Energy Storage System Sizing for Peak Shaving in Thailand

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ABSTRACT

This paper presents a mathematical model of energy storage systems (ESSs) to minimise daily electrical peak power demand in Thailand. A daily electrical load curve on a peak day obtained from Electricity Generating Authority of Thailand (EGAT) is used to analyse the capability of energy storage system for electrical peak power demand reduction with different ESS sizes. It is found that with power rate of 50 percent of the difference between the minimum and the maximum demands of the daily load curve and with energy capacity of 50 percent of the sum of each time step absolute energy difference between the demand and the average demand of the daily load curve, ESS can decrease daily electrical peak demand approximately 7.4 percent and increase daily load factor approximately 9.9 percent.

Keywords: Energy storage, Load management, Power demand

1. INTRODUCTION

Energy Storage Systems (ESSs) recently plays an important role in electrical power system energy management. ESS can be used to decrease electrical peak demand of power systems by mean of load shifting. Intermittent renewable energy sources such as solar and wind energy are facilitate by using ESS. During the period when the renewable energy sources supply energy to a power system more than it demand required, ESS can be managed to store energy and then use it later when necessary. With ESS in electrical generation systems, the reduction of CO_2 emission can be achieved by utilising more renewable energy sources to replace the conventional non-renewable energy sources. Furthermore, ESS can be used as stand by units to increase power system security and reliability [1]. Pump storage hydro power plants are a conventional energy storage technology used. At present, many types of energy storage technologies such as compressed air, cooling or heating storage, hydrogen technology with fuel cell, battery, super capacitor, fly-wheel, and electric vehicle are researched [1], [2]. These energy storage types have different ca-

pacities, different charge-discharging times and different efficiencies [3], [4].

2. ESS MODEL

ESSs have been modelled using linear equations [5]-[13]. The equations are in the form of an objective function with predefined constraints. These constraints are predefined ESS initial/final energy levels, ESS energy balance, ESS min/max energy levels, ESS min/max power. ESS load power balance and energy loss in ESS. The decision variables are the charging/discharging activities of the ESS.

This paper presents a simplified mathematical model of ESS aiming to minimise daily electrical peak demand in order to increase daily load factor. The model can be applied for different ESS types. The simplified formulation of ESS equations are shown below.

2.1 Base input parameters of EES

t	Time
Δt	Time step duration
k	ID for Energy Storage (ES) type
n_k	Number of ES types k
N_k^{ES}	Number of controllable devices within the group of ES type k
i	ID for ES belonging to the ES type k. This is an integer that varies from 1 to number of ES with controllable device within each storage type (1, 2 , ..., N_k^{ES})
$P_L(t)$	Electrical consumption at time t (base case)
$n_{ES,k}$	Efficiency of ES device for the ES type k based on hourly losses
$E_{ES,k}^{Min}$	Minimum level of energy required in ES type k
$E_{ES,k}^{Max}$	Maximum energy capacity of ES type k
$E_{ES,k}^{0}$	Percentage of initial energy level of ES type k
E_{Loss}^{ES}	Cumulative energy loss of ES
$P_{ES,k}^{Max}$	Maximum power rate that ES type k can be charged/discharged
C	A constant to weight the performance of the objective function between peak demand minimisation and energy loss minimisation

2.2 Decision variables

$P_{k,i,t}$ Charging/discharging power of storage
i of ES type k at time t

$E_{k,i,t}^{ES}$ Energy level of storage i of ES type k
at time t

2.3 Constraints

2.3.1 Predefined ES initial/final energy level

Initial and final time step energy level can be predefined as:

$$E_{k,i,1}^{ES} = E_{k,i,t_{end}}^{ES} = E_{ES,k}^0 E_{ES,k}^{Max}, \forall k, i \qquad (1)$$

2.3.2 ES energy balance

ES energy level is equal to ES energy level of previous time step multiplied by efficiency of the ES device plus charging/discharging energy of the current time step (charging/discharging power multiplied by time step duration).

$$E_{k,i,t}^{ES} = n_{ES,k} E_{k,i,(t-1)}^{ES} + P_{k,i,t} \Delta t, \forall k, i, \forall t > 1 \quad (2)$$

