversion of power to methane seems to be a potentially attractive option, however, more research is needed especially to reduce the PtG technology cost and to make it competitive relative to other storage technologies (Sterner 2014).

There have been a number of studies on the optimisation and design of renewable energy systems with storage. Battery sizing in a stand-alone wind-solar hybrid power system was performed using design space approach by Sreeraj et al. (2010). The proposed method that combines the advantages of deterministic and probabilistic approaches provide optimal system configuration in the entire design space based on the lowest cost of energy. Solar electric power technologies integrated with storage system was evaluated using fuzzy logic by Badran et al. (2012). Assessment of various parameters including storage capability provides the optimum solar technology on the basis of benefits and costs. Mukhtaruddin et al. (2015) applied an iterative-Pareto-Fuzzy (IPF) optimisation technique to establish the best hybrid combination of a PV-wind-battery system. The integration of the iterative, Pareto and Fuzzy techniques allows various design objectives such as the minimum total cost and the dump load size to be achieved.

Pumped storage hydro application in renewable plants in Ireland was reported by Crilly and Zhelev (2010). The authors determined the optimal energy resource mix while reducing the total greenhouse gas emissions using a linear programming CO₂ emissions Pinch Analysis. Optimisation of an integrated wind farm with pumped hydro storage was

done by Bayón et al. (2013) using a numerical tool. The results show that the incorporation of pumped hydro enhances the system's profitability as well as the potential to commercialise the wind farm. A model for thermo-economic analysis and optimisation of an HPS featuring compressed air energy storage (CAES) integrated with a wind farm and a PV plant was given by Marano et al. (2012). The optimal management of the HPS was achieved with the application of dynamic programming while considering the energy, economic and environmental aspects. Yang et al. (2014) recently developed a novel hybrid system on the basis of advanced adiabatic CAES. An increased in the power storage capacity was achieved with this newly proposed energy storage system concept that uses energy storage to recover thermal energy from air compression and electrical heating process.

Simulation of an isolated wind power system with FES was performed by Sebastián and Peña Alzola (2012). A low-speed iron flywheel was sized for the system. The authors proved that the FES system effectively stabilises the wind power and consumer load variations. Díaz-González et al. (2013) achieved power smoothing of a variable speed wind turbine using an energy management algorithm of a flywheel-based energy storage device. The optimal operation of the storage device was determined through the formulation and deterministic resolution of an optimisation problem in GAMS. Jin and Chen (2012) explored the application solutions and schemes of SMES technology for future smart grids. The particle swarm optimisation algorithm was used to obtain the ultimate optimal SMES scheme that yielded a reduced processing cost for the system. Design of a hybrid high-temperature SMES was performed by Zhu et al. (2013). The proposed dynamic simulation experiment provides an optimised SMES design, and validates the application capability of SMES systems in a power grid.

The aforementioned methods mostly involve formulating or modelling the HPS using mathematical programming. These approaches have been widely applied to large-scale optimisation of HPS as they are advantageous when handling complex systems. However, these methods provide designers with little insights on the network design, and hence, relatively lesser control over the solution space as well as little insights on network design.

Design of an HPS using an insight-based method such as the Power Pinch Analysis (PoPA) that integrates the various types of storage systems is a new development. There is a clear need to develop a generic Pinch-based approach for the design of an HPS with storage, because it offers vital visualisation insights for network targeting and design that can complement the mathematical programming techniques (Bandyopadhyay 2013). Pinch Analysis has so far been widely applied for the optimal targeting and

design of various resource networks—for an overview see, e.g. (Klemeš et al. 2013) and in more details, (Klemeš and Kravanja 2013). PoPA adapts the Pinch Analysis concept for the optimal design and allocation of an HPS. While the Heat Pinch Analysis is based on the graphical composite plot of temperature (°C) versus enthalpy (H), the defining feature of PoPA is the composite plot of time (h) versus electricity usage (kWh). PoPA provides graphical visualisation tools for users to systematically establish the electricity targets and perform power allocations for an HPS, thereby allowing users to have better control over the decision-making process. The targets include the real-time amount of minimum outsourced electricity, excess electricity, storage capacity and charging/discharging electricity. The graphical insights provided by PoPA can complement the various mathematical programming-based HPS approaches for the optimal design and planning of an HPS.

Earlier PoPA techniques (Wan Alwi et al. 2012) were focused on the targeting of HPS, and thereby assumed 100 % efficiencies for the power transfer and battery storage. Wan Alwi et al. (2013) extended the PoPA to perform load shifting to reduce the maximum battery capacity. Mohammad Rozali et al. (2013b) further developed the PoPA technique to consider the effects of power losses during conversion (inverter and rectifier efficiencies), transfer (charging/discharging of battery) and storage (battery's self-discharge) in the HPS. Based on the similar concept as PoPA, Ho et al. (2013b) proposed a novel graphical tool called the stand-alone hybrid system Power Pinch Analysis (SAHPPA) in order to optimise the capacity of power generators and battery storage for an HPS. Esfahani et al. (2015) presented an Extended-Power Pinch Analysis technique (EPoPA) for the design of an HPS with battery and hydrogen storage. The energy losses in the system, however, were assumed to be negligible.

This work presents a new systematic generic framework to select an optimal storage scheme for an HPS. One of the key steps is to perform the optimal power allocation for an HPS with different types of storage system using the proposed generic PoPA technique called the AC/DC modified storage cascade table (SCT). The storage systems were classified into three categories according to storage capacity and discharge time (Hou et al. 2011). The categories included bulk energy storage, distributed generation and power quality. Each storage scheme offers some unique advantages and capabilities depending on the application. The bulk energy storage is used to smooth the integrated power to grid, while a distributed generation system typically functions as a backup supply to ensure service continuity. For a system that requires power supply stability, power quality storage is used because it can operate within the time interval in the range of seconds. These

categories have different performances regarding levelling the power fluctuations based on their storage ability (Hasan et al. 2013).

The total losses in HPS depend on the power conditioning and storage system efficiencies. The efficiencies are different for each system due to the different mechanical equipment involved, as well as the various processes occurring during the charging, discharging and storage periods. Table 1 summarises the key comparisons between the storage characteristics, which are briefly described in the next section. Storage technologies that are discussed in this work are pumped hydro, CAES, SMES and FES. Lead–Acid battery technology is also included in Table 1 for easier comparison with the results of the previous analysis (Mohammad Rozali et al. 2013b). Note that development in battery technologies is steadily progressing. Other applicable battery technologies include Nickel–Cadmium, Lithium Ion, Sodium Sulphur, Zinc Bromine and Vanadium Redox. Lead–Acid batteries remain the most widely used, although Lithium-Ion batteries are becoming increasingly important (Hadjipaschalis et al. 2009).

