Technology description and corporate concept

GroNaS Energy Storage

Stable power supply from renewable sources. An essential contribution to the replacement of fossil power plants.

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Definitions

- **EEG**: German Renewable Energy Sources Act
- **Installed capacity**: Maximum available capacity of the storage facility for energy absorption or delivery.
- **Storage capacity**: Amount of energy held in the storage system.
- **Medium-term load balancing**: Compensation for power fluctuations in electric power production over one to several weeks.
- **Specific storage capacity**: Specifies the amount of time during which the storage unit can work at maximum capacity to absorb or release energy. specific storage capacity = absolute storage capacity / installed capacity
- **System efficiency:** Sum total of all efficiency rates from storing to discharging energy (including the efficiency of the converters)
- **Efficiency:** In this document, the term "efficiency" is used when a single conversion process (energy intake or release) is meant.

Note

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dark blue	links to the corresponding destination. (Footnotes, cross references to internal or external documents and entries in the Table of Contents) The link is red when the link's destination is on the same page (e.g., most footnotes).
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1.1 Executive Summary

1.1.1 Goal

We founded GroNaS GmbH to develop a novel technology which stationary electric energy storage systems can be based on, and built - all the way up to application maturity.
The possibility to store large amounts of electric energy is still missing, and the lack of viable solutions is currently blocking the replacement of fossil fuels in the electric power generation sector. Storage power plants built according to the GroNaS concept are able to eliminate this blockade.
A GroNaS storage power plant is a compact facility that fits into thermal power plants sites that were previously driven by fossil fuel. A GroNaS storage facility is capable of bridging gaps in the electricity supply from renewable energy sources for more than 14 days. The levelized cost of electrcity (LCOE) of a combination of solar and wind power plants and a GroNaS storage system will be 0.16 €/kWh and therefore lower than that of coal-fired power plants. Hence, if the GroNaS energy storage concept is successfully implemented, a regenerative base load supply can be established that is more cost-effective than the current one.
According to current knowledge, the sale of this kind of equipment can generate billions of euros over the next 20 years.

1.1.2 Market, demand for electric energy storage

Due to the so-called “energy transition”, there is currently a considerable demand for large storage facilities for electrical energy. The renewable energy that is currently available cannot always be fully utilized. With the continued addition of regenerative power, this will occur more and more often. Since the possibilities of energy export from irregularly fluctuating sources are rather limited, this creates a need to store large amounts of electrical energy.

- Minimum load in (at night, on weekends): 30 - 40 GW
- Installed renewable energy: wind energy 135 GW, photovoltaic 63 GW[2]

So far, there is no technology that enables the economically acceptable storage of this energy. In Germany there is a whole series of pumped storage plants. However, compared to the emerging needs, they have far too little storage capacity: At installed capacity, they can only consume or release energy for approximately 8-16 hours. However, facilities are needed that can do this under full load for several days. Energy experts assume that the demand for electric energy storage capacity will increase a thousand fold over the next 20 years, as one factor in the energy transition.

- Available storage capacity in Germany: 40 GWh
- Future demand: 20,000 - 40,000 GWh[3]

[2] Values for Germany, 2024
[3] http://www.fze.uni-saarland.de/AKE_Archiv/DPG2011-AKE_Dresden/Vortraege/**DPG2011_AKE7.3Troendle_Energiespeicher.pdf**

1.1.3 Requirements for storage technology

So far, none of the "medium-term equalization" application storage concepts that have been discussed by the experts in the energy branch could be made economically plausible currently, or in the future. A suitable storage facility for this application would have to meet the following requirements:

- ▷ Sufficient availability of the necessary raw materials or other natural resources.
- ▷ System efficiency: $\geq$ 85%
- ▷ Plant costs: $\leq$ 1300 €/kW_i (similar to conventional power plants)
- ▷ Sufficient specific storage capacity[4]: $\geq$ 336 h (14 days)

All previous concepts fail to meet at least one of these conditions.

1.1.4 GroNaS storage concept

Storage facilities built according to the GroNaS concept should be able to fulfill all the aforementioned requirements.

- ▷ Specific storage capacity: $\geq$ 336 h (14 days)
- ▷ System efficiency: 85 - 90%
- ▷ Plant costs (including energy carrier material for 336 h): approx. 1000 €/kW_i
- ▷ System size: 20 - 1000 MW_i

An actual (2024) calculation gives the following price for storing electric energy in a GroNaS facility:

- ▷ Cost for storing electric energy: 0.1 €/kWh

The cost for storing electric energy in a GroNaS facility were calculated as the amount of energy delivered from the facility during the depreciation period divided by the sum of costs in said period. As costs the are the following considered: purchasing price of the facility, financing costs (at 6% interest), costs for the facilites own energy consumtion, network charge driven by the own energy consumtion, personnel costs, and maintenance costs. As depreciation period 10 years are assumed.
A GroNaS energy storage facilility can be used as basic load provider. Then, the overall sum of levelized Costs of Electricity (LCOE), consisting of the LCOE of the solar and wind energy and the costs for storing the energy, are less then the the LCOE of caol power plants:

- ▷ Levelized Costs of Electricity (LCOE) for GroNaS base load provision: 0.16 €/kWh
- ▷ Levelized Costs of Electricity (LCOE) of lignite fueled power plants[5]: 0,21 €/kWh

[4] The specific storage capacity, relative to installed capacity, expresses how long a storage device can consume or dispense energy when operating at its maximum installed power. The actual storage capacity of a storage facility is the product of installed capacity and specific storage capacity.

[5] mean value according to an analysis, published by Fraunhofer-Gesellschaft: **DE2024_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf**

1.1.5 Technology

Apart from the newly developed, patented design of the electrochemical energy converter, the GroNaS concept is a currently uncommon, but essentially conservative technology. For example, no new materials have been used and no basic research is required.
Sodium and sulfur are used as energy carrier materials. Both materials are readily available in huge quantities and at acceptable prices. Contrary to a false assumption, which unfortunately is occasionally even voiced by chemists, the use of sodium and sulfur does not pose particularly high risks. The potential risk is comparable to that of other conventional facilities, such as oil refineries or natural gas supplies.
The most important innovation in the GroNaS concept is the paradigm shift from the concept of a storage system as a "battery of sodium-sulfur battery cells" to an "electrochemical system with sodium-sulfur fuel cells". The Na-S fuel cell has a similar active component as the Na-S battery cell and can be operated in reverse, as it can. The economic advantage results from the implementation of the following three principles:

- ▷ Separation of power and storage capacity.
  The intrinsically cheap energy carrier materials are no longer encapsulated together with the expensive, power-generating components within each battery cell case, instead they are stored separately. The specific storage capacity can therefore be increased to a few weeks at very low additional costs by procuring additional energy carrier material.
- ▷ Increase of power performance factor
  The performance must be limited to a relatively low value in conventional Na-S battery cells, otherwise it creates an undesirable effect — crystal formation — shortening the service life of the cell. This unwelcome effect does not occur in Na-S fuel cells. That's why the power, which is based on the existing active area in the energy converters, can be increased. So, for a specific projected power output, fewer expensive active components must be made.
- ▷ Reduction of manufacturing costs by increasing energy conversion units
  The energy converters (battery cells) of conventional Na-S storage technology have a capacity of approx. 0.2 kW. To provide 1 MW of power, about 35,000 components have to be manufactured and assembled. A GroNaS energy converter cell has a capacity of at least 20 kW. For a megawatt, only about 1200 parts are required.

1.1.6 Development status

In addition to the comprehensive technological-economic analysis, a design for a suitable energy converter was developed over several revised iterations. For one of its parts (a big ceramic base plate) a suitable manufacturing process has to be developed. The other components are designed to be manufactured using established manufacturing technologies, as it has been discussed with professionals in the relevant supply industries (oxide ceramics, metal processing).

1.1.7 Agenda

GroNaS GmbH will develop the technology to produce these large storage plants to application maturity in the next years. This development will take place over two phases:

2025 – 2026 Phase I

	▷ Construction of the first energy converter prototype (about 1 kW). ▷ Qualification of the current cost estimates for storage. ▷ Improvement of the yield forecast ▷ Capital Acquisition for the next phase.
2027 – 2029	Phase II ▷ Construction of energy converter prototypes (about 20 kW). ▷ Qualification of the current cost estimates for storage. ▷ Improvement of the yield forecast ▷ Capital Acquisition for the next phase.
after 2029	Phase III ▷ Scaling of the energy converter prototype up to $>$ 20 MW. ▷ Construction of a production facility for the energy converters. ▷ Planning and construction of marketable large storage facilities.

1.1.8 Funding

The first development phase should be realized by this time. We want to fund our activities by issue of shares. Our enterprise is eligible for funding through the a german federal program (8. Energieforschungsprogramm des BMWK) to contribute to our enterprise.

1.1.9 Contact and company data

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1.2 Company

1.2.1 Motivation and Approach

The starting point of our company are the current consequences and public discussion of the energy transition. In particular, we were struck by the fact that the goal of completely renewable energy supply is generally desirable, but to achieve this goal, there is still an important element missing, namely an economically viable storage technology for electric energy. Here, we see a huge opportunity.

From the very beginning, the focus of our concept development was not a solution based on the technical problem, but the economic problem. So, not the search for the answer to the question "How can we save electricity", but the search for the answer to "Will an investment in storage technology pay for itself? Can you make money with it?". This perspective determines our development goal.

We have tested very different technical options for storing electrical energy in regard to their economic viability. In particular, we considered the parameters development time, raw material availability, technology availability, efficiency, plant life cycle and potential risk. Our focus on sodium and sulfur as energy sources is not because we have been studying sodium and sulfur for some academic reason, and are now looking for a field of application, but is the result of that review.

We want to build competencies for the overall plant design as well as for the manufacturing of large sodium sulfur energy converters. We do not understand the application of high technology as creating large accumulations of complicated technology. On the contrary, it is about understanding complex problems well — and mastering them with the simplest possible solutions. In the realization of the concept, already established technologies should continue to be used wherever possible, with the involvement of suitable partners.

1.2.2 Legal form

First of all GroNaS GmbH was founded in 2012. The firms name was changed to GroNaS Verwaltungsgesellschaft mbH in 2023. To enable the issue of shares GroNaS GmbH & Co. KGaA was in 2024. This company is a limited partnership with a limited liability company as general partner. The domicile of GroNaS GmbH & Co. KGaA is Leipzig, Germany. It's general partner is GroNaS Verwaltungsgesellschaft mbH.

Commercial register entries:

- ▷ GroNaS GmbH & Co. KGaA: HRB 42520, AG Leipzig
- ▷ GroNaS Verwaltungsgesellschaft mbH: HRB 38124, AG Leipzig; director: Johannes Werner

1.2.3 Founders and Co-Owners of the general partner

- ▷ Johannes Werner[6], chemist, founder and shareholder (80%)
  - ◦ Comprehensive, interdisciplinary, scientific and technical knowledge.
  - ◦ Professional experience as a chemist, IT consultant and software developer.

[6] see **Appendix 2.1.1, CV "Johannes Werner"**

- Conception and implementation of an application research project funded by the BMBF.
  - Participation in several basic research projects.
- Hartmut Kiesel[7], lawyer, founder and co-owner (10%)
  - Many years of professional experience as a partner of the law firm Maier, Kiesel, Drabe in Halle (Saale)
  - Competence in the field of Intellectual Property management.
- Stefan Fritzsche[8], Account Manager EVU, co-owner (10%)
  - Collaboration in two olympic games and in some international sportive development projects
  - 5 years experience in b2b sales

1.2.4 Cooperation partners

An agreement has already been reached with the following companies and research institutions:

- Helmholtz Research Center Dresden Rossendorf (HZDR)
  Competence: Process engineering for liquid sodium
  Contact: Dr. Gerbeth
- Fraunhofer Institute for Ceramic Technologies and Systems (IKTS)
  Expertise: Fabrication of components made of sodium -aluminate
  Contact: Dr. Schulz

[7] see **Appendix 2.1.2, CV** "**Hartmut Kiesel**"
[8] see **Appendix 2.1.3, CV** "**Stefan Fritzsche**"

1.2.5 Contact information

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1.3 Product

1.3.1 Product description

GroNaS GmbH's products are medium-sized and large storage units that can absorb or dispense electrical energy for several weeks even at maximum power.

