BESS project

Smart grid ready
Battery Energy Storage System
for future grid

Final report

ForskEL project no. 10739

DANISH TECHNOLOGICAL INSTITUTE

1. Project details

Project title	BESS – SmartGrid ready Battery Energy Storage System for future grid
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Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Danish Technological Institute Kongsvang alle 29 DK-8000 Aarhus C
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2. Short description of project objective and results

2.1 Danish description of project objective and results

Formålet med Battery Energy Storage System (BESS)-projektet har været at samle praktisk erfaring med udvikling og drift af batterienergilagre til bl.a. stabilisering af fremtidens elnet.

Handelsstrategier og effektivitet er testet på et stort 1,6 MW/0,4 MWh anlæg med 2 container størrelse batterier. Opbygning af et nedskaleret nettilsluttet batterisystem har afdækket kritiske detaljer om design, teknik og kvalitet relevant for alle størrelser af lagringssystemer.

Optimeringsmuligheder og forretningsmodeller er analyseret på faktisk drift på et stort nettilsluttet batteri. Optimering af levetid baseres på degraderingstests udført på enkeltceller på Teknologisk Institut. Der er opbygget erfaring og viden om systemer, kvalitet og drift af nettilsluttet batterisystemer.

2.2 English description of project objective and results

The objective of the project is to generate hands-on experience developing and operating Battery Energy Storage Systems (BESS) suitable for the renewable energy-based power system of the future.

A full size grid-connected Battery Energy Storage System (BESS) plant with two container-size batteries of 0.4 MW/0.1 MWh and 1.2 MW/0.3 MWh was tested and monitored under operation. A smaller scale grid connected battery system was designed, grid connected, operated for test and analysis purpose. To optimise battery life degradation was tested at single cell level and computed into an expert battery model. Real commercial grid operation data has been used for business and technical analysis.

3. Executive summary

Battery based Energy Storage is expected to play an ever-increasing role in the future electric energy system. The project “SmartGrid ready Battery Energy Storage System for future grid” (with the short name “BESS”) has looked into the practical operation of Battery Energy Storage Systems to get hands-on experience with the technical and economic challenges and opportunities.
The objectives of the project are to generate hands-on experience of developing and operating Battery Energy Storage Systems (BESS) in the renewable energy-based power system of the future.
A full size Battery Energy Storage System (BESS) plant with two container-size batteries of 0.4 MW/0.1 MWh and 1.2 MW/0.3 MWh has been operated and monitored throughout the project period and even earlier data has been included in the study.
A smaller scale Battery Energy Storage System (scale BESS) has been designed, built, commissioned, grid connected, operated for test purpose and data is analyzed.
Degradation has been tested and analyzed at system level and at single cell level, to enable optimizing operation for longer battery life.

The operation of the full size BESS plant was traded on completely commercial conditions. The measurements and logged data from the real operation has been used for analysis of e.g. efficiency and financial performance of such systems. Different control strategies has been tested at full size level in order to generate valuable information regarding operation pattern. A test of a potential new definition and requirement of BESS as primary regulation has also been carried out. Possible business models for operating BESS systems has been analyzed along with scenarios with other tariff and tax regimes.
Building and testing a smaller scale grid connected battery system at DTI has provided valuable insight into the details that influence the efficiency, quality and reliability. The scale BESS is a test platform contributing essential data on operations related battery degradation, balancing and future experimental services.
Predicting battery degradation is complex since it depends on many different conditions. Since a reduced lifetime of a BESS system affects the business negatively, degradation has had focus in this project. Degradation data from battery suppliers are in best case very limited. Danish Technological Institute has tested more than 40 single battery cells in the dedicated degradation test lab. The results has been compiled into a degradation model for the specific type of batteries, to help an expert assess expected life. The degradation model seems to match the supplier’s nominal data but comparison to degradation at package level of the scale BESS has not been possible since the package degradation is too little to detect with statistical certainty at end of project (after the first approximately 140 equivalent cycles). Capacity degradation has also been monitored at the full size BESS plant but primary regulation operation results in a low cycle load (less than one equivalent full cycle per day). One of the full size BESS systems are based on the very robust Lithium titanate cells and the theoretic cycle life is more than 50 years doing primary regulation.
The degradation of batteries can be minimized by choosing suitable temperatures, and usage pattern, but it is a complex matter. Generally, operation between 15°C and 30°C is recommended.
In order to minimize auxiliary consumption for heating and cooling, the temperature operation window must be wider than is typically used with only a few degrees temperature span in such systems.

The project has been successful in several ways

- All the planned activities has been addressed
- The learnings from both full size and scale BESS systems are relevant and useful for future activities.
- The developed assessment methods for degradation, efficiency, economy can be reused for other BESS systems.
- The project has serviced the TSO regarding experimental test of alternative primary regulation
- Much has been learned from unforeseen challenges under the build and commissioning phase
- Several areas found with efficiency improvement potential
- Batteries are highly relevant measures for the future grid
- Knowledge and experience has already resulted in commercial activities as well as contribution to a H2020 project and 4 Danish energy research project applications.

The market conditions for electrical storage in the electric grid has not changed during the project period except for a reduction of the only marginally profitable market relevant for battery storage - Primary regulation. The introduction of primary regulation via Skagerrak-4 interconnector removed most of the potential market and reduced the value of the residual market. Still the project finds that BESS systems have demonstrated functionalities that could contribute services at different levels of the electric grid. Electrical storage often seems to be seen more as a potential problem to the grid rather than a stabilizing measure – also by the expected grid code for battery storage. A number of areas need reconsideration for BESS to become an equal measure to consider.

- The market for electrical services only recognize the existing system-types and tend to favor these. BESS-systems must be recognized at political and strategic governance level as well as on the executive and business levels. Grid codes and traditional subsidies on existing services must be reevaluated and adjusted in order to reflect the current situation and encourage development towards the 100% renewable set by the government.

- Also with respect to the 2022-plan for a common European market for system services, new technologies should be considered in grid and market codes.

- BESS systems recognized as voltage stabilizing measures in low and medium voltage grids not only as a technical measure but also as a tradeable service.

- The same energy should only be taxed once, and tariffs structure should favor efficient energy supply to the consumers but not penalize storage.

- Lowering prices is not a job for suppliers alone. They need to see business opportunities and stability to invest in improved technology. Subsidies may be needed in an interim period to encourage investment in storage.

- Research is still needed for better future technologies – better efficiencies, longer life and lower prices.

- For BESS systems to become commodities there is a need for regulation or at least recommendations for safety, installation, maintenance, environmental issues (recycling and decommissioning).

The tariffs and taxes plays a large part in the operational costs but also availability payment and better energy delivery conditions could be a way to improve condition for investing and operating BESS Systems.

An economic based analysis by Energi Danmark about BESS system operation in a Danish energy system has resulted in some general findings:

- There is a major gab between investment/cost and the possible earnings for batteries in the existing market (except for the primary reserve niche market).
- The tariffs for consumption in their current form are relatively high. Justifying operation in load-shifting mode (shifting energy from hour to hour) will require a highly volatile energy market not expected to emerge in the near future. Lower tariffs reduce the required volatility market.
- The auxiliary power consumption is so high it eats up any profit from a load-shifting mode operation.
- The primary reserve market is the only operation with a potential for achieving a profit.
- The profitability of BESS on the reserve market can be improved – priority-listed :
    - Ensure maximum availability of the reserve capacity on the market.
    - Optimize the auxiliary power consumption to reduce tariffs.
    - Improving the cycle efficiency in this operational mode is positive

Within primary reserve, there are some challenges with the current regulations, therefore a variation of the alternative primary regulation with incorporation of a continuous charge algorithm has been tested.
A battery degradation model for the tested batteries has been developed in the project, which can help specialists predict expected battery lifetime, depending on temperature and operational load pattern for Lithium Iron Phosphate batteries.

The efficiency and part load operation of battery systems are very important, especially when operated as primary reserve with low energy delivery. Generally, the batteries themselves have efficiencies above 95%, but auxiliary systems and losses in inverters and transformers can reduce the overall system efficiency to below 50% in low load operation.
Often systems are evaluated and purchased based on peak performance, overlooking part load performance. The stability and lifetime of auxiliary components is very important. Focus is mostly on the batteries and degradation, but the experience from both the scale system and the operation on the large-scale

systems in Lem Kaer is that these other factors are equally important. This is also the case when looking at cost of a full system relative to cost of the installed batteries.

It is essential for good economy to use batteries with high power delivery for the use of batteries for primary reserve or other high power services.
The BMS system and batteries used for the battery systems has to be suited for the actual operation. The BMS system needs to manage the battery system in order to maintain the batteries within safe operating area, but also for optimizing the performance of the batteries.

Some of the experience from the project has been put to work in a series of Energinet.dk workshops in connection with the development of a new grid code TF3.3.1 for operation of batteries connected to the electrical grid. This includes both data and active participation in the preparation meetings.
In order to make use of battery systems in larger volumes, the legal and economic frame including taxes and tariffs has to be transparent and predictable. To accelerate the growth rate for BESS capacity the politicians will need to review and rethink the tariff on storage, so that the same energy is only taxed and tariffed once – when it is used at the end consumer. The flexibility of BESS systems offers excellent Smart Grid functionality as required.

Concerning household and community batteries, which has not been a direct focus of this project, the market aspects are predicted to be very good in the coming years, especially in connection with solar power systems and the possibility of the introduction of tariffs based on the maximum power needed. The investment drivers are completely different when private people invest optimization of their own renewable energy production and consumption. Therefore the private home market for BESS is expected to start growing before larger grid connected BESS plants become competitive.
The work within batteries in connection with the electrical grid will continue in different aspects. DTI has increased the focus on batteries at all levels of the electrical grid from household to very large battery systems (GigaBAT).

4. Project objectives

The objectives of the project are to generate hands-on experience of developing and operating Battery Energy Storage Systems (BESS) in the renewable energy-based power system of the future.

- A full scale Battery Energy Storage System (BESS) plant with two container-size batteries of 0.4 MW/0.1 MWh and 1.2 MW/0.3 MWh will be operated and monitored
- Smaller scale grid connected battery system will be designed, grid connected, operated for test purpose and analyzed
- Degradation will be tested and analyzed at system and at single cell level

The full size BESS plant will be operated in order to gain hands on experience with operating battery systems and to optimize the financial output from operating such systems. This involves different control strategies in order to generate valuable information regarding operation pattern, mission profile, battery degradation and possible business models for operating such systems.
Building and testing a smaller scale grid connected battery system at DTI will enable deep insight into the details that influence the efficiency, quality and reliability. The scale BESS is a test platform contributing essential data on operations related battery degradation, balancing and future experimental services.
Degradation data will be found from single cell degradation test at Danish Technological Institute and compared to resulting degradation at scale BESS using the same type of battery cells. Capacity degradation is also monitored at the full size BESS plant.

An overview of project work-packages and milestones – all completed - can be found in Annex 1 of this report.

4.1 Project organization

The project is organized with a steering committee, a project manager and project responsible from each of the participating companies - Danish Technological Institute (DTI), Energi Danmark A/S (ED) and Vestas Wind Systems A/S (Vestas). An overview can be seen in Figure 1 below.

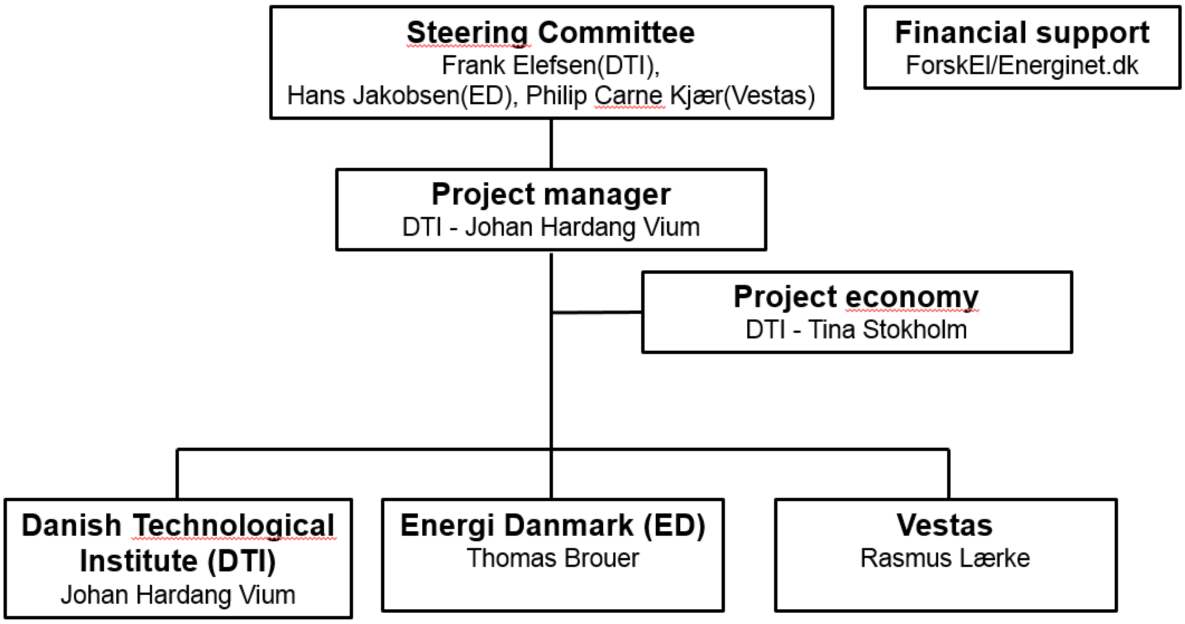


Figure 1: Project organization and responsible

Overall responsibilities in the project

DTI is project holder and is responsible for the overall project management of the project. DTI is also responsible for doing degradation of single cell batteries in their laboratories, and for design, development and implementation of a small scale BESS system. Vestas owns and are responsible for operating the large scale battery energy storage systems in Lem Kaer. Energi Danmark is Balance Responsible Party (BRP) for the large scale BESS systems and for the bid of the systems into the market. ED is also responsible for the economic calculations for operating BESS systems in the project. Milestones with responsible and status can be found in annex 1 of this project.

5. Project results and dissemination of results

The results section is organised in three sections.
Results from full scale storage systems providing primary reserve at grid-level is presented in the first section including project work-packages WP1a; WP3b; a major part of WP4 and an extra pilot test on alternative primary operation as agreed on with Energinet.dk.
In the second section the results and experiences from a scale BESS system are compiled. The project work-packages WP1b; WP2; WP3b and part of WP4 are compiled to present results from a real life grid connected storage system emulating different grid-services and energy storage.
Degradation test results are summarised in the third section (part of work packages WP1b and WP3b).
Further results and information from the project can be found in the annexes 1-4.
An overview of milestones, timetable and background material from this project can be found in annex 1.

Introduction to a complex project
The focus of this project is Battery Energy Storage Systems connected and managed at grid-level. Some experience and results comes from full size BESS grid-connected at 10 kV and the build-up of a representative scale BESS has provide knowledge and results at 0.4 kV level.
The first section (5.1) of the project results refer to activities and results from the full scale BESS systems in Lem Kaer. The ESS plant is owned by project partner VESTAS and trading of grid services is managed by project partner Energi Danmark as BRP (Balance Responsible Party). The BESS plant is mainly acquired on commercial terms for demonstration and in the BESS project period, energy and grid-services have been traded at full commercial basis.
The second section (from 5.2) of the project results refer to activities and results from the scale BESS system at Danish Technological Institute in Aarhus. DTI has designed the grid-connected scale BESS system from scratch to match the complexity of a high power storage system in the MW range even though the power and energy capacity is a 10-factor lower. The purpose of the scale BESS has partly been to analyse different operational strategies when providing different grid-services and partly to analyse battery degradation in relation to operational strategies and conditions. Most important has been the hands on experience gained through the complete process from specification, purchasing, building, commissioning, testing to operation. Having no commercial earnings target for the scale system allows dynamic planning of tests without concern for market dependent revenue loss.
In the third section (from 5.3) of the results chapter degradation and other common observations con be found.

5.1 Vestas full scale Battery Energy Storage System plant

Description and compiled results from the Vestas owned full size Battery Energy Storage System plant can be found in Annex 2. Below you can find some main topic of the full scale battery plant in Lem Kaer.
First a description of the system BESS plant consisting of two different BESS systems from two different suppliers.

5.1.1 BESS Plant Installation Lem Kaer

The energy storage installation consists of two battery energy storage systems from different manufacturers.

	BESS1:	BESS2:
Manufacturer:	A123 Systems	Altairnano
Dimension:	53’ container	53’ PM container and 20’ PCS container
Rated power and capacity:	0.4MW / 0.25h	1.2MW / 0.25h
Battery type:	LiFePO4	Li4Ti5O12
Control interface:	Modbus TCP	Modbus TCP

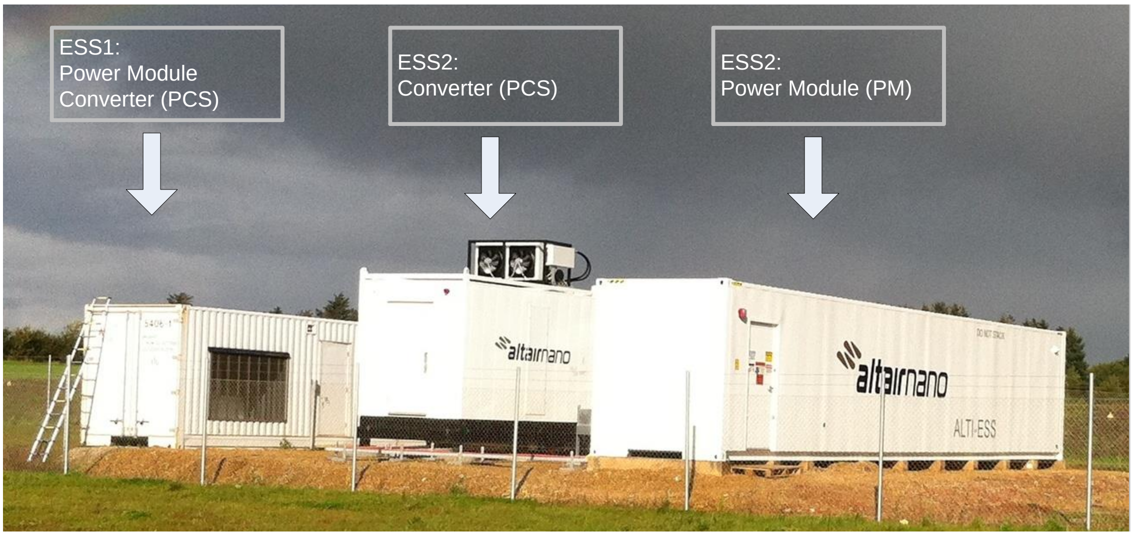


Figure 2: BESS plant installation in Lem Kaer

5.1.2 Communications Network and Control Loops

The management of BESS operation takes place over communication lines to VESTAS and the BRP (Energi Danmark). Vestas manage the technical setup and monitoring of technical health. The BRP trade the BESS services and can remotely enable and disable the power connection between ESS plant and the grid.
Communication between the major systems of the BESS plant in Lem Kaer can be seen in Figure 3: Overall control set-up for Vestas BES S- with physical distance between plant controller and actual BESS systems.

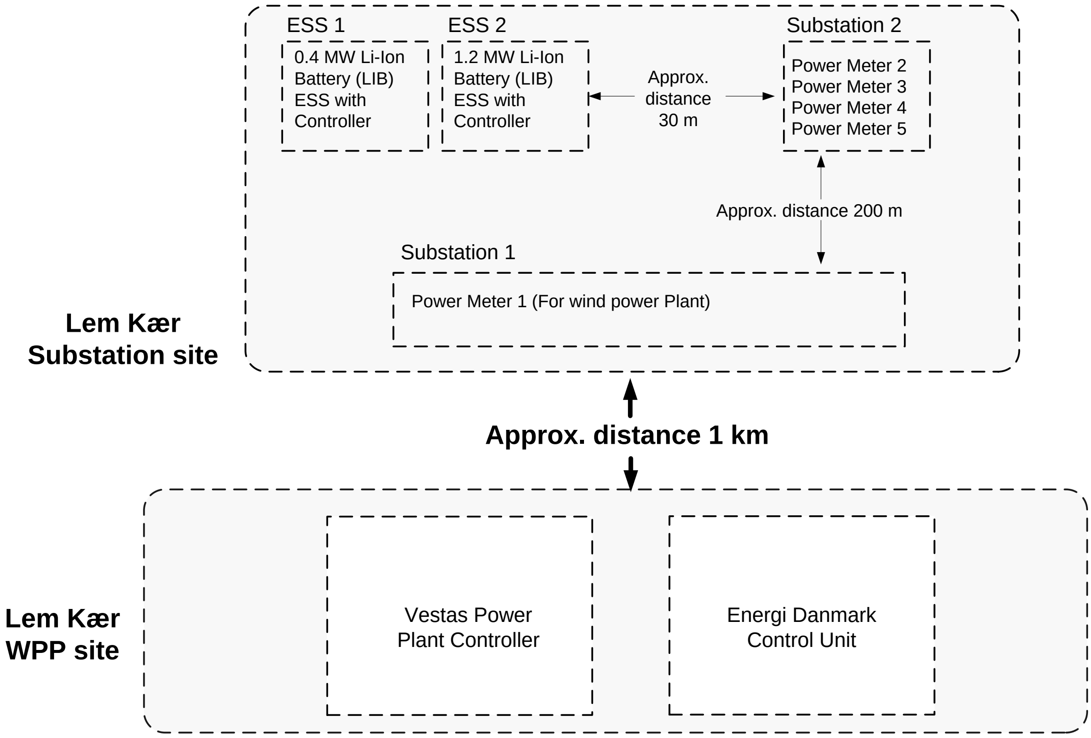


Figure 3: Overall control set-up for Vestas BES S- with physical distance between plant controller and actual BESS systems.

5.1.2.1 Control Loops

The control loop regulating e.g. the frequency regulation for primary reserve response takes place in the Vestas Power Plant Controller (VPPC).

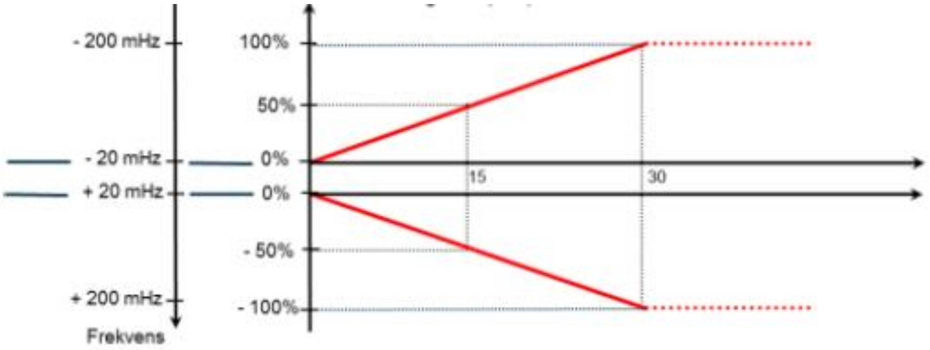


Figure 4: Required minimum power response to frequency deviation and minimum reaction time in seconds. The illustrated dead band of 20 mHz is likely to be cancelled in future.

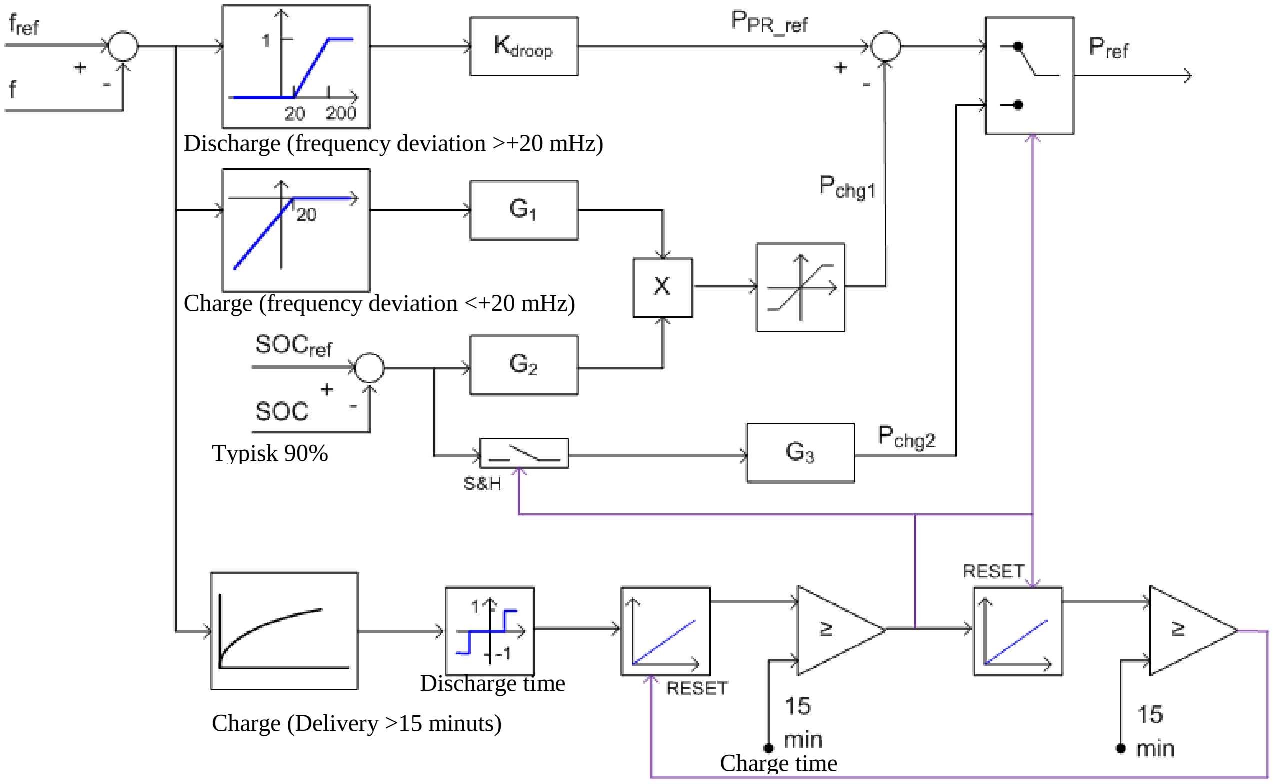


Figure 5: Illustration of a possible Primary reserve regulation for DK1 with SoC control

Beside the control loop managing the actual service delivery, housekeeping is a very critical function with the BMS as a core safety function. A number of auxiliary systems support the operation and thermal management, monitoring, fire detection, security etc.

5.1.3 Data analysis of data from Lem Kaer

Data from 776 days is recorded from the systems in Lem Kaer in the period between July 2013 and November of 2016 has been analyzed with a resolution of 10 Hz (670.230.958 time stamps).
There are some data missing in the period. This is caused by irreversible data loss, movement of the battery systems, defect of the used power meters (possible due to high overvoltage in the area), and the systems being out of operation.

The operation data from the smaller A123 system is limited since there has been issues, which has not been resolved which has put it out of operation. There has been no issues with the batteries, but auxilary systems (mainly control computers, and inverters). Therefore most of the analyzed battery system data from Lem Kaer is from the Altairnano system.

5.1.3.1 Frequency distribution

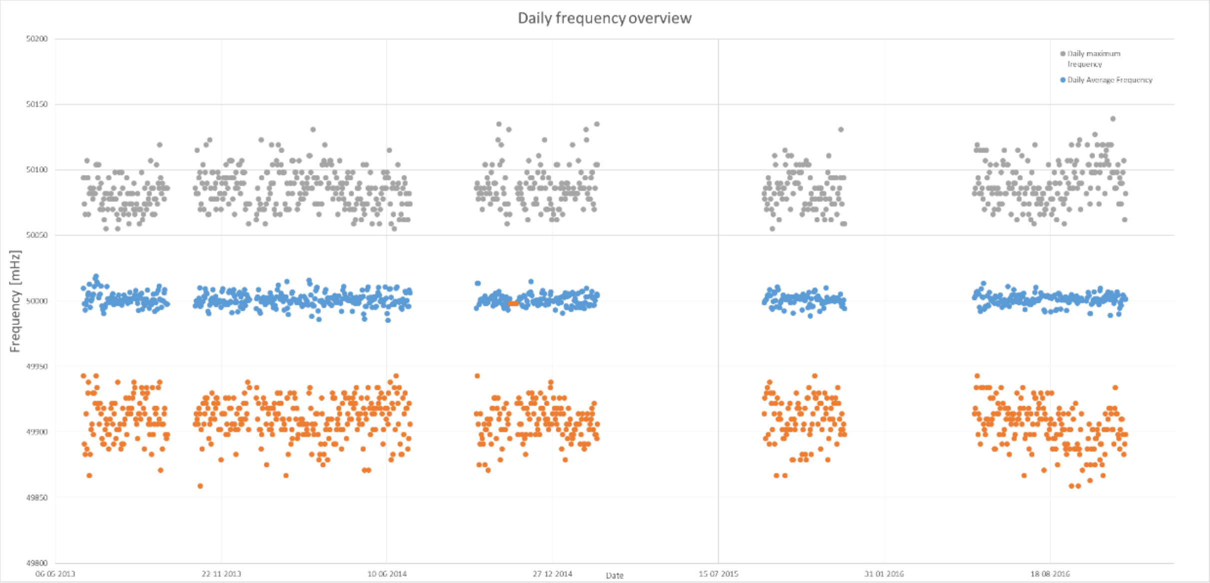


Figure 6: Graph of maximum (gray), average (blue) and minimum (red) frequency for each of the analyzed days (776 days in total).

The maximum frequency recorded during the period is 50.139 Hz, and the minimum frequency is 49.859 Hz (deviation of 141 mHz from 50 Hz). The frequency at maximum power when delivering primary reserve with a deviation of 200 mHz is not met in the analyzed data. The average measured frequency is very close to the nominal 50 Hz with 50,00098 Hz (deviation less than 0,02 ‰).

5.1.3.2 Necessary energy content for primary regulation

The necessary energy content for primary regulation has been calculated based on the maximum energy delivered in one single run for each day. This is converted into the equivalent minutes at full power.
The criteria for primary reserve in Denmark, at present, is a minimum delivery time of 15 minutes, and a deadband with no regulation within +/- 20 mHz. These criteria may change in the future.

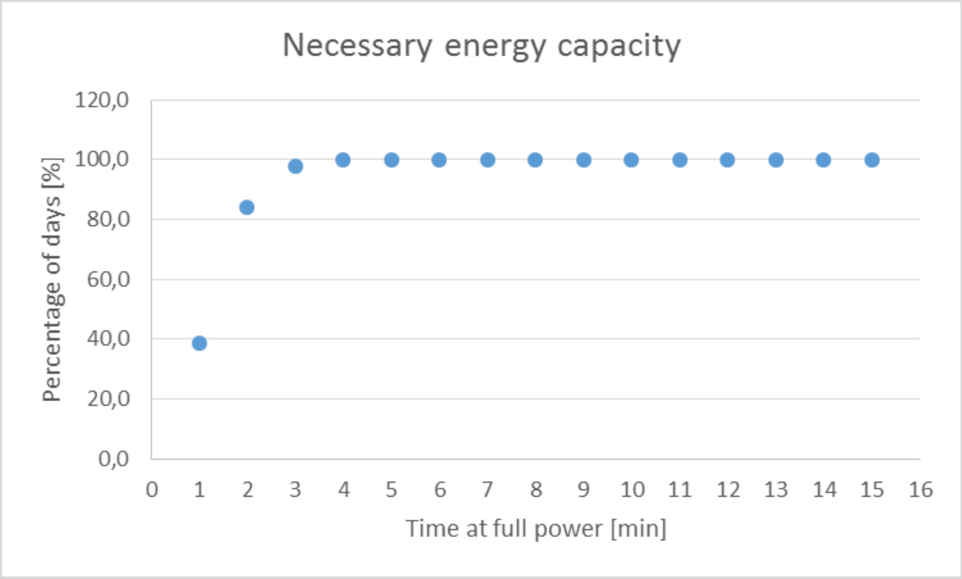


Figure 7: Necessary Energy capacity in minutes of full power in order to be able to deliver the requested power from primary reserve.

100% availability is achieved with a battery capacity equivalent to 6 minutes at full power. This means that a battery system with a capacity equivalent to 6 minutes at full power is able to deliver the requested power at all times in the analyzed data from 2013 to 2016 (more than 776 days).

5.1.3.3 Average day

Based on the available data there has been found one specific day, which reflects the average frequency pattern of the electrical grid. Data from this day is used as a setpoint file for the battery tests in the battery degradation laboratory and for tests of the Scale BESS system.

The average day was found based on maximum, minimum, average frequency and frequency distribution close to average. The day identified was the 2013-11-09.

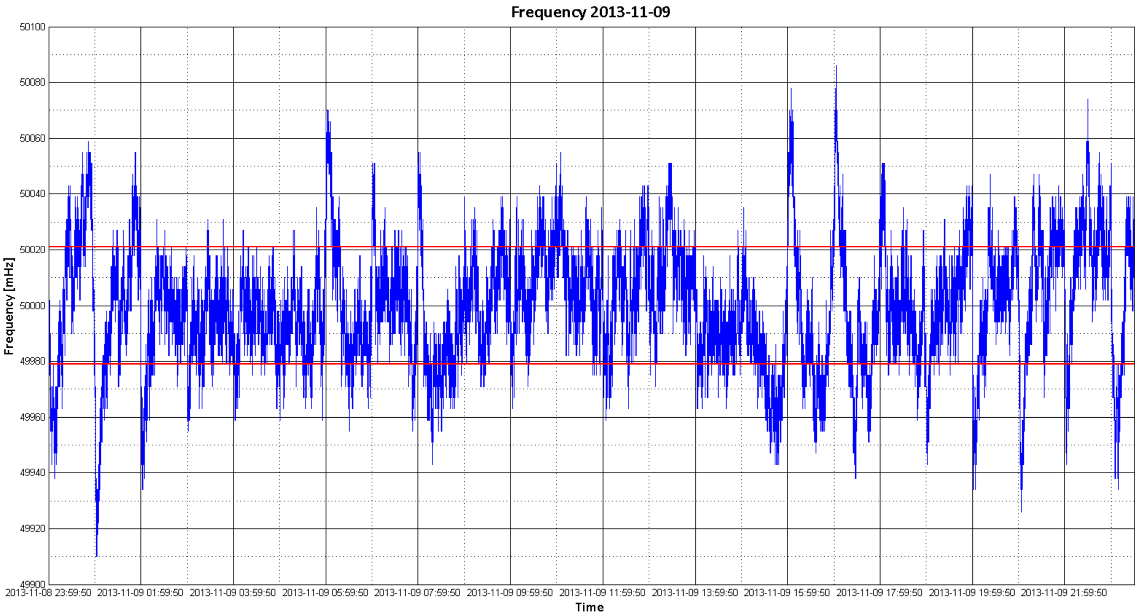


Figure 8: Illustration of frequency pattern from 2013-11-09. The red lines illustrates the current dead band of 20 mHz.

The frequency varies somewhat during the day, and especially during hour change the frequency varies. This is partly caused by some systems stopping production, and other systems starting production due to the electricity market with hourly bids and hourly operation.

5.1.3.4 Energy delivery during primary reserve.

The highest single energy delivery in the analyzed data has taken place on 2013-10-28. The delivery was 140 kWh.

The frequency drop lead to a primary reserve power delivery as seen below from the Altairnano system below.

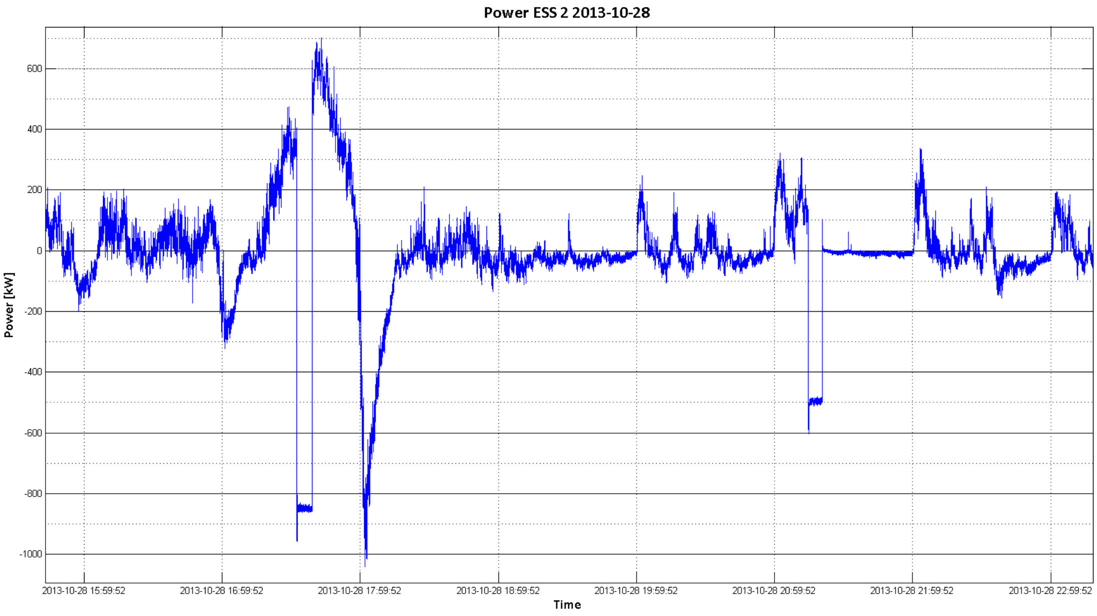


Figure 9: Graph of power delivery from Altairnano system during longer frequency drop, where the system starts charging after 15 minutes with underfrequency.

As seen on the graph, the system recharges after 15 minutes delivery in order to be able to deliver 15 minutes of frequency reserve at full power after a 15 minutes grace period. This system behavior is problematic in cases where a significant frequency deviation is present for more than 15 minutes, as it leads to a sudden change from delivering to absorbing power, and hence it contributes to further frequency deviation. This pattern happens quite regularly. This problem is looked into in a pilot test in cooperation with energinet.dk where no sudden change is made in order to perform charging, but instead a charging algorithm runs continuously, alongside the frequency regulation algorithm. See further information and results from this in section 5.1.9.

The average energy delivery for each day from the Altairnano system during primary up regulation is 237,6 kWh/day and the maximum value is 770 kWh/day. In average this means the system in average does 237,6/300 kWh = 0,8 full cycles per day. The theoretic maximum possible number of cycles is 2*24=48 cycles, which leads to a utilization degree below 2%.

Based on data from the average day the influence of deadband on energy delivery has been examined.

Calculations with bid of 1 MW power	Energy [kWh]	Energy Ratio
0mHz deadband	974,05	3,88
10mHz deadband	520,35	2,07
20mHz deadband	250,85	1,00

Table 1: Calculation of delivered energy demand and ratio compared to base of 20 mHz during primary reserve up-regulation. A power bid of 1 MW is used.

If the demands for delivering primary reserve is changed to a 0 mHz deadband from the current 20 mHz, without any other chances, this will lead to almost 4 times higher energy delivery and associated costs. In the future, primary regulation with batteries may end up with a deadband of 0 mHz, but with the use of a charge algorithm which will reduce the energy consumption to approximately the same as previously, but with the ability to always deliver, and no need for 15 minutes grace period for recharging.

5.1.4 Data from load shift test

A load shift test was conducted on the Altairnano system based on an optimal income analysis buying electricity when prices are low and selling, when prices are high. See also document on income from Energi Danmark on this issue.

The test lasted for four days, but due to technical issues in the beginning, the actual performance was operated according to setpoints for approximately two days.

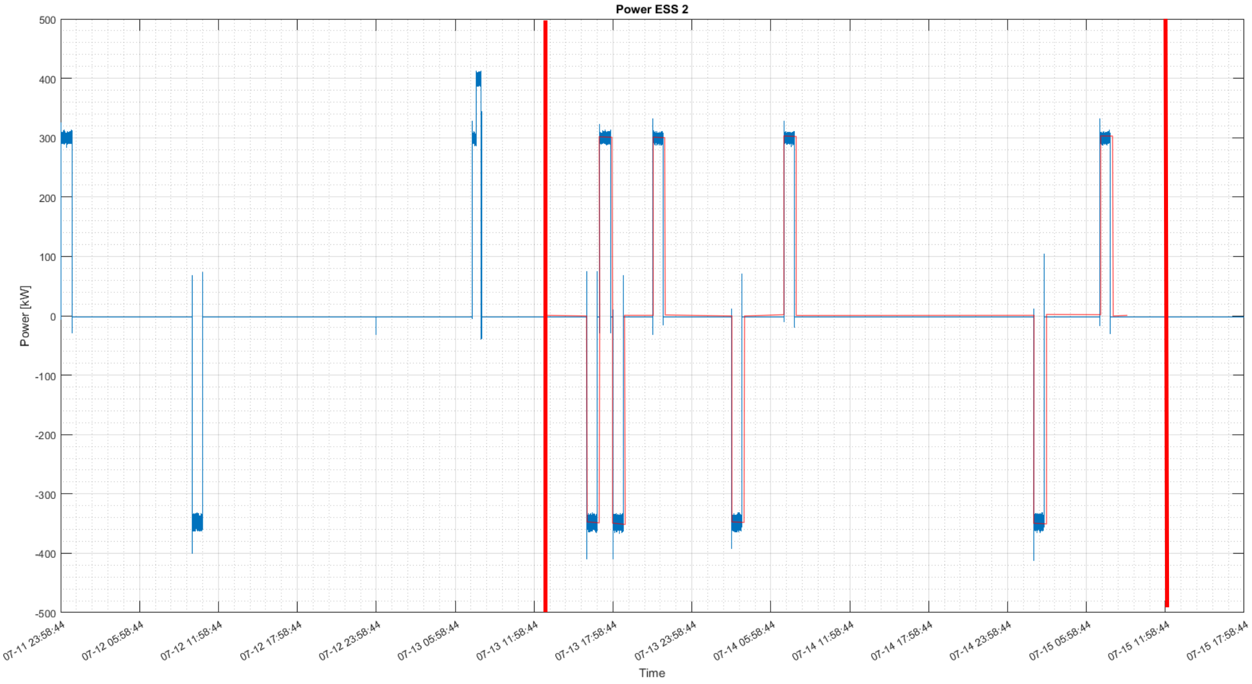


Figure 10: Graph of actual power (blue) delivered from the Altairnano system during Load shift test. The vertical red lines limit the period driven by the load shift test pattern (can be seen in thin red). Total time period of 4 days.

The system was set to operate between 5 and 90% SoC, and the power was set to 300 kW when delivering and 350 kW, when consuming energy.

The expected energy delivered from the system was approx. 300 kWh*(0,90-0,05)=255 kWh per cycle.

Cycle nr.	Delivered energy [kWh]	Consumed energy [kWh]	Efficiency [%]	Delivery time[min]
1	267,0	328,4	81,3	53,5
2	246,5	296,2	83,2	49,5
3	242,7	296,2	82,0	48,5
4	242,7	296,2	82,0	48,5
5	239,0	316,2	75,6	48,0
6	233,9	286,9	81,5	46,9
Total	1471,97	1819,875	80,94	49,16

Table 2: Energy delivered and consumed, and roundtrip efficiency of main system (without auxiliary consumption) when cycled between 5% and 90%.

The energy delivered in the loadshift pattern is reduced somewhat from cycle to cycle. This is most likely caused by rising imbalances between cells. The delivered energy is a little less than expected, and the delivery time is approximately 50 minutes.

5.1.4.1 Efficiency of systems in Lem Kaer

The efficiencies of the systems have been calculated from the analyzed data.

The average efficiency of the A123 system during primary regulation upwards is approximately 39%. The efficiency varies from day to day due to different energy content in the batteries in the start and end points, but the calculated average is correct.

