DTU Library

Na-S battery

Christensen, Rune

Published in:
Technology Data for Energy storage

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

182 NA-S BATTERY

Contact information

Danish Energy Agency: Thomas Mandal Østergaard , tmo@ens.dk
Energinet.dk: Rune Duban Grandal, rdg@energinet.dk
Author: Rune Christensen (runch@dtu.dk), DTU Energy

Publication date

December 2018

Amendments after publication date

Date	Ref.	Description

Brief technology description

Na-S batteries are secondary (i.e. rechargeable) batteries and are designed for system level applications. They are both power-intensive and energy-intensive. Larger installations (34 MW – 50 MW) are used for time shifting of production from renewable or conventional production plants. Smaller installations (400 kW – 8 MW) are used as back-up power, for off-grid applications, and for ancillary services. [1]–[3]

Na-S battery cells consist of a molten sodium anode, a molten sulfur cathode, and a β-alumina oxide solid state electrolyte (BASE) incased in a single tube. A schematic of a Na-S battery cell can be seen in Figure 1.

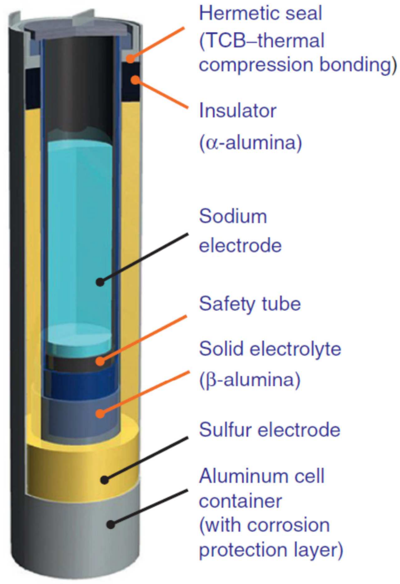


Figure 1: Schematic of a Na-S battery cell. [4]

The reactions taking place during discharge on the cathode and anode sides of the battery are [5], [6]

$$2\ Na - 2e^{-} \rightarrow 2\ Na^{+}\ \text{(Anode)}$$

$$xS + 2\ Na^{+} + 2e^{-} \rightarrow Na_2S_x\ (x=3\sim5)\ \text{(Cathode)}$$

During charge the reverse reaction occurs. A graphical schematic of the reaction process and the full cell reaction can be seen in Figure 2.