Even though the sources of the information are not fully exhaustive, Table 1 indicates that the parameters vary according to the different sources; see Chen et al. (2009), Ferreira et al. (2013), Komor and Glassmire (2012), Gonzalez et al. (2004). Some parameters are outside the range reported by most other sources. For example, Chen et al. (2009) claimed that CAES can reach up to 70–80 % efficiency, which is higher than the average efficiency reported by other sources, i.e. 45–70 %. The range of storage capacities for FES system as reported by Chen et al. (2009) is also not in the range of those reported by Ferreira et al. (2013). The cost of the storage systems varies according to various factors such as the country of origin and the technological advances.

Efficiency and operating scheme of storage systems

This section describes the operation of the pumped hydro, CAES, SMES and FES systems. The mechanical equipment involved in the charging and discharging processes as well as during the storage (self-discharge) period contributes to the total system losses. This paper identifies and assesses these losses. The efficiencies are taken into account by the proposed AC/DC modified SCT methodology. This methodology leads to the different results in the power allocation for each technology application. Table 2 shows the efficiencies of the storage systems extracted from the literature for each stage, i.e. charging, discharging and storage, based on the average ranges from Table 1.

Table 1 Key parameters and characteristics of storage technologies

	Pumped hydro	CAES	SMES	FES	Lead-Acid
Energy storage forms	Potential	Potential	Electrical	Kinetic	Electrochemical
Roundtrip efficiency (%)	70–85 ^a , 70–87 ^b , 75–80 ^c	70–80 ^a , 57–64 ^d , 45–60 ^e , 40–80 ^b	95–98 ^a , 90–95 ^f , 85–99 ^b	90–95 ^a , 85–95 ^c , 80–99 ^b	70–80 ^a , 70–90 ^c , 70–92 ^b
Self-discharge rate	Evaporation losses, rain gained	Air leaks	Refrigeration losses	Standby losses	Battery self-discharge
Charging efficiency	Pump and pipe	Compressor and motor	–	Electrical machine	Battery charging
Discharging efficiency	Turbine and pipe	Turbine and generator	–	Electrical machine	Battery discharging
Storage capacity (MW)	100–5000 ^{a,b} , ≥200 ^e	5–300 ^a , 1–400 ^b	0.1–10 ^a , 0.01–0 ^b	0–0.25 ^a , 0.002–20 ^b	0–20 ^a , 0.001–50 ^b
Lifetime (years)	40–60 ^a , 40–100 ^b	20–40 ^a , 20–00 ^b , 30 ^d	20 ^a , 30 ^d	15 ^a , 15–20 ^b	5–15 ^a , 5–10 ^d
Capital cost (\$/kW)	600–2000 ^{a, b} , 1190–1250 ^f	400–800 ^{a,b} , 510–650 ^f	200–300 ^{a,b}	250–350 ^{a,b} , 360–400 ^f	300–600 ^{a,b} , 150–300 ^f
Operation and maintenance cost (\$/kW/y)	3 ^a , 5 ^c	1.6–4.3 ^d , 5 ^c , 3–12 ^f	9.2–30 ^d , 12 ^f	15 ^c , 6 ^f	30 ^c , 6–18 ^f
Annualised total cost, million (\$/y) ^h	3.036 ^g	0.989 ^g	0.739 ^g	0.8000 ^g	1.300 ^g

^a Chen et al. (2009)^b Ferreira et al. (2013)^c Hadjipaschalis et al. (2009)^d Gonzalez et al. (2004)^e Komor and Glassmire (2012)^f Schoenung and Hassenzahl (2003)^g Sundararagan and Baker (2012)^h Based on the lifetime of storages, the annualised total cost is presented by arranging the technologies according to sub-groups i.e. (1) CAES and PHS, (2) Lead-Acid battery and (3) FES and SMES (Sundararagan and Baker 2012)

Table 2 Efficiencies in storage technologies presented by referenced works

	Charging (%)	Discharging (%)	Self-discharge rate (%/h)
Pumped hydro	90 (Wilde 2011)	90 (Wilde 2011)	≈ 0 (Schoppe 2010)*
CAES	84 (Hartmann et al. 2012)	89 (Hartmann et al. 2012)	≈ 0 (The Arizona Research Institute for Solar Energy 2010)
SMES	≈ 100 (Morandi et al. 2012)	≈ 100 (Morandi et al. 2012)	0.417 (Bradbury 2010)
FES	93 (Sebastián and Peña Alzola 2012)	93 (Sebastián and Peña Alzola 2012)	18 (Ruddell 2002)

* Depends on the climate–evaporation losses and gains due to rain

Pumped hydro storage

A pumped hydro storage system stores energy in the form of water, which is pumped from a lower to an upper reservoir (Bayón et al. 2013). A reversible AC pump-turbine unit is used in the system, i.e. using a single reversible machine as both a pump and a turbine (Liang and Harley 2010). Pump efficiency affects the charging process in pumped hydro, while electricity generation by turbine at peak load periods causes energy losses during discharging mode. The total charging and discharging rates are given by the product of the efficiencies of the pipe (friction losses) and the mechanical equipment and are assumed as 90 % (Wilde 2011). Analogous to the self-discharge rate in a battery, evaporation losses occur during the storage period in pumped hydro storage. The hourly evaporation loss is assumed to be negligible according to Schoppe (2010) because the amount of water evaporated is small as compared to the total water volume in the reservoir. The evaporation losses are, however, affected by the exposed water surface and the depth of the storage reservoir. Note that pumped hydro is the only storage that can achieve a positive change due to heavy rain, which will help to offset the loss from evaporation.

Compressed air energy storage (CAES)

CAES uses the readily available air as the storage medium. CAES stores high pressure air during off-peak hours and retrieves the energy later during the peak period. The excess electricity generated by RE is supplied to the AC electric motor-driven compressors (Succar and Williams 2008) for charging process. During the discharging process, the air is extracted from the reservoir and mixed with natural gas, combusted and expanded in a modified gas turbine, generating electricity (International Electrotechnical Commission 2011). The adiabatic CAES type is considered in this work, as it can reach an efficiency of 70–85 % (International Electrotechnical Commission 2011). The overall efficiency of an adiabatic CAES system is the product of the compressor, motor and thermal storage efficiencies during the charging process, turbine, generator and thermal storage efficiencies for discharging, as well as the thermal losses and

air leakage rate for storage efficiency (Elmegaard and Brix 2011). The charging and discharging efficiencies are assumed to be 84 and 89 % (Hartmann et al. 2012). A constant air temperature in the reservoir is assumed, and the heat losses of the storage can be neglected, as reported by Marano et al. (2012). In addition, air leaks (self-discharge) that may occur during the storage period can be eliminated in some cases, e.g. using a salt cavern as the air reservoir, because caves made in domal salt deposits will most likely be free of any air leaks (The Arizona Research Institute for Solar Energy 2010).

