Final report

1. Project details

Project title	Hybrid Storage
File no.	64020-1102
Name of the funding scheme	EUDP
Project managing company / institution	DTU Wind
CVR number (central business register)	30060946
Project partners	DTU Wind, Vestas
Submission date	19 September 2024

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future, both in English and in Danish. The summary will be published on www.eudp.dk and www.energiforskning.dk.

Project summary:

- **The purpose of the project**

The need for controllable resources in power systems will increase as renewable energy becomes more dominant. Energy storage can be an essential source of flexibility, but costs are still high.

The project addressed the hypothesis that by combining different energy storage technologies with different technical characteristics and exploit more revenue streams, the overall costs can be reduced.

- **Results, conclusions and perspective**

The project has investigated the benefits arising from combining storage technologies in a Hybrid Energy Storage System (HESS) and developed a sizing tool that can be applied to determine the optimal combination and size of a HESS.

The developed simulation tool was used to analyze the HESS’ real-time operation of the storage units and the controller that implements the control strategy. The real time simulation is part of the sizing tool. It provides the

degradation and efficiency parameters to the algorithm that optimizes the daily HESS scheduling and calculates the revenue and operational costs. The sizing level of the tool takes these as input and determines the optimal size.

A very important part of the project has been the establishment of a testbed in the facility SYSLAB at Risø DTU. The testbed combined a Vanadium-battery (large capacity/low efficiency), a Lithium-battery (degradation/medium cost) and a Supercaps (low degradation/high cost) unit into a HESS via a controller that implemented a control strategy exploiting the features. The technologies were characterized, and the data was used for calibrating the sizing tool. Additionally, experiments documenting the behavior of the combined system and the individual units when they provided frequency support were carried out.

The HESS technology will be further developed in the EU project 2lipp that will do demonstrations at Bornholm with molten salt storage, lithium battery and a flywheel.

Projektresumé

- **Formålet med projektet**

Behovet for styrbare ressourcer i elsystemet vil stige efterhånden som andelen af vedvarende energi bliver større. Energilagring kan blive en vigtig kilde til fleksibilitet, men det er stadig dyrt.

Projektet adresserer hypotesen om at ved at kombinere forskellige typer energilager med forskellige egenskaber, kan de samlede omkostninger reduceres.

- **Resultater, konklusioner og perspektiv**

Projektet har undersøgt fordelene ved at kombinere forskellige typer energilagring i et Hybridt Energilager System (HESS) og udviklet a dimensioneringsværktøj, der kan anvendes til at fastlægge den optimale kombination og størrelse af et HESS.

Det udviklede simuleringsværktøj er anvendt til at analysere real-time driften af lagerenhederne og styringen, der implementerer styrestrategien. Real-time simularingen er en del a dimensioneringsværktøjet. Det leverer degraderings og virkningsgrads parametre til algoritmen, der optimerer den daglige pln and udregner indkomst og omkostninger. Dimensioneringsniveauet of værktøjet, bruger dem som input og fastlægger den optimale størrelse.

En meget vigtig del af projektet var at etablere en prøveopstilling i SYSLAB på Risø DTU. Prøveopstillingen bestod af et vanadium-batteri (stor kapacitet/lav virkningsgrad), et lithium-batteri (degradering/middel pris) og Superkapacitorer (lav degradering/høj pris), der blev samlet i et HESS via en styring, der implementerede der udnyttede de karakteristika. De enkelte enheder blev karakteriseret og data blev brugt til at kalibrere dimensioneringsværktøjet. Endvidere blev tests, der dokumenterede opførsel af det samlede system og de enkelte enheder udført.

HESS vil blive yderligere i EU-projektet 2lipp, der vil gennemføre demonstrationer på Bornholm med et system der består af et smeltet salt enhed, et lithium-batteri og et svinghjul.

3. Project objectives

Objective form the application:

- *perform an in-depth evaluation of energy storage hybridization benefits and synergies. This will be achieved by comparing different hybridization scenarios, e.g. redox flow battery and supercapacitor vs. redox flow battery and lithium-ion battery, to a reference case containing a single energy storage technology.*
- *design and develop a proof-of-concept tool for the configuration and sizing optimization of hybrid energy storage systems (HESS) in different power system applications. The optimization will consider the techno-economic trade-offs of various hybridization scenarios differentiated by a variety of ES technologies, electrical network topologies as well as control and management strategies.*
- *develop, test and demonstrate HESS prototypes, both as standalone systems and integrated with intermittent renewables, e.g. a wind turbine generator (WTG).*
- *prepare for launching large scale demonstrations of HESS at TRL 7/8.*

During the project a test bed for the storage units was developed and implemented. The test bed was instrumental in obtaining characteristics of the individual participating technologies as as well as for testing controllers that combined the three storage units to HESS systems and investigated their combined ability to deliver frequency services.

A configuration/sizing tool has been developed. It links investment decisions with market participation and operation with ancillary service provision and the resulting degradation and losses. The impact of different controllers on service delivery and degradation can be studied and participation in different markets can be analyzed. The tool has been calibrated using the test results.

The effect of hybridization has been investigated using the developed tool. The tool allows easy configuration changes and variations.

As for the objective to demonstrate the HESS in large scale with WTG, this has not been implemented due several practical issues, see below.

4. Project implementation

The project has implemented the activities in WP1-4. The WP5 has been partially implemented. WP6 has not been implemented. (The project accounts reflect this).

