In the name of GOD

NaS (sodium sulfura) battery modelling

Course: Energy storage systems

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Introduction:

This study address wind generation curtailment minimization through the storage of wind energy surplus. NaS (sodium sulfura) battery modelling is used in this study in order to shift wind generation from off-peak to peak through a technical analysis.

NaS battery technology

This battery type uses molten sodium for the anode and liquid sulfur for the cathode. The positive and negative terminals are separated by a beta-alumina solid electrolyte. Initially developed for electric vehicles by Ford Motor Company, its evolution has been shifted to address power grid applications.

NaS battery technology

The technology became commercial in Japan and presently several real scale facilities are operating as demonstration units in countries like the United States.

In turn, NaS round-trip efficiency reaches 80% and self-discharge effect is less pronounced, which results in long time storing capability. In addition, its discharge capacity over a long-term cycling operation is significant. If operated at 100% depth of discharge, NaS battery can retain full battery capacity over 2500 cycles, while at 50% of full discharge the life cycle number rises up to 7000.

NaS battery technology

To promote sodium ions movement through the electrolyte the battery must run at a sufficiently high temperature. Otherwise, it is not possible to keep active electrode materials in a molten state. Therefore, a mandatory condition for ensuring good ionic conductivity is to keep the temperature at least at 300 C to maintain both electrodes in liquid state. Usually the operating temperature should be within the range of 290-390 C.

These batteries are being commercialized to target large electric energy storage. In effect, NaS storage commercial units provide several MW power and MWh order capacities. Due to their power ratings, they are designed for utility scale applications, providing a broad range of services for grid performance improvement as well as to support renewable power generation.

NaS cell model

- To analyse NaS battery cell an electric equivalent circuit is used. A generic model consists of an ideal DC electric source, representing an open circuit voltage in series with one or more resistances that model internal parasitic effects linked with electrolyte.

Battery types as well as the parameters available for its description along with the accuracy level required determine the complexity of the adopted electric model. For example, a more detailed model may include different resistive paths for taking into account differences in the charging/ discharge processes.

NaS cell model

Other types of modelling could be employed such as those supported on fundamental physical and electrochemical processes description instead of the electric circuit approach.

Typically, all battery technologies show a strong relationship with the SOC (state of charge) level, which is the percentage of the battery's rated capacity that is available at a given time. Equally, DOD (depth of discharge) ratio is also an equivalent way to quantify the electric charge available by withdrawing the minimum SOC from 100%.

Four parameters are used to model the electric battery operation: open circuit voltage (Voc), charging resistance (Rch), discharging resistance (Rd) and supplementary internal resistance (Rlc) due to the cycling activity of charging and discharging.

