LAPPEENRANNAN–LAHDEN TEKNILLINEN YLIOPISTO LUT
LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT

LUT School of Energy Systems
Department of Electrical Engineering
Laboratory of Electricity Markets and Power Systems

Flexens Oy Ab
Polar Night Energy Oy
Sustainable Energy Solutions Sweden Holding AB

LUT Scientific and Expertise Publications
Tutkimusraportit – *Research Reports*
163

Juhani Riikonen, Iisa Ollila, Alisdair Price, Juha Uppa, Ville Sihvonen, Samuli Honkapuro, Jasmin Jaanto, Narges Ghorbani, Markku Ylönen, Tommi Eronen, Ville Kivioja, Miika Peltola, Liisa Naskali, Terhi Moisala, Matti Ulvinen, Nikolas Georgii

NewSETS: New Energy Storages Promoting Sustainable Energy Transition in Societies

NewSETS – New Energy Storages Promoting Sustainable Energy Transition in Societies

Final Report 29.5.2024

Juhani Riikonen, Iisa Ollila, Alisdair Price, Juha Uppa

Flexens Oy Ab

Ville Sihvonen, Samuli Honkapuro, Jasmin Jaanto, Narges Ghorbani

LUT-yliopisto

Markku Ylönen, Tommi Eronen, Ville Kivioja, Miika Peltola, Liisa Naskali, Terhi Moisala, Matti Ulvinen

Polar Night Energy Oy

Nikolas Georgii

SENS Ab

Lappeenrannan-Lahden teknillinen yliopisto LUT
LUT School of Energy Systems
Yliopistonkatu 34
53850 Lappeenranta
ISBN 978-952-412-082-1
ISSN-L 2243-3376
ISSN 2243-3376
Lappeenranta 2024

Executive Summary

NewSETS was an R&D&I-project focusing on energy storage, especially seasonal sand-based heat storage and pumped hydro storage. NewSETS was led by project manager Flexens Oy Ab, with partners LUT University, Polar Night Energy Oy, and Pumped Hydro Storage Sweden AB (later acquired by SENS AB).

NewSETS linked demonstrations, feasibility studies, market, and system analyses with communication efforts. The team produced high-level scientific journal papers for the storage types as well as easy-to-read white papers. The project showed various outcomes and recommendations regarding energy storage for different stakeholders (Figure 1).

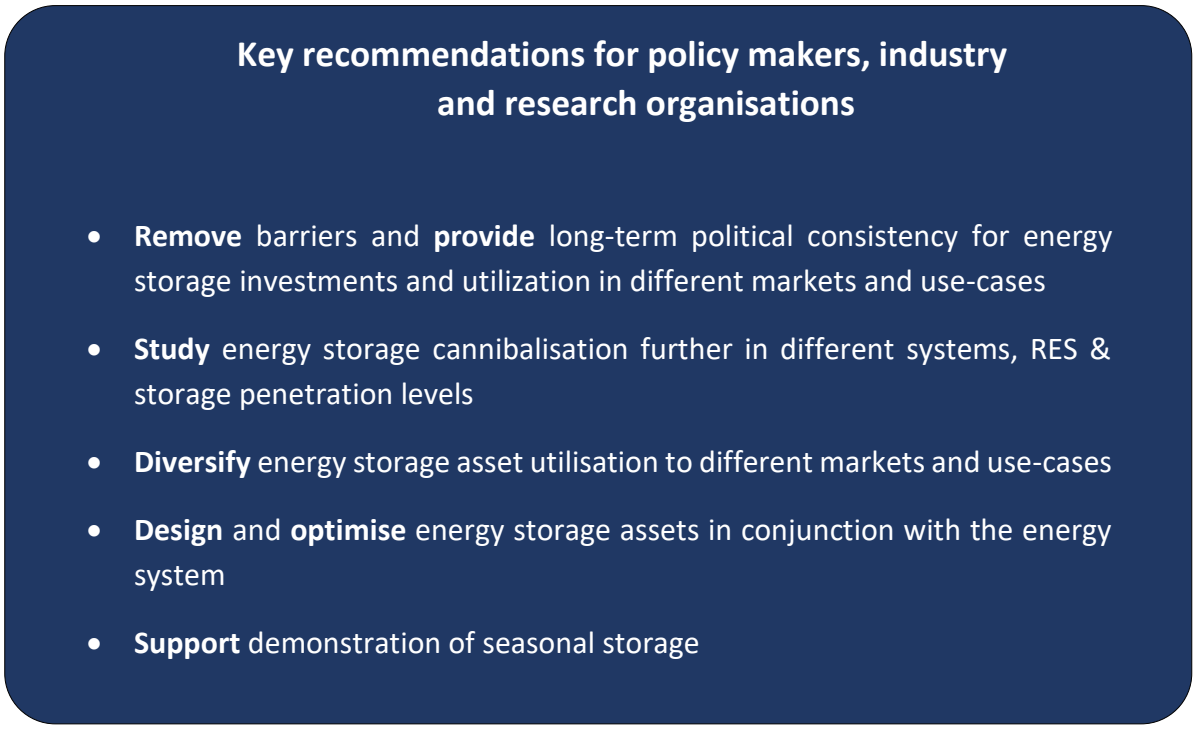

Figure 1: Essential recommendations for different stakeholders concerning energy storage.