The average efficiency of the A123 system during frequency upwards regulation is approximately 50%. The highest possible roundtrip efficiency of the Altairnano system is approximately 85% with full power, when not including auxiliary components.

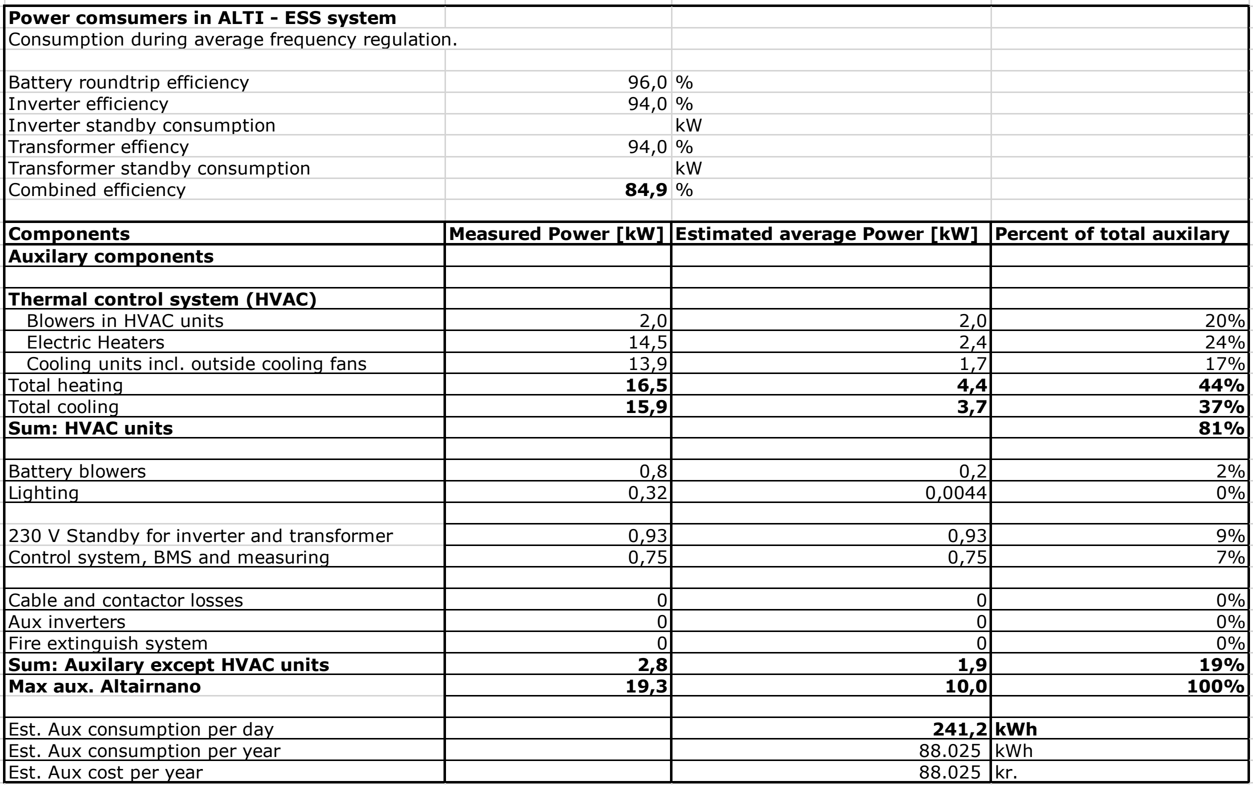
Operating pattern	Efficiency Altairnano	Average energy Delivery
Peak roundtrip	85,0%	
Load shift pattern	80,9%	368,0 kWh/day
Primary reserve up (20 mHz deadband)	50,0%	237,6 kWh/day

Table 3: Schematic overview of efficiency without auxiliary consumption of the Altairnano systems in Lem Kaer with different operation patterns

Besides the losses in the system included in the data above, which includes losses in transformers and inverters, there are also energy consumption for auxiliary components. This is further investigated in the next chapter.

5.1.4.2 Auxiliary consumption

The average auxiliary consumption for the two systems was determined to 291 kWh/day or 12.1 kW.
The auxiliary consumption has been investigated further on the Altairnano battery system. This has been done in order to identify the major energy users so these can be focused on for optimization of the system and knowledge in connection with other systems.



Power comsumers in ALTI - ESS system			
Consumption during average frequency regulation.			
Battery roundtrip efficiency	96,0	%	
Inverter efficiency	94,0	%	
Inverter standby consumption		kW	
Transformer effiency	94,0	%	
Transformer standby consumption		kW	
Combined efficiency	**84,9**	%	
Components	**Measured Power [kW]**	**Estimated average Power [kW]**	**Percent of total auxilary**
Auxilary components			
Thermal control system (HVAC)			
Blowers in HVAC units	2,0	2,0	20%
Electric Heaters	14,5	2,4	24%
Cooling units incl. outside cooling fans	13,9	1,7	17%
Total heating	**16,5**	**4,4**	**44%**
Total cooling	**15,9**	**3,7**	**37%**
Sum: HVAC units			**81%**
Battery blowers	0,8	0,2	2%
Lighting	0,32	0,0044	0%
230 V Standby for inverter and transformer	0,93	0,93	9%
Control system, BMS and measuring	0,75	0,75	7%
Cable and contactor losses	0	0	0%
Aux inverters	0	0	0%
Fire extinguish system	0	0	0%
Sum: Auxilary except HVAC units	**2,8**	**1,9**	**19%**
Max aux. Altairnano	**19,3**	**10,0**	**100%**
Est. Aux consumption per day		**241,2**	**kWh**
Est. Aux consumption per year		88.025	kWh
Est. Aux cost per year		88.025	kr.

Table 4: Measurements and estimated average auxiliary energy and power for the Altairnano system

As seen in the table above, most of the auxiliary energy used is used for temperature adjustment of the battery system (81%). The thermal control system blows conditioned air close to the battery boxes, which has separate blowers that leads the air thru the battery boxes.
Much energy can be saved with different temperature control and possible insulation of the container. In primary/frequency regulation mode, which the system is operated in most of the time, there is a limited energy throughput, and thereby also a limited energy loss in the batteries. This leads to quite high consumption for heating the system. During hot days the cooling system comes into operation. In fall and spring time, there are times where the system is cooled during the day and heated during the night. With

better insulation and a wider allowed temperature span, this can be reduced. Even though it wasn't in scope it was suggested to do changes to the temperature control in Lem Kaer, but it was not feasible. This must be taken into consideration with other systems. The scale BESS system at DTI is therefore constructed with insulation of the battery compartment. Here is also a delay on shift from heating and cooling, and future possibilities for a wider temperature operating range.

5.1.5 Operating experience from Lem Kaer

There has been different system errors in the large-scale battery systems during the project period. The errors are listed below:

- Pump errors
- Heating/cooling system error
- Control computer malfunction
- Data measure and recording errors (Elspec power meters)
- Inverter errors (degraded capacitors)
- Movement of battery systems
- Disconnection by DSO

During the project period the battery systems had to be moved, which caused a pause in operation, but also subsequent errors due to the movement. Furthermore, there has been situations where power to the site has been disconnected without prior notice from the local DSO.

Maintenance and support has to be taken care of, just as with any other larger systems in order to keep it running.

The smaller A123 battery system had several errors including control computer errors and inverter errors which would demand further substantial supplier investigations and investments, which was not able to be carried out in the project.

There has been no battery related errors with either of the systems!

5.1.6 Degradation in Lem Kaer

The degradation in Lem Kaer has been limited. Only the Altairnano system has been investigated with regards to degradation, since the A123 has been out of operation for most of the period. Due to the limited operation and limited power and energy throughput during primary reserve service minor degradation was expected. The nominal number of cycles for the Altairnano system is 16000 to reach 20% degradation. At 0.8 cycle per day as is typical during primary reserve, the degradation to 80% of initial capacity due to cycling will theoretically, take 16000/0.8/365 ≈ 55 years (equals 0.4% degradation per year). EIS (Electrochemical Impedance Spectroscopy) measurements (performed by AAU (Aalborg University) had started before this project and was planned to continue throughout this project but had to be cancelled for logistic reasons. Getting internal permissions for disconnecting battery packs in Lem Kaer became more complex as Vestas due to strict safety regulations affecting also Lem Kaer battery installation.

The nominal capacity of the Altairnano system is 420 Ah (60Ah per single cell at a discharge rate of 6C), and the nominal system voltage is 880 V (2.3 Volts per cell). The nominal energy capacity is 370 kWh.

The average measured energy capacity is 350 kWh, or 95% of the nominal capacity.

The measured difference in the capacity is mainly caused by different SoC calibration and difference in single cell voltages in the system. Measured degradation based on the previous data indicates a loss of energy capacity of the system of 7% during approximately 3 years of primary reserve operation.

The measured degradation of the Altairnano nanostructured lithium titanate battery is higher than theoretical target and is probably caused by battery cell differences and storage degradation. Since the capacity is measured at a rather high current rate of approximately 4C it is recommended to allow for full balancing of cells before the test. This battery system was not balanced before the capacity test. Depending on thermal management and temperature setpoint, the storage degradation may affect life of the battery even more than the cyclic load from primary frequency operation.

5.1.7 Conclusion from Lem Kaer operation

The system efficiency is rather low when operated as primary reserve, due to losses in inverters and transformers and due to consumption of auxiliary components – mainly the thermal control system.
This calls for the necessity of optimizing part load operation and also optimizing thermal control of battery systems. High part load efficiency is important for ROI. The information is highly relevant and should be requested from suppliers but may be hard to get.
There has been no battery related errors prior to or during the project period. The primary focus with regard to BESS systems are often the batteries and battery degradation. The batteries are of course important, but the experience from this project is that other system components are equally important in order to secure low energy losses and the up-time of the entire system.

5.1.8 Financial Experience from system operation in Lem Kaer

The BESS system has been operated in a real market environment for a number of years now. This section will summarize the main findings of the actual operations, and will compare the findings to the theoretical calculations presented in WP1 when it comes to the Operational income and profitability of the BESS system.

The BESS system has been test run in the following modes which is analyzed by Energi Danmark:

- As a load shifting unit
- As a primary reserve for delivering up-regulation.

The operation with alternative primary regulation has not been evaluated in this section.

5.1.8.1 Load-shifting operation

BESS was operated as a load shifting unit for 4 days starting on the 12th until the 15th of July 2016. In this period, the prices assumed were fictive (not real market prices) in order to ensure the operation of the unit. The unit was optimized assuming an advanced knowledge of the up and down regulating power prices. Charging takes place at the down regulation price, and production at the up-regulation prices. Figure 11 shows the assumed prices along with the resulting charging and production cycles.

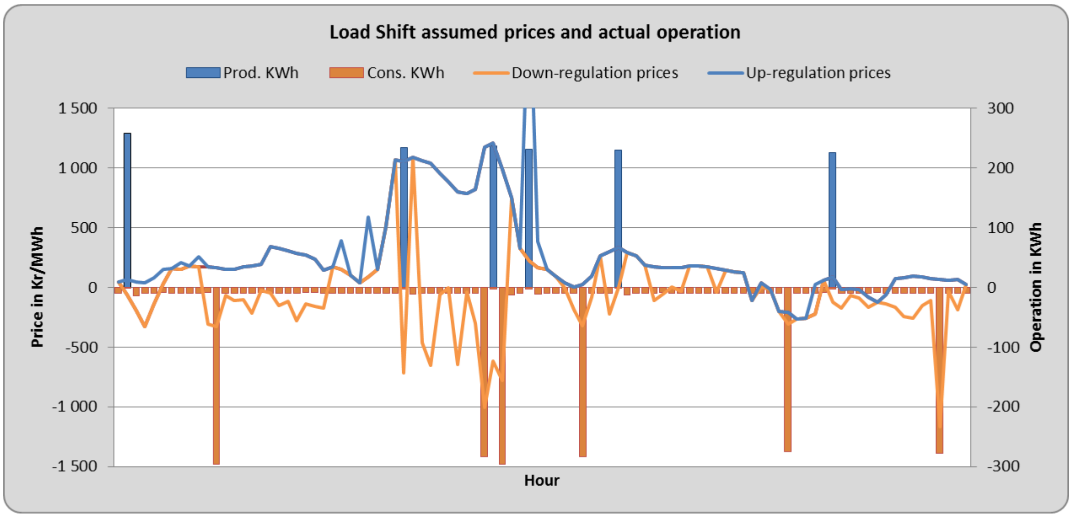
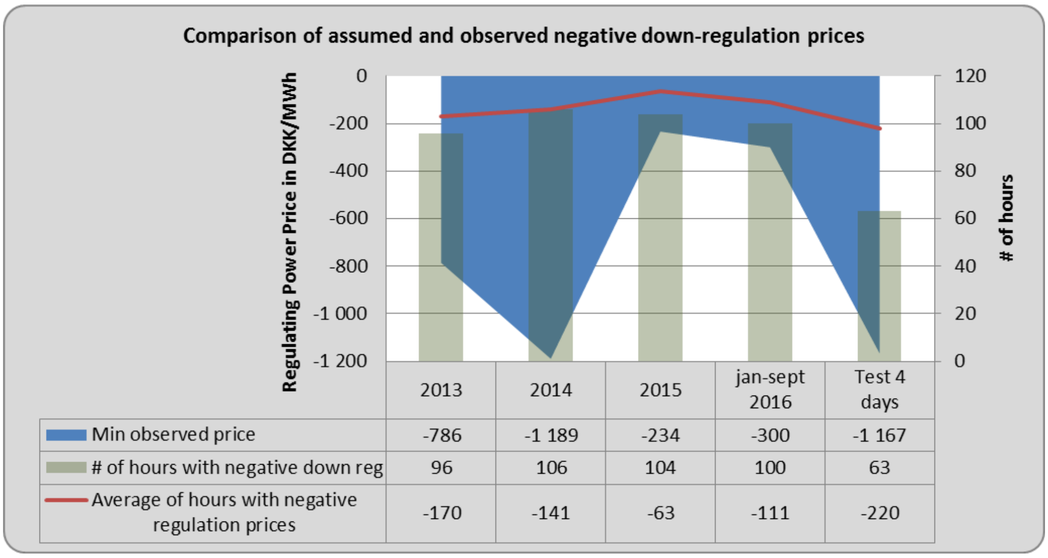


Figure 11: Load shift assumed prices and resulting operation

From the graph above, the following can be observed:

- The maximum utilized discharge capacity is around 240 kWh. This is 60% of the initial project capacity assumed in the WP1 calculations, which was around 400 kWh. This is due to the fact that one of the battery systems has been out of operation during the test period.
- The auxiliary power consumption is around 10 kWh per hour. This is below the assumed value in WP1 of 16,67 kWh per hour. This could be due to a variety of reasons such as the milder weather during the test period and the outage of one of the batteries.
- The auxiliary power consumption drops to around 3 KWh during the hours with production. This could probably be an indication that parts of the auxiliary system are powered by the produced power during these hours.

- The efficiency of the charge/discharge cycle is at around 85% (excluding auxiliary power)
- Charging occurs during hours with negative down regulation prices, meaning that the BESS receives a payment for charging. It should be noted that the occurrence and value of the negative prices assumed is exaggerated in the fictive price series used during the 4 days to be more than half the amount observed during a whole year, as shown in Figure 12.



	2013	2014	2015	jan-sept 2016	Test 4 days
🟦 Min observed price	-786	-1 189	-234	-300	-1 167
▨ # of hours with negative down reg	96	106	104	100	63
— Average of hours with negative regulation prices	-170	-141	-63	-111	-220

Figure 12: Negative down-regulating prices. The first 4 points are realized prices in the period 2013 until September 2014, while the last column is the assumed fictive price series used for the load-shift test run.

Figure 13 and Figure 14 show the main operational results based on the current and the reduced tariffs respectively. Table 5 shows the assumed current and reduced tariffs on consumption. The production tariffs is assumed at 3,59 DKK/MWh in all cases.

Table 5: Assumed tariffs on consumption

[DKK/MWh]	Fees on consumption		
	Current Tariffs	Reduced Tariffs Aux Power	Reduced Tariffs Charging Power
Consumption fee – TSO	1,31		
Grid tariff – TSO	42	42	
System tariff – TSO	24	24	
PSO – TSO	217	217	
Various fees for DSO	1084	251	251
Total	**1368,31**	**534**	**251**

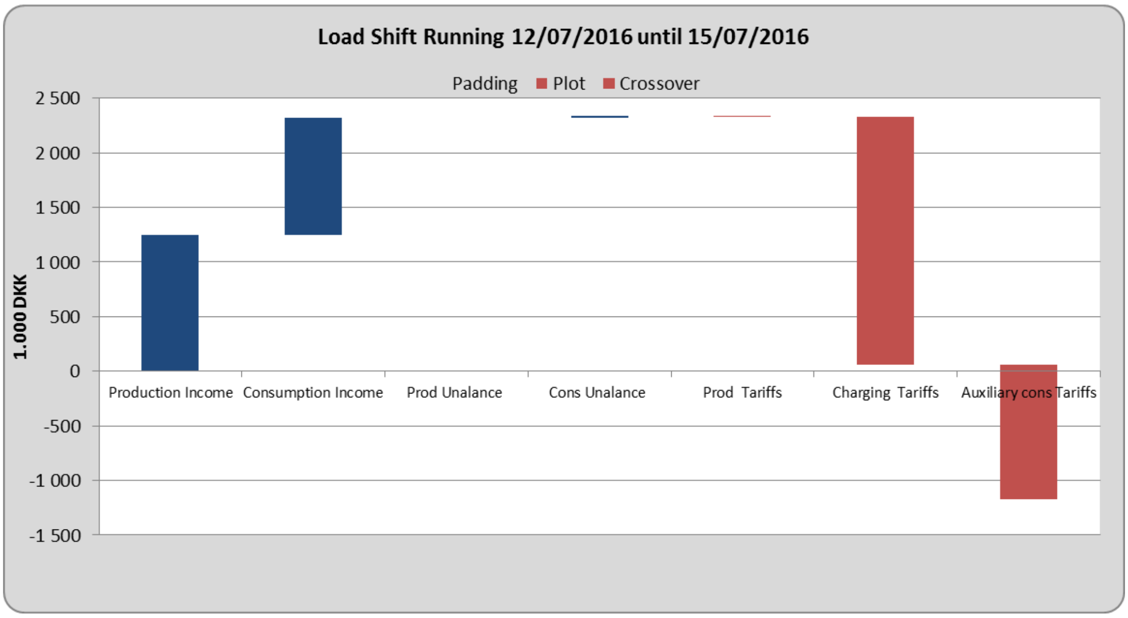


Figure 13: Load shift results based on the current tariffs

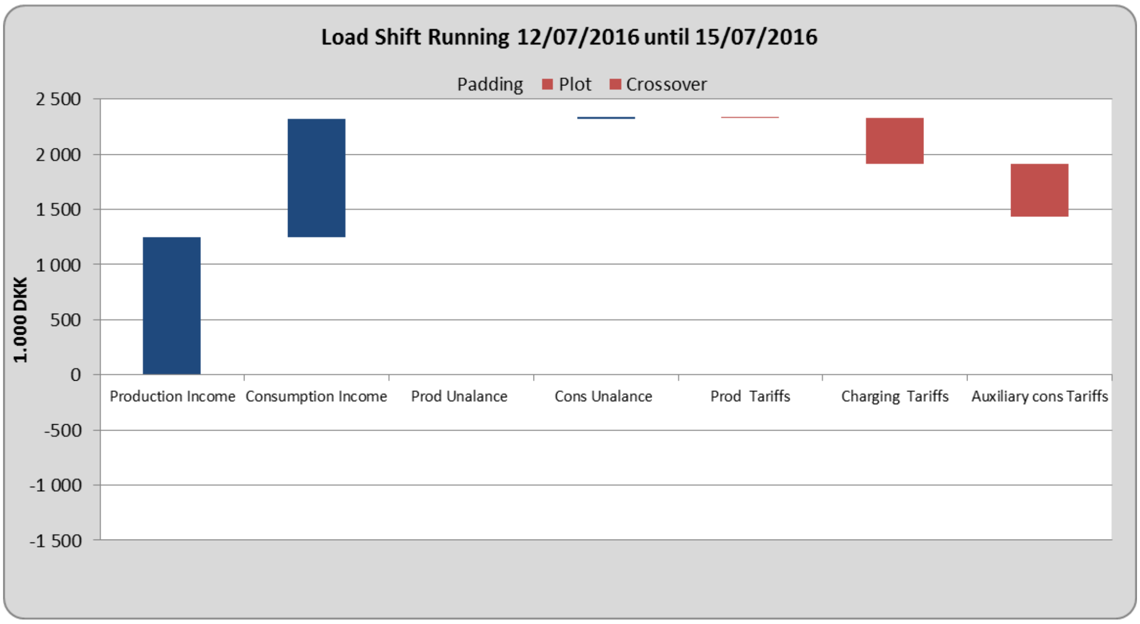
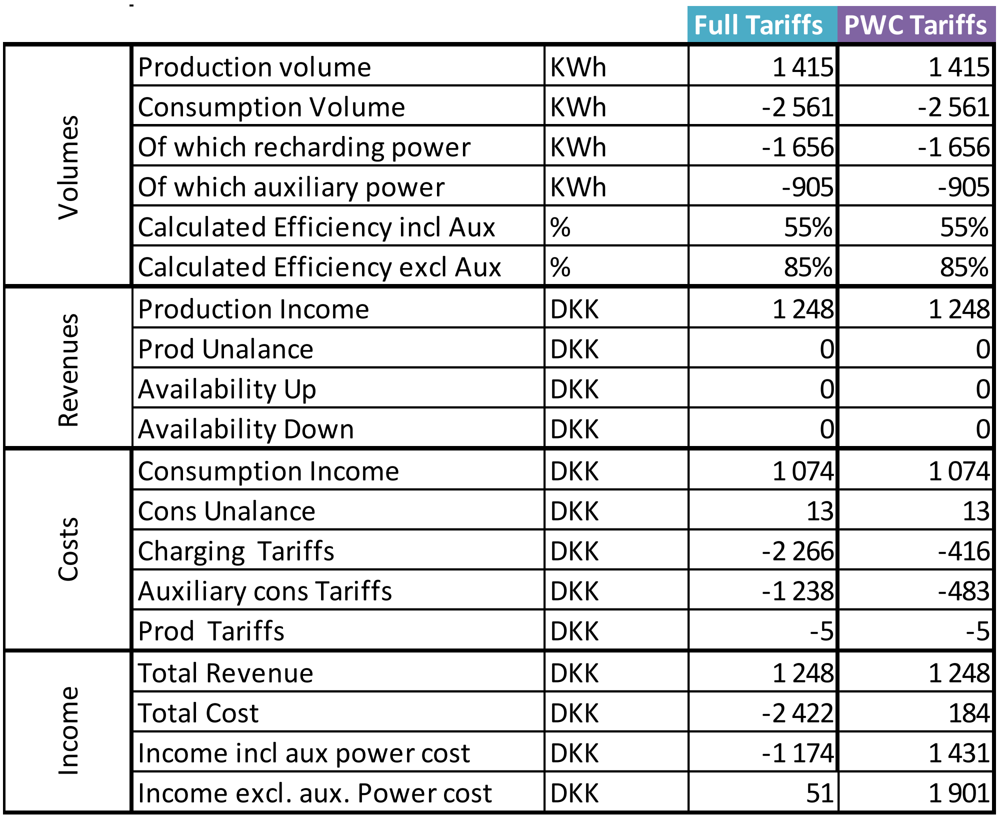


Figure 14: Load shift results based on the reduced tariffs assumed in WP1

Table 6 shows the same results shown in the graphs above in addition to some more statistics on the load shift operation. In this calculation, it is assumed that the auxiliary power is treated as a consumption unbalance, thus falling under the one price system. As can be seen from the result, whether this consumption is planned or not makes a little difference on the total result.

Table 6: Main results for load shift operation (PWC meaning reduced tariffs as mentioned previously)

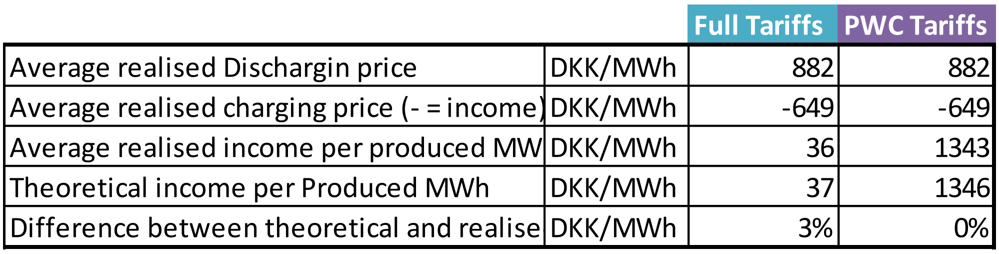


			Full Tariffs	PWC Tariffs
Volumes	Production volume	KWh	1 415	1 415
	Consumption Volume	KWh	-2 561	-2 561
	Of which recharding power	KWh	-1 656	-1 656
	Of which auxiliary power	KWh	-905	-905
	Calculated Efficiency incl Aux	%	55%	55%
	Calculated Efficiency excl Aux	%	85%	85%
Revenues	Production Income	DKK	1 248	1 248
	Prod Unalance	DKK	0	0
	Availability Up	DKK	0	0
	Availability Down	DKK	0	0
Costs	Consumption Income	DKK	1 074	1 074
	Cons Unalance	DKK	13	13
	Charging Tariffs	DKK	-2 266	-416
	Auxiliary cons Tariffs	DKK	-1 238	-483
	Prod Tariffs	DKK	-5	-5
Income	Total Revenue	DKK	1 248	1 248
	Total Cost	DKK	-2 422	184
	Income incl aux power cost	DKK	-1 174	1 431
	Income excl. aux. Power cost	DKK	51	1 901

Comparison with the prior theoretical calculations

Given that the consumption time series available contains both auxiliary and charging power, a threshold of 15 kWh/hour was used based on the observed data to filter auxiliary power consumption from charging consumption. This resulted in an average cycle efficiency of 85% when ignoring auxiliary power, which matches very well with the assumed efficiency from previous. Given that the efficiency matches, it is no surprise that the theoretical and realized profit per produced MWh matches as shown in Table 7.

Table 7: Average charging and discharging prices, and the comparison between the theoretical and realized income per produced MWh. PWC meaning reduced tariffs.



		Full Tariffs	PWC Tariffs
Average realised Dischargin price	DKK/MWh	882	882
Average realised charging price (- = income)	DKK/MWh	-649	-649
Average realised income per produced MW	DKK/MWh	36	1343
Theoretical income per Produced MWh	DKK/MWh	37	1346
Difference between theoretical and realise	DKK/MWh	3%	0%

From Table 7, it also follows that it is enough to know the average charging and discharging price during the period to deduce the income. Therefore, the optimization strategy needs only to ensure that the average charging and discharging price pairs fall in the designated areas shown in Figure 15. The graph below can facilitate decision taking when trying to capture prices on the balancing market.

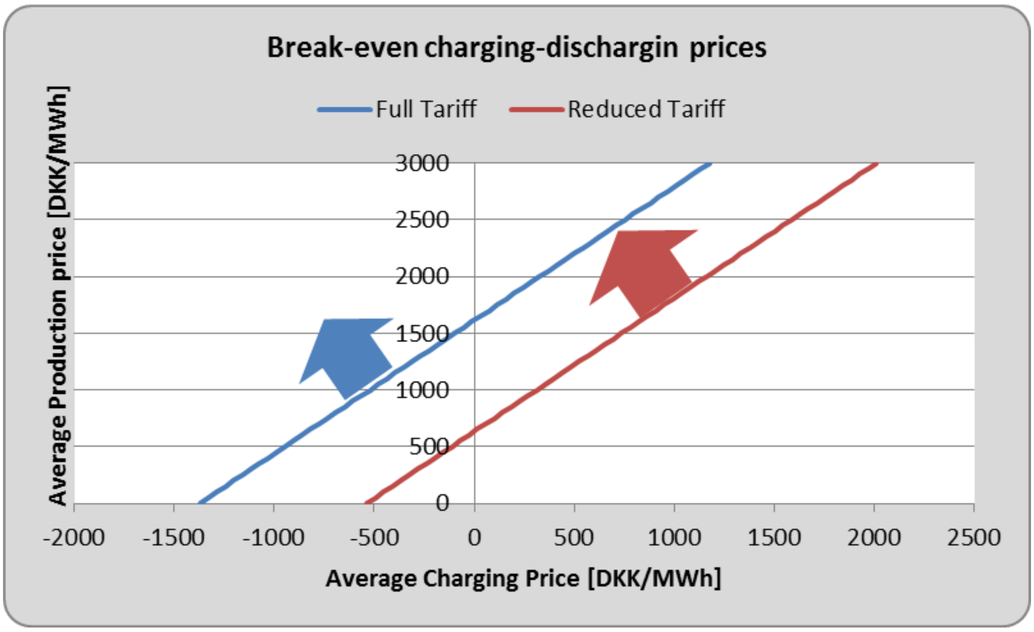


Figure 15: Break even and desired charging/discharging price combinations during load shift

Finally, it is noted that auxiliary power results in a substantial burden on the profitability of BESS, and the effect is especially prominent in the current tariff situation. Keeping in mind that the number of cycles per year is much less than that observed in the 4 days test, the auxiliary power will play an even more prominent role as its volume would be larger compared to the operational cycles. It is therefore of high importance to reduce the auxiliary power consumption if BESS is to be profitable on the market.

5.1.8.2 Primary reserve operation

During the previous years, the BESS system was sold as an up-regulation primary reserve. This means that the unit received an income for being available to deliver production on the market. The production volume on the other hand is treated as an imbalance. In our calculation, we also assume that the whole consumption is treated as an imbalance.[1] It should be noted that starting from July 2014, the storage capacity dropped from due to the outage of one of the batteries, and therefore the accepted up-regulation power was reduced from 1.4 MW to 1 MW after that date.

Figure 16 shows the operational revenues and costs along with the resulting operational income in case of the full tariff and the reduced tariff scenarios. What is clear in the graphs is that the reserve payment is the major post leading to the profitability of BESS. This is due to the fact that the actual production and consumption volumes under this mode of operation are relatively low, as shown in Table 8. Note that in order to be able to separate the auxiliary power from the total consumption, the efficiency of 50% is assumed as reported by Vestas in WP1 for this mode of operation.

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[1] Although one could plan for the auxiliary power in advance, the difference is negligible as would be seen in the results. In fact due to the consumption being treated under the one-price balance system, some years result in a positive income due to the consumption imbalance.

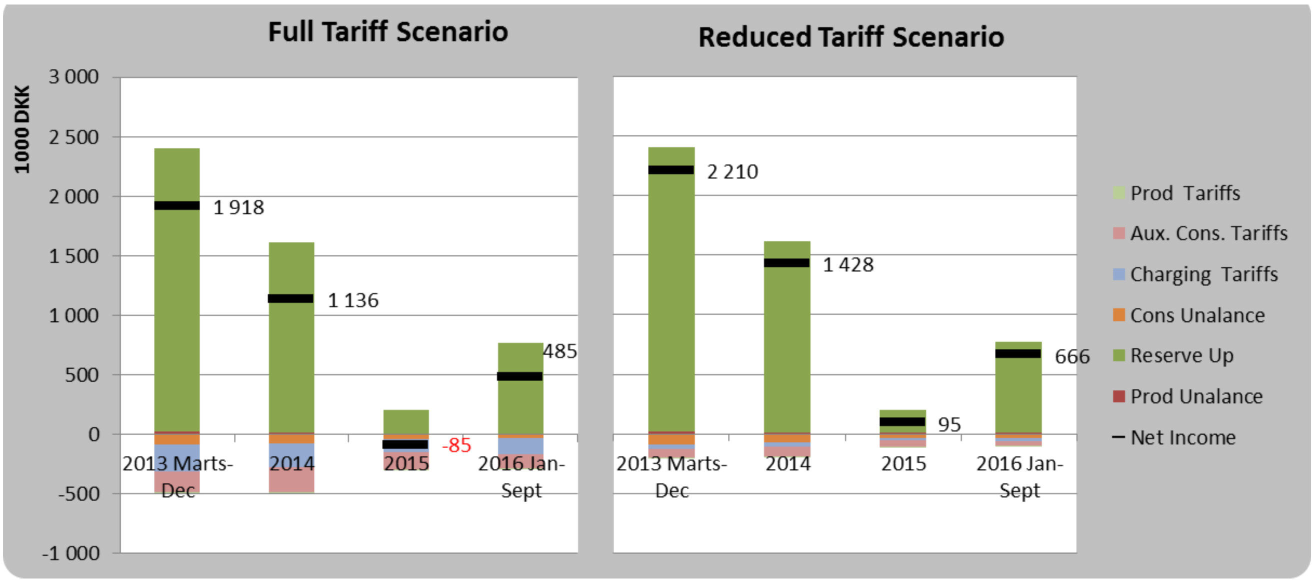


Figure 16: Realized revenues and costs and operational income per year starting from March 2014 until September 2016. The reason for discarding the first 2 months of 2013 is defect consumption readings in the data series available.

Table 8: Resulting production and consumption volumes during reserve market operation

			2013 Marts-Dec	2014	2015	2016 Jan-Sept
Volumes	Production volume	MWh	84	74	42	49
	Consumption Volume	MWh	-293	-300	-187	-183
	Of which recharging power	*MWh*	*-168*	*-147*	*-83*	*-99*
	Of which auxiliary power	*MWh*	*-126*	*-153*	*-104*	*-85*
	Calculated total efficiency	%	29%	25%	22%	27%
	Assumed Efficiency excl. Aux	%	50%	50%	50%	50%

With the cost side of the equation being limited by the low operational volumes, the income thus depends mainly on the earnings on the reserve market. These earnings are dependent on 3 main factors:

- Unit availability
- Sold reserve capacity
- Reserve market prices

Table 9 shows the variation of these three factors for the BESS system, which explains the variation of the reserve payment column shown in Figure 16:

- Unit availability, which was highest in 2015, and was particularly low during 2015
- Sold reserve capacity, where the average sold volume per hour dropped from 1.4 MWh to 1 MW following the outage of part of the battery in 2014
- Reserve market prices: The reserve market prices have in general been dropping. In 2015, the weighted average price for the hours sold was even lower than the average market prices during that year.

Table 9: Factors affecting the earnings of BESS on the reserve market

			2013 Marts-Dec	2014	2015	2016 Jan-Sept
Reserve Statistics	% of hours sold	%	96%	84%	35%	77%
	Average volume sold	MWh	1,40	1,33	1,00	1,00
	Average market price	DKK/MW/h	239	159	114	146
	Weighted average price	DKK/MW/h	240	167	55	166

5.1.9 Alternative primary reserve in connection with pilot project

There has been done efforts in the project in order to evaluate how battery systems can operate as primary reserve in the future and avoid some of the issues discovered in the project. Several different solutions has been suggested and together with Energinet.dk a real life test was decided upon and carried out in connection with pilot project arrangement from Energinet.dk. Here, a new, hopefully better control algorithm which takes both grid, battery and business case into consideration was tested while participating up-regulation in the primary reserve market. The new alternative is analyzed, and live tests are performed on the Altairnano BESS system in Lem Kaer.

Traditionally primary reserve operation up, calls for power delivered to the grid when the frequency drops below 49,980 Hz in order to maintain the nominal frequency of 50 Hz and secure grid stability. There was a deadband of 20 mHz, in which the systems should not deliver. This delay is not ideal from a grid perspective.

The reason for the involvement in this BESS project is that there are no clear technical rules or guidelines on how battery systems should be operated in primary reserve at the moment. The existing rules are designed primarily for thermal power generation and does not comply well with how a battery can operate, and does not take into consideration the fast acting possibilities of a battery system.

According to previous regulations a system which delivers primary reserve must always be able to deliver for a minimum of 15 minutes, and thereafter has 15 minutes for recharge. When introducing primary reserve units with limited energy storage, this means that a system must shot down after 15 minutes of delivery independent of energy delivered and start charging in order to be able to deliver full power for 15 minutes again, 15 minutes later. This is not very attractive for either electrical grid or battery system, as seen previously in this report. Also the allowed delay of up to 30 seconds before full power is reached is not wanted.

The overall operating pattern of an alternative primary reserve with batteries were:

1. Always keep the battery system online and calculate Frequency response power demand linearly from 0 to maximum power depending on deviation from 0 to 200 mHz from 50Hz (No deadband)

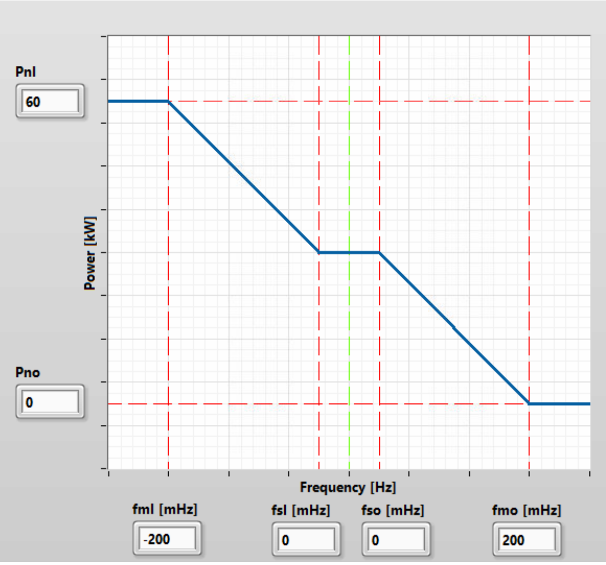
2. Calculate charge power demand linearly depending on deviation in SoC from setpoint and maximum power

3. The actual delivered power is calculated as the sum of frequency response demand (1) and charge demand (2)

4. Deliver power as fast as possible without intentional time delay (and without deadband)

5. Auxiliary consumption of system is not included

6. The bid into the primary reserve market depends on the energy capacity of the energy storage system (how long the system can deliver full power) and the maximum power of the battery system, depending on how fast secondary reserve can take over



Pnl 60

Pno 0

fml [mHz] -200

fsl [mHz] 0

fso [mHz] 0

fmo [mHz] 200

Figure 17: Illustration of frequency deviation and requested power. In alternative primary reserve, the deadband is 0 mHz. Pnl=Power Nominal Levering(delivery), Pno=Power Nominal Optag(consumption), fsl=frequency deadband delivery), fso=frequency deadband consumption, fml and fmo is deviation at full power.

5.1.9.1 Size of market bid in alternative primary regulation

The size of the market bid in the alternative primary/frequency regulation is calculated on the basis of battery storage capacity and available maximum power. The background for the calculations by energinet.dk is that secondary reserve must be able to take over (time delay of 200 seconds.) The approved bid relative to number of minutes at full power can be seen below in Table 10.

Energy capacity measured in minutes at full power	*Percentage of maximum power bid into the primary reserve market*
5	*70%*
15	*85%*
30	*91%*
60	*95%*
120	*98%*
>120	*100%*

Table 10: Example of calculated approved percentage of max. power depending on the energy capacity of the BESS system. The values are inspired by preliminary calculations made by energinet.dk.

Since the Altairnano system is capable of delivering full power for 15 minutes, the percentage is 85%, and the maximum power is 1.250 MW, the bid into the market in the pilot test is:

1.250 MW*0,85 = 1.062 MW, which is rounded down to 1 MW.

The maximum power bid into the traditional primary reserve market by the system is also 1 MW of power for the Altairnano system in order to recharge and overcome energy losses within 15 minutes. Since the income is approximately the same, the energy consumption and cost for this is very important for the business case.

Modelling of alternative primary regulation delivery

In order to evaluate the effects of a new operating pattern, different days and timespans were selected and calculations were done depending on the actual frequency, and a calculated SoC of the Altairnano battery system in Lem Kaer.

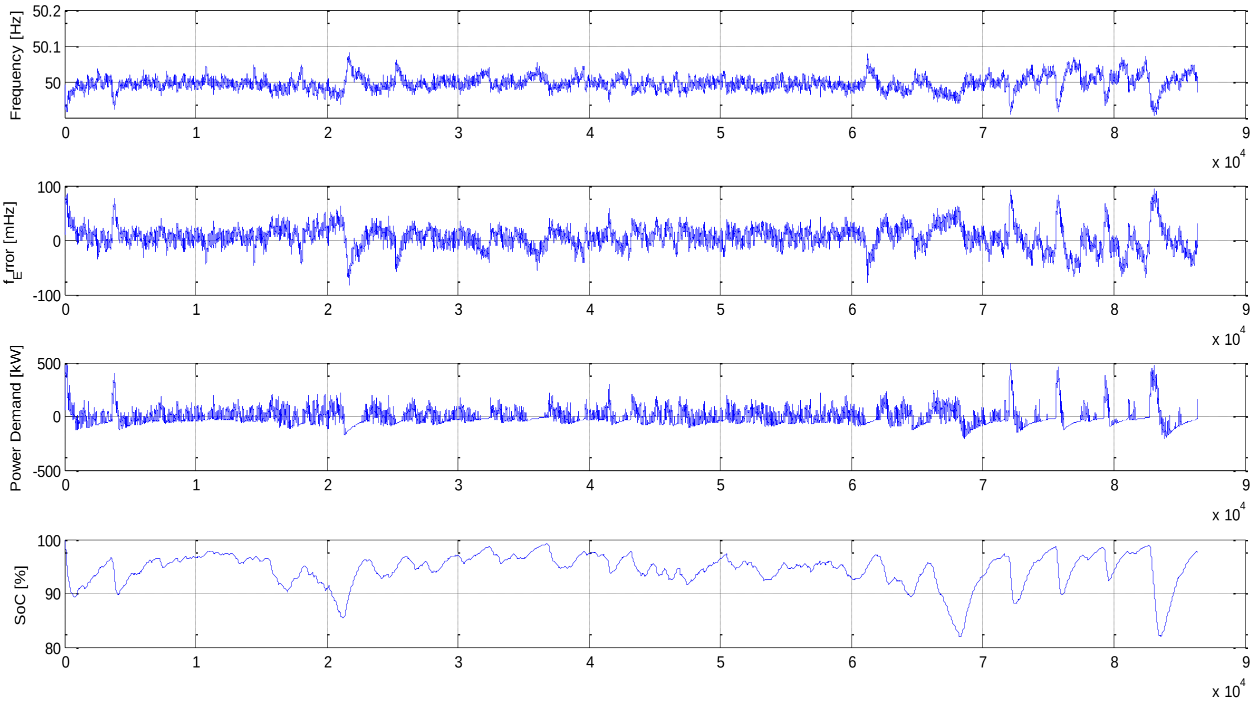


Figure 18: Example of modelling from average day (2013-11-09) performing alternative primary reserve operation upregulation. The time stamp on the x-axis is in seconds.

The modelling results are summarized in the table below together with a factor for comparison in the last column. It is seen that the average energy comsumption is expected to rise with between 5 and 32%. In the extreme scenarios, the energy delivered is lower, but this is not normal operation.

Frequency pattern	Standard (20 mHz)	Standard 0 mHz	New control, 0 mHz	New control, 10 mHz	New control, 20 mHz	Factor between standard og new 0 mHz
Average day (2013-11-09)	0,411	1,590	0,431	0,315	0,205	**1,05**
Day with single largest energy delivery (2013-10-28)	0,561	1,630	0,415	0,293	0,196	0,74
Typical month, February 2014	8,222	33,835	10,824	7,272	4,207	**1,32**
Typical month, March 2014	10,897	39,435	12,477	8,636	5,324	**1,14**
2006 extreme	0,320	0,361	0,167	0,172	0,174	0,52

Table 11: Energy delivered in kWh for the different recorded frequency patterns and the different operating scenarios.