Overall, the project has been significantly delayed. The main reasons for this have been:

- DEIF withdrawing from the project.
- Resources due to resignations and delays in new hirings and reorganisation
- COVID resulting in extended delivery times
- Several other unforeseen delays due to e.g. permitting and grid connection

WP1 (Project management and dissemination):

- As mentioned above there have been challenges with DEIF leaving and resources for the project.
- The publication of results has been less than planned (1 paper published) but results from sizing tool is planned to be published.

WP2 (HESS configuration and sizing tool):

- The tool has been developed. The tool has a layered structure that splits the optimizartion problem into a sizing level, an daily optimal revenue level and real-time operation.

- Calibrating the tool using results from the testing
- A significant feature is that at the real-time level the tool allows for switching between simulations (for the sizing) and operation in the lab.
- The use cases has been the foundation for the description of the functionality and the primary focus has been on optimizing the concurrent provision of frequency services and exploiting energy arbitrage.
- The tool allows for flexibility in the daily optimization module and for the configuration of the HESS under study.

WP3 (Design and development of HESS for test campaign):

- The review of the state of the art was completed and it confirmed the hypothesis of the value of hybridization of the storage system.
- The uses cases developed by the partners where identified as commercially interesting.
- The tests system was specified and components acquired. There was a delay in this process due the issues mentioned above and the final equipment arrived late.
- The control system supercaps+Li-battery system was developed and implemented by Vestas and the combined system was installed at Risø and integrated with the Va-battery.
- A coordinating controller was implemented to allow combined operation of the three units.
- Due to its prototype nature the operation was a less stable than production systems. This resulted in a longer period for testing and tuning until the system has adequate stability of operation. However, the system still has operational limitations that result in tripping of units and manual intervention to recover to normal operation.

WP4 (Test campaign of HESS without WTG):

- Two measurement campaigns have been executed:
    - Component characterization with focus on efficiency and response time
    - Provision of frequency service for different configurations with different parameter settings
- The tests have been successfully completed, however, as mentioned above, the prototype nature of the underlying controllers caused operational issues that required manual intervention. This extended the testing period.

WP5 (Design of full-scale HESS integrated with a WTG):

- This task was severely impacted by the decision of DEIF to withdraw from the project. It meant that this part had to replanned with completely different hardware from alternative suppliers. This caused significant delay. Additionally, due to COVID the delivery of the hardware was further delayed.
- During the project period a new collaboration with Total Energies was initiated by the department and a major activity in that collaboration was a hybrid power plant that combined WTG, PV and storage and with potential extensions into PtX.
- Due to the size of the combined system several permitting and grid connection issues appeared. This resulted in very long delays and the completion of the facility is now outside the project period.
- As a result of this the funding allocated to this activity is not spend and is returned.

WP6 (Demonstration of full-scale HESS with an integrated WTG):

- Due to the delay in establishing the facility this activity has not been executed and has not been included in the projected expenses.

- It should be noted that the facility is being completed but outside the frame of the project. Activities within the scope of the project is foreseen to be carried out once the facility is in operation.

5. Project results

As mentioned above the project had four objectives

- Evaluation of benefits of hybridization of storage system
- Sizing tool
- Testbed for hybrid storage systems
- Integration with wind/renewables in a Hybrid Power Plant setup

The project results will be presented in relation to each of these objectives.

Evaluation of befits of hybridization

The benefit of hybridization comes from the different technical and economic performance characteristics of the different storage options that can be part of the HESS. The advantages and disadvantages of the three different technologies are very low degradation/high costs for Supercaps, degradation/medium cost for Li-battery and low efficiency at low power/low cost for Va-battery.

The revenue streams for the HESS comes from its provision of system services. These are mainly frequency-based services or balancing services that are requested by the TSO. Often the services consist of a reserve-part and the actual activation and delivery. For a given configuration, the performance and impact on the storage units depend on the service provided, the amount that is provided and how it is provided. The control strategy implemented in the HESS determines usage pattern of the storage units depending on size of the units and how the combined system is used.

A rule-based controller that implements a control strategy based on the characteristics of the storage units has been implemented for the physical system as well as for the simulations.

The tests document the expected behavior, see Figure 1. It is noted that the Va-battery is only used in the high power range and that the supercaps is the fast acting unit. It is also noted that the HESS tracks the desired output very well and the SOC range of the supercaps is very well exploited. In the following figure, Figure 2, is documented how the rate of change of the output for the participating units changes as the configuration of the HESS is changed. It is seen how the priority of the Va-battery to only deliver high power output transfers some of the fast changes to the other units if they are part of the configuration. When the Va-battery is combined with the Li-battery, the large power output from the Li-battery will be reduced but the Rate of Change pattern remains the same. When the supercaps are added to the system, they take over the role as the unit that handles the rapid changes, and the usage pattern of the Li-battery has much reduced range.

Similarly, the simulations show how the number of cycles for the is shifted toward the supercaps as their capacity increases. The simulation tool also illustrates how the usage pattern changes as the frequency service capacity increases from the size of the units to the sum of the units. As the reserve capacity is increased the Va-battery contributes increasingly to the provision of services.

It can be concluded that from the results of the experiments and the simulations, the HESS can exploit the features of the participating units and that the resulting efficiency and degradation functions can be determined to be applied in the sizing tool.