Fig. 1 presents the characteristics of open circuit voltage Voc via battery DOD

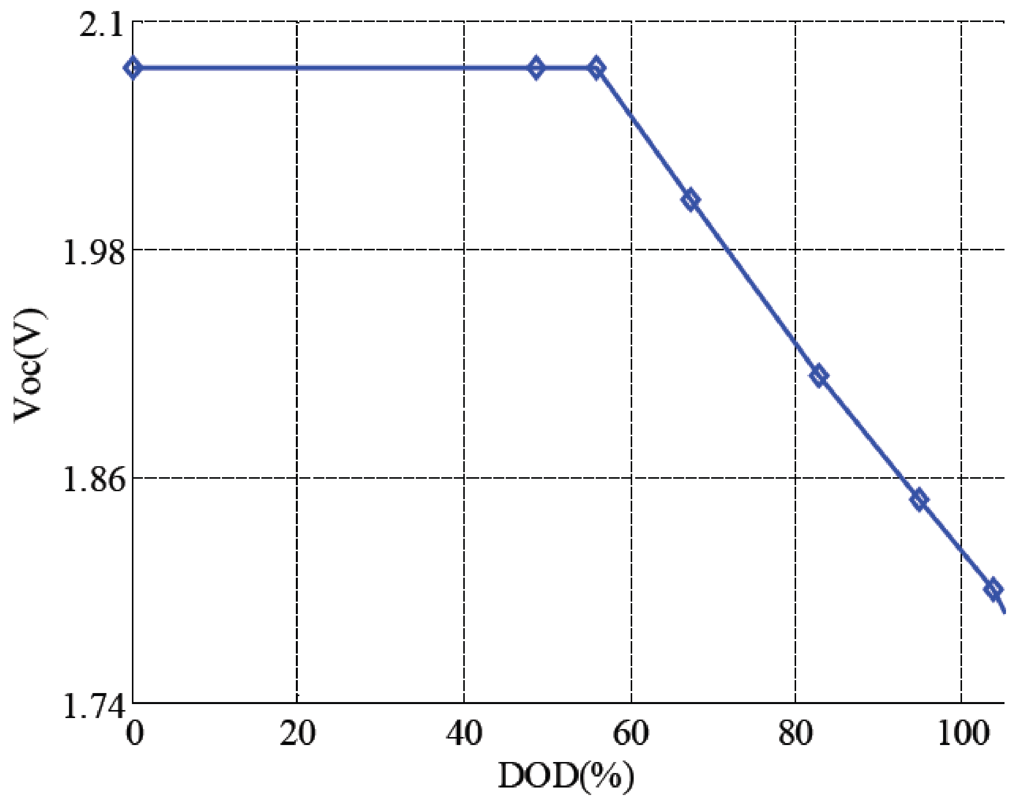

Fig. 1. Open circuit voltage as function of battery DOD.

Fig. 2 ,3 shows resistances Rch and Rdis relationship to battery DOD and temperature

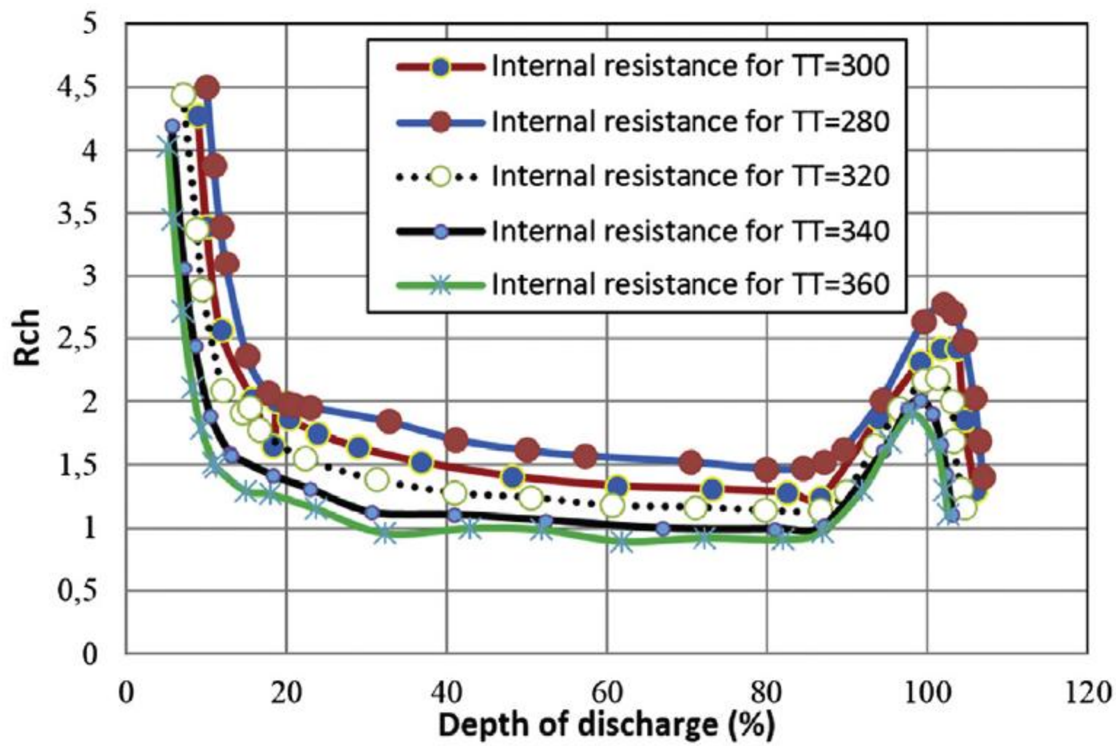

Fig. 2. NaS cell resistance in charging mode vs DOD at different temperatures.