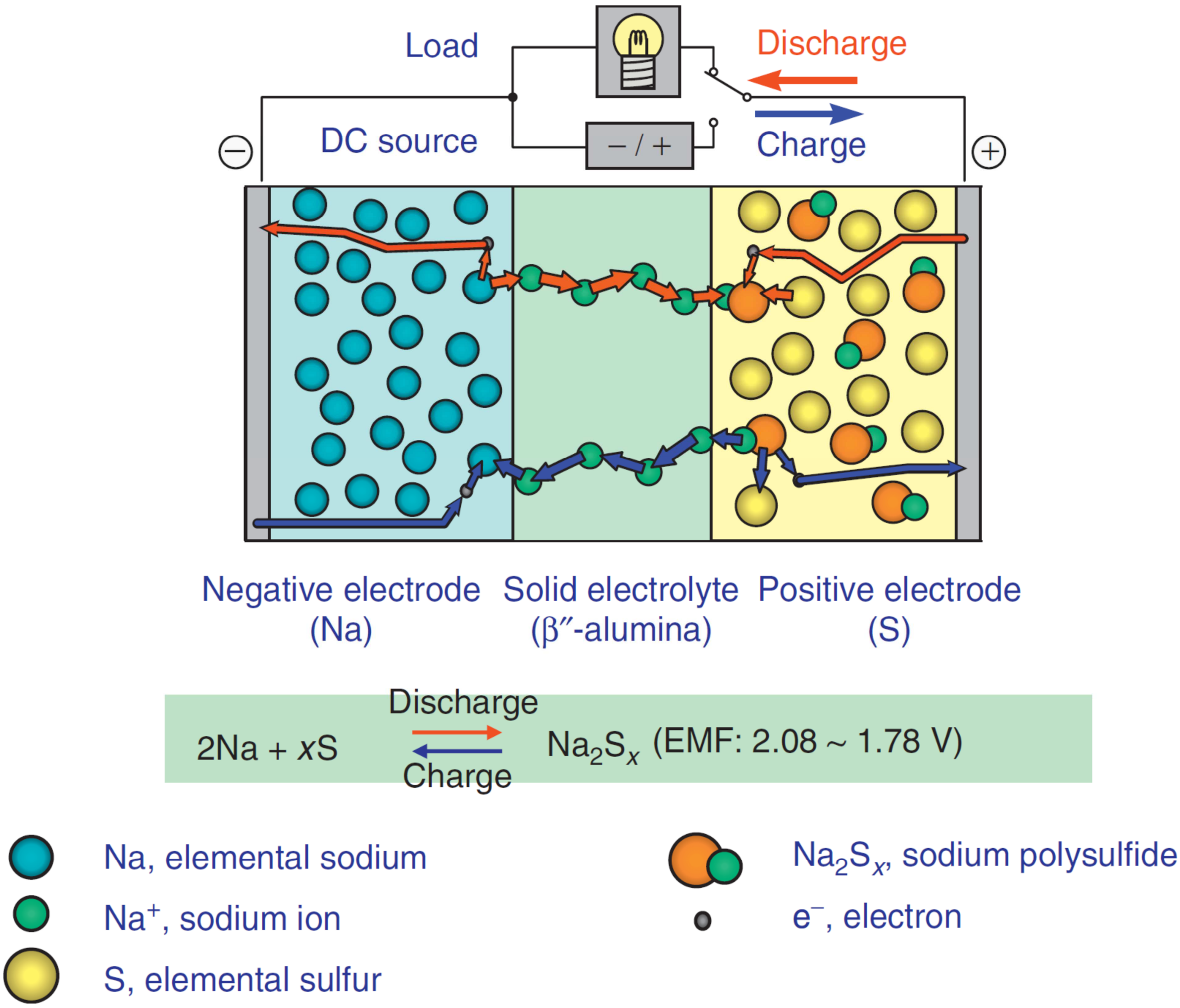


Figure 2: Graphical schematic of the reaction process and the full cell reaction. EMF: electromotive force. [4]

During continued discharge the value of x in Na_2S_x will gradually decrease and more sodium rich discharge products will be formed. The reaction occurs at a potential of 1.78 – 2.08 V at 350 °C depending on the state of battery charge. Relatively high temperatures (300-350 °C) are required for the reaction to take place. Elevated temperatures are required to keep the electrodes molten (98 °C for Na, 115 °C for S, and > 250 °C for Na_2S_x products [7]). A temperature of 300 °C or more is required to ensure sufficient Na ion conductivity through the BASE. The production of BASE has large impact on both battery performance and cost [6].

Cells are arranged in modules with thermal enclosures to minimize heat loss. An illustration of a module can be seen in Figure 3.

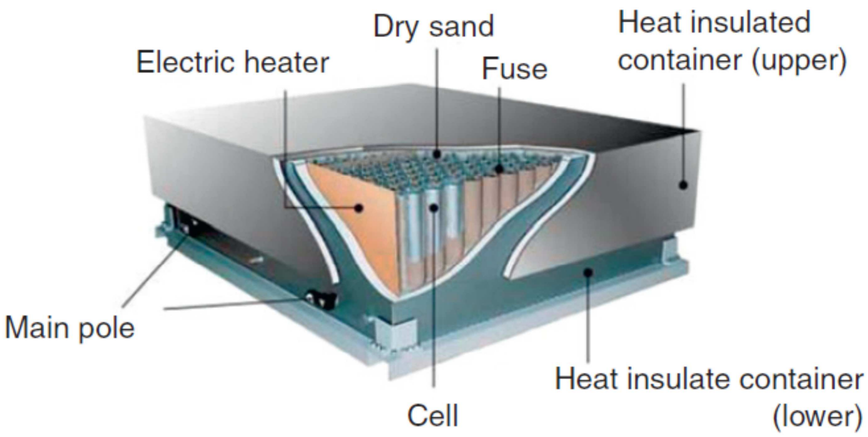


Figure 3: Illustration of Na-S battery module. [4]

A Na-S battery installation consists of one or more Na-S battery units containing the battery modules (shown in Figure 3), a battery management system, and a power conversion system required to connect the batteries to the grid. A schematic and a picture of an older 1 MW Na-S battery installation can be seen in Figure 4. For current market standard units see "

An alternative research route is to use the Na-S chemistry in a flow battery [20], [21].

Due to the similarity with Na-NiCl2 batteries, synergies in research and development efforts can be expected.

Examples of market standard technology".

