Comprehensive summary of best practice site visit reports

Created by:

Matouš Kostomlatsky

Introduction

This report consolidates the findings from three best practice site visits focused on innovative energy solutions in Europe. These visits, conducted in **Békéscsaba and Csillebérc (Hungary), Rubensdorf (Austria), and Fuchstal/Apfeldorf (Germany)**, examined various technologies and strategies aimed at enhancing **renewable energy generation, storage, and grid integration**. The overarching goal of these projects is to create sustainable, efficient, and community-driven energy solutions that support decarbonization and energy security.

1. Best practice site visits Reports

Each site showcased different energy storage and smart grid approaches:

- **Békéscsaba:** A lithium-ion battery-based Smart Grid system integrated with a solar park.
- **Rubensdorf:** Hydrogen energy storage in underground gas reservoirs (Underground Sun Storage 2030 project).
- **Fuchstal/Apfeldorf:** A multi-source renewable energy project incorporating wind, solar, power-to-heat, and battery storage.
- **Csillebérc:** NAS Battery Energy Storage System.

Best practice site visit

Békéscsaba

2024.03.06

Created by:

Tímea Bartucz

Jenő Szécsi

Smart Grid in Electric Power Systems (lithium-ion battery storage system)

- **Location:** Solar PV Park in Békéscsaba (HU)
- **Date:** 2024.03.06
- **Installed Technology**: Smart Grid system (lithium-ion battery storage system), Solar Park
- **Operator:** Békéscsaba Energia Esco Ltd.
- **Participants:**

LP1- Békéscsaba City of County Rank:

- Gyula Kovács
- Adrián Szél
- Jenő Szécsi
- Mihály Rapajkó
- Gyöngyi Cseténé Bognár
- Sándor Nyeste

PP2- University of Pannonia:

- Dr. Attila Fodor
- Dr. Endre Domokos
- Dr. Viola Somogyi

PP4- EG - Elektro Gorenjska, electrical distribution company, JSCo.:

- Ambrož Bogataj

PP6- CEEO - Center for Energy, Energy Efficiency and Environment:

- Aldin Hodžić
- Emina Mravovic
- Jasmina Bešić

PP7- ICUK - Innovation Centre of the Usti Region:

- Marek Hart
- Zdeněk Hušek

PP8- ZMO - Oradea Metropolitan Area Intercommunity Development Association

- Florina Flore
- Letitia Motoc
- Adrian Crainic

PP9- AUF - Municipality of Fuchstal:

- Erwin Karg
- Gerhard Schmid
- Thomas Reukauf

PP11- UNIZAG FSB - University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture:

- Hrvoje Mikulčić
- Luka Herc

- Petar Lonić

PP12- UNS-FTN - University of Novi Sad Faculty of Technical Sciences:
- Dr. Bane Popadić
- Nikola Vukaljović

PP13- STP MNE - Science and Technology Park Montengro:
- Radivoje Drobnjak
- Milica Bozović
- Katarina Kovacevic

Introduction

Solar PV Park, Békéscsaba (HU): This event, hosted by Békéscsaba Energia Esco Ltd. (established in 2020 and indirectly owned by the local government of Békéscsaba), aims to support the implementation of complex energy projects within the Modern Cities Programme. Their focus includes operational tasks related to energy and smart infrastructures in Békéscsaba, as well as promoting, developing, and managing innovative projects such as energy-related developments, smart transformation, and greenport initiatives.

During the visit to the Békéscsaba Solar Park, Mr. Gyula Kovács, the Managing Director of Békéscsaba Energia Esco Ltd., presented the operation of the Smart Grid system and the Solar Park at the Visitor Center. The Smart Grid system in Békéscsaba is the first of its kind in Hungary, offering real-time monitoring of energy conditions.

Visitor Center, Békéscsaba (HU)

Smart Grid Components:

PV Solar Parks:

We visited three interconnected PV solar parks, with a combined output of 1.3 MWp, supported by over 3000 panels. The system is managed by two inverters, each with a capacity of 650 kW, allowing for future expansion.

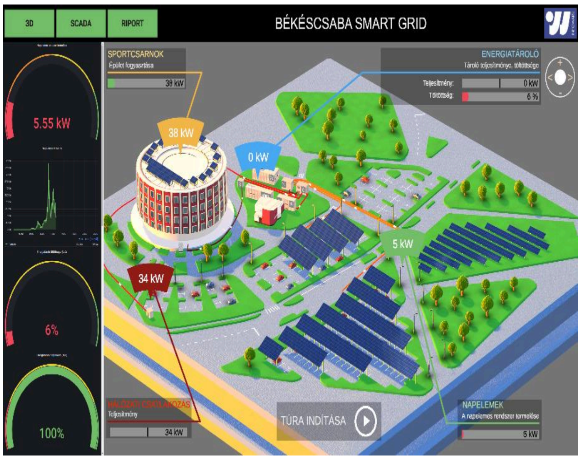
Energy Storage Unit:

The energy storage unit has a total output of 1.2 MW and a capacity of 2.4 MWh, utilizing Samsung lithium-ion batteries with over 7000 cells. It features a unique fire protection system for enhanced safety and optimizes usage by maintaining the State of Charge (SoC) between 15% and 85%.

Lithium-ion Battery Energy Storage System (BESS)

Visitor Center and Smart System Control:

The Visitor Center educates the public about the Smart Grid System through interactive touch screens, 3D animations, and real-time reports. The Smart System Control operates remotely, ensuring security through a redundant system that includes both landline and mobile connections. On-site requirements are minimal, limited to technical maintenance.



Visitor Center, Smart Grid System

System Overview:

The Békéscsaba Smart Grid system includes a solar power plant with a peak capacity of 1.3 MW, consisting of three solar parks, a 1.2 MW capacity battery storage system with 2.435 MWh, a smart center to control these elements, and connecting electrical/data transmission and data collection network components and equipment. It connects to the distributor's medium voltage network (11 kV) and holds licenses for small-scale power generation (50 kW – 50 MW output) and storage. Key electrical consumers currently include the Sports Hall, the Fencing Hall, and auxiliary operations necessary for the Grid system itself (including control systems, computers, fire and security systems, lighting, heating, and cooling) and a 150 kW bus charger. Surplus energy is stored and fed back to the electricity provider according to existing agreements. The storage system can meet consumption needs during night-time and low-light periods, minimizing the increasingly costly grid electricity purchases in the future.

[Lithium-ion Battery Energy Storage System (BESS)]

Operational Aspects Examined

During the on-site visit, we thoroughly examined the system's operational aspects, including transformers (11 kV / 0.36 kV / 0.36 kV, 2 x 800 kVA), converters (600 kW each), an ICU controller, and a Battery Management System (BMS). The energy storage units contain DC distribution cabinets and multiple battery banks, each with a BMS for precise management. Equipped with certified safety mechanisms, fire protection compartments, and advanced climate and ventilation systems managed by the ICU controller, the system uses INFOWARE and INTILION technologies, and AI-based forecasting and optimization algorithms to ensure efficient operation. With a capacity of 1.2 MW / 2.4 MWh, the system optimizes energy production and consumption, reduces dependency on the public grid, provides backup power during grid failures, and supports off-grid mode and synchronous reconnection under load. Operating costs are low due to the efficiency and long lifespan of the lithium-ion batteries, and maintenance mainly involves regular inspections of the battery units and control systems.

Disadvantages:

- The operation of lithium-ion energy storage systems presents several challenges. Chief among these is the occurrence of energy losses during storage and retrieval, which typically range between 5% and 15%, depending on factors such as ambient temperature, system efficiency, and cycle depth. These losses can add up significantly over time, reducing the overall system efficiency and increasing operational costs. Another notable issue is the difficulty in accurately determining the energy charge level, or State of Charge (SoC), which limits precise energy management and forecasting capabilities.
- A recurring issue faced by the operator is the regularity of malfunctions within the system. These malfunctions typically require maintenance and occur approximately 6–8 times annually, leading to temporary suspensions of solar PV operations. Such interruptions can last several hours to days, depending on the nature of the fault, creating inefficiencies and lost production time. Although the system is equipped with advanced control and diagnostic tools, the frequency of these events underscores the need for robust maintenance schedules and contingency measures.
- Another significant challenge is the reliability of the indicated SoC provided by the Battery Management System (BMS). Operators have observed discrepancies between the actual SoC and the system's estimated values. This is primarily due to the BMS relying on computational algorithms to estimate the SoC rather than direct measurements. Such deviations can lead to unexpected drops in the battery's functional capacity, affecting the system's ability to meet energy demands or maintain grid stability during critical periods. Addressing these issues would require advancements in BMS technology to ensure more accurate and reliable SoC estimations.
- Additionally, the system's operational capacity is constrained by measures taken to preserve the battery's health and longevity. To mitigate degradation, the battery is charged and discharged only between 85% and 15% of its nominal capacity. While this approach significantly extends the battery's lifespan and reduces the risk of performance drops, it also means that only 70% of the battery's capacity is available for use. This limitation, while necessary, reduces the system's overall efficiency and may necessitate larger or additional storage units to meet energy demands effectively.

Operational Experiences:

- Park1 solar park produces a maximum output of 650 kW in ideal sunny conditions.
- Park2 and Park3 can produce a maximum output of 650 kW in similar conditions.

- The energy storage unit can produce a maximum output of 1.2 MW at full charge, and the combined output of the solar park and storage unit reaches 2.5 MW.
- As describe above, to maximize battery lifespan, the system regulates the state of charge, avoiding levels below 10% and above 90%. Additionally, the charge rate is reduced above 85%, and the discharge rate is limited below 15%. The storage unit consists of two sub-units to balance the state of charge and utilization, further extending battery life.
- Remote Access and Monitoring: Remote access for system diagnostics is established through a VPN connection. The Smart Grid monitoring interface is accessible via a web interface, displayed on a touchscreen TV at the local smart center. The interface consists of:
    - A graphical overview with a 3D site illustration and simplified circuit paths, showing real-time solar park production, storage status, and current consumption and output.
    - The SCADA interface, which details the technical operation of the facility's components, including events, fault indications, circuit paths, voltage/current/power values, and other numerical data. This interface does not allow intervention but serves as a central software control tool for the technical operator.
    - The "Historian" interface, which provides graphical visualization and retrieval of previously measured and recorded quantities.

Energy Storage Unit's Role in Schedule Adherence:

- If solar panel production exceeds expectations, excess energy is stored in the unit up to a 85% charge, preventing surplus power from being fed into the grid and maintaining the schedule.
- If solar panel production is lower than expected, the storage unit meets the shortfall, maintaining the schedule up to a minimum 15% charge. At dusk, when no further solar charging is expected, the converters switch to a low-power mode, minimizing standby power consumption and drastically slowing the self-discharge rate during evening or low-sunlight hours.

In case of overproduction, if the battery's capacity does not allow further storage, the solar park inverters can regulate down to prevent excess energy from being fed into the grid.

Consumer Experiences:

As the heating season ended, consumption decreased, then gradually increased again with the onset of summer cooling needs. Grid power consumption steadily decreased to a minimal level, due to faster daytime charging of the battery storage and increasingly accurate consumption/production forecasts from learning optimization algorithms in the plant's control technology. The amount of power that can be drawn from the grid is a critical parameter, as it determines the performance fee paid to the distribution licensee. The medium voltage network and connection point from the substation have a maximum capacity of 2.548 kW, designed to handle the maximum output of the solar panels and storage unit.

Conclusion

The best practice visit to the Solar PV Park in Békéscsaba underscored the potential of energy storage systems in enhancing the efficiency and reliability of renewable energy projects. Lithium-ion storage systems, with their high energy density, operational flexibility, and advanced optimisation capabilities, have proven to be effective in supporting clean energy goals. Their ability to reduce grid dependency, provide backup power during outages, and balance energy production and consumption offers significant advantages for modern energy infrastructures.

However, the challenges associated with lithium-ion technology, such as limited operational capacity due to conservation measures, environmental concerns related to mining and disposal, and frequent maintenance interruptions, highlight the need for alternative solutions. Additionally, the reliance on finite resources like lithium and cobalt makes the long-term sustainability of this technology questionable. While lithium-ion systems have laid the groundwork for large-scale energy storage, their limitations emphasise the urgency of developing more environmentally friendly and resource-efficient alternatives.