From conversion efficiency point of view (minimizing internal ohmic power losses), it seems adequate to operate NaS battery within a 20-70% range.

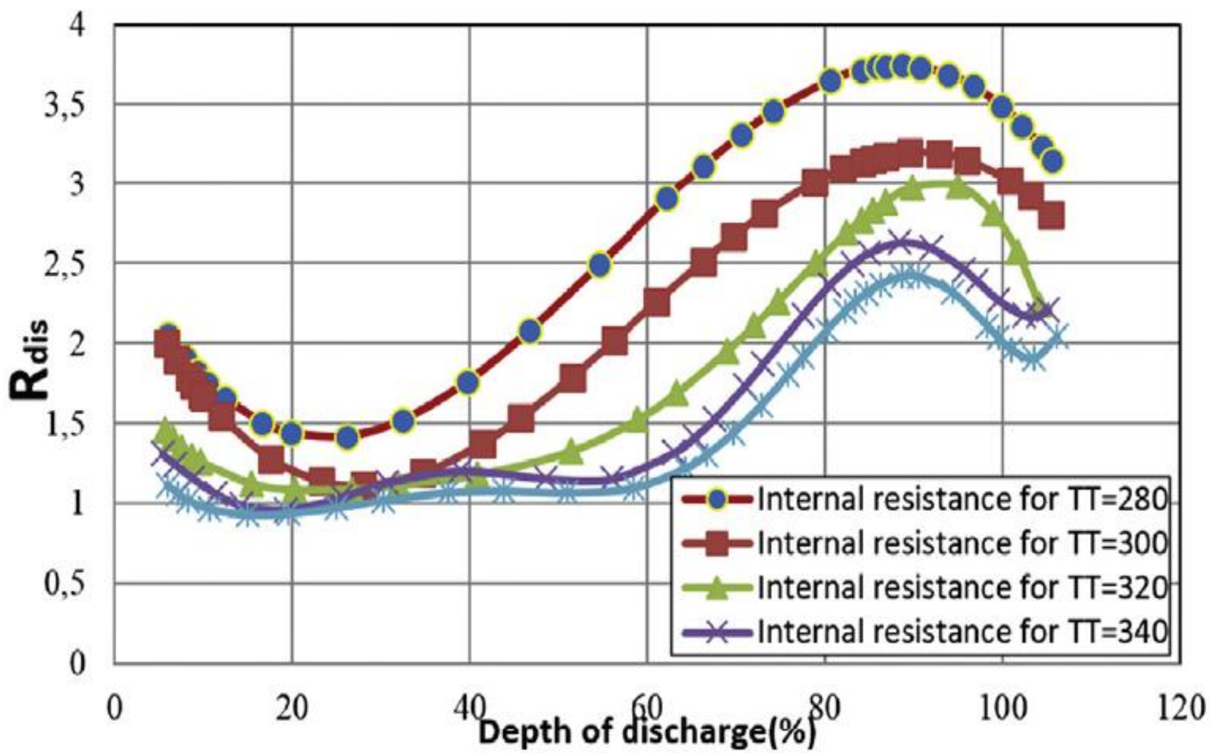

Fig. 3. NaS cell resistance in discharging mode vs DOD at different temperatures.

Voltage at battery output terminals (V_{bat}) depends on operation mode. For discharging state, it can be expressed as:

$$V_{bat} = V_{oc} - R_{dis}I_{bat} - R_{lc}I_{bat} \quad (1)$$

and for charging mode as:

$$V_{bat} = V_{oc} + R_{c}I_{bat} + R_{lc}I_{bat} \quad (2)$$

where both R_{dis} and R_{ch} depend on battery DOD and can be approximated by polynomial regression of degree 9 and 10, respectively:

$$R_{dis} = a + bDOD^2 + cDOD^3 + dDOD^4 + eDOD^5 + fDOD^6 + gDOD^7 + hDOD^8 + iDOD^9 \quad (3)$$

$$R_{ch} = a + bDOD^2 + cDOD^3 + dDOD^4 + eDOD^5 + fDOD^6 + gDOD^7 + hDOD^8 + iDOD^9 + jDOD^{10} \quad (4)$$

Curve fit coefficients are shown in Tables 1 and 2.