NewSETS aimed to establish a positive outlook among energy stakeholders and to make climate change mitigation efforts visible to everyone through skilful communication. The project hosted several events for the public, including seminars and workshops where key stakeholders could steer the direction and research questions of the project and communicate further research and development needs for future projects and public funding.

The project was launched in the summer of 2021 and lasted for three years, until May 2024. NewSETS was funded under the ERA-NET SES MiCall19 (Joint Call19).

ACKNOWLEDGEMENTS

This project has received funding in the framework of the focus initiatives Smart Grids Plus and Integrated, Regional Energy Systems of the joint programming initiative ERA-Net Smart Energy Systems, with support from the European Union Horizon 2020 research and innovation programme under grant agreements No 646039 and 775970.

The content and views expressed in this material are those of the authors and do not necessarily reflect the views or opinion of the ERA-Net SES initiative. Any reference given does not necessarily imply the endorsement by ERA-Net SES.

NewSETS project team expresses our sincere gratitude for the funders and all the people who have participated in any way to NewSETS. The team wants to thank you the government of Åland and Johnny Lindström for participating to the steering group of the project.

Table of contents

Executive Summary

1 NewSETS – Introduction 5
2 Company Descriptions 7
2.1 Flexens 7
2.2 LUT University 8
2.3 Polar Night Energy Oy 8
2.4 SENS AB and Pumped Hydro Storage Sweden AB 9
3 Scientific Research Findings 10
3.1 Combined utilization of electricity and thermal storages in a highly renewable energy system within an island society 10
3.2 Role of power-to-heat and thermal energy storage in decarbonization of district heating 11
3.3 Developing a Replicable Methodology for Assessing Pumped Hydro Energy Storage Potential: Mapping, Estimation, and Economic Analysis 12
3.4 Thermal storage deployment in the framework of current electricity market design 12
3.5 Energy storage as an enabler of a renewable island energy ecosystem 13
3.6 Evaluating Business Strategies for Thermal Energy Storages: Participation in the Nordic Electricity Markets 14
4 Technology Development & Feasibility Studies 15
5 Communication & Dissemination Activities 18
6 Conclusions 20
References 23

1 NewSETS – Introduction

NewSETS, short for “New energy storages promoting sustainable energy transition in societies”, was all about storing energy. The project centred around two main storage types: seasonal heat storage and underground pumped hydro storage.

The former storage type is developed by the Finnish company Polar Night Energy Oy and uses high-temperature sand to store heat. The latter, provided by the Swedish company SENS, employs conventional pumped hydro methods in a new space: underground. Both technologies present low-emission and innovative approaches to energy storage.

NewSETS linked demonstrations, feasibility studies, market and system analyses with communication efforts. The team produced high-level scientific journal papers of the storage types as well as easy-to-read white papers. The performance of the storage types was assessed as well as their effects on the energy system – also in combination with other storage solutions.

The project aimed to establish a positive outlook among energy stakeholders and to make climate change mitigation efforts visible to everyone through skilful communication. NewSETS hosted several events for the public, including seminars and workshops where local people could steer the direction and research questions of the project.

NewSETS started in the summer of 2021 and lasted for three years, until May 2024. NewSETS was funded under the ERA-NET SES MiCall19 (Joint Call19).

Many of the NewSETS activities used the Åland Islands as a case example. The Åland Islands are located between Southwest Finland and Sweden in the Baltic Sea, inhabiting roughly 30 000 people.

Figure 2 on the next page summarises the original project plan of NewSETS and different work packages.