Superconducting magnetic energy storage (SMES)

Energy is stored in the form of DC electricity in SMES, which is induced in a superconducting coil (Hassenzahl 1989). This coil is cryogenically cooled to a temperature below its superconducting critical temperature by a refrigerator. During the off-peak time, the excess electricity is fed to the power conditioning and switching devices, which provide energy to charge the coil for storing energy (Sheikh and Tamura 2012). When the electricity is required, the coil is discharged through the switching devices, thereby feeding conditioned power to the load (Sheikh and Tamura 2012). The rate of the charging and discharging processes in SMES is therefore influenced only by the efficiency of the power conditioning system, i.e. inverter and rectifier. The loss of power due to the resistance is small because the superconductor has the ability to carry direct current without any resistance (Morandi et al. 2012). Although the overall efficiency of the coil is almost 100 %, losses due to the cooling system (refrigeration losses) for the coil contribute to a significant rate of self-discharge, which is assumed as 10 %/days (Bradbury 2010).

Flywheel energy storage (FES)

FES is a form of mechanical energy storage that stores energy in a rotating mass in the form of kinetic energy. Kinetic energy is charged and discharged from the flywheel with an AC electrical machine, which functions either as a motor or generator, depending on the load angle (Bolund

et al. 2007). During the charging mode, the electrical machine acts as a motor that converts the AC electricity supplied to the stator winding into torque. In generator mode, which occurs during the discharging process, the kinetic energy stored applies a torque and is converted to AC electricity. The rate of charging and discharging is therefore affected by the rotor losses in the electrical machine (motor/generator). The efficiency is assumed to be 93 % (Sebastián and Peña Alzola 2012). The aerodynamic friction torque can be eliminated by confining the flywheel into a vessel with absolute vacuum (Sebastián and Peña Alzola 2012), while the losses due to the bearings (eddy current and hysteresis losses) are minimised by deploying magnetic bearings, which have no friction and wearing (Long and Zhiping 2009). However, standby losses within 18–20 %/h of the stored capacity are wasted through self-discharge (Ruddell 2002).

Generic framework for storage system selection

The new generic framework to decide on the most worthwhile storage system for the HPS consists of three main steps, as summarised in Fig. 1. Each stage addresses the different aspects that affect the results and the decisions of the final storage.

Stage 1: Identification

In the first stage, the profiles of the sources and demands of the HPS are identified. Assuming that all of the generated electricity is sent to storage, the upper limit for the required storage capacity is set. Referring to the stored capacity, the applicable storage for the studied HPS is determined based on the categories of application, as listed in Table 3 (Schoenung and Hassenzahl 2007).

Stage 2: Generic AC/DC modified storage cascade table

Following the identification step is the analysis of the efficiencies of each storage technology. The losses that occur during power conversion, transfer and storage are considered with the implementation of the generic AC/DC modified SCT for the targeting and allocation of electricity. The analogous concept to the problem table algorithm (Linnhoff and Flower 1978) in Heat Pinch is adapted into this AC/DC modified SCT methodology. The electricity storage is cascaded to the future time interval and can be discharged when required by the demand. The SCT shows the amount of electricity surplus and deficit at each time interval and offers insights for the optimum allocation of the HPS. Assuming the initial storage capacity to be zero,

the surplus electricity is cascaded to the future time interval and cumulatively added to the storage capacity. The stored electricity can be discharged to satisfy a required demand. Apart from providing the numerical power recovery targets in the form of storage capacity, outsourced electricity and charging/discharging amount for the HPS, the SCT also shows the flow of electricity at each time interval.

This new modified AC/DC SCT technique was developed to address the issues in HPS with a combined AC/DC topology. The application of both AC and DC electricity as the power source and demand in an HPS makes the selection of the storage system crucial. To address the problems involving storage systems that operate with AC electricity (referred to as AC storage in this paper), the modified SCT (Mohammad Rozali et al. 2013b) is extended to overcome its limited application for DC storage (batteries) only. This new development can ensure that the method is more applicable to widespread applications involving various energy storage technologies. The general procedure for the method construction is shown in Fig. 1. As observed, different computations are used when AC storage is applied instead of DC storage. This requirement for different computations is caused by the different processes that occur in both storage systems.

It can be observed that the separate routes involve steps where conversion of AC and DC electricity is required. The charging and discharging processes are the stages where the conversion occurs. As opposed to DC storage operation, the charging electricity in AC storage has to be AC electricity. The discharged AC electricity requires a rectifier if DC demands are to be satisfied. Figure 2a summarises the electricity flow and losses in a system with an AC storage scheme. Mechanical equipment such as a pump, a compressor or a turbine is the appliance used in the system to convert stored energy to electricity, and vice versa. For example, stored energy is discharged in a pumped hydro storage system when a turbine converts the potential energy from water in the reservoir to electricity. Conversely, electricity is required to drive the pump and to charge water with the energy it requires to be transported. Note that the mechanical equipment operated with AC electricity requires a different electricity conversion step as compared to the one for DC electricity (see Fig. 2b). This consequently affects the total losses as well as the power allocation in an HPS.

The step-wise construction of the modified AC/DC SCT for an AC storage is demonstrated with an example using pumped hydro storage efficiencies. The reversible pump-turbine unit used in the storage system is assumed to be operated with AC current (Liang and Harley 2010). Apart from the efficiencies listed in Table 2, the efficiencies of inverter and rectifier for the power conversion (AC–DC or DC–AC) are assumed to be 95 % (Burger and Ruther