Table 1
R_{ch} curve fit coefficients.

T (°C)	a	b	c	d	e	f	g	h	i	j
360	1,48E+01	−3,603443562	4,00E-01	−2,41E-02	8,70E-04	−1,96E-05	2,76E-07	−2,38E-09	1,14E-11	−2,34E-14
340	20,11296449	−4,387864529	0,447506939	−0,02529688	0,000867232	−1,87394E-05	2,56423E-07	−2,15338E-09	1,01172E-11	−2,03428E-14
320	2,01E+01	−4,387864529	4,48E-01	−2,53E-02	8,67E-04	−1,87E-05	2,56E-07	−2,15E-09	1,01E-11	−2,03E-14
300	2,95E+01	−6,366800815	6,23E-01	−0,033715155	1,11E-03	−2,31952E-05	3,08E-07	−2,51496E-09	1,15E-11	−2,26649E-14
280	3,35E+01	−6,547631017	5,79E-01	−0,028617152	8,73E-04	−1,70977E-05	2,16E-07	−1,70125E-09	7,60E-12	−1,46673E-14

Table 2
R_{dis} curve fit coefficients.

T (°C)	a	b	c	d	e	f	g	h	i
360	1,69E+00	−1,61E-01	1,45E-02	−7,53E-04	2,52E-05	−5,29E-07	6,52E-09	−4,24E-11	1,11E-13
340	1,451739659	0,005037734	−0,009187198	0,00072225	−2,2882E-05	3,51828E-07	−2,5947E-09	7,34538E-12	
320	1,94274868	−0,115341762	0,005817645	−0,000139602	1,63197E-06	−6,94486E-09			
300	2,612556873	−0,122419802	0,002916653	−1,64878E-05					
280	2,601052094	−0,110064786	0,002933269	−1,74444E-05					

The R_{lc} lifecycle resistance, which is updated as the battery cycle number increases, has the following expression and can be observed in Fig 4:

$$R_{lc} = 0,0108N^{0.4844} \tag{5}$$

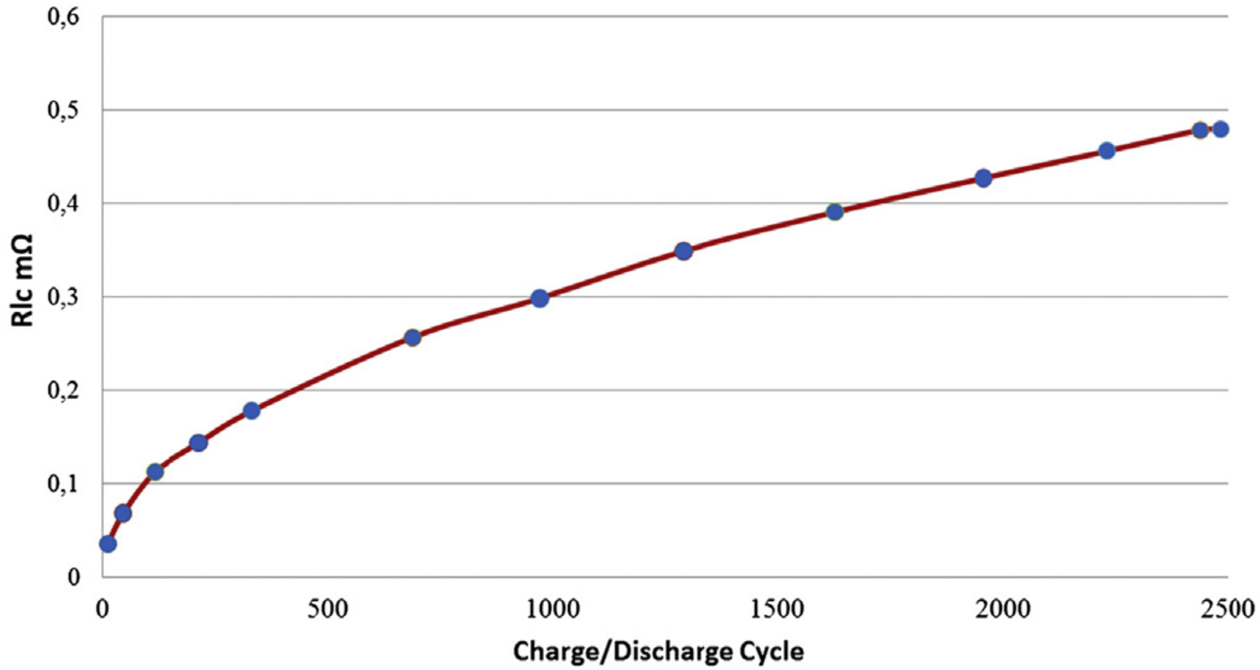

Fig. 4. Variation in internal resistance of NaS battery as a function of charge-discharge cycles.

while Voc experimental data changing with DOD is expressed as:

$$V_{oc} = \begin{cases} 2.076, & DOD \leq 0.56 \\ 2.076 - 0.00672DOD, & DOD > 0.56 \end{cases} \tag{6}$$

The capacity fade depends strongly on the application itself, usage conditions, SOC and temperature. The NaS lifetime model can be expressed as:

$$N_{cy} = 1.978 \times 10^6 (DOD)^{-1.73} + 3101 \tag{7}$$

Excess wind power ($P_j^{Exc\ WP}$) is given by:

$$P_j^{Exc\ WP} = P_j^{WG_{Theo}} - P_j^{WG_{Grid}} \tag{8}$$

The energy stored can be expressed as:

$$E_j = E_{j-1} + P_j^m \Delta t \eta_j^{bat\_m} \eta_j^{conv\_m} \quad (9)$$

where *Ej* is the energy stored at instant j, *Ej-1* is the energy stored at previous instant *j-1*, P_j^{bat-m} is the storage banks power transit at instant j, η_j^{bat-m} is the storage banks efficiency at instant j; η_j^{conv-m} is the power converter efficiency at instant j, is Δt is the period for storage bank operation and the *m* upper index designates battery usage mode (*ch* for charging and *dis* for discharging).

One way is to approximate battery energy conversion efficiency as:

$$\eta_j^{bat\_dis} = \frac{V_j^{oc} I_j - I_j \left(R_j^{dis} + R_j^{lc} \right)^2}{V_j^{oc} I_j} \quad \text{discharge mode}, \quad P_j^{dis} < 0 \tag{10}$$

$$\eta_j^{bat\_ch} = \frac{V_j^{oc} I_j}{V_j^{oc} I_j + I_j \left(R_j^{ch} + R_j^{lc} \right)^2} \quad \text{charge mode}, \quad P_j^{ch} > 0 \tag{11}$$

Regarding the conversion efficiency from AC to DC power and vice-versa, it is assumed as constant in both directions and set at 90%.

a SOC algorithm has been implemented according to:

$$SOC_j = SOC_{j-1} + \int_0^t \frac{P_j^m \eta_j^{bat\_m} \eta_j^{conv\_m} dt}{E_{rat}} \tag{12}$$

$$0 \leq SOC_j \leq 1 \tag{13}$$

where E_{rat} is the rated energy capacity of the NaS storage unit. Typically, it is desired to confine the SOC of a battery within suitable limits, for example 20% < SOC < 95%.