To ensure the sustainability and scalability of renewable energy systems, the exploration and adoption of alternative storage technologies—such as solid-state batteries, flow batteries, or hydrogen-based systems—are crucial. These emerging solutions offer the promise of greater environmental compatibility, reduced resource dependence, and improved system longevity, paving the way for a more sustainable energy future.

Best practice site visit

Underground Sun Storage 2030 (Rubensdorf)

2024.11.12

Created by:

Marek Hart

Activiti 1.4: Best practise site visit: Underground Sun Storage 2030 (Rubensdorf)

Introduction

On December 11, 2024, we visited the hydrogen storage facility in Rubensdorf, part of the *Underground Sun Storage 2030* project (USS 2030). The purpose of this visit was to learn about the technologies and benefits of this innovative solution for seasonal renewable energy storage.

Visit Overview

10:00 – Meeting with Project Partners

We gathered at the site with project partners who provided a detailed introduction to the facility's operation, its technical parameters, and environmental benefits.

Description of the Hydrogen Storage Facility

The visited facility is one of the first of its kind, combining green hydrogen production via electrolysis with underground storage in former natural gas reservoirs. Hydrogen is produced using renewable energy, primarily from solar sources, and stored in underground porous rock formations. This facility allows for efficient seasonal energy storage—excess energy from the summer months is stored and utilized during the winter period.

The project is also innovative because it tests the use of the original natural gas pipelines for hydrogen distribution. From Rubensdorf, a pipeline transports hydrogen to Gampeng, where it is blended with natural gas in the local gas grid. Currently, the hydrogen admixture is 10%. In the future, the aim is to use pure hydrogen to supply a steelworks located approximately 50 km away, significantly reducing the carbon footprint of local industry.

This strategy leverages existing gas infrastructure, presenting an economically efficient and environmentally friendly approach to integrating hydrogen into the energy system. The tour also highlighted how the facility connects to the regional energy infrastructure and detailed the safety measures in place for handling hydrogen.

Future challenges and solutions:

- **Construction of a Research Facility**:
  By 2025, a specialized research facility will be built in Gampern, Upper Austria, at a small former natural gas storage site. This facility will enable interdisciplinary technical and scientific studies under real-world conditions.
- **Development of Hydrogen Processing Technologies**:
  The project focuses on developing suitable technologies for hydrogen processing to ensure its efficient use across various sectors.
- **Modeling Future Energy Scenarios**:
  The aim is to create models of future energy scenarios that incorporate hydrogen into the energy system and assess its impact on decarbonization.
- **Techno-Economic Analyses**:
  The project will conduct techno-economic analyses to evaluate the economic viability and scalability potential of hydrogen storage technologies.

These activities are supported within the "Vorzeigeregion Energie" initiative of the Climate and Energy Fund, financed by the Ministry for Climate Protection (BMK). The project was successfully submitted under the "WIVA P&G" framework and is now in progress.

Climate Minister Leonore Gewessler highlighted the importance of innovative renewable energy storage solutions on the path to achieving climate neutrality by 2040. Theresia Vogel, Managing Director of the Climate and Energy Fund, emphasized the dynamic development of hydrogen research and the significance of partnerships with RAG Austria AG in advancing green hydrogen applications.

The project builds on previous initiatives, *Underground Sun Storage* and *Underground Sun Conversion*, which demonstrated the feasibility of safely storing hydrogen in underground natural gas reservoirs with a blend of up to 20%. Laboratory tests suggest this proportion could be increased to 100%. Under USS 2030, the potential for storing pure hydrogen, produced from renewable sources, in former natural gas reservoirs will be explored through a field experiment led by RAG Austria AG.

11:30 – Departure

The visit concluded with a summary of key points, and we departed the site at 11:30 AM.

Conclusion

The visit to the hydrogen storage facility in Rubensdorf provided valuable insights into renewable energy storage technologies, their environmental and economic benefits, and the potential of this technology in the future. The *Underground Sun Storage 2030* project not only showcases an innovative approach to energy transition but also demonstrates how existing infrastructure can be effectively repurposed for new sustainable applications. This project has significant potential to contribute to industrial decarbonization and increase the share of renewable energy in the energy mix.

Best practice site visit

Fuchstal/Apfeldorf

2024.15/16.09

<u>Created by:</u>

Thomas Reukauf

Smart Grid in Electric Power Systems (renewable generation, sector coupling,lithium-ion battery storage system,)

- **Location:** Energiezukunft Fuchstal, in Fuchstal (GE)
- **Date:** 2024.03.06
- **Installed Technology**: renewable energy system, smart Grid system windmills, Solar PV Park , powerto heat generation and battery storage system (lithium-ion battery storage system)
- **Operator:** Fuchstal municipality
- **Participants:**

LP1- Békéscsaba City of County Rank:
- Gyula Kovács
- Jenő Szécsi

PP2- University of Pannonia:
- Dr. Attila Fodor
- Dr. Tamás Miseta
- Dr. Béla Varga

PP3- BSC, Business support Centre L.t.d., Kranj
- Blanka Odlazek

PP4- EG - Elektro Gorenjska, electrical distribution company, JSCo.:
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- Szilagyi Zoltan
- Duna Csongor
- Batori Geza
- Biro Ferenc Sandor
- Baba Petru Teodor

- Gligor Ioan
- Ludovic Somogyi
- Marcus Ioan   Pasca Ioan
- Craciun Adrian Petru
- Togor Dumitru

PP9- AUF - Municipality of Fuchstal:

- Erwin Karg
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PP11- UNIZAG FSB - University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture:

- Luka Herc
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- Dr. Bane Popadić
- Nikola Vukaljović

PP13- STP MNE - Science and Technology Park Montengro:

- Radivoje Drobnjak
- Milica Bozović

I Energiezukunft Fuchstal EZF 15.10.2024

Energiezukunft Fuchstal, Fuchstal (GE): This event, hosted by the municipality of Fuchstal. (established from 2017 and directly owned by the local government of Fuchstal and the citizens), aims to point out the realization of the local energy transition and the partzipationn of citizens. The focus includes building and operating energy and smart infrastructures in Fuchstal supported by local service providors, as well as promoting, developing, and managing innovative projects such as data driven energy management/energy storage/heat supply.

During the visit to Energiezukunft Fuchstal , Mr. Erwin Karg, the Mayor of Fuchstal and Thomas Reukauf the project manager presented the operation of Energiezukunft Fuchstal at the Visitor Center. Energiezukunft Fuchstal is one of the biggest power to heat system operated by a local community in Bavaria.The virtual power plant managing the access the renewable energy system to the wholesale energy market for a local community is one of the first of its kind in Germany.

Visitor Center, Fuchstal (GE)

Smart Grid Components:

- **Wind turbines, bird monitoring:** We visited 2 windparks with an installed capacity of 29 MWp, supported by 7 wind turbines (4 in 2016, hub height 149 m, and 3 more in 2024 hub height 166 m)). The total energy generation (4 wind turbines) in 2023 was 24 Mio. kWh , from 31.12.2024 (3 more wind turbines connected to the grid) the generation will increase to 54 Mio. kWh due to the installation of three more wind turbines with a capacity of6 The actual electrical energy demand of Fuchstal is 24 Mio kWh, meaning that the wind turbines generate 2 times the consumption of Fuchstal (4500 inhabitants). We also visited the first Bavarian camera-based detection system that slows down the wind turbines when birds approach, which is installed near the three new wind turbines in the Fuchstal community forest. These two observation towers with a technology platform, each 42 meters high, is equipped with several cameras and uses the latest technology from radar and video systems. The project has been supported by the Bavarian State Office for the Environment and the Weihenstephan-Triesdorf University of Applied Sciences.

wind turbines Fuchstal (GE)

- **<u>Solar power plant:</u>** We visited one solar park of Fuchstal with a total output of 750 kWp and an anual generation of 1,3 Mio. kWh.

  This photovoltaic project is one of three photovoltaic projects in Fuchstal with a total installed capacity of 3 MWp. It has been initiated and implemented by the municipality. The municipal photovoltaic system is owned by the municipality of Fuchstal. This means that all income benefits the community of Fuchstal and all its citizens.The system is ecologically improving an area that was used intensively for agriculture before.


solar park Fuchstal (GE), bird monitoring system for new wind park 2024 ,Fuchstal (GE)

- **<u>Energy Storage Unit:</u>** The energy storage unit has a total output of 5,8 MW and a capacity of 3200 kWh, utilizing Samsung P3 78 Ah lithium-ion batteries with over 11.000 cells. (6,35 kWh/22 Cells). State of Charge (SoC) between 25% and 80% can be realized, it consists of 1 battery container with 45 ft and 2 inverters of 40 ft.

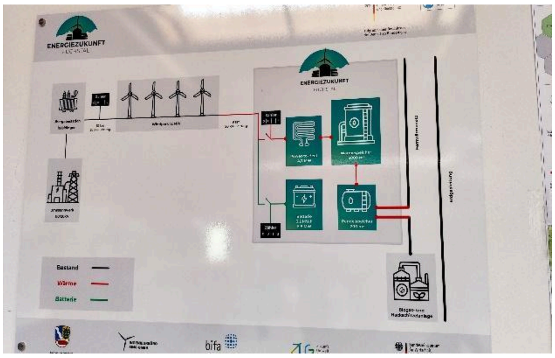
Lithium-ion Battery Energy Storage System (smart power GE))

- **Power to heat supply:** The main component of the power to heat supply is a heat storage with a volume of 5000 m ^{3}and a pendulum storage of 200 m^3. The diameter of the heat storage is 21 m and it height is 16 m , fitting the capacity of 25.000 bathtubs. The heat storage has been built in order to avoid the cuirtailment of electricity generation from the wind and the solar park by generating heat for the local heat supply with its 210 connection points , 13 km of length and 6000 MWh consumption. Heat supply is supported by a 800 kW

  bioggas plant and a 1000 kW wood chips plant. There are now also 2 gymnasiums, a 7-group daycare center, the Raiffeisenbank, the sports center and 200 properties in Asch and Leeder. The heating network is built and operated by the municipality of Fuchstal. Fuchstal community buildings receive the heat from the biogas plant through a heat supply contract. The biogas/mass power plants contribution to Fuchstal renewable generation portfolio is 8 Mio. kWh/a.

heat supply Fuchstal (GE)

System Overview: The Energiezukuft Fuchstal includes a solar power plant with a peak capacity of 2 MW, 7 wind turbines with a total capacity of 29 MW , a 5,8 MW capacity battery storage system with 3.200 MWh, a biogas plant with 900 kW , a woodship plant with 1000 kW, a heat storage of 5000 m³ and a smart center to control these elements, and connecting electrical/heat /data transmission and data collection network components and equipment. It connects to the distributor's medium voltage network (20 kV) and a local heat supply with a length of 12 km. The renewable generation is sold to the wholesale market , Surplus energy is stored and marketed by a virtual power plant. The virtual power plant is optimizing the energy sales to the German wholesalemarket and the supply of Fuchstal.