Fig. 1 Generic framework for cost-effective storage determination

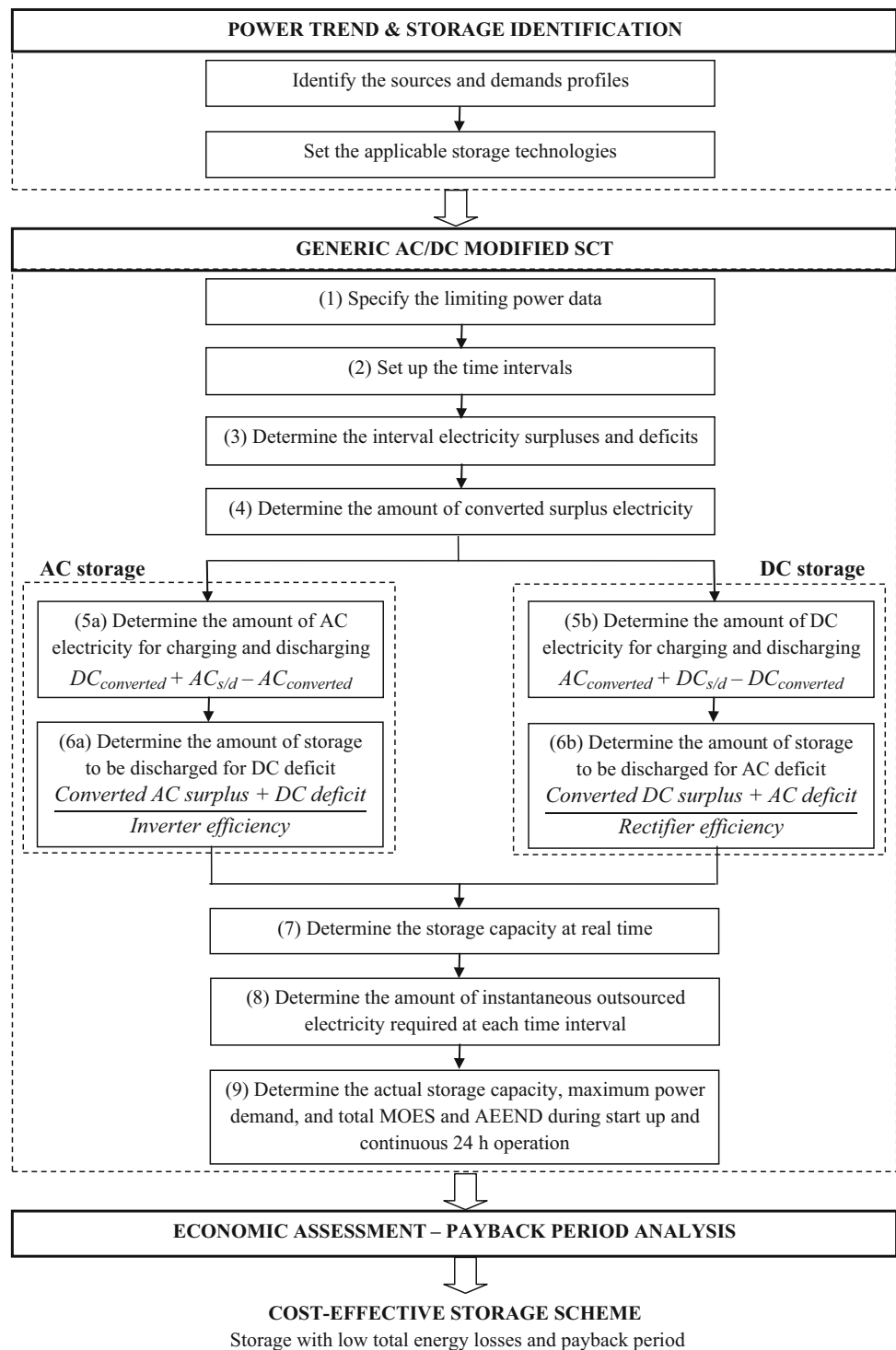


Table 3 Application category specifications (Guerrero-Lemus and Martínez-Duart 2013)

Category	Stored energy (MWh)	Storage technologies
Bulk energy storage	10–8000	Pumped hydro, CAES, Lead–Acid
Distributed generation	<8	CAES, SMES, FES, Lead–Acid
Power quality	<0.02	SMES, FES, Lead–Acid

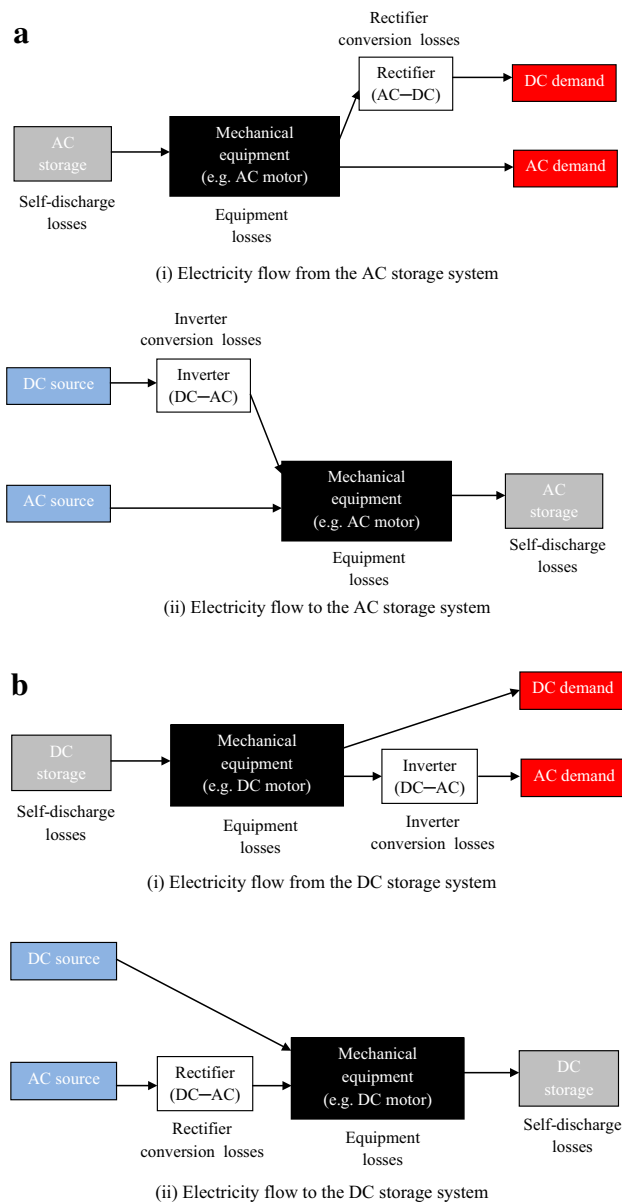


Fig. 2 a Electricity flow and losses in HPS with AC storage. b Electricity flow and losses in HPS with DC storage

2005). This efficiency value is identical for all storage systems because the same power conditioning systems (inverter and rectifier) are used in each system. The modified AC/DC SCT technique is performed in two key steps described below.

Step 1: Specify the limiting power data

The limiting power data consist of the minimum available power sources and the maximum load demand for every time interval. Tables 4 and 5 tabulate the limiting power source and demand data for Illustrative Case Study 1. In order to illustrate the methodology, the average value for the generated power from RE is considered for the specified time range. For example, it

is assumed that 60 kW of power is generated (after considering the solar PV panels efficiency) from the total solar radiation available between 8 am and 6 pm. Similarly for power demand, the average power demand rating is assumed for the time intervals. In real cases (see “Case Studies” section 1 and 2), the hourly power generation and consumption is utilised as the data to achieve more accurate and reliable results

Step 2: Determine the optimal power allocation and minimum electricity targets

The modified AC/DC SCTs that provide the electricity allocation and targets for the HPS-integrated pumped hydro storage are shown in Tables 6 and 7. Table 6 is constructed as described in Mohammad Rozali et al. (2013b) as follows:

- (1) The time for power sources and power demands is listed in Column 1 in ascending order, while Column 2 gives the duration between two adjacent time intervals.
- (2) The total sum of ratings for power sources and power demands for each time interval is given in columns 3 and 4. These values can be obtained from the power cascade table (Mohammad Rozali et al. 2013c). The sources and demands for the AC and DC electricity are listed separately.
- (3) The quantities of the electricity sources and demands between time intervals are obtained using Eq. 1, and listed in Columns 5 and 6.

$$\begin{aligned} \sum \text{Electricity source/demand} \\ = \sum \text{Power rating} \times \text{Time interval duration.} \end{aligned} \quad (1)$$

- (4) The sources are sent directly to the demands accordingly for the AC and DC. The surpluses and deficits for the AC and DC electricity between time intervals are calculated using Eq. 2, and listed in Column 7.

$$\begin{aligned} \text{Electricity surplus/deficit} \\ = \sum \text{Electricity source} - \sum \text{Electricity demand.} \end{aligned} \quad (2)$$

Equation 2 should be applied separately for AC and DC electricity. A positive value indicates an electricity surplus while a negative value represents electricity deficit.