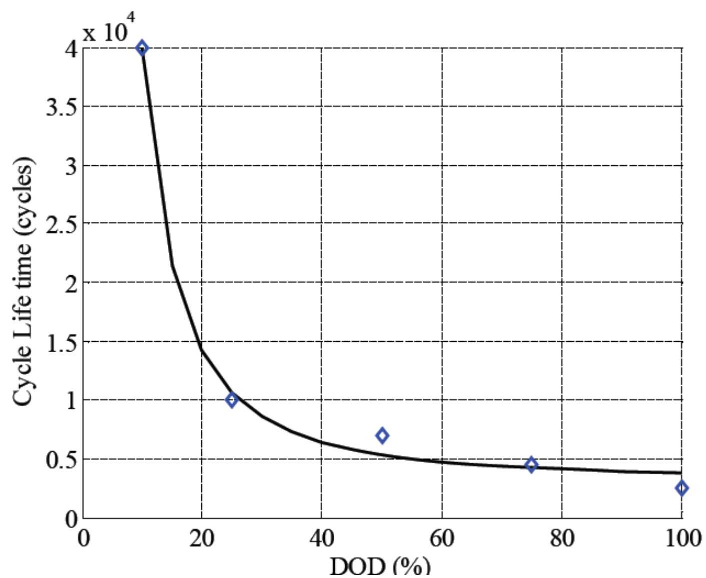

Fig. 5. Depth of discharge vs lifetime in cycles for NaS battery.

Scenario I

Discharge action runs for almost 8 h covering peak power demand during morning (08.00 AM) until mid-afternoon (03.00 PM). Stored energy is released and controlled to supply constant power output as a function of the 2 MW modules connected in parallel which implies nominal power output is given by the modules sum affected to the bank. Storage system charging mode is initiated during off-peak hours starting at 10.00 PM and remaining that way for 8 h;

Fig. 6 depicts daily stored energy level for three power-to-energy ratio scenarios. In the lowest one, nominal capacity is fully utilized. Between the three scenarios, the largest battery bank stores the highest amount of energy.