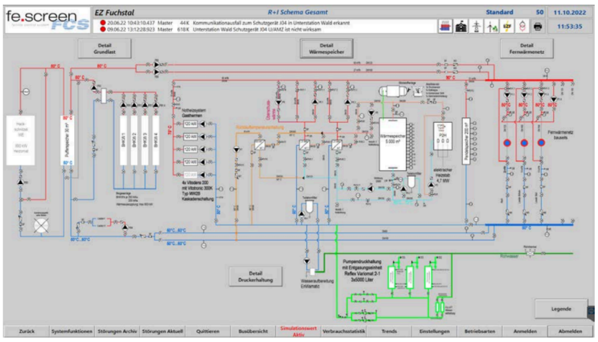
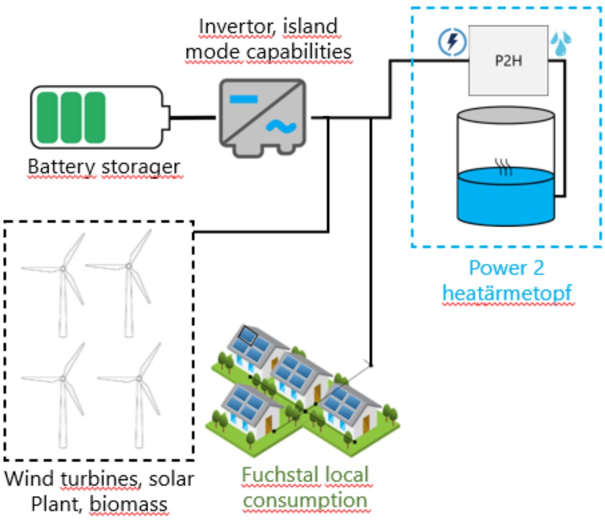


Abb. 4 Startbild, R+I Schema gesamt

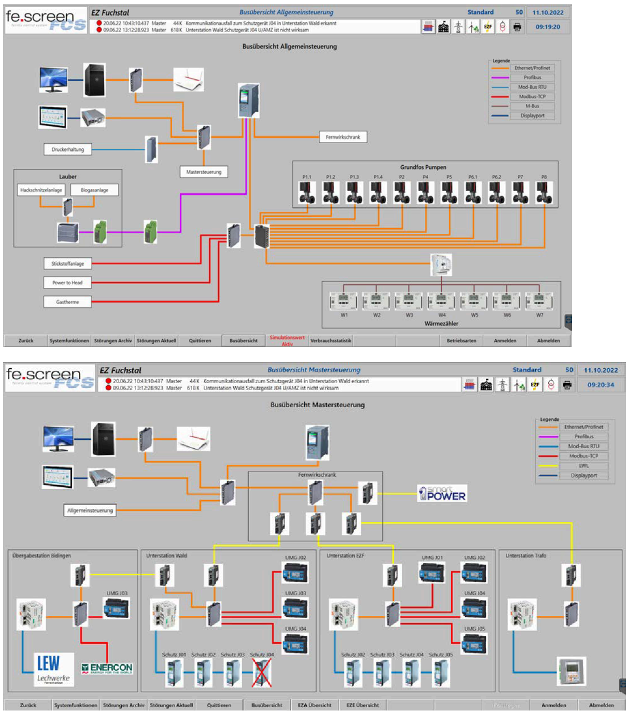


Energiezukunft Fuchstal EZF.y Fuchstal (GE)

Operational Aspects Examined: During the on-site visit, we thoroughly examined the system's operational aspects, including the Steering of the energy and heat supply systems suppported by a Virtual power plant.

A SIMATIC S7-1500 with digital and analog input and output modules is used to control the district heating distribution. A 19" touch panel with a box PC is installed in the on-site control cabinet and there is also a master computer in the energy center office. The system components can be operated, monitored and adjusted on the operating devices. Communication between the individual components takes place via various digital bus systems, with some being actively controlled (pumps and valves) and others only being monitored or read out (autonomous components such as pressure maintenance, heat meters, etc.).

A SIMATIC S7-1500 with digital and analog input and output modules is also used to control and monitor the power generation system, which is also located on site in the control cabinet. This master control is connected via fiber optic cable (LWL) to the substations in Bidingen, in the forest, in the EZF and the transformer station in which the WAGO PFC200 controls are used. It is also operated via the touch panel in the control cabinet or the master computer in the headquarters office. The master control is in the same network as the general control, which means that certain control commands can be exchanged between the two parts of the system.



EZF, screenshots from SCADA,Fuchstal (GE)

Operational Experiences power to heat , sector coupling:

- If the energy generation from the wind park and the solar park exceeds expectations or if the market prices are negative, excess energy

  - is stored in the battery unit up to a 90% charge, preventing surplus power from being fed into the grid and maintaining the schedule.
  - Is used in order to generate heat in a heat storage which feeds the local heat supply, supplying heat to 200 supply points.
- If the energy production from the solar panels and the wind turbines are lower than expected, the storage unit meets the shortfall, maintaining the schedule up to a minimum 10% charge.

Consumer Experiences:

Energiezukunft Fuchstal points out that small communities can play a significant role in the realization of the energy transition using storage to create aditional value for energy and heat supply.

Around €4.5 million in added value remains with the citizens of the community of Fuchstal from realizing the projects described. Furthermore, the added value of agriculture remains. Properties that supply the biogas plant as well as the delivery of wood chips from the community forest as added value on site. The value added from EEG systems and marketing of power remains with the local citizens and remains in the village.

II Energiewende Apfeldorf 16.10.2024

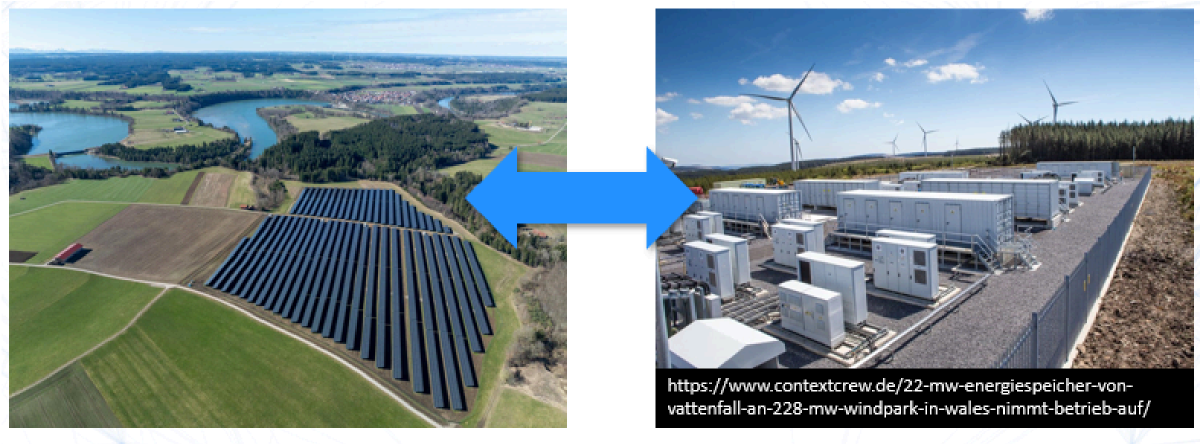
Energiewende Apfeldorf, Apfeldorf (GE): This event, hosted by the municipality of Apfeldorf. (established from 2020 and directly owned by the local government of Fuchstal and the citizens), aims to point out the realization of the local energy transition and the partzipationn of citizens. The focus includes building and operating a solar park and a smart local heat supply using a combination of enpower and heat storage.

During the visit to Energiewende Apfeldorf , Mr. Gerhard Schmid, the Mayor of Apfeldorf presented the operation of Energiewende Apfeldorf and the village developping project Village center with Future at the Visitor Center.

Visitor Center, Apfeldorf (GE)

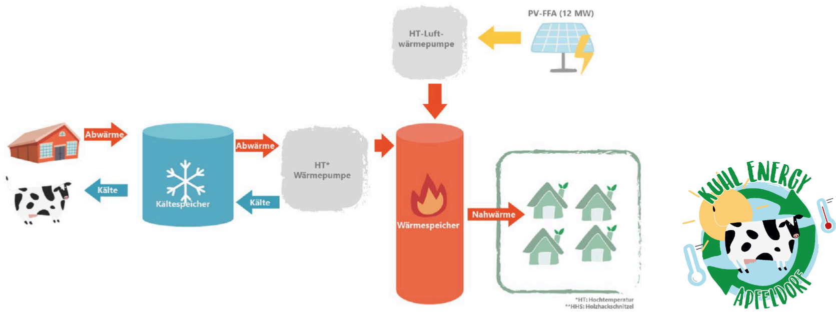
Smart Grid Components:

- **Solar power plant:** We visited the solar power plant with an installed capacity of 14 MWp, supported by 25.926 solar modules from Canadian Solar and a Huawei Sun2000-330 KTL -H1 invertor. The actual total energy generation is 15.500 kWh/a. The total investment of aprox. 15.5 Mio is 22% equity financed with funding from the community, the land owners and the local citizens which founded together the company Sonnenenergie Apfeldorf GmbH Co. KG. The actual power demand of Apfeldorf is 5 Mio kWh, meaning that the solar park genrates 3 times the consumption of Apfeldorf (1500 inhabitants).
- **Large volume Energy storage :** The mayor of Apfeldorf reported its ongoing plans to invest into a storage capacity of 11 MWp and a capacity of 222 MWh connected to the grid of the regional utility. The target is to integrate the storage facility into the existing virtual power plant.



Apfeldorf solar powar plant-storage project, Apfeldorf (GE

- **Kuhl energy Apfeldorf:** The mayor of Apfeldorf presented the ongoing project of the development of a village heat supply from a mix of renewable energy sources with innovative use of an existing milk cooling system. he previously conventionally operated milk cooling system is to be converted to heat pump operation. To provide this heat pump with the best possible emission-free supply, electricity from locally generated solar energy is used. The waste heat from milk cooling is to be used to supply the base load of a heating network.
  The planned heating network will be supplied via a newly built heating center (HZ), which is to be located between the planned PV-FFA and the settlement. Project started in 2024 and it will receive a funding from German national climate protection initiative of 80%.



- **Outlook Store More:** a potential pilot project within store more has been proposed to the project coordinator. The main target is to pilot a new storage technology to be rolled out in rural areas of Danube region

In addition to building-up a renewable energy-based heat supply of the small village of Apfeldorf an innovative storage solution is envisioned to replace state of the art heat storage and battery. This innovative storage is comprised of a **Vanadium-Redox-Flow Battery (VFB) with a small auxiliary lithium-ion battery and a heat recovery system that enables higher efficiency and furthermore, due to an altered electrolyte, enables heat storage within the same battery** that already saves the electricity.

The following scheme shows the part of the energy system that would be connected to the hybrid heat and power storage.

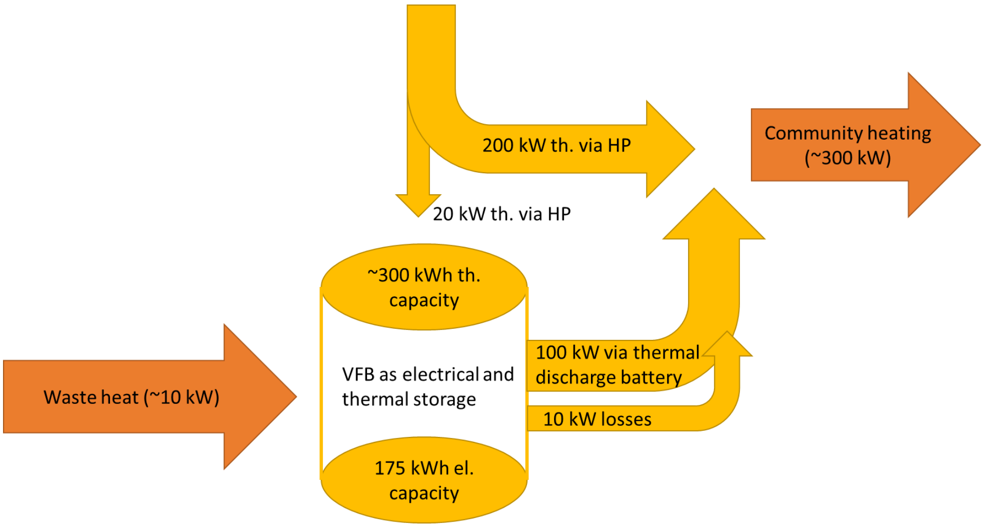


Figure 1 - Thermal power flows along the hybrid heat storage

As in real life the application would be highly dynamic between (partly) charging and discharging the battery thermally and (partly) directly powering the heat supply via the large heat pump, it is very hard to visualise within one simple scheme. Here the focus was laid on the probable thermal power capability. As to date no load thermal profile of the village and other requirements for a good sizing are unknown the following list of components represent a very rough estimation of the necessary size in order to compose a well fitted energy system. The necessary components of the hybrid storage system and their estimated size and costs are:

- 175 kWh / 30 kW (@ 600€/1 kWh[1]) 105.000 €
- 50 kWh / 30 kW (@ 300€/1 kWh[2]) 15.000 €
- Thermal Coupling Module + licence 30.000 €
- Sizing, Simulation, development EMS (4 PM @ 10.000€) 40.000 €

1

2

The estiimated total costs for a hybrid energy storage system in the village of Apfeldorf amounts to 190.000 €. The idea is to spend part of Fuchstal/Apfeldorf project budget in order to realize the pilot installation together with a German research center.