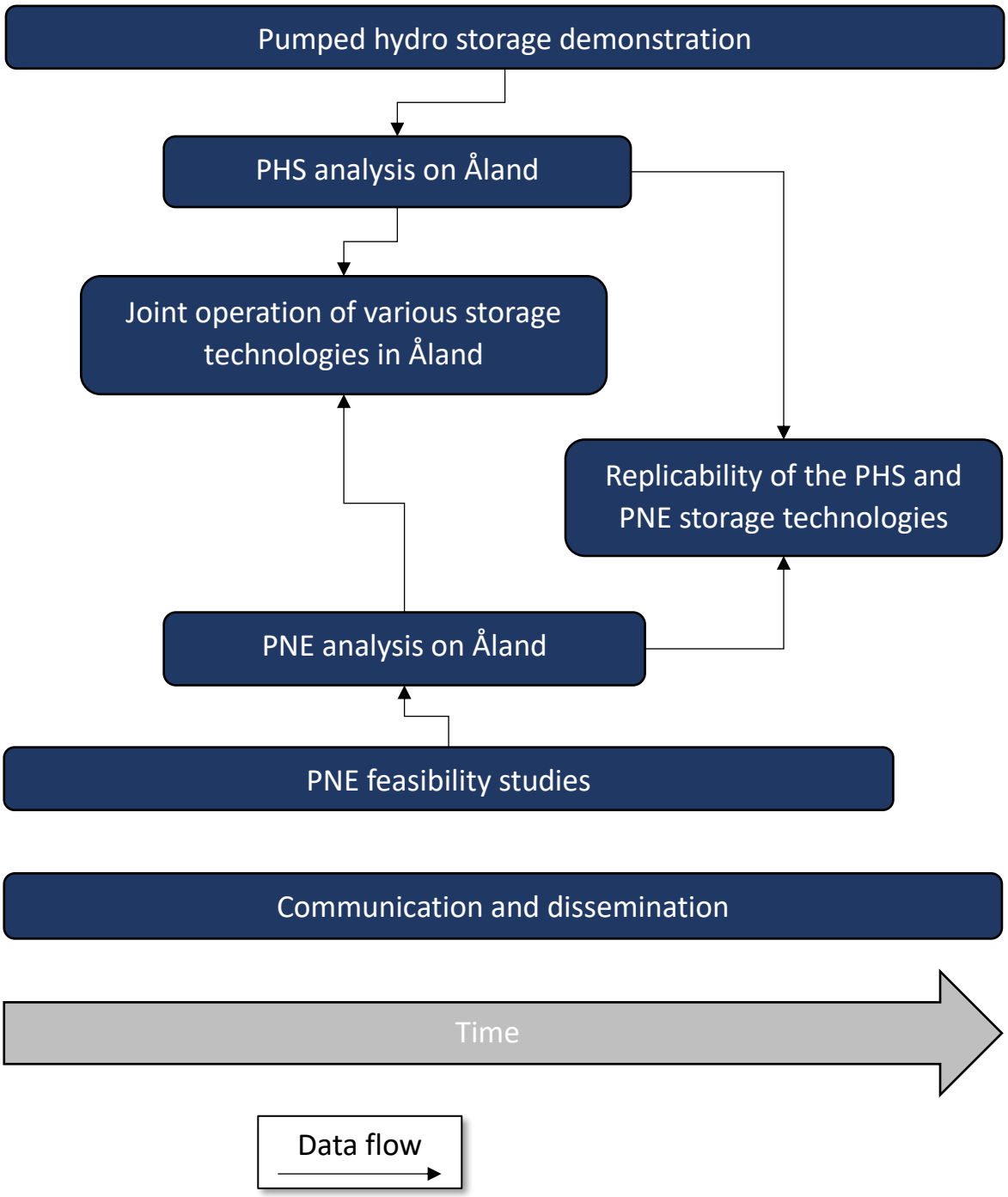

Figure 2: NewSETS work packages

2 Company Descriptions

NewSETS consortium partners were Flexens Oy Ab (project manager), LUT University, Polar Night Energy Oy, and Pumped Hydro Storage Sweden Ab. PHSS was acquired by SENS during the project.

2.1 Flexens

Flexens Oy Ab is a project developer implementing Power-to-X technologies to enable societies to run on a 100 % renewable energy mix. Flexens was founded in 2018 to capitalise on the skills and capabilities created in building the world-leading RES testbed and demo, Smart Energy Åland, to capture the rapidly growing demand for renewable energy systems.

The large-scale rollout and integration of variable renewable energy sources is one of the largest challenges facing the energy industry. It requires new solutions, implementation of new technologies and multi-technology system integration. Flexens was created with the mission of becoming a market-leading company in this rapidly growing renewable energy sector.

Flexens was created as the result of an extensive research program and the cooperation of some of the leading energy sector stakeholders in Northern Europe. The company was founded to take advantage of the growing market opportunities associated with the shift towards clean energy and the need to replace fossil fuels.

Today, Flexens has come a long way in making our vision a reality. Flexens' core capabilities in system integration and sector coupling are utilised to create attractive large-scale Power-to-X assets in a rapidly growing market. Flexens collected skills and research background provide a unique position to develop green hydrogen projects, which are now company's primary focus area. With the ability to invest both know-how and arrange funding in renewable energy assets, Flexens add value throughout the project development life cycle – from early-stage concept development and modelling to financing and construction. Flexens has a solid commercial pipeline with substantial foreseen capacity in Finland and abroad.

2.2 LUT University

Clean energy, water, and air are life-giving resources for which we at LUT University seek new solutions with our expertise in technology, business, and social sciences. We help society and businesses in their sustainable renewal. Our international community consists of nearly 8 000 members. Our campuses are in Lappeenranta and Lahti, Finland. We are one of the world's top universities for climate action.

The global energy sector is undergoing a major transition from a fossil fuel burning system to a carbon dioxide free system based on electricity. Finding new energy-efficient solutions requires extensive research. At LUT School of Energy Systems, our goal is a deep system-level understanding of the transition to a carbon-neutral energy system and its economic, environmental, technical, and competitiveness factors.

Our research covers the technologies and systems required for the production, transmission, distribution, and use of energy, from equipment manufacturing and fuels to energy end-use. Our strengths are our understanding of the system level of energy systems, the digital design and production of machines and equipment, and demanding welded metal structures.

2.3 Polar Night Energy Oy

Polar Night Energy Oy designs, develops, manufactures, delivers, and operates high temperature thermal energy storages. The technology is based on sensible heat of solid materials and a patented closed-loop air circulation system for heat transfer. The company has a commercial product with Technology Readiness Level 9; the first commercial system has operated in Kankaanpää since summer 2022 and the construction of a much bigger system is starting in Pornainen early summer 2024.