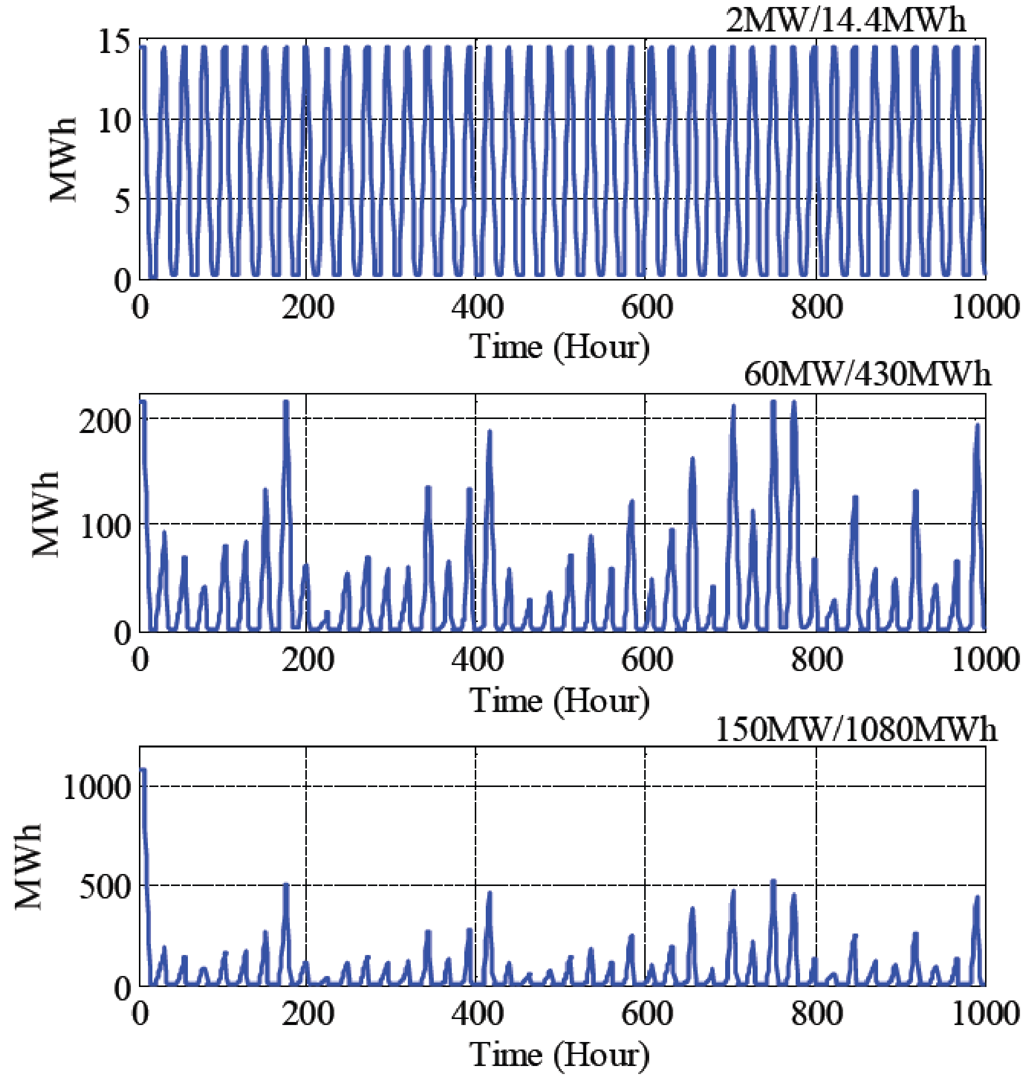

Fig. 6. State of charge profile at daily operation

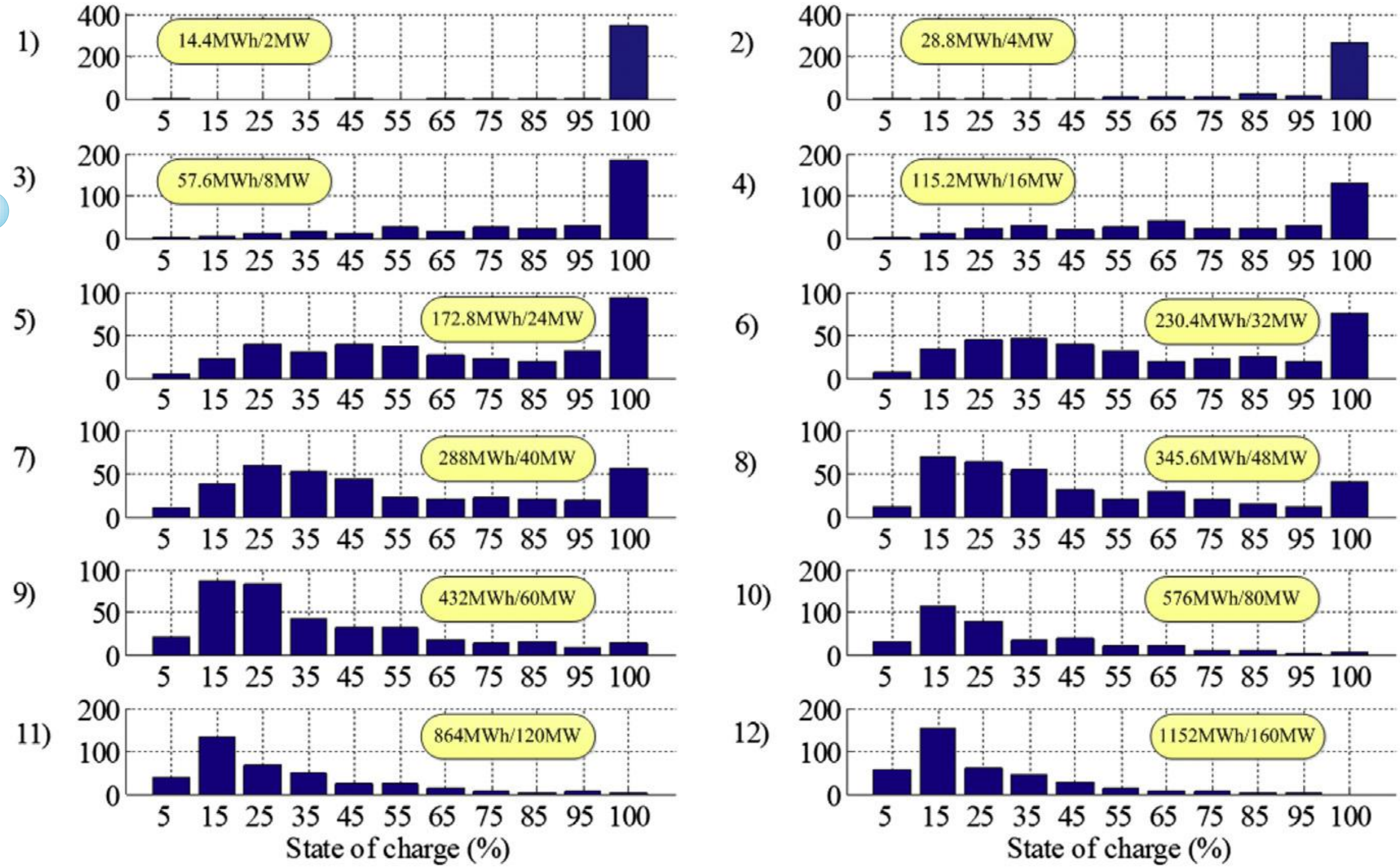

Fig. 7. DOD distribution for one