- ▷ Performance capacity: 20 - 1000 MW
- ▷ specific storage capacity: $\geq$ 336 h (14 days)
- ▷ absolute storage capacity: 6 - 336 GWh
- ▷ System efficiency: 75 - 90%

A GroNaS storage facility can adjust its power from zero to full load and vice versa within a few seconds, both in the energy intake and in the energy delivery mode. It is therefore suitable for both base load and peak load operation.
The storage plant is a compact system. The energy sources required to store 336 GWh[9] of energy fit into two tanks, each 100 meters in diameter and 20 meters high.
The storage units are modular. The performance of an existing system can be increased by adding additional energy converters. A subsequent extension of storage capacity extension is even easier. All you have to do is enlarge the tank system and procure additional energy carrier material.
The storage plants are expediently established at suitable nodes in the energy supply network, preferably at locations where conventional power plants that are no longer required exist.
Using GroNaS technology for small plants, for example, in single-family homes as storage for a small photovoltaic generator to use, is not meaningful for two reasons. On the one hand, one would then not only generate increased production costs, but also increased costs for customer and warranty management. On the other hand, the plants would also be more expensive because the dimensional effect of thermal insulation[10] cannot be exploited, and a significantly more complex thermal insulation would have to be used. In any case, both factors mean that it will be cheaper to set up medium and large storage facilities within the reach of producers and consumers and to store the energy from the small producers there rather than completely decentralize storage.

1.3.2 Customer benefits, use cases

1.3.2.1 Energy supply in Germany

An important application for the GroNaS storage facility is the provision of renewable electrical energy to cover the base load. An important criterion for determining whether a storage technology can be used for this task is the so-called storage costs. The sum of the storage costs is the amount it costs to take one kilowatt hour of electricity from the storage system (since the overall efficiency is always less than 100%, more than one kilowatt hour of energy must be taken in). The storage costs of an electricity storage system are the equivalent of

9 The amount of energy generated by 200 large wind turbines of 5 MW each with maximum power in two weeks.
10 see **Appendix 2.8, "Efficiency and heat balance"**

the LCOE (levelized cost of electricity) related to power generation in power plants. If a network of electricity generators and a electricity storage facility is operated, the LCOE of the network is the sum of the power plants LCOE and the storage facilities storage costs. We have estimated the electricity storage costs for GroNaS technology[11] The result shows that the LCOE of a combination of solar and wind power plants and a GroNaS storage system can be lower than the current LCOE of coal-fired power plants:

- ▷ LCOE of ground-mounted PV systems[12]: 0,03 - 0,05 €/kWh
- ▷ LCOE of wind turbines (offshore und onshore)[12]: 0,04 - 0,10 €/kWh
- ▷ **Storage costs, GroNaS-Technologie: 0,1 €/kWh**[11]
- ▷ **LCOE of a GroNaS-Solar-Wind combination: 0,16 €/kWh**[11]
- ▷ LCOE of coal power plants[12]: 0,15 - 0,29 €/kWh

1.3.2.2 Provision of balancing power

If a GroNaS storage facility is designed to work with a system efficiency of 90% in base load operation mode, the technically possible maximum power will not be achieved. The remaining power reserve opens up the possibility of simultaneously providing balancing power. In this case efficiency would fall below the value of 85%. However, the efficiency-related losses in this case would be smaller than the additional gains on the base load provision business.

1.3.2.3 Power supply to remote regions

Electricity supply in far-off regions, such as the Canary Islands, is usually more expensive than in highly industrialized areas. Small or medium-sized diesel generators are often used, and the electricity is quite expensive as a result of the comparatively high fuel price. Power generation by wind turbines is there currently but it is often economically not useful, because the diesel generators then still need to be maintained for periods without wind. Together with GroNaS storage facilities, wind turbines in this case form a full-fledged replacement solution that can be more cost-effective than the old fossil-fueled power supply.

1.3.3 Technical description

The profitability of the GroNaS storage facilities is achieved by the following approach to this storage principle, which is modified from the existing sodium-sulfur technology described below.

1.3.3.1 Energy carrier material and storage principle

If an electric energy storage device with a storage capacity of 5 - 500 GWh is to be designed as a compact system, the storage principle is to only store high-energy materials. GroNaS storage facilities use sodium and sulfur[13] as energy carrier materials. This has the following advantages:

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[11] see **Appendix 2.5.2.4, "Storage costs"**
[12] **EN2024_ISE_Study_Levelized_Cost_of_Electricity_Renewable_Energy_Technologies.pdf**
[13] see **Appendix 2.3, "Sodium and sulfur"**

- ▷ Sodium and sulfur are available in huge quantities as major constituents of the Earth's crust. Also, the procurement of many millions of tons of these materials would not unduly affect their price.
- ▷ The specific energy is sufficiently large with 0.755 kWh per kilogram of energy carrier material. To store the amount of energy that 200 large wind turbines generate at peak power in two weeks, two tanks would be sufficient, each 100 meters in diameter and 20 meters high.
- ▷ In the case of electrochemical energy converters, the efficiency rate of a particular power plant is greater when more active surface area is available in the energy converter. Therefore, the efficiency depends on the system price. In electrochemical conversion in the sodium-sulfur system, affordable systems can also achieve a system efficiency of 75 - 90%.
- ▷ The processes of transforming the energy carrier material from a high-energy form to its low-energy form and back again are simple and complete. There are no waste products. All the construction materials involved in this energy conversion are only subject to minor corrosion. A system lifespan of more than 20 years is therefore realistic.
- ▷ Na Na-S storage technology has been extensively researched and the research results are publicly available. Basic research to clarify open questions is not required.

The energy conversion is carried out by chemical processes in the electrochemical sodiumsulfur cell. In the energy extraction mode, sodium reacts with sulfur in the energy converter. This forms sodium sulfides and electrical energy is generated. During the energy storage process, the reverse process takes place: while absorbing energy, sodium and sulfur are formed from sodium sulfides.
The sodium-sulfur cell is a high-temperature system. It works in the range of 270 to 400 °C. Both sodium and sulfur, as well as the product mixture consisting of various sodium sulfides are liquid at these temperatures.

1.3.3.2 Conventional Sodium Sulfur Storage Technology

Sodium and sulfur are currently used in medium-sized (1 - 2 MW) storage modules from the Japanese company NGK Insulators as energy carrier materials[14].
The technology from NGK Insulators follows the accumulator (rechargeable battery) paradigm. In this case, the energy carrier materials are encapsulated in small portions together with other components that are required for the provision of power in sealed cells. 'Accumulators' and the batteries that they are comprised of have a constructive conditional, fixed relationship of maximum power to storage capacity. It should be emphasized here that the production of a Na-S battery cell and its integration into an electrical functional unit are many times more expensive than the storage material used in the cell.
The cell type currently produced in mass production is a variant of a design from the 1980s, which was actually developed for the electromobility application (use in automobiles and other transportation).
NGK-Insulators manufactures cylindrical accumulator cells that are approx. 10 cm in diameter and 50 cm in height. One cell has a power rating of 0.2 kW and can store 1.2 kWh of energy. The NGK batteries have a limited life cycle under realistic operating conditions, which is stated as 4,500 full cycles (about 12 years during the operation of the storage system with one charge cycle per day). Approximately 300 battery cells are electrically connected to a unit, and several

[14] see **Appendix 2.4.1, "Storage Technology of NGK Insulators"**

of these units, together with the necessary electrical equipment, complete modules with a rated power of 1 MW and a storage capacity of 7.2 MWh. Large plants from many of these modules have already been built.
A tender process was announced for a large but unrealized storage project with the NGK technology (2009, Dubai, UAE). As a result, the following specific equipment costs were determined:

- ▷ Plant price, based on the installed capacity: 1560 € / kW_i
- ▷ System price, based on the storage capacity: 260 € / kWh

The investment price for NGK technology is too high, especially in applications that require a large specific storage capacity. This technology is therefore not suitable for the medium-term equalization of renewable energy production. The aforementioned use case (medium-term compensation) requires a specific storage capacity of one to two weeks. Using NGK technology would result in a specific system price of € 87,300 / kW_i. The NGK technology misses the equipment price point that is necessary for profitable operation, especially for the following reasons (A - D):

A High manufacturing effort as a consequence of the small functional units.
The energy converter used in the NGK memory modules, the battery cell T5, has a rated power of approx. 0.2 kW and is therefore far too small, measured in terms of the power range of the desired storage unit.
The small size of this battery makes its negative characteristics noticeable in two ways. First, because of the need to manufacture and accurately assemble many small units in high quality, a great deal of manufacturing effort is required. To provide 1000 megawatts of power, 5 million of these battery cells would have to be built and integrated into electrical functional units. On the other hand, for design reasons, it is not easy to connect thousands of battery cells directly to form large units. Therefore, the power converters must be designed as small units. The modules of NKG each contain 300 battery cells in a group of 60 kW. Each of these groups requires one converter unit, i.e., 17 converter circuits per MW of installed capacity. It would be much cheaper, instead of using many circuits, to build a few at 60 kW, equipped with power converters with more powerful components.
The small maximum size of the battery cell is due to the fact that its most important component, the solid electrolyte membrane, cannot be manufactured in larger dimensions and still be safely operated. This component is formed in the T5 accumulator as a thin-walled tube. It has to be made of a special ceramic called sodium β-aluminate. The thinnest possible wall thickness is essential for the simultaneous achievement of high efficiency and high performance. Sodium -aluminate has, like all ceramic materials, only a relatively low fracture resistance. It is therefore possible to manufacture a stable, larger solid electrolyte component of this type only when the wall thickness is also increased. However, with the increase in wall thickness you would have to make unacceptable reductions in efficiency or rated power. If one enlarges the tube with a constant, thin wall thickness, a very fragile structure is created, which can no longer be produced efficiently and operated safely.

B Fixed ratio of performance and storage capacity.
The ratio of maximum power to storage capacity is constructively specified in the energy converter according to the battery principle. For the NGK technology this means that it is only suitable for short-term storage. Only then can a system price of 1000 to 1500 € / kW_i be achieved. Of course, one could also build storage facilities for longer periods from the NGK modules. For this purpose, however, a multiple of the modules required for

short-term storage would have to be set up. Naturally, the investment costs multiply. To increase the storage capacity, it would actually be sufficient to procure much cheaper energy carrier material. Because of the fixed installation of the cheap energy storage material in production-intensive complete modules, and with the purchase of more modules to expand storage capacity, additional production-intensive, expensive, power generating elements and electrical functional units must always be procured. These will never be fully utilized later.

C Bad heat insulation concept.
When designing the NGK memory modules, the system price was the priority in the special market for these modules. Therefore, compared to the modules that are technically possible, they are only moderately well insulated. As a result, they do not reach 90% system efficiency, which would be possible electrochemically and electrotechnically. As a result of excessive heat release, it is necessary to heat them up, which limits the system efficiency in real operation to about 75%.
It should be pointed out, that the heat loss depends on the size of the system. The heat loss depends primarily on its surface area. When expanding the system, the surface / volume ratio decreases increasingly. In a building with double the dimensions of length, width and height, eight times the number of energy converters can fit, which then convert eight times the electrical power. But it only has four times the surface. Therefore, large systems do not have the same cumbersome thermal insulation as small ones. However, the NGK modules with 1 - 2 MW are still too small for an effective use of this dimension scaling effect.

D Poor utilization of the performance potential of the solid electrolyte membrane as a result of Na_2S_2 and Na_2S crystal formation.[15]
In NGK batteries, diffusion is the only material transport option. However, because diffusion is a slow process, high power, and thus high current density, on the surface of the solid electrolyte membrane causes Na_2S_2 and Na_2S crystals to form. These crystals accumulate there because they dissolve too slowly. They reduce the effective surface of the solid electrolyte membrane and thus the electrical power. An aging of the battery cell is the result. This aging process is performance-related. The maximum power of the NGK batteries was therefore set so low that a life cycle of about 12 years is reached. Regardless of aging, each battery cell could be taken or supplied with a multiple of power. The power limitation has a negative impact on the investment costs in applications that require only low efficiency: For a particular planned installed power, more battery cells and power converter circuits must be built than would be required without the crystal formation process.

1.3.3.3 New Type of Sodium Sulfur Storage Technology

The GroNaS concept results in significantly improved economic parameters. Because performance and storage capacity can be set independently, specifying a specific price based on installed capacity or storage capacity no longer makes sense. However, a specific asset price can now be calculated from a performance and a storage capacity component:

▷ Performance-based price component (target position): 684 €/kW$_i$[16]
▷ Storage capacity-dependent price component: 0,6 €/kWh[17]
▷ Specific system price for a specific storage capacity of 336 h: 1000 €/kW$_i$

[15] see **Appendix 2.6, "Lifetime of Na-S storage facilities"**
[16] see **Appendix 2.5.2.1, "Performance-related costs"**
[17] see **Appendix 2.5.2.2, "Storage capacity dependent costs"**

The lower equipment costs should be made possible because this novel concept results in improvements in all four of the above-mentioned problems:

A Using energy converters with significantly higher performance.[18].
The design of conventional Na-S battery cells does not comply with the guidelines normally followed in the design of industrial ceramic parts (it is not "ceramic-grade"), because there was a compromise made for the "electromobility" use case, which demanded low battery cell mass. Unlike the GroNaS energy converter. Since the mass of the energy converter for stationary storage is irrelevant, it could be consistently designed to be appropriate for ceramic materials. As a result, energy converter cells with more than 20 kW can be manufactured. Now that significantly fewer electrochemical energy converters and power converter circuits have to be manufactured and assembled, the costs are considerably reduced.