2.3.3 ES min/max energy

ES minimum and maximum energy levels can be predefined as:

$$E_{ES,k}^{Min} \leq E_{k,i,t}^{ES} \leq E_{ES,k}^{Max}, \forall k, i, t \qquad (3)$$

2.3.4 ES min/max power

ES minimum and maximum power rates that ES can be charged and discharged can be predefined as:

$$-P_{ES,k}^{Max} \leq P_{k,i,t} \leq P_{ES,k}^{Max}, \forall k, i, t \qquad (4)$$

2.3.5 New peak demand

New peak demand (to be minimised) must be greater or equal than the new demand with ES for all time step.

$$P_{newpeak} \geq P_L(t) + \Delta P_{ES}(t), \forall t \qquad (5)$$

where the modification of the total electrical load due to ES activity is

$$\Delta P_{ES}(t) = \sum_{k=1}^{n_k} \sum_{i=1}^{N_k^{ES}} P_{k,i,t}, \forall t \qquad (6)$$

2.3.6 Total energy loss in ES

The total energy loss in ES can be calculated from the cumulative energy loss of all time steps of all ES.

$$E_{Loss}^{ES} = \sum_{k=1}^{n_k} \sum_{i=1}^{N_k^{ES}} \sum_{t=1}^{t_{end}} (1 - n_{ES,k}) E_{k,i,t}^{ES}, \forall k, i, t \quad (7)$$
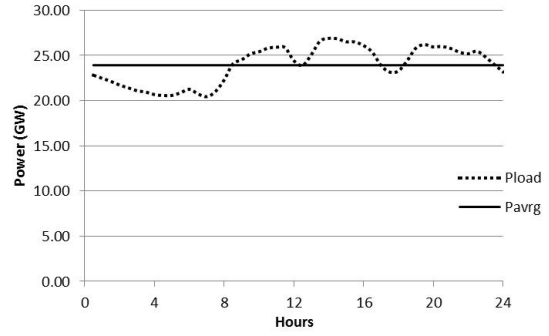

Fig. 1: *EGAT daily load curve of 23rd April 2014 (Pload) and the average load (Pavrg) (GW).*

2.4 Objective function

Using peak minimisation, ESS can be charged early at all t to store the energy to discharge during the t when peak load occur. When storing energy, there will be hourly energy loss in the ESS at all t. Therefore, the storage should be charged just the time before the discharging period in order to minimise the energy loss. The realistic total load due to ESS activity can be obtained by minimising the peak demand together with minimising the total energy loss in the ESS as shown below.

$$\min P_{newpeak} + C.E_{Loss}^{ES} \qquad (8)$$

3. SIMULATION RESULTS

Daily load curve of EGAT on the summer peak day, 23rd April 2014, shown in Fig. 1 are used for the input $P_L(t)$ of the model.

From the data obtained, the daily maximum, minimum and average demands are 26,898.8 MW, 20,446.5 MW and 23,931.28 MW respectively. The daily energy consumption calculating from the area beneath the daily load duration curve is 574,350.7 MWh. $P_L(t)$ are converted into per unit using maximum demand 26,898.8 MW as a base for convenience. Therefore, the energy consumption is 574,350.7/26,898.8 = 21.35 per unit. The difference between the minimum and the maximum of the daily load curve is 26,898.8-20,446.5 = 6,452.3 MW or 0.2399 per unit. The sum of absolute energy difference of each time step between $P_L(t)$ and the average demand is 43,983.96 MWh or 1.6352 per unit. For the ESS parameters, the maximum power rate, $P_{ES,k}^{Max}$, is assumed to be varied from 10% to 50% of the difference between the maximum and the minimum demand of $P_L(t)$ (this is equal to 10% to 50% of 0.2399 per unit). The maximum electrical energy capacity, $E_{ES,k}^{Max}$, is assumed to be varied from 10% to 50% of sum of absolute energy difference of each time step of $P_L(t)$ and the average of $P_L(t)$ (this is equal to 10% to 50% of 1.6352 per unit). C is set to 10^{-9} to enhance the peak minimisation over the ESS energy