year of operation as function of battery bank size.

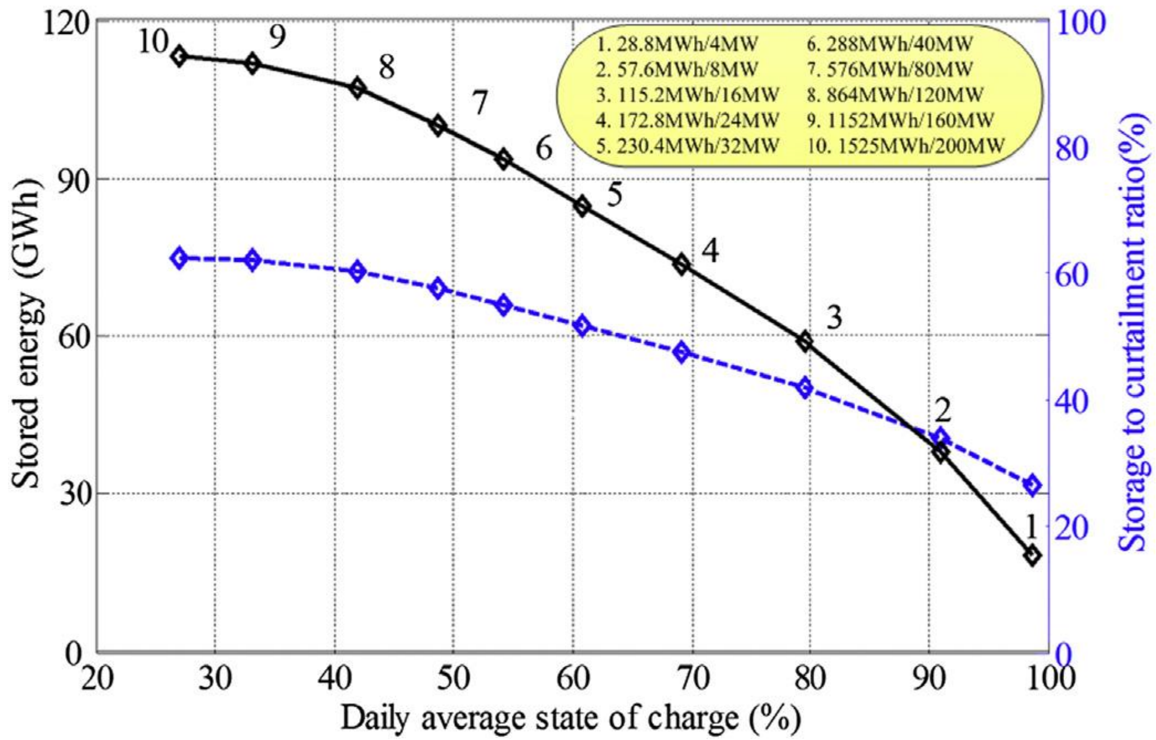

Fig. 8. NaS battery storage system performance (Scenario I).

Thank you