Key advantages of the thermal energy storage design of the company include

- The possibility to provide heat output effectively at high temperatures, exceeding 200 degrees Celsius, thus facilitating a wide range of applications.

- Low cost for capacity leading to naturally long storage times, from days to weeks. This aligns perfectly with long cycles of wind power, which is the predominant renewable energy source in regions with high heat demand.
- High energy density and low heat losses compared to many other thermal energy storage solutions.
- Simple and robust design makes it possible to adopt the solution quickly world-wide, also because the medium can be locally sourced.
- Very long lifetime of structural components and any parts requiring replacement can be easily serviced.

2.4 SENS AB and Pumped Hydro Storage Sweden AB

The original consortium partner, Pumped Hydro Storage Sweden AB applied conventional pumped hydro storage technology in new methods: underground mines. Pumped Hydro Storage was started by enthusiasts with a background from renewables, and with a strong desire to make a difference in the energy transition.

During NewSETS, Pumped Hydro Storage Sweden AB was acquired by SENS - Sustainable Energy Solutions Sweden Holding AB. SENS provides sustainable energy solutions enabling the transition to a fossil-free and CO2 neutral energy mix. SENS develops, designs, constructs, and sells large-scale energy projects combining renewable energy sources with the next generation energy storage technologies such as underground pumped hydro storage (UPHS) and/or battery energy storage systems (BESS). The company also conducts technical advisory consultancy services within energy storage and energy systems optimisation. The company is listed on NGM Nordic SME under the short name SENS.

3 Scientific Research Findings

This chapter gives an overview of the scientific research and publications prepared under NewSETS. The research focused on studying the two specified storage technologies, seasonal heat storage and underground pumped hydro storage.

It was found that the energy storage technologies increased the flexibilities of both power and heat sectors and enabled higher utilisation of variable renewable energy by reducing curtailment. Energy storage also allowed to take advantage of the increased electricity price volatility, by avoiding use of energy during the high-cost hours and charging the storage during the low-cost hours.

3.1 Combined utilisation of electricity and thermal storages in a highly renewable energy system within an island society[1]

In this paper, a comparative analysis was performed on the two energy storage solutions: small-scale underground pumped hydro storage (PHS) and high-temperature thermal energy storage (HTTES). Using the PLEXOS energy and power system modelling software, the study analysed the operation and performance of these storage systems in Åland. The novelty of the paper was in evaluating the business cases of these storage solutions when operating separately and combined. Business cases were studied by comparing annual energies, operating hours, price paid, and price received of the storage types in different scenarios.

The results showed that both storages promoted electrification and renewable energy integration, with the HTTES reducing curtailment by 77% and the PHS by 4%. The storage systems were also able to take advantage of lower-cost hours of external electricity markets, with the PHS increasing electricity imports by 0.2% and the HTTES by 1.5%. Moreover, the PHS enabled the sale of excess electricity to external markets, leading to an increase in exports by 0.3%. In contrast, the HTTES increased local consumption of excess production, reducing exports by 1.1%.

[1] Sihvonen et al., 2024

Results showed that integrating both storage systems in the same energy system could achieve significant benefits, such as reduced curtailment of renewable energy. However, the study also highlighted that the two systems could compete for the same resources in an open energy market, leading to a decrease in annual energy and net revenue for both systems. A PHS exhibited an 11% reduction in annual energies, when compared with operating alone, whereas for an HTTES, the reduction was 1%. Similarly, the net revenue of the PHS was reduced by 25.2% and that of the HTTES by 4.9%. Concluding the business case analysis, changes in annual energy and operation hours were not linearly correlated with revenue and charging cost, and the dynamics of the electricity market and the studied energy system must also be considered. Finally, energy storage could be considered a key element in supporting the energy transition; however, the importance of careful planning must be emphasised when integrating energy storage systems into an energy market.

3.2 Role of power-to-heat and thermal energy storage in decarbonisation of district heating[2]

In this study, pathways to decarbonise the district heating system in Åland were explored. Especially, the roles of different power-to-heat technologies, e.g., heat pumps and direct electric heating, and thermal energy storage were investigated in decarbonisation of the district heating system. The focus was on finding the most cost-effective approach to achieving the climate neutral district heating system. For this, three scenarios were modelled over the five-year period of 2018–2022 with varying demand and electricity market prices by using the modelling software PLEXOS. The study showed that electricity prices, but also reserve market prices, have a very significant impact on the structure of the most cost-effective district heating system.

Overall, electrification has strong potential to reduce emissions cost-effectively in a district heating system, but it also makes the system vulnerable to electricity price volatility. It can be concluded that thermal energy storage and reserve market participation are crucial for protecting against cost increases and reducing the investment risk.

[2] Sihvonen et al., 2024

3.3 Developing a Replicable Methodology for Assessing Pumped Hydro Energy Storage Potential: Mapping, Estimation, and Economic Analysis[3]

This research developed a replicable methodology for identifying potential pumped hydro energy storage sites and respective storage capacities, covering all water bodies, including seawater, within a country. The methodology utilised a Geographic Information System based on an automated model for topographical analysis. Subsequently, an economic analysis evaluated the costs associated with each identified site. The automated model facilitated precise topographical analyses on a country level, as well as on a global scale. This methodology is adaptable to any chosen region by modifying the input data.