B Freely adjustable ratio of power and storage capacity.
GroNaS concept power-generating elements and energy sources are not encapsulated together in sealed battery cells. Instead, the energy carriers are contained in simple, heatinsulated tanks, from which they are pumped to the energy converters. Performance and storage capacity are scalable independently. The working principle of a GroNaS storage facility is the sodium-sulfur fuel cell[19]. Due to the separation of the power generating elements from the energy supply, only additional inexpensive energy carrier material has to be procured during the transition to medium and long term storage. Multiplying the costs of long-term storage by installing poorly utilized energy converters and superfluous electrical engineering is thus avoided.

C Improved thermal insulation concept exploiting the dimension effect[20].
The tanks and all the components of the system that are traversed by one of the energy carrier components, must constantly be kept at high temperature. In order to provide the heat required for large systems ($>$ 20 MW_i), the power loss of the electrochemical reaction (2 - 10% of the energy conversion in the energy converter) inevitably occurs in the energy converters. It does not have to be heated. The overall efficiency is thus not affected by heat emission to the environment (see also **Appendix 2.8, "Efficiency and heat balance"**).

D Suppression of Crystal Formation.[21].
The mass transfer in the GroNaS energy converter is not by diffusion, but by forced flow. This prevents Na_2S_2 and Na_2S crystal formation. On the one hand, there is no lifetime limitation, on the other hand, the solid electrolyte membrane can be operated with four times the current density compared to conventional technology. If the plant is to be designed for a total efficiency of 75%, the maximum power of the energy converter can be increased fourfold for the same membrane area. As a result, only a quarter of energy converters would have to be built. A further cost reduction results from the decrease in the number of converter circuits that need to be manufactured.

A **GroNaS storage facility** consists of tanks for the energy carrier materials, the energy converters, a powerhouse with pumps, control equipment and inverters as well as the high-voltage transformer and high-voltage switchgear required for grid connection. It has the following performance parameters:

[18] see **Appendix 2.5.1, "Technical description GroNaS"**
[19] The term "redox flow battery" should be avoided here, since these systems usually work with aqueous solutions of the reactants. This is not the case here.
[20] see **Appendix 2.8, "Efficiency and heat balance"**
[21] see **Appendix 2.6, "Lifetime of Na-S storage facilities"**

- ▷ Power: 20 - 1000 MW
- ▷ Storage capacity: 5 - 2000 GWh
- ▷ System efficiency: 75 - 90%

A large plant with an installed capacity of 1000 MW_i would consume 336 GWh of energy in 14 days if it is operating at full power during this time. To store this amount of energy, two cylindrical tanks of 100 m in diameter and 20 m in height are sufficient.
Accordingly, for a small plant with 20 MW_i two tanks of 20 m in diameter and 10 m in height are sufficient.
A GroNaS storage facility operates emission-free in normal operation.[22] Even in the event of an accident, there is no disproportionate risk to the system.

1.3.4 State of development

Sodium and sulfur energy storage has been extensively researched in the past, especially in the 1970s and 1980s. The results are available in a variety of publications.
The handling of liquid sodium requires a special know-how, which has already been developed and published. In addition, the chemical industry has decades of operating experience with hot, liquid sodium, as it is produced in large scale electrochemical plants, such as MSSA Metaux Speciaux (Pombliere, France) in quantities of tens of thousands of tonnes per year.
The separation of performance and storage capacity, i.e., the storage of the energy sources sodium and sulfur in tanks separated from the energy converter, was successfully demonstrated by a BASF team. This construction principle is comparatively easy to implement.
So far, the element still missing for the economic success of the technology was a costeffective, large energy converter. The GroNaS GmbH has developed a design to build such an unit. To accomplish this, extensive research on material properties and a repeated rethinking of the various requirements (in electrical, thermal, aerodynamic and production engineering dimensions) were necessary. The basic design principle is described in the patent "Large energy converter based on the sodium-sulfur fuel cell", which has already been granted. A design based on that, still further improved, has been described in the patent application "Operational Sodium-Sulfur Energy Converter". Further development work resulted in the patent "Sodium-sulfur cell-based electric energy storage plant" and "Reinforced sodium ion-conducting solid electrolyte membranes and their production"
The design of the two main components of the GroNaS energy converter (ceramic unit and bipolar plate) has already been discussed with the partner companies consulted as suppliers. These components can be manufactured using standard suppliers' procedures.

1.3.5 Manufacturing requirements

If a single energy converter cell has a power of 20 kW, 1000 units are required for a small system with an installed capacity of 20 MW. This is why establishment of a series production is necessary.

[22] see **Appendix 2.7, "Safety aspects"**

1.4 Industry and Market

1.4.1 Industrial Analysis

The storage of electric energy in quantities on the order of magnitude that entire regions consume or generate within several days is a completely new task. For a hundred years, electric power has been generated from extremely well-available sources. With little energy needed, it was easy to reduce power plant output, increase energy requirements and boost performance. To optimize the operation of the old energy supply, a sophisticated storage technology was used, the pumped storage technology. Above all, it served to cover peak loads and system minimums as a result of the slow power adjustment of nuclear and thermal power plants, that could not be compensated for. For an installed capacity of about 8 MW and a storage capacity of about 40 MWh (for Germany) was sufficient.
As a result of the current conversion of electricity supply to renewable sources, a completely new situation has meanwhile appeared. Energy production from these sources, in particular wind and solar energy, depends on the weather conditions. Making energy available in synch with the consumption of the energy supply is impossible. Until recently, it was possible to compensate for fluctuations by reducing the output of conventional power plants during the production peaks of wind energy. However, the limits of this compensation have already been reached.
For this reason, the renewable energy can no longer be fully utilized. If a high power is provided by wind generators due to a strong wind conditions, network congestion occurs because of the existing grid network, which is not equipped for the construction of generating capacity. Then wind generators must be taken off the grid ("EinsMan" so-called feed-in management), and it is given up, along with a part of the regenerative energy. This unused energy potential (so-called failure work) continues to increase:

- Losses in Germany[23]
  - 2009: 74 GWh
  - 2011: 421 GWh
  - 2013: 555 GWh
  - 2015: 4772 GWh
  - 2017: 5518 GWh
  - 2019: 6482 GWh
  - 2021: 5818 GWh
  - 2023: 10478 GWh

The construction of large-scale electric energy storage facilities in areas with high levels of wind energy would relieve the high-voltage power lines and make this energy usable.

1.4.2 Market potential

A study by the University of Heidelberg[3] has concluded that in Germany total storage capacity of 40 TWh is required for a renewable electricity supply. This is a thousand times the storage capacity currently provided by pumped storage hydroelectric power plants. Storage of this size

[23] Information from the German Federal Network Agency

is possible with storage facilities built according to the GroNaS concept. There is a market potential with a volume of several billion euros for storage facilities in Germany alone. A multiple of this potential continues to exist on the international market.

1.4.3 Market segments

1.4.3.1 Medium-term compensation of regenerative energy production

The future, medium-term balancing of weather-related energy production fluctuations over a few days deals with very large amounts of energy. For this, many new storage systems with large storage capacity are needed.
The installed capacity of wind and solar power plants alone exceeds the maximum load. For weather conditions without significant wind and sunshine almost the entire conventional power plant capacity must still be maintained (so-called backup power).
In the future, additional renewable generating capacity will be added. The available amount of energy increases continuously. With a storage plant that is available at a similar cost to a conventional power plant and has a specific storage capacity of about 2 weeks, all conventional power plants can gradually be replaced. Even with the generous assumption that half of the current installed conventional capacity can be eliminated as a result of a successful introduction of load management measures, the market is huge for Germany alone.

- Installed capacity of conventional power plants in Germany 2011: approx. 100 GW_i
- Estimated future demand for available storage capacity: approx. 50 GW_i
- Annual demand for electric energy storage with replacement of conventional power plants within 20 years: 2.5 GW_i / a
- Annual turnover at an investment price of 1000 €/kW_i: 2 billion €

In other countries, a market could also develop on a similar scale.

1.4.3.2 Autarky (self-sufficient) solutions for remote areas

Power through a combination of wind power and storage facilities can be used in remote areas, on islands such as Mauritius or the Canary Islands it will be cheaper than conventional oil-based thermal power plants. This also creates a market for GroNaS storage facilities.

1.4.4 Competition

At present, there are no other electric energy storage technologies that would be economically relevant for the application “medium-term compensation of strongly fluctuating regeneratively produced energy production”. All other storage technologies are clearly inferior in one or more key figures to the GroNaS concept.

- Pumped storage hydroelectric power plants
  Pumped storage power plants are currently the best large storage facilities for electrical energy. The plants installed in Germany have a total performance capacity of 7 GW and a storage capacity of 40 GWh. Some additional plants are currently being planned, including the Schluchseewerk, with 1.4 GW / 15 GWh. Measured against future needs, however, the

availability potential is many times too small. Another disadvantage is that the pumped storage plants are currently far away from the regions that have strongly fluctuating energy production (the windy coastline). This results in additional storage and recovery efficiency losses that affect the storage price very adversely. This would also be the case with the use of foreign pumped storage plants (e.g., in Norway, as occasionally discussed in the public). System efficiency: 85%, investment costs: 500 - 1000 € / kW_i

- Conventional Sodium Sulfur Storage Technology (NGK Insulators)
  The storage modules from the Japanese company NGK Insulators are an alternative to pumped storage systems, where these are not available. With this technology, only operation in the short-term mode can be profitable because the investment costs increase greatly as the storage duration increases.
  System efficiency: 75%, investment costs: approx. 1500 € / kW_i
- Further projects with sodium and sulfur as energy source
  A Laboratory stand in which the energy carrier materials were located in tanks separated from the energy converter was operated by a development team from BASF in Ludwigshafen. However, the energy converter here was a variation of the construction of small scale battery cells, so that the economically necessary technology enlargement is unimaginable and the production costs would be, predictably, too high. A subsidiary of BASF continues to pursue the development of sodium sulfur storage technology. However, we have no information about the details of the technology concept currently in progress.
- Adiabatic compressed air storage
  Adiabatic compressed air accumulators have a maximum efficiency of approx. 70%. However, the available specific storage capacity is too low.
- Methane conversion ("Power to Gas")
  Excess electrical energy can be used to generate hydrogen. These can then be converted with carbon dioxide to methane (natural gas). The facilities for this conversion are very cost effective and an existing infrastructure for natural gas storage can be used. If the stored energy is to be recovered as electricity, however, a system efficiency of approximately only 37% results. This is far too little for a profitable operation. When recovering the stored energy as heat, the efficiency would be somewhat better at 55%, but storage would be a loss due to the very low price of the natural gas offered in competition.
- Vanadium-based redox flow battery
  This technology achieves a very good efficiency of about 80%. However, vanadium resources available worldwide are far too small in terms of storage requirements.
- Lithium and lead batteries
  When stored in conventional lead, lithium and other accumulators, an efficiency of over 90% is achieved. The availability of these elements would also be sufficient for a portion of the memory requirements. The investment costs and the resulting storage costs are, however, many times too high due to complex production and limited battery life.

1.5 Marketing

1.5.1 Sales

The aim of the first phases of our project is to develop a technology, i.e. a comprehensive collection of detailed knowledge. We assume that this knowledge will have considerable value. In combination with components and services already available on the market, it will become a product. The next capital increase will be used to plan and build up production capacity. This will enable the production of the innovative core components of GroNaS energy storage technology immediately after the completion of technology development. The business will then consist of the sale of these components and the sale of planning services for storage power plants.

1.5.2 Promotion

New technologies often raise irrational fears. For example, when we mentioned a large tank of liquid sodium, our project was commented on with the words: ". . . there is a huge bomb in the landscape!". The danger of sodium is obviously even spontaneously misjudged by experts, at least if they have not dealt with it further. Sodium is not particularly dangerous. The energy content is no bigger than a tank full of diesel and it cannot explode. When moisture is allowed to form, there is a possibility of hydrogen formation, but the handling of explosive gases is also required in many other sectors of our industry and is very well controlled.