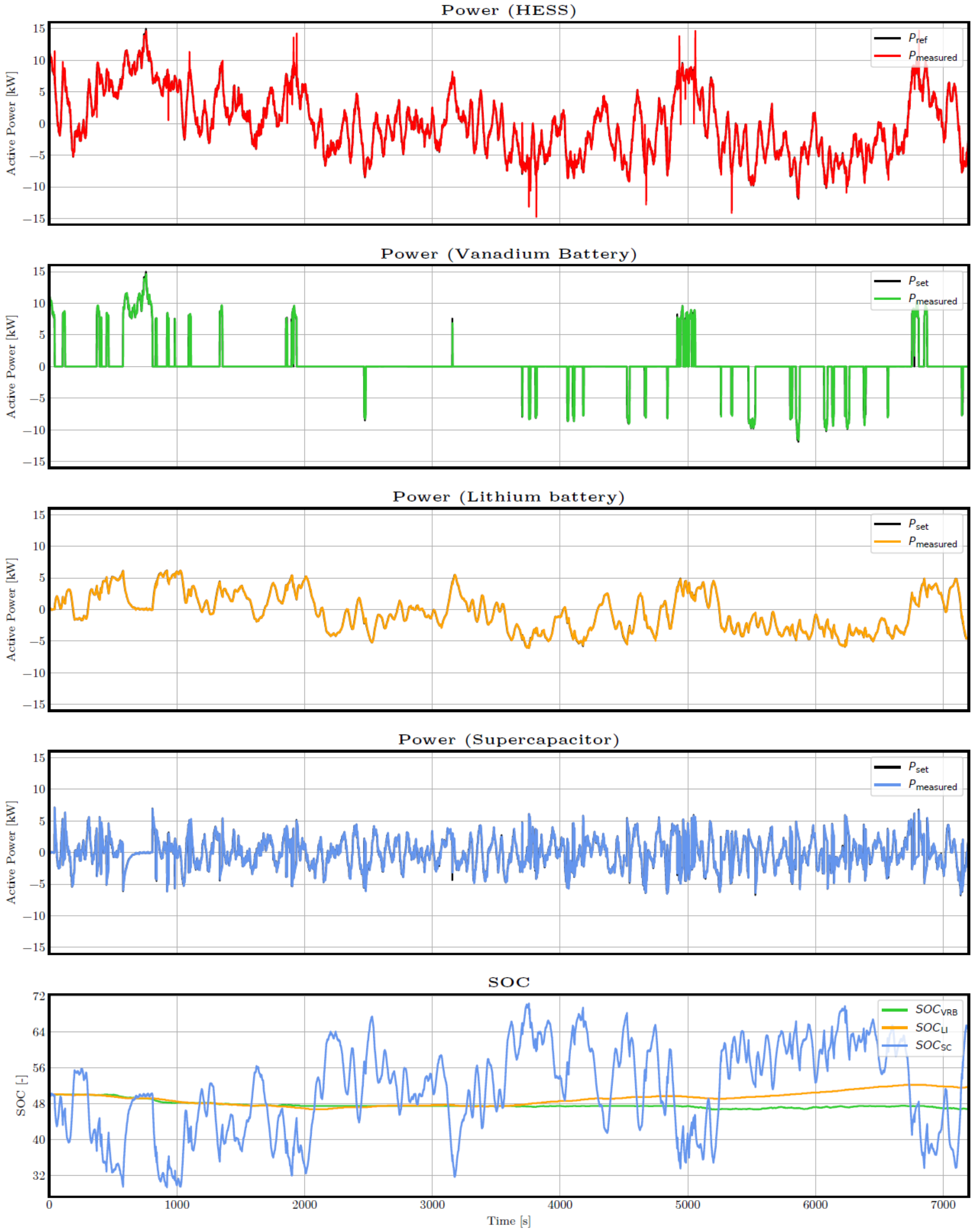

Figure 1 Operation of HESS with all three storage technologies. Results form the test setup.