In this study, the methodology was applied to India, where the model identified 297 pumped hydro energy storage sites, with a total technical potential capacity exceeding 38 TWh (4758 GW for an 8-hour cycle), surpassing anticipated storage demands for 2050 by a factor of 9. Madhya Pradesh emerged as the region with the highest estimated potential, exceeding 11 TWh. The economic analysis underscored the significant pumped hydro energy storage potential in India, with most locations proving cost-effective compared to current lithium-ion batteries and expected to remain competitive in the future. This highlighted the critical role of pumped hydro energy storage in shaping India's energy landscape, indicating its importance for ensuring a sustainable and reliable energy supply.

3.4 Thermal storage deployment in the framework of current electricity market design[4]

In this paper, the participation of power-to-heat technologies and thermal energy storages in the electricity market were examined. In particular, the paper aimed to review the key enablers, barriers, and drivers for power-to-heat and thermal energy storages in the context of electricity markets. Additionally, the technical potential of power-to-heat technologies combined with thermal energy storages were examined. The study was based on a literature review and examined especially the context of Finnish energy system and market.

[3] Ghorbani et al., 2024.
[4] Jaanto et al., 2023

Different identified applications for thermal energy storage and the added value from these services are presented in the Figure 3. Thermal energy storages were identified to be very versatile source of flexibility for the entire energy system, not only for the heat sector.

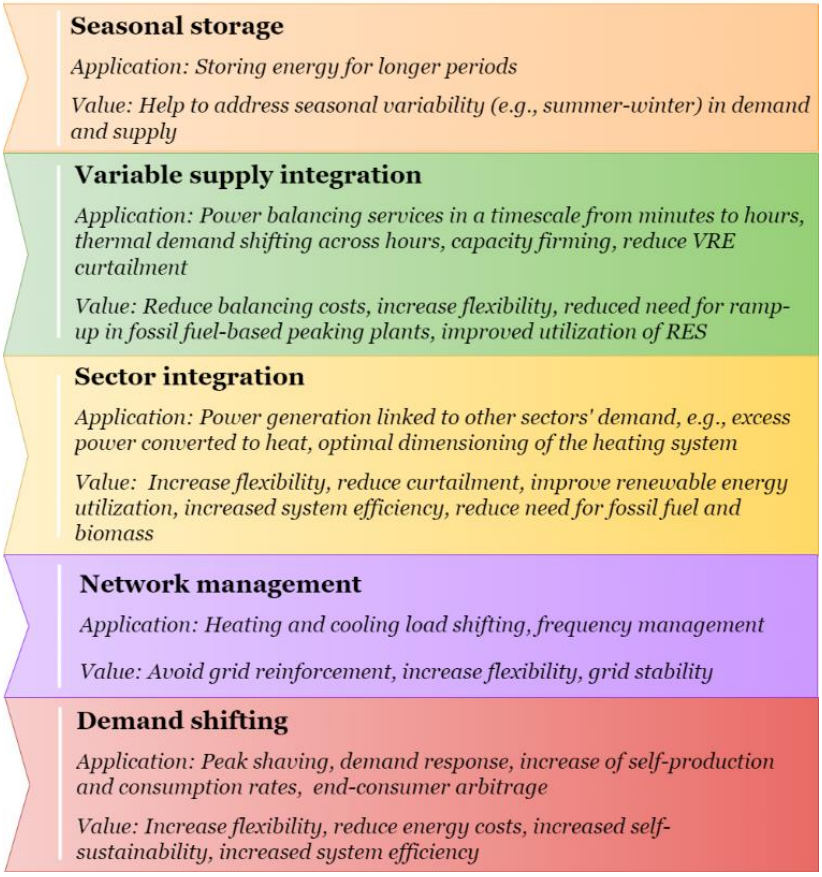

Figure 3: Thermal energy storage services, applications, and the received value (Jaanto et al., 2023).

3.5 Energy storage as an enabler of a renewable island energy ecosystem[5]

This paper analysed the role of energy storage in promoting reliable and sustainable energy transition and decarbonisation in Åland. The analysis examined battery energy storage, pumped hydro storage, and thermal energy storage technologies in a 100% renewable scenario using the EnergyPLAN energy system analysis tool. Results pointed to a strong potential for energy storage to reduce curtailment of renewable energy, increase the use of locally produced renewable energy, and further promote electrification of the energy sector. While complete

[5] Sihvonen and Honkapuro, 2023

energy independence was not possible with the studied technologies, the island's dependency on importing and exporting electricity was greatly reduced.