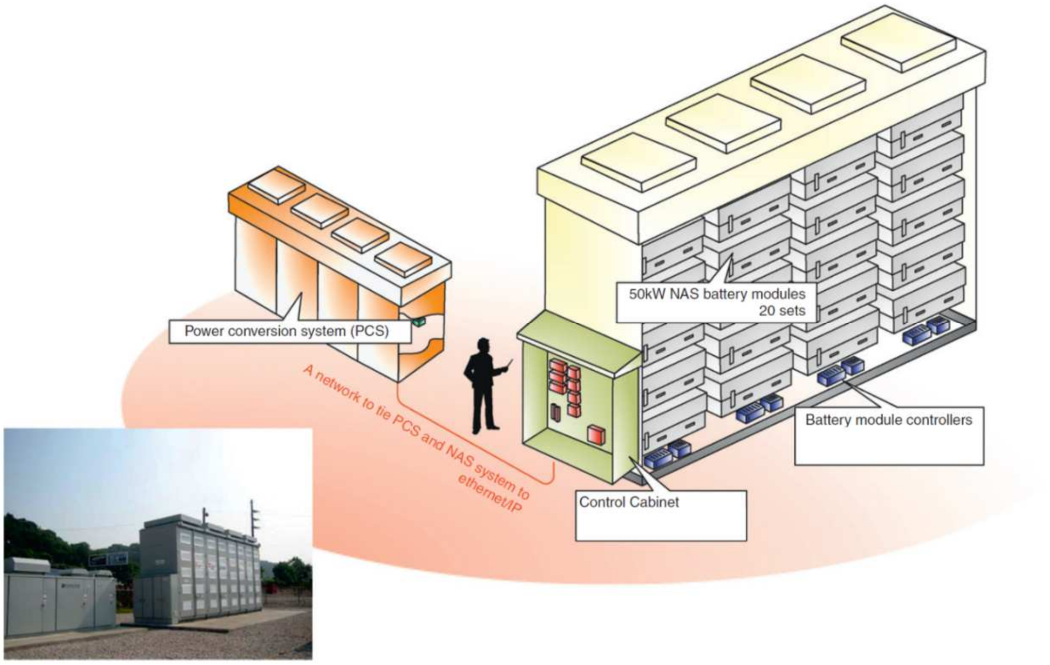


Figure 4: Schematic and picture of a 1 MW Na-S battery installation. [4]

For a more detailed technology description the reader is referred to "Encyclopedia of Electrochemical Power Sources" [8].

Input/Output

Primary input and output are both electricity. Electricity is converted to electrochemical energy during the charge process and converted back to electricity during the discharge process as described above.

Energy efficiency and losses

The heat loss from each battery module will be 2.2 – 4.0 kW [4]. This loss amounts to approximately 1 % per hour, and the Na-S batteries are thus not ideal for long term storage. During continued operation, which can include some hours of idle time, the Ohmic losses in the charge/discharge reaction will balance the heat loss [8]. The heat loss should thus not be treated as an independent source of energy loss during operation as it is included in the battery efficiency. Simple air cooling is sufficient for maintaining temperature and build into standard battery units. The battery temperature should be maintained to prevent the electrodes from solidifying since freeze-thaw cycles significantly reduce battery lifetime [9].

Individual battery cells have been measured with efficiencies at 89 % [9]. The efficiency of a grid size battery unit including auxiliary losses has been measured to be 83 % for an Italian installation primarily used for time shifting [9]. Reliable data for the efficiency in operation mode with constant power adjustment is not available for recently produced Na-S battery units.

Regulation ability and other system services

The response time (i.e. the time it takes for the battery to supply requested charge or discharge power) is according to the manufacture <1 ms at operation temperature[10]. Measurements find that the battery can change from full rated charging power to full rated discharging power in less than 50 ms [9] This is possibly limited by the power conversion system (PCS). Na-S batteries are able to provide energy pulses above rated discharge power for up to minutes at a time [8]. Pulses can be as large as 6 times rated power capacity for 30 s [11]. The other systems in the total installation, e.g., the PCS, and the grid connection must, however, be dimensioned accordingly for the pulse power capability to be utilized. This will increase cost.

Grid scale battery operation depends on the application. Batteries used for time shifting will generally complete a single charge/discharge cycle over 24 hours. Batteries used for various other grid services including stabilization of input from renewables will often not undergo traditional battery cycling but frequently switch between being charged and discharged according to demand.

Due to its short response time combined with relatively large storage and power capacity, Na-S batteries can provide a range of system services. NGK Insulators states: "The NAS battery systems also provide additional functions, including primary reserve, secondary reserve, load balancing and voltage control." [1]

Typical characteristics and capacities

Na-S battery installations come in two typical sizes. The larger installations used for time shifting have 34-50 MW capacity with 6-7.2 hours of storage capacity at full load (245-300 MWh). Information for three such installations are shown in Table 4. Smaller installations of up to 8 MW capacity have been installed during the last 20 years in 200 different locations [1]. In all cases the storage capacity corresponds to 6-8 hours of full power output capacity. As the batteries are highly modular, the installation size can be easily be varied according to demand. The power capacity to storage capacity is, however, for currently available commercial products fixed at a ratio of 1:6-8 [10].

Location	**Rokkasho village, Aomori, Japan**	**Campania Region (3 sites), Italy**	**Buzen City, Fukuoka, Japan**
			
Commissioned	2008	2015	2016

Storage capacity	245 MWh	250 MWh	300 MWh
Power capacity	34 MW	34.8 MW	50 MW
Energy density		<41.6 kWh/m^3*	26 kWh/m^3
Specific energy		<76 Wh/kg**	56 Wh/kg
Total land use	17.5 m^2/MWh	77 m^2/MWh	47 m^2/MWh

Table 4: Larger Na-S battery installations [1], [9], [12]. *Value for individual battery assembly units. ** Value for individual battery modules

New installations will for economic reasons likely consist of the standard commercially available units mentioned in

An alternative research route is to use the Na-S chemistry in a flow battery [20], [21].