GroNaS storage is characterized by very little negative impact on the environment. Also, the footprint in the landscape is much smaller than the construction of a pumped storage plant. This must be convincingly communicated to the public.

Sales of energy storage technology in Germany, but also in other countries, are influenced not only by market events, but also by laws and regulations. In Germany, these are in particular the Renewable Energy Sources Act (EEG) and the Energy Industry Act (EnWG). To avoid discrimination against our company as a result of new regulations in this area, we believe that communication with politicians is necessary.

1.6 Management and key persons

- Management: Johannes Werner[24]
- Management support: Stefan Fritzsche[25], Hartmut Kiesel[26]

[24] see **Appendix 2.1.1, CV "Johannes Werner"**
[25] s. a. **Anhang 2.1.3, Lebenslauf "Stefan Fritzsche"**
[26] see **Appendix 2.1.2, CV "Hartmut Kiesel"**

Appendix

2.1 CVs of the shareholders and managing directors

2.1.1 Johannes Werner

1969	born 6.2.1969, in Schönebeck
1985 - 1988	Vocational training with Abitur, Weißenfels
1990 - 1995	Chemistry studies (diploma), Merseburg and Halle
1995 - 1999	Research Associate, Institute of Physical Chemistry, Martin-Luther-Universität Halle ▷ organic synthesis ▷ dielectric and electro-optical measurements ▷ Construction and programming of a dielectric measuring station
2000	programmer, bitstone-GmbH, Leipzig
2001 - 2002	IT Consultant, santix AG, Unterschleißheim ▷ Installation, maintenance and customer-specific modification of the "Peregrine ServiceCenter" helpdesk software for customers such as Zeiss, Audi, ETH Zurich, Nürnberger Versicherungsgruppe, AOK.
2003	scientific Staff, Institute of Plant Biochemistry Halle ▷ System and database administration independent
2004 - 2006	freelance work ▷ Development of the patent "disposable inhaler" ▷ Development of the Patent "Semi-conductive Polyadducts with Columnar Structure": High-order, ultrathin layers of organic semiconductors for use in photovoltaics and as OLEDs
2006	scientific Staff, Martin Luther University Halle ▷ Synthesis of a platinum-containing drug for the chemotherapy of tumor diseases
2007	scientific Employee, BioSolutions Halle GmbH ▷ Synthesis optimization
2007 - 2008	Project Manager, Martin-Luther-University Halle ▷ Conception and direction of the research project "Nanokos - highly ordered, ultrathin, organic semiconductor layers" (German Federal Ministry for Vocational Education and Training, Reference number: 03ESFST040)
2008 - 2009	scientific Employee, BioSolutions Halle GmbH ▷ Syntose optimization, AAS trace analysis of heavy metals
2010	software developer, cleanenergies GmbH, Berlin ▷ Development of a database-supported program for the planning of photovoltaic systems
2011	chemist, rosseta Technik GmbH, Dessau-Rosslau ▷ Development work for an electrolysis plant, analysis of energy storage concepts
2012	entrepreneur, GroNaS Verwaltungsgesellschaft mbH ▷ provision of IT-services ▷ Foundation of GroNaS Verwaltungsgesellschaft mbH (former GroNaS GmbH) ▷ Foundation of GroNaS GmbH & Co. KGaA

2.1.2 Hartmut Kiesel

1966	born 8.3.1966, in Hilden
1985	Abitur Selb
1987	Law degree, Freiburg i. Br.
1993	1st state examination, Freiburg i. Br.
1996	2nd state examination, Dusseldorf
seit 1996	lawyer, Halle (Saale) ▷ Partner in the law firm Maier, Kiesel, Dietrich ▷ since 2005: main focus on intellectual propertyp
2012	entrepreneur, GroNaS GmbH ▷ Foundation of GroNaS GmbH

2.1.3 Stefan Fritzsche

1985	born 22.8.1985, Leipzig
2004	Abitur, Brandis
2005 - 2011	Studies for Diploma in Sports Engineering, Otto-von-Guericke University, Magdeburg ▷ Specialization on integrated product development
2011, 2014	worked for two Olympic Games and several international development projects in sports
2011 - 2014	Project- and service engineer, ST Sportservice GmbH, Leipzig ▷ Lead of project teams up to 15 people ▷ B2B Sales Manager Eastern Germany, Mizuno Corporation
2014 - 2015	Training for IPMA certified project manager level-D
2019 - 2022	Studies M.Sc. Energy Management (part-time)
since 2019	Communication & sales for GroNaS GmbH, Leipzig (part-time)
since 2020	Account manager for energy producers and industry partners at Energy2Market GmbH, Leipzig
since 2021	Partner, GroNaS GmbH, Leipzig

2.2 Patents, licenses, property rights

GroNaS GmbH or its founders hold three patent applications and one patent has already been granted.

- Patent application "storage plant for electric energy based on the sodium-sulfur cell"
  DE 10 2011 110 843 A1
  Owner of the application: Johannes Werner
- Granted patent "Reinforced sodium ion conductive solid electrolyte membranes and their manufacture"
  DE 10 2012 013 921 B4
  Holder of the registration: GroNaS GmbH
- Granted patent "Large energy converter based on the sodium-sulfur fuel cell"
  DE 10 2012 021 151 B3
  Holder of the patent: GroNaS GmbH
- Patent Application "Safe Sodium-Sulfur Energy Converter" registered on 17.5.2013
  DE 10 2013 008 031 A1
  Holder of the application: GroNaS GmbH

2.3 Sodium and sulfur

2.3.1 Commodity prices and availability

Sodium and sulfur are excellently suited as energy carriers for the storage of electric energy. The energy efficiency of storage is high, the specific energy (amount of energy that can be stored with one kilogram of material) is sufficient, the transformations do not cause any material losses and the storage system is long-lasting.

- ▷ System efficiency, technically relevant Battery cell constructions comprising injection and withdrawal as well as flow direction: up to 90%
- ▷ specific energy: 0,755 kWh / kg
  1 kg of storage material = 0.32 kg of sodium + 0.68 kg of sulfur.
  To store one kilowatt hour of electricity, you need 0.43 kg of sodium and 0.895 kg of sulfur.

The specific energy given here is the net value relevant to energy storage in large stationary systems (quotient of the amount of energy and mass of sodium and sulfur). In the 70's and 80's, the usability of the sodium-sulfur high-temperature accumulator for electric vehicles was tested. For this application, the gross value (including the mass of the housing and other components of the battery) is more interesting. Most publications (e.g., Wikipedia) give this gross value (about 0.26 kWh / kg).
To store the amount of energy that 200 large 5 MW wind turbines produce at full power in two weeks (336 GWh), you need 142,000 t of sodium and 303,000 t of sulfur. This quantity fits into two cylindrical tanks, each 100 m in diameter and 20 m in height.
Sodium and sulfur are major components of the earth's crust and are available at relatively low prices. Even if one stored the entire electrical energy production of the earth over months with sodium and sulfur as energy carrier materials, the availability of sodium and sulfur would not be affected.

Sulfur stockpiles at Fort McMurray

Rock salt mining in Bernburg

Figure 3.1

On the one hand, sulfur occurs in large natural deposits; on the other hand, large quantities are produced in the desulphurization of crude oil and natural gas. The sulfur from refineries in the vicinity of highly industrialized areas was usually bought by the chemical industry and recycled. Overall, however, in recent decades, a multiple of the required amount of desulfurization was produced. The surpluses of many distant refineries were collected on huge heaps.

Estimation of the costs for the procurement of sulfur.

Typical sulfur prices (commodity market)[27]

Date	Price $ / t	Price € / t	Specific price[28] € / kWh
01/2010	30	21,4	0,019
11/2010	150	107,1	0,096

Sodium is available as an ingredient of rock salt in even greater amounts than sulfur. For energy storage, metallic sodium is needed. It is produced by electrolysis of a molten salt. Since rock salt as a harmless bulk material is much easier to transport than metallic sodium, the production of sodium should take place at the location of the storage plant. The production of sodium from sodium chloride is energy-consuming. However, one-third of this energy is not lost, but is stored in the metallic sodium, so to speak, and is released again at the first energy withdrawal from the storage plant.

Estimation of the costs for the procurement of sodium.

Salt (NaCl):

Date	Price $ / t	Price € / t	Specific price € / kWh
2006	146	104,2	0,114
2010	170	121,4	0,132

Electric power:
For the production of 1.0905 kg of sodium with an efficiency of 70%, 3.03 kWh of electrical energy are required. Result takes into account the amount of energy remaining in the metallic sodium.

For an energy price of 0.07 € / kWh:	0.141 € / kWh

Limestone for chlorine disposal:

Date	Price $ / t	Price € / t	Specific price € / kWh
2006	8	5,7	0,013
2010	10	7,1	0,017

Hydrogen for chlorine disposal: (from natural gas):

For a gas price of 2,766 € / MMBTU (09/2011):	0,0098 €/kWh

[27] USGS figures, converted to the former euro / dollar exchange rate of 1 / 1.4:
[28] Price needed to provide a storage capacity of 1 kWh

Chlorine is produced during sodium electrolysis. At best, this chlorine can be sold to the chemical industry. In the less favorable case it would have to be converted to hydrochloric acid with cheap hydrogen obtained from natural gas and neutralized with limestone. Storage and disposal of resulting calcium chloride are unproblematic.

Total cost of energy carrier materials with inflationary adjustment (2010 - 2024, 36.8%)

Material	*spec. Demand kg / kWh*	*Price, € / kWh (optimistic)*	*Price, € / kWh (pessimistic)*
Sodium	*0,429*	*0,285*	*0,410*
Sulfur	*0,895*	*0,026*	*0,131*
Total:	*1,324*	*0,311*	*0,541*

The energy carrier materials are not consumed and do not age (because they are always transformed into elemental state).If an energy storage facility contains a large amount of it, provided that this type of storage technology is also used after depreciation, it represents an asset of considerable value.

2.3.2 Sodium-sulfur cell

An "electrochemical cell" in chemistry is an arrangement of two electrodes separated by an electrolyte. Chemical reactions are in general terms, always also electrical processes, because with them an electron transfer takes place. In the case of "normal" chemical reactions, however, this takes place directly between the molecules or atoms involved and therefore cannot be used technically as "electricity". However, if one finds an "electrolyte", i.e., a medium that does not conduct electrons, but is permeable to ions of one of the reactants, this becomes possible. In an electrochemical cell, the materials making up the electrodes react with each other, and the energy converted thereby can be used as an electric current.
The sodium-sulfur cell, compared with many known electrochemical systems, such as the lead-acid battery or zinc-carbon batteries, is a special system. While in most other electrochemical cells solid electrodes (reactants) are separated by a liquid electrolyte, here it is reversed. One of the electrodes is liquid and an important part of the electrolyte system is a solid. In order to keep the negative electrode (sodium) and the sulfur-containing component of the electrolyte system liquid and to allow ionic conduction in the solid electrolyte, the cell must be operated at high temperature.
The negative electrode of the Na-S cell consists of liquid sodium. The electrolyte is formed by two components. Directly adjacent to the negative electrode is the solid electrolyte. It consists of a ceramic material, sodium -aluminate. It is permeable to sodium ions at higher temperatures. On the other side of the solid electrolyte is the positive electrode formed by carbon fibers and an emulsion of sodium sulfide and liquid sulfur when the system is "charged", i.e., in the high energy state. This emulsion is part of the electrolyte system. In the low-energy state, there is no emulsion but a homogeneous mixture of the sodium sulfides Na_2S_2 and Na_2S_4.
In order to be able to use the electrical energy generated by the cell, the actual electrodes must be provided with fixed contacts. The contact for the negative electrode is a piece of steel (because it is not soluble in liquid sodium). The carbon fibers are in contact with a piece of molybdenum-coated metal as a conductor.