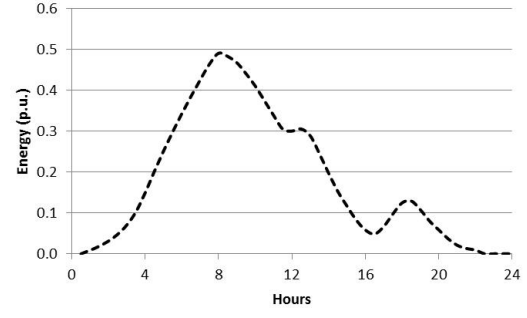**Table 1:** *The average array detection in terms of* $(SNR_1 \times L)$ *for different orders of statistic.*

Variable	value
$n_{ES,k}$	90% [14]-[16]
$E_{ES,k}^{Min}$	0
$E_{ES,k}^{Max}$	10% to 50% of 1.6352 per unit
$E_{ES,k}^{0}$	0
$P_{ES,k}^{Max}$	10% to 50% of 0.2399 per unit
C	10^{-9}
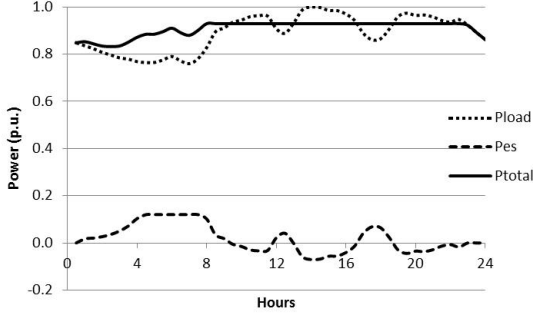
Fig.2: *Daily load curve without ESS (Pload), with ESS (Ptotal) and ESS charge/discharge power (Pes) of maximum energy capacity,$E_{ES,k}^{Max}$ =30% and maximum power rate, $P_{ES,k}^{Max}$, =50%.*

Fig.3: *Energy stored in ESS of maximum energy capacity,$E_{ES,k}^{Max}$ =30% and maximum power rate,$P_{ES,k}^{Max}$, =50% of Fig. 2.*
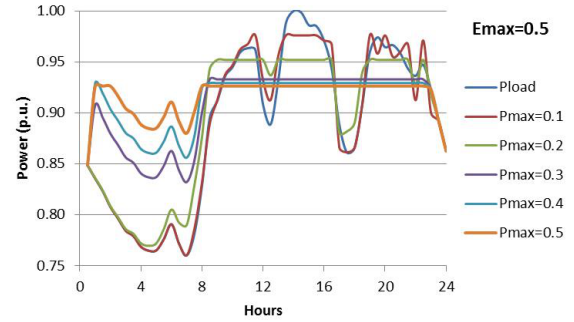
Fig.4: *Daily load curve without ESS (Pload), with ESS of maximum energy capacity,$E_{ES,k}^{Max}$, =50% (Emax=0.5) while maximum power rate, $P_{ES,k}^{Max}$ (Pmax), are varied from 10% to 50%.*

loss minimisation objective function. The predefined variables of ESS used in the simulation are shown in table 1.

Linear programming is used to solve the equation to obtain the new peak demand with ESS in operation,$P_{newpeak}$. In order to simplify the equation, the groups of ES are assumed to operate as one large ESS with the total capacity equal to the sum of the capacity of the ES groups. Therefore,n_k is set to 1 in this case. For a very large ideal ESS, $P_{ES,k}^{Max}$ and $E_{ES,k}^{Max}$ are not limited and $n_{ES,k}$ is 100%. The daily load curve with the large ideal ESS is the average load (Pavrg) of the original daily load curve (Pload) in Fig. 1. For a realistic ESS,$P_{ES,k}^{Max}$ and $E_{ES,k}^{Max}$ are limited by their sizes and $n_{ES,k}$ is less than 100%.In these case studies,$P_{ES,k}^{Max}$ and $E_{ES,k}^{Max}$ are varied as shown in table 1. $P_{newpeak}$ from each $P_{ES,k}^{Max}$ and $E_{ES,k}^{Max}$ are compared.