Due to the similarity with Na-NiCl2 batteries, synergies in research and development efforts can be expected.

Examples of market standard technology. NGK Insulators states that container type units as those used for the Buzen City installation will decrease construction time and cost compared to previous installations.

The lifetime in number of cycles for Na-S batteries depend on the usage. The number of cycles can be increased by utilizing less than the full storage capacity in each cycle as can be seen in Figure 5. The ratio of energy discharged from the battery relative to the fully charged state is referred to as the Depth of Discharge (DoD). At 0 % DoD the battery is fully charged. At 100 % DoD the battery is fully discharged.

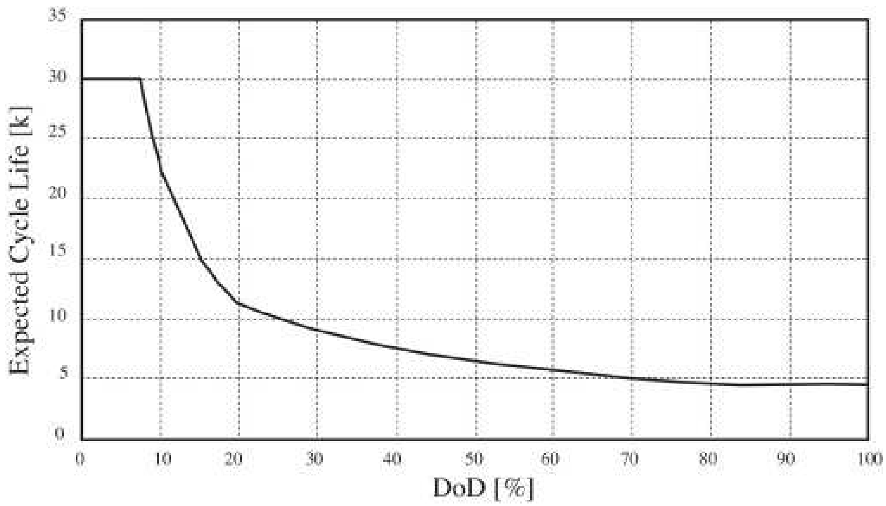


Figure 5: Expected number of cycles (in thousands) as function of Depth of Discharge (DoD) during cycles [9].

A Na-S battery used for time shifting with daily cycles of >80 % DoD will have an expected lifetime of 4500 cycles. If used for grid services, the average DoD will likely be smaller increasing the expected cycle lifetime. The technical lifetime is expected to be 15 years at a usage of 300 cycles at >80 % DoD per year [13] [14]. Longer technical lifetimes have not been reported. This is potentially due battery lifetime being limited by cycle lifetime during standard battery operation. An extended technical lifetime might not be obtainable by simply reducing the number of annual cycles or DoD for various reasons such as corrosion.

Typical storage period

The typical storage period depends on operation. It ranges from minutes to hours. With charge/discharge times of 6-8 h the normal storage period will be on this scale for optimal battery storage utilization.

Space Requirement

Space requirement per MWh are given in Table 4. The space requirements in Table 4 are calculated by dividing the total land use of the installations with the storage capacities. Footprint of current grid scale installations vary from 17.5 to 77 m^2/MWh. The footprint is highly sensitive to the layout of the installation and the used battery units and other equipment. The value of 47 m^2/MWh for Buzen City, where highly standardized container units are installed, is likely the most representative for future grid scale installations.

Advantages/disadvantages

General advantages and disadvantages of batteries in comparison to other technologies for energy storage are listed in Table 4.

Advantages	Disadvantages
Short response time	
Flexible installation size	Relatively short lifetime
High energy efficiency	
Versatile application	Large investment cost
Relatively compact	
Low maintenance	

Table 5: General advantages and disadvantages of batteries in comparison to other technologies for energy storage

Compared to many other batteries, Na-S batteries have the advantage that they a composed of inexpensive and abundant raw materials. Therefore, they have the potential to be very low cost and be manufactured on very large scale. Na-S batteries are well proven and developed for grid scale applications and have been commercially available for grid scale purposes for 15 years. They are well suited for energy intensive storage applications but can also be used for power intensive purposes. The cost per MW power capacity is, however, larger than for batteries mainly intended for power intensive applications. Na-S batteries have significant pulse power capabilities, i.e. they can operate at higher power than rated for short durations of time [8], [11].