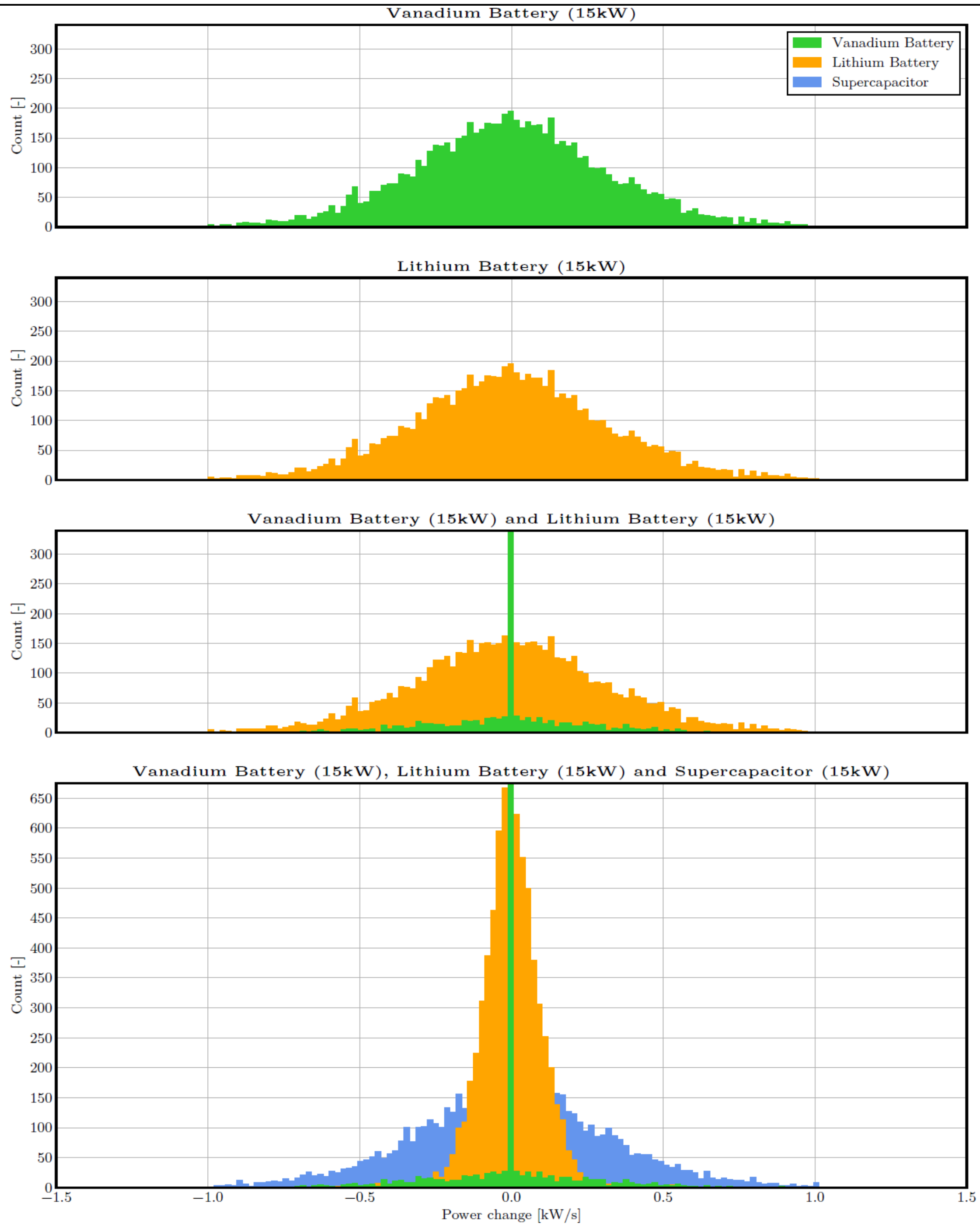

Figure 2 operational pattern for different storage configurations. Results from the test setup.

Sizing tool

The objective of the tool is to enable a system designer to determine the optimal configuration (size and technologies) for a HESS in a particular market setup for a given budget limit or size limits.

The developed tool has a layered architecture with three layers, Figure 3. The upper layer is the actual optimal sizing problem. This module has the objective to search for the optimal combination of technologies and power and energy capacity based on maximizing the expected profit. The middle layer determines the profit for a particular configuration. It is calculated as optimal scheduling of the HESS regarding system service provision and energy arbitrage and the lower layer simulates the real-time operation for providing the scheduled service and arbitrage.

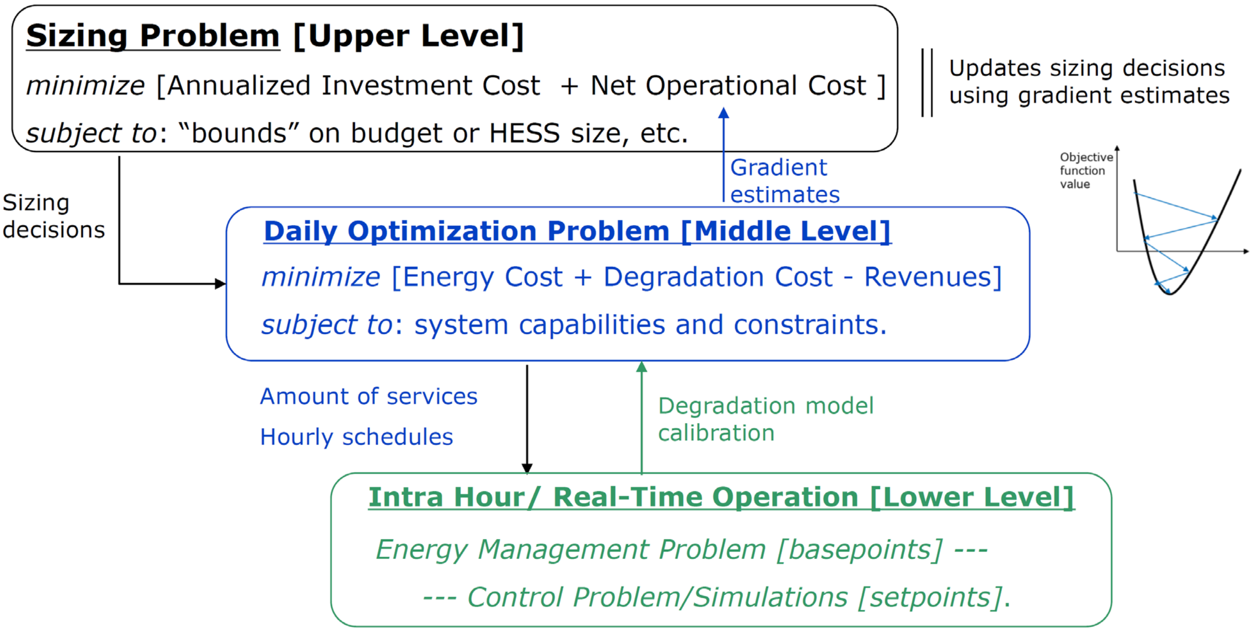

Figure 3 Outline of the sizing tool with its three layers and their interaction

The upper layer determines the optimal configuration through a gradient search that uses the middle layer to find the most profitable direction to improve the current configuration.

In the middle layer the daily profit is calculated as the anticipated profit resulting from an optimal schedule for the operation of the assets included in the HESS and the realization of that. Determination of the optimal schedule includes degradation of the storage units in their current configuration and control and similarly for the losses.

These values are calculated at the lower layer and are based on simulations of the real-time operation of the HESS delivering the services determined by optimal schedule. At the real-time operation level, the simulation model is based on relatively detailed models of the technologies and their control. This enables the determination of the degradation resulting from the usage pattern that the controller and external signal impose on the storage units.