Table 7 is constructed independently for the DC and AC storages, as the construction involves the computation of different occurrences of power conversion, as well as the different efficiencies of each storage. It is constructed as outlined:

Table 4 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	60	1680
	Solar	8	18	10	60	600

Table 5 Limiting power demands for illustrative Case Study 1

Power demand appliances		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

Table 6 Modified storage cascade table for illustrative Case Study 1

1	2	3		4		5		6		7	
Time (h)	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	60	0	0	50	120	0	0	100	120	-100
2	6	110	0	0	50	660	0	0	300	660	-300
8	2	110	60	140	50	220	120	280	100	-60	20
10	8	60	60	140	50	480	480	1120	400	-640	80
18	2	60	0	40	50	120	0	80	100	40	-100
20	4	60	0	0	50	240	0	0	200	240	-200
24											

(1) Column 8 gives the amount of electricity converted from DC surplus. It is calculated via Eq. (3), which can also be used for AC surplus, only if the quantity of AC surplus is lower than the deficit in DC electricity. If the surplus in AC is higher, Eq. (4) is utilised instead because only the exact amount needed to satisfy the DC load is converted. This can minimise the conversion losses because the excess DC electricity (from AC surplus) would have to be converted back to AC before it can be stored. This energy management is performed by a controller to ensure an optimal operation of the system (Manolakos et al. 2004).

$$\begin{aligned} &\text{Amount of converted DC electricity to AC} \\ &= \text{DC electricity surplus} \times \text{Inverter efficiency,} \end{aligned} \tag{3}$$

$$\begin{aligned} &\text{Amount of AC electricity surplus to} \\ &\text{be converted to DC} = \frac{\text{Amount of DC deficit}}{\text{Rectifier efficiency}}. \end{aligned} \tag{4}$$

(2) Equation (5) is derived to give the quantity of AC electricity available for storage after load utilisation (see Column 9). The amount of charging is represented with the positive value, while the negative figure denotes the discharging quantity.

Table 7 Modified storage cascade table for illustrative Case Study 1

8		9		10		11		12		13		14	
						Start-up				24 h operation			
Converted surplus (kWh)		Charging/ discharging quantity (AC) (kWh)		Discharge for DC deficit (kWh)		Storage capacity (kWh)		Outsourced electricity (kWh)		Storage capacity (kWh)		Outsourced electricity (kWh)	
AC-DC	DC-AC							AC	DC			AC	DC
						0					26.53		
105.26		14.74				13.26					39.79		
315.79		344.21				323.05					349.58		
	19	-41.00				277.50					304.02		
	76	-249.75				0		314.25		0		290.38	
38.00		0				0			62.00	0			62.00
210.53		29.47				26.53					26.53		

$$C_t/D_t = AC_{s/d} + DC_{converted} - AC_{converted}, \tag{5}$$

where C_t = charging quantity; D_t = discharging quantity; $AC_{s/d}$ = AC electricity surplus/deficit; $DC_{converted}$ = amount of AC converted from DC electricity surplus; $AC_{converted}$ = amount of DC converted from AC surplus.

- (3) Step 2 only provides the discharging quantity for the AC deficit. The amount of discharge for the DC deficit as listed in Column 10 is obtained using Eq. (6).

$$D_t \text{ for DC deficit} = \frac{\text{Converted AC surplus} + \text{DC deficit}}{\text{Inverter efficiency}}. \tag{6}$$

If the storage capacity is less than the AC discharge requirement to meet the deficit, the storage is discharged to the depth of discharge (DoD) of hydro storage. The DoD is assumed to be 80 % of the maximum storage capacity (Notton et al. 2011). In this scenario, the quantity of the available AC electricity from storage that can be discharged to supply the deficit in demand is obtained using Eq. (7). For instance, 484 kWh (640-76 = 564 kWh) of AC deficit is still not fulfilled between times 10 and 18 h. This amount is higher than the storage capacity of 277.50 kWh. Considering the losses due to the discharging and self-discharge, 249.75 kWh can be supplied for the AC deficit by storage (Column 9). If the deficit is DC instead of AC, the conversion efficiency expression is included in Eq. (7), and the amount of electricity that can be supplied to the DC deficit is listed in Column 10.

$$\begin{aligned} \text{AC electricity available from storage} \\ = S_{t-1}(1 - \sigma \times T) \times \eta_d, \end{aligned} \tag{7}$$

where S_{t-1} = storage capacity at the previous time interval [kWh]; σ = hourly self-discharge rate; t = time [h]; T = time interval [h]; η_d = discharging efficiency (0.9).

- (4) Based on the charging and discharging quantities (Columns 9 and 10), the cumulative storage capacity shown in Column 11 is obtained using Eq. (8),

$$S_t = S_{t-1}(1 - \sigma \times T) + (C_t \times \eta_c) + D_t/\eta_d, \tag{8}$$

where S_t = storage capacity [kWh]; C_t = charging quantity [kWh]; D_t = discharging quantity [kWh]; σ = hourly self-discharge rate [%/h]; t = time [h]; T = time interval [h]; η_c = charging efficiency = 0.9; η_d = discharging efficiency = 0.9.

Equation (8) has to be carefully applied because a positive value in Column 9 represents C_t , while a negative value indicates D_t . The electricity cascade for the subsequent time interval continues at zero if the hydro storage has been discharged to its DoD (e.g. between times 10 and 18 h).

- (5) Equation (9) was derived to calculate the actual maximum storage capacity, based on the largest value in Column 9.

$$S_{(t)\text{actual}} = S(t)/\text{DOD} \tag{9}$$

- (6) Electricity should be outsourced from the grid if the amount of storage is still not enough to satisfy the demand. The required amount of outsourced electricity as shown in Column 12 is the residual electricity demand that has not been fulfilled by the storage discharged quantity. Equation (10) is used to compute the instantaneous external power demand.

$$\text{Outsourced power rating} = \frac{\text{Outsourced electricity}}{\text{Time interval}} \tag{10}$$

For Illustrative Case Study 1, 39.28 kW of electricity has to be outsourced to supply the AC demand between times 10 and 18 h. Between times 18 and 20 h, 32.63 kW of external electricity is needed to be sent to DC demand. Note that the 32.63 kW is obtained after the conversion (DC–AC) losses of 5 % are taken into consideration because the grid provides electricity in AC.