3.6 Evaluating Business Strategies for Thermal Energy Storages: Participation in the Nordic Electricity Markets[6]

In this study, the profitability of a thermal energy storage operating in electricity markets was assessed. The electricity markets considered in the study were day-ahead markets and reserve markets. The study was a case study of a high temperature sand battery in the context of Finnish electricity markets. An optimisation method based on a specific price limit mechanism was developed for the study. The study revealed that it is not a profitable business case for the storage to purchase the electricity from the day-ahead market and sell the produced heat to the district heating network at fixed price. Participating in reserve markets would be a significant part of the sustainable business for the thermal energy storage but the profits are dependent on whether the storage runs at full power, and participates only in the down regulation, or runs mostly at half power and participates in both up and down regulation. More volatile electricity markets indicate higher profits in reserve markets and less losses in the day-ahead market.

[6] Jaanto and Honkapuro, 2024

4 Technology Development & Feasibility Studies

Most of the NewSETS technology development and feasibility studies focused on the seasonal heat storage developed by Polar Night Energy The technology development considered the details of the technological solutions in the basic heat storage product, such as the optimal arrangement of heat transfer pipes and devices, the active treatment of heat losses through layered charging and discharging, and the design of the proper measurement arrangements for knowing the storage state precisely enough at any given time.

Additionally, technology development of the seasonal heat storage also considered studying the capability of electricity production, and this study was done in a broader perspective, analysing the process diagrams and the requirements of the solution when a turbine is attached to the thermal energy storage system to produce electricity back from the stored heat. As planned, this project considered electricity production only preliminarily and its role was minor. However, over the course of the project, electricity production was identified as an extremely promising product. Consequently, Polar Night Energy is next about to start a major research and development project related to upgrading the present product with electricity production capability.

When it comes to the feasibility studies around the seasonal heat storage, in the early phase of the project, the feasibility of repurposing old oil caverns to sand-based heat storage facilities was explored. Despite its appeal from a circular economy perspective, this option was rather swiftly deemed unfeasible for Polar Night Energy’s technology. It became evident that a costly cleaning process would be necessary, and that the working conditions for the installations of the heat storage equipment were very challenging, especially in terms of limited space to manoeuvre. It was estimated that this option would be clearly more costly than building a new above-ground storage from scratch.

Additionally, during NewSETS, Polar Night Energy developed expertise and capability in conducting feasibility studies for its potential customers. These feasibility studies were formulated as a product, and this product had a high demand and generated crucial income for the company already during the project and will stay to serve the company in the future. It's important to note that these studies were independently funded by customers and not by project funding.

Nevertheless, the project played a pivotal role in developing the tools needed to conduct the feasibility studies. The studies required effective tools to find a correct scale of a heat storage facility for different customer needs, and to simulate how a specific heat storage facility would work in a specific customer case. The customer case may have restrictions in electricity transfer and specific needs for output temperature levels, for example. Emissions and electricity costs were evaluated within these studies using simulations.

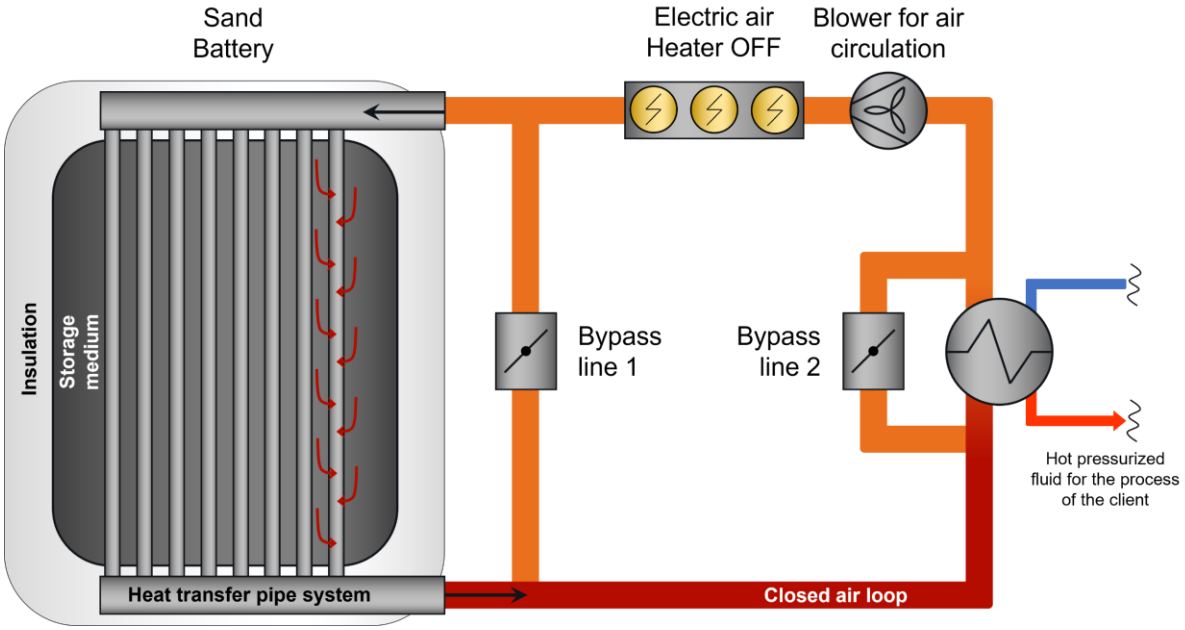

Figure 4: Description of the operation of the heat storage solution of Polar Night Energy in the discharging mode. The patented closed loop air circulation handles the charging mode analogously, with electric air heating ON, heat flowing from heat transfer piping to the storage medium, and air flowing through the bypass line 2 instead of through the heat exchanger (unless the user wants to discharge also during the charging).