Fig. 2 shows the comparison between daily load curve without ESS (Pload), with ESS (Ptotal) and ESS charge/discharge power (Pes) of $P_{ES,k}^{Max} = 50\%$ and $E_{ES,k}^{Max} = 30\%$. The ESS are charged during the first 8 hours of "off peak" period and then discharged during "on peak" periods at 8 to 11, 12 to16 and 18 to 24 hrs. Fig. 3 shows the energy stored in the ESS of Fig. 2 which $E_{ES,k}^{Max}$ is limited at 30% of 1.6352 per unit. The energy level in the ESS agrees to their charge/discharge power in Fig. 3. It can be seen

that the daily load curve with ESS can reduce peak demand 0.07021 per unit which is 4.15% lower than it capacity at 0.12 per unit. This is because of the limitation of the energy stored in the ESS and also the energy loss of ESS during each time step.

Fig. 4 shows daily load curve without ESS (Pload), with ESS of $E_{ES,k}^{Max} = 50\%$ while $P_{ES,k}^{Max}$ are varied from 10% to 50%.

Fig. 5 shows energy stored in ESS of Fig. 4 of $E_{ES,k}^{Max} = 50\%$ while $P_{ES,k}^{Max}$ limits are varied from 10% to 50%. The results show that the peak loads in Fig. 4 continue decreasing while increasing $P_{ES,k}^{Max}$ until 50% because the ESS can charge more power during the first 8 hours of "off peak" period and then discharge more power during "on peak" periods at 8 to 11, 12 to 16 and 18 to 24 hrs. In Fig. 5, the peak energy of the ESS increases while increasing $P_{ES,k}^{Max}$ until 50% of 0.2399 per unit but not reach the $E_{ES,k}^{Max}$ limit of 50% of 1.6352 per unit. Fig. 6 shows daily load curve without ESS (Pload), with ESS of $P_{ES,k}^{Max} = 50\%$ while $E_{ES,k}^{Max}$ are varied from 10% to 50%. Fig. 7 shows energy stored in ESS of Fig. 6 of $P_{ES,k}^{Max} = 50\%$ while $E_{ES,k}^{Max}$ limits are varied from 10% to 50% . The results show that the ESS can charge more en-
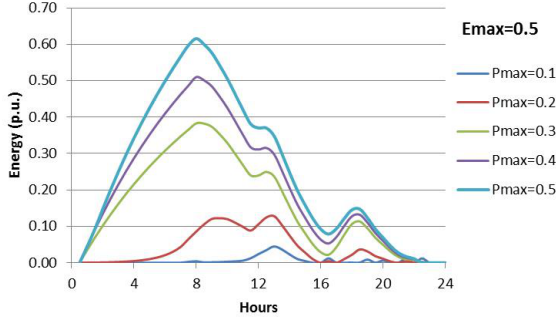
Fig.5: *Energy stored in ESS of maximum energy capacity,$E_{ES,k}^{Max}$,=50% while maximum power rate,$P_{ES,k}^{Max}$, limits are varied from 10% to 50% of Fig. 4.*
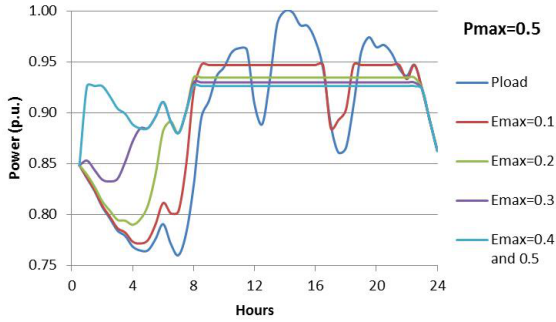

Fig.6: *Daily load curve without ESS (Pload), with ESS of power rate,$P_{ES,k}^{Max}$, =50% (Pmax=0.5) while maximum energy capacity,$E_{ES,k}^{Max}$ (Emax), are varied from 10% to 50%.*

ergy during the first 8 hours of "off peak" period and then discharge more energy during "on peak" periods at 8 to 11, 12 to 16 and 18 to 24 hrs. The maximum demand decrease until $E_{ES,k}^{Max} = 40\%$ of 1.6352 per unit and cannot decrease further when $P_{ES,k}^{Max}$ is limited at 50% of 0.2399 per unit.