- (7) The remaining electricity in the storage at $t = 24$ h during start-up is brought to the next day (normal 24 h) operation and set as the storage capacity at $t = 0$ h (26.53 kWh). Equation 8 is utilised to obtain the cumulative storage capacity for the 24 h operation as listed in Column 13. Based on the biggest value in Column 13 (349.58 kWh), the actual storage capacity is determined using Eq. (9) as 436.98 kWh.
- (8) The required outsourced electricity for each AC and DC demand during 24 h of operation is given in Column 14. Between times 10 and 18 h, 36.30 kW of AC demand occurs, while 32.63 kW of electricity is required to be outsourced for DC demand between the time intervals of 18 and 20 h.

Note that Illustrative Case Study 1 presented is used only to demonstrate the steps of the methodology. The storage capacity range for pumped hydro is far larger than the results obtained. The same methodology can be performed to determine the optimal power allocation for an HPS with CAES and FES storage by changing the efficiencies in the methodology. However, the SMES system falls into the same category as battery storage and hence is designed with the same methodology as presented by Mohammad Rozali et al. (2013b). Table 8 shows that the results of the implemented methodology for all of the storage schemes including the Lead–Acid battery. The variations in the capacity scales for the storage technologies have been neglected in the analysis of Illustrative Case Study 1, in order to provide an overview of the diverse results of storage capacity and outsourced electricity targets as established by the AC/DC modified SCT for different storages. Note that the DoD value used for all storage types is assumed as 80 % of the maximum capacity.

The results indicate that the SMES has the largest maximum storage capacity (459.64 kWh) compared to the other storage systems. In addition, the SMES also imported the lowest amount of minimum outsourced electricity supply (MOES), and has the highest amount of available excess electricity for the next day (AEEND), which is mainly due to the avoided energy conversion as well as the tolerable self-discharge losses of this technology. FES, in contrast, has the largest total losses, as its maximum power

demand reached 68.35 kW with the smallest storage capacity of 269.74 kWh. The high self-discharge rate in this storage system is seen to be the main factor for its poor performance because the charging and discharging processes in FES are very efficient.

Stage 3: Economic assessment

In the final stage, the determined storage capacity and the amount of imported outsourced electricity from the AC/DC modified SCT are inserted into the cost function to obtain the payback period for each investigated storage scheme. The cost for the RE generating equipment as well as the power conditioning hardware is not included in the calculation because the analysis aims to compare the storage systems. There is a trade-off between the installed storage sizes with the amount of the outsourced electricity. When the storage capacity increases (cost increases), the total amount of imported electricity is reduced (cost decreases). The storage cost is also dependent on the storage size, which determines its category of application. This dependence on storage size is because the advantage of the economy-of-scale principle is applied, where the unit cost decreases with every increase in the storage capacity (Seider et al. 2010). The payback period for the investment on the storage systems is calculated via Eq. (11).

$$\text{Payback period} = \frac{\text{Net capital investment}}{\text{Net annual savings}}. \quad (11)$$

The net capital investment is the capital cost of the storage. The net annual savings are the difference in the storage systems maintenance cost and the reduced MOES cost with the residential tariff rate of the required outsourced electricity. Equation (12) is derived to calculate the net annual savings.

$$\text{Net annual savings} = (O \times D \times T_E) - (O_{\text{HPS}} \times D \times T_E) - (S \times OM) \quad (12)$$

where O = total daily outsourced electricity without HPS [kWh]; D = total days for a year operation [d]; T_E = tariff rate for electricity; O_{HPS} = total daily outsourced electricity with HPS [kWh]; S = storage capacity [kW]; OM = annualised operating and maintenance cost of the storage [\$/kW].

The currency used for cost calculations is standardised to USD [USD]. The electricity tariff rate used in Eq. (12) depends on the types of customers or sectors, i.e. residential, commercial or industrial. The fluctuations of solar and wind energy throughout the year are taken into account in the analysis by assuming three possible operation days,

Table 8 Results from modified SCT for illustrative Case Study 1

	Maximum storage capacity (kWh)	Maximum demand (kW)	MOES (kWh)	AEEND (kWh)
Pumped hydro	436.98	32.63	379.52–start-up	26.53–start-up
			355.64–operation	26.53–operation
CAES	402.99	48.07	449.80–start-up	24.46–start-up
			431.69–operation	24.46–operation
SMES	459.64	36.69	358.77–start-up	28.00–start-up
			334.13–operation	28.00–operation
FES	269.74	68.35	612.04–start-up	27.41–start-up
			611.39–operation	27.41–operation
Lead–Acid	415.11	42.84	407.96–start-up	25.20–start-up
			386.43–operation	25.20–operation

D. The total of the days when the RE sources are available is assumed as (i) 365 days (an ideal, but unrealistic case), (ii) 300 days and (iii) 200 days.

The net present value (NPV) for each storage technology is calculated by considering the electricity cost savings attained over the storage lifetime relative to capital costs, annual OM costs as well as the discount rate (Nottrott et al. 2013). The NPV can be written as follows:

$$\text{NPV} = \sum_{n=0}^N \frac{C_n}{(1+r)^n}, \quad (13)$$

where n = year of cash flow; C_n = annualised financial flow at year n [\$/y]; r = discount rate [%]; N = storage lifetime [y].

The annualised financial flow, C_n is equivalent to the annual electricity cost savings as obtained in Eq. (12), while the discount rate, r is assumed to be 10 % (Hernandez-Torres et al. 2015).

At the completion of all three stages, designers can choose the ultimate storage technology for the final design of the HPS based on their preferences to meet the targeted system's reliability and profitability. To better illustrate the application of the framework, two case studies are scrutinised in the following "Case studies" section.

Case studies

Two case studies involving different locations and applications were selected. The first case study involves an HPS for a typical household scenario (Ho et al. 2013a). The second case study is on the design of an industrial HPS involving a chemical plant (Masjuki et al. 2006).

Household application (small-scale system)

The limiting power source and demand data for a residential house in Malaysia are presented in Table 9. Solar energy is

the only power source of the system that generates DC electricity supply. The equipment, however, consists of both DC and AC appliances. Summing up the generated electricity from $t = 0$ to $t = 24$ h, the upper limit of the storage capacity is set to 0.03 MWh. It can be concluded based on Table 3 that this case is best applied with FES, SMES or Lead–Acid battery storage (Ibrahim et al. 2008).

Stage 2 is then executed for the specified storage technologies. The results from the AC/DC modified SCT for the three applicable storage systems are illustrated in Fig. 3. As observed, from the total amount of electricity surpluses available, SMES manages to store the highest capacity compared to the other two technologies. Installation of SMES and Lead–Acid battery storage provides over 50 % reduction in the MOES for start-up (compared to MOES without integration), while FES reduces only 38.66 % of the start-up MOES. For the 24-h normal operation, a further reduction in the MOES amount is achieved by SMES and Lead–Acid storage, but the MOES for FES storage exhibits no further decrement. The highest AEEND is given by the system with SMES, which is 10.32 kWh, while Lead–Acid allows 8.03 kWh of electricity to be brought for the next day's use. FES storage, in contrast, has no excess electricity at the end of the day.