Na-S batteries require high temperatures and should remain heated, as the battery can only survive a limited (in the order of 20) freeze-thaw cycles in which the temperature is lowered and the molten electrodes solidify [9]. They are thus not suited for longer periods of idle storage with resulting heat losses but should ideally always be charging or discharging for optimal utilization. The market for Na-S batteries is currently limited, due to only one commercial manufacturer existing. Due to the elevated temperatures and the highly reactive molten electrode materials, safety concerns and requirements are also higher for Na-S batteries than most other types of batteries. However, only one safety incident has been reported as a battery caught fire in 2011 [6].

Environment

The batteries contain molten sodium, sulfur and polysulfides. These all pose potential safety risks. Detailed safety and risk assessments are available in references [4], [9]. Sodium is the only material which must be recycled as hazardous [4].

Research and development perspectives

It is not possible to quantify the full potential for improvements through R&D at the given time. The potential is however, estimated to be substantial in terms of both technical and financial specifications [15].

All critical components of the battery are undergoing active research. These include the BASE, the sealing materials, the sodium electrode, the sulfur electrode, and battery interfaces [16]. Research efforts are especially focused on geometry optimizations [17] [18] and improvement of Na ionic conductivity through the BASE [19]. New solid electrolytes to replace BASE are also being considered [15].

An alternative research route is to use the Na-S chemistry in a flow battery [20], [21].

Due to the similarity with Na-NiCl2 batteries, synergies in research and development efforts can be expected.

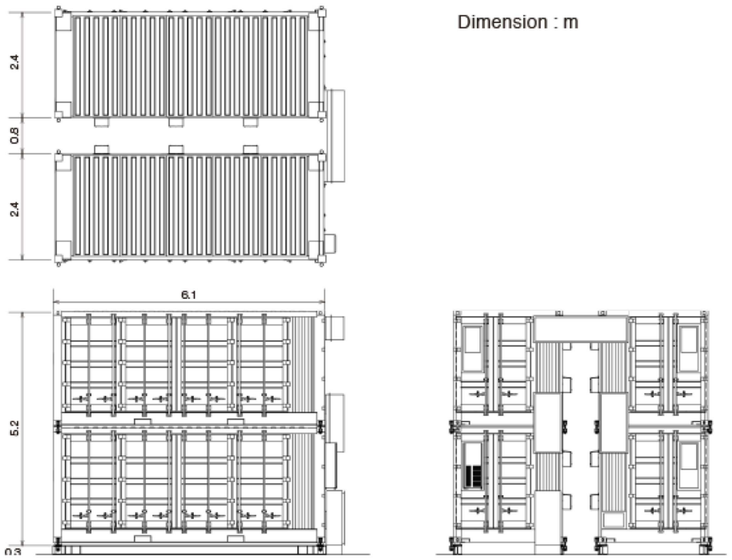
Examples of market standard technology

NGK Insulators is the only commercial manufacturer of Na-S batteries. They currently supply two types of modular units which are shown in Figure 6. These modular units can be used to form installations of the desired size. The recently installation in Buzen City consist of container type units such as the units shown in Figure 6.

New container type unit

The NAS battery system is a “Plug and Play” design built around standard 20 foot ocean freight containers. The containerized design expedites transportation and installation and helps minimize installation costs.

Rated Output	800kW and 4,800kwh
Configuration	Four container subunits,series connected. A subunit includes six NAS modules, each rated at 33kW and 200kWh.
Dimension	6.1W x 5.6D x 5.5H (m)
Weight	86tonnes



Package type unit

The enclosure package and battery modules are installed on site. This design achieves more compact system comparing with containerized design.

Rated Output	1,200kW and 8,640kWh
Configuration	40 NAS modules, each rated at 30kW and 216kWh.
Dimension	10.2W x 4.4D x 4.8H (m)
Weight	132tonnes

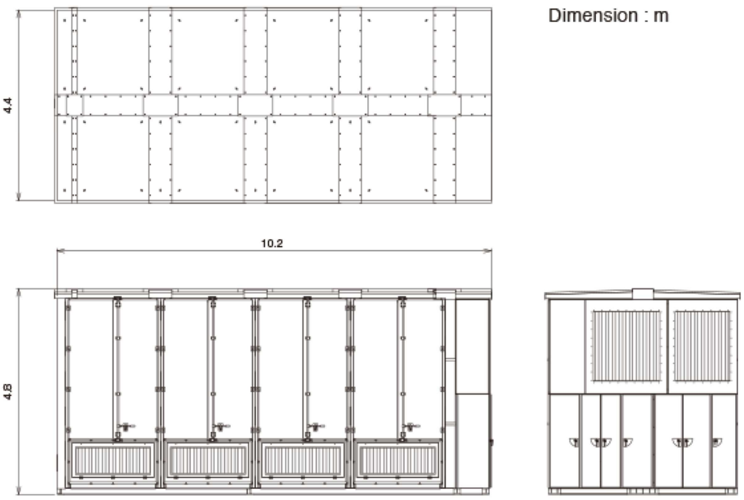


Figure 6: Commercial units available from NGK Insulators (https://www.ngk.co.jp/nas/) [10].