Best practice site visit
Csillebérc
2024.12.09

Created by:

Jenő Szécsi

NAS Battery Energy Storage System – Csillebérc (HU)

- **Location:** HU-REN Centre for Energy Research, Csillebérc (HU) - Hungary's first Na-S type battery
- **Date:** 2024.12.09.
- **Installed Technology**: NAS battery energy storage system
- **Operator:** HU-REN Centre for Energy Research
- **Participants:**

  DC Therm Üzleti Szolgáltató Kft.
  - Attila Solcz

  STATUS KPRIA
  - Gábor Nagy

  LP1- Békéscsaba City of County Rank:
  - Gyula Kovács
  - Adrián Szél
  - Jenő Szécsi

1. Introduction

1.1. Background and Project Context

The StoreMore project is an initiative funded by the Interreg Danube program, aiming to advance the development and deployment of innovative energy storage solutions in the Danube region. The project focuses on addressing the increasing demand for renewable energy integration and grid stability by exploring and promoting the use of various energy storage technologies, including battery systems.

This report documents a site visit to a location utilizing Sodium-Sulfur (NAS) battery technology. The purpose of the visit was to gain first-hand insights into the operational characteristics, performance, and potential applications of NAS batteries, specifically within the context of the StoreMore project.

Disclaimer:

It is important to note that this particular installation was selected due to its status as the first and longest-operating NAS battery system in Hungary. As such, it provides a valuable opportunity to gain insights into the long-term performance and operational characteristics of this technology in the Hungarian context.

1.2. About NGK Insulators, Ltd.

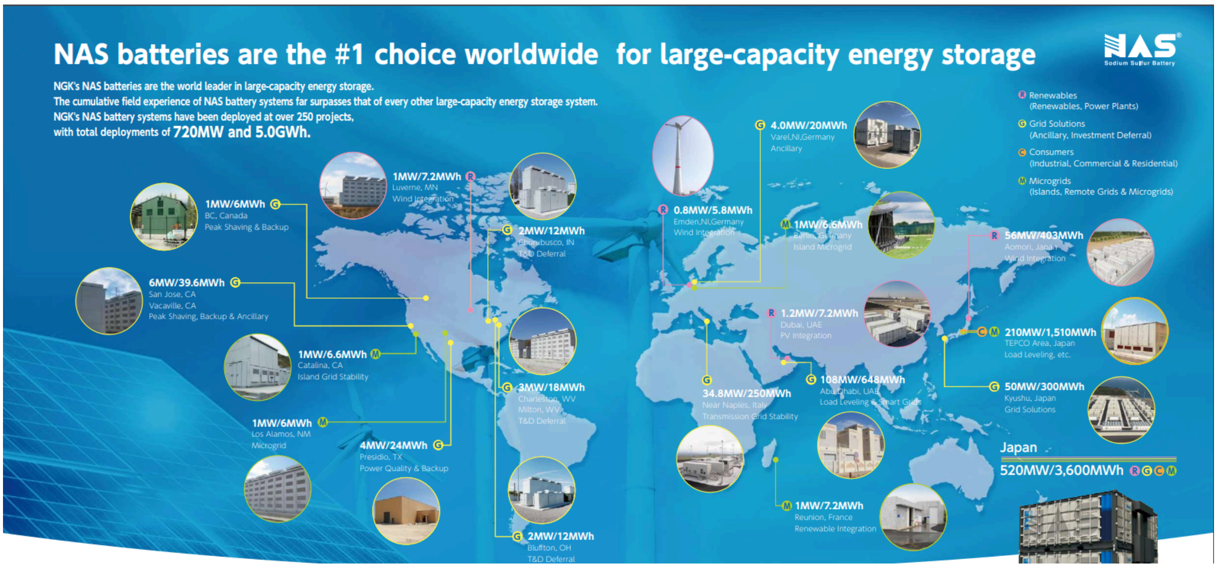
NGK Insulators, Ltd., headquartered in Nagoya, Japan, is a global leader in the manufacturing of advanced ceramics and insulators for various industries, including power transmission and distribution, electronics, and environmental protection. Founded in 1919, NGK has a long and rich history of innovation and technological excellence.

The company's core expertise lies in the development and production of high-performance ceramics, including alumina, silicon carbide, and zirconia. These materials exhibit exceptional properties such as high strength, excellent thermal conductivity, and superior resistance to corrosion and wear.

In recent years, NGK has diversified its business portfolio to include energy storage solutions, leveraging its expertise in materials science and engineering. The company has emerged as a prominent player in the global NAS battery market, with a strong focus on research and development, manufacturing, and system integration.

NGK's NAS batteries have been successfully deployed in various applications worldwide, demonstrating their reliability, durability, and suitability for large-scale energy storage projects. The company has established a strong reputation for providing innovative and high-quality energy storage solutions that meet the evolving needs of the global energy market.

NGK's NAS batteries over the World



Source: NGK Insulators Ltd leaflet

1.3. Sodium-Sulfur (NAS) Battery Technology: An Overview

Sodium-Sulfur (NAS) batteries are a type of high-temperature molten salt battery that employs sodium metal as the anode, sulfur as the cathode, and a solid ceramic electrolyte to separate the two. This unique combination of materials results in several distinct characteristics that differentiate NAS batteries from other energy storage technologies.

Operating Principle:

NAS batteries operate at high temperatures (around 300°C), which allows for the use of molten sodium and sulfur as active materials. During charging, sodium ions migrate from the anode to the cathode through the solid electrolyte, combining with sulfur to form sodium polysulfides. During discharge, the process is reversed, with sodium ions moving back to the anode, generating electrical energy.

The solid electrolyte, typically made of beta-alumina, is a key component of the NAS battery. It allows for the passage of sodium ions while preventing direct contact between the sodium and sulfur, which would cause a short circuit and damage the battery.

Key Characteristics:

NAS batteries exhibit several unique characteristics that differentiate them from other battery technologies:

- **High Energy Density:** NAS batteries offer a high energy density, allowing for compact and efficient storage of large amounts of energy.
- **Long Cycle Life:** With proper operation and maintenance, NAS batteries can achieve a long cycle life, typically exceeding 15 years or 4,500 cycles.
- **Fast Response:** NAS batteries can respond quickly to changes in grid demand, making them suitable for applications requiring fast frequency regulation and voltage support.
- **High Efficiency:** NAS batteries exhibit high round-trip efficiency, meaning a significant portion of the stored energy can be recovered during discharge.
- **Long Duration Storage:** NAS batteries are well-suited for long-duration energy storage applications, enabling the storage of energy over extended periods.
- **Environmental Benefits:** NAS batteries are environmentally friendly, with no harmful emissions during operation.

Construction and Design:

NAS batteries typically consist of several key components:

- **Battery Cells:** Individual battery cells contain the sodium anode, sulfur cathode, and solid electrolyte.

- **Battery Modules:** Multiple battery cells are connected in series and parallel to form battery modules, increasing the overall capacity and voltage of the system.
- **Battery Container:** Battery modules are typically housed in insulated containers to maintain the operating temperature and ensure safety.
- **Power Conversion System (PCS):** The PCS converts the DC output of the battery system to AC power for grid connection and controls the charging and discharging processes.
- **Thermal Management System:** A thermal management system is essential to maintain the optimal operating temperature of the battery cells.

Applications:

NAS batteries have a wide range of applications in the energy sector, including:

- **Grid Stabilization:** Balancing supply and demand, providing frequency regulation, and maintaining grid stability.
- **Renewable Energy Integration:** Storing excess energy from renewable sources such as wind and solar power to ensure a consistent and reliable power supply.
- **Peak Shaving:** Reducing peak demand by discharging energy during peak hours and charging during off-peak hours.
- **Microgrid Applications:** Providing reliable power supply and grid support for isolated communities and microgrids.
- **Backup Power:** Serving as a backup power source for critical loads during grid outages.

Advantages of NAS Batteries:

- High energy density and long cycle life
- Fast response and high efficiency
- Suitable for long-duration energy storage
- Environmentally friendly with no emissions
- Modular design allows for flexible system scaling

Challenges and Considerations:

- **High Operating Temperature:** Maintaining the high operating temperature requires careful thermal management.
- **Safety Considerations:** Handling molten sodium requires careful safety precautions.
- **Capital Cost:** The initial capital cost of NAS battery systems can be significant.

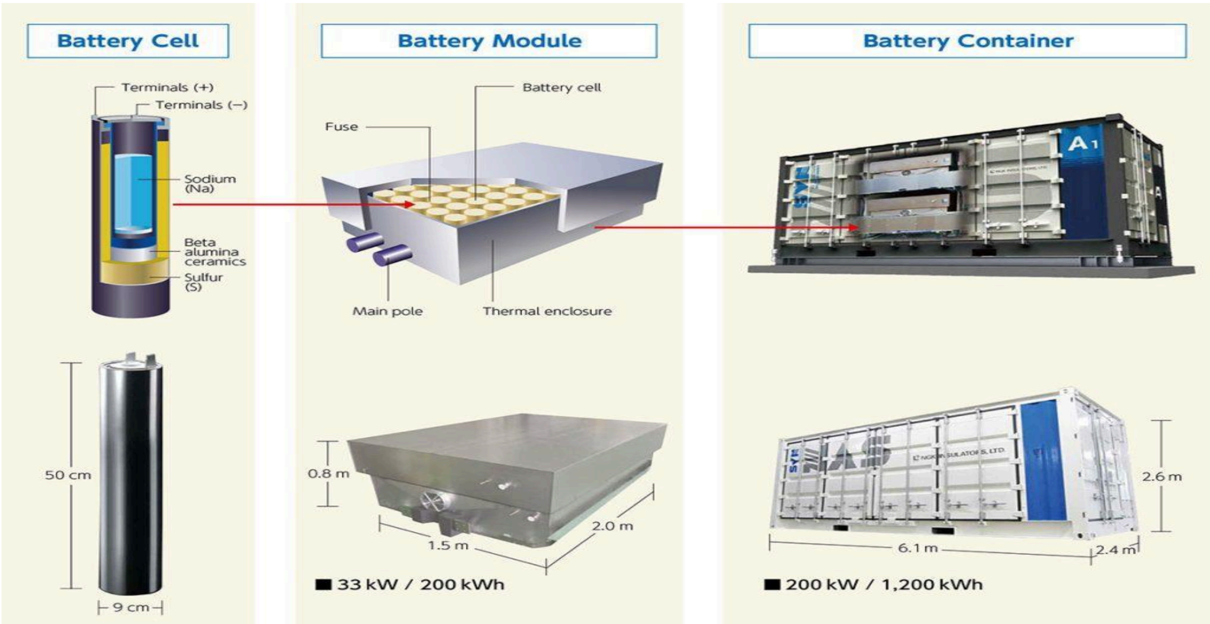
Despite these challenges, NAS batteries offer a promising solution for addressing the growing demand for energy storage and grid modernization. Continued research and development efforts are focused on improving the cost-effectiveness, safety, and overall performance of NAS battery technology.

2. Observations and findings

2.1 System Setup

The site at Csillebérc HUN-REN Research Facility has a standard 20 feet container battery module with DC250kW power and DC1,450kWh (BOL) capacity.