Frequency pattern	New control, 0 mHz	New control, 10 mHz	New control, 20 mHz
Average day (2013-11-09)	81,757	84,026	86,167
Day with single largest energy delivery (2013-10-28)	57,119	59,754	62,624
Typical month, February 2014	72,329	75,547	79,267
Typical month, March 2014	72,786	75,943	79,321
2006 extreme	42,362	43,181	44,042

Table 12: Minimum State of Charge (SoC) for the different frequency patterns and varying deadband in connection with the new control. 0 mHz is most likely

It is seen in Table 12 that in normal operation, the minimum state of charge is not expected to become lower than 70%. The extreme scenario from 2006 with separation of the European electrical grid would lead to a calculated minimum SoC of 42%.

5.1.9.2 Operating experience alternative primary regulation

The developed regulation pattern was put into operation on the Altairnano system in Lem Kaer, and the overall operation can be seen in Figure 19 and Figure 20 below.

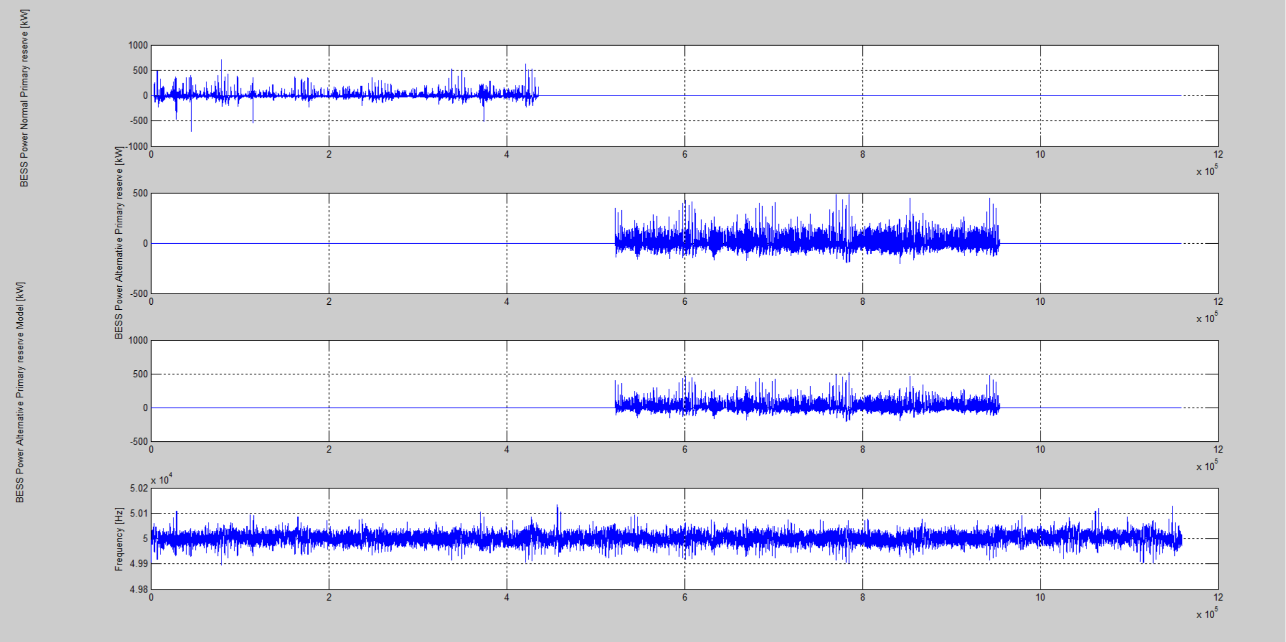


Figure 19: Graph showing traditional primary reserve in the beginning (5 days) and subsequent delivering the alternative primary regulation for five days. And the frequency throughout the period. The x-axis is time in seconds (December 1st to December 14th, 2016).

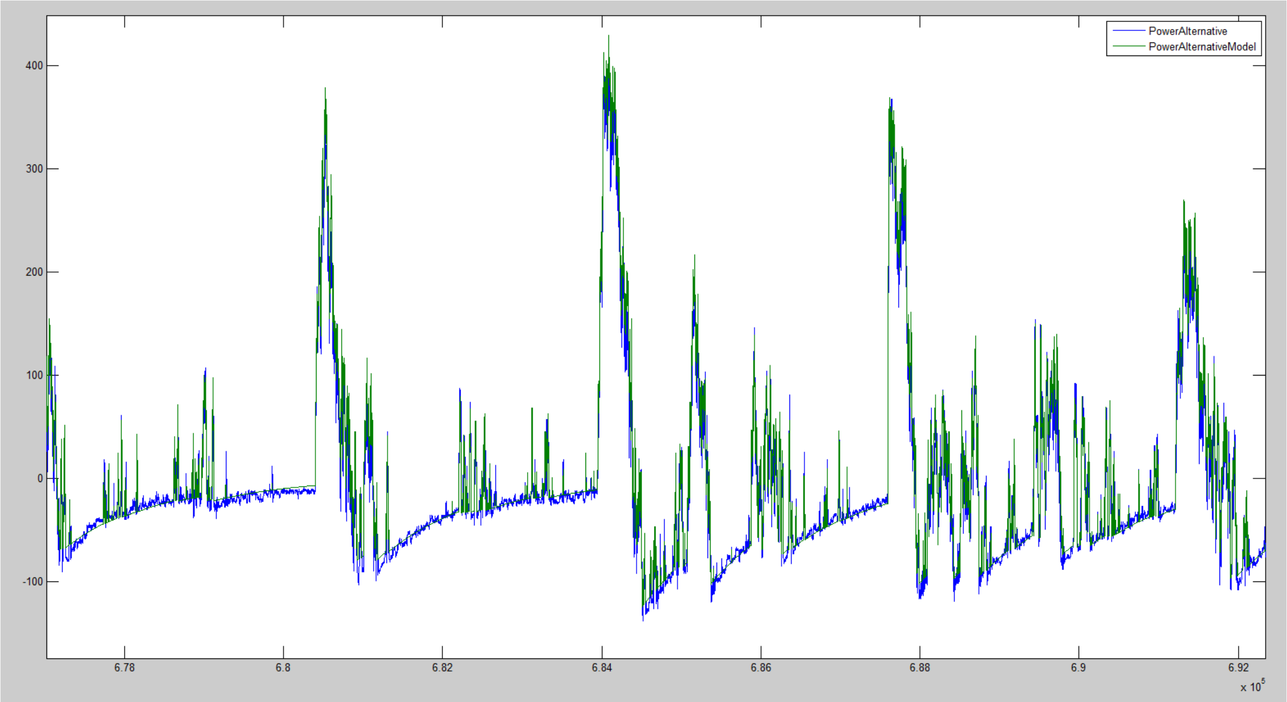


Figure 20: Comparison between modelling (green) and actual power (blue) in kW from the alternative primary regulation tests in Lem Kaer. The x-axis is time in seconds.

The SoC setpoint which was 100% in the modelling is set to 95% in the real tests. There are also small differences in the calculated and actual SoC. There is also a short time delay for delivery due to data interpretation and the shift of power in the live test, even though the system reacts fast. The time delay is not included in the modelling. Still, the modelling and actual delivery has a relatively good match as seen in Figure 20.

5.1.9.3 Conclusion of alternative primary reserve delivery

The system performed good and as expected with the alternative primary reserve operating pattern, but the energy delivery and hereby associated additional cost is higher than during traditional primary reserve.

The overall expected additional energy delivery is expected to be 5-32% higher than during the traditional primary reserve. An estimated additional energy delivery based on the average of the most probable calculations is 20%. The BESS system is technically fully capable of delivering the alternative primary reserve regulation.

The cost for operating a battery energy storage system is largely dependent on the cost for electricity in order to compensate for the energy losses in the system and for tariffs and taxes. Economically the tested alternative primary reserve is not attractive for the operation of a BESS system for primary reserve. If the availability prices for primary reserve becomes larger in the future due to more fluctuating renewable energy, the operation will of course become more attractive.

5.2 Scale Battery Energy Storage System at DTI

5.2.1 Initial thoughts and design process

The small scale Battery Energy Storage System (BESS) described in this document is designed to reflect the complexity of a larger BESS for example the system located at a wind farm in Lem Kaer, in the western part of Denmark which is also a part of this project.

Prior to the preparation of the requirement specification, a number of thoughts and ideas where discussed. Some of the desired system properties and functionalities are listed below.

- Complexity similar to a large scale system
- Same safety measures as a large scale system
- System assembled as a mobile unit
- High efficiency and low requirements for heating/cooling
- Opportunity to use the system with different battery packs
- Acquisition of a large amount of data; individual cell voltages, detailed monitoring of energy consumptions, temperatures etc
- Remote access to control functionalities and SMS error notifications
- Flexible interfacing to other systems, to accomplish a smarter grid
- Possibility to operate as primary reserve
- Flexible control in order to operate with different control strategies (manual control, frequency control, load shift, voltage control, setpoints from file etc.)
- Operation based on a predefined sequence, as well as regulation based on local measurements

Furthermore, it was agreed on that reliable component suppliers willing to cooperate and offer support was of great importance. And that the availability of single battery cells for test purposes had to be considered, if a battery module was decided on.

Following the idea process a generic requirement specification for BESS systems as well as specific requirements for the scale system were developed, besides the system properties and functionalities listed above, the specific key requirements for the scale system were:

- Connectivity to 0.4 kV grid
- Maximum power: 60 to 85 kW
- VAR support (ability to inject/absorb reactive power)
- Ability to deliver/absorb full power for minimum 15 minutes

A general procurement specification for BESS Battery System was also made during the project.

5.2.2 System implementation

The implementation process began with a screening of the market, to map potential suppliers of major system components, like batteries BMS system, inverter, data loggers and heat pump. Parameters such as technical specifications, price, delivery time and the suppliers willingness to provide information and prices were considered. Subsequently, after pointing out the components and suppliers fitting our requirements, negotiations on prices, delivery times and terms were carried out.

Along with the negotiation process, the interfaces of all system components were analyzed to prepare the system integration process. As the ordered quantity of each component was small and delivery time was of the essence, it was not possible to dictate the communication interface and protocol of these components, meaning that a great number of communication methods had to be handled by the system controller, this includes 2 x CAN, 2 x Modbus RTU (RS485), 1 x Modbus TCP (Ethernet), 2 x RS232, a number of USB devices and a number of digital and analog inputs and outputs.

The specialty house made to contain the BESS system, is specially designed to allow separation of battery and inverter section, was produced in Hirtshals in the northern part of Denmark and the inverter and an electrical equipment cubicle was mounted in the house during the building process. All subsequent installations were done at DTI in Aarhus.

5.2.3 System description

This chapter briefly describes the grid to which the BESS is connected.

The BESS is located at DTI in Aarhus and is connected to a 1 MVA 10/0.4 kVA transformer, along with a number of other energy producing and consuming systems as shown in Figure 21.

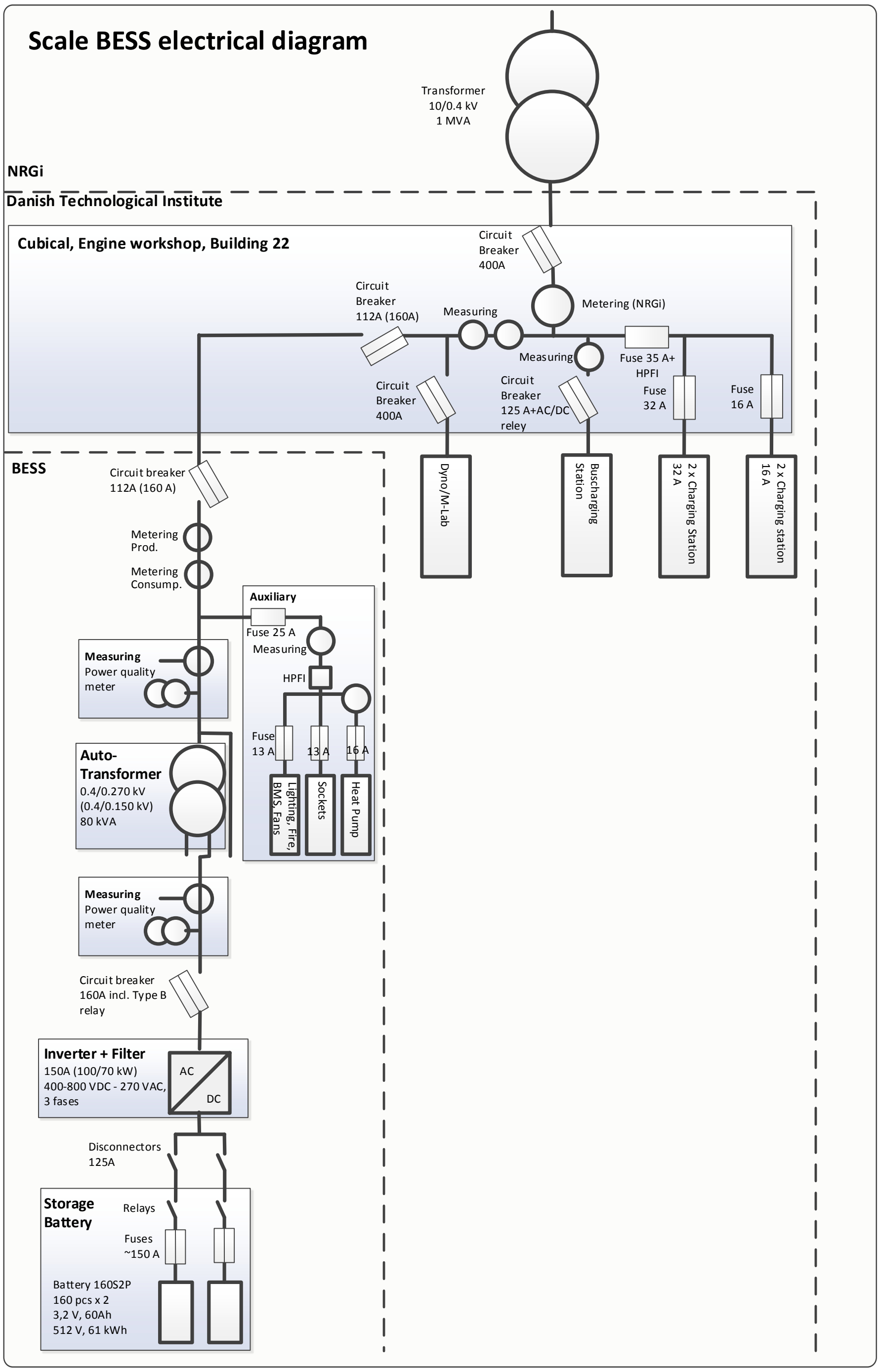


Figure 21: Single line connection diagram for major BESS components and external systems. The scale BESS system is market with the perforated line in the lower left corner.

The implemented system is able to absorb and store energy of approximately 61 kWh from the electrical grid, as well as deliver the stored energy to the grid. The energy flow pattern can be altered using a number of different control algorithms implemented in the controller software. The BESS system includes two parallel battery strings, each consisting of 160 battery cells, with a rated capacity of 60 Ah, and a nominal cell voltage of 3.2 V. Hence, the nominal battery pack voltage is 512 V_{DC}. The energy flow between the battery pack and the grid is handled by a bi-directional inverter, which is connected to the grid at $400V_{AC}$ level through a transformer. The entire system is installed in an isolated movable lightweight specialty house, as shown below.

Figure 22: Picture of the installed scale BESS system

Further pictures of the system and installations can be seen in annex 3.

5.2.4 Recorded data and results

Data from the Scale BESS system is recorded at a sampling rate of 1 sample/sec. Data recordings from November 2015 to December 2016 is recorded. However, design adjustments based on initial tests, as well as defects and ongoing software improvements have meant that the system has been out of operation for certain periods.
Different tests have been performed on the scale BESS system. The tests have been performed in order to evaluate the operation of the system and also to look at different possible operation patterns for battery systems in the electrical grid.

The following tests have been performed:

1. Preliminary: Functionality, Safety, data logging
2. Capacity measurements
3. Internal resistance measurements
4. Maximum power
5. Frequency regulation from recorded data (including temperature variation)
6. Accelerated frequency regulation pattern
7. Load shift test
8. Frequency regulation based on actual frequency measurement
9. Voltage regulation based on local voltage measurement

The results from the different tests can be found in the following sections of this report.

5.2.4.1 Frequency regulation from recorded data

Based on the available data from Lem Kaer, one specific day, which reflects the average, has been found. Data from this day is used as a setpoint file for the battery tests of the Scale BESS system.
The average day was found based on maximum, minimum, frequency distribution and average frequency. The day located was the 2013-11-09.
This pattern was transformed into a test pattern for the BESS system by scaling the frequency and power from the actual day, and converting it into a current setpoint file.

Data from the reference day was also converted into an accelerated frequency pattern to accelerate the energy throughput and hence the degradation. The test pattern can be seen in Figure 23.

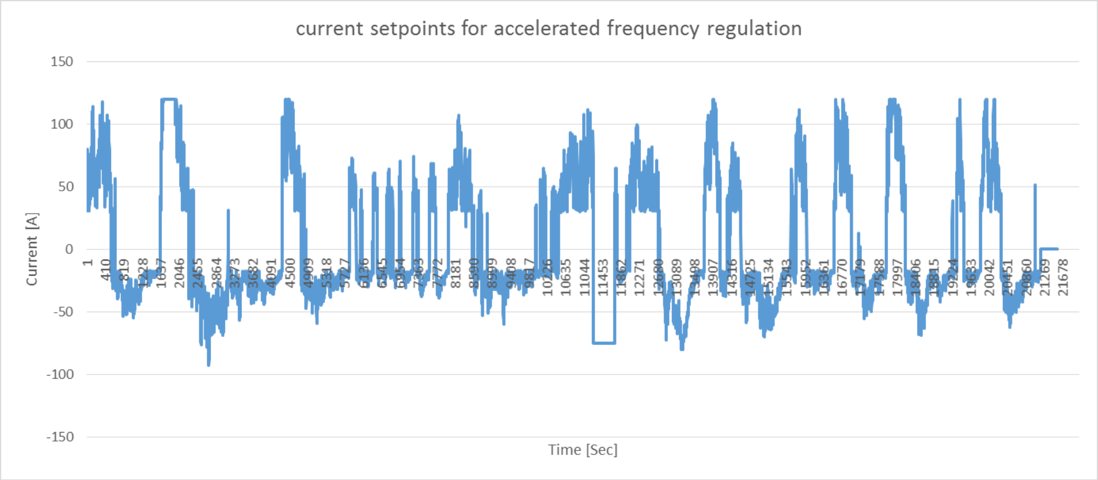


Figure 23: Current setpoints for accelerated frequency regulation. The total duration of the accelerated file is 6 hours.

5.2.4.2 Load shift test

A load shift test was conducted based on an optimal income analysis buying electricity when prices are low and selling, when prices are high. See also document on income from Energy Denmark on this issue.

The Scale BESS system was set to operate between 5 and 95% SoC, and the current was set to 102 A when delivering and 103 A, when consuming energy.

The high currents with rather long duration causes problems. As can be seen in the chart below, the first discharging period is executed as expected, however the magnitude of the cell voltage rise causes the system to stop prematurely, meaning that the battery is only charged to approximately 20% SoC. Hence, the subsequent discharging duration is reduced accordingly. The problem is caused by a single battery cell having an abnormal high internal resistance. Note that the initial charging at 60 A do not cause problems.

Figure 24: Chart showing problem caused by high voltage rise during charging at high C rate. Current set-points (green), actual current in (blue)

The theoretic energy delivered from the system was approx. 320*60Ah*3,2V/1000*(0,95-0,05)=55 kWh per cycle.

As described above, the charged energy during the loadshift test was limited due to one week battery cell, hence the usable energy content was a lot less than expected.

In order to operate as a load shift unit with full delivery and full charge during one hour, the battery with the high internal resistance has to be exchanged.

5.2.4.3 Real time alternative frequency regulation

A control algorithm applying power based on the frequency deviation has been implemented and tested according to primary reserve regulation. The implementation is prepared to allow adjustment of nominal power, and deadband for both up- and down regulation, however during the executed test the configuration was setup to only perform upregulation as this is the most economic attractive regulation. A charging algorithm that runs continuously in parallel with the frequency dependent algorithm has been implemented, to ensure that the applied charging power is proportional to the SoC deviation from target SoC. The user-defined inputs for these algorithms can be seen in Figure 79 in annex 3.

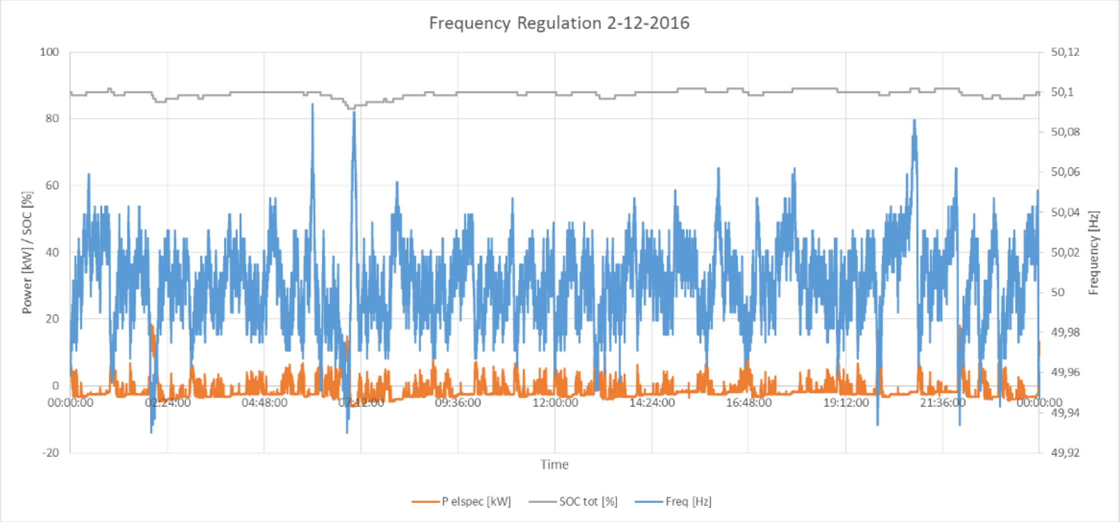


Figure 25: Graph from test of alternative frequency regulation; Power (red), Frequency (blue), SoC (gray)

5.2.4.4 Local voltage regulation

Tests was performed with voltage regulation based on the local voltage measurement in the BESS system. The regulation is performed based on the local grid voltage measurement. When the voltage is outside the deadband the power is delivered starting from 50% of P_{nominel} and linearly increased to P_{nominal} as the deviation increases.

The position of the system close to a 10/0.4 kV transformer and the overall grid, and typically low consumption on this transformer makes the test location unsuitable. Therefore, the tests were mainly conducted to see if the regulation worked. The limits during voltage regulation had to be reduced from the standard deviation of maximum 10% (40 V) and start at 5% (20 V) to 20 V and 5 V deviation from the nominal RMS value of 400 V. The change in regulation parameters was done during the test on the 7. of December. It can be concluded that the direct change from a voltage regulation above 405 V to a charging algorithm when below 405 V, causes power oscillations when the grid voltage fluctuates near the threshold voltage. This can be avoided with introduction of a delay in the programming.

5.2.4.5 Degradation of the scale BESS system

Apart from an abnormal single battery cell no degradation have been detected.
The tests of load shift and maximum power has illustrated how important cell balancing and initial well matched cells are, since the usable energy capacity depends very much on this. This was mainly seen during load shift pattern and extreme tests due to the higher currents and large SoC span.
The total amount of energy delivered from the scale BESS system is approximately 8500 kWh, equivalent to approximately 138 full cycles.

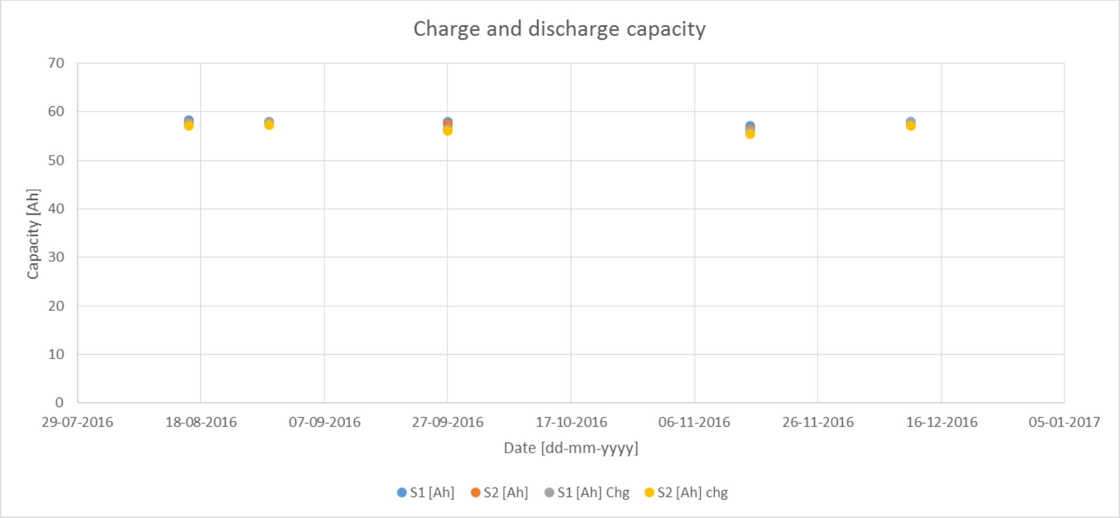


Figure 26: Charge and discharge capacity for each of the two strings in the scale BESS system

The time period and energy throughput thru the Scale BESS system is too low to detect an overall degradation. The average discharge capacity of each the battery strings is 57.6 Ah. The nominal capacity of each battery is 60A. 96% of the nominal Ah-capacity can be utilized from in the system with a discharge of 1/3C.
For more knowledge about degradation, see the separate degradation report on single cell tests.

5.2.4.6 Internal resistance measurement

Current pulses were implemented as part of the standard capacity test sequence to allow subsequent calculation of the internal resistance of the batteries. Starting from a SoC of 0% a charging pulse of 120 A (1C) is applied followed by an idle period with 0 A, hereafter charging and discharging pulses of 120 A are applied for each 25% change in SoC (45min. charging at 40 A).
The pulses were reduced in some of the positive current tests due to one weak battery cell cells reaching maximum voltage. For optimizing the system, this cell needs to be changed, but it illustrates well the difference between using and testing battery systems compared to testing single cells.

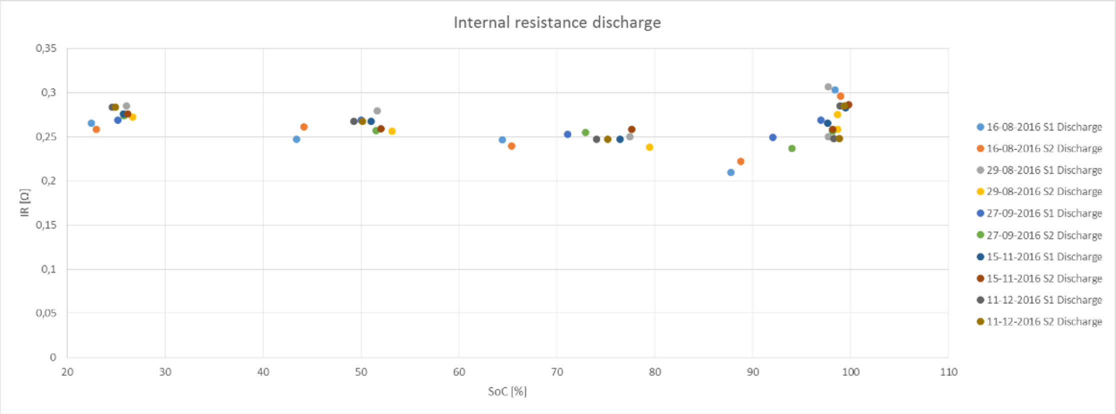


Figure 27: Battery string resistance during discharge at different State of charge. Negative pulses of 1C (120 A); Similar pattern is seen during charge.

The internal resistance generally becomes lower at higher SoC except for close to maximum SoC. The average measured resistance per string is 272 mΩ.
The nominal internal resistance of the cells is ≤1 mΩ, which makes up a total cell resistance of ≤160*1mΩ= 160 mΩ. The measured resistance is up to double that of the nominal internal resistance of the cells. This is due to resistance in cabling, interconnections and breakers. Some of the resistance uncertainties are also related to the different ways of determining this in terms of different step duration etc.

A problematic cell, which has the higher resistance and reduces the maximum charge current of the system, has an internal resistance of 5 mΩ.

An average increase or decrease of the internal resistance due to degradation of the cells has not been possible since the operation time has not been long enough. For information about this, see the separate BESS degradation report on single cells.

5.2.5 Efficiency of scale BESS system

The efficiency of the scale BESS system is determined during different load patterns.
The peak efficiency is determined for a test of approximately 6 hours with 1/3 C charge and discharge. The other calculations has been done for a full day. The initial cycles were done with 1/3C charge, discharge, equalization, and one cycle per day. The accelerated day is performed using an accelerated test pattern based on primary regulation for the average day. The average day is accelerated with a factor of 4 in time, making it possible to do the equivalent of 4 days in one single day.

	Delivered energy [kWh]	Consumed energy [kWh]	η System [%]	η Ex. Aux. [%]	η Battery [%]
Peak (1/3 C)	53,3	66,3	80,3	85,3	98,2
Init. cycles 1/3C	54,2	95,6	56,8	66,5	93,9
Accelerated Avg. Day	201,9	263,6	76,3	82,6	96,3
Avg. Day	34,3	75,9	45,2	56,4	95,9

Table 13: Table with energy delivered and consumed, efficiency of complete system with and without auxiliary consumption and for batteries only during different test patterns.

Generally, the system efficiency gets higher the more energy throughput. This is caused by many of the losses and auxiliary consumption being more or less independent of system load.
The efficiency of the batteries has an average value of 96%, so for optimizing the efficiency of the system the focus has to be on auxiliary and power conversion losses.
During the primary reserve average day test pattern the efficiency of the batteries are approximately 96% and the system efficiency is reduced to less than half of that at 45%. The total efficiency ranges from above 80% to 45% in the low load of the normal average day primary reserve pattern.
The losses in energy conversion and consumption for auxiliary components is very important when the system is operated at low loads.

5.2.5.1 Auxiliary consumption

The variation of auxiliary consumption has been tested with different temperatures of the battery room in the system.

	System η [%]	E Aux [kWh]	E Heat Pump [kWh]	Avg. inside temperature [°C]	Avg. Outside temperature [°C]	Delta T [°C]
Avg. Day (31°C)	44.9	19.2	6.4	33.6	15.5	18.1
Avg. Day (25°C)	45.2	13.8	1.4	28.0	13.2	14.8
Avg. Day (18°C)	50.5	10.1	1.6	20.1	10.0	10.1
Avg. Day (off)	*49.0*	*9.0*	*0.0*	17.8	7.8	10.0

Table 14: Efficiency of complete system, and energy used on auxiliary and heat pump and average inside outside and temperature difference. Tests have been performed with the same test pattern but different settings of the thermal control system.

At the temperature set point of 18°C, the heating and cooling unit has periods when the air is heated and other periods where the air is cooled. The average inside temperature during a rather cold becomes approximately 18°C. The temperature of the batteries is a few degrees higher since they are used.
The temperature tests show that the auxiliary consumption for the heating and cooling unit can be reduced with approximately 1.5 kWh per day with the days analyzed without additional degradation or damage to the batteries compared to 25 °C. The total auxiliary consumption can be reduced with approximately 4 kWh. The higher consumption for auxiliary at higher temperatures room temperatures is caused both by

the heat pump but also the 60 blowers that sucks air thru the 20 battery compartments, which is controlled depending on the temperature in the smaller battery compartments. The battery blowers can have a total consumption of up to 60*3W*24h=4.3 kWh/day. The temperature control can be better optimized in order to reduce energy consumption, but still taking degradation at higher temperatures into consideration.

Additional tests performed for longer periods of time and during hot summer days would have had great value.

5.2.6 Overall system and operating experience from the Scale BESS system

There has been different system errors, lack of documentation on delivered units etc. in the Scale BESS battery system during the project period. These are listed below.

- Electrical noise on the DC bus causing data communication errors.
- PE ground current triggering type-B relay
- Faulty battery Fan
- Heat-pump/air-condition control errors
- Defective LAN interface on system controller
- Necessity to alter control software
- Lack of expanded manual for inverter
- False triggering of the error relay on the fire extinguishing system

A few battery single cells, which had a lower capacity than the rest has been switched.
Overall, the task of integrating battery pack, BMS system, control systems etc. has been a challenge, which has taken much effort and time.

5.2.6.1 Balancing of cells

Cell to cell unbalance occurs due to differences in cell characteristics. The battery cells used for the Scale BESS system are not all from the same batch, due to too long delivery times. Hence, the Scale BESS system may have an increased need for balancing compared to a battery pack containing perfectly matched cells. The balancing can be done in a number of ways, but the overall goal is to equalize the SoC/Voltage, so that the available capacity of the battery pack is maximized. The most energy efficient way to perform balancing is through active balancing, where energy is transferred from cells with too high SoC to cells with too low SoC. Another method is passive balancing, where excessive energy of high SoC cells is dissipated in a power resistor or semiconductor. The algorithm to control which cells needs balancing can be based on the measured cell voltages or on individual SoC history. Often the balancing is performed as passive balancing based on a voltage algorithm applied at high SoC, this is also the case for the BMS installed in the Scale BESS system. This method is simple but requires that the use pattern of the BESS includes occasional full charges, and that the battery is left in charging mode long enough to allow the balancing to take place. The balancing of the battery strings in the Scale BESS system is handled entirely by the BMS, this means that it is up to the user to ensure that the SoC is regularly increased to a level where the balancing is applied. An improvement to the current configuration would be to let the system controller influence on the balancing threshold, to ensure that balancing occurs at the target SoC configured in the system controller software. Furthermore, another great improvement to the balancing system would be to upgrade the BMS, so that the balancing algorithm is performed based on all individual cell voltages within the string and not, as it is the case now, only based on the neighbor cells within the same BMS slave (8 cells per LMU(Local Monitoring Unit)). This would furthermore decrease the balancing time, as the settings are currently set to allow a very small cell to cell voltage deviation. A lack of an algorithm taking all cell voltages into account, means that the PCB (Printed Circuit Board) temperatures of the BMS slaves occasionally rises to a level where the BMS slave disables the balancing circuit. The BMS master then requests the charging current to be further reduced. A workaround is for the control system to reduce current before the BMS limits are reached.

5.2.7 Part conclusion for Scale BESS system

The battery efficiency in the system is higher, at approximately 96%, but the efficiency of the system is low when operated as frequency control, due to losses in inverters and transformers and due to consumption of auxiliary components.

This calls for the necessity of looking at and optimizing part load operation and thermal control for optimization of BESS systems. This has to be taken into account when buying or using battery systems.

Much focus concerning BESS systems is on the batteries. The experience from this project is that other system components and general system integration and interaction between system components are equally important in order to secure the up time of the entire system. In addition, the price of the system is much influenced by other components than batteries. The battery price is approximately 15% of the designed Scale BESS system.

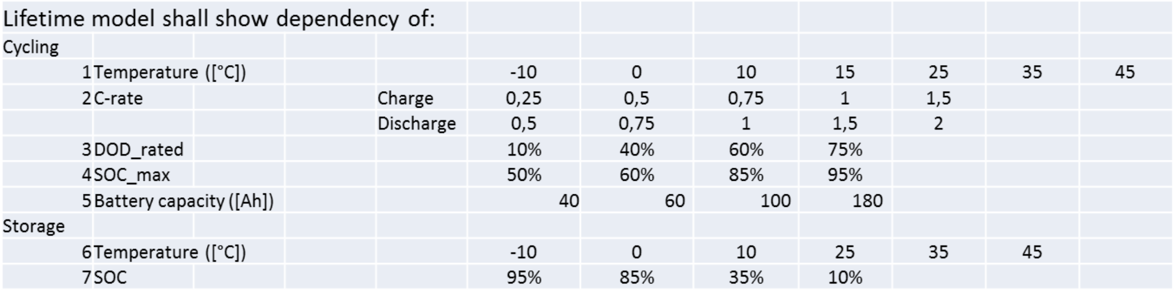
5.3 Degradation test on single cell batteries

Lithium-ion batteries are electro-chemical devices, and apart from the intended chemical reactions some unintended side reactions takes place because of the battery cell design. Side reactions as for instance: electrode passivation layer formation, lithium plating, electrolyte decomposition and binder decomposition may all occur during normal use of the battery cell, thus degrading the cell by decreasing the cell capacity and increasing the internal impedance of the cell. This degradation, which is also called aging, depends on usage pattern, the environmental conditions at which the battery cell is used and the battery cell design. A lithium-ion battery cell degrades whether in operation (charge & discharge action) or not (storage).

So, when a battery cell type is chosen, it is desirable know how to operate it in a way which yields a long life of the battery pack and therefore the best pay back of the investment made. Especially when investing in large batteries like in a BESS system. Many battery cell specifications indicates an expected lifetime at temperature=25°C, Charge rate=1C, Discharge rate=1C and 100% DoD. This information is far from enough to determine the optimum operation conditions, and if the desired lifetime information cannot be provided by the battery supplier, a degradation test or lifetime test must be performed.

A comprehensive lifetime test is performed in the BESS project and the results are given in the sections below.

Usually, the lifetime is stated as the number of cycles, which can be performed before the remaining capacity has dropped to 80% of the initial capacity, but the lifetime could be defined as any capacity loss depending on the battery application. In this report, a capacity loss of 20% is applied to define the battery lifetime for the purpose of comparison.



Lifetime model shall show dependency of:										
Cycling										
	1	Temperature ([°C])		-10	0	10	15	25	35	45
	2	C-rate	Charge	0,25	0,5	0,75	1	1,5		
			Discharge	0,5	0,75	1	1,5	2		
	3	DOD_rated		10%	40%	60%	75%			
	4	SOC_max		50%	60%	85%	95%			
	5	Battery capacity ([Ah])		40	60	100	180			
Storage										
	6	Temperature ([°C])		-10	0	10	25	35	45	
	7	SOC		95%	85%	35%	10%			

Table 15: Overview of different test parameters in single cell tests. C-rate= ratio between current ([A]) and battery capacity ([Ah]). Dod=Depth of Discharge, SoC=State of Charge. Tests has also been done with an accelerated primary reserve load pattern and with 100% DoD cycles for comparison with datasheet.

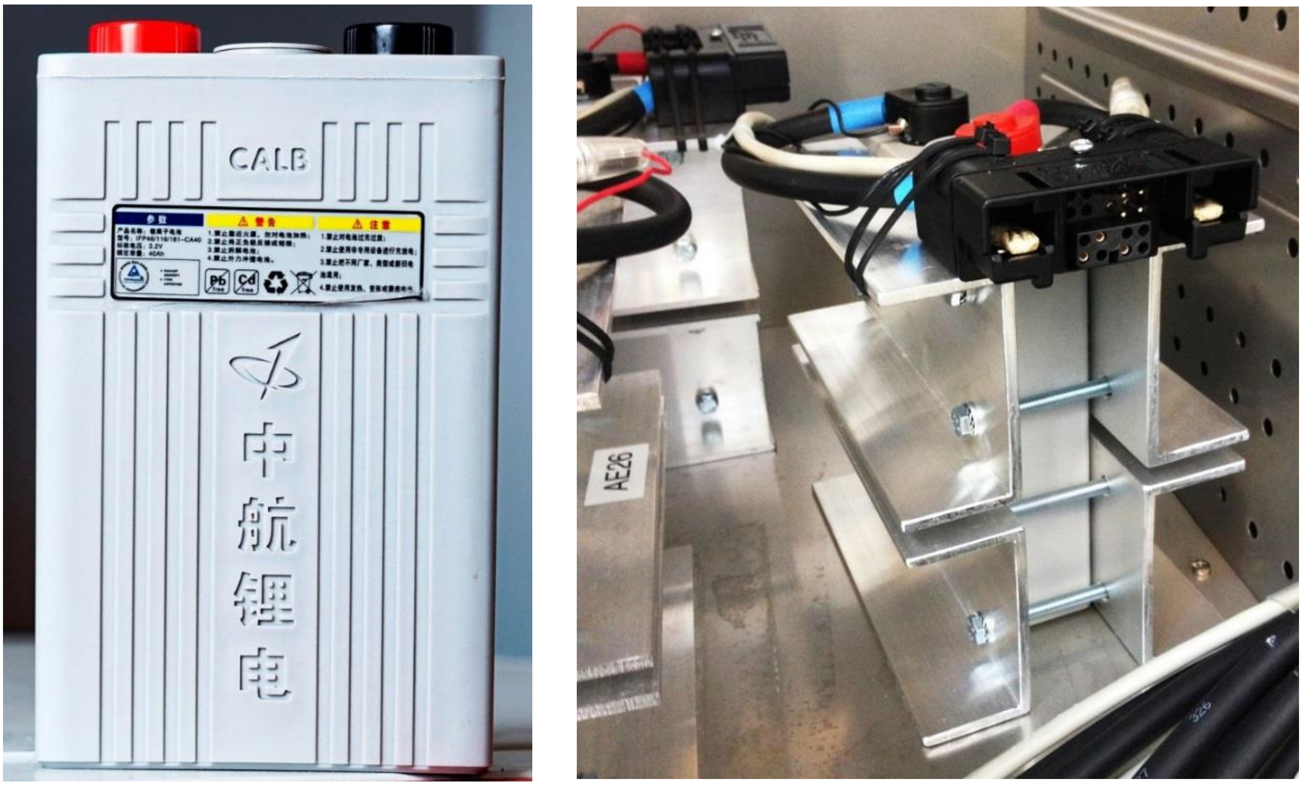


Figure 28: CALB 40 Ah prismatic cell

Constant ambient temperatures are provided by five Binder chambers with forced airflow. The heart of the test setup is a battery test system, which is a Maccor 4000 test system as shown in Figure 29. For each cell, a program is written in order to perform each specific test.

Figure 29: Binder chambers and Maccor 4000 Battery test system in the background

5.3.1.1 Test protocol

The overall test procedure is as follows

1. Performance test
2. Initialization
3. Performance test
4. Cycle / storage test
5. Performance test
6. Repeat item 4 and 5 until end of test

Performance test

The performance test characterizes the cell by measuring capacity and internal resistance at 25°C.

Initialization

Initialization is performed in order to "kick start" the cell after storage for some time. It is well known that during the first cycles of a new cell, the capacity increases.

Cycle test / Storage test

The purpose cycle test is to degrade the cells according to the specified test conditions.

A more extended description of the test procedures can be found in appendix 4.

5.3.2 Test results

A brief overview over the test results is given in Table 16 and Table 17 below.