One of the main features of the tool is that it implements the controller directly as on the physical setup in the testbed and that allows for immediate switching between simulated storage units and physical units. In Figure 2 is shown how the usage pattern changes depending on configuration. This will be reflected in the amount of degradation and that is output from the real-time operation simulations to the daily optimization layer.

The storage technology models can be exchanged for more advanced models with improved representation of the loss of health and reflecting the operational conditions for establishing the realized efficiency.

Similarly, the control of the HESS can be exchanged. This allows for delivery of other services as well as different ways of exploiting the features of the individual storage elements.

The simulation tool can also be used for investigating and establishing an overview of the impact of control parameters.

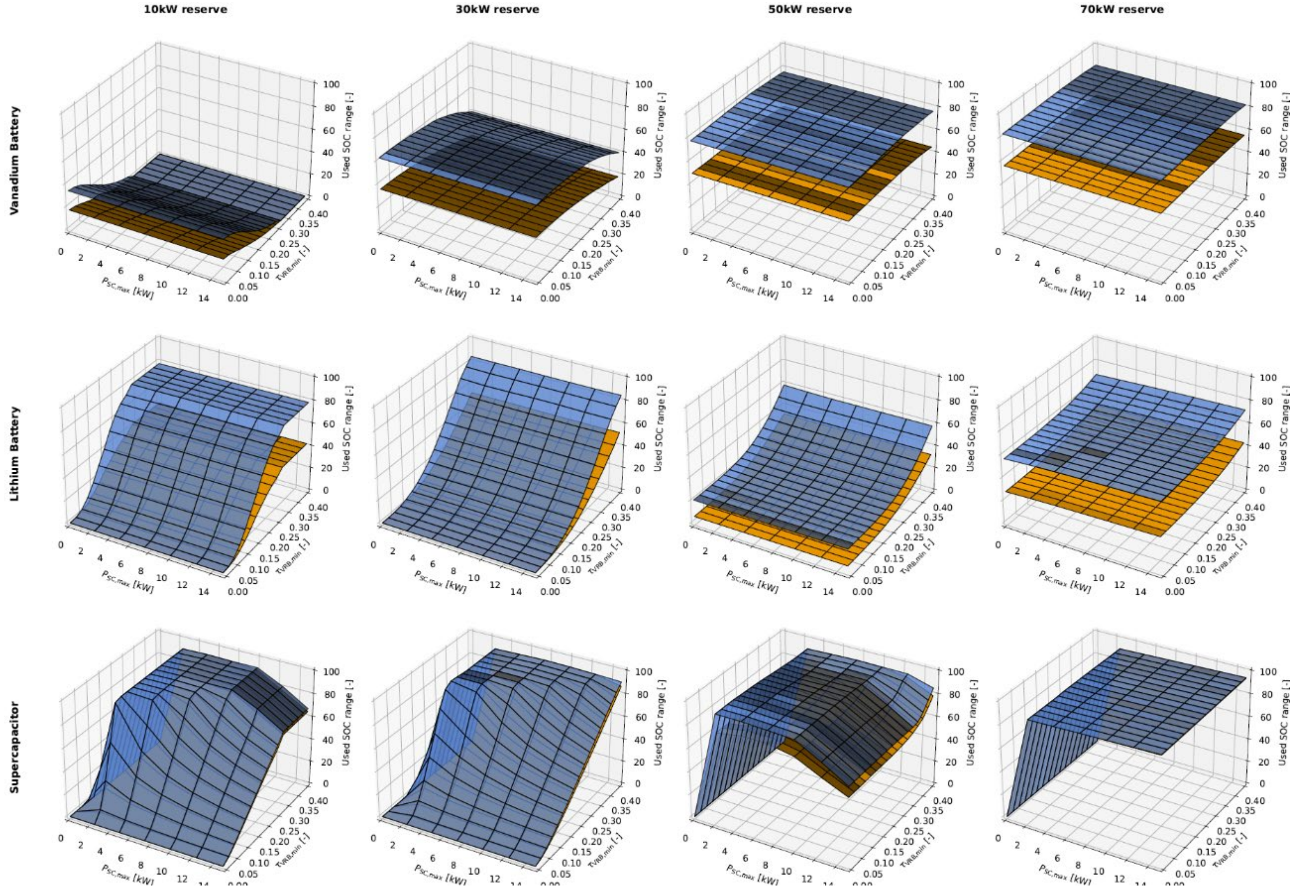

Figure 4 Simulation results illustrating how the storage capacity is exploited when the offered reserve capacity is changed

In Figure 4 is an example of simulation results illustrating how the storage capacities of the three units are utilized depending on how large capacity of a frequency service is provided. It can be noted from the figure hat the larger the capacity of the service the more of the Li-battery and Va-battery capacities are utilized and that the Supercaps are close to fully exploited also for smaller reserve capacities.