Standard NAS Battery System of NGK

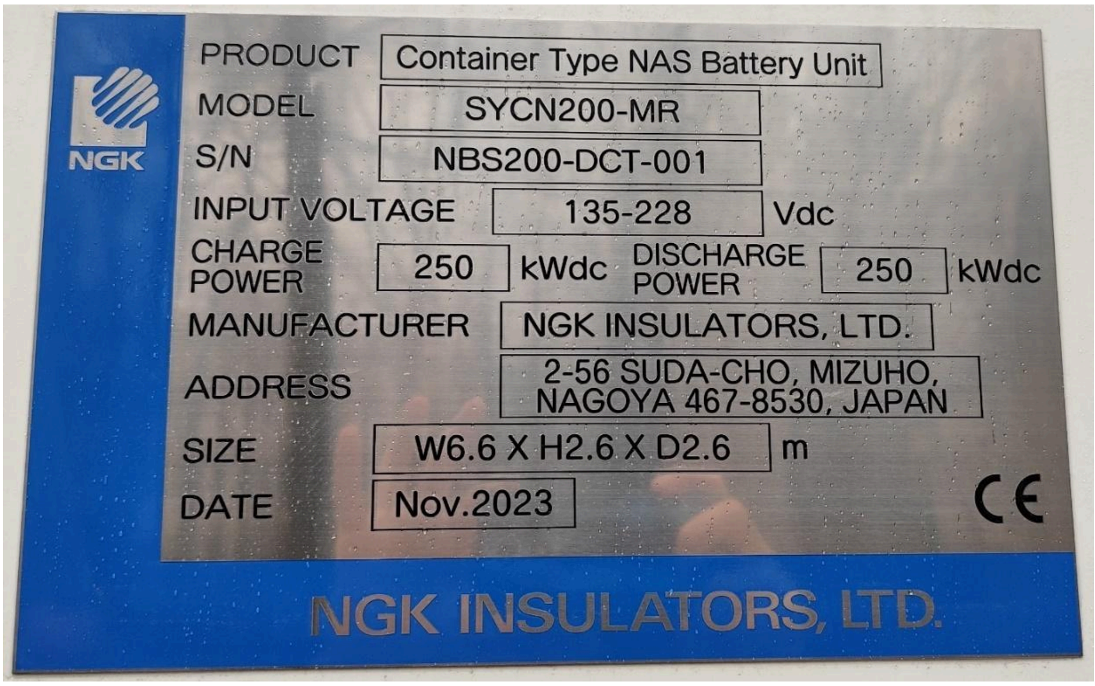


Source: https://www.ngk-insulators.com/en/product/nas-configurations.html

Battery and BMS containers

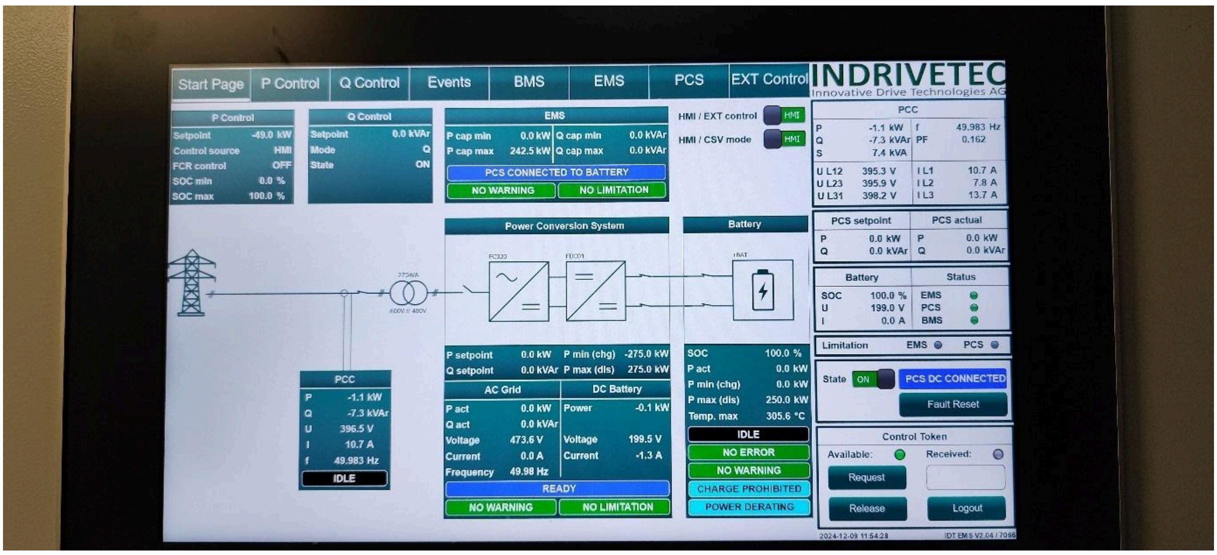
Container setup: battery container to the left, converter and BMS on the right

System parameters



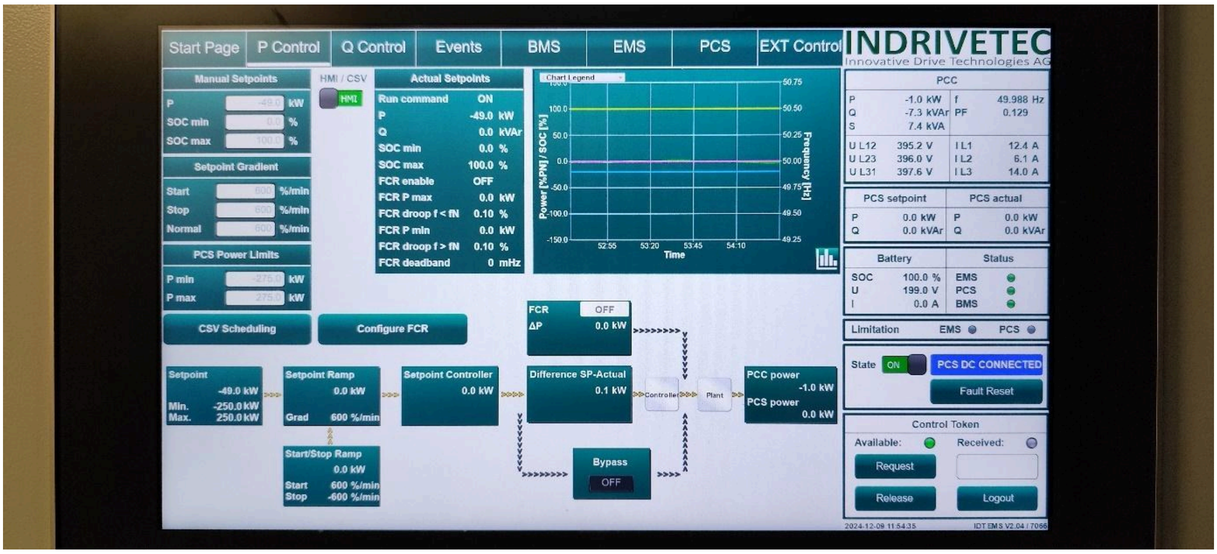
BMS system screens

BMS Start page



Operational interface of a Battery Management System (BMS) connected to a NAS battery. Key metrics visible include the state of charge (SoC) at 100%, indicating the battery is fully charged. The battery voltage is measured at 199.5V, and the system is in an "IDLE" state, with no active power output or input (P act = 0.0 kW). The Power Conversion System (PCS) is connected and ready, with no errors or warnings flagged. The system highlights essential statuses for the Energy Management System (EMS), PCS, and BMS, all showing as operational (green indicators). The interface also includes controls for setpoints, system limitations, and fault resets, displaying a robust real-time monitoring and management setup for grid-connected operations.

Power Conversion System



Detailed overview of the Power Conversion System (PCS) control and configuration for the NAS battery. Key parameters include the setpoint for power (P) at -49.0 kW, with manual limits for the PCS power defined as -275.0 kW to 275.0 kW. The battery state of charge (SoC) remains at 100%, and the system is operating within its nominal voltage range (199.0V). A graphical plot indicates grid frequency stability over time, centred around 50 Hz, as the system is monitoring grid interactions.

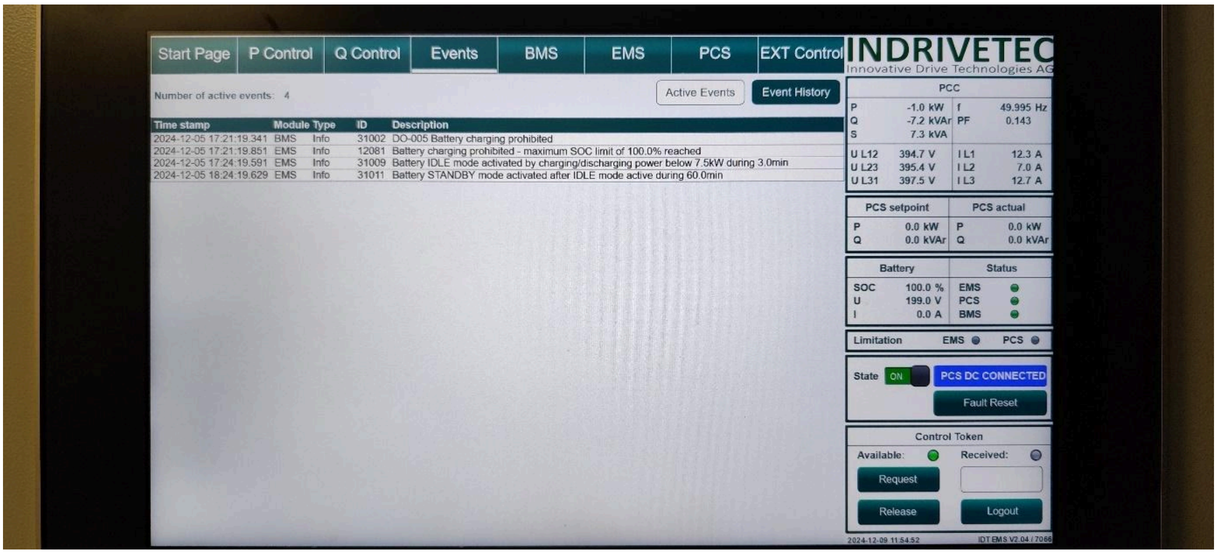
The "FCR" (Frequency Containment Reserve) mode is turned off, but its configuration options are available for dynamic grid support. The system allows for ramp gradients of up to 600% per minute for operational adjustments, ensuring rapid response to grid or storage requirements. Both the PCS and EMS statuses are operational (green indicators), with no errors or warnings. The screen also provides tools for fault resets and the ability to toggle bypass functionality, further enhancing operational flexibility and control.

Q Control – power flow management

Q Control screen, which manages reactive power flow in the system. The mode is activated, and the Q Controller is set to "ON," allowing for reactive power regulation. The system indicates a setpoint of 0.0 kVAr, with the current power output at -7.3 kVAr, signifying an underexcited state. The maximum allowable limits for reactive power are set between -250.0 kVAr (underexcited) and +250.0 kVAr (overexcited).

A live chart displays reactive power and voltage trends over time, providing real-time monitoring of grid dynamics. The interface also outlines the flow from the setpoint to the actual output, highlighting the difference (-7.3 kVAr). The bypass function remains off, suggesting direct control over reactive power is actively engaged. The system's battery remains fully charged (SoC: 100%), with all critical components (EMS, PCS, BMS) functioning correctly (green indicators). The interface reflects a stable operation designed to balance grid voltage and improve power quality.

Recent Events

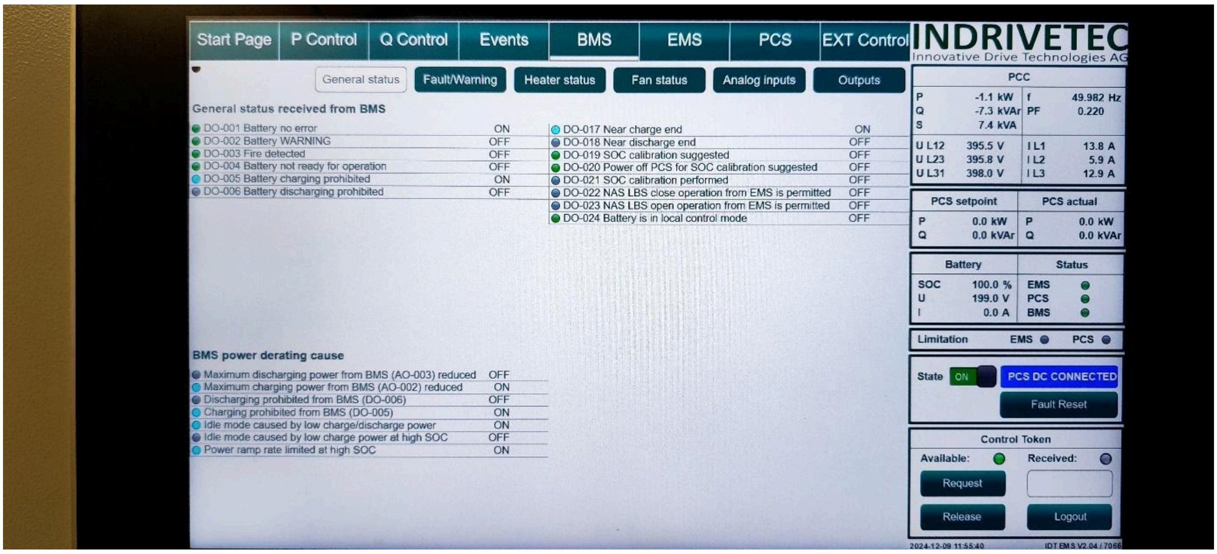


"Event History" for the NAS battery system, listing four active events. Key details include timestamps, module types, event IDs, and descriptions. Notably:

- Two events indicate "Battery charging prohibited" due to the maximum State of Charge (SoC) limit of 100% being reached.
- Another event records "Battery IDLE mode activated" as the charging or discharging power dropped below 7.5 kW for 3.0 minutes.
- A final event notes the activation of "Battery STANDBY mode" after IDLE mode was active for 60.0 minutes.