Storage test matrix					
Test focus	Temperatur	SOC	Days	Cap loss	Avg. loss
Temperatur	45	70%	293	14%	4,7%
	35		174	5%	2,6%
	25		553	5%	0,9%
	10		230	1%	0,6%
	0		499	3%	0,7%
	-10		56	1%	1,1%
SoC	45	95%	252	16%	6,3%
		85%	243	14%	5,7%
		35%	242	11%	4,4%
		10%	242	9%	3,8%
	25	95%	587	8%	1,4%
		85%	611	10%	1,6%
		35%	553	3%	0,6%
		10%	613	3%	0,4%

Table 16: Storage test results overview

Cycle test matrix								
Test focus	Temperature	C-Rate chg	C-Rate dis	DOD_rated	SOC_max	E Cycles	Cap loss	Avg. Loss
Temperatur	45	**0,5**	**1**	**50%**	**75%**	1149	33%	2,9%
	35					830	12%	1,5%
	25					1149	14%	1,2%
	10					765	12%	1,6%
	0					765	18%	2,4%
	-10					194	8%	3,9%
C-rate	25	0,25	1	50%	75%	639	7%	1,1%
		0,75				638	9%	1,4%
		1				638	9%	1,4%
		1,5				681	9%	1,4%
		0,5	0,5			681	6%	0,9%
			0,75			617	7%	1,2%
			1,5			639	11%	1,8%
			2			637	15%	2,4%
	10	0,25	1			766	11%	1,4%
		0,75				765	12%	1,6%
		1				765	12%	1,6%
		1,5				766	11%	1,4%
DoD	25	0,5	1	10%	75%	1305	15%	1,2%
				40%		1226	15%	1,3%
				60%		1102	17%	1,6%
				75%		1242	8%	0,7%
SoC	25	0,5	1	50%	50%	382	3%	0,8%
					60%	382	4%	1,1%
					85%	383	6%	1,6%
					95%	384	7%	2,0%
Datasheet	25	0,5	1	100%	100%	512	6%	1,1%
60Ah cell	25	0,5	1	50%	75%	211	3%	1,3%
100Ah cell	25	0,5	1	50%	75%	486	3%	0,7%
180Ah cell	25	0,5	1	50%	75%	292	2%	0,6%
Load pattern	25	Max. 1C	Max. 1C	N/A	N/A	287	6%	2,0%

Table 17: Cycle test results overview

The impact of each stress factor can be seen in graphical form in annex 4.

5.3.2.1 Degradation

Lithium-ion batteries degrade when in operation (cycling) and when left inactive on the shelf (storage). In the latter case, it is well known from the literature that the degradation at storage depends on the battery temperature and the state of charge (SoC). The different influences can be seen below.

5.3.3 Optimum settings for a long storage life

The yearly capacity loss can be kept below 6%, if the cells are stored at room temperature or below, and if the state of charge is 35% or less. If stored at a temperature between 0°C and 10°C, and the state of charge is 10%, the yearly capacity loss is less than 3%.

The optimum setting in order to minimize degradation during storage are shown in Table 18.

Storage stress factor optimum		
Stress factor	**Optimum**	**Comment**
Temperature	10°C	Between 0°C and 10°C
SoC	10%	

Table 18: Long life stress factor settings for storage

If the battery is stored for a longer period of time it should be kept at low temperature, low humidity and low state of charge. Normally the self-discharge rate is very low for lithium-ion batteries, but only if all loads, including the battery management system and other safety electronics, are disconnected.

5.3.4 Optimum cycle settings for a long lifetime

Based on the test results, the cycling stress factor settings, which are optimum for the battery lifetime, are shown in shown in Table 19.

Cycling stress factor optimum		
Stress factor	**Optimum**	**Comment**
Temperature	25°C	Between 10°C and 35°C
Chg rate 25	0.25 C	
Dis Rate 25	0.5C	
Chg rate 10	0.25 C	Between 0.25C-1.5C
DoD	Below 60%	
SoC	50%	

Table 19: Long life stress factor settings for cycling

The optimum somewhere between 10°C and 35°C - 25°C is proposed. The optimum charge rate and discharge rate at 25°C is 0.25C and 0.5C respectively. The difference between the losses for charge rate at 10°C is almost negligible, but the loss at 0.25C is the lowest.

If the cell is discharged to 0% SoC, the lowest capacity loss was achieved in this test, however, this is normally not desirable, so it is concluded that DoD should rather be kept below 60% for optimum low capacity loss. The optimum SoC level is 50% and maybe even lower.

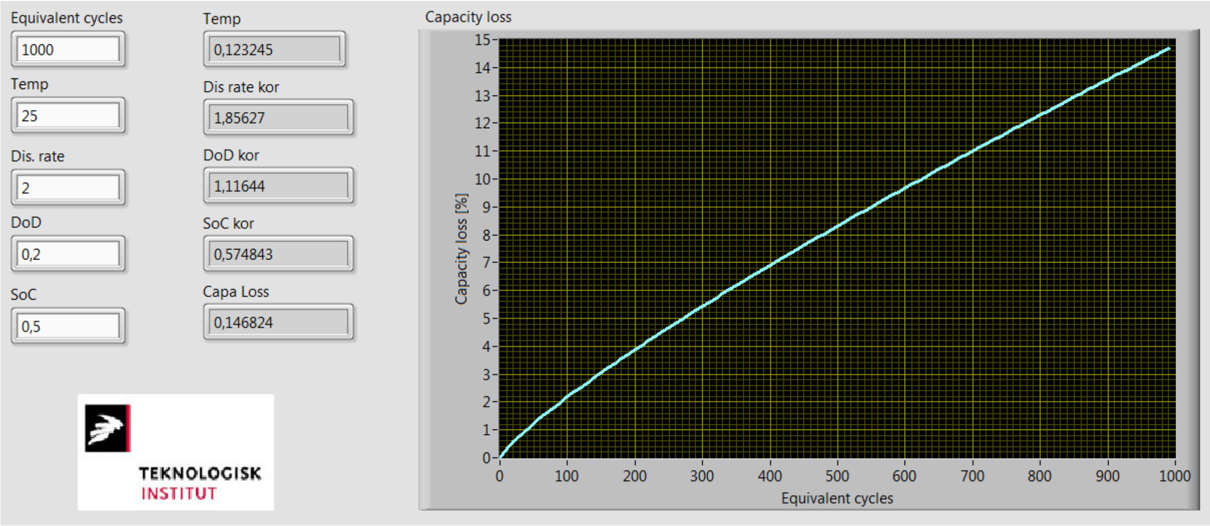
The capacity loss of different cell sizes shown in indicates that increase cell size results in decreasing capacity loss. Although the number of cycles processed is inadequate for two of the cells, it is true for the 40Ah and the 100Ah cell. Since the loss for the 40Ah cell is more than twice as large as for the 100Ah cell, the optimum choice is a large cell.

5.3.5 Battery degradation model

The capacity loss is affected more by temperature than any of the other parameters tested. Therefore, the temperature data will form the basis of the degradation model.

The most significant stress factors are implemented in the model.

The model is implemented in a Labview program as shown in Figure 30 to easyly change parameters and secure that the parameters stay within the model limitations.



Equivalent cycles: 1000
Temp: 25
Dis. rate: 2
DoD: 0,2
SoC: 0,5
Temp: 0,123245
Dis rate kor: 1,85627
DoD kor: 1,11644
SoC kor: 0,574843
Capa Loss: 0,146824

Figure 30: Battery model as implemented in a Labview program

5.3.6 Discussion on degradation

Normally the storage capacity loss is an exponential function of temperature. An Arrhenius function to be more specific. It describes the chemical reaction rate of the most common side reaction, development of a solid electrolyte interface (SEI) between the anode and the electrolyte. Degradation when cycling at temperatures above approximately 15°C is normally governed by the same side reaction but at a higher rate. When this is not the case in this lifetime test, it may be because that other side effects interferes. One suggestion for such a side effect is evaporation of electrolyte, since a bad smell of organic solvents was present throughout the test. Unfortunately, the weight of the cells was not determined, so this theory can not be verified.

One of the most surprising findings is that full discharge only degrades the battery half as much as if the battery is discharges to lower DoD. There may be a connection with another surprising result. Cycling the battery between 25% and 75% SoC degrades the battery more than if the battery is cycled between 0% SoC and 100% SoC although the same amount of Ah-throughput is processed by the two cells. One theory could be, that all available lithium at the anode is moved to the cathode at full discharge. Then the intercalation at the anode will run more smoothly at the following charge. In the first place however, these tests should be repeated.

Due to some problems with the test equipment a satisfying amount of equivalent cycles was impossible to achieve for a few cells. In general the capacity loss rate may well differ over the lifetime as different degradation mechanisms dominate. Hence, it is desirable to keep testing until more than 50% of the capacity is lost. Especially if second life applications could be relevant for an application. Unfortunately very few projects have the time and resources for that sort of tests.

The internal resistance, Ri, are measured by applying a 2C pulse in the performance test. The results of these measurement are not included in this report, since the development in Ri due to degradation is very limited for the CALB cells as for most LFP cells.

5.3.7 Conclusion on battery degradation

A comprehensive degradation test was performed comprising LFP cells at cycling and storage condition, and the capacity loss of each cell as a function of equivalent cycles is shown in this report. To summarize the findings for optimum operation parameters with regard to the battery package lifetime, these parameters are listed in Table 20.

Storage stress factor optimum	
Stress factor	**Optimum**
Temperature	0°C-10°C
SoC	10%
Cycling stress factor optimum	
Stress factor	**Optimum**
Temperature	10°C-35°C
Chg rate 25	0.25 C
Dis Rate 25	0.5C
Chg rate 10	0.25 C-1.5C
DoD	Below 60%
SoC	0,5
Size of cell	180Ah

Table 20: Stress factor optimum for a long cell life

Other regards such as demands for the usage pattern and the investment payback time must be taken into account, and thus a battery cell degradation model has been establish and implemented in a Labview program, based on the cycling test results.

The cell degradation is found to be a power function of equivalent cycles. A number of stress factors affects the degradation and the four most significant of these, which are temperature, discharge rate, DoD and SoC, are implemented in the model.

Applying the model and extrapolating with regard to the number of equivalent cycles, yields the four scenarios shown in Table 21 below. The column denoted Lifetime is the number of equivalent cycles, which can be performed before the capacity loss has reached 20%.

Temp	Dis rate	DoD	SoC	Lifetime
25°C	0.5C	30%	50%	5500
45°C	2C	95%	95%	330
5°C	2C	95%	95%	170
25°C	0.3C	100%	100%	990

Table 21: Calculated degradation by model with estimated lifetime measured in equivalent full cycles

Studying the results in Table 21 it becomes obvious that the operation conditions have a huge impact on the battery lifetime and thus the investment pay back. It demonstrates how difficult it is for the battery supplier to specify a lifetime in the datasheet as well. The manufacturer guarantees least 1000 100% cycles at 0.3C and 25°C. Simulating this test in the model results in 990 cycles as shown in the fourth row in Table 21.

The degradation test performed revealed some new findings, which is not common knowledge according to the literature, and nor is it to DTI.

- Nor is the storage degradation, neither the cycle degradation is an exponential function of temperature. The latter not even at high or low temperatures alone.
- The discharge rate has much more impact on degradation than the charge rate.
- Full discharge degrades only the battery half as much as if the battery is discharges to lower DoD.
- Cycling the battery between 25% and 75% SoC degrades the battery more than, if the battery is cycled between 0% SoC and 100% SoC.

Findings like these reveals the need for more comprehensive tests than normally published in the literature or in sales material.

The model developed is very useful when designing, operating and predicting the lifetime of a BESS battery pack, which an expert can use for lifetime estimation.

5.4 Dissemination

Several dissemination opportunities has been used throughout the project period.

The BESS project has been publicized on the websites[2] of Danish Technological Institute and Energi Danmark[3]

Presentations including presentation of the BESS project:

- December 10th 2013 at DTI ”Batteries – en del af fremtiden”-seminar; Rasmus Lærke / Vestas: “Erfaringer med primær reserve leveret fra batterilager”
- September 16th 2015. A battery seminar and official inauguration of the Scale BESS system was held, with approximately 75 participants.
    - Johan H. Vium / DTI: “om BESS projektet og introduction til BESS forsøgsanlæg”
    - Rasmus Lærke / Vestas: ”En mølleproducents erfaringer med storskala batterianlæg”
    - Thomas Brouer / Energi Danmark: ”Økonomi i storskala batterianlæg”
- September 28th 2015. The project was also presented at an ATV seminar at DTU “Energy storage – a must for successful conversion to green energy” by Vestas.
- December 1st, 2015 at DTI. The Scale BESS system and BESS project was presented at the advanced energy storage seminar with approximately 75 participants.
    - Bjarne Johnsen / DTI: “Batteri system test”
    - Rasmus Rode Mosbæk / Lithium Balance: ”Energy Storage Systems” (addressing BMS function and other aspects)
    - Johan H. Vium / DTI: “Showcase presentation and discussion by the Scale BESS System installation”.
- January 26th, 2016, Rasmus Lærke, Vestas: ”Large Battery Systems To Stabilize Frequency Output From Wind Farms And For Provision Of Primary Reserve Power”. Held at Grid+Storege reginal workshop”, Helsinki,

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[2] www.dti.dk/projects/project-bess-large-scale-batteryenergy-storage/34503

[3] www.energidanmark.dk/markedsinfo/nyheder/energi-danmark-deltager-i-projekt-bess/

- February 25th, 2016, Johan H. Vium, DTI: "Batterilagre til udbalancering af elnettet" held at IDA Mechanical Energy Storage symposium in Copenhagen
- November 2nd, 2016. Kjeld Norregaard, DTI: "Batterilagre til udbalancering af elnettet". Held at IDA Mechanical Energy Storage symposium in Aarhus.
- December 1st, 2016, BESS project overall and degradation results at Battery and Energy Storage seminar at DTI in Aarhus with approximately 100 participants
    - Johan H. Vium / DTI: "Battery Energy Storage Systems – results from a project between Vestas, Energi Denmark and DTI"
    - Bjarne Johnsen / DTI: "Battery degradation – stationary and fast charge"
    - Kjeld Nørregaard / DTI: "Danish Battery Challenges – a very short status and possible glimpse into the future for battery activities"
    - Johan H. Vium / DTI: "Showcase presentation and discussion by the Scale BESS System installation".
    - Bjarne Johnsen / DTI: "Showcase presentation and discussion by the Battery single cell degradation lab"
    - Kjeld Nørregaard / DTI: "Showcase presentation and discussion by the Scale BESS System demonstration-module".

Media reference to the BESS project:

- 12th August 2015 recording for a Danish DR television program named "So Ein Ding" with focus on technology. The Scale BESS battery system was used as an example of a large battery energy storage system and a story about batteries on the electrical grid.
- "#Smart energi nr. 6" udgivet af Energinet.dk og Dansk Energi[4] "BATTERIERNE KOMMER … hvad skal elsystemet bruge dem til?
- In connection with the inauguration seminar on September 16th 2015 articles were published in magazines (e.g. "Ingeniøren", "Magasinet Idag", "Teknovation"[5] and "Nyhedsbladet Dansk Energi") and in local radio.

It is expected that the results from single cell degradation and system operation are used for one or more international academic papers after the project period.
Energinet.dk may use part of this report in their discussions in ENTSO-E context especially on the alternative primary reserve regulation.

Work has also gone into the development of the first edition of Grid code (Teknisk forskrift) TF 3.3.1 for Batteries connected to the electrical grid in connection with Energinet.dk which is expected to be utilized widely in the future.

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[4] www.danskenergi.dk/smartenergi

[5] www.teknovation.dk/?type=page&id=755&itemid=7997

6. Utilization of project results

The results will be utilized in the three involved companies. The understanding and knowledge about operation, cost and degradation in connection with operating BESS systems in the present and future grid has been expanded.

Vestas

The project has provided Vestas with extensive experience and in depth knowledge in relation to operation of grid connected battery systems as well as ancillary services based on provision of primary reserve from batteries in DK1.

The pilot experiment for alternative primary reserve from batteries has resulted in several proposed concepts for primary reserve delivery. The results from the alternative concept selected for field implementation indicates an increased energy exchange between storage and grid compared to existing technical rules for market participation in DK1. This underlines the importance of having the capability to understand and analyse the mission profile of a battery applications up-front as it can significantly influence the energy cost and lead to faster degradation of battery capacity, hence affect the business case for a battery installations.

Vestas has demonstrated the flexibility and capabilities of storage during the project through varied applications. However, the project has not resulted in specific product offerings as a business case yet remain unattractive due to high battery cost and absence of sufficient market remuneration of storage capacity to balance the investment.

The knowledge generated from the project equip Vestas to engage in a professional dialogue with potential clients, to better understand storage technologies and navigate among storage solution suppliers.

In a longer perspective, Vestas continues to see a potential for applying storage technologies together with wind power in various markets to gain synergies in terms of flexibility and capabilities not achievable without storage.

Energi Danmark

Energi Danmark plans to incorporate the knowledge obtained from this project in the dialogue it has with its current and potential customers, in particular those who have or plan to invest in electricity storage.

Electricity storage is frequently referred to as the solution to the fluctuating production from renewable energy sources. With the PSO tariff being removed in November 2016 by the Danish government, debate is expected to continue about the restructuring of the remaining electricity tariffs in a way that promotes system flexibility. Energi Danmark will be referring to the experiences gained from the BESS project in guiding the public debate on these topics.

Danish Technological Institute

Energi Danmark and Danish Technological Institute has in cooperation requested support funds for being able to continue the work and investigate in which cases Battery systems can contribute and are economic attractive in the project BESS relevance. Economic funding has been applied for at ForskEL.

On top of this, a battery related project with focus on safety and standards has also been applied for at ForskEL (BESS safety). A battery related project with focus on benchmark of battery systems for household and housing associations has been applied for at Elforsk.

H2020 LCE-01 application SMILE (SMart IsLand Energy systems EU-no: 731249) has been approved. An application is in preparation for Landsbyggefonden in 2017 with focus on community battery energy storage.

A commercial assignment directly related to the BESS project has also been carried out.

Different services are also offered to Danish and international customers. The services can be viewed here: http://www.teknologisk.dk/ydelser/batterisystemer-til-elnettet/36402

7. Project conclusion and perspective

The project “SmartGrid ready Battery Energy Storage System for future grid” (with the short name “BESS”) has been successful in several ways.

- All the planned activities have been addressed
- The learnings from both full size and scale BESS systems are relevant and useful for future activities
- It is not the batteries that cause problems but rather auxiliary equipment and communication.
- The developed assessment methods for degradation, efficiency, economy can be reused for other BESS.
- The project has serviced the TSO regarding experimental test of alternative primary regulation
- Much has been learned from unforeseen challenges under the build and commissioning phase
- Several areas found with potential for efficiency improvement
- Batteries are highly relevant measures for the future grid
- Knowledge and experience has already resulted in commercial activities as well as contribution to a H2020 project and 4 Danish energy research project applications.

The market conditions for electrical storage in the electric grid has not changed during the project period except for a reduction of the only marginally profitable market relevant for battery storage - Primary regulation. The introduction of primary regulation via Skagerrak-4 interconnector removed most of the potential market and reduced the value of the residual market. Still the project finds that BESS systems have demonstrated functionalities that could contribute services at different levels of the electric grid. Electrical storage often seems to be seen more as a potential problem to the grid rather than a stabilizing measure – also by the expected grid code for battery storage. A number of areas need reconsideration for BESS to become an equal measure to consider.

- The market for electrical services only recognize the existing system-types and tend to favor these. BESS-systems must be recognized at political and strategic governance level as well as on the executive and business levels. Grid codes and traditional subsidies on existing services must be reevaluated and adjusted to reflect the current situation and encourage development towards the 100% renewable goal set by the government.

- Also with respect to the 2022-plan for a common European market for system services, new technologies should be considered in grid and market codes.

- BESS systems recognized as voltage stabilizing measures in low and medium voltage grids not only as a technical measure but also as a tradeable service.

- The same energy should only be taxed once, and tariffs structure should favor efficient energy supply to the consumers but not penalize storage.

- Lowering prices is not a job for suppliers alone. They need to see business opportunities and stability to invest in improved technology. Subsidies may be needed in an interim period to encourage investment in storage.

- Research still needed for better future technologies – better efficiencies, longer life and lower prices.

- For BESS systems to become commodities there is a need for regulation or at least recommendations for safety, installation, maintenance, environmental issues (recycling and decommissioning).

Based on the analysis by Energi Danmark, some general conclusions can be drawn about BESS system operation in the Danish energy system:

- There is a major gab between investment/cost and the possible earnings for batteries in the existing markets (except for the primary reserve niche market).
- The tariffs for consumption in their current form are relatively high. It makes it necessary to have high volatility on the market prices (large price variations from one hour to another) for justifying operation in load-shifting mode (shifting energy from hour to hour). This level of volatility is not expected in the near future. Reducing the tariffs results in clearly reduced volatility requirements.
- The auxiliary power consumption is quite sizable, which erodes the low income possible in the load-shifting mode.

- Operation on the primary reserve market is the main potential for BESS achieving a profit. The following can be done to improve the profitability of BESS on the reserve market:
    - Ensure the maximum availability of the reserve capacity on the market, this clearly being the task with highest return value.
    - Continue to strive for reducing the auxiliary power consumption, which has a limited, although sizable effect in the case of full current tariffs.
    - Improving the cycle efficiency in this operational mode is positive, though of relatively lower value compared to the above to points.

The project has confirmed that battery systems can be used for multiple purposes on the electrical grid. The best economic opportunity for large-scale battery systems is primary reserve.

Within primary reserve there are some challenges with the current regulations, therefore a variation of the alternative primary regulation with incorporation of a continuous charge algorithm has been tested. In order for the alternative primary reserve to become economical viable, some changes are needed.

The tariffs and taxes plays a large part in the operational costs but also availability payment and better energy delivery conditions could be a way to improve condition for investing and operating BESS Systems.

The degradation of batteries can be minimized with the choosing of suitable temperatures, and usage pattern, but it is a complex matter. Generally, operation between 15°C and 30°C is recommended. In order to minimize auxiliary consumption for heating and cooling, the temperature operation window must be wider than is typically used with only a few degrees temperature span.

A battery degradation model for the tested batteries has been developed in the project, which can help specialists predict expected battery lifetime, depending on temperature and operational load pattern for Lithium Iron Phosphate batteries.

The efficiency and part load operation of battery systems are very important, especially when operated as primary reserve with low energy delivery. Generally, the batteries themselves have efficiencies above 95%, but auxiliary systems and losses in inverters and transformers can reduce the overall system efficiency to below 50% in low load operation.

Often systems are evaluated and bought based on peak performance, overlooking part load performance. The stability and life of auxiliary components is very important. Focus is mostly on the batteries and degradation, but the experience from both the scale system and the operation on the large-scale systems in Lem Kaer is that these factors are equally important. This is also the case when looking at cost of a full system relative to cost of the installed batteries.

It is essential for good economy to use batteries with high power delivery for the use of batteries for primary reserve or other high power services.

The BMS system and batteries used for the battery systems has to be suited for the actual operation. The BMS system needs to manage the battery system in order to maintain the batteries within safe operating area, but also for optimizing the performance of the batteries.

Hands on experience from realization of a scale BESS system has highlighted the multiple disciplines that has to be mastered, and the many components and systems that has to be combined and operate reliably together in order to have a functioning system. There are many aspects to this including suppliers providing necessary support on e.g. communication protocols and having a hotline to qualified engineers in order to promptly remove errors and inexpedient operation.

Some of the experience from the project has been put to work in a series of Energinet.dk workshops in connection with the development of a new grid code TF3.3.1 for operation of batteries connected to the electrical grid. This includes both data and active participation in the preparation meetings.

The financial aspect is that in the current market the economy could be better for large-scale battery systems on the electrical grid. The economy is very dependent on tariffs, taxes, political incentives, and sudden changes in the market e.g. with opening of international interconnectors and a chance / risk of larger European markets in the future.

With increasing delivery from fluctuating renewable energy, the need for local energy storage will likely increase. The European and worldwide goals of using renewable energy and combined heat and power plants being phased out from the market, the need for versatile and fast acting energy storage and short term power delivery may grow rapidly in the future.

In order to make use of battery systems in larger volumes, the legal and economic frame including taxes and tariffs has to be transparent and predictable. To accelerate the growth rate for BESS capacity the politicians will need to review and rethink the tariff on storage, so that the same energy is only taxed and tariffed once – when it is used. The flexibility of BESS systems offers excellent Smart Grid functionality as required.

Concerning household and community batteries, which has not been a direct focus of this project, the market aspects are predicted to be very good in the coming years, especially in connection with solar power systems and the possibility of the introduction of tariffs based on the maximum power needed. The investment drivers are completely different when private people invest optimisation of their own renewable energy production and consumption. Therefore the private home market for BESS is expected to start growing before larger grid connected BESS plants become competitive.

The work within batteries in connection with the electrical grid will continue in different aspects. DTI has increased the focus on batteries at all levels of the electrical grid from household to very large battery systems (GigaBAT).

8. Annexes

Annex 1 Overview of milestones, material, timetable and status

In this annex, a quick overview of work packages, background material made during the project, timetable and milestones can be found.

Tasks	Status	Responsible	Comment
WP1a: Technical specification - Lem Kaer ESS tests			
1. Report with results from theoretic modelling of different Scenarios (ED)	Finished		See subdescription below
1a:Present commercial market	Finished	ED	Analyses of operation including all taxes and tariffs are made
1b: Future commercial market	Finished	ED	Future commercial market analysis is performed for primary reserve market and and loadshift
1c: Reduced texes	Finished	ED	Analysis is made with reduced taxes and tariffs
2. Tests to be carried out in real life	Finished	DTI/ED/Vestas	Initial suggestion was made, but altered during the project
3. Description of control possibilities and specification of control interface for Lem Kaer ESS (Vestas)	Finished	Vestas	Report on control possibilities at Lem Kaer is made
4. Draft of grid code for technical requirements for connection of BESS system to the electrical grid (Vestas)	Finished	Vestas/DTI	There has been participation in Pilotordning with new control algorithm for BESS systems supplying Primary reserve and participation with development of grid code TF 3.3.1. for battery systems connected to the electrical grid
WP1b: Technical specification - Scale BESS tests			
1. Specification of BESS scale system incl. data collection and communication	Finished	DTI	A generic specification for BESS systems has been made. Scale system specific requirements are included in the BESS scale report
2. Specification of site for installation	Finished	DTI	Specification of Scale BESS and site is investigated, and subsequently the system has been connected to the electrical grid at DTI in Aarhus
3. Test sceme for single cell tests	Finished	DTI	Test Sceme is developed. Description of test matrix and procedures is incorporated in the degradation report on single cells
WP2: Design and development of Scale BESS			
1. Scale BESS system is installed at DTI	Finished	DTI	The scale BESS system has been installed at DTI in Aarhus. Description of plant and learnings is reported in scale system report and BESS scale system Technical Documentation
2. Data collection system for scale system is developed	Finished	DTI	Data collection system is developed and described in BESS scale report and BESS Scale System Technical Documentation
3. Scale BESS control system is developed	Finished	DTI	Control system is developed and described in BESS scale report and BESS Scale System Technical Documentation
4. BESS inspection guideline/procedure	Finished	DTI	A BESS inspection guideline is developed and used for inspection of scale BESS system
WP3a: Subsystem and system functional testing - Lem Kaer ESS			
1. Control Interface for control af battery systems at Lem Kaer (ED)	Installed	ED/Vestas	A new extended control interface between Energy Danmark and Vestas site in Lem Kaer has been installed.
2. System efficiency of systems at Lem Kaer	Finished	DTI	The efficiency of the systems in Lem Kaer has been calculated, and further investigations has been done with regard to localization of auxilary consumption. This is included in Technical Lem Kaer report.
WP3b: Subsystem and system functional testing - Scale System			
1. Report (on data) from small scale system	Finished	DTI	A manual is written for the BESS scale System and a BESS scale report which includes test and analysis performed has been written
2. Report on data from single cell tests	Finished	DTI	A report with description of the single cell degradation tests and the test results and description of model is made
3. Battery degradation model with respect to temperature and load profile	Finished	DTI	A labview based model based on the data from single cells tests has been made
WP4: ESS system operating testing			
1. Compiled operating experience from ESS test scenarios at Lem Kaer (ED)	Finished	ED	A report is made based on the overall operational uptime, income and expences. This includes both primary reserve and loadshift tests
2. Report on data collection and actual usage (DTI)	Finished	DTI	A technical report with analysis of frequencies, powerdelivery, efficiencies and degradation is made based on data from Lem Kaer.
WP5: Evaluation and report			
1. Final report including analysis of system operation performance, battery degradation and results of research work (DTI)	Finished	DTI	A final report is made for the project with the most interesting results and experience gained in the project
2. Report on economic feasibility for different load scenarios, present (ED)	Finished	ED	Data analysis from WP1a and experience from Lem Kaer tests have been incorporated into an updated report.
3. Report on economic feasibility for different scenarios, future (ED)	Finished	ED	Data analysis from WP1a and experience from Lem Kaer tests have been incorporated into an updated report.
4. Report on technical findings on battery degradation at Lem Kaer (DTI)	Finished	DTI (Vestas)	Degradation in Lem Kaer is integrated in the overall Technical Lem Kaer report
WP6: Project management			
1. Periodical reporting	Finished	DTI	Periodical technical reports are made, delivered and approved by ForskEl/Energinet.dk
2. Project economy reporting	Final economic report in feb. 2017	DTI	Periodical economic reports are made and approved. Final economic report is finalized in february 2017
3. Final Seminar	Finished	DTI	Official opening of scale BESS system and battery theme day was held on september 16, 2015 with inauguration by Energinet.dk with approximately 75 participants. Planning and several presentations at advanced energy storage seminar in 2015 and finally results in 2016 at DTI (75-100 participants per arrangement). There has also been written articles and done presentations in Denmark and abroad.

Table 22: Overview of work packages, milestones and status

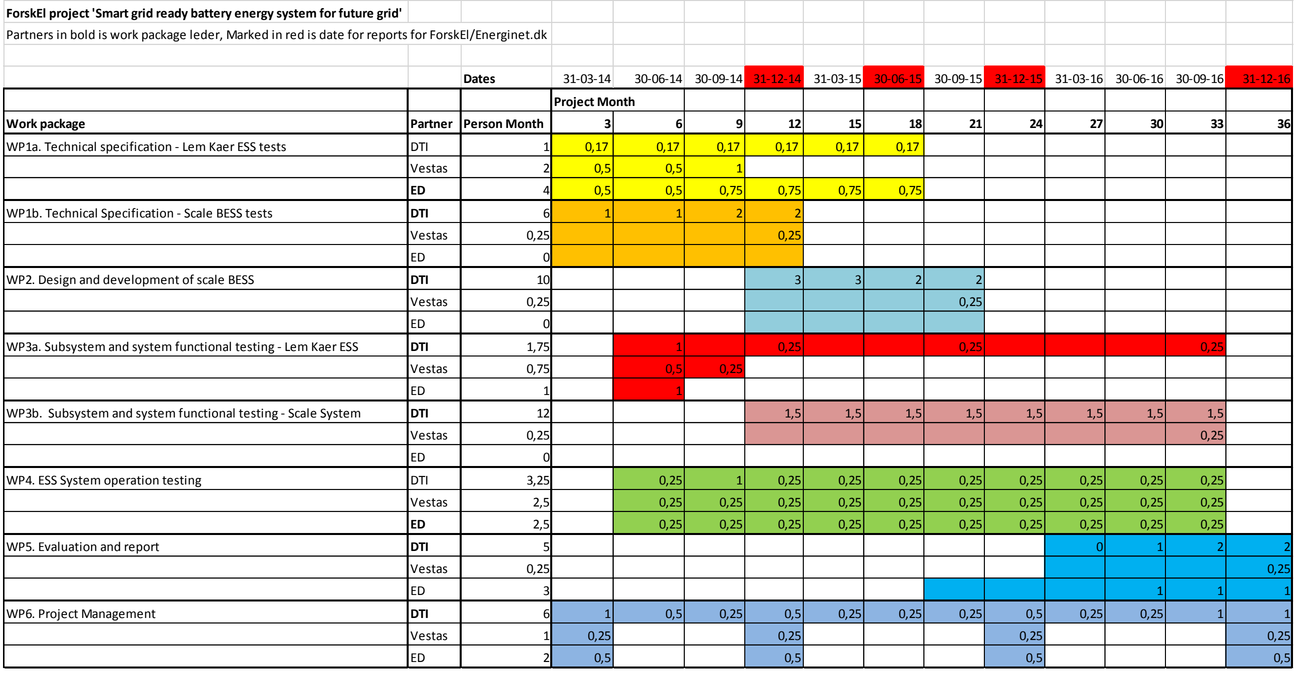
Background material

The following reports has been made during the project. They are considered project material and is not made public available. The key results are included in the annexes and in the main report.

- Economic analysis of present and future market (essence included in final report and annex 2)
- Control possibilities for control of systems in Lem Kaer
- Report on possible smart grid connection of BESS systems (essence included in final report and annex 2)
- Generic specification of BESS system
- Inspection guideline for BESS systems
- Lem Kaer technical report (including degradation, the essence seen in final report and annex 2)
- Economic report on Lem Kaer operation
- Scale BESS report (essence seen in final report and annex 3)
- Single cell degradation report (essence seen in final report and appendix 4)
- Scale BESS Technical documentation
- Grid code 3.3.1 (Teknisk Forskrift 3.3.1) connection of batteries to the electrical grid

Timetable

The overall timetable of the 3 year project can be seen below. The project start was January 1st, 2014.



ForskEl project 'Smart grid ready battery energy system for future grid'

Partners in bold is work package leder, Marked in red is date for reports for ForskEl/Energinet.dk

		Dates	31-03-14	30-06-14	30-09-14	31-12-14	31-03-15	30-06-15	30-09-15	31-12-15	31-03-16	30-06-16	30-09-16	31-12-16
			Project Month											
Work package	**Partner**	**Person Month**	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**33**	**36**
WP1a. Technical specification - Lem Kaer ESS tests	DTI	1	0,17	0,17	0,17	0,17	0,17	0,17						
	Vestas	2	0,5	0,5	1									
	ED	4	0,5	0,5	0,75	0,75	0,75	0,75						
WP1b. Technical Specification - Scale BESS tests	**DTI**	6	1	1	2	2								
	Vestas	0,25				0,25								
	ED	0												
WP2. Design and development of scale BESS	**DTI**	10				3	3	2	2					
	Vestas	0,25							0,25					
	ED	0												
WP3a. Subsystem and system functional testing - Lem Kaer ESS	**DTI**	1,75		1		0,25			0,25				0,25	
	Vestas	0,75		0,5	0,25									
	ED	1		1										
WP3b. Subsystem and system functional testing - Scale System	**DTI**	12				1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	
	Vestas	0,25											0,25	
	ED	0												
WP4. ESS System operation testing	DTI	3,25		0,25	1	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	
	Vestas	2,5		0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	
	ED	2,5		0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25	
WP5. Evaluation and report	**DTI**	5									0	1	2	2
	Vestas	0,25												0,25
	ED	3										1	1	1
WP6. Project Management	**DTI**	6	1	0,5	0,25	0,5	0,25	0,25	0,25	0,5	0,25	0,25	1	1
	Vestas	1	0,25			0,25				0,25				0,25
	ED	2	0,5			0,5				0,5				0,5

Table 23: Overall timetable for the project

Short status and desctiption of milestones and status

See the overall work packages marked in bold, the milestone in normal font, and a short description and status in italic below. Selected technical results are described in the main report under chapter 5. A quick schematic overview of milestones can be found above.

WP1a: Technical Specification – Lem Kaer ESS tests

1. Report with results from theoretic modelling of different scenarios (Energi Danmark)
    a) Report on theoretic modelling of different scenarios in the present commercial market. Delivery project month 12.
    b) Report on theoretic modelling of different scenarios in the expected future commercial market. Delivery project month 15.
    c) Report on theoretic modelling of different scenarios in the present and future commercial market with alternative taxes. Delivery project month 18.

The commercial modelling is performed and a report has been written. Overall, the taxes and tariffs on the electricity consumption of the BESS systems has a great impact on the result. The most attractive market is the primary reserve market in which the BESS system in Lem Kaer also participates. The tax and tariff issues has been updated with exemption of some of the taxed on basis of report from pwc with experience in these issues. Modelling has also been done on future aspects for primary and load shift operation.

2. Tests to be carried out in real life (Energi Danmark)

The tests to be carried out in Lem Kaer has been evaluated based on the report in MP1 and described. The systems are mainly operated for frequency control. Tests with load shift operation and with alternative primary reserve has also been carried out. The actual tests and results in Lem Kaer are described in WP 4.

3. Description of control possibilities and specification of control interface for Lem Kaer ESS

The control possibilities in Lem Kaer has been described, and the control interface has been agreed on and the control interface has been installed in Lem Kaer as part of WP3a.

4. Draft of grid code for technical requirements for connection of BESS system to the electrical grid (Vestas)

There has been participation in the development of grid code TF. 3.3.1 for grid connection of batteries to the electrical grid. Danish Technological Institute, and Vestas with observational status has taken part in this work. An alternative operation pattern for primary reserve for batteries has also been carried out in cooperation with Energinet.dk and pilot setup.

WP1b: Technical Specification – Scale BESS tests

WP1b has been finalized.

1. Specification of BESS scale system incl. data collection and communication.

The specification of the BESS scale system is included in the BESS Scale System report and a more general BESS specification has been made.

2. Specification of site for installation

The specification and investigation of site for installation at DTI has been done, the work and components has afterwards been ordered, and the BESS scale system has been connected to the electrical grid (as part of WP2).

3. Test scheme for single cell tests

A test procedure and scheme matrix for single cell batteries has been developed. The procedure is described in the report on degradation of single cells. The tests are done on mainly on 40Ah prismatic Lithium Iron Phosphate battery cells from CALB. The actual tests are being carried out as a part of WP3b. An overall plan for the tests to be performed in the scale BESS system has also been made.

WP2: Design and development of scale BESS

1. Scale BESS system is installed at DTI

The Scale BESS system is installed at DTI. The official inauguration was held on September 2016 with opening by Energinet.dk. There has been software and hardware issues underway, which has been, solved which has created much experience for installation and operation of other battery systems.

2. Data collection system for scale system is developed

The data collection system has been developed with registration of all major information from the many current, temperature, voltage and humidity sensors.

3. Scale BESS control system is developed

The Scale BESS control system has been developed. The system can operate depending on manual setpoints, setpoint files, local frequency and local voltage measurements. This can be expanded after time and needs.

4. BESS inspection guideline/procedure

A BESS inspection guideline has been developed. The inspection guideline was used as a control of the scale BESS system.

WP3a: Subsystem and system functional testing – Lem Kaer ESS

1. Control interface for control of battery systems at Lem Kaer

An updated control interface extending Energi Danmark's remote control possibilities has been installed at the Lem Kaer site. Vestas has tested the communication between Energi Danmark and Vestas site. The purpose of the control interface is to enable Energi Danmark to initiate and terminate grid-operation of the battery systems in Lem Kaer.

2. System efficiency of systems at LEM Kaer

Initial calculations of system efficiency in Lem Kaer has been done and system optimization possibilities has been discussed. Measurements and evaluation is incorporated in the Technical report from Lem Kaer. The measurements also include measurements of auxiliary consumption of different system components in the Altairnano system.

WP3b: Subsystem and system functional testing – Scale System

1. Report on data from small scale system

There has been made a report on the results from the BESS scale system at DTI, and Technical Documentation for the system.

2. Report on data from single cell tests

The tests on single cells according to the test scheme in WP1b has been performed in the battery test laboratory at Danish Technological Institute, and a single cell degradation report including the test procedures has been made.

3. Battery degradation model with respect to temperature and load profile

A battery degradation model has been made based on the tests on single cells. A model description is included in the single cell degradation report.

WP4: ESS system operation testing

1. Compiled operating experience from ESS test Scenarios at Lem Kaer

An economic operating experience report has been on the system in Lem Kaer with operation as primary reserve and load shift.

2. Report on data collection and actual usage

A report has been made based on the data collected in Lem Kaer.

The BESS systems in Lem Kaer has been and is operated for frequency control, and data is recorded. There has been some challenges due to the need to move the BESS systems, so there has been a period without operation. There has also been some issues with different pumps and touch panels, which has been replaced for the system to operate. The smaller of the battery systems in Lem Kaer was not put back into operation, and has had very limited operation in the project period due to problems with control system, auxiliary components and grid inverter. There has been no issues with the actual batteries.

WP5: Evaluation and report

1. Final report including analysis of system operation performance, battery degradation and results of research work

A final report is made for the project with the most interesting results and experience gained in the project. The report summarises work from the different sub reports made during the project.

2. Report on economic feasibility for different load scenarios, present

An update of the economic report at present market is made based on the analysis performed WP1a and experience gained through the project and from the tests in Lem Kaer.

3. Report on economic feasibility for different load scenarios, future

An update of the economic report at future market is made based on the analysis performed WP1a and experience gained through the project and from the tests in Lem Kaer.

4. Report on technical findings on battery degradation at Lem Kaer

An analysis of battery degradation and operation in Lem Kaer is included in the overall Technical Lem Kaer report.

WP6: Project management

1. Periodical reporting

The technical periodical reporting is carried out throughout the project. All have been delivered and approved by ForskEL/energinet.dk

2. Project economy reporting

The economic periodical reporting is carried out throughout the project. All have been delivered and approved by ForskEL/energinet.dk

3. Final seminar

The official opening of scale BESS system and battery theme day was held on September 16, 2015 with inauguration by Energinet.dk with approximately 75 participants. There was also planning and several presentations at advanced energy storage seminar in 2015 with approximately 75 participants.
A seminar was also carried out on December 1st 2016 at DTI in Aarhus with the overall title "Advanced Energy Storage" with battery related subjects and results from the BESS project was presented. There was approximately 100 participants for the seminar.
There has also been other dissemination activities including articles and presentations in Denmark and abroad. See further information in the dissemination section.

General project management has also been handled in this work package, as well as meetings, periodical reporting and steering group meetings.

Annex 2 Vestas full scale Battery Energy Storage System plant

Description and results from the Vestas owned full size Battery Energy Storage System plant can be found in this annex.
First a description of the system BESS plant consisting of two different BESS systems from two different suppliers.

Annex 2.1 BESS Installation Lem Kaer

The energy storage installation in Lem Kaer consists of two energy storage systems from different manufacturers.