Testbed

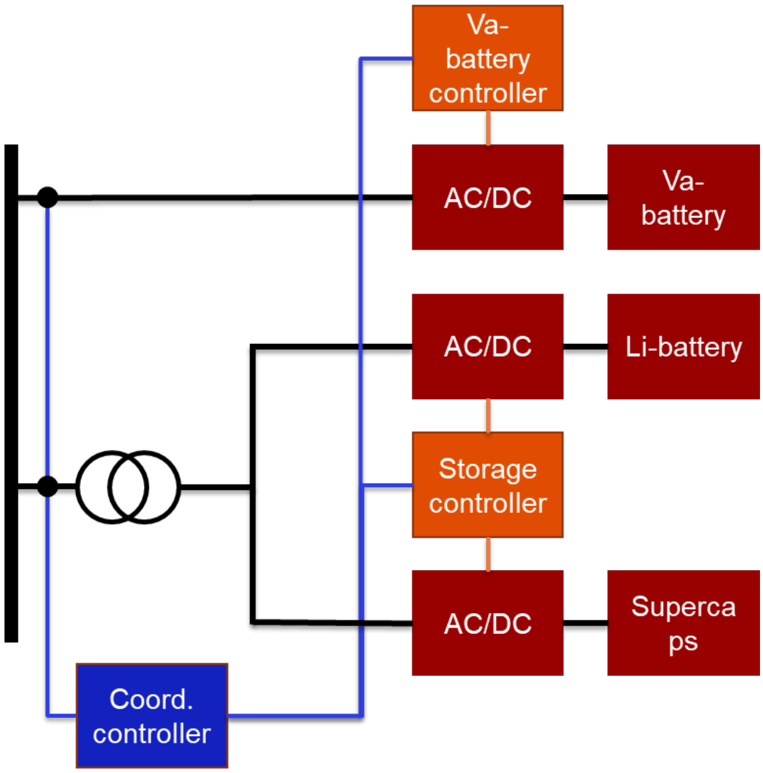

Figure 5 Experimental setup in SYSLAB

SYSLAB is an experimental facility for intelligent energy systems at DTU Risø. It is a facility that is based on real physical units such as wind turbines, pv systems and storage units. It has a very high degree of automation, and its software infrastructure enables large flexibility in the control of the units.

A testbed was established in SYSLAB to be able to validate the behavior of the combined HESS with a coordinating controller and to provide experimentally based data to calibrate the developed sizing tool. The setup in SYSLAB is shown in Figure 5. In the figure it can be seen that the Li-battery and the Supercaps share the same grid connection via a shared transformer that steps up the voltage of the power converters, and a Storage controller that handles the fast control loops and the safe of operation of the two storage units. Additionally, the VA-battery is connected to its own bay in the switchboard and has its own controller. The setup also includes the coordinating controller that receives measurement values from SYSLAB, states and measurements from the storage units and calculates and forwards relevant setpoints to them. The Li-battery is supplied by Vestas as is the controller for it and the Supercaps.

The control system is hierarchical. The local controllers for the Va-battery, Li-battery+Supercaps ensures safe operation of the units by keeping them within the operational limits. They actuate the setpoints that are communicated to the and they forward measured and calculated values such as power and SOC.

The coordinating controller calculates the individual setpoints based on the received schedules and the current service that is provided by the HESS. It implements the control strategy for the utilization of the storage units.

Additionally, there is an additional functional unit that executes the actual experiment, i.e. handles relevant time series with frequency values that is forwarded to the coordinating controller and is driving the experiment and changing control parameters between individual experimental runs. It also ensures that units are returned to the initial SOC between experiments.

The experiments fall in two classes. The first one is characterization of the individual units in terms of efficiency and capacities. The second class of experiments contains all the combined HESS behavior and performance.

In the first class of experiments, in Figure 6 are the time series showing an example of an experiment to determine the efficiency pf the Li-battery operating at a 15kW square signal and Figure 7 shows the calculated efficiency curves based on those experiments.

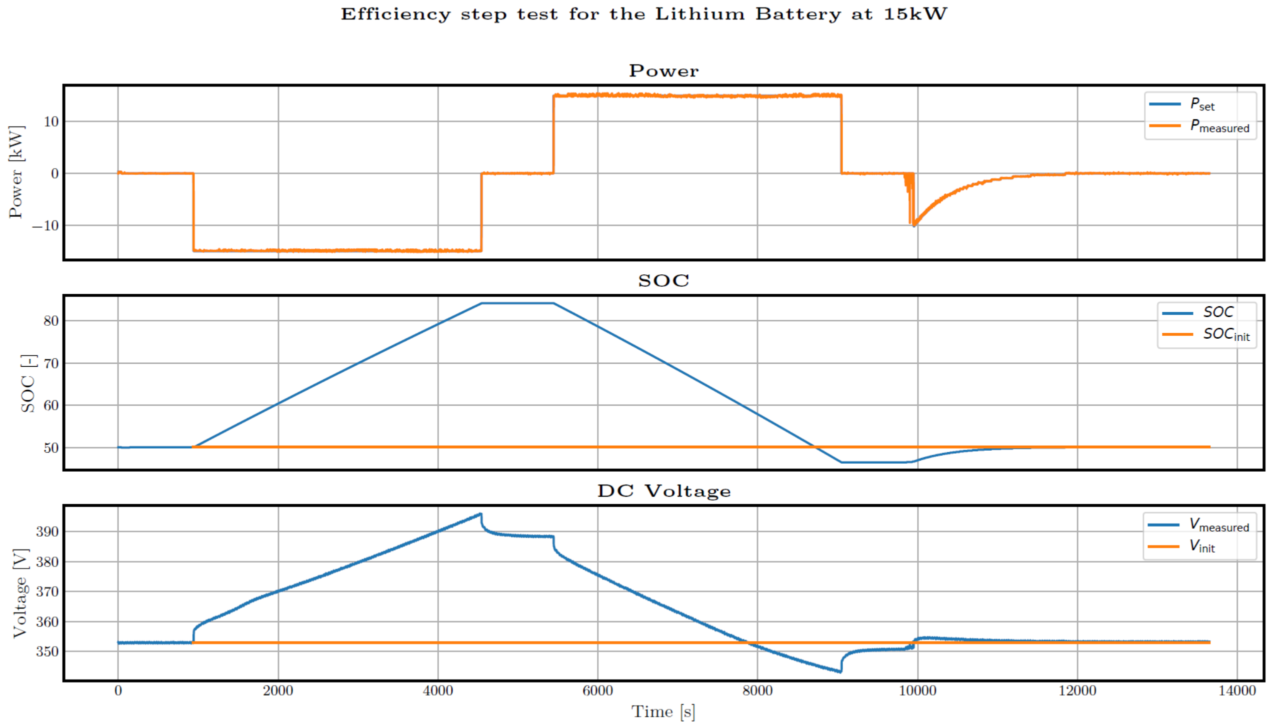

Figure 6 Example of efficiency measurement experiment for the Li-battery.