These events demonstrate automated system behaviour designed to maintain operational safety and efficiency, particularly regarding SoC management and transitioning between operational states. The system status (EMS, PCS, BMS) shows no errors or warnings, confirming stable conditions despite the logged events.

Battery Management System (BMS) screen General status



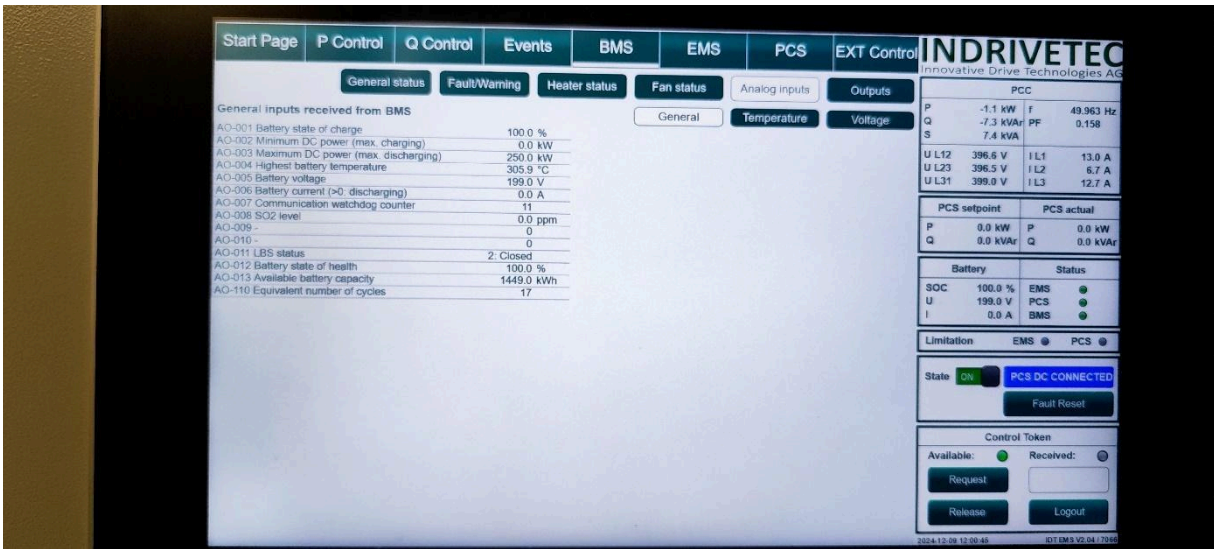
The screen provides a general status overview of the Battery Management System (BMS). Key indicators show that the battery has no errors (DO-001 is ON), but charging is currently prohibited (DO-005 is ON) due to the 100% State of Charge (SoC). Other critical statuses, such as fire detection and discharging prohibition, are OFF, indicating no active safety concerns.

The "BMS power derating cause" section highlights factors impacting power operations. Active causes include:

- Charging prohibition (DO-005 ON),
- Idle mode due to low charge/discharge power, and
- Power ramp rate limitation at high SoC.

Additional statuses, such as "Near charge end" (DO-017 ON), further confirm the system’s operational focus on preventing overcharging while maintaining safety and performance. The system remains stable and operationally responsive, with no indications of critical faults or emergencies.

Battery Management System (BMS) screen – General analog inputs

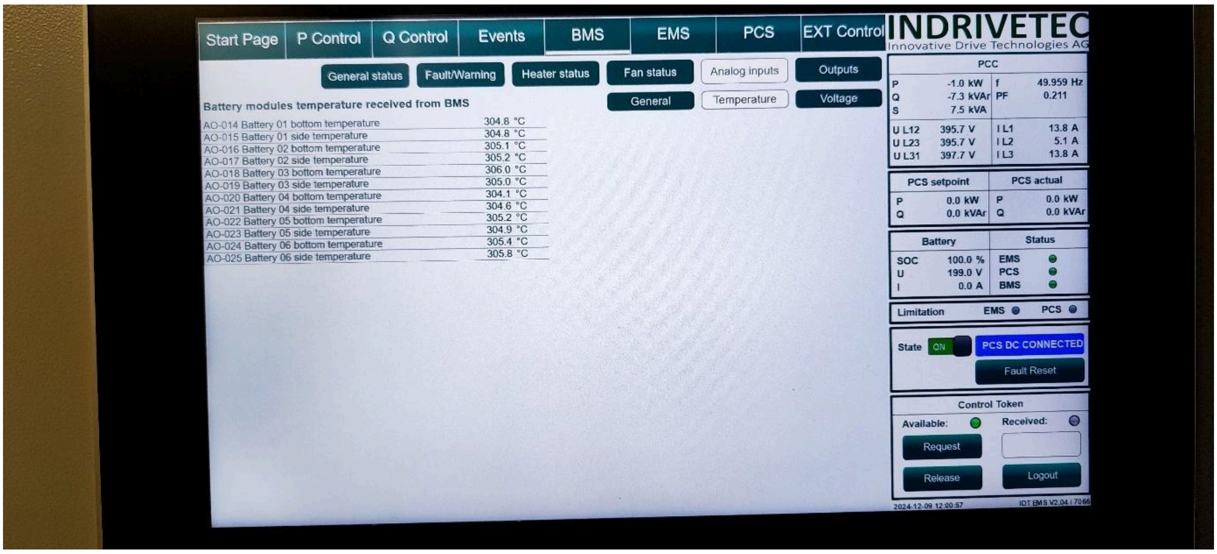


This screen provides a detailed overview of general inputs received from the Battery Management System (BMS). Key parameters include:

- **Battery state of charge (SOC)**: 100.0%, indicating the battery is fully charged.
- **Battery voltage**: 199.0V, which aligns with the nominal voltage for stable operation.
- **Battery state of health**: 100.0%, suggesting no degradation or wear, with the system performing at optimal capacity.
- **Available battery capacity**: 1449.0 kWh, reflecting the current energy storage availability.
- **Equivalent number of cycles**: 17, indicating the battery has undergone relatively few full charge/discharge cycles.
- **Highest battery temperature**: 305.9°C, highlighting the thermal state, which is expected given the sodium-sulfur chemistry's high operating temperature range.

Additional entries like communication watchdog counter and SO2 level (0.0 ppm) confirm operational safety and connectivity. The LBS (Load Break Switch) status is "Closed," indicating the battery is connected to the grid. These parameters collectively suggest that the system is in excellent condition, with no significant anomalies or performance issues.

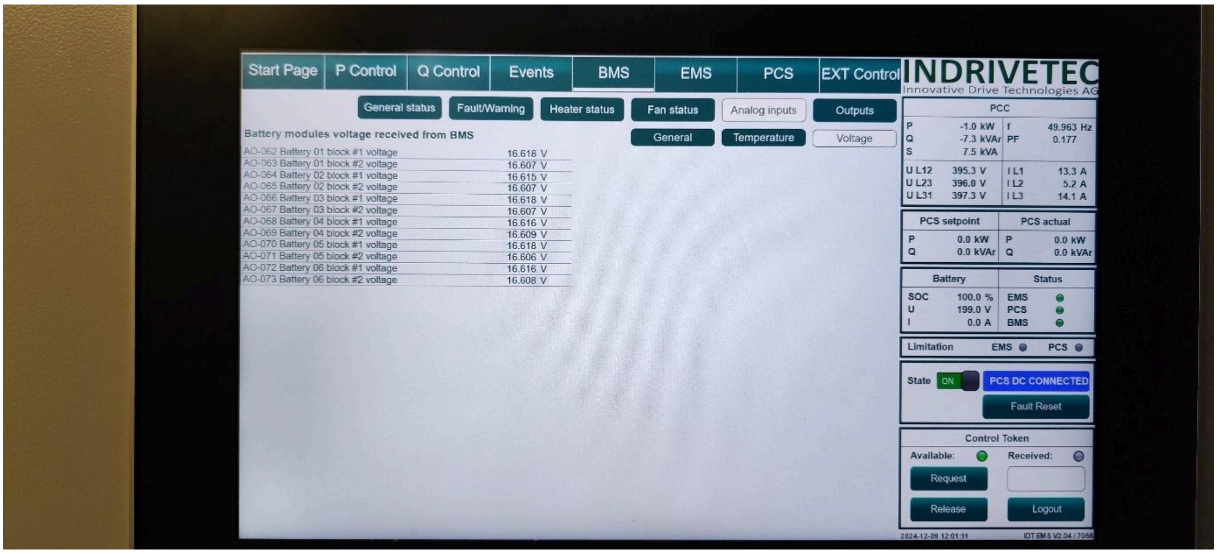
Battery Management System (BMS) screen – Temperature analog inputs



This screen focuses on the temperature monitoring of individual battery modules within the NAS battery system. Key data points show the bottom and side temperatures for six modules, with values ranging from **304.1°C to 305.8°C**. These temperatures are within the expected operating range for NAS batteries, which require high temperatures to maintain the molten state of the sodium and sulfur electrodes.

The uniformity in temperature readings indicates stable thermal management across the modules, ensuring consistent operation and efficiency. The slight variation between modules (less than 2°C) suggests effective heat distribution and minimal thermal imbalance. Maintaining such precise temperature control is critical for the performance, safety, and longevity of the NAS battery system.

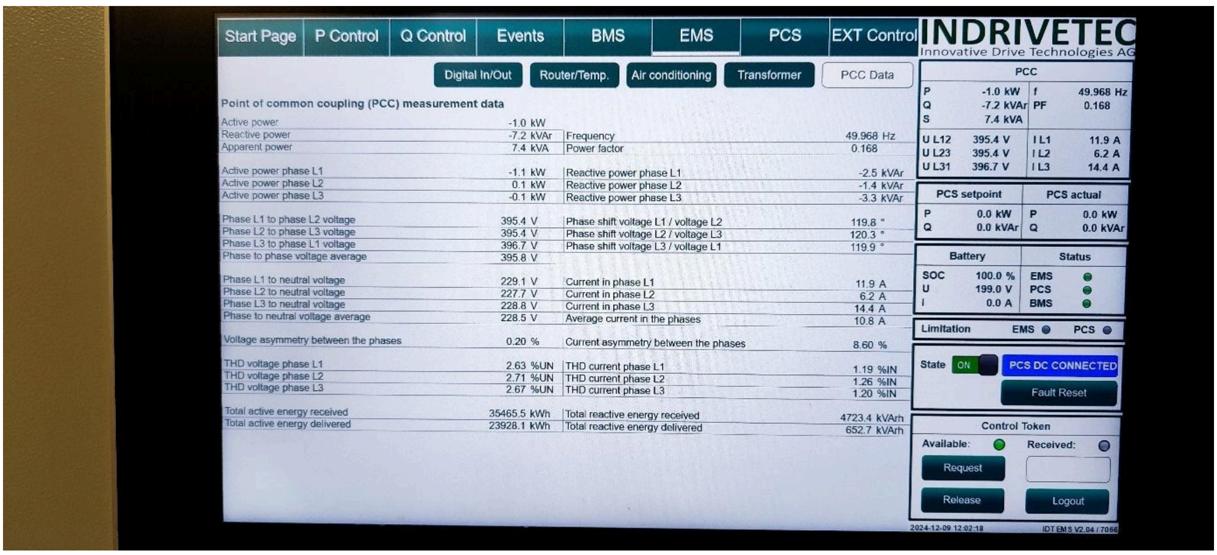
Battery Management System (BMS) screen – Voltage analog inputs



The screen provides the voltage readings for individual blocks within the battery modules, as received from the Battery Management System (BMS). Each block voltage is consistent, ranging from **16.607V to 16.618V**, indicating a high level of uniformity across the system.