	BESS1:	BESS2:
Manufacturer:	A123 Systems	Altairnano
Dimension:	53’ container	53’ PM container and 20’ PCS container
Rated power and capacity:	0.4MW / 0.25h	1.2MW / 0.25h
Battery type:	LiFePO4	Li4Ti5O12
Control interface:	Modbus TCP	Modbus TCP

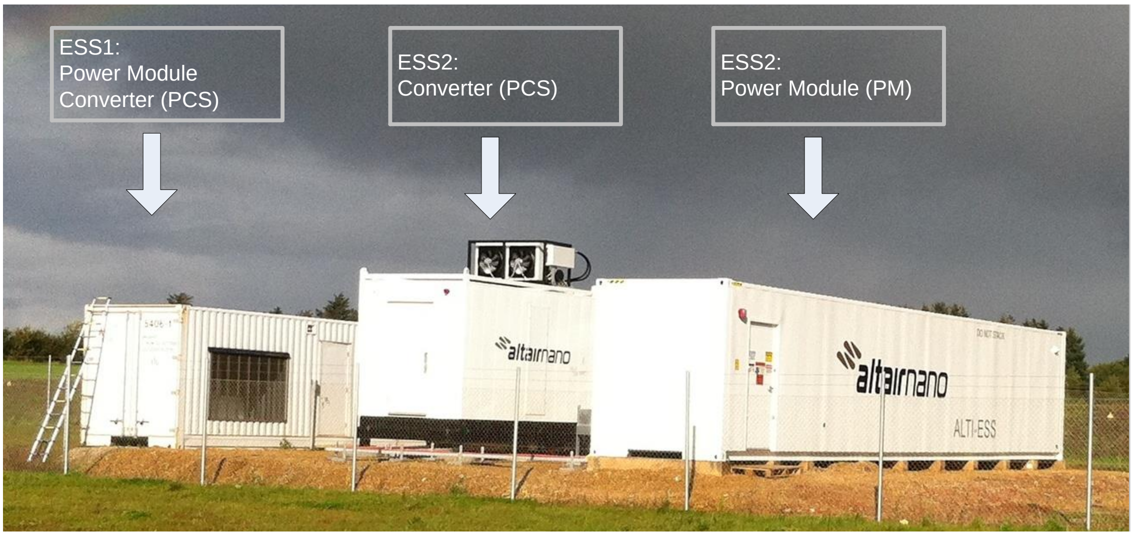


Figure 31: *Picture of BESS installation in Lem Kaer*

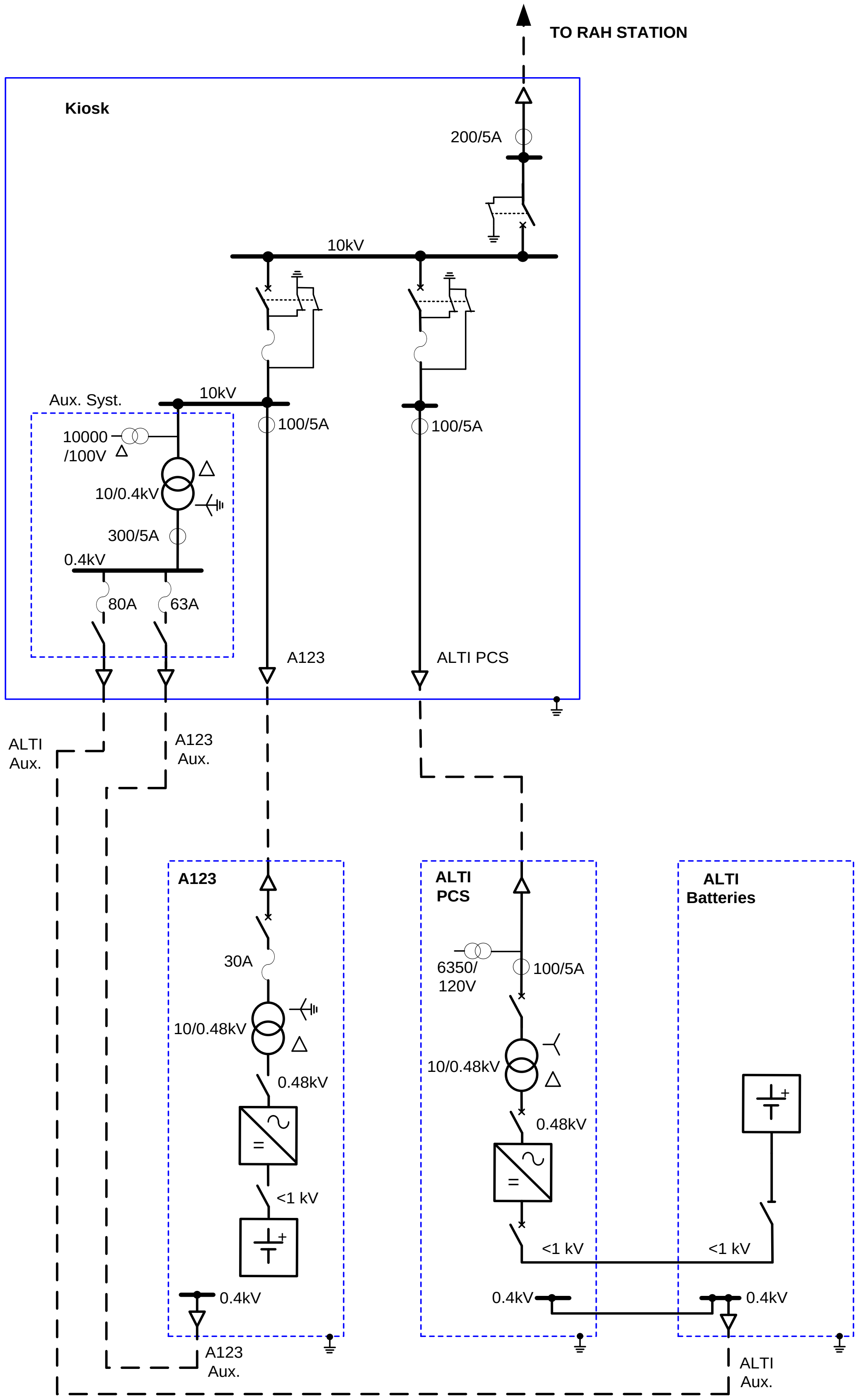


Figure 32: Single line diagram for BESS installation in Lem Kaer

Annex 2.1.1 Communication Network layout

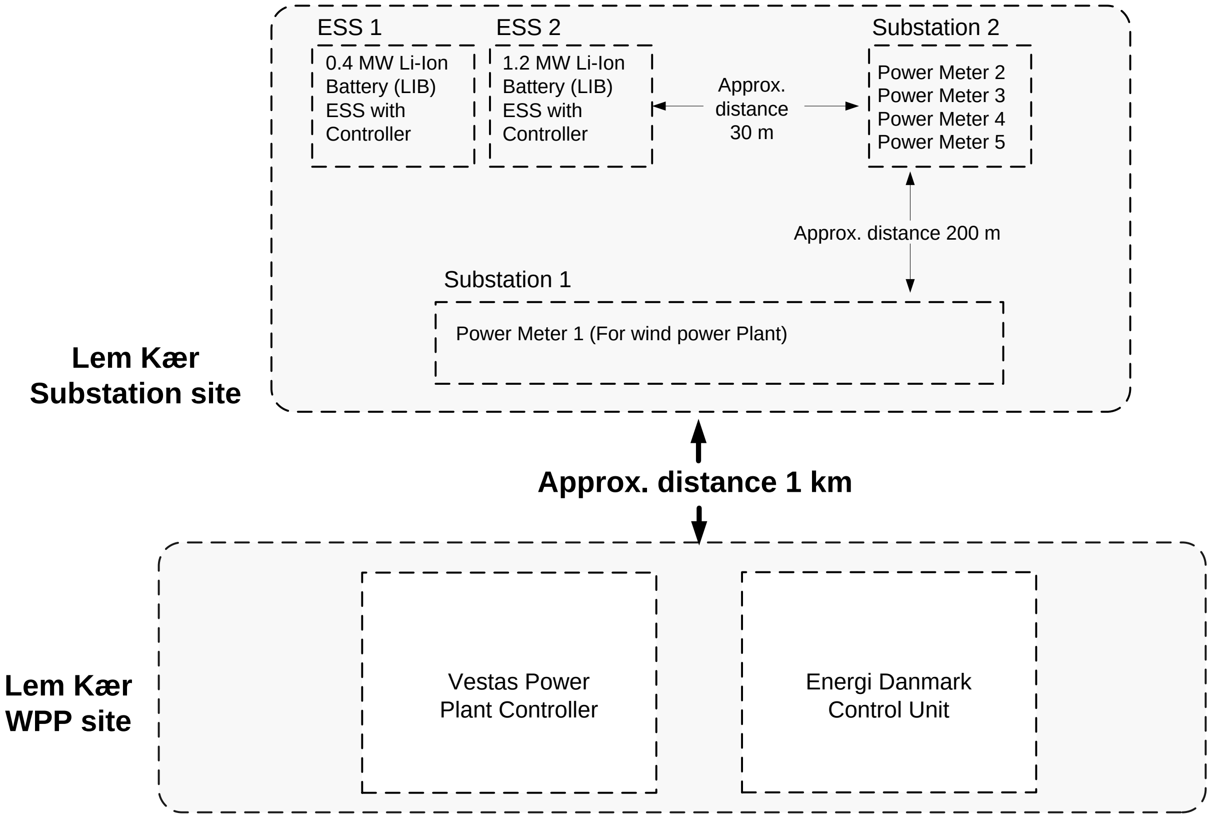


Figure 33: Overall control set-up for Vestas BESS- with physical distance between plant controller and actual ESS devises

The communication layout is slightly different from the two different suppliers.
The A123 control system is placed behind a Vestas router on the Vestas Network. The internal A123 network consists of two main subnets as shown in the figure below.

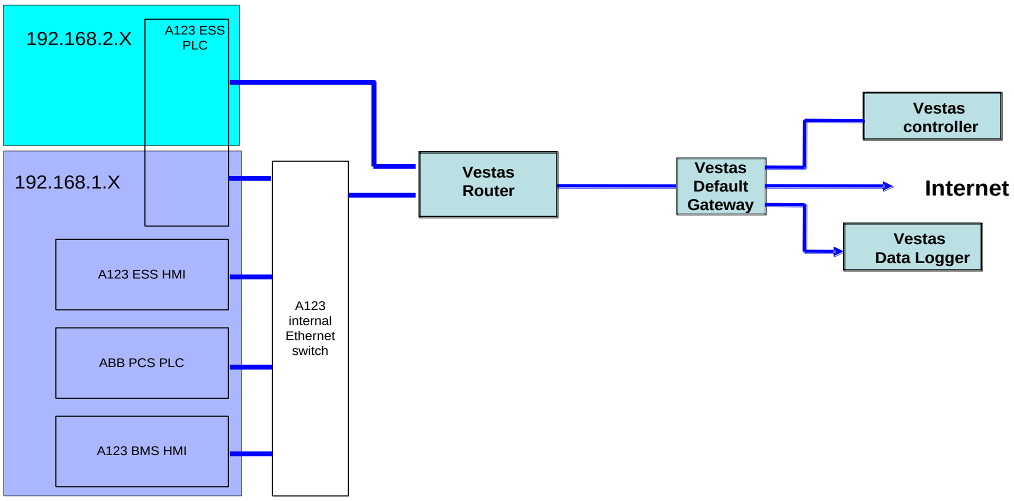


Figure 34: A123 BESS internal network layout

The Altairnano control system is also placed behind a router on the Vestas Network. The Altairnano router is configured to match the properties of the Vestas Network enabling communication as well as remote access to the control system without connecting to the site through VPN. The Power Module is connected with the PCS through a fiber loop. The Altairnano system is also capable of uploading data logs to a cloud server through a secured tunnel .

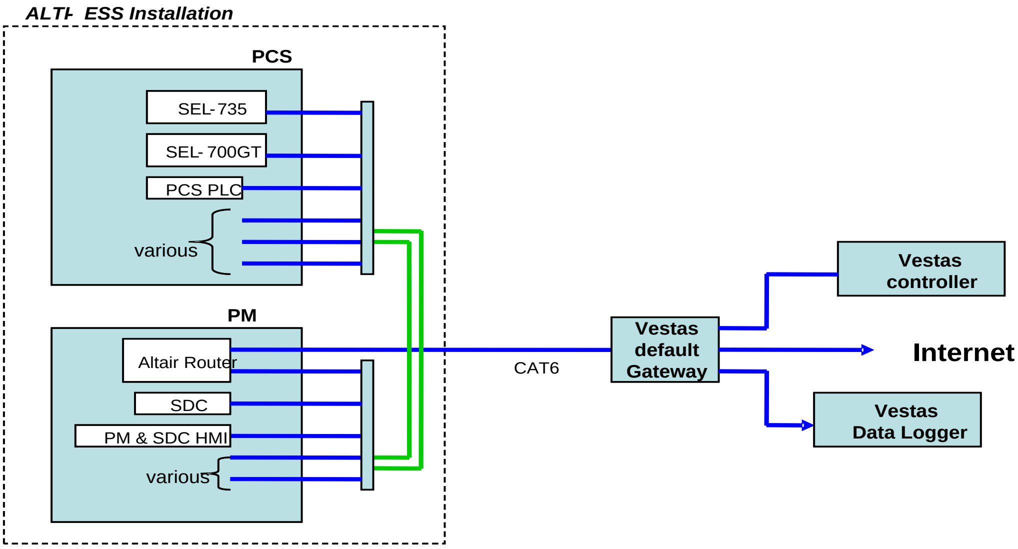


Figure 35: Altairnano ESS internal network layout

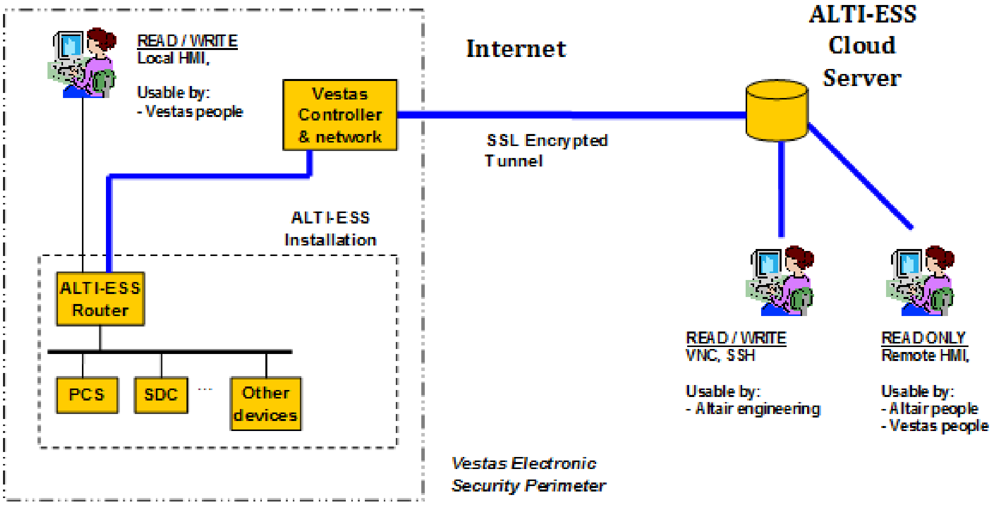


Figure 36: Altairnano ESS communication overview

Annex 2.1.2 Control architecture

The control system manage the housekeeping of the BESS and the actual delivery of the required service commanded via the communication interface.

The actual regulation and housekeeping are described in connection with the testing of functions and systems. Beside exchanging and interpreting information, the actual execution must account for signal latency through different sub-functional blocks of software and hardware. This will limit the reaction time on any change even if detection of a situation is detected fast.

Annex 2.1.3 Timing diagram example

For the A123 ESS, a complete signal relay chain results in signal latency.

- The Elspec power meter computes the power measurements once per 10 ms.
- The controller module on the Vestas controller polls the Elspec power meter once per 10 ms.
- The major control loop runs one cycle per 100 ms to generate the power reference.
- The Modbus TCP module on the Vestas controller polls the controller module once per 5 ms.
- The Modbus TCP module on the Vestas controller polls the SDC once per 100 ms to write the power reference to the SDC.
- According to measurement of response time during A123 FAT, the A123 PLC uses the power reference to compute the actual power reference and causes a delay of 80 - 180 ms.
- According to measurement of response time during A123 FAT, the PCS PLC causes a delay of 26 ms.
- According to measurement of response time during A123 FAT, the PCS causes a delay of 50 ms.

In worst case, the theoretical response time of the whole system would reach nearly 500 ms with a jitter of some 200 ms. This equals approximately 10 full cycles of the 50 Hz. Any reaction to variations within a single cycle of the 50 Hz must be handled autonomously by the inverter control.

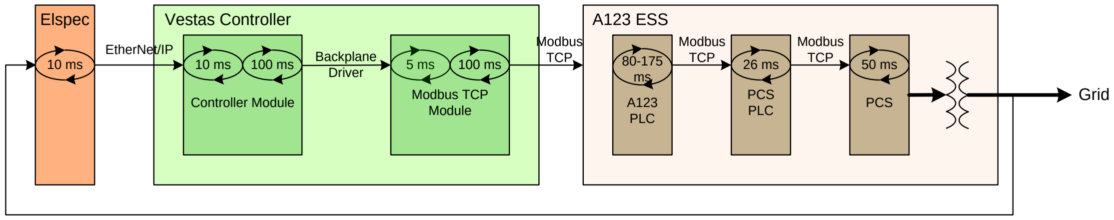


Figure 37: Latency Vestas controller – A123 ESS caused by each signal relaying process

Annex 2.1.4 Control interface

For the Lem Kaer ESS Vestas has a Vestas Power Plant Controller (VPPC), that host the control loops for controlling the ESS according to a selected application by dispatching power references to the ESS. The Vestas PPC also host the control interface to external communication partners such as the BRP (Energi Danmark).

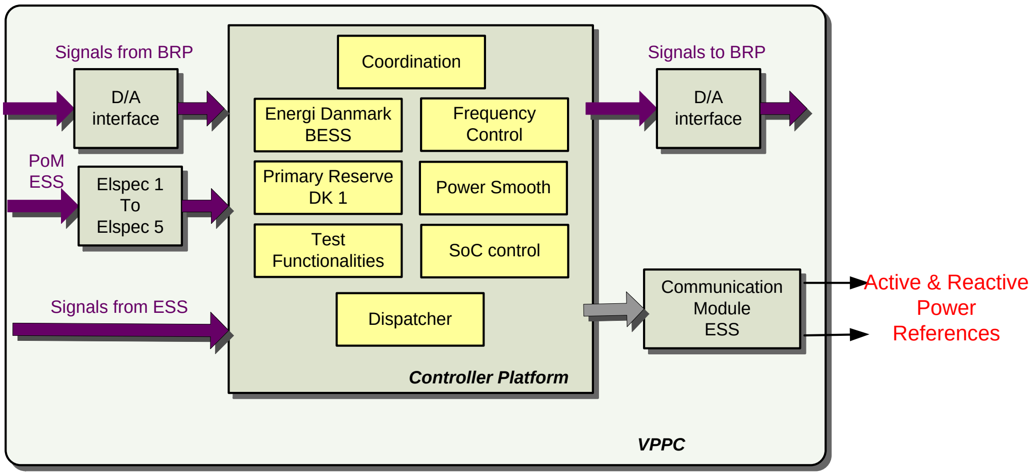


Figure 38: Block diagram of Vestas PPC

Annex 2.1.5 Programmed Functionalities

Several functionalities used during commissioning and test of the ESS are implemented in the VPPC and can be activated in operation.

- SoC cycle: Cycles the SoC of the ESS with a configurable SoC amplitude and time period. Used for measuring remaining battery capacity.
- Power cycle: Cycles the power input/output of the ESS with a configurable power amplitude and time period. Useful for testing batteries.
- Manual dispatch: Enables manual dispatch of power references to the ESS.
- AAU capacity test: Automatic capacity test procedure according to AAU specification.
- Primary/Frequency regulation

To enable fast upload of a series detailed commands a look up table is used. The look up table dispatch functionality enable the VPPC to perform dispatch of a series of predefined power references to the ESS which are generated based on desktop simulations of various applications. The references are uploaded to the VPPC using a Rockwell Automation "Tag Upload Download Tool" that is able to read and write values to tags defined in the controller. The dispatch of the power references according to the uploaded look up table is initiated by a user input to the VPPC. The Look up table size is 5000 Integers with a sampling time of 100 ms.

Annex 2.1.6 Communication Interfaces

The Vestas PPC controller (client) communicates with the A123 ESS (server) and Altairnano ESS (server) by means of Modbus TCP protocol using the internal Vestas 100 Mb/s network. The VPPC uses a Modbus module supplied by Prosoft for Modbus communication which supports multiple clients. The Prosoft Modbus module is placed in the same hardware rack as the PPC CPU.

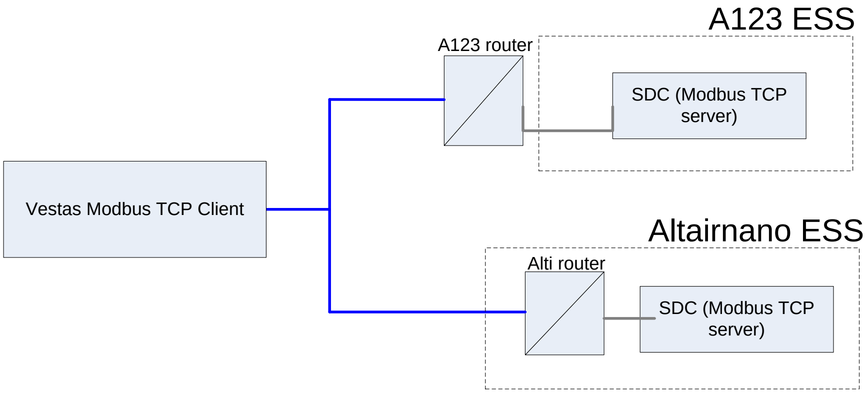
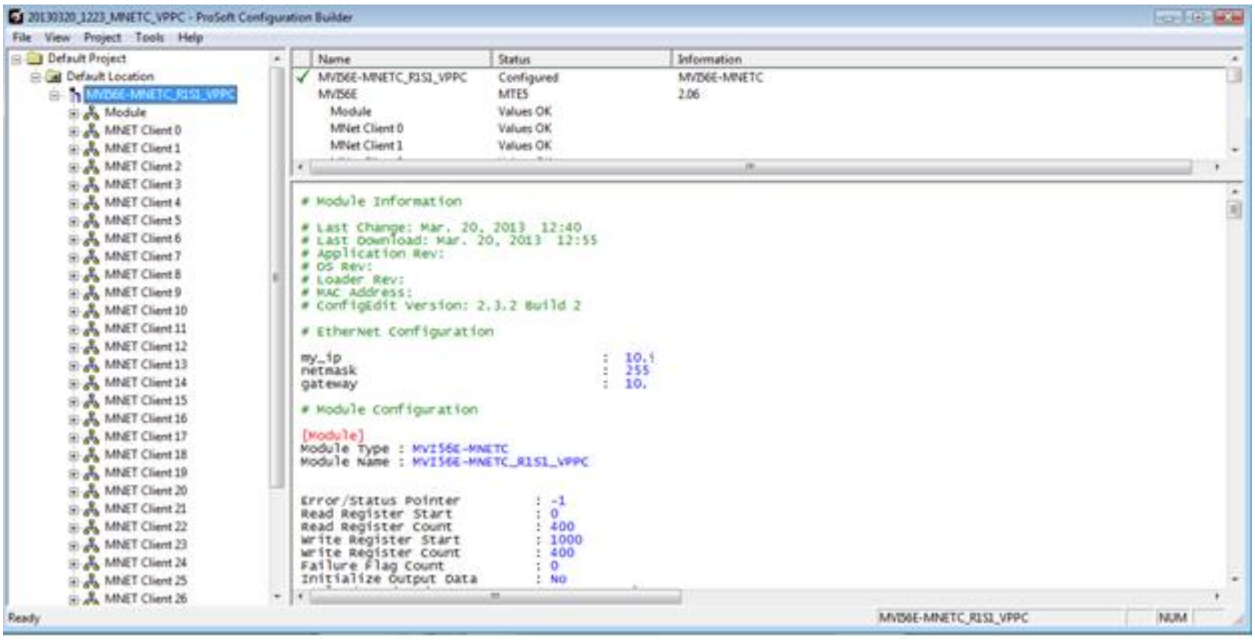


Figure 39: Modbus TCP network

The Modbus TCP communication between Vestas PPC and ESS is using the Vestas Turbine Net the update rate is controlled by the Vestas Modbus TCP client through Prosoft Configuration Builder. Prosoft Configuration Builder can be downloaded from the Prosoft web page.



	Name	Status	Information
✓	MVI56E-MNETC_R1S1_VPPC	Configured	MVI56E-MNETC
	MVI56E	MTES	2.06
	Module	Values OK	
	MNet Client 0	Values OK	
	MNet Client 1	Values OK	

```
# Module Information

# Last Change: Mar. 20, 2013  12:40
# Last Download: Mar. 20, 2013  12:55
# Application Rev:
# OS Rev:
# Loader Rev:
# MAC Address:
# ConfigEdit Version: 2.3.2 Build 2

# EtherNet Configuration

my_ip                                    :  10.
netmask                                  :  255
gateway                                  :  10.

# Module Configuration

[Module]
Module Type : MVI56E-MNETC
Module Name : MVI56E-MNETC_R1S1_VPPC


Error/Status Pointer          : -1
Read Register Start           : 0
Read Register Count           : 400
Write Register Start          : 1000
Write Register Count          : 400
Failure Flag Count            : 0
Initialize Output Data        : No
```

Figure 40: Prosoft Configuration for Modbus TCP client

The Modbus module supports configuration of up to 30 communication clients. Each client supports up to 16 commands for communicating with external devices as e.g. ESS. However, the number of commands and update rate of communication impacts the deterministic performance of the module hence the communication between the Vestas PPC and ESS has been divided to ensure that time critical communication has highest priority.

Annex 2.1.7 Control Loops

The control loop regulating e.g. the primary reserve depending on frequency response takes place in the VPPC.

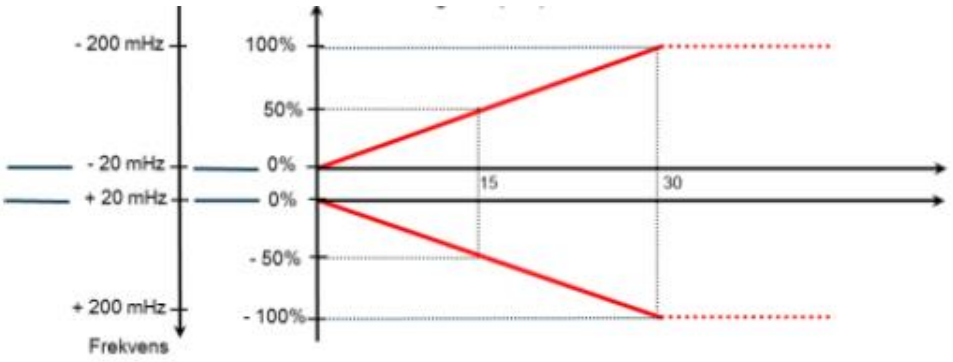


Figure 41: Required minimum power response to frequency deviation and minimum reaction time in seconds. The illustrated dead band is likely to be cancelled in future.

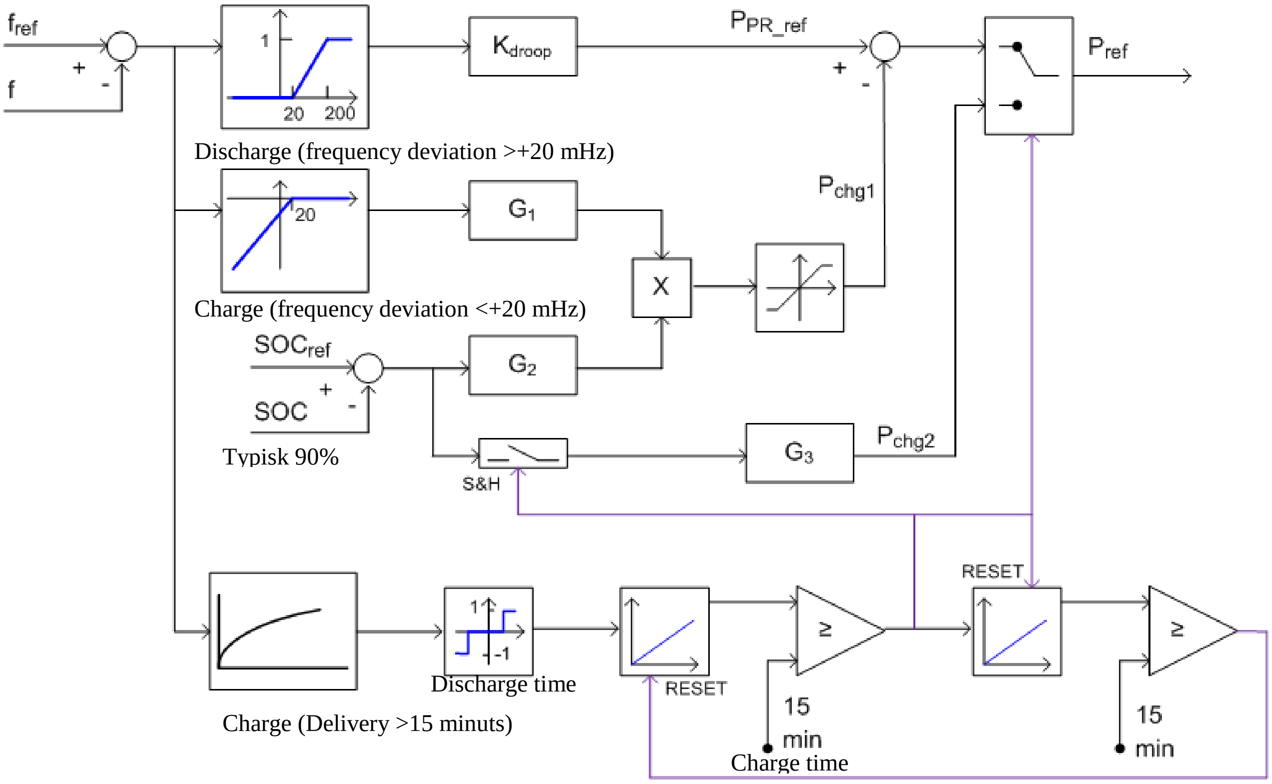
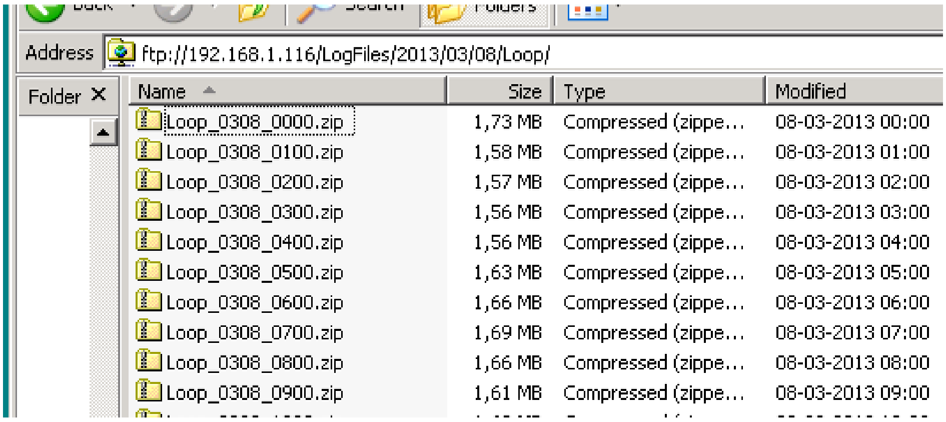


Figure 42: Illustration of a possible Primary reserve regulation for DK1 with SoC control

Beside the control loop managing the actual service delivery, housekeeping is a very critical function with the BMS as a core safety function. A number of auxiliary systems support the operation and thermal management, monitoring, fire detection, security etc.

Annex 2.1.8 Data Logging

During operation data related to operation ESS is logged continuously to a PC. The PC is remotely accessible and it is possible to retrieve log files through an FTP client. The logged data is zipped in a file every hour and stored in a folder which can contain logged files for one day i.e. 1 folder a day with 24 zip files.



Address ftp://192.168.1.116/LogFiles/2013/03/08/Loop/

Name	Size	Type	Modified
Loop_0308_0000.zip	1,73 MB	Compressed (zippe...	08-03-2013 00:00
Loop_0308_0100.zip	1,58 MB	Compressed (zippe...	08-03-2013 01:00
Loop_0308_0200.zip	1,57 MB	Compressed (zippe...	08-03-2013 02:00
Loop_0308_0300.zip	1,56 MB	Compressed (zippe...	08-03-2013 03:00
Loop_0308_0400.zip	1,56 MB	Compressed (zippe...	08-03-2013 04:00
Loop_0308_0500.zip	1,63 MB	Compressed (zippe...	08-03-2013 05:00
Loop_0308_0600.zip	1,66 MB	Compressed (zippe...	08-03-2013 06:00
Loop_0308_0700.zip	1,69 MB	Compressed (zippe...	08-03-2013 07:00
Loop_0308_0800.zip	1,66 MB	Compressed (zippe...	08-03-2013 08:00
Loop_0308_0900.zip	1,61 MB	Compressed (zippe...	08-03-2013 09:00

Figure 43: Log files for a few hours, data is zipped every 1 hour

The content and update rate of the log files are configured in the Vestas PPC controller.

Annex 2.1.9 Control Interface between BRP and BESS plant

The control interface between Energi Danmark Control unit and the Vestas Power Plant Controller is based on Boolean and floating number telegrams.

Table 24: Signals that the Energi Danmark controller must send to Vestas

Signal	Description	Telegram Type	Scale	Comment
Drift Kommando	Energi Danmark aktiverer en enhed (Gasmotor/Dieselmotor/Elkedel/Batteri)	Boolean	True / False	
Aktiver Primær	Energi Danmark aktiverer en enhed for primær reserve	Boolean	True / False	
Opregulering	Energi Danmark aktiverer opregulering hos kunden (producerende Enheder aktiveres)	Boolean	True / False	
Nedregulering	Energi Danmark aktiverer nedregulering (El forbrugende enheder aktiveres)	Boolean	True / False	
Baseload	Baseload er den værdi som sættes i primær regulatoren, hvorfra der opreguleres eller nedreguleres, eller begge dele.(afhængig af hvilke bud som vinder udbuddet hos Energinet.dk)	Float	kW	
Opregulering setpunkt	Den værdi i MW man ønsker at byde ind i markedet som opregulering	Float	kW	
Nedregulering setpunkt	Den værdi i MW man ønsker at byde ind i markedet som nedregulering.	Float	kW	

Table 25: Signals that the Vestas controller must send to Energi Danmark

Signal	Description	Telegram Type	Scale	Comment
Fejl	Dette er et "flag" som sættes i vores PBA system, såfremt der er en fejl hos kunden, som ønskes videregivet til Energi Danmark	Boolean	True / False	Tilknyttet en SMS funktion, så kunden får en tilbagemelding om fejlen
Klar	Dette er et "flag" som sættes i vores PBA system, når kunden melder Energi Danmark at de er klar til at blive aktiveret/styret af Energi Danmark.	Boolean	True / False	
Drift	Dette er et "flag" som sættes i vores PBA system, når enheden er aktiv	Boolean	True / False	
Primær reg fejl	Fejl på primær reg. hos kunden	Boolean	True / False	
Primær reg on	Energi Danmark har aktiveret Primær reg. hos kunden. (Tilbagemelding)	Boolean	True / False	
Elproduktion	Elproduktionen hos kunden (Gasmotor/Diselmotor/Vindmøller/Batteri)	Float	kW	
Elforbrug	Elforbrug hos kunden (Elkedel)	Float	kW	

Annex 2.2 BESS system operation testing

The systems in Lem Kaer has been operated with three different operation patterns. The majority of the time it was operating in the primary reserve market with upward regulations.

The three operation patterns were:

1. Primary reserve traditional (20 mHz deadband, max. delivery 15 minutes)
2. Loadshift (buing electricity when prices are low and selling when high)
3. Alternative primary reserve (0 mHz deadband and charge algorithm)

Pictures of BESS systems and the main project team in Lem Kaer

Annex 2.2.1 Data analysis of data from Lem Kaer

Data from 776 days recorded from the systems in Lem Kaer has been analyzed with a resolution of 10 Hz (670.230.958 time stamps).
There are some data missing in the period. This is caused by irreversible data loss, movement of the battery systems, defect of the used power meters (possible due to high overvoltage in the area), and the systems being out of operation.

The operation data from the smaller A123 system is limited since there has been issues, which has not been resolved which has put it out of operation. There has been no issues with the batteries, but auxilary systems (mainly control computers, and inverters). Therefore most of the analyzed battery system data is from the Altairnano system.

Frequency distribution

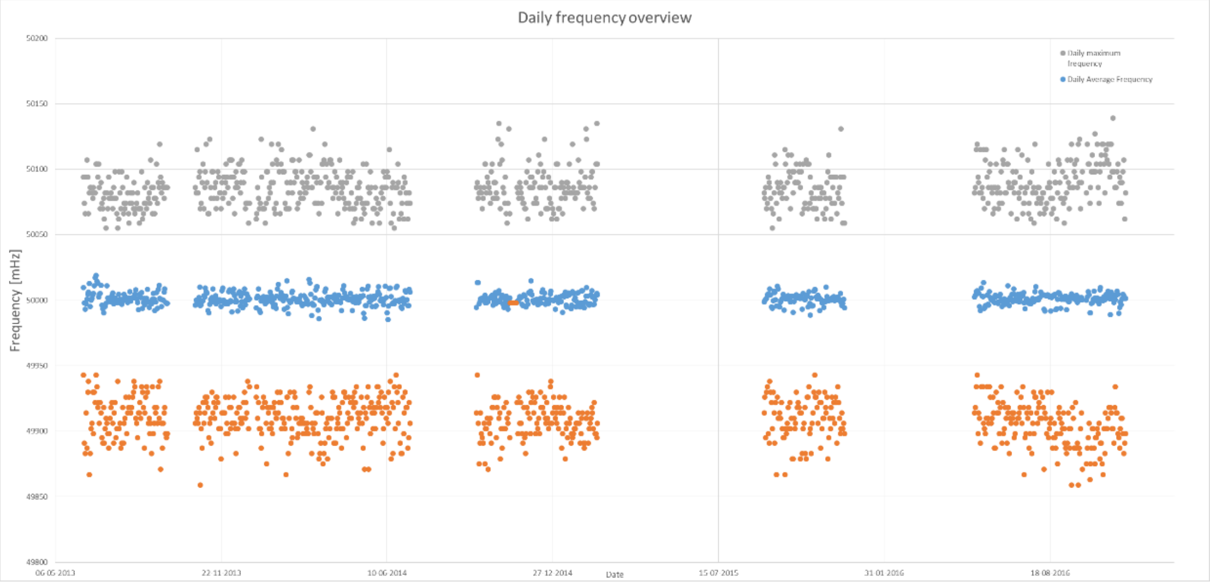


Figure 44: Graph of maximum, average and minimum frequency for each of the analyzed 776 days from July 2013 to November 2016

The maximum frequency recorded during the period is 50.139 Hz, and the minimum frequency is 49.859 Hz (deviation of 141 mHz from 50 Hz). The frequency at maximum power when delivering primary reserve with a deviation of 200 mHz is not met in the analyzed data. The average measured frequency is very close to the nominel 50 Hz with 50,00098 Hz (deviation less than 0,02 ‰).

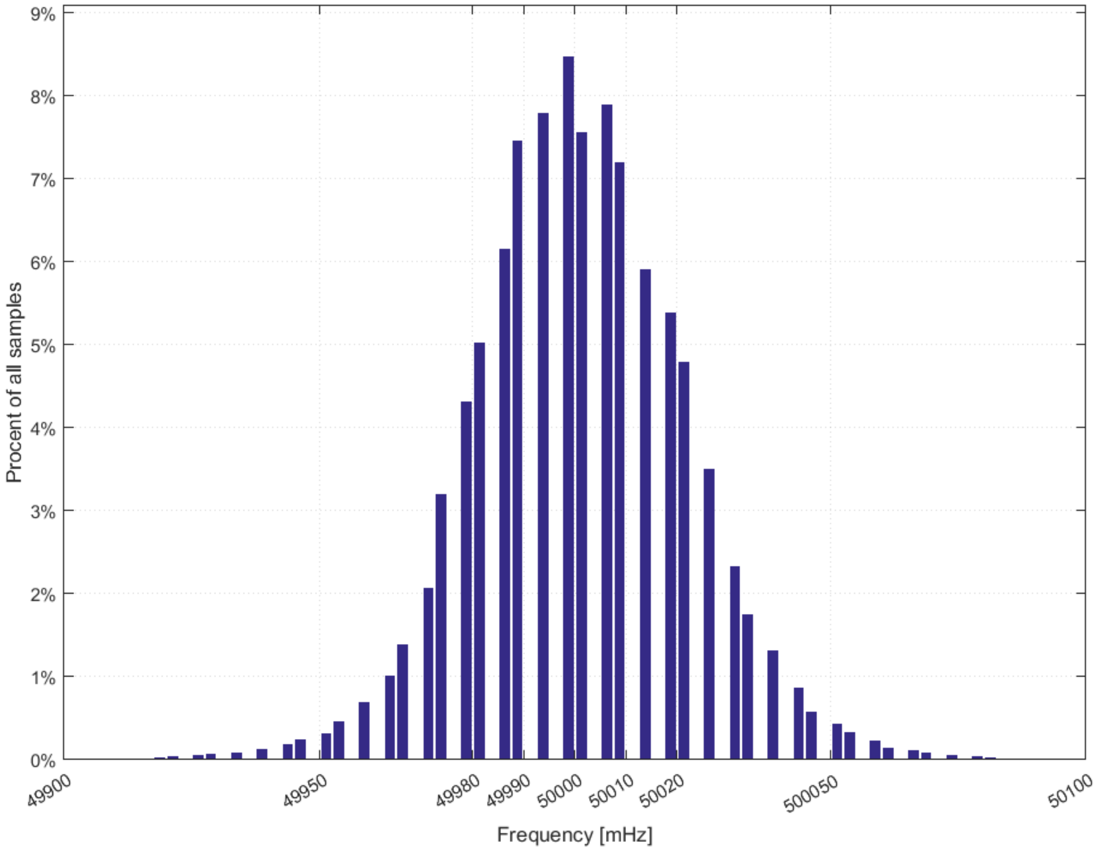


Figure 45: Frequency distribution of all the analyzed data

The distribution of the frequencies can be seen above. 38,9% of the time, the frequency is within +/-10 mHz from 50 Hz, and 68,9% of the time, the frequency is within +-20 mHz. Approximately 0,02% of the time, the frequency is either above or below +-100mHz.
This means that a system operated as primary reserve will be inactive 69,9% of the time, with the current regulations due to the deadband of 20 mHz, the requested power is also limited, and very rarely more than 50% of maximum power. The maximum requested power in the period is approximately 70% of the market bid.

Annex 2.2.2 Necessary energy content for primary regulation

The necessary energy content for primary regulation has been calculated based on the maximum energy delivered in one single run for each day. This is converted into the equivalent minutes at full power.
The criteria for primary reserve in Denmark, at present, is a minimum delivery time of 15 minutes, and a deadband with no regulation within +/- 20 mHz. These criteria may change in the future.

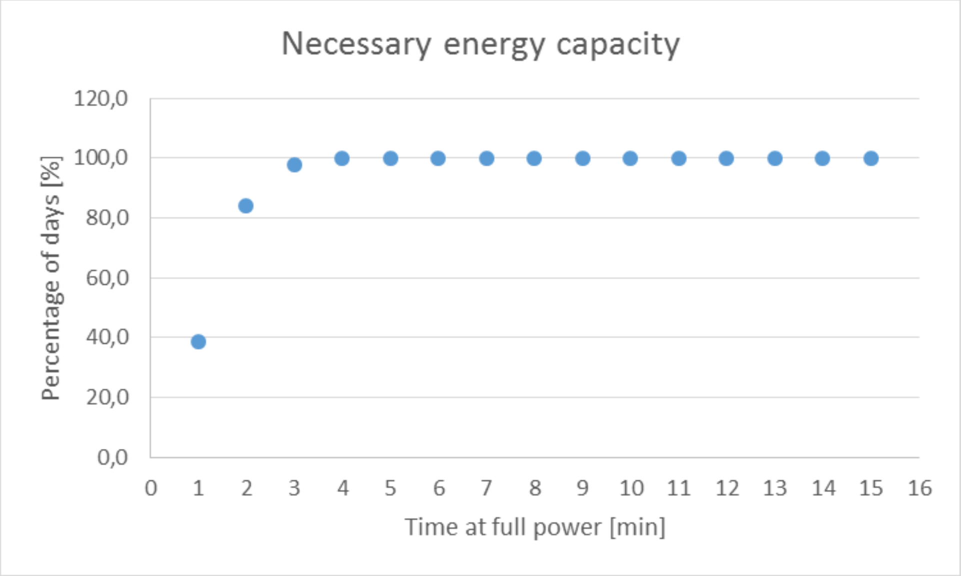


Figure 46: Necessary Energy capacity in minutes of full power in order to be able to deliver the requested power from primary reserve.

100% availability is achieved with a battery capacity equivalent to 6 minutes at full power. This means that a battery system with a capacity equivalent to 6 minutes at full power is able to deliver the requested power at all times in the analyzed data from 2013 to 2016 (more than 776 days).

Annex 2.2.3 Average day

Based on the available data there has been found one specific day, which reflects the average. Data from this day is used as a setpoint file for the battery tests in the laboratory.
The average day was found based on maximum, minimum, average frequency and frequency distribution close to average. The day identified was the 2013-11-09.