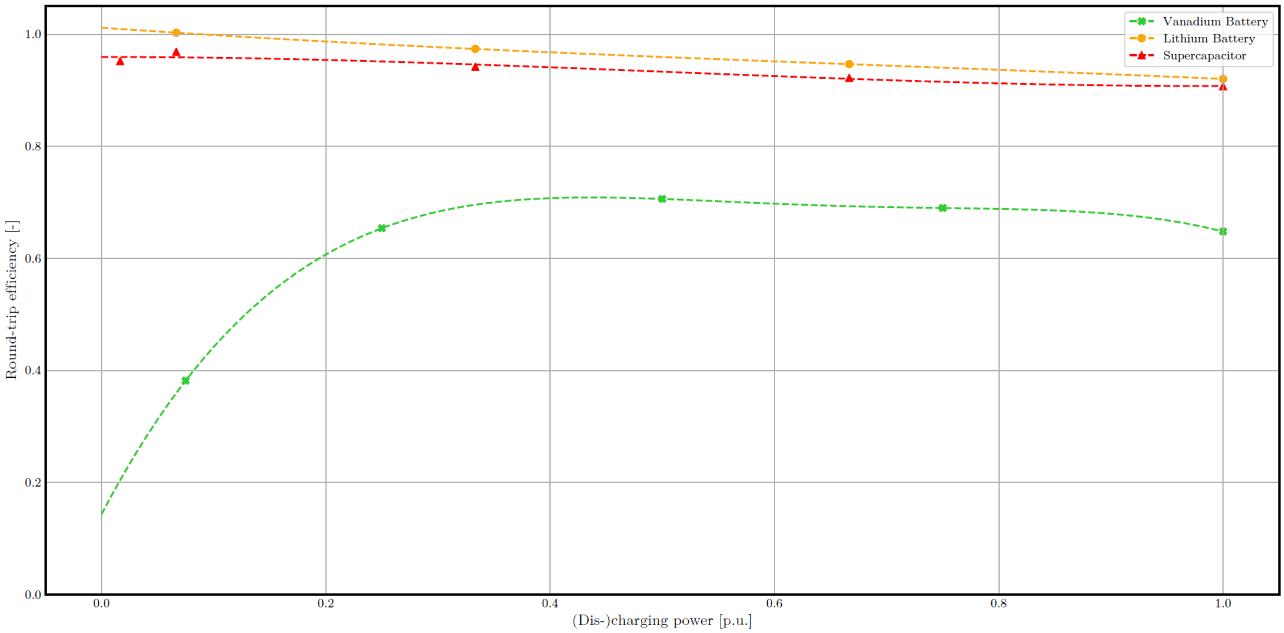

Figure 7 Measured efficiency curves for the three storage units

For the second class of experiments, the figures, Figure 1 and Figure 2, illustrate the combined behavior of the HESS and how the three different units are contributing to the service provision. It is also clear how the operating patterns are different for them.

Integration with wind/renewables

The objectives associated with the integration with wind has not been achieved. The activities towards this objective have been challenged by the exit of DEIF and the consequences of that as well as by the required permits coming from the increased scope of the test facility.

The power converters, storage systems and switchboards that are part of the facility were ordered and delivered, however, the system integration was not completed due to the complexity of the new setup.

During the same period the DTU Total Energie Center of Excellence (DTEC) Hybrid Power Plant facility was conceived and merged with the previous design. This increase in scope resulted in an increasing need for space and additional complexity in the system integration. The larger space requirement had the consequence that the system had to be established at another site on Risø Campus due to coastal protection lines.

The new facility is still under construction but will be finalized by the end of 2024.

As part of the Hybrid Storage project only initial steps of the planned activities were carried out. These included specifications of the components and the ordering of them.

However, since the anticipated experiments could not be executed the costs associated with this activity are not claimed.

Dissemination

A paper has been published on af hybrid power plant with combined with supercaps for delivering fast frequency support *(L Long, Q., Celna, A., Das, K., & Sørensen, P. (2021). Fast Frequency Support from Hybrid*

Wind Power Plants Using Supercapacitors. Energies, 14(12), Article 3495). It is planned to present results on the sizing tool and testing at scientific/technical conference at Cyprus in October 2024 (Synergy Med 2024, Cyprus).

6. Utilisation of project results

The market for stand-alone storage systems and for storage embedded with renewables is still very relevant as indicated by the number of storage plants that are being deployed for provision of frequency services in Europe. The current size of the utility scale market is more than 3GWh/y (2023) and growing rapidly. The stand-alone systems primarily providing frequency support and the embedded systems enabling renewables to deliver frequency services as well as making better use of the grid connection.