Table 2 shows peak demands of the daily load curve with different ESS sizes and they are plot in Fig. 8. Table 3, shows load factors of the daily load curve with different ESS sizes and they are plot in Fig. 9. Table 2 and Fig. 8 show that with $P_{ES,k}^{Max}$ = 10% and $P_{ES,k}^{Max} = 20\%$, the peak demands are not changed when $E_{ES,k}^{Max}$ varies from 10% to 50%. With $P_{ES,k}^{Max} = 30\%$, the peak demand decrease when $P_{ES,k}^{Max}$ varies from 10% to 30%. With $P_{ES,k}^{Max} = 40\%$ and $P_{ES,k}^{Max} = 50\%$, the peak demand decrease when $P_{ES,k}^{Max}$ varies from 10% to 40%.

The load factors with different ESS sizes in table 3 and Fig. 9 are correlated with their peak demand reduction in table 2 and Fig. 8.

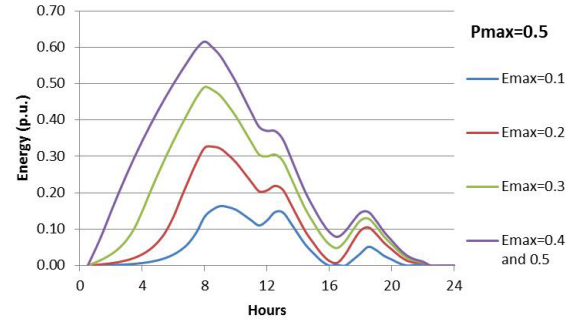Tables 2, 3, Figs. 8 and 9 show that the peak demand decrease 0.07536 per unit and load factor in-

Fig.7: *Energy stored in ESS of maximum power rate,$P_{ES,k}^{Max}$, =50% (Pmax=0.5) while maximum energy capacity, $P_{ES,k}^{Max}$ (Emax), limits are varied from 10% to 50% of Fig. 6.*
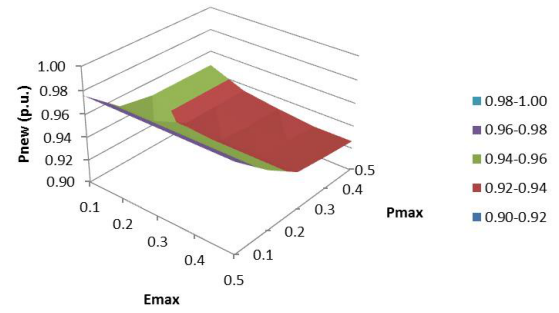

Fig.8: *Peak demands of the daily load curve with ESS when $E_{ES,k}^{Max}(Emax)$ and $P_{ES,k}^{Max}(Pmax)$ are varied from 10% to 50%.*
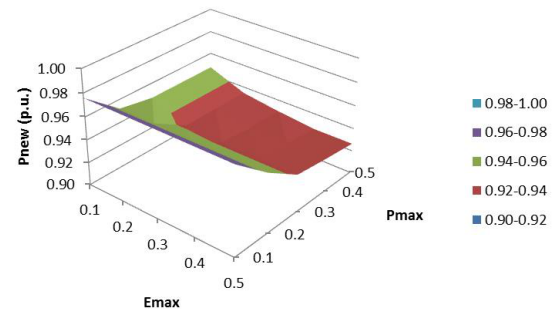

Fig.9: *Load factors of the daily load curve with ESS when $E_{ES,k}^{Max}$ (Emax) and $P_{ES,k}^{Max}$ (Pmax) are varied from 10% to 50%.*

Table 2: *Peak demands of the daily load curve with different ESS sizes.*

Peak Demand (p.u.)		$E_{ES,k}^{Max}$				
		10%	**20%**	**30%**	**40%**	**50%**
$P_{ES,k}^{Max}$	**10%**	0.97601	0.97601	0.97601	0.97601	0.97601
	20%	0.95203	0.95203	0.95203	0.95203	0.95203
	30%	0.94694	0.93460	0.93285	0.93285	0.93285
	40%	0.94694	0.93454	0.92979	0.92924	0.92924
	50%	0.94694	0.93454	0.92979	0.92623	0.92623

Table 3: *Load factors of the daily load curve with different ESS sizes.*

Load Factor (p.u.)		$E_{ES,k}^{Max}$				
		10%	**20%**	**30%**	**40%**	**50%**
$P_{ES,k}^{Max}$	**10%**	0.91214	0.91214	0.91214	0.91214	0.91214
	20%	0.93861	0.93861	0.93861	0.93861	0.93861
	30%	0.94494	0.96555	0.97130	0.97130	0.97130
	40%	0.94486	0.96417	0.97875	0.98074	0.98074
	50%	0.94486	0.96361	0.97674	0.98854	0.98854

crease 0.09888 per unit when $E_{ES,k}^{Max} = 50\%$ and $P_{ES,k}^{Max} = 50\%$.