Sodium sulfur cell:

Temperature:	270 – 400 °C
Cell voltage:	approx. 2V
negative electrode:	liquid sodium
positive electrode:	liquid sulfur / liquid sodium sulfide
Electrolyte:	sodium β-aluminate (sodium ion conducting, ceramic material)
Negative electrode contact:	steel
Positive electrode contact:	chromium alloy
Conductive material (current collector) in the positive electrode:	carbon fiber felt

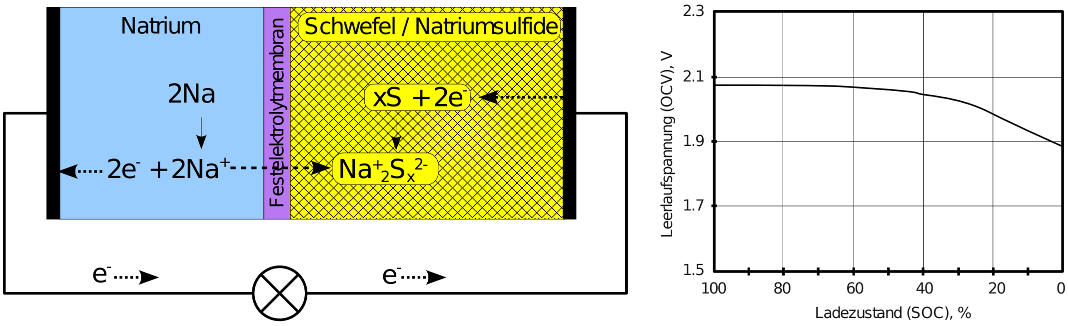


Figure 3.2
Processes in the Na-S cell and voltage during discharge

In-cell reactions:

$2Na + 5S \rightleftarrows Na_2S_5$	energy turnover approx. 62%
$2Na + 4Na_2S_5 \rightleftarrows 5Na_2S_4$	approx. 15%
$2Na + 3Na_2S_4 \rightleftarrows 2Na_2S_2 + 2Na_2S_4$	approx. 23%

The efficiency of the sodium-sulfur cell depends on the available membrane area and the extracted or injected power. With previously existing technically feasible solid electrolyte membranes, the following efficiencies can be achieved:

Efficiency of commercially available cells (state of charge range 60 - 100%) :

Current density in eolid electrolyte, A / m^2	cell voltage, V	Available power, kW / m^2	electrochemical efficiency η_E (single process)
650	2,04	1,33	0,98
1066	2,0	2,13	0,965
2180	1,95	4,25	0,94
3252	1,87	6,08	0,9
4203	1,8	7,57	0,87
6503	1,7	11,05	0,82

2.3.3 Sodium-sulfur fuel cell

A sodium-sulfur fuel cell[29] is formed by providing the space for the negative electrode with one access and that for the positive electrode with two accesses.
In the energy extraction mode, sodium can now be continuously supplied to the space for the negative electrode. Sodium atoms are oxidized there to sodium ions and diffuse through the solid electrolyte membrane into the space for the positive electrode.
In the energy extraction mode the space for the positive electrode is fed through one access with an emulsion of sulfur and sodium sulfides (e. g., 95% sulfur and 5% sodium sulfide[30]) or a homogeneous mixture of sodium sulfides (e.g. a mixture of Na_2S_5 and Na_2S_4). These substances absorb sodium ions coming from the solid electrolyte membrane and electrons from the carbon fibers and are thereby reduced.
The reaction products leave the positive electrode space through the second access. Continuous power generation is possible as long as the supply of energy supplying materials lasts and the reaction products are removed. In the energy intake mode, all processes are reversed.

[29] The term “sodium-sulfur fuel cell” is used here to differentiate from the so-called “redox flow cell”. Redox flow cells usually work with aqueous solutions of the redox partners. This is not the case with the Na-S system.
[30] The sodium sulfide portion provides sufficient conductivity.

2.4 Conventional Na-S Storage Technology

2.4.1 Storage Technology of NGK Insulators

The Japanese company NGK Insulators manufactures medium-sized storage modules with sodium and sulfur as energy carrier materials.

60 kW 1 MW 34 MW

Figure 4.1 Storage Technology of NGK Insulators

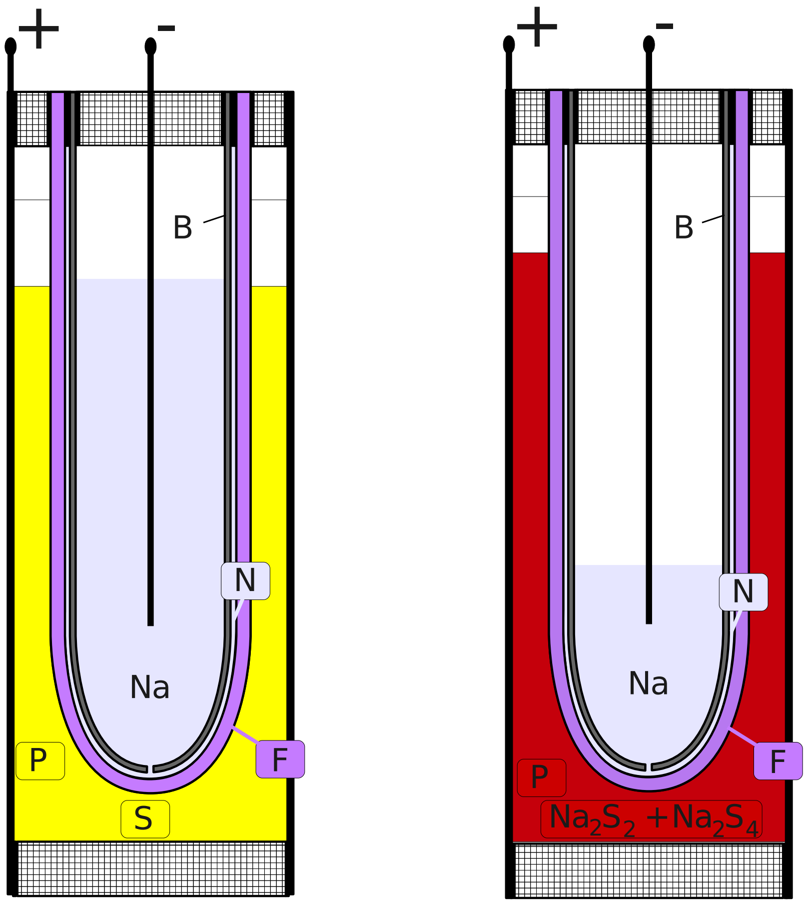
As energy converters, type T5 battery cells (also a NGK development) are used. This is currently the largest commercially available sodium sulfur battery cell. 300 of these cells are connected together to form a battery of 60 kW. Several of these batteries are then assembled together with the associated charge controllers, inverters, heating elements and control and telemetry devices in a module.

Battery cell NGK T5	
Operating temperature:	290 – 360 °C
Voltage:	1,7 – 2,04 V
Storage capacity:	1.22 kWh
Surface of the solid electrolyte:	0,094m^2
Dimensions:	91 x 550 mm

The design principle of conventional Na-S battery cells, which includes the T5 battery, is shown in Figure **Figure 4.2**. The solid electrolyte membrane (F) of this battery is a thin-walled tube of sodium β-aluminate. It has a hemispherical terminal at one end and is connected to the lid of the cell at the other end. The sodium reservoir is housed in a steel container (B).From there it passes through a small hole in the actual space for the negative electrode, the gap between the solid electrolyte tube (F) and the container (B). This arrangement was chosen so that in the event of breakage of the solid electrolyte membrane, not all of the sodium supply can react quickly with the sulfur, because that would lead to enormous heat and pressure buildup in the cell.
The space for the positive electrode (P filled with S or Na_2S_x) is the space surrounding the solid electrolyte tube.

2.4.2 Critical consideration of the conventional technology

The NGK memory modules are, due to the small size of the battery cells used, constructed from very small parts. For example, for each battery unit of 60 kW, one current transformer module is required, i.e., 16 current transformers per MW. There is a comparatively large manufacturing



P: space for the positive electrode, at the same time supply of sulfur / sodium sulfides
B: reservoir for sodium
F: solid electrolyte membrane
N: space for the negative electrode (gap between B and F)

Figure 4.2 conventional battery cell in cross-section, charged and discharged state

effort involved (during the development of the cell design described above in the 70s and 80s, the application "Electromobility" was in the foreground. For this application, the design of the energy storage is acceptable as a small cell battery).
The construction principle with the one-side mounted ceramic tube, serving as a solid electrolyte component may be one of the reasons why this type of cells can only be made in small sizes. The solid electrolyte membrane must be as thin as possible, so that a good efficiency and, based on the membrane surface, high performance can be achieved. If the cell is enlarged while the wall thickness of the solid electrolyte membrane remains constant, it becomes more and more fragile.
At the head of the cell, a gas-tight connection is required. Otherwise, air would enter the top of the negative electrode space (the gap between the solid electrolyte membrane and the containment). As the discharge progresses, the sodium would then no longer rise to the very top and the effective membrane area, and therefore also the power, become smaller and smaller. Glass solder is used to fix the solid electrolyte tube in the cell cover and to make this point gas-tight. Because of the difficulties of matching the thermal expansion coefficients of the glass

solder and the ceramic components over a wider temperature range (which must be passed through during the manufacturing of the battery), this design feature is likely to limit the maximum size too.

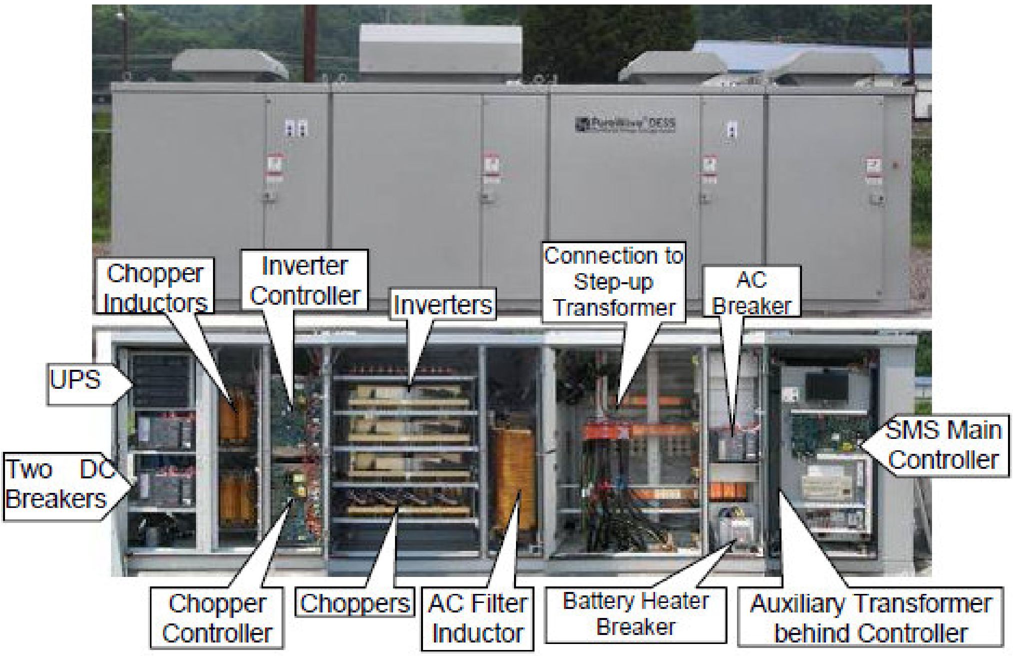


Figure 4.3 An NKG module consists of very small components.

The storage modules of NGK Insulators still do not achieve the efficiency that the electrochemical system and the electrical equipment would actually allow.[31] This is the product of the electrochemical efficiencies of charging (η= 0.97), of discharging (η= 0.97), of the inverter (= 0.98) and of the charge controller (η= 0.98). Since the NGK modules are only moderately well insulated, it is necessary to heat them again and again so that the operating temperature can be maintained. The energy consumption required has the consequence that the practical efficiency is significantly less.

▷ Electro-electrochemical efficiency: 85 - 90%
▷ Efficiency in practical operation: 75 - 80%

Another disadvantage is that the current density in the battery cells must be limited to the rather low value of about 1000 A / m^2. A further increase in the current density would have the consequence that the crystallization process occurring in closed cells[32] would be enhanced. The lifecycle of the system would be significantly shorter. At a current density of 1000 A / m^2, the cells provide an available capacity of approx. 2 kW / m^2. An increase of the performance can only be made possible by the installation of additional solid electrolyte membrane surface (therefore more cells must be deployed). The low maximum current density in the battery cells is one of the reasons for the relatively high value of the specific investment of around 1500 € / kW_i compared to other power plants.