The results of the project in terms of insights into operation of a storage system that is built from different storage technologies are being applied in the EU-project 2lipp. In this project a hybrid storage system with molten salt storage, second hand li-batteries and flywheel is developed and constructed at the power plant at Rønne Harbor. The design idea behind this project is similar to Hybrid Storage by exploiting the strengths of each technology to mitigate the weaknesses that they also have. The developed simulation tool will be an essential tool for the development of the energy management system of the HESS in the 2lipp project and it will take advantage of the capability to seamlessly change between simulated and real units. This will be particular advantageous as it allows for a development cycle that integrates well with the tool chain of the EMS supplier. The outcome of the Hybrid Storage project will directly benefit the commercial partners in the 2lipp project due to the insights into coordinated operation of the different types of technologies and the contribution to the analysis and demonstration activities in the project.

HESS and the outcome of the project will also be a significant input to the follow up activities in the frame of DTU Total Excellence Center (DTEC) Hybrid Power Plant planned activities with the establishment of the Risø HPP test facility. The outcome of these activities will be similar to the outcome anticipated in the original Hybrid Storage project and will feed into the ongoing international development of hybrid power plants and improve their capabilities to better integrate into the power system as well as open for new or increased streams of revenue.

At the project preparation phase Vestas anticipated that stand-alone storage solutions for microgrid applications would be product. However, during the project Vestas decided that they would not develop a stand-alone storage solution but focus on embedded storage systems in hybrid power plants. They are still developing hybrid power plant solutions where storage is one of the options. They have recently put in operation a hybrid power plant that can provide frequency services for the Nordic power system. Therefore, Vestas is still pursuing activities with storage technologies for improving performance of hybrid plants. The insights from the project will be applied in their solutions but due to the new situation at Vestas, direct impact on number of employees and turnover cannot be attributed to the project.

As can be concluded from the above the commercial development will take a different path from the expected in the proposal. The direct continuation as HESS will be via activities with DTU participation e.g. the 2lipp project. The other main direction of development is hybridization of other types of plants. This include the Vestas main line of development that now focuses on hybrid power plants i.e. the combination of RE generation and storage. Another variations of hybridization that is currently getting much attention is the combination of PtX and batteries. The sizing tool with its simulation part will be further developed to include these configurations, fluctuating RE and flexible consumption with an additional product output. It will be DTU that will be developing the tool further.

7. Project conclusion and perspective

The anticipated project output:

- Evaluation of energy storage hybridization and synergies
- Sizing tool for HESS
- Demonstrate HESS prototypes
- Preparation of large scale demonstration

The project has investigated the effects of hybridization of storage systems to improve the feasibility of storage. The simulations have demonstrated how the features of the participating storage technologies can be exploited by a coordinating controller and the impact of the controller can be assessed on the resulting changes degradation and efficiency. The simulations are based on provision of system services, mainly frequency support, and an overall control strategy implemented directly in the simulation tool. The tool is flexible in terms of services that can be provided and the control strategy.

The developed sizing tool can calculate the optimal combination (technologies and size) of a HESS for a given service in a market-based system. The optimization includes degradation and efficiency resulting from the particular service provision and operating strategy.

The sizing tool has been calibrated against the parameters derived from the lab tests of Va- and Li-batteries and supercaps.

From the project results, it can be concluded that there are significant benefits from combining different storage technologies and that both CAPEX and OPEX has an impact of the optimal combination.

The optimal configuration will depend on the particular case in terms of market setup and power system services as well as the actual costs of the technologies, but this can be assessed with the flexible sizing tool.

A test platform has been established that includes the three technologies. As mentioned above, it has been used to characterize the individual technologies in terms of efficiency and capacity. Further, the platform has been an integral part of the development of a coordinating controller that implements a control strategy that exploits the strength of each technology. The main strategy investigated has been provision of frequency service, FCR, since this is the most relevant for the combined HESS. The characterization was used for calibration of the tool and the testing of the controller validated control strategy. Microgrid operation was not investigated due to the changed strategic focus of Vestas during the project period. The established platform will (pending Vestas approval) continue to be used for investigations into operation of HESS.

The operation of HESS with wind energy developed a controller and published a paper, however, the experimental platform was not finalized during the project period but the activities are continued in the frame of DTEC HPP.

The future perspectives exploiting the project results include some direct next steps in the EU-projects 2lipp and STORies.

The next activities are the direct application of the tools in the EU project 2lipp. Here the tools will be used for development of the Energy Management System for a HESS consisting of Molten Salt storage (from Danish company Hyme) and second life Li-batteries (PLS, SWE) and flywheel (Quitech, NL) in direct collaboration with the suppliers. The insights gained on operation of a HESS and implementation will be carried over and expanded in 2lipp. The sizing tool will be part of an investment analysis in the project i.e. the sizing tool will be augmented with a site specific part that will take local conditions such as grid connection, space for the different technologies and the power system services into consideration. The simulation model will also still be developed as part of the development of an Energy Management System for the demonstration at Rønne Power Plant.

Additionally, the project outcomes will be contributing to the Hybrid Power Plant activities at DTU and Vestas. This will follow the lines of development that was initiated in the project but not completed. Initially, this will focus on the dynamic and short-term operation of the combined system and optimize for delivery of power system services.

The direct commercial development at Vestas was discontinued as part of their new strategy and reorganization. The activities at Vestas will continue in a modified form in the frame of Hybrid power plants.

This means that the expected job creation at commercial partners and the CO2 reduction will not be realized as anticipated. It is, however, the expectation that the 2lipp project via the Hybrid Storage project results, will result in commercial deployment of HESS. The 2lipp project has the additional perspective that it will re-use existing grid and power plant infrastructure and thus save additional CO2.

8. Appendices

L Long, Q., Celna, A., Das, K., & Sørensen, P. (2021). Fast Frequency Support from Hybrid Wind Power Plants Using Supercapacitors. *Energies*, *14*(12), Article 3495. https://doi.org/10.3390/en14123495