The excellent performance of the SMES and Lead–Acid battery in this system compared to FES is mainly due to the DC storage type of both technologies. The trends for the power sources that consist only of DC electricity allow for the total AC–DC conversion processes in the system to be minimal. Most of the appliances operate with DC electricity as well.

To support the results of the losses analysis, economic evaluation (Stage 3) is performed for each system. Using a tariff rate of 0.16 \$/kWh that is charged by the utility company for residential customers (Tenaga Nasional Berhad 2014b), the payback period and the NPV (year 10) for the studied storages are obtained via Eqs. (11) and (13).

Table 9 Limiting power data for Case Study 1 (Ho et al. 2013a)

Time (h)		Power source rating (kW)	Power demand rating (kW)									
From	To		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
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	0	0	0

Table 10 provides the extracted economic data required in the equations for the storage technologies involved in Case Study 1, which is classified under the distributed generation (≤ 8000 kWh) application (Schoenung and Hassenzahl 2003).

Table 11 lists the financial results of each of the storage system applications for the three scenarios. It can be observed that the economic analysis results are in parallel with the results of the losses analysis using the modified SCT. The SMES application has been proven to be the most worthy technology to be installed with the house PV system because of its shortest payback period and highest NPV.

Industrial-scale HPS application (large-scale system)

Table 12 presents the power source and demand data of a chemical plant (Bureau of Energy Efficiency 2013). The

end-use electricity consumptions are divided into AC (electrical motors, pumps, workshop machines, overhead cranes, ventilation, furnace, boilers, dust collecting equipment and escalators) and DC (air-compressors, air-conditioning systems, lighting, conveyor systems, refrigeration systems, and others) according to Masjuki et al. (2006). The renewable sources available are the solar (DC) and wind (AC) energy. Assuming that all of the generated electricity is sent to storage, the upper limit of the storage capacity for this HPS is set to 43.88 MWh. The applicable storage technologies for this system are categorised under the bulk energy storage, which consists of pumped hydro, CAES and Lead–Acid (Table 3).

Based on the specified storage types, Stage 2 is performed. Figure 4 represents the results of the AC/DC modified SCT method for the three storage schemes. The maximum storage capacity of CAES (14.23 MWh) exhibits a significant gap with the capacity of pumped hydro (15.24 MWh) and Lead–Acid batteries (15.38 MWh). The

Fig. 3 Modified SCT results for Case Study 1

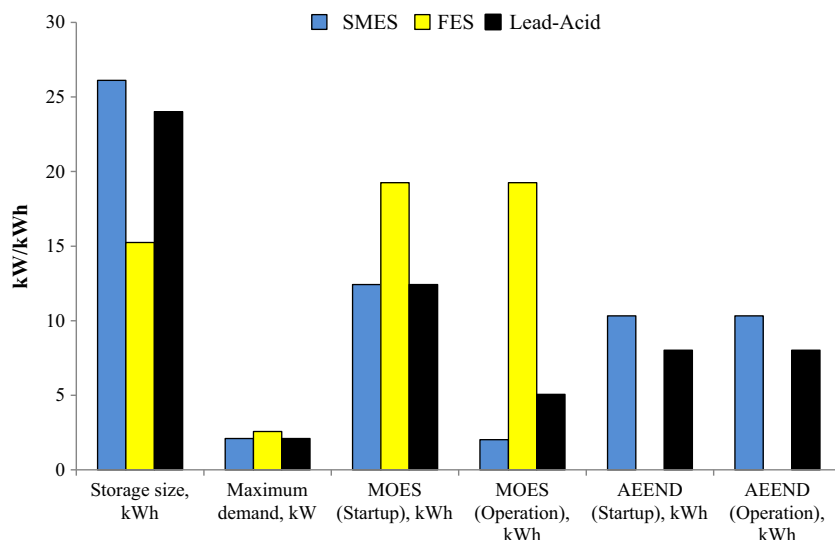


Table 10 Costs of storage technologies for distributed generation applications (Schoenung and Hassenzahl 2003)

	SMES	FES	Lead-Acid
Capital cost (\$/kW)	200	300	250
Operation & maintenance cost (\$/kW _y)	10	5	10

required MOES for start-up does not exhibit a large difference between the storage types, but CAES still imports more MOES than pumped hydro and Lead-Acid batteries due to its lower efficiency during the transfer process. The amount of AEEND for all storage types exhibits no changes between start-up and continuous 24 h operation, with Lead-Acid batteries providing the highest electricity excess (6.76 MWh), followed by pumped hydro (6.71 MWh) and CAES (5.83 MWh).

Lead-Acid battery storage was found to be the most efficient storage for this plant application. Pumped hydro storage, however, provides a very good performance as well. The effect of the power trend is seen as the main reason for this outcome because both storage schemes have the same charging/discharging efficiencies, while the self-discharge rate in pumped hydro storage is negligible. In contrast, the CAES system exhibits the worst performance because higher losses occur during its charging and discharging processes.

Using the established results from the modified SCT, the economic assessment for Case Study 2 is performed (*Stage 3*). The industrial peak and off-peak tariff rates are considered (Tenaga Nasional Berhad 2014a). Outsourced electricity imported between 10 pm and 8 am (time intervals of 22–24 and 0–8 h) is charged with the off-peak usage tariff rate (0.07 \$/kWh), while the grid electricity required during the peak period (8 am to 10 pm) is charged

Table 11 Economic evaluation for Case Study 1

	SMES	FES	Lead-Acid
<i>D</i> = 365 d			
Net capital investment (\$)	5224	4571	6002
Net annual savings (\$/y)	1453	622	1297
Payback period (year)	3.60	7.35	4.63
Net present value (\$)	8926	3823	7967
<i>D</i> = 300 d			
Net capital investment (\$)	5224	4571	6002
Net annual savings (\$/y)	1147	498	1023
Payback period (year)	4.55	9.18	5.87
Net present value (\$)	7049	3059	6285
<i>D</i> = 200 d			
Net capital investment (\$)	5224	4571	6002
Net annual savings (\$/y)	677	306	601
Payback period (year)	7.71	14.91	9.98
Net present value (\$)	4161	1883	3696

with 0.11 \$/kWh. The economic parameters for bulk energy (10–8000 MWh) applications are listed in Table 13 for the three storage systems involved (Schoenung and Hassenzahl 2003).