[31] **http://www.xcelenergy.com/staticfiles/xe/Corporate/Renewable Energy Grants/Milestone 6 Final Report PUBLIC.pdf**
[32] s. **Appendix 2.6, "Lifetime of Na-S storage facilities"**

2.4.3 Equipment price NGK technology

According to a known tender result[33], the parameters listed in the table can be estimated for a large NGK storage facility:

Data from a large storage park[35] built with NGK modules

Location; Investor:	Dubai, VAE; Rubenius (amplex)
installed capacity:	330 MW
Storage capacity:	1.98 GWh (330MW for 6h)
Energy carrier material:	approx. 3000 t (1000 t Na + 2000 t sulfur) in 1.6 million rechargeable batteries
Lifetime:	4,500 full cycles
Utilization in real operation:	The offer has a lifespan of 12 to 15 years. With 4500 charging cycles this corresponds to a utilization of approx. 50%.
Purchase price:	€ 514 million ($ 720 million, 2009)
Share for energy carrier material:	approx. € 0.8 million
cumulated inflation 2009 - 2024:	37,2%
specific investment, based on the installed capacity[34]:	2140 € / kW_i
specific investment in terms of storage capacity[34]:	357 € / kWh

Installed power and storage capacity are in the fixed ratio of 1:6 (1 kW_i / 6 kWh, specific storage capacity: 6 h) with the NGK technology. During continuous operation at maximum power, the system has therefore absorbed or discharged the maximum possible amount of energy every 6 hours.
Due to the very high specific investment (in terms of storage capacity), the technology is only affordable for use cases in which a fluctuating supply or decrease performance is compensated for within a few hours.

33 **http://energystoragenews.com/NGK Insulators Sodium Sulfur Batteries for Large Scale Grid Energy Storage.html**
34 with inflationary adjustment 2009 - 2024
35 prospected but not realized

Use case	short-term power compensation	medium-term power compensation
required energy consumption and delivery time	6 h	14 d (336 h)
Investment per kW of installed capacity	€ 2,140	€ 2,140
Investment, based on the maximum performance in the case of use	€ 2,140	€ 119,840
Purchase price of a reference investment for 20 MW application	€ 43 million	€ 2,397 million

Table 4.1 Plant Costs for Low- and High-Capacity Use Cases Using NGK Insulators Modules

2.5 New Na-S Storage Technology

2.5.1 Technical description GroNaS

2.5.1.1 Energy converter cell

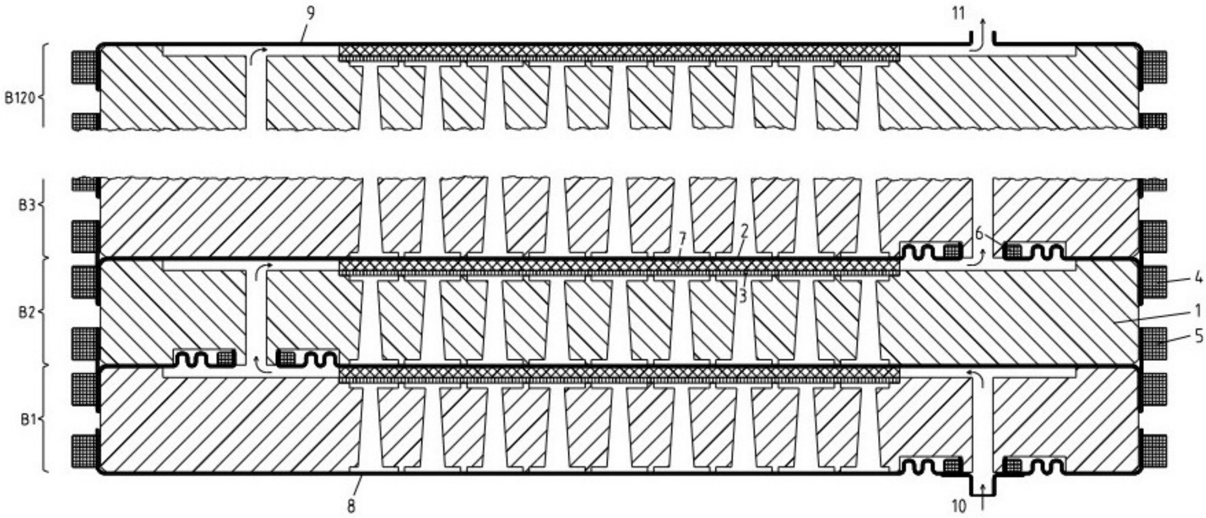


Figure 5.1 Draft: Section through a network of GroNaS energy converter cells, older design

One of the key elements of the GroNaS concept is the patent-pending energy converter.
An energy converter cell of the GroNaS design is shaped like a flat round disc. This design of the cell makes it possible to design the entire energy converter as a cell stack and to carry out the contacts of both electrodes as a common bipolar plate.
The spaces for the positive electrode are linked together. In the energy delivery mode, sulfur is fed to the bottom of the stack and the reaction product (sodium sulfide) exits the topmost cell. In the energy absorption mode, the flow direction is reversed.
The liquid sodium-containing space for the negative electrode of each energy converter cell has a terminal for the supply or discharge of sodium. Each connection line to the common sodium tank initially leads to a simple device, also patent pending, which lets through liquid sodium without creating an electrical connection. It serves to separate the electrical potentials, without which a series connection and thus the generation of a sufficient voltage would not be possible.
In the older design of the energy converter cell, a planar solid electrolyte membrane was used. In the more advanced design, however, the solid electrolyte membrane is no longer designed as a flat component. As a result, the membrane surface area could be increased even further. A state-of-the-art GroNaS energy conversion cell enables the construction of an energy converter cell that is one hundred times the power of conventional sodium-sulfur battery cells.

- ▷ diameter: 0.8 -1.2 m
- ▷ Height: 6 - 12 cm

- ▷ Voltage: 2V
- ▷ Power: 10 - 20 kW

A GroNaS energy converter cell, including the device for electrical isolation, only consists of approx. 12 immovable, simple metal and ceramic parts as well as a ceramic composite membrane carrier plate and approx. 300 membrane sleeves. The metal parts can be manufactured conventionally. There is also an established manufacturing technology for the membrane sleeves, but existing production lines for similar sleeves made of ordinary ceramic materials must be adapted to the special sodium β-aluminate material. All membrane sleeves are connected together in one step with the carrier plate.
The performance increase over conventional Na-S battery cells results from the combination of two effects:

- ▷ Enlargement of the solid electrolyte membrane surface (power increase: approx. Factor 20).
- ▷ Exploiting a higher current density. This is possible because Na_2S_2-Kristallbildung crystal formation does not occur[36] as a result of forced flow through the positive electrode space. (Performance increase: factor 2).

Because of the increased power of the energy converter cell and its straightforward design, far fewer components have to be produced and assembled for the energy converter to function in the storage system than in a conventional design consisting of small battery cells.

- ▷ conventional Na-S storage technology: approx. 35000 components / MW_i
- ▷ GroNaS technology: approx. 1200 components / MW_i

[36] see **Appendix 2.6, "Lifetime of Na-S storage facilities"**

2.5.1.2 Energy converter cascade

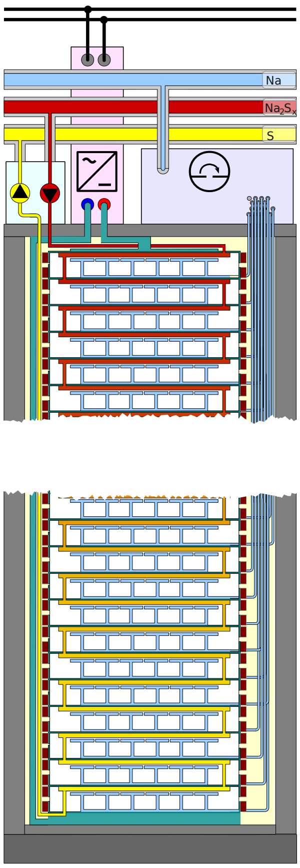


Figure 5.2 Energy converter cascade (Stack)

A single energy converter cell only provides a voltage of 2V. However, to operate an inverter, you need a multiple of that. Therefore, a stacked cascade of about 100 cells is assembled. The energy converter cells are connected electrically and fluidically in series. The stacked arrangement of energy converters with bipolar plates has the advantage that the electrical resistance between the energy converters is minimal due to the short distances. Furthermore, this way there is no manufacturing effort for the production of lowresistance electrical connections (the cascade flows a current of up to 10,000 A otherwise relatively complex electrical contacts would be necessary).

- ▷ Height: 10 - 20 m
- ▷ Diameter: 2 - 3 m
- ▷ Voltage: approx. 200 V
- ▷ Power: approx. 2 MW
- ▷ Feed pressure sulfur / sodium sulfide: <5 bar
- ▷ Sodium pressure: <6 bar

In the energy extraction mode, the cascade is fed with sulfur. The liquid subsequently flows through all energy converters and absorbs sodium. The flow through the cascade is controlled so that at the end of the full conversion of the energy carrier material is done and a 1:1 mixture of Na_2S_4 und Na_2S_2 leaves the cascade.
Because liquid sodium is itself a very good electrical conductor, the energy converters cannot be supplied with sodium from a common conduit. In the machine house, at the head of the cascade, there is a device for electrical isolation. A line for liquid sodium leads from there to each of the disk-shaped energy converter cells. Only small diameter, thin-walled tubes, are needed, because there is only a pressure of 10 bar at the most, and the delivery rate of sodium is only about one cubic centimeter per second.
In the energy absorption operation, reversing the flow direction, the reconversion of sodium sulfides into sulfur takes place.
The energy converter cascades are placed in concrete tubes, which are lowered into the earth. To increase fire safety (in the case of a leak in one of the sodium supply pipes), the remaining space between the wall of the concrete pipe and the cascade can be filled with sand.

2.5.1.3 Storage facility

A GroNaS storage system consists essentially of two heat-insulated tanks and a machine house (M). The machine house houses the energy converter cascades (W) and electrical and chemical process engineering functional units. Furthermore, a protective gas system (G), a cooling device (K), a high-voltage field with transformer (T) and switching devices as well as the control and communication devices belong to the storage plant.

Figure 5.3 shows an older idea of the storage facility, which is characterized by sodium and sulfur storage tanks lowered into the ground. Sinking it into the earth was intended to achieve a particularly low risk potential in case of accident. According to recent findings, an equivalent, low risk potential can also be achieved with above-ground tanks. The construction costs would be significantly lower in this case.

One tank is for liquid sodium. It is full when the accumulator is charged with the maximum energy and empty when the accumulator has exhausted all the energy. In the energy delivery mode, sodium is pumped to the energy converter cascades. During energy absorption, sodium forms in the energy converters and is pumped back into the tank.

The second tank contains sulfur when energy is stored in the storage tank and sodium sulfide when the energy is released. For power generation, sulfur is taken from the top of the tank and pumped through the energy converter cascades. In the process, it converts to sodium sulphide, absorbing sodium. After leaving the cascade, the sodium sulfides are fed down into the same tank from which the sulfur was taken. This tank thus serves at the same time as the reservoir for the high-energy and the low-energy form of the positive electrode. This is possible because sulfur and sodium sulfides are immiscible, like oil and water. Down in the tank is the sodium sulfide mixture with the higher density, and above the sulfur with the lower density.

A cooling device for the energy carrier materials is required, because the energy converters generate more waste heat than is needed to maintain the operating temperature[37].

2.5.2 Equipment price and LCOE, GroNaS technology

The main criterion for determining whether it makes sense to invest in the development of GroNaS- technology is the future achievable system price, as it has the greatest influence on the storage costs (the amount required to withdraw one kilowatt hour of energy from the storage system).

A GroNaS storage facility consists of components readily available on the market and new components. The former include, for example, electrical equipment and buildings, and the latter, especially the electrochemical energy converter. You can specify a price for the components already available on the market. For the new components, this is unfortunately only partially possible. However, the price of the intended energy converter solid electrolyte component was calculated years ago. This solid electrolyte component, a type of sleeve of sodium β-alumina, a special ceramic material, is believed to be the most expensive component of the energy converter.

In a GroNaS storage system, performance and storage capacity are scalable independently. This results in each a performance and a capacity-dependent cost component.