The relationships between the capacity of ESS and the peak demand reduction are nonlinear.

4. DISCUSSIONS

Under the high penetration of intermittent renewable power sources such as solar and wind powers, ESS absorb the excessive free energy when the intermittent generation exceeds load levels and providing it back when generation levels fall short.

To investigate the economic beneficial of ESS, the construction and operation cost between different ESS types of ESS needed to be compare among different types of power plants. In other word, their construction costs per MW installed plus their operation costs per MWh should be compared. Table 4, shows the comparison of construction and operation cost of conventional combustion turbine among different ESS technologies [17].

It can be seen from table 4 that the sum of capital costs, operation cost and maintenance cost per kW of ESS are higher than those of power plants. The total cost differences are the cost per kW to be trade of with the cost of free energy obtaining during the peak load when ESS providing back from the excess renewable energy sources.

For example, the economic beneficial between the conventional combustion turbine power plant and the pump hydro (the highest capital cost in table 4) are compared. From table 4, the total cost of the conventional combustion turbine is 695 + 12.75 = \$707.75/kW-year while the total cost of pumped hydro is 1750 + 4.6 = \$1,754.6/kW-year. Therefore, the cost difference is 1754.6 - 707.75 = \$1,046.85/kW-year.

For the ESS size at $P_{ES,k}^{Max} = 50\%$, the ESS power

= 0.5 * 0.2399 per unit * 26,898.8MW = 3,226.5MW therefore, the pump hydro cost is higher than the conventional combustion engine cost = \$1,046.85/kW-year * 3,226.5MW = \$3,377.7m-year.

The area of the graph during the peak period 13:30 to 16:00 when the ESS discharged energy is 0.3701 per unit = 0.1855 * 574,350.7 = 106,283.6 MWh. Assume that this discharged energy is 10% absorbing form the excess intermittent renewable energy sources therefore, the free energy is 10,628.36 MWh. If the operation and maintenance cost including fuel of a conventional the combustion turbine is assumed \$100/MWh[18], the cost will be \$1,062,836 on a peak day or 365 * \$1,062,836 = \$387,935,140 or about \$388m-year.

The investment return period of a pumped hydro ESS is estimated = \$3,377.7m / \$388m = 8.7 years comparing with a conventional combustion turbine. The same calculations can be applied to other ESS type to obtain their investment return periods.

5. CONCLUSIONS AND FUTURE WORKS

The simple model of energy storage systems is used to find the ability of the energy storage system to minimise daily peak demand of EGAT on the peak day 23rd April 2014. The peak demand of the daily load curve decreases 7.38% and load factor increases 9.89% when using ESS which have charge/discharge power = 50% of difference between the minimum and the maximum of the daily load curve and at energy capacity = 50% of the sum of the absolute energy difference between each time step demand and the average demand. The investment return period of a pumped hydro ESS at this capacity is estimated less than 10 years comparing with a conventional combustion turbine.

In future, annual hourly load curve will be used in

Table 4: *Load factors of the daily load curve with different ESS sizes.*

Powers	Combustion turbine	Pumped hydro	NaS battery	Li-ion battery
System Capital cost $/kW	695	1750	-	-
Battery Capital cost $/kW	-	-	415	1000
Power Conversion System $/kW	-	-	200	200
Balance of Power $/kW	-	-	100	100
O&M fixed $/kW-year	-	-	0.46	0.46
O&M fixed $/kW-year	12.75	4.6	2	2

the ESS model to investigate the capability of ESS operation to manage electrical demand across the year. The ESS model will be included in an economic dispatch model of a generation system with high penetration of renewable energy sources in order to investigate the capability of the ESS to decrease the total generation cost of the generation system.

6. ACKNOWLEDGEMENT

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