The results presented in Table 14 show that the application of Lead-Acid battery guarantees a very short pay-back period compared to the other storage schemes. However, its NPV at year 10 is the lowest. Even though it takes longer for CAES to recover the invested capital as compared to the Lead-Acid, CAES gives a higher NPV at year 10. This may be due to the high annual OM costs of the Lead-Acid battery, which leads to a lower annualised cash flow. Despite its good performance, pumped hydro storage is not economical for application in the system. The

Table 12 Limiting power data for Case Study 2 (Feroldi et al. 2013)

Time (h)		Power source rating (kW)		Power demand rating (kW)	
From	To	AC	DC	AC	DC
0	1	219.82	0	903.96	311.04
1	2	248.46	0	803.52	276.48
2	3	248.46	0	669.60	230.40
3	4	147.26	0	502.20	172.80
4	5	295.92	0	435.24	149.76
5	6	295.92	0	368.28	126.72
6	7	545.87	0	468.29	116.71
7	8	907.45	0	540.34	134.66
8	9	907.45	328.00	1765.10	439.90
9	10	805.46	951.20	2017.26	502.74
10	11	1056.34	1049.60	2017.26	502.74
11	12	1136.53	1935.20	1584.99	395.01
12	13	3023.02	2263.20	1260.79	314.21
13	14	2301.00	2460.00	1584.99	395.01
14	15	3434.72	2197.60	1945.22	484.79
15	16	3023.02	1213.60	1945.22	484.79
16	17	2301.00	1115.20	1621.01	403.99
17	18	1136.53	1148.00	1801.13	448.88
18	19	1308.90	393.60	1693.06	421.94
19	20	233.85	164.00	1071.36	368.64
20	21	451.17	0	970.92	334.08
21	22	521.06	0	1640.52	564.48
22	23	1497.86	0	1540.08	529.92
23	24	1814.10	0	1540.08	529.92

payback period for pumped hydro storage is the longest due to its high cost of installation. It is therefore recommended that the Lead–Acid system is installed instead, as it

Fig. 4 Modified SCT results for Case Study 2

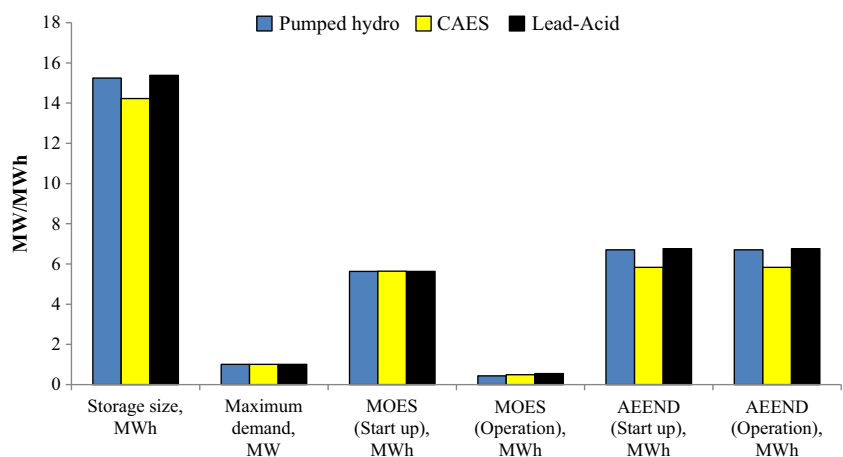


Table 13 Costs of storage technologies for bulk energy storage applications (Schoenung and Hassenzahl 2003)

	Pumped hydro	CAES	Lead–Acid
Capital cost, \$/kW	1000	650	125
Operation & maintenance cost, \$/kW	2.5	2.5	5

has the shortest payback period apart from its lower total losses compared to CAES.

Based on the results from the two case studies, Lead–Acid battery storage exhibits good features for both HPS applications in small and large scales. The environmental issue of Lead–Acid battery storage, however, may influence the decision choice. Lead–Acid batteries contain toxic lead and hazardous sulphuric acid, which has to be neutralised and disposed of safely (Bradbury 2010). Recycle processes have been the solution and have proven to be cost effective because of the value of the materials recovered (European Commission 2000). FES has been the most environmentally friendly storage, while SMES suffers from strong magnetic field effects. CAES operation produces emissions due to combustion, while pumped hydro storage construction affected the local ecological system (Chen et al. 2009).

Conclusion

A new systematic generic framework for the analysis of different storage technology applications in HPS was developed. Various factors, including the storage efficiencies, power trends and economic aspects, were addressed for five types of electrical energy storage systems, i.e. pumped hydro, CAES, SMES, FES and Lead–Acid. A new AC/DC modified SCT method for the AC storage type has been developed to determine the power allocation in storage systems. This use of the proposed framework can be extended as a generic tool for the design of an HPS with other storage technologies such as ultra-capacitor, hydrogen storage, lithium-ion batteries, fuel cells and thermal

Table 14 Economic evaluation for Case Study 2

	Pumped hydro	CAES	Lead–Acid
<i>D</i> = 365 d			
Net capital investment (\$)	15,242,320	9,247,004	1,922,731
Net annual savings (\$/y)	1,388,292	1,388,485	1,344,829
Payback period (year)	10.98	6.66	1.43
Net present value (\$)	8,530,452	8,531,641	8,263,391
<i>D</i> = 300 d			
Net capital investment (\$)	15,242,320	9,247,004	1,922,731
Net annual savings (\$/y)	1,134,200	1,134,812	1,091,569
Payback period (year)	13.44	8.15	1.76
Net present value (\$)	6,969,166	6,972,929	6,707,217
<i>D</i> = 200 d			
Net capital investment (\$)	15,242,320	9,247,004	1,922,731
Net annual savings (\$/y)	743,289	744,546	701,938
Payback period (year)	20.51	12.42	2.74
Net present value (\$)	4,567,189	4,574,910	4,313,104

Table 15 Results summary

Storage	Power storage form	Type of application	Economic	Amount of energy losses
Pumped hydro	AC	Large industry and mini grid	High capital but low OM cost	Low
CAES	AC	Medium to large commercial and industry	Reasonable cost	High
SMES	DC	Single residential, small to medium commercial and small industry	High OM cost	Lowest
FES	AC	Single residential, small to medium commercial and small industry	Low capital and OM cost	Highest
Lead–Acid	DC	Single residential, small to large commercial and industry	Reasonable cost	Low

storage, as these options may have higher compatibility with the HPS applications that are being designed.

Two case studies representing different locations, scales and applications are used to evaluate the investigated storages based on the aspects considered. The overall conclusion that can be drawn from the results is summarised in Table 15. Note that the storage type for pumped hydro, CAES and FES may be different from the one applied in this paper because the choice depends on the mechanical equipment (pump, motors, electrical machine, etc.) used in the storage system. The mechanical equipment that was used for these three storage systems in this paper operates with AC electricity; as a result, these storage technologies are categorised as AC storage.

The SMES has the highest overall efficiencies (based on AC/DC modified SCT results), but it has a very limited range of applications, as it is not applicable in large industrial sectors. Although the total losses in pumped hydro are small, it is uneconomical for smaller systems because of its high investment cost. The Lead–Acid battery has good performance (small total losses), can be applied for a wide range of applications, and is cost effective.

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Conflict of interest This work has no potential conflicts of interest, and does not involve any human participant or animal. There is also no involvement or requirement for consent with other parties.

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