[37] see **Appendix 2.8, "Efficiency and heat balance"**

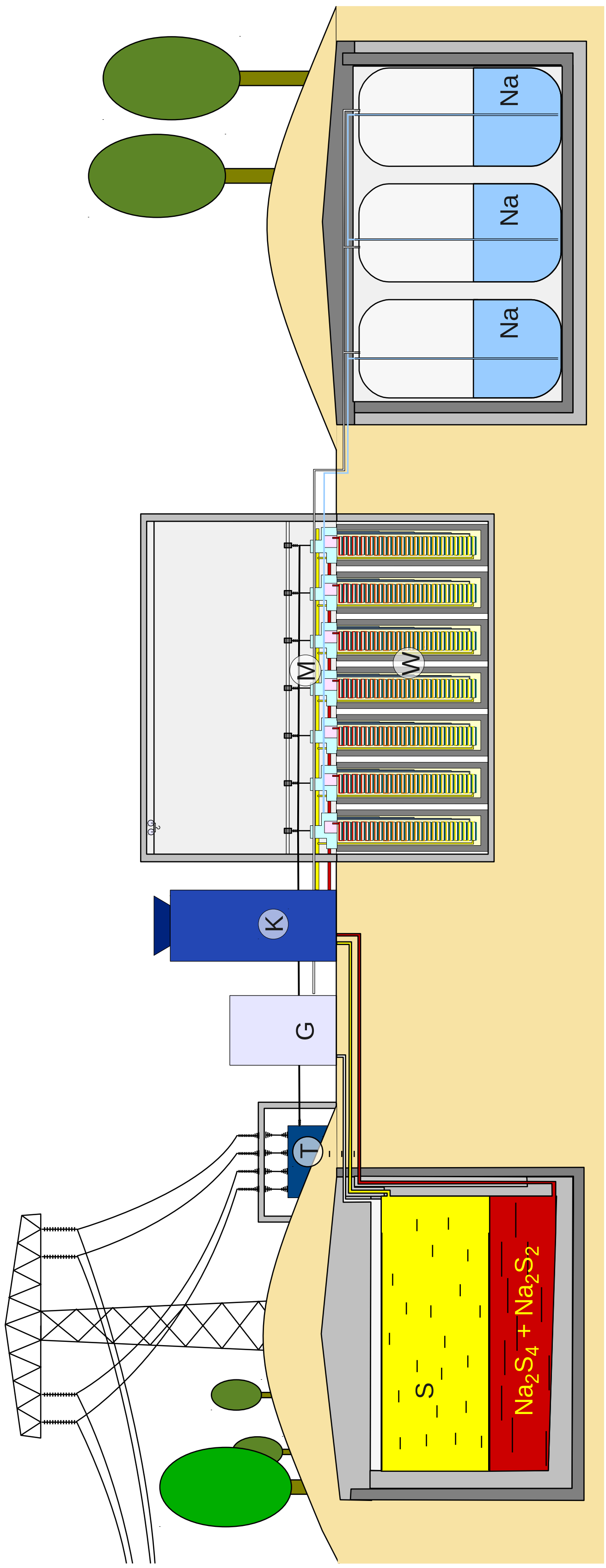


Figure 5.3 **GroNaS storage facility**

2.5.2.1 Performance-related costs

- **Electrochemical energy converters:** An energy converter cell consists of several metal components as well as a ceramic carrier plate and the membrane sleeves made of sodium alumina. These membrane sleeves are, in terms of material, the most demanding components of the energy converter. They are currently not available as standard parts,but can be manufactured in a pilot plant of Fraunhofer IKTS in Hermsdorf.
The manufacturing price of the pods was determined as early as 1980 in an industry-related study carried out at Friedrichsfeld GmbH[38] in Mannheim. The study came to the conclusion that the pods at the price of 9 DM, which, taking into account inflation at the current time (2024), can be produced at about 11 €.
If an overall efficiency of 75% is to be achieved, 13 membrane sleeves per kW of installed capacity are required. This corresponds to a cost component of 143 € / kW_i. If a higher efficiency is to be achieved, more membrane sleeves are required (per kW). Accordingly, the price for the energy converter rises to 539 €/kW_i.
Productivity increases in the years since 1980 have made it possible to significantly reduce the specific price of components made of sodium-β-aluminate. We therefore assume that the specific price of €539/kW_i is sufficient to also manufacture and assemble the other, far more cost-effective components of the energy converter.
- **Electrical engineering (high-voltage system and power converter):** The basis for the cost estimate is on the one hand the result of a tender for a DC back-to-back station[39,40] and on the other the purchase price for a large (4800kVA) converter unit for a battery of a UPS system.
The DC back-to-back station consists of two almost identical units of high-voltage transformer, power converters and a control module and the buildings enclosing these components. Each of these units is equivalent to the high and medium voltage technology required in the GroNaS storage facility, resulting in a cost contribution of recent (2024) € 145 / kW_i for the $ 60 million tender for a 220 MW installation[41].

2.5.2.2 Storage capacity dependent costs

Capacity-dependent costs are currently estimated at 0.94 € / kWh. This includes the following components:

- **Energy carrier material:** The raw material prices used in the estimates are the upper, pessimistic values from the fluctuation range of the prices on the commodity exchanges. These give a price of about 0.54 € / kWh.
- **Tank system:** A preliminary search for purchase prices of tank systems available on the market has resulted in a price of approx. 0.4 € / kWh.

2.5.2.3 System cost estimate

The following costs result for the investment in a GroNaS storage facility:

38 Today, this company is called FRIATEC.
39 http://news.thomasnet.com/companystory/ABB-Awarded-60-Million-HVDC-Order-to-Support-Grid-Reliability-in-Texas-853518
40 http://www.abb.com/industries/ap/db0003db004333/3AB2736FA99B8203C1257A6100474870.aspx?
41 Dollar 8/2012: 1 € = 1.25 $, cumulated inflation 2012 - 2024: 32%

Design					
System efficiency at maximum power (%)	75	75	80	85	90
specific storage capacity (h)	168	336	336	336	336
Current density in the solid electrolyte (A / m^2)	4800	4800	3600	2400	1300
Number of solid electrolytic components per kW_i	13	13	17	26	49
Demand-related cost					
Solid electrolytic components (€ / kW_i)	143	143	187	286	539
Electrical engineering and buildings (€ / kW_i)	145	145	145	145	145
Storage capacity dependent costs					
Energy carrier material (€ / kW_i)	91	181	181	181	181
Tank system (€ / kWi)	67	134	134	134	134
Sum of the estimated specific Costs (€ / kW_i)	446	603	647	746	999

Table 5.1 Estimated plant costs for GroNaS storage facilities depending on the required overall efficiency

2.5.2.4 Storage costs

An important use case is the provision of base load power from regenerative sources. An important criterion for determining whether a storage technology can be used for this task is the so-called storage costs. The sum of the storage costs is the amount it costs to draw one kilowatt hour of electricity from the storage system. As no storage system has a system efficiency of 100%, the calculation also includes the costs for the amount of energy that is lost from the storage system through heat dissipation. The storage costs of an electricity storage system are the equivalent of the levelized cost of energy (LCOE) of a power plant. If a network of electricity generators and electricity storage systems is operated, the electricity generation costs of the network are the sum of the electricity generation costs and the storage costs. If different types of electricity generation are used, the respective LCOE must be weighted according to their shares in the mix.
The storage costs for GroNaS technology were estimated based on the following assumptions:

- The GroNaS storage facility has a specific storage capacit of 336 h and a overall efficiency of 90%].
- The storage facility is directly connected to the extra-high-voltage transmission grid.
- The storage facility loads 1248 hours a year solar generated electric energy. The weather data from Munich Airport served as the basis for estimating this loading time. There has been an average of 1983 hours of sunshine there in the last ten years. For the following reasons, it is assumed that the storage system draws solar energy via the grid in 70% of these hours, primarily from ground-mounted PV systems: 1) The total installed capacity of PV systems in Germany is already greater than the maximum load (2024: 99 GWi). 2) The correction factor of 70% takes into account that the first hour after sunrise and

the last hour before sunset contribute very little to energy generation. The value used in the estimate for the LCOE of ground-mounted PV systems is the average value for such systems in a current Fraunhofer study[42].

- In addition to solar power, the storage system draws the same amount of wind power. The cumulative installed capacity of wind plants in 2026 was 63.5 GW and is therefore significantly smaller than that of PV plants, but the amount of energy generated was roughly twice as high (wind: 135 TWh, solar 63 TWh). The value assumed here for the LCOE of wind power plants was calculated from the two mean values for onshore and offshore plants, weighted by the amount of energy produced in each case.
- The costs for own energy consumption over 10 years and the associated grid fee are € 259/kW_i and € 183/kW_i respectively.
- The GroNaS facility is depreciated over 10 years.
- A value of € 1000/kW_i was used for the system costs. Financing costs of € 373/kW_i are incurred through an annuity loan with an interest rate of 6% and a term of 10 years.
- Operating costs of around €708/kW_i are incurred during the amortization period

Duration of energy consumption during the depreciation period	27762 h
Duration of energy output during the depreciation period	24986 h
Costs for own energy requirements	173 €/kW_i
Grid fees caused by own energy consumption	165 €/kW_i
Construction costs for a GroNaS storage facility with 336 h specific capacity	1000 €/kW_i
Financing costs	359 €/kW_i
Operating costs during the depreciation period	700 €/kW_i
Total costs over the depreciation period	2.396 €/kW_i
Storage costs	0.096 €/kWh
Weighted electricity production costs for solar and wind energy	0.062 €/kWh
Electricity production costs of a network consisting of GroNaS storage facilities and wind and solar power plants	0.158 €/kWh

Table 5.2 Storage costs for GroNaS storage facilities with 336 hours of specific capacity and overall efficiency of 90%

[42] EN2024_ISE_Study_Levelized_Cost_of_Electricity_Renewable_Energy_Technologies.pdf

2.6 Lifetime of Na-S storage facilities

2.6.1 conventional technology

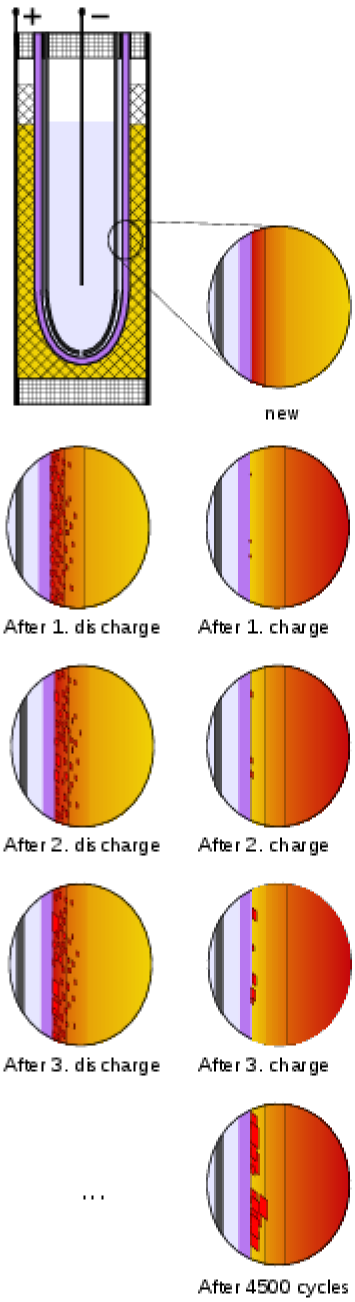


Figure 6.1 Crystal formation in conventional Na-S batteries

Conventional Sodium-Sulfur batteries have a limited life under practical operating conditions. The aging is due, inter alia, to the formation of Na_2S_2 crystals on the side of the solid electrolyte membrane in contact with the positive electrode of sulfur and sodium sulfides. Na_2S_2 conducts the electric current only in liquid form, in crystal form it is an insulator. Due to the deposit of the crystals on the solid electrolyte membrane, its effective surface is reduced and the electrical parameters (maximum power and efficiency) deteriorate.

The reason for the aging seems paradoxical at first glance, because Na_2S_2 is not an unusable waste product, but a regular component in the processes of transformation during the processes of energy conversion in the cell.[43] In fact, Na_2S_2 is soluble in the Na_2S_4 present at 0-25% charge states, as shown in the phase diagram. Thermodynamically speaking, these crystals should not exist.

The process of crystal formation can be understood only when one considers that transport processes in the positive electrode chamber come about only by diffusion. The liquid in the chamber stands still and even small convective movements are suppressed by the presence of the carbon fiber felt. However, diffusion is a slow process.

When discharging with high current density, a supersaturated zone is now formed on the solid electrolyte membrane in which Na_2S_2 crystals precipitate. Because of the limited mass transport, the largest of them are not completely dissolved when loading. The remaining crystals remain as crystallization nuclei. That is, where such a seed crystal is located, on the next formation of the supersaturation zone it attracts further material in crystal form and is now more than ever not dissolved during subsequent loading. A self-reinforcing process has begun.

The kinetically induced crystal formation occurs above all when the cell is discharged quickly, i.e., at high power, and when a very low state of charge is achieved. However, both are desirable: at higher power you do not need so many energy converters and when you use very low charge states, the specific energy[44] is higher.

[43] see **Appendix 2.3.2 "Sodium-sulfur cell"**
[44] Energy quantity that can be stored with one kilogram of energy carrier material.

A battery cell affected by crystal formation could probably be regenerated by extremely slow charging. “Extremely slow” means in the field of chemistry, however, that it is a difference over at least one, but usually even several orders of magnitude. For a recharge process, it would take a lot of time. The plant is then not productive, the load decreases, the costs increase.