The simulation tools encompass the true automation logic of the heat storage facility, and hence they give a realistic description on how the heat storage solution would work within the energy system of the customer, provided the input data on heating demand and electricity markets is considered representative and reliable description of the future. Figure 4 describes the operation of the heat storage solution under the simulation and Figure 5 shows an example how could the results found by the simulation appear.

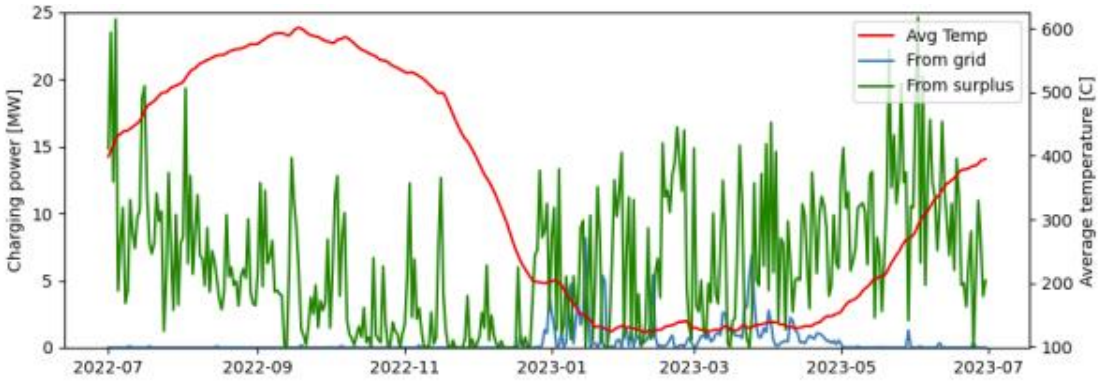

Figure 5: Evolution of average temperature (representing the state of charge) of a heat storage solution in a specific use-case under the simulation. The charging of the heat storage from a wind farm and from the local grid is also shown, for illustration purposes.

The dimensioning tools on the other hand consider the problem of being quickly able to choose a design for specific performance requirements. Since the company does not yet have long list of references, the designs offered need to be chosen on theoretical grounds, rather than based on real-life experience. To achieve a performance that is found optimal by the simulation tools, dimensioning tools aim to find a cost-optimal choice of design parameters (such as various dimensions) so that the heat storage unit achieves the specified performance. These tools at disposal, the company can analyse the energy system of the customer and test various different heat storage products to achieve the best possible pay-back time and emission reductions for the customer.

5 Communication & Dissemination Activities

NewSETS included the efficient communication and dissemination activities in addition to comprehensive R&D efforts. A target was to establish a positive outlook among energy stakeholders and to make climate change mitigation efforts visible to everyone through skilful communication. NewSETS hosted several events for the public, including seminars and workshops where local people could steer the direction and research questions of the project.

Regular NewS-updates in our website were the backbone of the communication and dissemination activities. They described how the project progressed, published mainly bi-monthly to quarterly intervals.

NewSETS was featured in seminars, workshops, presentations, university lectures as well as online media. Some highlights include International Conference on European Energy Markets 2023 (https://www.lut.fi/en/eem23) and Åland Energy Day (https://www.ha.ax/changing-energy-systems/).

In 2022, NewSETS hosted an event for Åland key energy actors, in collaboration with the Horizon 2020 project LocalRES (https://www.localres.eu/). The audience included officials from the Åland Government, representatives such as the CEO from the island's major DSO, the Åland University of Applied Science as well as the chamber of commerce. The audience was able to participate in the NewSETS project's steering by voting on the most exciting research questions.

Ultimately, the final seminar in May 2024 wrapped the key findings of the project to a half-day event combining presentations, a panel discussion, and a workshop about energy storage and sector integration. The event was held in the premises of the LUT University, and the participants ranged from researchers and consultants to utilities and project developers.

The workshop part consisted of first identifying barriers for energy storage investment, and then identifying research and development and innovation (R&D&I) needs for energy storage investments and sector coupling. In total, the workshop gathered 44 answers for the investment barriers and 33 answers for the R&D&I needs. Finally, workshop participants were able to vote on the answers that they felt were the most important.

The unpredictability of political decision-making received the highest number of votes and was seen as the largest energy storage investment barrier. Similarly, long-term uncertainty of energy markets received the second highest number of votes. Both highlight the fact that long-term investments also require in turn long-term stability and predictability, both from regulation and markets to minimise investment risks. The concerns regarding the ownership structure of the district heating companies and the distribution of ownership of the heating plants received the third highest number of votes. Fourthly, the maturity of technological solutions was seen as a barrier to investments.

Support for demonstration sites of seasonal storage (heat or other energy carriers) was seen as the most important R&D&I need. Secondly, it was seen as necessary to take innovations into practice and further into business to enable wider integration of energy storage and sector coupling. Simulation of business models, while taking the markets into account, received the third highest number of votes, highlighting the need for studying business cases for the storage, but also further verifying the important role of the energy market in investment decisions. Finally, it was seen as important that awareness and knowledge of the energy storage technologies would be increased for different stakeholders.