Prediction of performance and cost

Data for 2015

The Italian case (Campania Region) presented above has been used for economic data to as large an extent as possible [9], [22]. A significant reason for placing emphasis on this specific installation is that the owner, Italian grid operator Terna, has made financial and measured technical data available. Using real data is preferred over the use of estimates. However, it should be noted, that the cost might be relatively large compared to the market situation since Terna, for safety considerations following a 2011 fire incident in a Na-S battery, have requested fewer battery cells in each module than standard.

The balance between power capacity and energy storage capacity in battery installations will influence the investment costs per MW and MWh. The ratio can be quantified through the discharge time at rated power, *h.* It is nearly constant at 6-7.2 hours for currently available units. *h* is used to calculate the investment cost per storage capacity from the investment cost per power capacity.

O&M costs are obtained from Carlsson et al. [23] (assumed similar to 2013 values), and Zakeri and Syri [24].

Assumptions for the period 2020 to 2050

Estimates for 2020 and 2030 in the data sheet below are based on data from IRENA [25]–[27]. Values in USD have been converted to € using an exchange rate of 0.86. The specific investment cost is adjusted to account for an expected decrease in *h* for the most common market-standard units from 7.2 h to 6 h.

As discussed in the Chapter Electricity Storage, the current PCS cost including grid connection is 0.4-0,5 M€/MW. This is used as reference value for the "capacity component". The inverter costs, which account for approximately 50 % of cost [13], [22], [24], is predicted to decrease by 20 in 2020 % and 50 % in 2030 [25], [26]. The other 50 % of cost is assumed constant. Cost reductions of capacity components is assumed to not occur beyond 2030.

2050 values of the battery cost (here "energy component") predicted from learning curves have previously found cost reductions of approximately 10 % [23] and 25 % [28] for the period 2030 to 2050. The average (17.5 %) is used for the energy component cost in 2050.

"Other project costs" is assumed to be 14 % of CAPEX (here "Specific investment"), as was the case for the Terna unit [29].

O&M costs are assumed to be constant in the given units.

No development in calendar lifetime, cycle lifetime, and efficiency is assumed to take place beyond 2030. The regulatory ability is assumed to not improve.

Learning curves and technological maturity

Cost has been reduced with the introduction of large scale production of highly standardized units [12]. The level of maturity for system level scale is late "Category 2: Pioneer Phase" but entering "Category 3: Commercial technologies with moderate deployment".

Uncertainty

As the technology is just about to enter Category 3 level maturity, a technology development track cannot yet be established without large uncertainty. Uncertainties for 2020 and 2030 are when possible obtained from IRENA [26], [27]. Uncertainties in 2050 are assumed to be percentagewise similar to those in 2030. For the “capacity component” the maximum values for PCS cost found by Zakeri and Syri [24] are used as baseline. The uncertainties are calculated for future years by keeping the relative uncertainty compared to the cost prediction constant.

The uncertainties for O&M costs are determined using the literature review by Zakeri and Syri [24]. The uncertainties are calculated from the expected value using the relative difference between the extrema and the average in the literature review. Uncertainties are in general large.

Additional remarks

Since battery units are highly modular and equipment is the main cost of a full installation, a close to linear scaling in total cost vs. installation size is expected from a technological point of view. Significant financial benefits from increasing installation sizes will rely on negotiations with the manufacturer.

Even though Na-S batteries have high commercial potential, rapid cost reduction of alternative storage solutions, e.g., Li-ion batteries, might halter commercial deployment and technological development of Na-S batteries. This can prevent Na-S batteries from reaching full commercial potential.