This minimal variation in block voltages highlights the effective balancing of cells within the battery, which is critical for maintaining overall system health and efficiency. Uniform voltages also ensure that no individual block is overcharged or undercharged, which could otherwise lead to capacity loss or potential safety risks. These readings affirm that the NAS battery system's voltage management and cell balancing mechanisms are functioning as intended.

Energy Management System Point of Common Coupling (PCC) screen



This screen presents detailed Point of Common Coupling (PCC) measurement data, illustrating the interaction between the NAS battery system and the grid. Key parameters include:

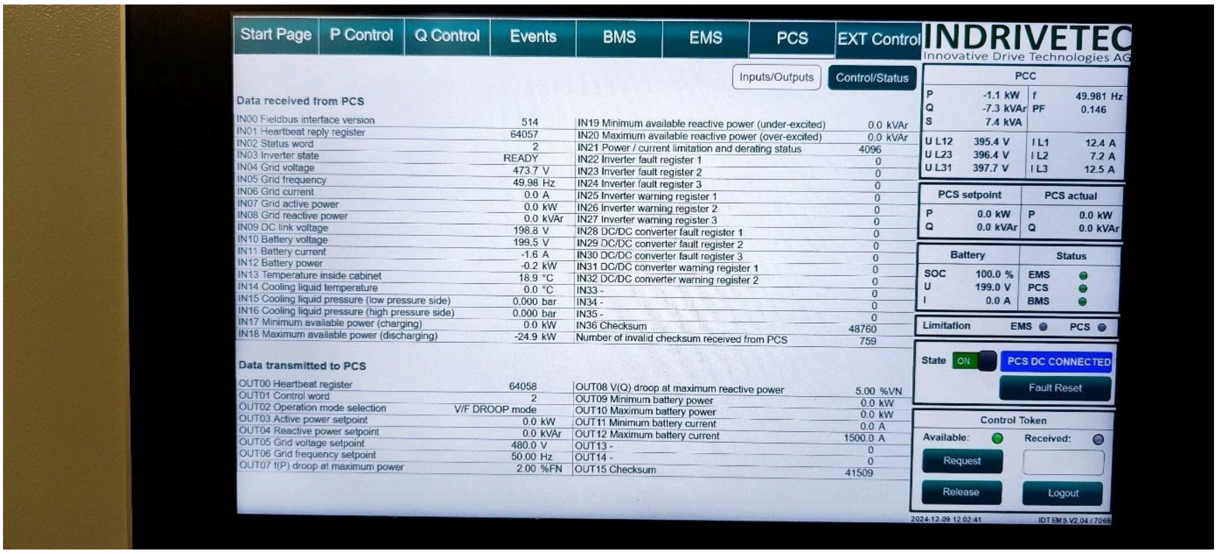
- **Active power**: -1.0 kW (exporting a small amount of power to the grid).
- **Reactive power (Q)**: -7.2 kVAr, indicating the system is providing reactive power to support voltage stability.
- **Apparent power (S)**: 7.4 kVA.
- **Frequency**: 49.968 Hz, which is within the expected range for grid stability.
- **Power factor (PF)**: 0.168, suggesting significant reactive power relative to active power.

Voltage measurements across phases L1, L2, and L3 are consistent (395.4V to 396.7V), with a minimal phase-to-phase voltage asymmetry of 0.20%. Current levels vary across phases, with L3 carrying the highest load at 14.4A, followed by L1 (11.9A) and L2 (6.2A).

Total Harmonic Distortion (THD) for voltage is low across all phases (2.63–2.71% UN), indicating good power quality. Current THD is also minimal (1.19–1.26% IN), reflecting stable and efficient operation.

Energy metrics highlight **total active energy received** (35,465.5 kWh) and **delivered** (23,928.1 kWh), as well as reactive energy exchange. These values confirm the system's active role in balancing energy demands and supporting grid operations. Overall, the PCC data indicates the NAS battery is effectively managing power flow and maintaining grid stability.

Power Conversion System (PCS)



This screen displays detailed data exchanged between the Power Conversion System (PCS) and other components, divided into "Data received from PCS" and "Data transmitted to PCS."

Key data received from PCS:

- **Grid voltage**: 473.7 V, indicating stable grid conditions.
- **Grid frequency**: 49.98 Hz, within the acceptable range for grid synchronisation.
- **Battery voltage**: 199.5 V, consistent with operational norms.
- **Battery current**: -1.6 A (charging), indicating a small inflow of current to the battery.
- **Battery power**: -0.2 kW, reflecting minimal power transfer during current conditions.
- **Temperature inside cabinet**: 18.9°C, which is well within the safe operating range.
- **Available power**: -24.9 kW (discharging), indicating readiness for a controlled energy release if needed.

Key data transmitted to PCS:

- **Grid voltage setpoint**: 480.0 V, used for grid interaction control.
- **Grid frequency setpoint**: 50.0 Hz, aligning with the nominal grid frequency.
- **Droop settings**: Configured at 5.00% for voltage and 2.00% for power frequency, enabling dynamic control to stabilise grid power.

No faults or warnings from the inverter, DC/DC converter, or related components are logged, confirming stable performance across subsystems. This data reflects precise monitoring and control for both battery and grid interactions, ensuring reliability and safety.

Electrical panel and control hardware for the NAS battery system

2.2 Operational Performance

Efficiency and Output

The NAS battery system at the Csillebérc facility demonstrates high efficiency and output capacity, designed to optimise grid operations and renewable energy integration. With a round-trip efficiency typically ranging between 85–90%, the system minimises energy losses during charge and discharge cycles. The battery operates at a nominal voltage of 199.5V (per battery module) and achieves consistent performance due to its unique sodium-sulfur chemistry, which is ideal for long-duration energy storage. The ability to provide a continuous discharge for up to six hours at rated output makes it a reliable solution for peak shaving, load levelling, and voltage support. Additionally, its reactive power management capabilities, evident in the data showing -7.2 kVAr of reactive power supplied to the grid, highlight its effectiveness in stabilising grid voltage during fluctuations.

The system's ability to balance active and reactive power seamlessly supports grid demands in real-time. Voltage uniformity across all battery modules (16.607V to 16.618V per block) ensures optimal energy utilisation and reduces the risk of performance degradation. Furthermore, the system’s capacity to handle large-scale energy flows—evidenced by the total energy delivered (23,928.1 kWh) and received (35,465.5 kWh)—positions it as a key asset for grid-connected renewable energy projects. These metrics underline the system's operational reliability and its capability to contribute to energy resilience in demanding applications.

Maintenance Requirements and Procedures

The NAS battery system at Csillebérc is designed for minimal and infrequent maintenance, a key feature that enhances operational efficiency and reduces downtime. Preventative maintenance can be scheduled outside of peak operational seasons to ensure seamless grid support during critical periods. One of the standout advantages of the system is its modular design, allowing maintenance to be conducted on partial sections of the battery while the rest of the system remains operational. This feature ensures uninterrupted energy storage and delivery, making it an ideal solution for applications requiring high reliability and availability.

The maintenance tasks include routine checks for abnormalities, cleaning components, and inspecting subsystems such as heaters, cooling systems, and power distribution. Periodic replacement of consumable parts and functional tests, recommended every four years, help maintain the system's 20-year lifespan and over 7,000 charge-discharge cycles. The thermal management system, critical for operating at the high temperatures required by sodium-sulfur chemistry (above 300°C), also receives special attention during maintenance to ensure uniform temperatures across modules. By combining these maintenance practices with remote monitoring capabilities, the system balances long-term durability with ease of operation, further solidifying its reputation for reliability.

Monitoring and Control Systems

The NAS battery system at Csillebérc is equipped with a sophisticated monitoring and control system that ensures seamless operation and efficient management of energy storage. The system integrates multiple layers of oversight, including the Battery Management System (BMS), Power Conversion System (PCS), and Energy Management System (EMS). These components work together to provide real-time data on key operational parameters such as State of Charge (SOC), battery voltage, current, and temperature. For instance, the BMS consistently tracks uniformity across modules, with SOC maintained at 100% and voltage readings between 16.607V and 16.618V per block, ensuring optimal energy utilisation and preventing imbalance. The PCS adds another layer of control by managing power flows, reactive power output, and grid synchronisation, as evidenced by its ability to provide -7.2 kVAr of reactive power for voltage stabilisation.

The system's user interface further enhances operational control by offering detailed visualisations of performance metrics and system states. Screenshots from the Csillebérc NAS reveal dashboards displaying power flows, grid parameters, voltage uniformity, and thermal conditions in a clear and intuitive layout. Alerts and fault logs, such as charging prohibitions or maintenance triggers, are readily available, enabling operators to respond quickly to any issues. Moreover, advanced features like bypass functionality, live frequency plots, and control token systems allow for precise adjustments and operational flexibility. This robust monitoring infrastructure, combined with remote access capabilities, ensures that the system operates reliably and efficiently, even in complex grid environments.

Safety Protocols

The NAS battery system at Csillebérc is equipped with comprehensive safety protocols to ensure secure operation and mitigate risks associated with high-temperature sodium-sulfur chemistry. Key safety measures include continuous monitoring by the Battery Management System (BMS), which tracks critical parameters such as temperature, voltage, and current across all modules. The BMS immediately flags any deviations, such as overvoltage, undervoltage, or excessive temperature, to prevent thermal runaway or other hazardous conditions. Additionally, the system incorporates moulded case circuit breakers (MCCBs) for power isolation, allowing operators to disconnect specific sections of the system in the event of a fault. Fire detection systems are also integrated, with automatic triggers to shut down the battery and isolate it from the grid in case of emergencies.

Another critical safety feature is the system's thermal management. Operating temperatures are maintained uniformly across all modules (approximately 304–306°C) to prevent hotspots or thermal imbalances. The robust housing and insulation ensure that even under high thermal stress, the risk of external exposure to heat or chemical leakage is minimised. The modular design also enhances safety, as maintenance or troubleshooting can be performed on specific sections without shutting down the entire system. Furthermore, charging and discharging are tightly controlled, with the system automatically enforcing limits to avoid overcharging or deep discharging. These safety protocols, combined with clear fault logs and alerts, ensure the Csillebérc NAS battery operates reliably and securely, even under demanding conditions.

2.3 Environmental Considerations

Thermal Management and Energy Consumption

The thermal management system of the Csillebérc NAS battery is a critical component for maintaining the high operating temperatures (above 300°C) required for sodium-sulfur chemistry. While this system ensures optimal performance and longevity, it does consume energy, which contributes to the overall environmental footprint of the installation. Typically, the heaters and insulation work continuously to maintain the required temperature, with the energy consumption varying depending on ambient conditions and system size. For a NAS battery, thermal management can account for approximately 5–10% of the total energy input over its operational lifespan. This translates to about 1-2% of energy used for thermal management in the daily charge-discharge cycle of the battery. However, the environmental impact is mitigated by the system's high energy density, long operational lifespan (20+ years), and reduced need for frequent maintenance or replacement. By minimizing energy losses during storage and retrieval (85–90% round-trip efficiency) and offering high cycle stability, the thermal management system balances its energy demands with the broader environmental benefits of enabling renewable energy integration and grid stabilization.

Emissions, Recycling, and Disposal

The NAS battery system at Csillebérc is designed to have minimal environmental impact during operation, as the cells are hermetically sealed, preventing any emissions or leakage of chemicals into the environment. This sealed design ensures that no gases or by-products are released during charging, discharging, or thermal management processes, making it an environmentally friendly choice for large-scale energy storage. The lack of operational emissions aligns the system with stringent environmental standards, further supporting its role in renewable energy integration and sustainable grid operations.

Regarding end-of-life management, the materials used in NAS batteries, such as sodium, sulfur, and beta-alumina ceramics, are recyclable to a significant extent. Sodium and sulfur can be recovered and reused, reducing the environmental footprint of battery disposal. However, the recycling process requires specialised facilities due to the unique chemistry and high-temperature requirements of the battery. The ceramic electrolytes and thermal enclosures are also recyclable but may require additional energy and resources for processing. Proper disposal practices and adherence to recycling protocols are crucial to minimising the environmental impact at the end of the battery's lifecycle, ensuring that NAS batteries remain a sustainable option from production to disposal.