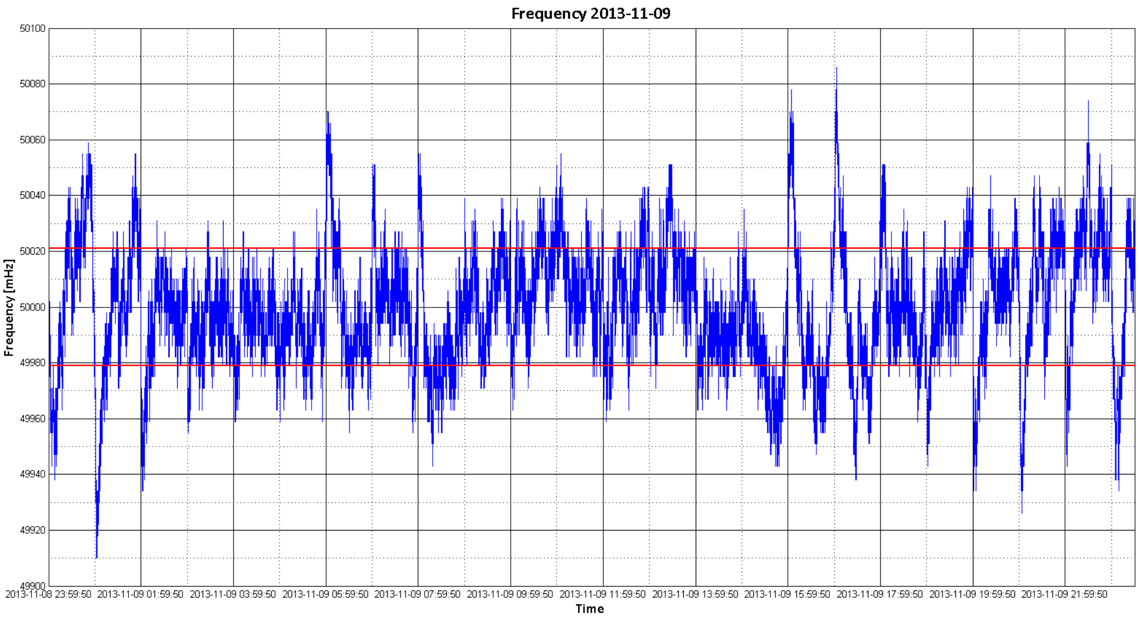


Figure 47: Illustration of frequency pattern from 2013-11-09. The red lines illustrates the current dead band of 20 mHz.

The frequency varies somewhat during the day, and especially during hour change the frequency varies. This is mainly caused by some systems stopping production, and other systems starting production due to the electricity market with hourly bids and hourly operation.

Annex 2.2.4 Highest energy delivery

The highest single energy delivery in the analyzed data has taken place on 2013-10-28. The delivery was 140kWh. The frequency can be seen below.

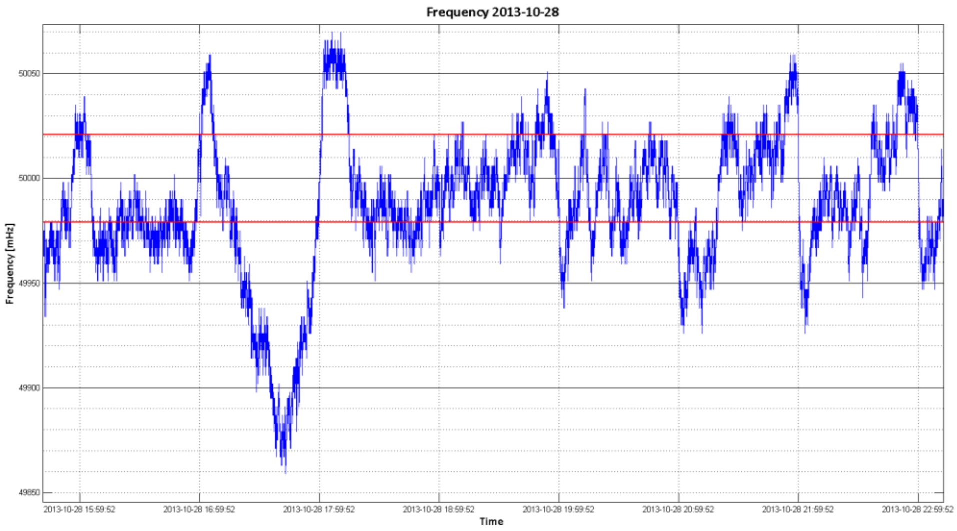


Figure 48: Frequency pattern from the day with the highest single energy delivery (2013-10-28)

The frequency drop lead to a primary reserve power delivery as seen below from the Altairnano system below.

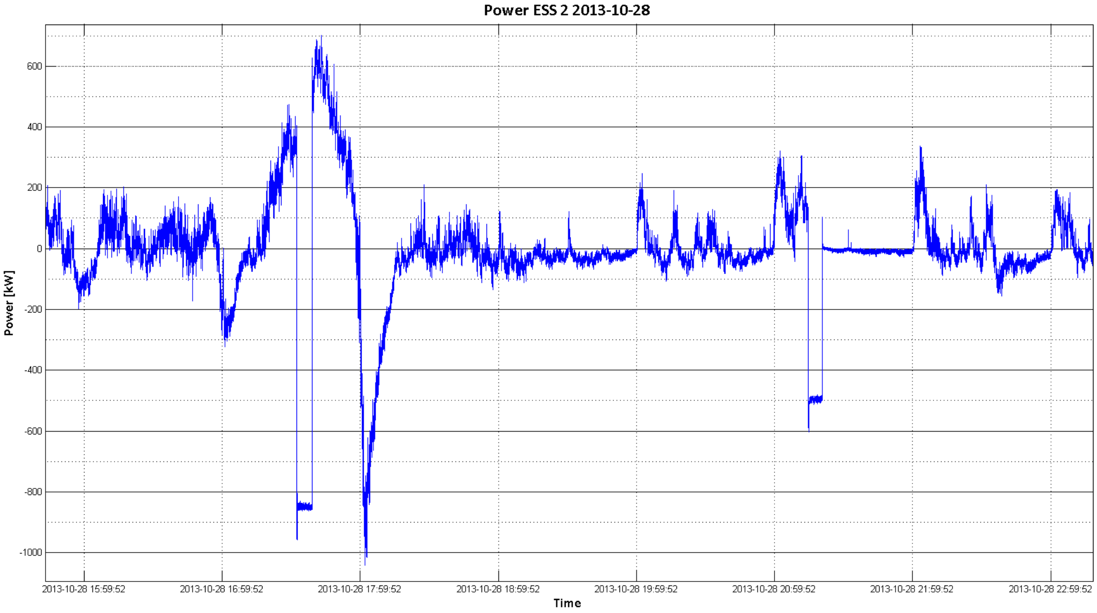


Figure 49: Graph of power delivery from Altairnano system during longer frequency drop

As seen on the graph, the system recharges after 15 minutes delivery in order to be able to always being able to deliver 15 minutes of frequency reserve at full power. This system behaviour is problematic in cases where a significant frequency deviation is present for more than 15 minutes, as it will lead to a sudden change from delivering to absorbing power, and hence it contributes to further frequency deviation. This pattern happens quite regularly. This problem is looked into in a pilot test in cooperation with energinet.dk where no sudden change is made in order to perform charging, but instead a charging algorithm runs continuously, alongside the frequency regulation algorithm.

Annex 2.2.5 Energy delivery

The energy delivery from the Altairnano system from each of the analyzed days can be seen below

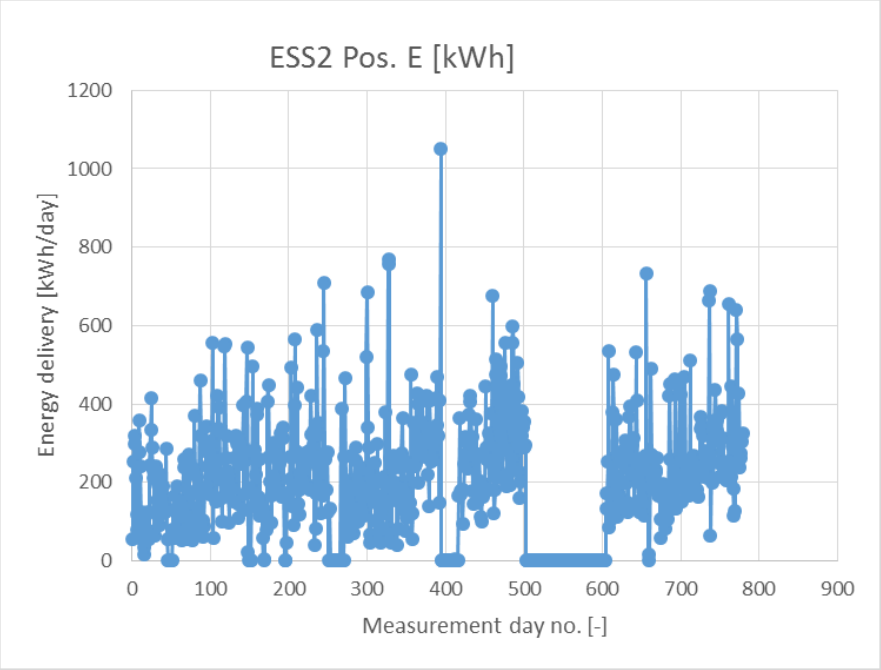


Figure 50: Energy delivery from the Altairnano system. The highest peak of 1050 kWh/day from day no. 399 is not during primary reserve.

The average energy delivery for each day from the Altairnano system during primary up regulation is 237,6 kWh and the maximum value is 770 kWh. In average this means the system in average does 237,6/300 kWh = 0,8 full cycles per day. The theoretic maximum possible number of cycles is 2*24=48 cycles, which leads to a utilization degree below 2%.

Annex 2.2.6 Influence of deadband and response time

Based on data from the the average day the influence of deadband on energy delivery has been examined.

Calculations with bid of 1 MW power	Energy [kWh]	Ratio
0mHz deadband	974,05	3,88
10mHz deadband	520,35	2,07
20mHz deadband	250,85	1,00

Table 26: Calculation of delivered energy demand and ratio compared to base of 20 mHz during primary reserve up-regulation. A power bid of 1 MW is used.

If the demands for delivering primary reserve is changed to a 0 mHz deadband from the current 20 mHz, without any other chances, this will lead to a 4 times higher energy delivery and associated costs. In the future, primary regulation with batteries may end up with a deadband of 0 mHz, but with the use of a charge algorithm which will reduce the energy consumption to approximately the same as previously, but with the ability to always deliver, and no need for 15 minutes grace period for recharging.

The response time has no measurable impact on the delivered energy. This is due to the fact that the frequency changes rather slow, and that full power request is never met in the calculations. Calculations has been done with 30 seconds and 0 seconds from 0 to setpoint power.

Annex 2.2.7 Data from load shift test

A load shift test was conducted on the Altairnano system based on an optimal income analysis buying electricity when prices are low and selling, when prices are high. See also document on income from Energi Danmark on this issue.

The requested load pattern looks as following:

Figure 51: Graph of loadshift testpattern with delivery positive, and consumption negative. Pattern of 4 days (96 hours). The red lines illustrates the period identical to the performed test below.

There were some technical issues with the system in the beginning, so the actual test was different from the setpoints in the beginning. The test pattern equals the performed test from approximately hour 37 which is illustrated on the figures. Also the final discharge was not performed.

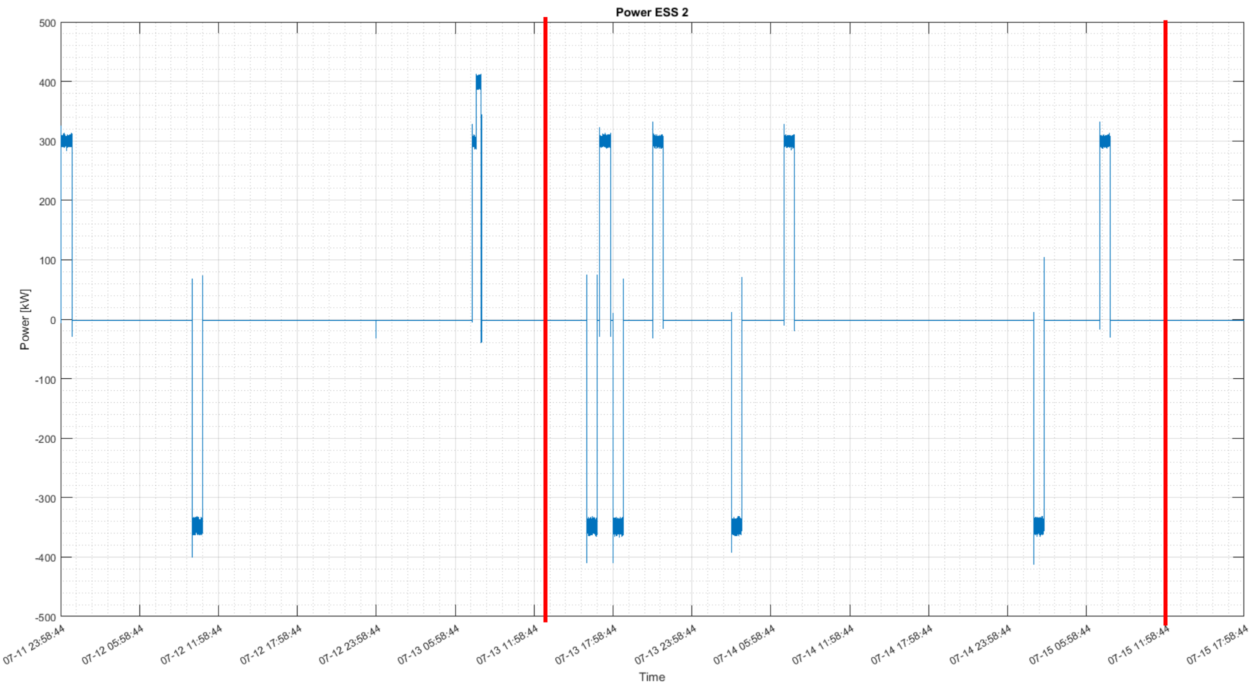


Figure 52: Graph of actual power delivered from the Altairnano system during Load shift test. The red lines illustrates the period identical to the setpoint above.

The system was set to operate between 5 and 90% SoC, and the power was set to 300 kW when delivering and 350 kW, when consuming energy.
The expected energy delivered from the system was approx. 300 kWh*(0,90-0,05)=255 kWh per cycle.

Cycle nr.	**Delivered energy [kWh]**	**Consumed energy [kWh]**	**Efficiency [%]**	**Delivery time[min]**
1	267,0	328,4	81,3	53,5
2	246,5	296,2	83,2	49,5
3	242,7	296,2	82,0	48,5
4	242,7	296,2	82,0	48,5
5	239,0	316,2	75,6	48,0
6	233,9	286,9	81,5	46,9
Total	1471,97	1819,875	80,94	49,16

Table 27: Energy delivered and consumed, and roundtrip efficiency of main system (without auxiliary consumption)

The energy delivered in the load shift pattern is reduced somewhat from cycle to cycle. This is most likely caused by rising imbalances between cells. The delivered energy is a little less than expected, and the delivery time is approximately 50 minutes.

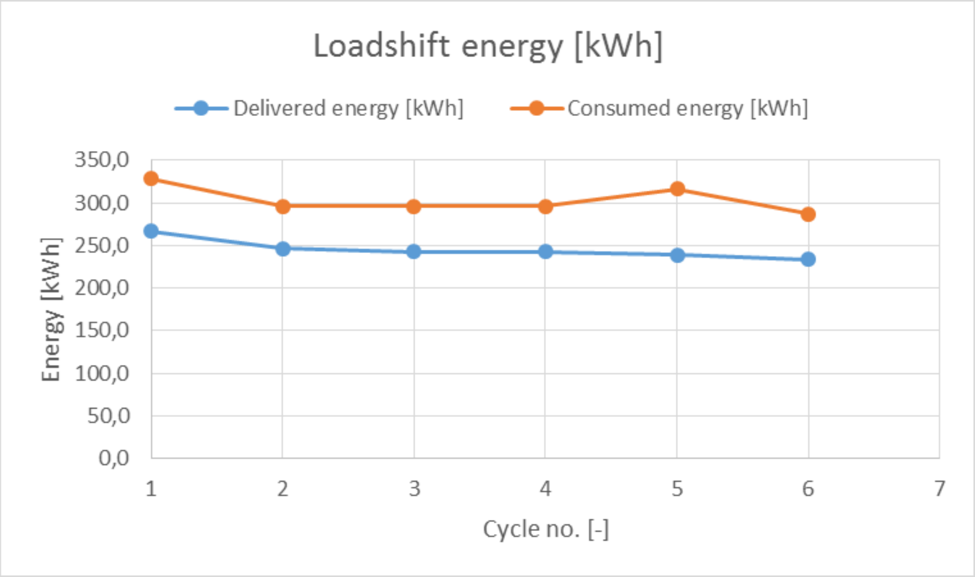


Figure 53: Graph of energy delivered from Altairnano system with load shift test pattern

Annex 2.2.8 Degradation in Lem Kaer

The degradation in Lem Kaer has been limited. Due to the limited operation and limited power and energy throughput during primary reserve small degradations was expected. The nominal number of cycles for the Altairnano system is 16000 to reach 20% degradation. At 0.8 cycle per day as during primary reserve, the degradation to 80% of initial capacity due to cycling will take 16000/0.8/365 ≈ 55 years. The equivalent of approximately 0.4% degradation per year. The continuation of detailed EIS (Electrochemical Impedance Spectroscopy) measurements was arranged with AAU (Aalborg University) in the beginning of the project but was canceled due to time restraints and lack of internal permissions for disconnecting battery packs in Lem Kaer.

The nominal capacity of the Altairnano system is 420Ah (60Ah per single cell at a discharge rate of 6C), and the nominal system voltage is 880V (2.3 Volts per cell). The nominal energy capacity is 370 kWh.

Measurements of capacity in Ah and energy capacity in kWh can be seen in the table below. The last test was finished prematurely and hereby carried out without power roll off which has caused a lower capacity. The interruption was probably caused by cell imbalance at the high power discharge.

	Capacity [Ah]	**Energy Capacity [kWh]**
20130227	444,4	359,3
20130325	441,3	356,9
20130406	428,4	346,9
20130815	441,8	357,4
20160701	412,2	331,2
20161213	384,9	314,9

Table 28: Capacity and energy capacity of Altairnano system. The last test was finished without power roll off.

The discharge power during the tests are 1200 kW (≈4C). The current and power is rolled off at the end of the tests (except for the last test).

The data from the table can also be seen in the figures below.

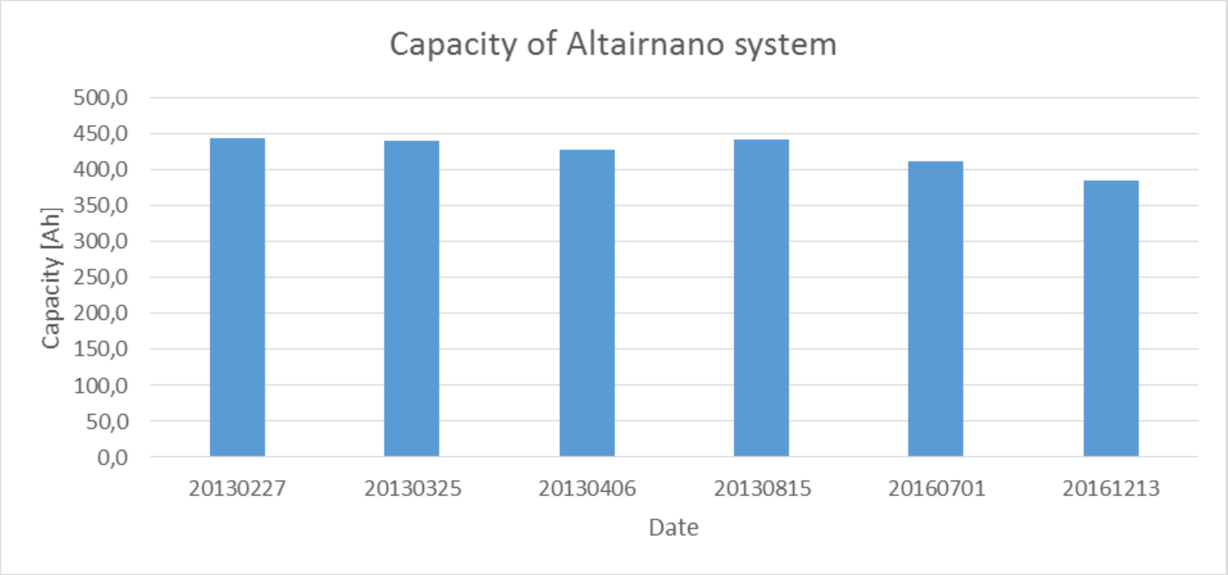


Figure 54: Measured capacity of Altairnano system. The last test was finished prematurely.

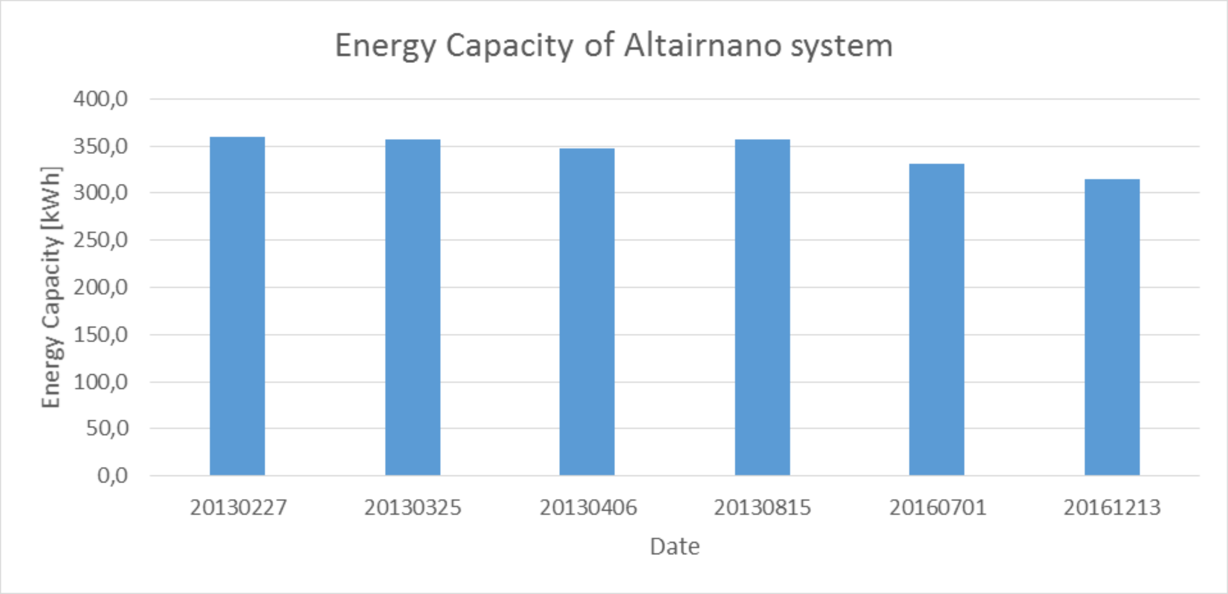


Figure 55: Measured Energy capacity of Altairnano system. The last test was finished prematurely.

The average measured energy capacity, when disregarding the last measurement is 350 kWh, or 95% of the rated capacity of 369,6 kWh.

The measured difference in the capacity is mainly caused different SoC calibration and difference in single cell voltages in the system. Especially since the last test was finished prematurely. A slight degradation based on the previous data indicates a loss of energy capacity of the system of 7% during approximately 3 years of primary reserve operation. The reduction of energy capacity may be possible to retrieve by taking more time to balancing before measurements. Especially since the capacity is measured at a rather high current rate of approximately 4C.

Annex 2.2.9 Efficiency of systems in Lem Kaer

The efficiencies of the systems have been calculated from the analyzed data.

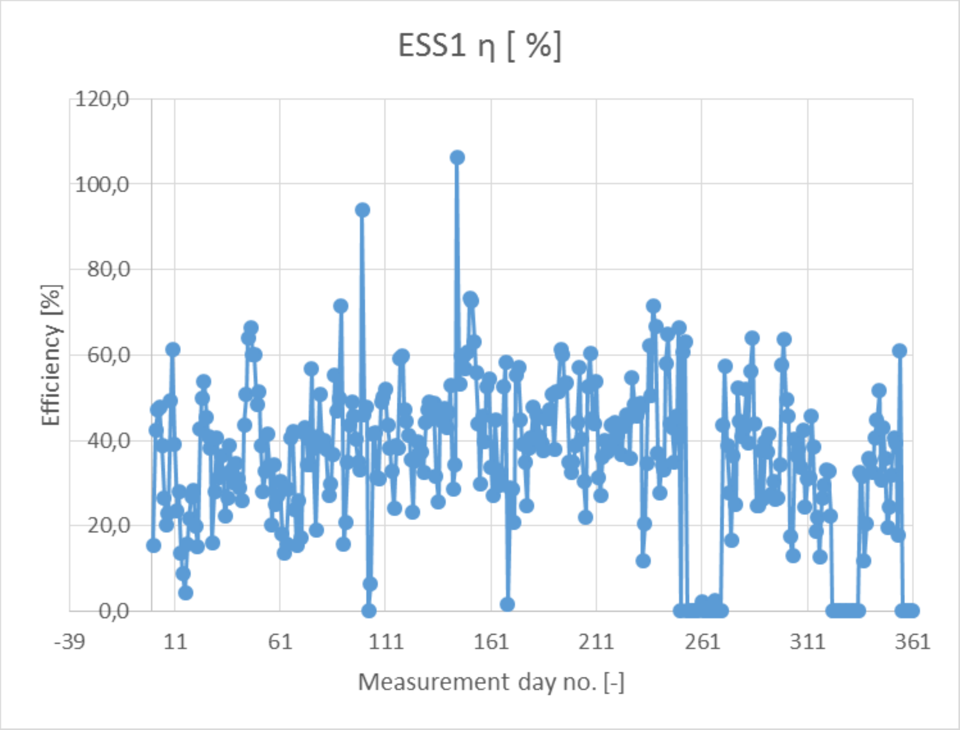


Figure 56: Efficiency of A123 system during primary regulation without auxiliary consumption. Data is based on energy transfer per day, which can lead to daily averages above 100%.

The average efficiency of the A123 system during primary regulation upwards is approximately 39%. The efficiency varies from day to day due to different energy content in the batteries in the start and end points, but the calculated average is correct.

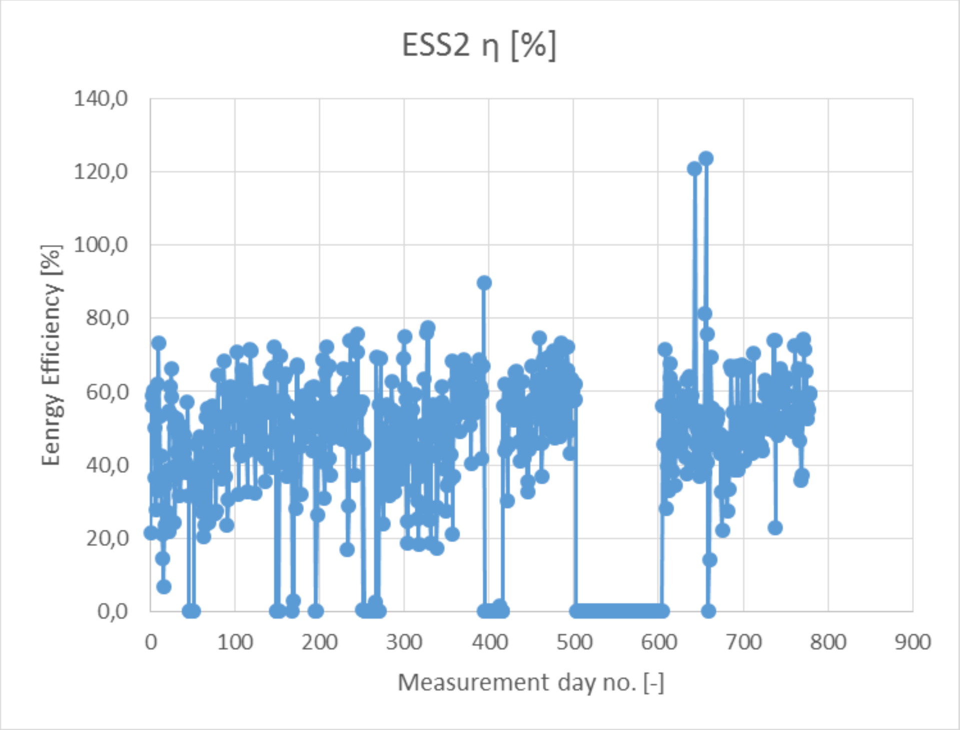


Figure 57: Efficiency of Altairnano system during primary reserve regulation without auxiliary consumption. Data is based on energy transfer per day, which can lead to daily averages above 100%.

The average efficiency of the A123 system during frequency upwards regulation is approximately 50%. The highest possible roundtrip efficiency of the Altairnano system is approximately 85% with full power, when not including auxiliary components.

Operating pattern	Efficiency Altairnano	Average energy Delivery
Peak roundtrip	85,0%	
Load shift pattern	80,9%	368,0 kWh/day
Primary reserve up (20 mHz deadband)	50,0%	237,6 kWh/day

Table 29: Scematic overview of efficiency of the Altairnano systems in Lem Kaer with different operation patterns

Besides the losses in the system included in the data above, which includes losses in transformers and inverters, there are also energy consumption for auxiliary components. This is further investigated in the next chapter.

Annex 2.2.10 Auxiliary consumption

The auxiliary consumption of both BESS systems in Lem Kaer can be seen in the figure below.

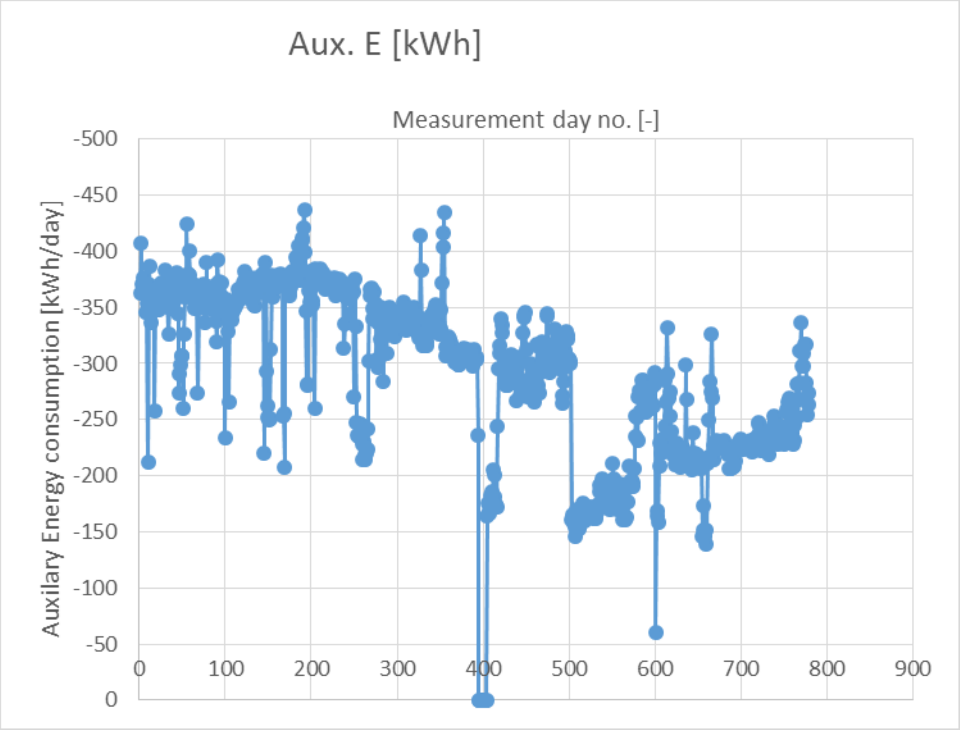


Figure 58: Auxiliary consumption for the two battery systems in Lem Kaer

The average auxiliary consumption for the two systems are 291 kWh/day or 12.1 kW.
The auxiliary consumption has been investigated further on the Altairnano battery system. This has been done in order to identify the major energy users so these can be focused on for optimization of the system and knowledge in connection with other systems.

Power comsumers in ALTI - ESS system		
Consumption during average frequency regulation.		
Battery roundtrip efficiency	96,0	%
Inverter efficiency	94,0	%
Inverter standby consumption		kW
Transformer effiency	94,0	%
Transformer standby consumption		kW
Combined efficiency	**84,9**	%

Components	**Measured Power [kW]**	**Estimated average Power [kW]**	**Percent of total auxilary**
Auxilary components			
Thermal control system (HVAC)			
Blowers in HVAC units	2,0	2,0	20%
Electric Heaters	14,5	2,4	24%
Cooling units incl. outside cooling fans	13,9	1,7	17%
Total heating	**16,5**	**4,4**	**44%**
Total cooling	**15,9**	**3,7**	**37%**
Sum: HVAC units			**81%**
Battery blowers	0,8	0,2	2%
Lighting	0,32	0,0044	0%
230 V Standby for inverter and transformer	0,93	0,93	9%
Control system, BMS and measuring	0,75	0,75	7%
Cable and contactor losses	0	0	0%
Aux inverters	0	0	0%
Fire extinguish system	0	0	0%
Sum: Auxilary except HVAC units	**2,8**	**1,9**	**19%**
Max aux. Altairnano	**19,3**	**10,0**	**100%**
Est. Aux consumption per day		**241,2**	**kWh**
Est. Aux consumption per year		88.025	kWh
Est. Aux cost per year		88.025	kr.

Table 30: Measurements and estimated average auxiliary energy and power for Altairnano system

As seen in the table, most of the auxiliary energy used is used for temperature adjustment of the battery system (81%). The thermal control system blows conditioned air close to the battery boxes, which has separate blowers that leads the air thru the battery boxes.

Much energy can be saved with different temperature control and possible insulation of the container. In primary/frequency regulation mode, which the system is operated in most of the time, there is a limited energy throughput, and thereby also a limited energy loss in the batteries. This leads to quite high consumption for heating the system. In hot days the cooling system comes into operation. In fall and spring time, there are even times where the system is cooled during the day and heated during the night. With better insulation and a wider allowed temperature span, this can be reduced. It was not possible to do changes on the system in Lem Kaer, but this must be taken into consideration with other systems. The scale system at DTI is therefore constructed with insulation of the battery compartment. Here is also a delay on shift from heating and cooling, and future possibilities for wider temperature operating range.

Annex 2.2.11 Operating experience from Lem Kaer

There has been different system errors in the large Scale battery systems during the project period. The errors are listed below.

- Pump errors
- Heating/cooling system error
- Control computer malfunction
- Data measure and recording errors (Elspec meters)
- Inverter errors (degraded capacitors)
- Movement of battery systems
- Disconnection by DSO

During the project period the battery systems had to be moved, which caused a pause in operation, but also subsequent errors due to the movement. Furthermore, there has been situations where power to the site has been disconnected without prior notice from the local DSO.

Maintenance and support has to be taken care of, just as with any other larger systems in order to keep it running.

The smaller A123 battery system had several errors including control computer errors and inverter errors which would demand further substantial supplier investigations and investments, which was not able to be carried out in the project.

There has been no battery related errors with either of the systems!

Annex 2.2.12 Conclusion from Lem Kaer operation

The system efficiency is rather low when operated as primary reserve, due to losses in inverters and transformers and due to consumption of auxiliary components – mainly the thermal control system.
This calls for the necessity of optimizing part load operation and also optimizing thermal control of battery systems. High part load efficiency is important for ROI. The information is highly relevant and should be requested from suppliers but may be hard to get.
There has been no battery related errors prior to or during the project period. The primary focus with regard to BESS systems are often the batteries and battery degradation. The batteries are of course important, but the experience from this project is that other system components are equally important in order to secure low energy losses and the up-time of the entire system.

Annex 2.3 Financial Experience from operation in Lem Kaer

The BESS system has been operated in a real market environment for a number of years now. This section will summarize the main findings of the actual operations, and will compare the findings to the theoretical calculations presented in WP1 when it comes to the Operational income and profitability of the BESS system.

The BESS system has been test run in the following modes which is analyzed by Energi Danmark:

- As a load shifting unit
- As a primary reserve for delivering up-regulation. The results here will include the period

The operation with alternative primary regulation has not been evaluated in this section.

Annex 2.3.1 Load-shifting operation

BESS was run as a load shifting unit for 4 days starting on the 12th until the 15th of July 2016. In this period, the prices assumed were fictive (not real market prices) in order to ensure the operation of the unit. The unit was optimized assuming an advanced knowledge of the up and down regulating power prices. Charging takes place at the down regulation price, and production at the up-regulation prices. Figure 59 shows the assumed prices along with the resulting charging and production cycles.

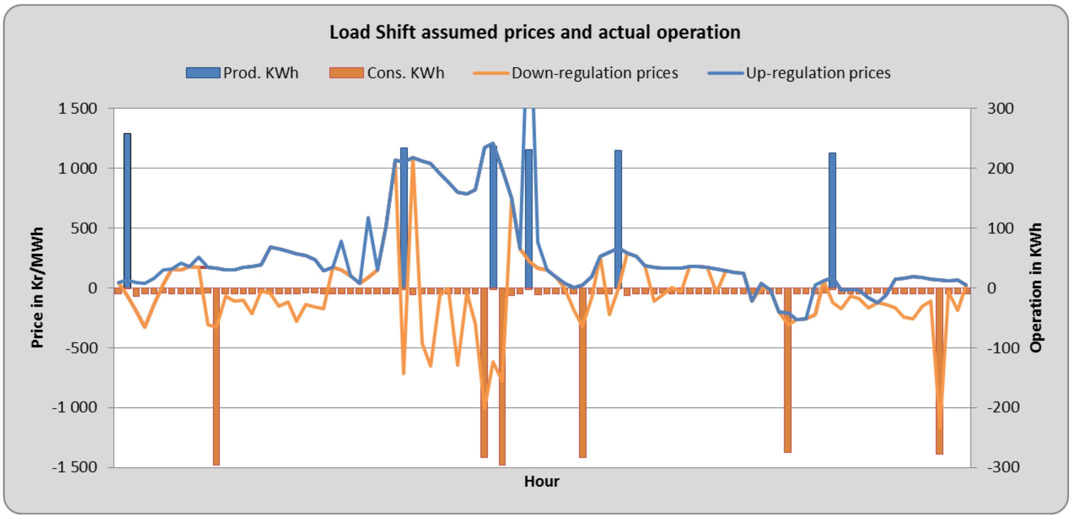
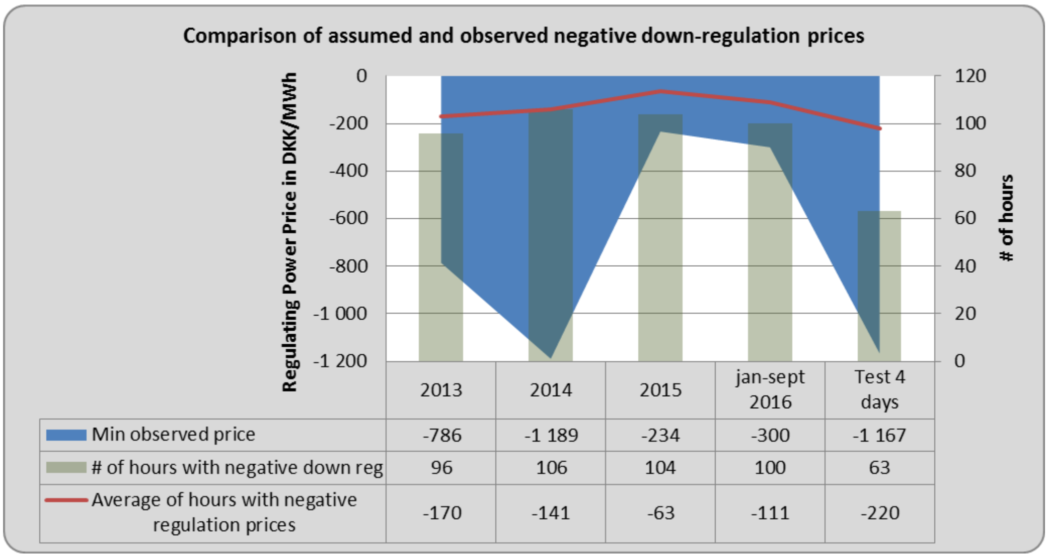


Figure 59: Load shift assumed prices and resulting operation

From the graph above, the following can be observed:

- The maximum utilized discharge capacity is around 240 kWh. This is 60% of the initial project capacity assumed in the WP1 calculations, which was around 400 kWh. This is due to the fact that one of the battery systems has been out of operation during the test period.
- The auxiliary power consumption is around 10 kWh per hour. This is below the assumed value in WP1 of 16,67 kWh per hour. This could be due to a variety of reasons such as the milder weather during the test period and the outage of one of the batteries.
- The auxiliary power consumption drops to around 3 KWh during the hours with production. This could probably be an indication that parts of the auxiliary system are powered by the produced power during these hours.

- The efficiency of the charge/discharge cycle is at around 85% (excluding auxiliary power)
- Charging occurs during hours with negative down regulation prices, meaning that the BESS receives a payment for charging. It should be noted that the occurrence and value of the negative prices assumed is exaggerated in the fictive price series used during the 4 days to be more than half the amount observed during a whole year, as shown in Figure 60



	2013	2014	2015	jan-sept 2016	Test 4 days
🟦 Min observed price	-786	-1 189	-234	-300	-1 167
▨ # of hours with negative down reg	96	106	104	100	63
— Average of hours with negative regulation prices	-170	-141	-63	-111	-220

Figure 60: Negative down-regulating prices. The first 4 points are realized prices in the period 2013 until September 2014, while the last column is the assumed fictive price series used for the load-shift test run.

Figure 61 and Figure 62 show the main operational results based on the current and the reduced tariffs respectively. As a reminder, Table 31 shows the assumed current and reduced tariffs on consumption. Production tariffs is assumed at 3,59 DKK/MWh in all cases.