6 Conclusions

NewSETS linked high-level scientific research on energy storage with feasibility studies and market analyses. The project showed various key outcomes regarding energy storage for policy makers, research organisations, technology providers as well as project developers. The conclusions and recommendations are further elaborated below in Figure 6.

Key recommendations for policy makers, industry and research organisations

- **Remove** barriers and **provide** long-term political consistency for energy storage investments and utilization in different markets and use-cases
- **Study** energy storage cannibalisation further in different systems, RES & storage penetration levels
- **Diversify** energy storage asset utilisation to different markets and use-cases
- **Design** and **optimise** energy storage assets in conjunction with the energy system
- **Support** demonstration of seasonal storage

Figure 6: Recommendations from the project to the key stakeholder groups.

NewSETS demonstrated various effects of different storage types populating energy systems. The research indicated that energy storage promoted renewable energy integration, as the RES curtailment could be significantly decreased. Energy storage decreased electricity price volatility and stabilised the electricity prices shaving high-price peaks and low-price bottoms. By introducing different storage technologies with various energy carriers to the same system, it is possible for different energy sectors to take better advantage of renewable energy and low electricity prices.

Thermal energy storage was found crucial in supporting the cost-efficient decarbonisation of heating. While electrification and power-to-heat technologies have a strong potential to reduce

emissions in district heating systems, they also make the systems vulnerable to electricity price volatility. Thermal energy storage could hedge against this price volatility.

For the storage asset investors and technology providers, NewSETS came across some critical information that should be considered. The different storage assets might cannibalise each other's business cases if they operate on the same use case, e.g. energy arbitrage. The assets might compete of the same low-price hours for charging and the same high-price hours for discharging. As mentioned above, this decreases volatility, shaving price peaks. For the consumers this manifests itself as stable electricity prices but cannibalises the energy arbitrage business case. Hence, NewSETS research suggests that it is important that storage assets participate widely in all feasible energy markets (e.g. day-ahead, intraday, balancing & reserve markets). This can provide additional income for the storage owners.

Consequently, policy makers should remove barriers for energy storage to participate in different energy markets and use cases to further promote investments. Policy makers should also aim to provide long-term political consistency and regulatory stability. The need to support seasonal storage demonstration was clearly identified as well.

When considering detailed storage design, NewSETS' feasibility studies demonstrated that energy storage assets should be simulated and designed in conjunction with the energy system. An integrated approach would provide a deep understanding of the needs of the energy system and the possible role of energy storage in it. Then again, merely designing a storage unit based solely on specific energy capacity or output power may result in selecting a suboptimal solution.

In future research, novel optimisation tools should be implemented to ensure optimal design and use of energy storage in integrated energy systems with multiple energy carriers. Different energy storage types can support each other, and one storage can increase its value creation by participating in multiple markets. To promote cost-efficient energy system design, such optimisation tools that can be implemented in the design and operation of energy storage are needed. AI-based forecasting can be used to optimise the dispatch of the storage capacity, while, for instance, game theory-based solutions provide opportunities for system design optimisation. However, more research on these themes is needed for the practical implementation of such methodologies.

Further research will also be needed on the cannibalisation of energy storage when more and more storage assets are implemented to energy systems. Will it be possible to install enough energy storage capacity to support the penetration of RES while still maintaining the business case for the storage asset owners?

References

Sihvonen, V., Riikonen, J., Price, A., Nordlund, E., Honkapuro, S., Ylönen, M., Kivioja, V., Hedman, Å., Tulberg, R. 2024. Combined utilization of electricity and thermal storages in a highly renewable energy system within an island society. Journal of Energy Storage. https://doi.org/10.1016/j.est.2024.111864

Sihvonen, V., Ollila, I., Jaanto, J., Grönman, A., Honkapuro, S., Riikonen, J., Price, A. 2024. Role of power-to-heat and thermal energy storage in decarbonization of district heating. Submitted for a review. Journal publication.

Ghorbani, N., Sihvonen, V., Makian, H., Breyer, C., Honkapuro, S. 2024. Developing a Replicable Methodology for Assessing Pumped Hydro Energy Storage Potential: Mapping, Estimation, and Economic Analysis. Manuscript under finalization. Journal publication.

Jaanto, J., Sihvonen, V., Honkapuro, S., Riikonen, J., Price, A., Ylönen, M., Kivioja, V. 2023. Thermal storage deployment in the framework of current electricity market design. 19th International Conference on the European Energy Market (EEM). IEEE. DOI: https://doi.org/10.1109/EEM58374.2023.10161744

Sihvonen, V., Honkapuro, S. 2024. Energy storage as an enabler of a renewable island energy ecosystem. Submitted for a review. Conference publication.

Jaanto J., Honkapuro, S. 2024. Evaluating Business Strategies for Thermal Energy Storages: Participation in the Nordic Electricity Markets. Manuscript under finalization. Journal publication.

ISBN 978-952-412-082-1

ISSN-L 2243-3376

ISSN 2243-3376

Lappeenranta 2024