2.6.2 GroNaS technology

In the energy transformers of the GroNaS technology, the mass transfer occurs through forced flow and is therefore much more intense. For this reason, no crystal formation takes place. The energy converters can even be operated with higher power and the storage potential of the energy carrier material can be fully utilized. A lifetime of more than 20 years is achieved.

2.7 Safety aspects

An electric energy storage system based on the GroNaS concept operates emission-free in normal operation. The risks of different accident scenarios can be limited to an acceptable level by a coordinated design of the entire system and appropriate design measures. The hazard potential of a GroNaS storage system is comparable to that of "normal" chemical plants. Below are some serious incidents that bear closer inspection:

- ▷ Sodium major fire
  The risks of a large sodium burn are often overestimated by experts. Although a sodium fire can only be extinguished with special extinguishing agents (e.g., graphite flakes), it runs at a much lower rate of combustion than, for example, kerosene fires. The reason for this is the high enthalpy of evaporation of sodium. As a result, only a comparatively low rate of sodium is vaporized under the flame and carried into the combustion zone. Sodium fires have little impact on the environment. As smoke forms strongly corrosive, aggressive sodium oxide directly above the flame, but this reacts within minutes with the carbon dioxide present in the air completely to sodium carbonate (soda). Because of the low risk, the best approach would be in an actual major fire not to attempt to quench it and just wait until the fire is burned itself out.
- ▷ Gas explosion as a result of air and water entering the sodium tank
  In the sodium tank, an overpressure of the protective gas atmosphere is constantly maintained. In normal operation, the ingress of air and water is therefore excluded. In the case of a fault in the inert gas system, however, there is the possibility that air, and therefore also water at the same time, would penetrate into the tank because of always present humidity. In this case, there would be an immediate formation of oxyhydrogen gas and subsequent ignition of this explosive mixture.
  Gas explosions of this kind take place as so-called radical chain reactions. The detonation spreads by rapidly moving, activated particles. This detonation propagation can be prevented by the presence of collision surfaces. Thus, in a tank, no explosion occurs when it is filled with an open-pore material and the gas mixture is in the pores. Even in a honeycomb structure with open, interconnected honeycombs no explosion takes place. In the worst case, the gas mixture burns at a relatively low speed. The released energy can be largely absorbed by the material that makes up the collision surfaces. Steel foil would be a suitable material for a honeycomb structure in the sodium tank.
  Alternatively, however, a tank can also be designed so that it opens upwards in the event of an explosion, and the pressure wave thus spreads in a direction in which it can do little damage.
- ▷ Large sulfur fire and gas explosions in the tank for sulfur and sodium sulphides
  Sulfur is processed by the chemical industry at hundreds of thousands of tons per year. For this reason, extensive experience exists with the help of which a low-risk manipulation of liquid sulfur is possible.
  The tank for sulfur and sodium sulfide can be equipped with a floating lid. The formation of a gas bubble with an explosive sulfur vapor-air mixtures can be excluded as far as possible. Nevertheless, it is still possible that the tank is completely destroyed, for example by a plane crash. A subsequent major fire, which would release huge amounts of toxic sulfur dioxide, can be suppressed by an appropriate tank pit design.[45] You would provide it with a

[45] A tank pit includes a kind of huge saucer (usually made out of concrete) on which the tank stands.

variety of short drains. The liquid sulfur would then run into these drains, thereby cooling and going out. Once cooled, there is no danger from it.

▷ Large-scale sodium or sulfur fires in the machine house
Sodium and sulfur pass through pumps or passively flow as a result of overpressure in the inert gas volume into the machine house and to the energy converters. If a fire starts as a result of a damaged line, it is sufficient to interrupt the power supply to the feed pumps or discharge a portion of the inert gas through emergency valves. The fire then comes to a halt as a result of lack of fuel supply. Because the feed pumps have only low production rates (more is not required for regular operation), even if the emergency shutdown fails, this would not lead to an uncontrollable major fire endangering the environment.

▷ Endangering groundwater
Sodium and sulfur are major constituents of the earth's crust and belong to the chemical inventory of the biosphere. For this reason, natural degradation paths exist for all occurring in the energy storage system compounds of these elements. The only problem would be the sudden emission of large quantities of these materials. However, this can be prevented by structural measures, such as a simple steel sheet pile around the system.

Additional questions about handling liquid sodium

▷ *Demonstrations in chemistry lectures sometimes show how sodium, potassium or magnesium burns rapidly. How does that fit with the statement that large sodium fires are slow?*
In these demonstrations, it is actually only shown that combustible materials burn particularly well when they are divided into small pieces. By applying the principle of division, however, even steel can be lit with a lighter (go to a hardware store, buy some steel wool and hold it over a lighter). It is not possible to deduce any statements about the behavior of a major fire from such experiments.

▷ *In a major fire of a sodium tank with a diameter of 100 m and a height of 20 m, an amount of energy of approx. 1500 TJ is released - in the explosion of the atomic bomb in Hiroshima it was only 56 TJ.*
Such an amount of energy (1,500 TJ = 417 GWh) is something quite commonplace in the energy industry. It's about the amount that a 1000 MW power plant generates at full load in 14 days. Of course, the material in the tank contains such large amounts of energy, which is ultimately the purpose of storage. Substances (petroleum, diesel, gasoline) found on most petroleum refineries would release even more energy. The comparison with an atomic bomb explosion is nonsensical, because all energy is converted in fractions of a second. Sodium cannot explode, it burns down. The burning rate is significantly lower than with kerosene fires.

▷ *In the event of a fire, large amounts of Na_2O_2, a corrosive material, still occur. Is not this an enormous threat?*
That is not completely right. Directly above the flame, Na_2O_2 is formed. In a major fire, this oxide is carried by the hot combustion gases into the air. It reacts with the CO_2 present in the air in the presence of atmospheric moisture, to form sodium carbonate. This reaction proceeds with 100% conversion within a few minutes. As a result, no clouds of corrosive Na_2O_2 are formed above the fire, but relatively harmless sodium carbonate (soda, Na_2CO_3) is formed.

▷ *Weren't technical problems when pumping liquid sodium one of the key reasons for abandoning sodium-cooled fast breeder reactor projects?*

In fast breeders, liquid sodium must be pumped through the reactor at rates up to 500 t / min as a refrigerant. This is a very demanding task. The main risk, however, is not from the sodium, but from the failure of the cooling effect, which would result in a meltdown. This results from a specific problem of breeder reactors: If sodium escapes from the cooling circuit through a leak, it immediately starts to burn outside the pipeline. However, in order to maintain the cooling effect on the reactor core, one is forced to continue to pump sodium through the reactor, which means it is always replenished with more fuel.
Quite different in GroNaS storage: For full-load operation of a 500 MW turbine, only 3.5 t / min have to be pumped. The energy converter complex is modular. If it comes to the sodium outlet in one of the modules, the sodium supply to this module can be stopped without problems.

▷ *Does any technological experience for handling large quantities of liquid sodium exist?*
Large plants with liquid sodium have been in operation for decades. These are the factories for the production of sodium. In them, sodium is produced in liquid form at over 600 ° C, on a scale of tens of thousands of tonnes per plant a year , and conveyed within the plant from the electrolysis cells to the packaging machinery.
A GroNaS storage facility is ultimately a similar chemical plant with a similarly low risk.

2.8 Efficiency and heat balance

Depending on the design, storage facilities based on the GroNaS concept can achieve an overall efficiency of up to 90%.
In a sodium-sulfur electric energy storage, there are basically three processes in which energy is lost to the environment.

- Current direction and voltage adjustment
  Converters (DC and inverter) according to the current state of the art work with efficiencies of 98% ($\eta = 0,98$). In the overall process (energy absorption + energy output) an efficiency of 96% ($\eta = 0,98^2 = 0,96$) is achieved. The resulting waste heat is generated at low temperatures (<100 ° C) and is therefore difficult to use.
- Electrochemical conversion processes
  The efficiency of the electrochemical conversion depends mainly on the electrical resistance of the electrolyte membrane. The lower the resistance, the higher the efficiency. The resistance of the solid electrolyte membrane is essentially determined by three parameters.
  1) Specific resistance of the material: This depends on the material composition and the temperature. In contrast to electron conductors (metals), the specific electrical resistance of ion conducting solids decreases as the temperature increases. This is also the case with sodium β-aluminate, the material that makes up the solid electrolyte membrane.
  2) Area of the solid electrolyte membrane: The larger the area, the lower the resistance. For the same current intensity, therefore, a higher efficiency can be achieved by increasing the membrane area.
  3) Thickness of the solid electrolyte membrane: The thinner the solid electrolyte membrane, the lower its resistance. Cells with a thin solid electrolyte membrane have a higher efficiency than those with a thick membrane.
  Under actual conditions, storage modules with conventional sodium-sulfur batteries achieve an electrochemical conversion efficiency of 95% ($\eta = 0.95$ at a conversion, $\eta = 0.95^2 = 0.9$ in the overall process, synonymous with the so-called "DC efficiency" of 90% as documented on page 101 of the final report[46] on the test operation of a system with conventional Na-S batteries).
  To achieve the maximum overall efficiency of 90% provided by the GroNaS concept, an electrochemical efficiency of efficiency of 97% ($\eta = 0.97$ in a conversion process, efficiency of the electrochemical processes in a complete storage cycle: $\eta = 0.97^2 = 0.94$) is required. The increase to this value is achieved in the GroNaS energy converter by the higher operating temperature of 400 ° C (conventional battery cells: 330 ° C), a thinner solid electrolyte membrane and the increase of the specific membrane area.
  The waste heat of the electrochemical conversion processes is generated at the operating temperature of the energy converter, i.e., at a high temperature level.
- Energy losses through heat dissipation to the environment
  Sodium-sulfur energy converters must be operated at high temperature (> 270 ° C). Depending on the heat insulation used, a certain amount of energy in the form of heat is constantly released to the environment.
  Memory modules available on the market achieve an efficiency of 97% for the current conversion and 95% for the electrochemical processes. Without heat losses they would

[46] **http://www.xcelenergy.com/staticfiles/xe/Corporate/Renewable Energy Grants/Milestone 6 Final Report PUBLIC.pdf**

have an overall efficiency of 85% ($0.97^2 \cdot 0.95^2 = 0.85$). However, these modules are quite small. They thus have a low volume / surface ratio and lose so much heat that they must be heated in periods when the module is operating at low power. This results in a system efficiency of only 75 - 80%.
Due to its size (minimum size according to the GroNaS concept: approx. 20 MWi), a GroNaS storage system has a much more favorable volume / surface ratio. Even if only 2 to 3% of the power of the energy storage plant incurred as heat at 400 ° C, the amount of heat supplied to the storage plant is sufficient to keep the system permanently at its operating temperature. There is no additional energy needed for heating. The electro-technical-electrochemical possible overall efficiency of 90% can thus be achieved in practical continuous operation. The calculation results listed in 8.1 show that larger facilities produce a significant excess of heat. In order to keep the operating temperature constant, the facility then must even be cooled.

Calculation of heat balance: The values in Table 8.1 were calculated using the following assumptions: Both tanks and the energy converter complex are designed as separate units and surrounded by a shell of (cost-effective) aerated concrete with a thickness of 1 m. The length, width and height of the components of the storage components are significantly larger than the thickness of the thermal insulation, so that the formula below is sufficient to calculate the heat flow. A value of 98% is assumed as the efficiency for the electrochemical processes (A system operated at an electrochemical efficiency of 97% or lower would produce even more heat at a high temperature level).

Average output (MW)	specific storage capacity (d)	surface (m^2)	heat loss (MW)	Heat generation (MW)[47]
0,5 MW	6; 0,5	343[48]	0,01	0,01
	168; 14	208 + 272	0,017	0,01
5 MW	60; 0,5	104 + 430	0,018	0,1
	1680; 14	966 + 430	0,048	0,1
50 MW	600; 0,5	486 + 2000	0,085	1
	16800; 14	4484 + 2000	0,224	1
500 MW	6000; 0,5	2257 + 10800	0,449	10
	168000; 14	20815 + 10800	1,088	10

Table 8.1 Comparison of heat loss and heat generation in GroNaS storage facilities of different dimensions

Thermal conductivity of aerated concrete: = 0.08 $Wm^{-1}K^{-1}$
Thickness of the insulating layer: d = 1 m
ΔT: Temperature difference between the inside of the system and the environment: 430 K
Heat output: $P = \lambda \cdot A \cdot \Delta T / d$

47 in the electrochemical conversion process, temperature level: 400 C°
48 As a basis for the estimation, it was assumed here that tanks and energy converters are located together in a cube with an edge length of 7 m