3. Potentials in StoreMore

The inclusion of sodium-sulfur (NAS) battery technology in the Analysis and Cataloguing of Energy Storage Solutions activity within the StoreMore project offers significant potential. The A1.3 Energy Storage Outlook has already recognised NAS technology as a viable long-duration energy storage solution, highlighting its technical feasibility, high energy density, and long operational lifespan. Given these strengths, the Csillebérc NAS battery installation provides an excellent real-world case study to enrich the project's catalogue of sustainable energy storage solutions.

NAS batteries stand out for their unique combination of sustainability and performance. Their hermetically sealed design eliminates emissions during operation, ensuring minimal environmental impact. Furthermore, their recyclability, with recoverable sodium and sulfur components, aligns well with StoreMore's emphasis on environmental assessment. The robust thermal management system, while energy-intensive, is integrated into the overall high round-trip efficiency (85–90%) of the technology, making it competitive with other advanced storage solutions. Evaluating NAS batteries in-depth as part of A1.5 would also allow the consortium to explore their CAPEX implications, particularly in scenarios where long-duration storage and grid stabilisation are prioritised.

By incorporating NAS technology into the StoreMore analysis, the consortium could provide a well-rounded view of its capabilities, limitations, and potential environmental and economic benefits. This would enhance the value of the Catalogue of Sustainable Energy Storage Solutions by offering decision-makers a proven, scalable, and durable alternative to conventional lithium-ion systems. Including NAS technology could also bolster the modelling and optimisation tools developed in subsequent activities, ensuring that the StoreMore project addresses a broader spectrum of real-world storage needs.

4. Conclusions

The Csillebérc NAS battery site visit demonstrated the remarkable capabilities and potential of sodium-sulfur technology in addressing modern energy storage challenges. Its high efficiency, long-duration capacity, and environmentally friendly design underscore its suitability for renewable energy integration and grid stabilisation. The system's robust monitoring, control, and safety protocols, combined with its modular and low-maintenance nature, make it a prime candidate for broader adoption in energy storage projects across the Danube region and beyond.

As the StoreMore project continues to evaluate and catalogue sustainable energy storage solutions, incorporating insights from this site visit into its activities will provide valuable real-world context. The NAS battery's proven durability, emission-free operation, and recyclability align seamlessly with StoreMore's goals of fostering sustainability and innovation in energy storage.

2. Site Visit Summaries

2.1 Békéscsaba (Hungary) – Smart Grid and Lithium-Ion Battery Storage

- **Technology Overview:**
  - A **Smart Grid system** integrated with a **solar park**.
  - **Lithium-ion battery energy storage** with a capacity of **1.2 MW/2.4 MWh**.
  - **Real-time monitoring** and remote control via a centralized smart control center.
- **Key Features & Benefits:**
  - **Energy Optimization:** Reduces reliance on grid electricity during peak hours.
  - **Grid Resilience:** Provides backup power during failures.
  - **Surplus Energy Management:** Excess solar energy is stored and used when needed.
  - **Community Engagement:** A visitor center educates the public on smart energy solutions.
- **Challenges & Drawbacks:**
  - **Energy Losses:** Storage inefficiencies range between **5-15%**.
  - **Battery Degradation:** Operational capacity limited to **15-85%** of charge to extend lifespan.
  - **Maintenance Issues:** Frequent malfunctions (6-8 times annually) require interventions.
- **Conclusion:**
  Békéscsaba's **smart grid system** demonstrates how **battery storage** can enhance solar energy utilization. However, limitations such as battery degradation and maintenance challenges highlight the need for **alternative or improved energy storage solutions**.

2.2 Rubensdorf (Austria) – Hydrogen-Based Seasonal Energy Storage

- **Technology Overview:**
  - **Hydrogen production via electrolysis** using excess renewable electricity.
  - **Underground storage** in former natural gas reservoirs.

  - **Hydrogen blending** with natural gas in pipelines (currently at 10%, aiming for 100%).
- **Key Features & Benefits:**
  - **Seasonal Storage:** Surplus summer energy is stored as hydrogen and used in winter.
  - **Decarbonization Potential:** Enables green hydrogen supply to industry (e.g., steel production).
  - **Infrastructure Repurposing:** Utilizes existing natural gas pipelines, reducing costs.
- **Future Developments:**
  - **Dedicated Research Facility (2025):** Aims to advance hydrogen processing technologies.
  - **Energy System Modeling:** Analyzing future scenarios for full-scale hydrogen integration.
  - **Economic Feasibility Studies:** Evaluating hydrogen storage's long-term viability.
- **Conclusion:**
  The **Underground Sun Storage 2030** project offers a **scalable and efficient** approach to **long-duration renewable energy storage**. It effectively addresses **seasonal energy fluctuations**, but **hydrogen infrastructure adaptation** remains a key challenge.

2.3 Fuchstal/Apfeldorf (Germany) – Community-Driven Renewable Energy Transition

- **Technology Overview:**
  - **Wind turbines (29 MW)** with **bird monitoring systems** to prevent wildlife harm.
  - **Solar power (3 MW)** providing electricity to the local community.
  - **Power-to-heat system:** Converts excess electricity into heat for district heating.
  - **Lithium-ion battery storage (5.8 MW/3.2 MWh)** optimizing energy use.
  - **Virtual Power Plant (VPP):** Balances renewable energy supply and market integration.
- **Key Features & Benefits:**
  - **High Energy Autonomy:** Local generation exceeds consumption, making the town energy-independent.

- **Heat Storage Integration:** A **5,000 m³ heat storage** facility balances energy supply and demand.
- **Community Ownership Model:** Energy revenue benefits local citizens, creating a sustainable economic model.

- **Future Innovations (Apfeldorf):**
  - **Hybrid Storage System:** Combining **Vanadium-Redox-Flow Batteries (VFB)** with lithium-ion batteries.
  - **Milk Cooling Waste Heat Recovery:** Innovative heat pump technology for **sustainable heat supply**.
- **Conclusion:**
  Fuchstal/Apfeldorf exemplifies how **local energy cooperatives** can drive **decentralized energy solutions**. The integration of multiple technologies—including **wind, solar, battery storage, and power-to-heat**—ensures high energy security and economic benefits for the community.

2.4 Csillebérc (Hungary) – NAS Battery Energy Storage System

- **Technology Overview:**
  - First **sodium-sulfur (NAS) battery** system in Hungary.
  - Part of the **StoreMore project**, funded by the **Interreg Danube program**.
  - Located at the **HU-REN Centre for Energy Research**.
  - Developed by **NGK Insulators, Ltd.**, a global leader in ceramic-based battery technologies.
- **Key Features & Benefits:**
  - **Long-duration storage**: Capable of **storing energy for extended periods** (ideal for grid stabilization and peak shaving).
  - **High Energy Density & Efficiency**: **85–90% round-trip efficiency**, reducing energy losses during storage and retrieval.
  - **Long Operational Lifespan**: **15–20 years or 7,000+ cycles**, outperforming many lithium-ion alternatives.
  - **Fast Response & Grid Support**: Suitable for **voltage stabilization, frequency regulation**, and supporting **renewable energy sources**.
  - **Environmental Benefits**: **Zero emissions**, **recyclable components**, and **reduced reliance on critical minerals** compared to lithium-ion batteries.
- **Operational Insights:**
  - **Capacity**: **DC250 kW power, DC1,450 kWh energy storage**.

    - **Battery Management System (BMS)**: Advanced **monitoring, fault detection, and charge/discharge optimization**.
    - **Power Conversion System (PCS)**: Enables **bidirectional energy flow and reactive power control**.
    - **Thermal Management**: Operates at **300+°C**, requiring **continuous heating but ensuring stable performance**.
    - **Monitoring & Control**: Equipped with **real-time data logging, remote management, and advanced grid integration features**.
- **Challenges & Drawbacks:**
    - **High Operating Temperature**: Requires **careful thermal management** to maintain optimal performance.
    - **Safety Considerations**: Uses **molten sodium**, requiring **strict handling and containment measures**.
    - **Initial Capital Costs**: Higher upfront investment compared to **lithium-ion systems**, but offsets costs with **longer lifespan and efficiency**.
- **Conclusion:**
  The **Csillebérc NAS battery system** offers **a scalable, durable, and emission-free alternative to lithium-ion batteries** for **long-duration storage**. It demonstrates **strong potential** for **renewable integration, grid flexibility, and decentralized energy solutions**, aligning with EU energy transition goals.

3. Comparative Analysis of the Three Sites

Feature	Békéscsaba (HU)	Rubensdorf (AT)	Fuchstal/Apfeldorf (DE)	Csillebérc (HU)
Storage Type	Lithium-ion battery	Hydrogen storage in gas reservoirs	Lithium-ion, hybrid battery (planned)	Sodium-Sulfur (NAS) battery
Capacity	1.2 MW / 2.4 MWh	Large-scale underground storage	5.8 MW / 3.2 MWh	250 kW / 1.45 MWh
Energy Source	Solar PV	Renewable electrolysis (solar)	Wind, solar, power-to-heat	Grid-connected (renewable integration)
Grid Integration	Smart grid with real-time monitoring	Hydrogen blending with natural gas	Virtual power plant for energy trade	Frequency regulation, peak shaving, voltage support
Challenges	Battery degradation, maintenance needs	Infrastructure adaptation for hydrogen	Complex multi-tech integration	High temperature maintenance, safety handling
Community Involvement	Visitor center & public education	Industry-focused	Direct ownership by residents	Research-driven, part of StoreMore project

4. General Findings and Recommendations

Key Takeaways

1. **Greater Diversity in Energy Storage is Needed:**
    - **Csillebérc's NAS batteries** add another **long-duration storage option**, complementing the **short-term benefits of lithium-ion (Békéscsaba)** and **seasonal storage potential of hydrogen (Rubensdorf)**.
2. **Scaling Up Long-Duration Storage Technologies is Critical:**
    - The **Csillebérc NAS battery project** demonstrates the **value of high-energy-density, long-cycle-life systems** for **grid reliability**.
3. **Infrastructure Adaptation for Energy Storage Needs Acceleration:**
    - **Hydrogen (Rubensdorf) and NAS (Csillebérc) batteries** require **new infrastructure investments** to **scale up deployment and drive cost reductions**.
4. **Investment in Research-Backed Storage Technologies Yields Long-Term Benefits:**
    - The **StoreMore project (Csillebérc NAS system)** showcases how **publicly funded research** can **accelerate commercialization** of **innovative storage solutions**.

Recommendations

- **Expand NAS Battery Deployment:**
    - **Csillebérc's success with NAS batteries** should inform future investments in **alternative, long-duration storage solutions** across the EU.
- **Pair NAS Batteries with Renewable Energy Projects:**
    - NAS batteries are ideal for **smoothing intermittent renewable generation** and could be integrated with **wind and solar farms** in the **Danube region**.
- **Develop Policy Incentives for High-Efficiency Energy Storage Systems:**
    - The EU should support **cost reduction mechanisms for NAS and hydrogen storage**, **similar to existing incentives for lithium-ion technology**.
- **Leverage StoreMore Project Insights for Future Energy Planning:**
    - The **Csillebérc NAS battery case study** provides **real-world data** to refine **EU-wide energy storage modeling and policy frameworks**.

5. Conclusion

The **integration of best practices from Csillebérc, Békéscsaba, Rubensdorf, and Fuchstal/Apfeldorf** showcases the **growing diversity in energy storage solutions**. The **Csillebérc NAS battery system** provides an **efficient, emission-free, and long-duration alternative** that aligns with **EU energy resilience and sustainability goals**.

With the addition of **NAS batteries to the EU's energy storage portfolio**, policymakers and industry stakeholders can explore **new opportunities for grid stability, renewable integration, and energy security**. The **StoreMore project**, under which the Csillebérc battery was analyzed, highlights the **need for continued research, cross-border cooperation, and targeted investment** to fully **realize the potential of emerging energy storage technologies**.

Final Impact on the EU Strategy for the Danube Region (EUSDR)

- **Aligns with Priority Area 2 (Sustainable Energy)** by **introducing new storage technologies**.
- **Supports the EU Green Deal** with **scalable, zero-emission energy solutions**.
- **Enhances regional energy independence** by **reducing reliance on imported fossil fuels**.
- **Promotes innovation and competitiveness** through **research-backed commercialization of NAS batteries**.

By **leveraging insights from all four best practice visits**, the **Danube region can emerge as a leader in next-generation energy storage solutions**, paving the way for **a cleaner, more resilient European energy system**.