Table 31: Assumed tariffs on consumption

[DKK/MWh]	Fees on consumption		
	Current Tariffs	Reduced Tariffs Aux Power	Reduced Tariffs Charging Power
Consumption fee – TSO	1,31		
Grid tariff – TSO	42	42	
System tariff – TSO	24	24	
PSO – TSO	217	217	
Various fees for DSO	1084	251	251
Total	**1368,31**	**534**	**251**

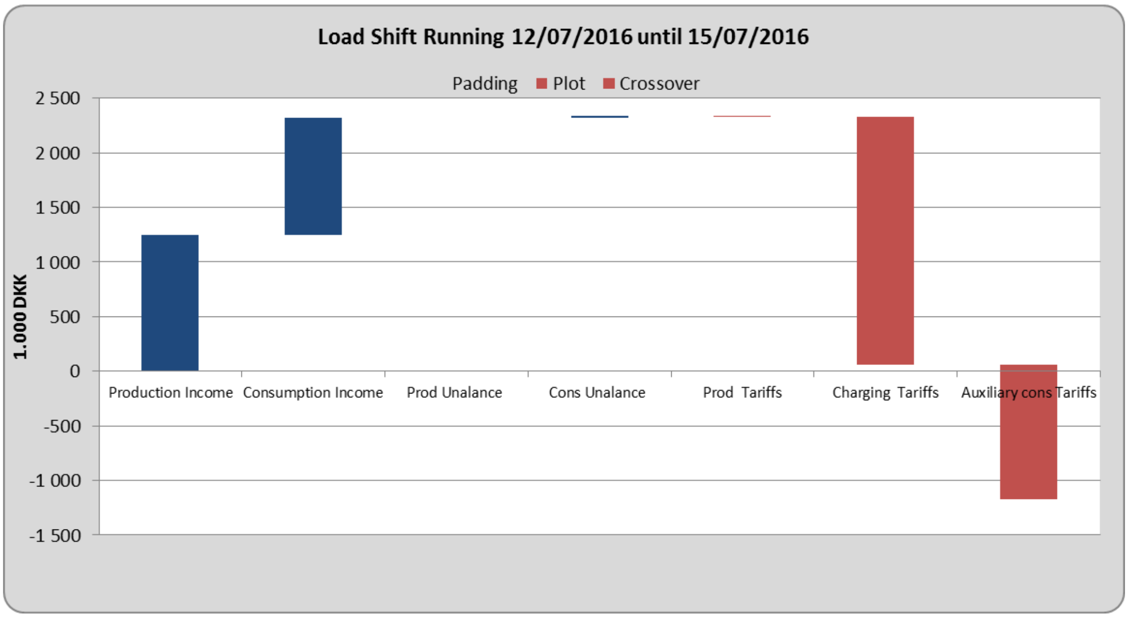


Figure 61: Load shift results based on the current tariffs

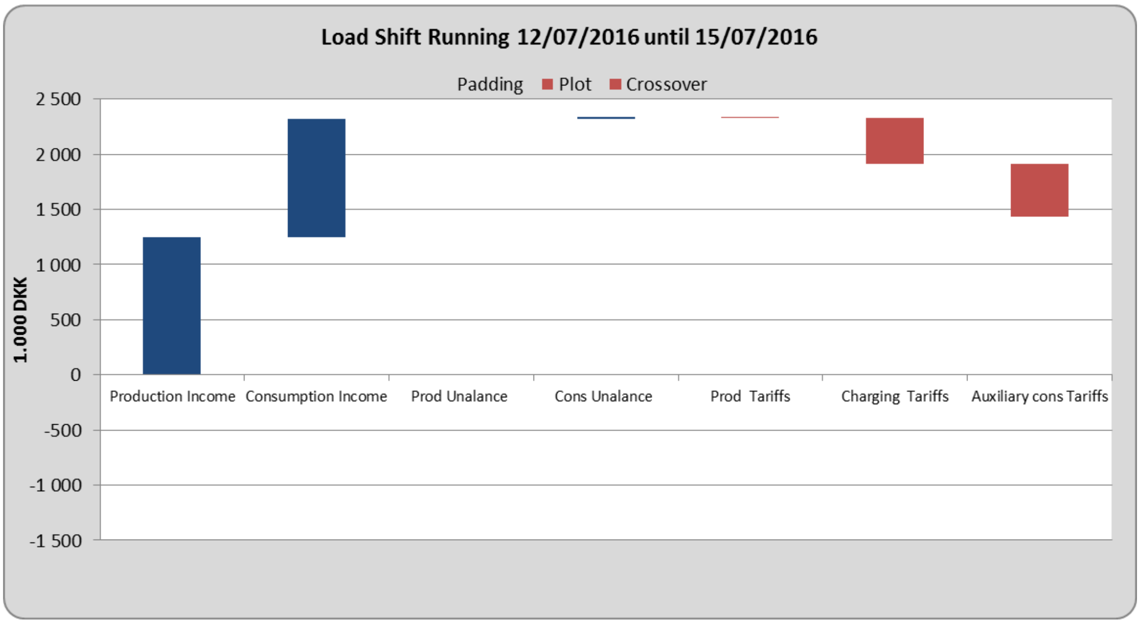


Figure 62: Load shift results based on the reduced tariffs assumed in WP1

Table 32 shows the same results shown in the graphs above in addition to some more statistics on the load shift operation. In this calculation, it is assumed that the auxiliary power is treated as a consumption unbalance, thus falling under the one price system. As can be seen from the result, whether this consumption is planned or not makes a little difference on the total result.

Table 32: Main results for load shift operation

			Full Tariffs	PWC Tariffs
Volumes	Production volume	KWh	1 415	1 415
	Consumption Volume	KWh	-2 561	-2 561
	Of which recharding power	KWh	-1 656	-1 656
	Of which auxiliary power	KWh	-905	-905
	Calculated Efficiency incl Aux	%	55%	55%
	Calculated Efficiency excl Aux	%	85%	85%
Revenues	Production Income	DKK	1 248	1 248
	Prod Unalance	DKK	0	0
	Availability Up	DKK	0	0
	Availability Down	DKK	0	0
Costs	Consumption Income	DKK	1 074	1 074
	Cons Unalance	DKK	13	13
	Charging Tariffs	DKK	-2 266	-416
	Auxiliary cons Tariffs	DKK	-1 238	-483
	Prod Tariffs	DKK	-5	-5
Income	Total Revenue	DKK	1 248	1 248
	Total Cost	DKK	-2 422	184
	Income incl aux power cost	DKK	-1 174	1 431
	Income excl. aux. Power cost	DKK	51	1 901

Comparison to the prior theoretical calculation

Given that the consumption time series available contains both auxiliary and charging power, a threshold of 15 kWh/hour was used based on the observed data to filter auxiliary power consumption from charging consumption. This resulted in an average cycle efficiency of 85% when ignoring auxiliary power, which matches very well with the assumed efficiency in WP1. Given that the efficiency matches, it is no surprise that the theoretical and realized profit per produced MWh matches as shown in Table 33.

Table 33: Average charging and discharging prices, and the comparison between the theoretical and realized income per produced MWh

		Full Tariffs	PWC Tariffs
Average realised Dischargin price	DKK/MWh	882	882
Average realised charging price (- = income)	DKK/MWh	-649	-649
Average realised income per produced MW	DKK/MWh	36	1343
Theoretical income per Produced MWh	DKK/MWh	37	1346
Difference between theoretical and realise	DKK/MWh	3%	0%

From Table 33, it also follows that it is enough to know the average charging and discharging price during the period to deduce the income. Therefore, the optimization strategy needs only to ensure that the average charging and discharging price pairs fall in the designated areas shown in Figure 63. The graph below can facilitate decision taking when trying to capture prices on the balancing market.

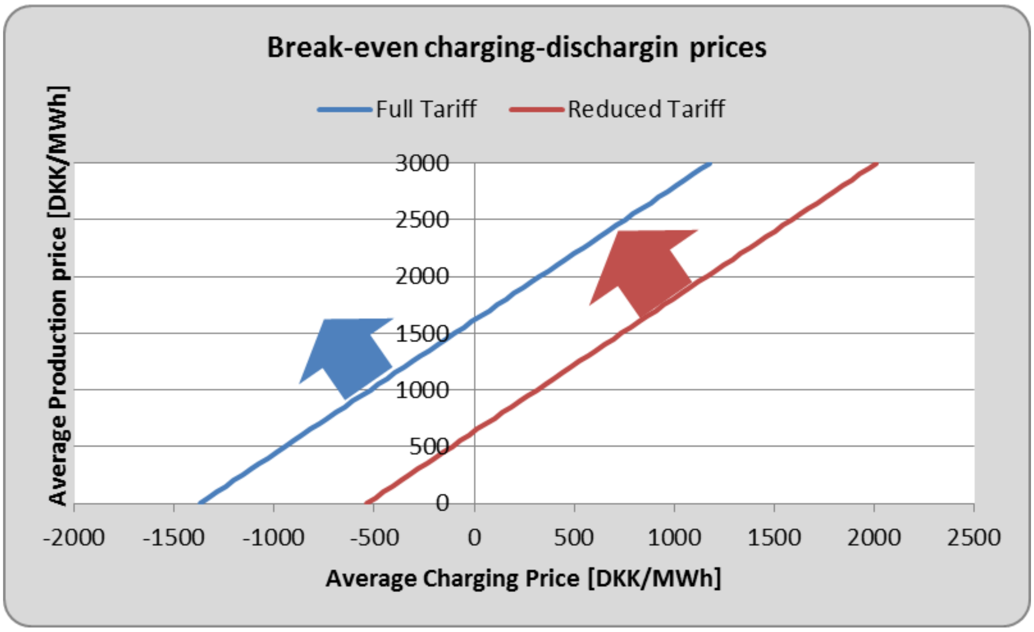


Figure 63: Break even and desired charging/discharging price combinations.

Finally, it is noted that auxiliary power results in a substantial burden on the profitability of BESS, and the effect is especially prominent in the current tariff situation. Keeping in mind that the number of cycles per year is much less than that observed in the 4 days test, the auxiliary power will play an even more prominent role as its volume would be larger compared to the operational cycles. It is therefore of high importance to reduce the auxiliary power consumption if BESS is to be profitable on the market.

Annex 2.3.2 Primary reserve operation

During the previous years, the BESS system was sold as an up-regulation primary reserve. This means that the unit received an income for being available to deliver production on the market. The production volume on the other hand is treated as an imbalance. In our calculation, we also assume that the whole consumption is treated as an imbalance.[6] It should be noted that starting from July 2014, the storage capacity dropped from due to the outage of one of the batteries, and therefore the accepted up-regulation power was reduced from 1,4 MW to 1 MW after that date.

Figure 64 shows the operational revenues and costs along with the resulting operational income in case of the full tariff and the reduced tariff scenarios. What is clear in the graphs is that the reserve payment is the major post leading to the profitability of BESS. This is due to the fact that the actual production and consumption volumes under this mode of operation are relatively low, as shown in Table 31. Note that in order to be able to separate the auxiliary power from the total consumption, the efficiency of 50% is assumed as reported by Vestas in WP1 for this mode of operation.

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[6] Although one could plan for the auxiliary power in advance, the difference is negligible as would be seen in the results. In fact due to the consumption being treated under the one-price balance system, some years result in a positive income due to the consumption imbalance.

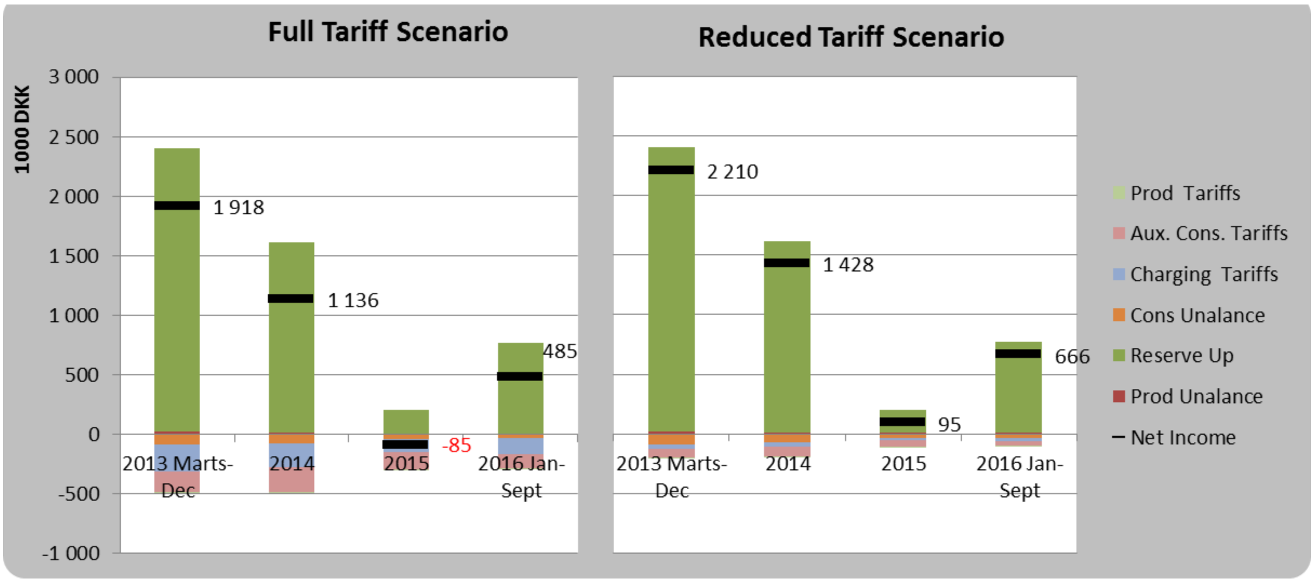


Figure 64: Realized revenues and costs and operational income per year starting from March 2014 until September 2016. The reason for discarding the first 2 months of 2013 is defect consumption readings in the data series available.

Table 34: Resulting production and consumption volumes during reserve market operation

			2013 Marts-Dec	2014	2015	2016 Jan-Sept
Volumes	Production volume	MWh	84	74	42	49
	Consumption Volume	MWh	-293	-300	-187	-183
	Of which recharging power	*MWh*	*-168*	*-147*	*-83*	*-99*
	Of which auxiliary power	*MWh*	*-126*	*-153*	*-104*	*-85*
	Calculated total efficiency	%	29%	25%	22%	27%
	Assumed Efficiency excl. Aux	%	50%	50%	50%	50%

With the cost side of the equation being limited by the low operational volumes, the income thus depends mainly on the earnings on the reserve market. These earnings are dependent on 3 main factors:

- Unit availability
- Sold reserve capacity
- Reserve market prices

Table 35 shows the variation of these three factors for the BESS system, which explains the variation of the reserve payment column shown in Figure 64:

- Unit availability, which was highest in 2015, and was particularly low during 2015
- Sold reserve capacity, where the average sold volume per hour dropped from 1,4 MWh to 1 MW following the outage of part of the battery in 2014
- Reserve market prices: The reserve market prices have in general been dropping. In 2015, the weighted average price for the hours sold was even lower than the average market prices during that year.

Table 35: Factors affecting the earnings of BESS on the reserve market

			2013 Marts-Dec	2014	2015	2016 Jan-Sept
Reserve Statistics	% of hours sold	%	96%	84%	35%	77%
	Average volume sold	MWh	1,40	1,33	1,00	1,00
	Average market price	DKK/MW/h	239	159	114	146
	Weighted average price	DKK/MW/h	240	167	55	166

Annex 2.4 Alternative primary regulation

There has been done efforts in the project in order to evaluate how battery systems can operate as primary reserve in the future and avoid some of the issues seen in the project. Several different solutions has been suggested and together with Energinet.dk a real life test was decided upon and carried out in connection with pilot project arrangement from Energinet.dk. Here, a new, hopefully better control algorithm which takes both grid, battery and business case into consideration was tested while participating up-regulation in the primary reserve market.

Traditionally primary reserve operation up, calls for power delivered to the grid when the frequency drops below 49,980 Hz in order to maintain the nominal frequency of 50 Hz and secure grid stability. There was a deadband of 20 mHz, in which the systems should not deliver. This delay is not ideal from a grid perspective.

The reason for the involvement in this BESS project is that there are no clear technical rules or guidelines on how battery systems should be operated in primary reserve at the moment. The existing rules are designed primarily for thermal power generation and does not comply well with how a battery can operate, and does not take into consideration the fast acting possibilities of a battery system.

According to previous rules a system which delivers primary reserve must always be able to deliver for a minimum of 15 minutes, and thereafter has 15 minutes for recharge. When introducing primary reserve units with limited energy storage, this means that a system must shot down after 15 minutes of delivery independent of energy delivered and start charging in order to be able to deliver full power for 15 minutes again, 15 minutes later. This is not very attractive for either electrical grid or battery system, as seen previously in this report. Also the allowed delay of up to 30 seconds before full power is reached is not wanted.

The overall operating pattern of an alternative primary reserve with batteries were:

1. Always keep the battery system online and calculate Frequency response power demand linearly from 0 to maximum power depending on deviation from 0 to 200 mHz from 50Hz (No deadband)
2. Calculate charge power demand linearly depending on deviation in SoC from setpoint and maximum power
3. The actual delivered power is calculated as the sum of frequency response demand (1) and charge demand (2)
4. Deliver power as fast as possible without intentional time delay (and without deadband)
5. Auxiliary consumption of system is not included
6. The bid into the primary reserve market depends on the energy capacity of the energy storage system (how long the system can deliver full power) and the maximum power of the battery system, depending on how fast secondary reserve can take over

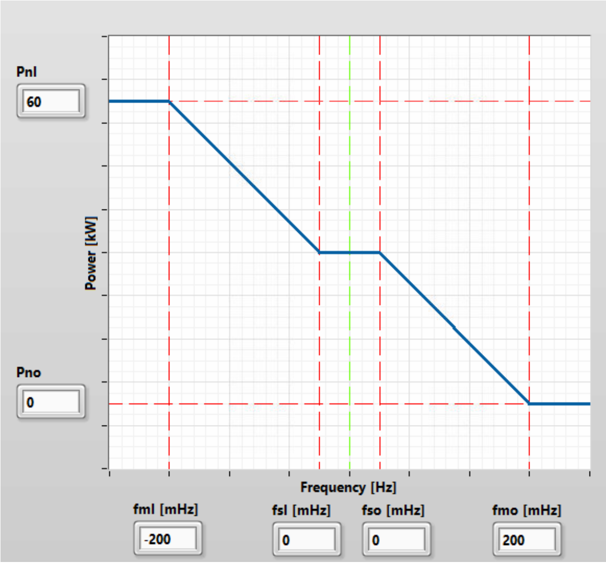


Figure 65: Illustration of frequency deviation and requested power. In alternative primary reserve, the deadband is 0 mHz. Pnl=Power Nominal Levering(delivery), Pno=Power Nominel Optag(consumption), fsl=frequency deadband delivery), fso=frequency deadband consumption, fml and fmo is deviation at full power.

Size of market bid in alternative primary regulation

The size of the market bid in the alternative primary/frequency regulation is calculated on the basis of battery storage capacity and available maximum power. The background for the calculations by energinet.dk is that secondary reserve must be able to take over (time delay of 200 seconds.) The approved bid relative to number of minutes at full power can be seen below in Table 36.

Energy capacity measured in minutes at full power	*Percentage of maximum power bid into the primary reserve market*
5	*70%*
15	*85%*
30	*91%*
60	*95%*
120	*98%*
>120	*100%*

Table 36: Example of approved percentage of power depending on the energy capacity of the BESS system. Inspired by calculations from energinet.dk.

Since the Altairnano system is capable of delivering full power for 15 minutes, the percentage is 85%, and the maximum power is 1.250 MW, the bid into the market in the pilot test is:

1.250 MW*0,85 = 1.062 MW, which is rounded down to 1 MW.

The maximum power bid into the traditional primary reserve market is also 1 MW of power for the Altairnano system in order to recharge and overcome energy losses within 15 minutes. Since the income is approximately the same, the energy consumption and cost for this is very important for the business case.

Modelling of alternative primary regulation delivery

In order to evaluate the effects of a new operating pattern, different days and timespans were selected and calculations were done depending on the actual frequency, and a calculated SoC of the altairnano battery system in Lem Kaer.

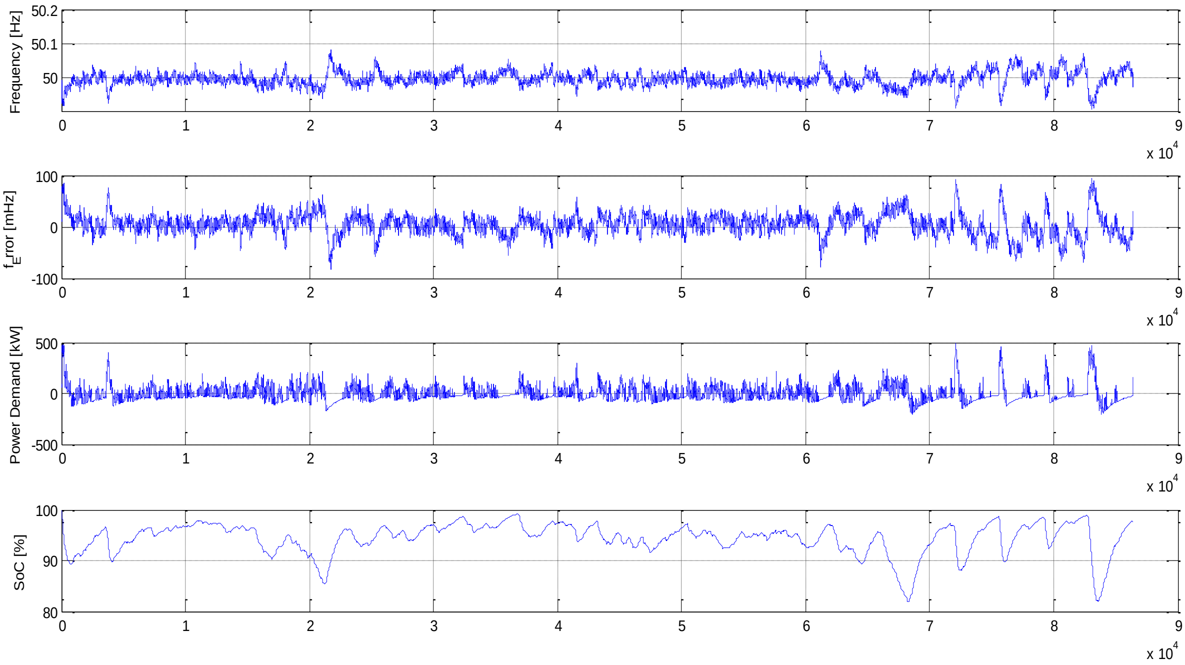


Figure 66: Example of modelling from average day (2013-11-09) performing alternative primary reserve operation upregulation. The time stamp on the x-axis is in seconds.

The modelling results are summarized in the table below together with a factor for comparison in the last column. It is seen that the average energy comsumption is expected to rise with between 5 and 32%. In the extreme scenarios, the energy delivered is lower, but this is not normal operation.

Frequency pattern	Standard (20 mHz)	Standard 0 mHz	New control, 0 mHz	New control, 10 mHz	New control, 20 mHz	Factor between standard og new 0 mHz
Average day (2013-11-09)	0,411	1,590	0,431	0,315	0,205	**1,05**
Day with single largest energy delivery (2013-10-28)	0,561	1,630	0,415	0,293	0,196	0,74
Typical month, February 2014	8,222	33,835	10,824	7,272	4,207	**1,32**
Typical month, March 2014	10,897	39,435	12,477	8,636	5,324	**1,14**
2006 extreme	0,320	0,361	0,167	0,172	0,174	0,52

Table 37: Energy delivered in kWh for the different recorded frequency patterns and the different operating scenarios.

Frequency pattern	New control, 0 mHz	New control, 10 mHz	New control, 20 mHz
Average day (2013-11-09)	81,757	84,026	86,167
Day with single largest energy delivery (2013-10-28)	57,119	59,754	62,624
Typical month, February 2014	72,329	75,547	79,267
Typical month, March 2014	72,786	75,943	79,321
2006 extreme	42,362	43,181	44,042

Table 38: Minimum State of Charge (SoC) for the different frequency patterns and varying deadband in connection with the new control. 0 mHz is most likely

It is seen that in normal operation, the minimum state of charge is in normal operation not expected to become lower than 70%. The extreme scenario from 2006 with separation of the European electrical grid would lead to a calculated minimum SoC of 42%.

Operating experience alternative primary regulation

The developed regulation pattern was put into operation on the Altairnano system in Lem Kaer, and the overall operation can be seen in Figure 67 and Figure 68 below.

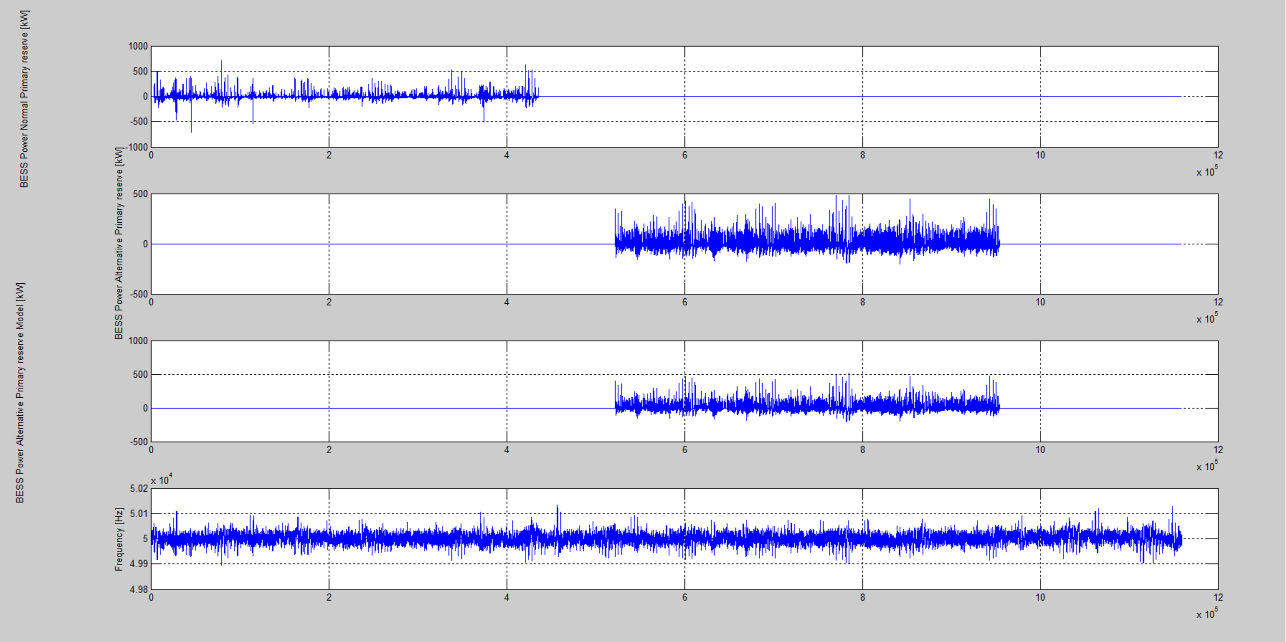


Figure 67: Graph showing traditional primary reserve in the beginning (5 days) and subsequent delivering the alternative primary regulation for five days. And the frequency throughout the period. The x-axis is time in seconds (December 1st to December 14th, 2016).

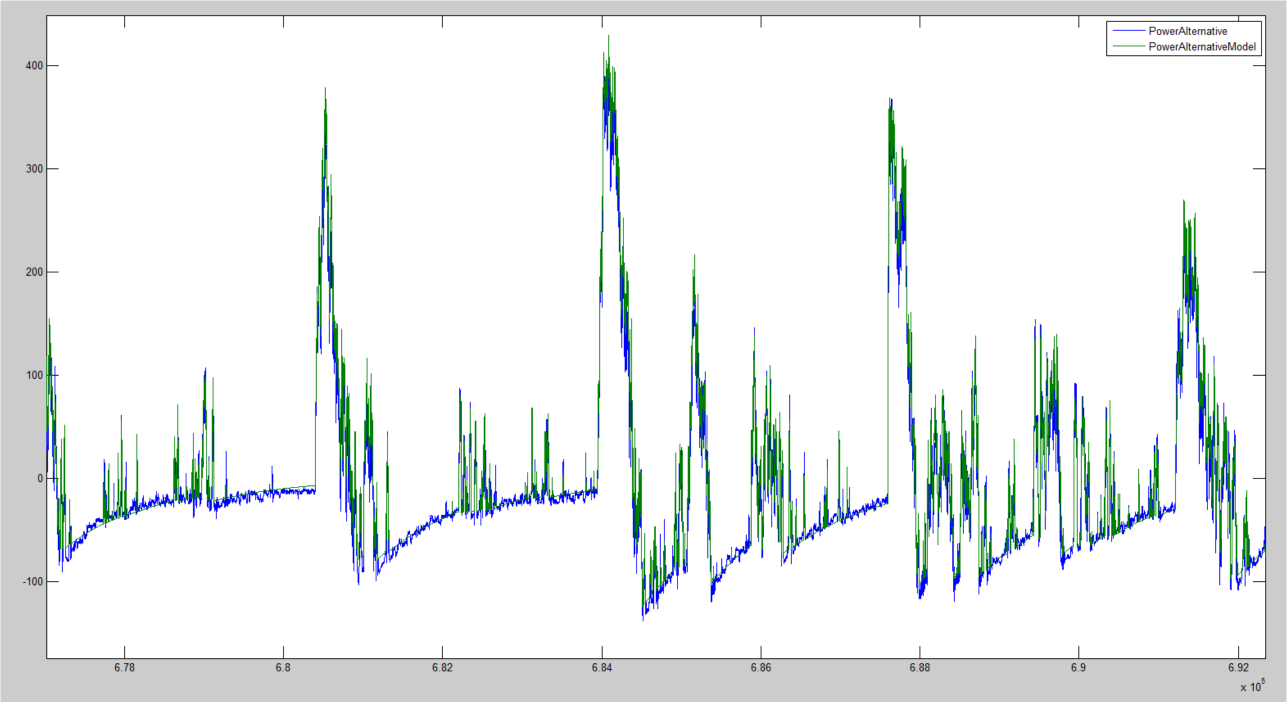


Figure 68: Comparison between modelling (green) and actual power (blue) in kW from the alternative primary regulation tests in Lem Kaer. The x-axis is time in seconds.

The SoC setpoint which was 100% in the modelling is set to 95% in the real tests. There are also small differences in the calculated and actual SoC. There is also a time delay for delivery due to data interpretation and the shift of power in the live test, even though the system reacts fast. The time delay is not included in the modelling. Still, the modelling and actual delivery has a relatively good match as seen in Figure 68.

	Average discharge power pr. Day [MWh]	Average charge power pr. Day [MWh]
Traditional primary reserve from Dec. 1st to Dec. 5th (5days)	0.2272	-0.4063
Alternative primary reserve Alternative Dec. 7th to Dec. 12th (5days)	0.3843	-0.5674

Table 39: Table with energy delivery and charge from traditional primary reserve and Alternative primary reserve during the actual tests.

During the tests in December 2016 the delivery during the alternative primary reserve is much higher than during the traditional primary regulation (70% higher). This large difference is to a large extent caused by the a different frequency distribution during the two different periods.

Conclusion of alternative primary reserve delivery

The system performed good and as expected with the new operating pattern, but the energy delivery and hereby associated additional cost is higher than during traditional primary reserve.

The overall expected additional energy delivery is expected to be 5-32% higher than during the traditional primary reserve. An estimated additional energy delivery based on the average of the most probable calculations is 20%. The BESS system is technically fully capable of delivering the alternative primary reserve regulation.

The cost for operating a battery energy storage system is largely dependent on the cost for electricity in order to compensate for the energy losses in the system and for tariffs and taxes. Economically the tested alternative primary reserve is not attractive for the operation of a BESS system for primary reserve. If the availability prices for primary reserve becomes larger in the future due to more fluctuating renewable energy, the operation will of course become more attractive.

Annex 3 Scale Battery Energy Storage System at DTI

Information about the Scale BESS system, and tests and results from the system can be found in this annex.

Annex 3.1 Initial thoughts and design process

The small scale Battery Energy Storage System (BESS) described in this document is designed to reflect the complexity of a larger BESS for example the system located at a wind farm in Lem Kaer, in the western part of Denmark which is also a part of this project.

Prior to the preparation of the requirement specification, a number of thoughts and ideas where discussed. Some of the desired system properties and functionalities are listed below.

- Complexity similar to a large scale system
- Same safety measures as a large scale system
- System assembled as a mobile unit
- High efficiency and low requirements for heating/cooling
- Opportunity to use the system with different battery packs
- Acquisition of a large amount of data; individual cell voltages, detailed monitoring of energy consumptions, temperatures etc
- Remote access to control functionalities and SMS error notifications
- Flexible interfacing to other systems, to accomplish a smarter grid
- Possibility to operate as primary reserve
- Flexible control in order to operate with different control strategies (manual control, frequency control, loadshift, voltage control, setpoints from file etc.)
- Operation based on a predefined sequence, as well as regulation based on local measurements

Furthermore, it was agreed on that reliable component suppliers willing to cooperate and offer support was of great importance. And that the availability of single battery cells for test purposes had to be considered, if a battery module was decided on.

Following the idea process a generic requirement specification for BESS systems as well as specific requirements for the scale system were developed, besides the system properties and functionalities listed above, the specific key requirements for the scale system were:

- Connectivity to 0.4 kV grid.
- Maximum power: 60 to 85 kW
- VAR support (ability to inject/absorb reactive power).
- Ability to deliver/absorb full power for minimum 15 min.

See the document, Procurement Specification for BESS Battery System, for a detailed description of general BESS requirements and safety measures to be considered.

Annex 3.2 System implementation

The implementation process began with a screening of the market, to map potential suppliers of major system components, like batteries BMS system, inverter, data loggers and heat pump. Parameters such as technical specifications, price, delivery time and the suppliers willingness to provide information and prices were considered. Subsequently, after pointing out the components and suppliers fitting our requirements, negotiations on prices, delivery times and terms were carried out.

Along with the negotiation process, the interfaces of all system components were analyzed to prepare the system integration process. As the ordered quantity of each component was small and delivery time was of the essence, it was not possible to dictate the communication interface and protocol of these components, meaning that a great number of communication methods had to be handled by the system controller, this includes 2 x CAN, 2 x Modbus RTU (RS485), 1 x Modbus TCP (Ethernet), 2 x RS232, a number of USB devices and a number of digital and analog inputs and outputs.

The specialty house made to contain the BESS system, is specially designed to allow separation of battery and inverter section, was produced in Hirtshals in the northern part of Denmark and the inverter and an electrical equipment cubicle was mounted in the house during the building process. All subsequent installations were done at DTI in Aarhus.

Annex 3.3 System description

This chapter briefly describes the grid to which the BESS is connected, and the major functional blocks.
The BESS is located at DTI in Aarhus and is connected to a 1 MVA 10/0.4 kVA transformer, along with a number of other energy producing and consuming systems as shown in Figure 69.

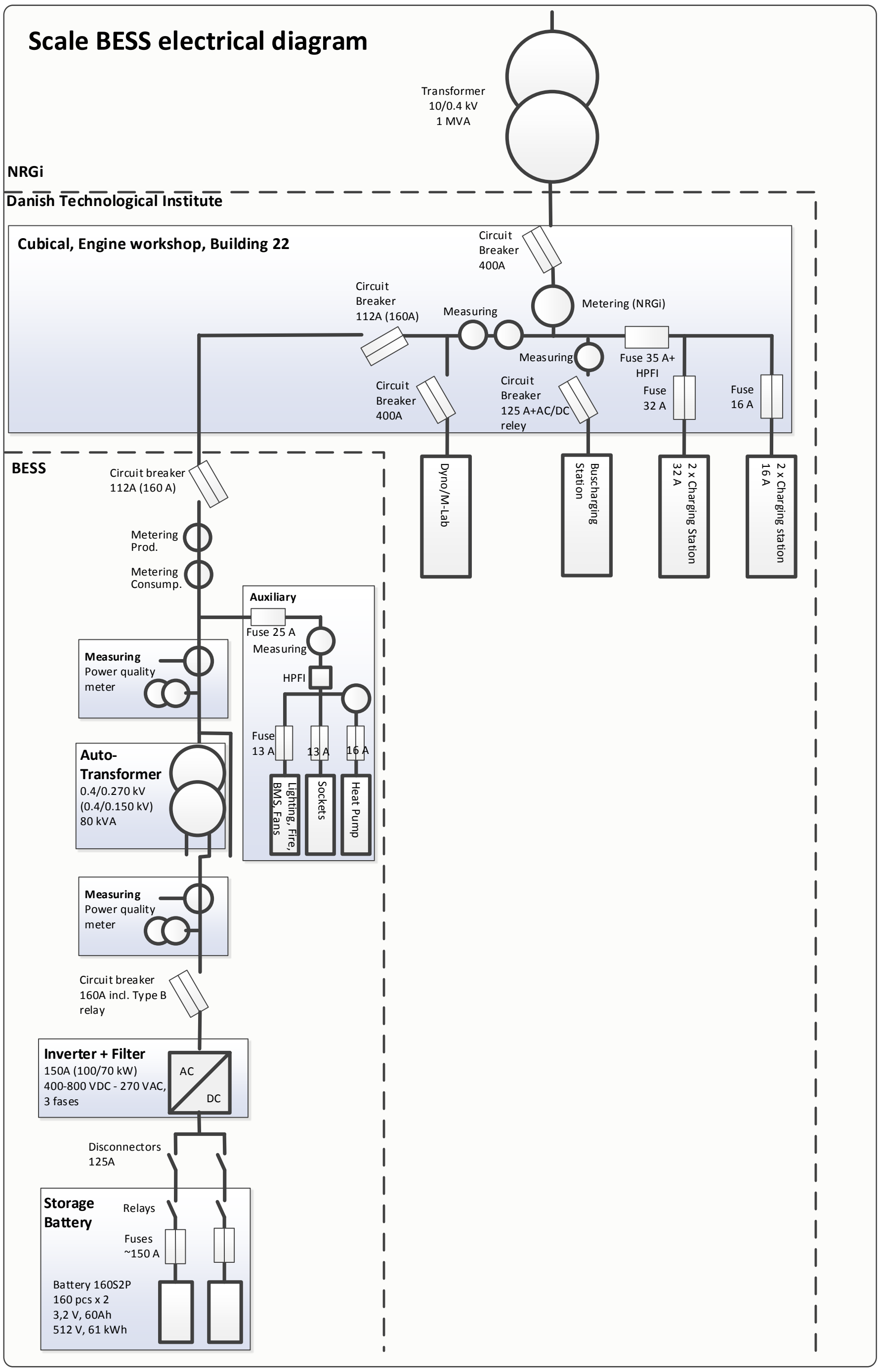


Figure 69: Single line connection diagram for major BESS components and external systems. The Scale BESS system is market with the perforated line in the lower left corner.

The implemented system is able to absorb and store energy of approximately 61 kWh from the electrical grid, as well as deliver the stored energy to the grid. The energy flow pattern can be altered using a number of different control algorithms implemented in the controller software. The BESS system includes two parallel battery strings, each consisting of 160 battery cells, with a rated capacity of 60 Ah, and a nominal cell voltage of 3.2 V. Hence, the nominal battery pack voltage is 512 V_{DC}. The energy flow between the battery pack and the grid is handled by a bi-directional inverter, which is connected to the grid at $400V_{AC}$ level through a transformer. The entire system is installed in an isolated movable lightweight specialty house, as shown below.

Figure 70: Picture of the installed Scale BESS system

The central components, ensuring the primary functionality, in the BESS are the battery pack, the bi-directional inverter, and the system controller. Furthermore, a number of auxiliary components are needed to manage heating/cooling, data acquisition and safety. Below the functionality of each functional block shown in Figure 69 is described, starting from the battery at the bottom and upwards.

Battery Pack and BMS system:
The battery pack, consisting of two parallel battery strings, functions as an energy reservoir. Having two strings adds complexity, but ensures redundancy in case of battery related defects, and gives the opportunity to test a single string at higher C-rates.
The BMS system ensures that all battery parameters are kept within the safe operation area. This is done by monitoring individual cell voltages, temperature for every 8 cells and the battery string currents. If needed the charging or discharging current will be reduced through a request sent to the system controller, which then lowers the inverter set point. Besides communication with the system controller, the BMS controls contactor relays which disconnects the battery from the inverter in case the current reduction through communication fails, and when the BESS is not in use. Furthermore, the BMS handles cell balancing.

DC Disconnectors:
Disconnectors are placed between each string and the inverter, these can be manually operated and will automatically disconnect the string if the string current exceeds 125 A. The Manual operation opportunity is intended for service and test purposes and is not operated during normal use.

Inverter/Filter:
The inverter is a redesigned version of a power quality filter, this means that besides the ability to act as a programmable bi-directional inverter, able to handle active and reactive power in both directions, it can function as a power quality filter as well if needed. The inverter, ABB PQFM-BESS, has been modified with an extra filter on the DC bus, in order to reduce the electromagnetic noise to an acceptable level.

Circuit breakers:
Circuit breakers are located between the inverter and the auto transformer and between the transformer and the point of connection. These breakers performs over current protection and can be manually operated for service purposes.

Auto Transformer:
Transforms the ac voltage level of 270 V_{AC} at the inverter side to the 400 V_{AC} grid voltage. The transformation ratio can be changed to achieve 150V_{AC} at the inverter side, hence the battery pack can be changed to a battery pack of lower voltage.

Power Quality Meter:
The power quality meter monitors multiple electrical parameters like frequency, voltages and currents, power, power factor, harmonics etc. all values are stored in a local HDD and relevant values are sent to the system controller for regulation and safety purposes as well as for data logging.

Metering:
The energy consumption as well as the energy delivered to the grid is monitored using energy meters. Furthermore, the energy consumed by auxiliary equipment in total is measured and a dedicated measurement is performed for the heat pump. Besides Energy information, the meters acquire actual power and power factor.

System Controller:
The system controller handles communication with BMS, inverter and a large number of peripheral units, and performs the system control according to the operating mode selected by the user. Depending on the selected mode, the control algorithm and its input parameters defines the current setpoint request sent to the inverter, based on a file of setpoint, a continues fixed input, the measured grid voltage or the measured grid frequency.
To allow maximum flexibility and uncomplicated implementation of GUI, remote access and, optionally in the future, communication with a number of controllers located remotely, the platform is an industrial PC and drivers and control software programmed using LabView. The software includes a driver for each type of system unit, which handles the communication with this particular unit. The sequential starting procedure for the system is implemented as a state machine and performs a number of checks during each step before it proceeds to the next step, for example correct precharging and connection of battery strings are required to proceed to starting the inverter. A number of safety checks and presence of communication heartbeats runs continuously and stops the system if critical errors are detected. A separate execution loop handles most of the task related to updating the GUI and critical input parameters from the GUI are handled as interrupts to ensure immediate system response. Similarly a dedicated loop handles the data logging.

Auxiliary:
The BESS installation includes a number of auxiliary units to support the primary system components, perform heating/cooling and lighting.
A heat pump that handles cooling/heating of the battery section. The inverter section is equipped with temperature controlled fans to handle thermal regulation. To ensure uninterrupted supply to the system controller, power quality analyser and BMS during power cuts, the BESS is equipped with a UPS (Uninterruptible Power Supply). Furthermore, the inverter and battery sections are equipped with individual LED lighting and and automatic fire extinguishing system which detects smoke and high temperature in the case of fire and extinguished the fire if possible using the advanced fluid Novec 1230.

Annex 3.4 Recorded data and results

Data from the Scale BESS system is recorded at a sampling rate of 1 sample/sec. Data recordings from november 2015 to december 2016 is recorded. However, design adjustments based on initial tests, as well as defects and ongoing software improvements have meant that the system has been out of operation for certain periods.
Different tests have been performed on the scale BESS system. The tests have been performed in order to evaluate the operation of the system and also to look at different possible operation patterns for battery systems in the electrical grid.

The following tests have been performed:

1. Preliminary: Functionality, Safety, data logging
2. Capacity measurements
3. Internal resistance measurements

4. Maximum power
5. Frequency regulation from recorded data (including temperature variation)
6. Accellerated frequency regulation pattern
7. Loadshift testpattern
8. Frequency regulation based on actual frequency measurement
9. Voltage regulation based on local voltage measurement

See results from the different tests in the following sections of this report.

The following test have been suggested and may be carried out on the system in the future.

1. Combination: Load and frequency regulation depending on prices
2. Voltage regulation based on recorded data
3. Peakshaving (local power limits)
4. Power factor regulation (local)
5. Power movement from phase to phase
6. Secondary reserve operation (automatic reserve/LFC based on power setpoint from TSO))
7. Virtuel Inertia (very fast regulation)
8. Islanding
9. Local blackstart

Annex 3.4.1 Preliminary tests

The system was tested in accordance with the developed BESS inspection guideline and procedure (see separate document on this). After revision of the system the intended tests were passed.

Annex 3.4.2 Capacity measurements

Capacity measurements have been done in order to determine if the battery system energy content was as high as expected, and in order to determine if there were any changes during the test period.
The capacity measurements were done with a current of 1/3C corresponding to 40A for the system during charging and discharging. The results can be see below in the degradation chapter.