Quantitative description

Technology	NaS battery									
	2015	**2020**	**2030**	**2050**	**Uncertainty (2020)**		**Uncertainty (2050)**		**Note**	**Ref**
Energy/technical data					**Lower**	**Upper**	**Lower**	**Upper**		
Form of energy stored	Electricity									
Application	System, power- and energy-intensive									
Energy storage capacity for one unit (MWh)	250	300	300	300	30	3000	30	3000	A B,Q	[9]
Output capacity for one unit (MW)	35	50	50	50	5	500	5	500	A,B,Q	[9]
Input capacity for one unit (MW)	35	50	50	50	5	500	5	500	A,B,Q	[9]
Round trip efficiency - DC (%)	83	83	85	85	71	92	74	96	C	[9];[26]
- Charge efficiency (%)	-	-	-	-	-	-	-	-		
- Discharge efficiency (%)	-	-	-	-	-	-	-	-		
Energy losses during storage (%/day)	0	0	0	0	0	1	0	1	D,Q	[11]/[30]/[26]
Forced outage (%)	0	0	0	0	0	2	0	2	E,Q	[13]
Planned outage (weeks per year)	0	0	0	0	0	0	0	0	F,Q	[13]
Technical lifetime (years)	15	19	24	24	10	28	14	36	G	[13];[25]+[27]
Construction time (years)	0.5	0.5	0.5	0.5	0.2	2.0	0.2	2.0	Q	[1]
Regulation ability										
Response time from idle to full-rated discharge (sec)	0.001	0.001	0.001	0.001	0.001	0.02	0.001	0.02	H	[10]+[28]
Response time from full-rated charge to full-rated discharge (sec)	0.050	0.050	0.050	0.050	0.001	0.05	0.001	0.05	H,I,Q	[9]
Financial data										
Specific investment (M€2015 per MWh)	0.46	0.37	0.23	0.20	0.25	0.73	0.13	0.39	G	[22];[25]+[26]
- energy component (M€/MWh)	0.31	0.25	0.14	0.11	0.18	0.50	0.08	0.23	G, J	[22]+[26]
- capacity component (M€/MW)	0.63	0.41	0.33	0.33	0.22	0.78	0.18	0.64	G, K	[22]+[26]
- other project costs (M€/MWh)	0.06	0.05	0.03	0.03	0.04	0.10	0.02	0.05	G	[22]+[26]
Fixed O&M (% total investment)	1.5	1.5	1.5	1.5	0.8	7.2	0.8	7.2	G,L,M	[23];[24]
Variable O&M (€2015/MWh)	1.8	1.8	1.8	1.8	0.3	5.6	0.3	5.6	G	[24]+[23]
Technology specific data										
Alternative Investment cost (M€2015/MW)	3.3	2.2	1.4	1.2	1.5	4.4	0.8	2.3	G	[22];[25]+[26]
Lifetime in total number of cycles	4500	5600	7500	7500	1100	11200	1500	15000	N, G	[9];[25]+[27]
Specific power (W/kg)	9.3	9.3	9.3	9.3	6.98	11.63	6.98	11.63	O,P,Q	[10]
Power density (W/m3)	4300	4300	4300	4.300	3225	5375	3225	5375	O,P,Q	[10]
Specific energy (Wh/kg)	56	56	56	56	42	70	42	70	O,P,Q	[10]
Energy density (Wh/m3)	26000	26000	26000	26000	19500	32500	19500	32500	O,P,Q	

Notes:

A Specific Italian installation from 2015 used here as example. Assuming installations similar to Buzen City discussed above to become standard in the future.

B Highly modular technology type with near linear scaling between total cost and installation size. Power and storage capacity cannot be varied independently.

C Grid size unit including balancing and auxiliary losses. Excluding converters. Assumes no improvement between 2030 and 2050.

D Ohmic losses maintain the temperature of the battery during operation. Losses are thus included in round trip efficiency [7]. No electrical self-discharge. If idle the heat loss is as much as 1 % of storage capacity per hour but highly variational. IRENA reports as "worst" value og 1.0 % [26]

E Forced outage is minimal. Only reported case is a 2011 fire incident [9].

F On the order of 1 h per year.

G Assumptions for development and uncertainty discussed above in "Prediction of performance" and "Uncertainty".

H Due to absence of predictions in literature, no development is assumed as an estimate.

I Measurement. Possibly limited by PCS.

J Includes "Batteries" from reference [22] for 2015 values.

K Includes "PCS-SCI", "Auxiliary equipment", and "Switching and actuating equipment" from reference [22] for 2015 values.

L Highly uncertain. Reported in range 2000 to 17300 €2015/MW/year [24]

M Does not include replacement costs. The batteries do not need replacement within lifetime [13],[10].

N See Figure 5.

O Data for standard NGK container unit.

P Not the technological maximum values, i.e., the density of single cells, but the specifications for a full market-standard commercial product.

Q Uncertainties are based on a qualified guess.

References

[1] NGK Insulators LTD, “Case Studies.” pp. 1–13, 2016.

[2] “DOE Global Energy Storage Database.” [Online]. Available: https://www.energystorageexchange.org/. [Accessed: 29-Mar-2017].

[3] IEC, “Electrical Energy Storage,” 2011.

[4] C.-H. Dustmann and A. Bito, “SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS | Safety,” in Encyclopedia of Electrochemical Power Sources, 2009, pp. 324–333.

[5] B. Dunn, H. Kamath, and J.-M. Tarascon, “Electrical Energy Storage for the Grid: A Battery of Choices,” Science (80-.)., vol. 334, no. 6058, pp. 928–935, 2011.

[6] J. Cho, S. Jeong, and Y. Kim, “Commercial and research battery technologies for electrical energy storage applications,” Prog. Energy Combust. Sci., vol. 48, pp. 84–101, Jun. 2015.

[7] J. Garche and C. K. Dyer, Encyclopedia of electrochemical power sources. Academic Press, 2009.

[8] R. Holze, “SECONDARY BATTERIES – HIGH TEMPERATURE SYSTEMS: Sodium-Sulfur,” in Encyclopedia of Electrochemical Power Systems, vol. 200, 2009, pp. 302–311.

[9] M. Andriollo et al., “Energy intensive electrochemical storage in Italy: 34.8 MW sodium-sulphur secondary cells,” J. Energy Storage, vol. 5, pp. 146–155, Feb. 2016.

[10] NGK Insulators LTD, “Structure of NAS Energy Storage System,” 2016. [Online]. Available: https://www.ngk.co.jp/nas/specs/.

[11] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” Prog. Nat. Sci., vol. 19, no. 3, pp. 291–312, 2009.

[12] NGK Insulators LTD, “The World’s Largest NAS Battery Installation Commences Operation Short Installation Period Achieved through Containerized, Compact Format,” 2016. [Online]. Available: http://www.ngk.co.jp/english/news/2016/0303.html.

[13] G. Huff et al., “DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA,” Rep. SAND2013- …, no. July, p. 340, 2013.

[14] NGK Insulators LTD, “Comparison of Battery Technologies | Why NAS? | NAS.” [Online]. Available: https://www.ngk.co.jp/nas/why/comparison.html. [Accessed: 13-Sep-2017].

[15] O. Teller et al., “Joint EASE/EERA Recommendations for a European Energy Storage Technology Development Roadmap Towards 2030,” 2013.

[16] Z. Wen, Y. Hu, X. Wu, J. Han, and Z. Gu, “Main Challenges for High Performance NAS Battery: Materials and Interfaces,” Adv. Funct. Mater., vol. 23, no. 8, pp. 1005–1018, Feb. 2013.

[17] G. Kim, Y.-C. Park, Y. Lee, N. Cho, C.-S. Kim, and K. Jung, “The effect of cathode felt geometries on electrochemical characteristics of sodium sulfur (NaS) cells: Planar vs. tubular,” J. Power Sources, vol. 325, pp. 238–245, Sep. 2016.

[18] S. I. Kim, W. Il Park, K. Jung, and C.-S. Kim, “An innovative electronically-conducting matrix of the cathode for sodium sulfur battery,” J. Power Sources, vol. 320, pp. 37–42, Jul. 2016.

[19] K. . Ahlbrecht, C. Bucharsky, M. Holzapfel, J. Tübke, and M. J. Hoffmann, “Investigation of the wetting behavior of Na and Na alloys on uncoated and coated Na-β”-alumina at temperatures below 150 °C,” Ionics (Kiel)., pp. 1–9, Mar. 2017.

[20] X. Yu and A. Manthiram, “Ambient-Temperature Sodium-Sulfur Batteries with a Sodiated Nafion Membrane and a Carbon Nanofiber-Activated Carbon Composite Electrode,” Adv. Energy Mater., vol. 5, no. 12, pp. 1–6, 2015.

[21] X. Yu and A. Manthiram, “Performance Enhancement and Mechanistic Studies of Room-Temperature Sodium–Sulfur Batteries with a Carbon-Coated Functional Nafion Separator and a Na 2 S/Activated Carbon Nanofiber Cathode,” Chem. Mater., vol. 28, no. 3, pp. 896–905, Feb. 2016.

[22] R. Benato, G. Bruno, F. Palone, R. Polito, and M. Rebolini, “Large-Scale Electrochemical Energy Storage in High Voltage Grids: Overview of the Italian Experience,” Energies, vol. 10, no. 1, p. 108, Jan. 2017.

[23] J. E. Al Carlsson, “ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050,” 2014.

[24] B. Zakeri and S. Syri, “Electrical energy storage systems: A comparative life cycle cost analysis,” Renew. Sustain. Energy Rev., vol. 42, pp. 569–596, 2015.

[25] K.-P. Kairies, “Battery storage technology improvements and cost reductions to 2030: A Deep Dive,” Int. Renew. Energy Agency Work., 2017.

[26] IRENA, “Electricity storage and renewables: Costs and markets to 2030 - Cost-of-service tool. Version 1.0,” 2017.

[27] P. Ralon, M. Taylor, and A. Ilas, Electricity storage and renewables: costs and market to 2030, no. October. 2017.

[28] L. Sigrist and E. Peirano, “E-Highway2050: Battery Storage Technology Assessment,” in WP3 workshop April 15th, 2014.

[29] R. Benato et al., "Sodium nickel chloride battery technology for large-scale stationary storage in the high voltage network," J. Power Sources, vol. 293, pp. 127–136, 2015.

[30] G. L. Soloveichik, "Battery Technologies for Large-Scale Stationary Energy Storage," Annu. Rev. Chem. Biomol. Eng, vol. 2, pp. 503–27, 2011.