Annex 3.4.3 Maximum power

The ability to deliver maximum Power for a period of 15 min, with a SoC starting point of 50%, has been tested.
As shown in Figure 71, the maximum discharge test was executed with the expected result, a battery current of 120 A and a power of 60 kW delivered to the grid.
During the initial testing of the system, it was capable of handling a charging current of 120 A. However the official Maximum test, performed after months of operation, revealed that the charging current was quickly derated, as shown in Figure 72, when a charging current of 120 A was requested. Further investigation showed that cell 157 in string 1 was causing this problem, as the voltage rise during charge was significantly higher for this particular cell, this can be seen in Figure 73. This cell must be replaced to re-establish optimum charging power. In its current condition, only approximately half of the rated charging current, 60 A, should be requested.

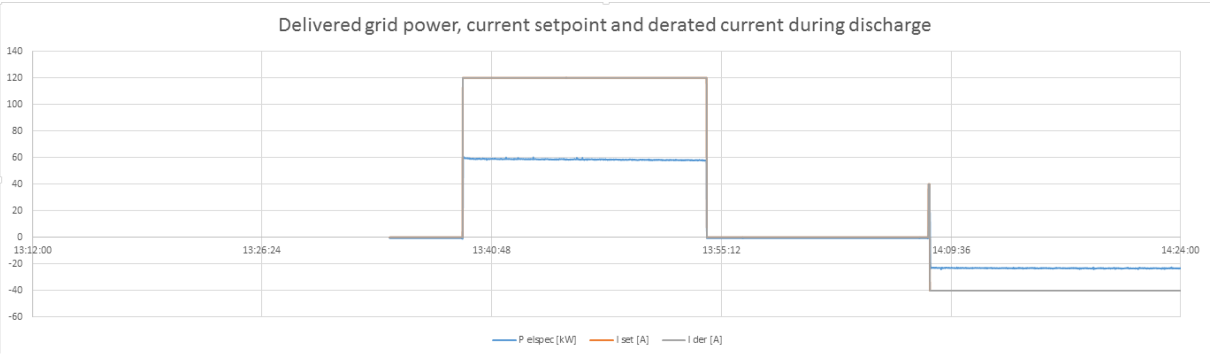


Figure 71: Chart showing maximum discharge for 15 minutes

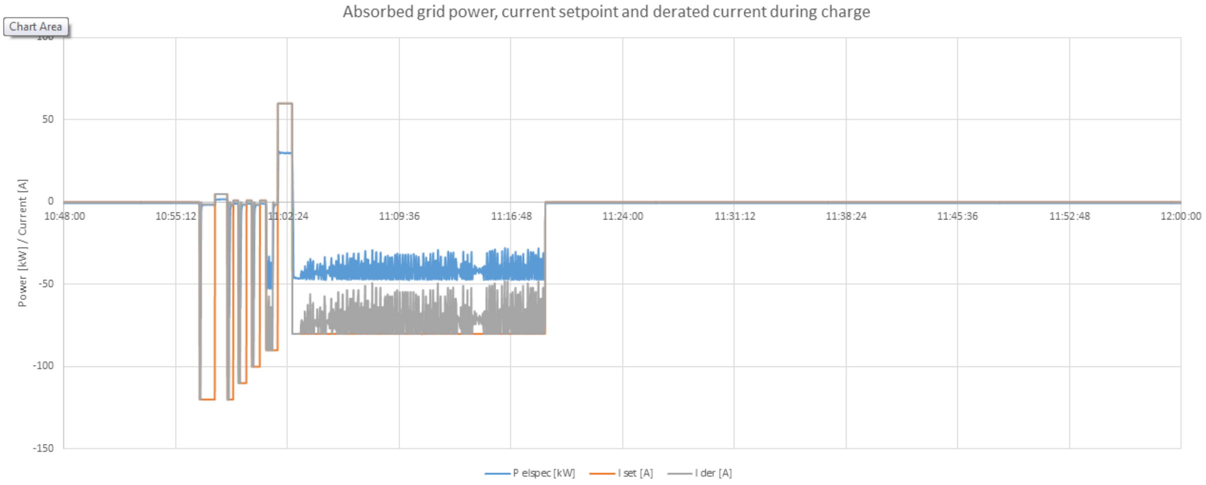


Figure 72: Chart showing immediate derating during maximum charge attempts

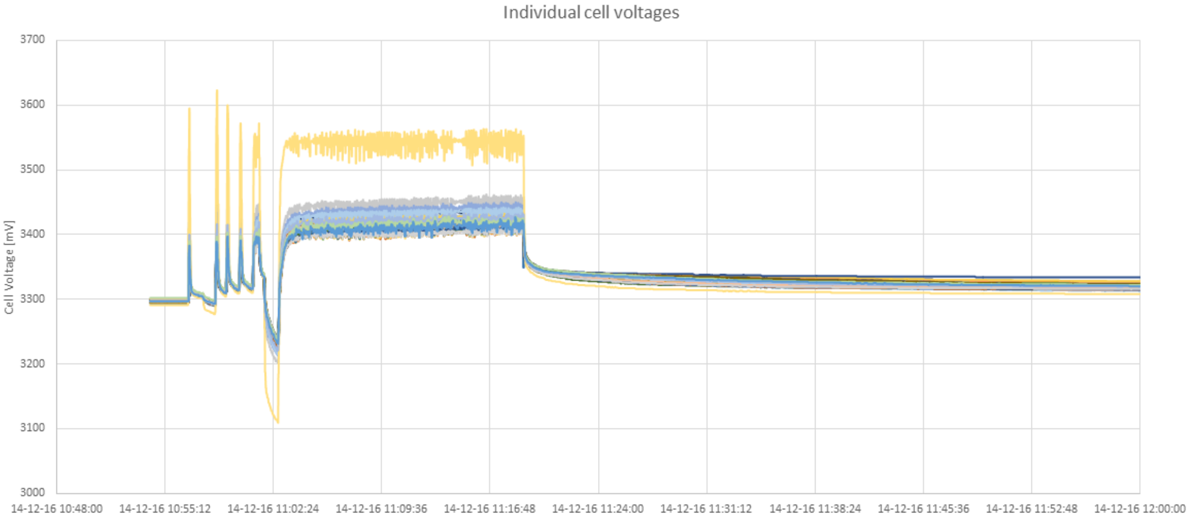


Figure 73: Individual cell voltages during charging

Annex 3.4.4 Frequency regulation from recorded data

Based on the available data from Lem Kaer, one specific day, which reflects the average, has been found. Data from this day is used as a setpoint file for the battery tests of the Scale BESS system.
The average day was found based on maximum, minimum, frequency distribution and average frequency. The day located was the 2013-11-09.

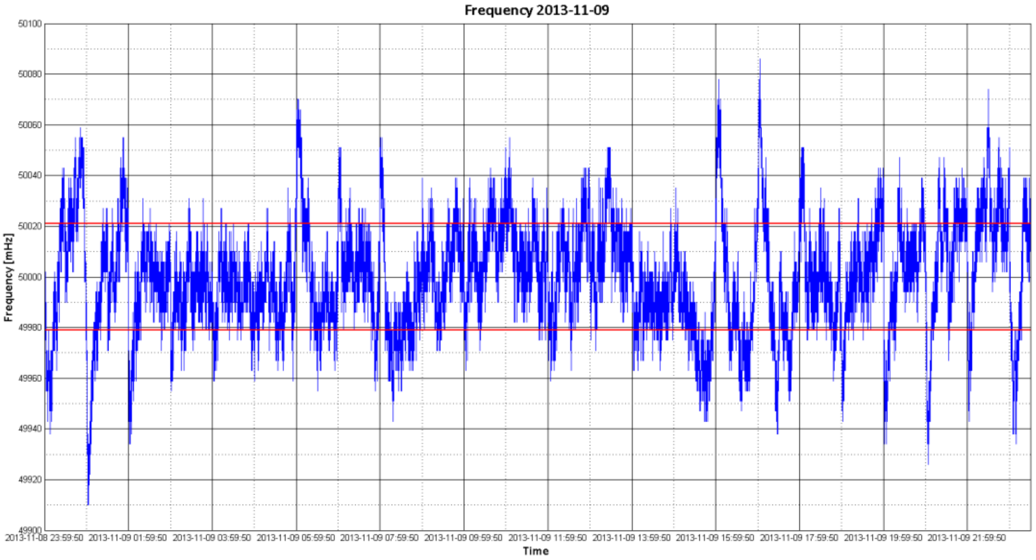


Figure 74: Chart shoving frequency measurements from average day

This pattern was transformed into a test pattern for the BESS system by scaling the frequency and power from the actual day, and converting it into a current setpoint file.
The test pattern looks as following.

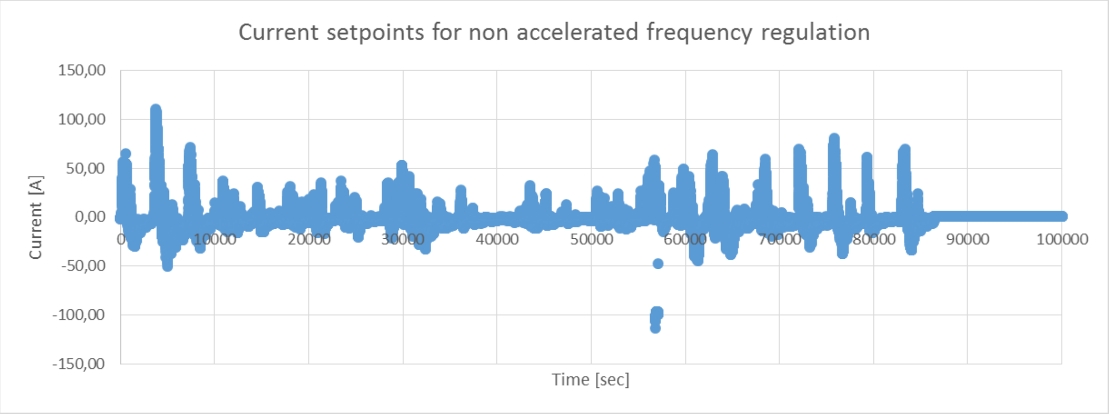


Figure 75: Setpoints for non-accelerated frequency regulation

Annex 3.4.5 Accelerated frequency regulation test

Data from the reference day was also converted into an accelerated frequency pattern. To accelerate the energy throughput and hence the degradation. The test pattern can be seen in Figure 76.

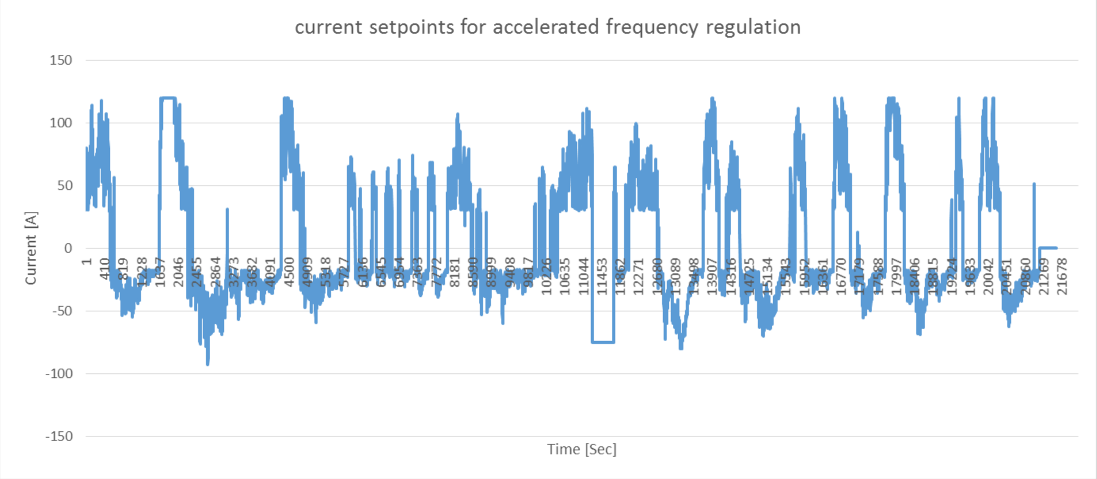


Figure 76: Current setpoints for accelerated frequency regulation. The total duration of the accelerated file is 6 hours.

Annex 3.4.6 Load shift test

A load shift test was conducted based on an optimal income analysis buying electricity when prices are low and selling, when prices are high. See also document on income from Energy Denmark on this issue.
The requested load pattern looks as following:

Figure 77: Graph of load shift test pattern. Positive setpoint calls for deliver for one hour, while negative calls for consumption for one hour. The pattern runs for 4 days (96 hours).

The Scale BESS system was set to operate between 5 and 95% SoC, and the current was set to 102 A when delivering and 103 A, when consuming energy.
The high currents with rather long duration causes problems. As can be seen in the chart below, the first discharging period is executed as expected, however the magnitude of the cell voltage rise causes the system to stop prematurely, meaning that the battery is only charged to approximately 20% SoC. Hence, the subsequent discharging duration is reduced accordingly. The problem is caused by high internal resistance in a specific cell, the problem was further investigated during the maximum power sequence, see section 4. Maximum power. Note that the initial charging at 60 A do not cause problems.

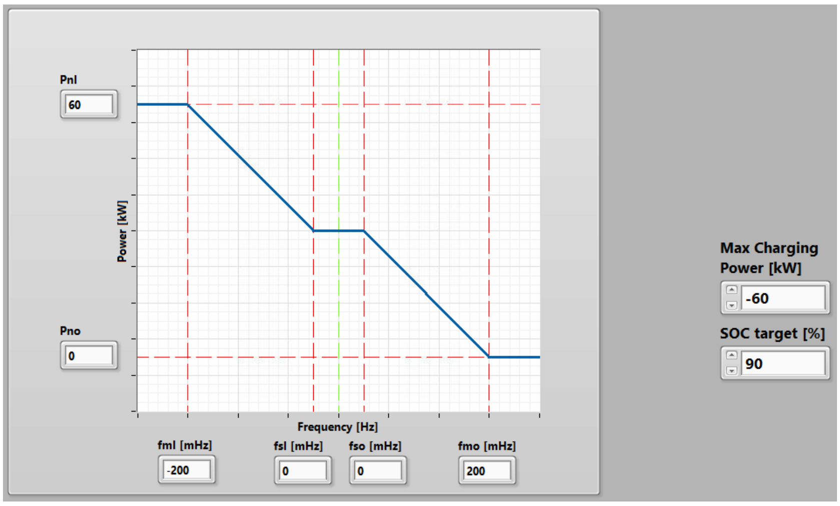
Figure 78: Chart showing problem caused by high voltage rise during charging at high C rate

The theoretic energy delivered from the system was approx. 320*60Ah*3,2V/1000*(0,95-0,05)=55 kWh per cycle.
As described above, the charged energy during the loadshift test was limited due to one week battery cell, hence the usable energy content was a lot less than expected.

In order to operate as a load shift unit with full delivery and full charge during one hour, the battery with the high internal resistance has to be exchanged.

Annex 3.4.7 Frequency regulation based on frequency measurement

A control algorithm applying power based on the actual frequency deviation has been implemented and tested according to primary reserve regulation. The implementation is prepared to allow adjustment of nominal power, and deadband for both up- and down regulation, however during the executed test the configuration was setup to only perform upregulation as this is the most economic attractive regulation. A charging algorithm that runs continuously in parallel with the frequency dependent algoritm has been implemented, to ensure that the applied charging power is proportional to the SoC deviation from target SoC. The user defined inputs for these algorithms can be seen in Figure 79.



Pnl 60
Pno 0
fml [mHz] -200
fsl [mHz] 0
fso [mHz] 0
fmo [mHz] 200
Max Charging Power [kW] -60
SOC target [%] 90

Figure 79: User defined parameters for frequency and charging regulation. Pnl (Power Nominal Levering(delivery)), Pno(Power Nominel Optag(consumption)), fsl (frequency deadband delivery), fso(frequency deadband consumption, fml and fmo is deviation at full power.

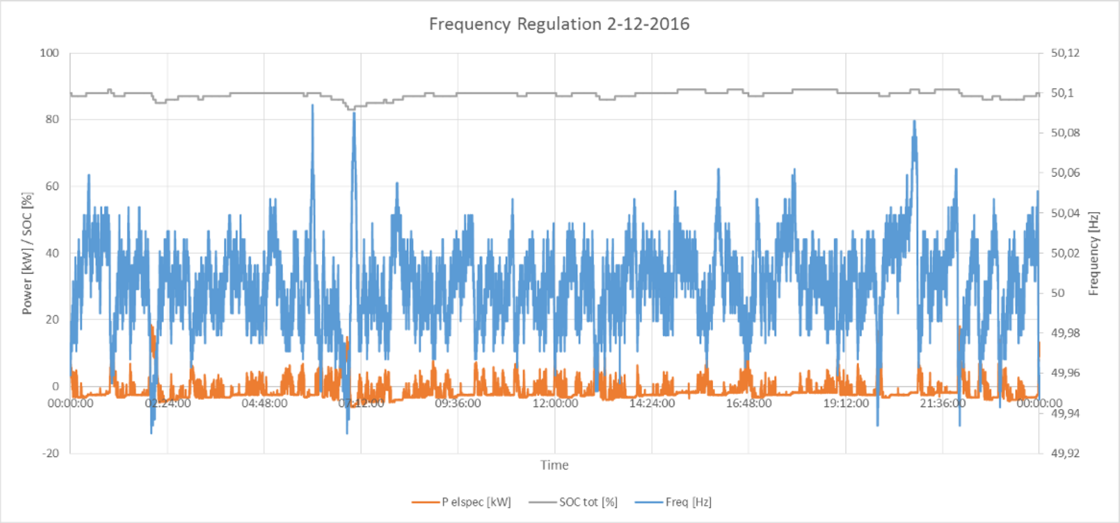


Figure 80: Graph from test of frequency regulation

Annex 3.4.8 Voltage regulation based on local voltage measurement

Tests was performed with voltage regulation based on the local voltage measurement in the scale BESS system. The regulation is performed based on the local grid voltage measurement. When the voltage is outside the deadband the power is delivered starting from 50% of $P_{nominel}$ and linearly increased to $P_{nominal}$ as the deviation increases.

The position of the system close to a 10/0.4 kV transformer and the overall grid, and typically low consumption on this transformer makes the test location unsuitable. Therefore, the tests were mainly conducted to see if the regulation worked. The limits during voltage regulation had to be reduced from the standard deviation of maximum 10% (40 V) and start at 5% (20 V) to 20 V and 5 V deviation from the nominal RMS value of 400 V. The change in regulation parameters was done during the test on the 7. of December, see Figure 81. It can be concluded that the direct change from a voltage regulation above 405 V to a charging algorithm when below 405 V, causes power oscillations when the grid voltage fluctuates near the threshold voltage. This can be avoided with introduction of a delay in the switching.

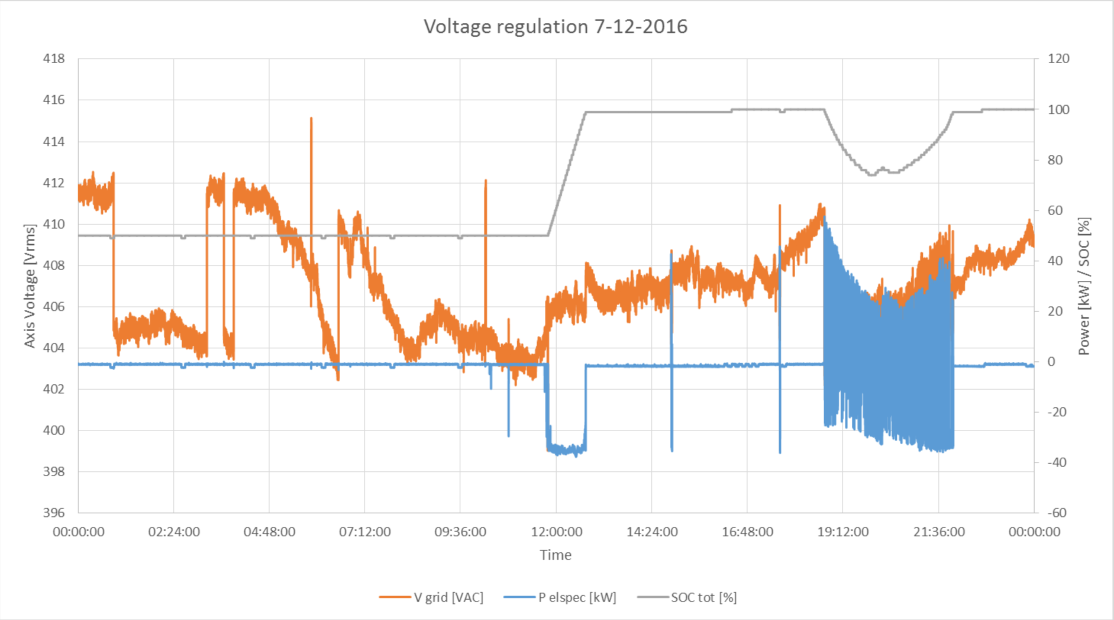


Figure 81: Illustration from voltage regulation test. The RMS voltage of the 400 V grid is shown together with system power and SoC for the battery system

Annex 3.5 Degradation of the Scale BESS system

It has not been possible to perform detailed degradation of the scale BESS system due to the reduced timespan and the other tests conducted.

The tests of load shift and maximum power has however illustrated how important cell balancing and well matched cells are, since the usable energy capacity depends very much on this. This was mainly seen during load shift pattern and extreme tests due to the higher currents and large SoC span.

The total amount of energy delivered from the scale BESS system is approximately 8500 kWh, equivalent to approximately 138 full cycles.

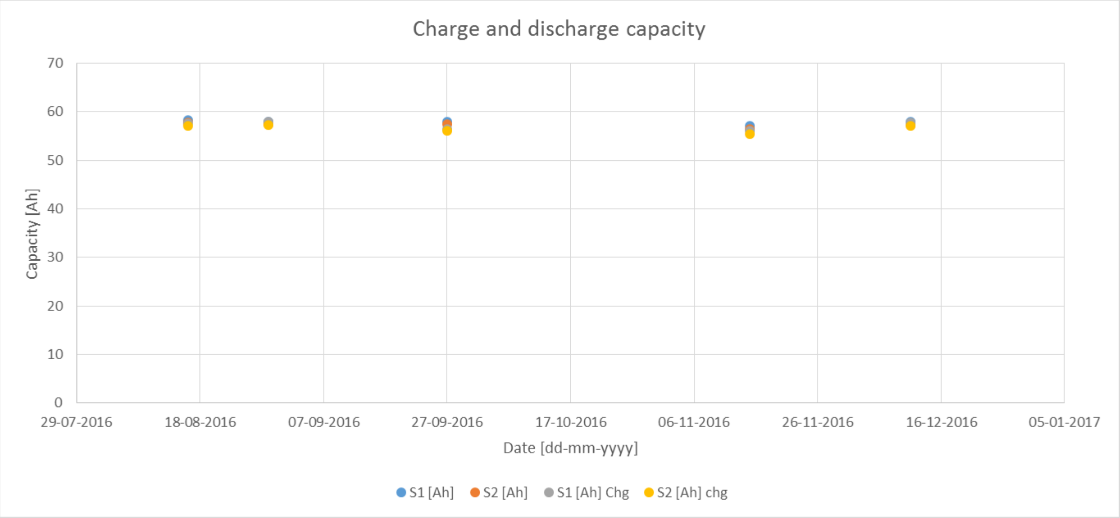


Figure 82: Charge and discharge capacity for each of the two strings in the Scale BESS system

The time period and energy throughput thru the Scale BESS system is too low to detect an overall degradation. The average discharge capacity of each the battery strings is 57,6 Ah. The nominal capacity of each battery is 60A. 96% of the nominal Ah-capacity can be used in the system.
For more knowledge about degradation, see the separate degradation report on single cell tests.

Annex 3.5.1 Internal resistance measurement

Current pulses were implemented as part of the standard capacity test sequence to allow subsequent calculation of the internal resistance of the batteries. Starting from a SoC of 0% a charging pulse of 120 A (1C) is applied followed by an idle period with 0 A, hereafter charging and discharging pulses of 120 A are applied for each 25% change in SoC (45min. charging at 40 A).
The pulses were reduced in some of the positive current tests due to one weak battery cell cells reaching maximum voltage. For optimizing the system, this cell needs to be changed, but it illustrates well the difference between using and testing battery systems compared to testing single cells.

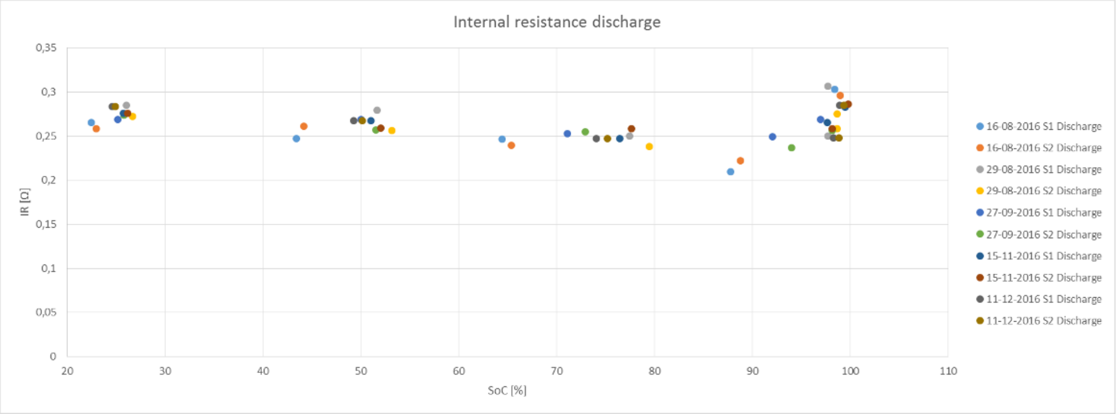


Figure 83: Battery string resistance during discharge at different State of charge. Negative pulses of 1C (120 A)

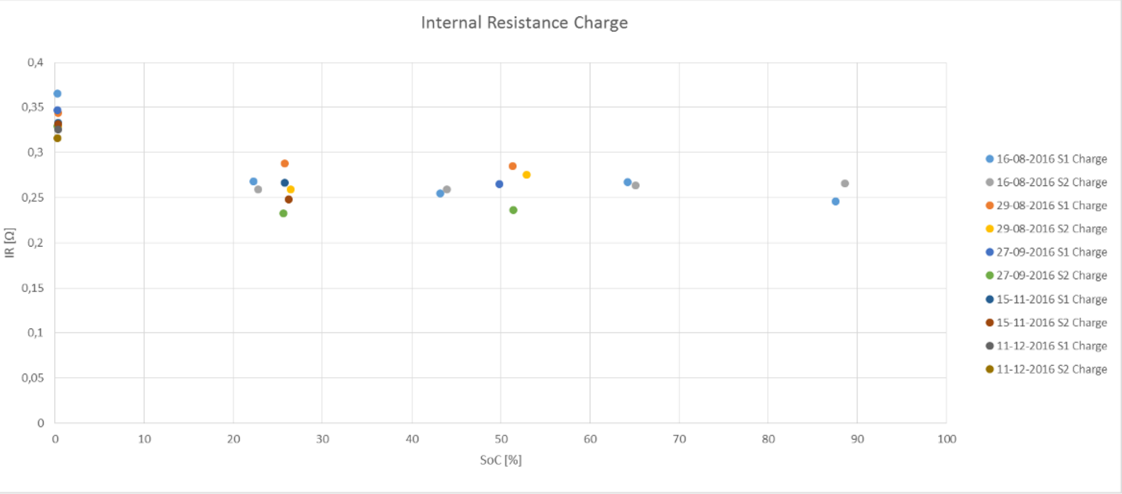


Figure 84: Battery string resistance during charge at different SoC. Positive pulses of 1C (120 A)

The internal resistance generally becomes lower at higher SoC except for close to maximum SoC. The average measured resistance per string is 272 mΩ.
The nominal internal resistance of the cells is ≤ 1mΩ, which makes up a total cell resistance of ≤160*1mΩ= 160 mΩ. The measured resistance is up to double that of the nominal internal resistance of the cells. This is due to resistance in cabling, interconnections and breakers. Some of the resistance uncertainties are also related to the different ways of determining this in terms of different duration of the applied step load.
A problematic cell which has the higher resistance and reduces the maximum charge current of the system has an internal resistance of 5 mΩ.

An average increase or decrease of the internal resistance due to degradation of the cells has not been possible since the operation time has not been long enough. For information about this see the separate BESS degradation report on single cells.

Annex 3.5.2 Efficiency of scale BESS system

The efficiency of the scale BESS system is determined during different load patterns.
The peak efficiency is determined for a test of approximately 6 hours with 1/3 C charge and discharge. The other calculations has been done for a full day. The initial cycles were done with 1/3C charge and discharge and equalization and one cycle per day. The accelerated day is performed using an accelerated test pattern based on primary regulation for the average day. The average day is accelerated with a factor of 4 in time, making it possible to do the equivalent of 4 days in one single day.

	Delivered energy [kWh]	Consumed energy [kWh]	η System [%]	η Ex. Aux. [%]	η Battery [%]
Peak (1/3 C)	53,3	66,3	80,3	85,3	98,2
Init cycles 1/3C	54,2	95,6	56,8	66,5	93,9
Accelerated Avg. Day	201,9	263,6	76,3	82,6	96,3
Avg. Day	34,3	75,9	45,2	56,4	95,9

Table 40: Table with energy delivered and consumed, efficiency of complete system with and without auxiliary consumption and for batteries only during different test patterns.

Generally the system efficiency gets higher the more energy throughput. This is caused by many of the losses and auxiliary consumption being more or less independent of system load.
The efficiency of the batteries has an average value of 96%, so for optimizing the efficiency of the system the focus has to be on auxiliary and power conversion losses.
During the primary reserve average day test pattern the efficiency of the batteries are approximately 96% and the system efficiency is reduced to less than half of that at 45%. The total efficiency ranges from above 80% to 45% in the low load of the normal average day pattern.
The losses in energy convertion and consumption for auxiliary components is very important when the system is operated at low loads.

Annex 3.5.3 Auxiliary consumption

The variation of auxilary consumption has been tested with different temperatures of the battery room in the system.

	System η [%]	E Aux [kWh]	E Heat Pump [kWh]	Avg. inside temperature [°C]	Avg. Outside temperature [°C]	Delta T [°C]
Avg. Day (31°C)	44.9	19.2	6.4	33.6	15.5	18.1
Avg. Day (25°C, auto)	45.2	13.8	1.4	28.0	13.2	14.8
Avg. Day (18°C)	50.5	10.1	1.6	20.1	10.0	10.1
Avg. Day (off)	*49.0*	*9.0*	*0.0*	17.8	7.8	10.0

Table 41: Efficiency of complete system, and energy used on auxiliary and heat pump and average inside outside and temperature difference. Tests have been performed with the same test pattern but different settings of the thermal control system.

At the temperature setpoint of 18°C, the heating and cooling unit has periods when the air is heated and other periods where the air is cooled. The average inside temperature during a rather cold becomes approximately 18°C. The temperature of the batteries is a few degrees higher since they are used.
The temperature tests show that the auxiliary consumption for the heating and cooling unit can be reduced with approximately 1.5 kWh per day with the days analyzed without additional degradation or damage to

the batteries compared to 25 °C. The total auxiliary consumption can be reduced with approximately 4 kWh. The higher consumption for auxiliary at higher temperatures room temperatures is caused both by the heat pump but also the 60 blowers that sucks air thru the 20 battery compartments, which is controlled depending on the temperature in the smaller battery compartments. The batteryblowers can have a total consumption of up to 60*3W*24h=4.3 kWh/day. The temperature control can be better optimized in order to reduce energy consumption, but still taking degradation at higher temperatures into consideration.

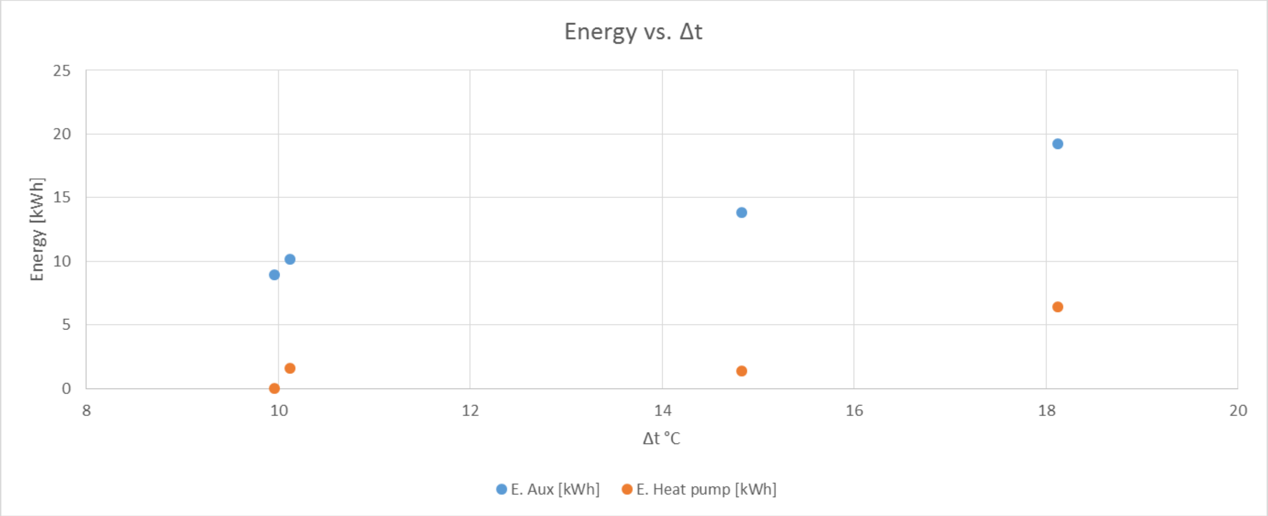


Figure 85: Energy consumption for heat pump and auxiliary during the temperature tests.

Additional tests performed for longer periods of time and during hot summer days would have had great value.

In Figure 85, the energy consumption at different temperature differences between inside and outside can be seen graphically. The energy consumption is also dependent on the internal temperature due to the battery blowers being dependent on these.

Annex 3.6 Overall system and operating experience from the Scale BESS system

There has been different system errors, lack of documentation on delivered units etc. in the Scale BESS battery system during the project period. These are listed below.

- Electrical noise on the DC bus causing data communication errors.
- PE ground current triggering type-B relay
- Faulty battery FanHeatpump/aircondition control errors
- Defective LAN interface on system controller
- Necessity to alter control software
- Lack of expanded manual for inverter
- False triggering of the error relay on the fire extinguishing system

A few battery single cells, which had a lower capacity than the rest has been switched.

Overall the task of integrating battery pack, BMS system, control systems etc. has been a challenge which has taken much effort and time.

Annex 3.6.1 Balancing of cells

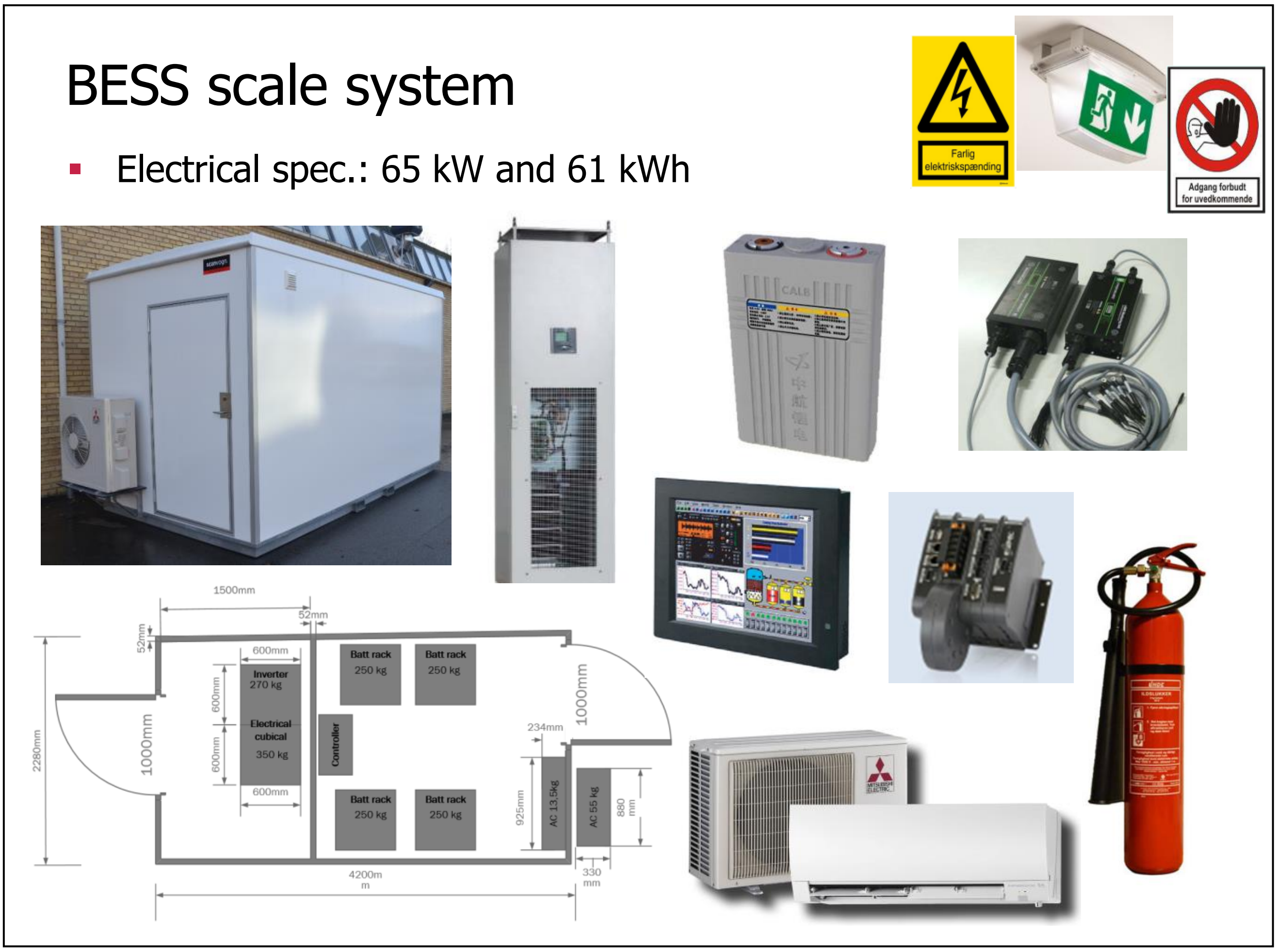
Cell to cell unbalance occurs due to differences in cell characteristics. The battery cells used for the Scale BESS system are not all from the same batch, due to too long delivery times. Hence, the Scale BESS system may have an increased need for balancing compared to a battery pack containing perfectly matched cells. The balancing can be done in a number of ways, but the overall goal is to equalize the SoC/Voltage, so that the available capacity of the battery pack is maximized. The most energy efficient way to perform balancing is through active balancing, where energy is transferred from cells with too high SoC to cells with too low SoC. Another method is passive balancing, where excessive energy of high SoC cells is dissipated in a power resistor or semiconductor. The algorithm to control which cells needs balancing can be based on the measured cell voltages or on individual SoC history. Often the balancing is performed as passive balancing based on a voltage algorithm applied at high SoC, this is also the case for the BMS installed in the Scale BESS system. This method is simple but requires that the use pattern of the BESS includes occasional full charges, and that the battery is left in charging mode long enough to allow the balancing to take place. The balancing of the battery strings in the Scale BESS system is handled entirely by the BMS, this means that it is up to the user to ensure that the SoC is regularly increased to a level where the balancing is applied. An improvement to the current configuration would be to let the system controller influence on the balancing threshold, to ensure that balancing occurs at the target SoC configured in the system controller software. Furthermore, another great improvement to the balancing system would be to upgrade the BMS, so that the balancing algorithm is performed based on all individual cell voltages within the string and not, as it is the case now, only based on the neighbour cells within the same BMS slave (8 cells per LMU(Local Monitoring Unit)). This would furthermore decrease the balancing time, as the settings are currently set to allow a very small cell to cell voltage deviation as a workaround for the lack of an algorithm taking all cell voltages into account, this workaround means that the PCB (Printed Circuit Board) temperatures of the BMS slaves occasionally rises to a level where the BMS slave disables the balancing circuit and the BMS master requests the charging current to be further reduced.

Annex 3.7 Part conclusion for the Scale BESS system

The efficiency of the batteries in the system is high at approximately 96%. On the contrary, the system is low, especially when operated as frequency control, due to losses in inverters and transformers and due to consumption of auxiliary components.

This calls for the necessity of looking at and optimizing part load operation and also thermal control for optimization of BESS systems. This has to be taken into account when buying or using battery systems.

Much focus with regards to BESS systems is on the batteries. The experience from this project is that other system components and general system integration and interaction between system components are equally important in order to secure the up-time of the entire system. Also the price of the system is much influenced by other components than batteries. The battery price is approximately 15% of the designed Scale BESS system.



BESS scale system

- Electrical spec.: 65 kW and 61 kWh

Figure 87: Picture of 1 battery string and control boxes installed in specialty House.

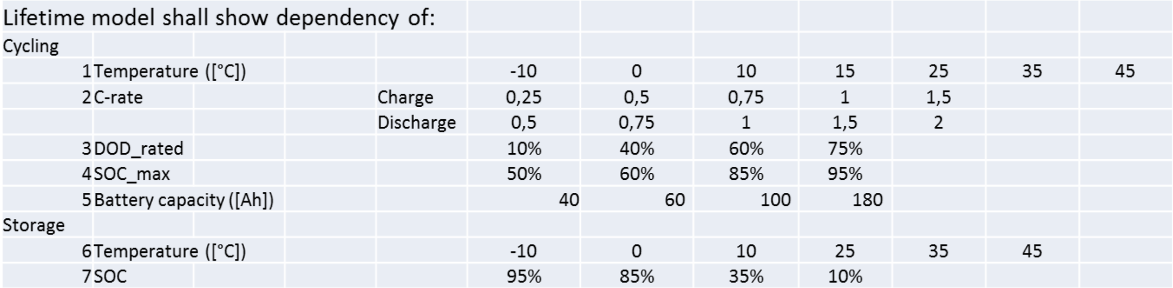
Figure 88: Picture of inverter and electric cubical incl. transformer installed in the specialty house.

Annex 4 Degradation test of single cell batteries

The test setup, procedures and results from the degradation tests on single cells can be found in this annex.

Annex 4.1 Degradation test

There has been made a test matrix for cell tests with tests of cycling and storage in order to estimate lifetime with different use patterns and temperatures in a BESS system. The tests include 45 cells in total and the tests will take place over aprx. 2 years in the battery lab at DTI. A brief overview of the different parameter variations is shown in table 1 below.



Lifetime model shall show dependency of:										
Cycling										
	1	Temperature ([°C])		-10	0	10	15	25	35	45
	2	C-rate	Charge	0,25	0,5	0,75	1	1,5		
			Discharge	0,5	0,75	1	1,5	2		
	3	DOD_rated		10%	40%	60%	75%			
	4	SOC_max		50%	60%	85%	95%			
	5	Battery capacity ([Ah])		40	60	100	180			
Storage										
	6	Temperature ([°C])		-10	0	10	25	35	45	
	7	SOC		95%	85%	35%	10%			

Table 1: Overview of different test parameters in single cell tests. C-rate= ratio between current ([A]) and battery capacity ([Ah]). Dod=Depth of Discharge, SoC=State of Charge. Tests has also been done with an accelerated primary reserve load pattern and with 100% DoD cycles for comparison with datasheet.

Initial tests on battery pack and cells have been done. See example of temperature distribution on cell in Figure 89 and test of battery stack setup in Figure 90. These tests were performed in order to evaluate how to stack and manage temperatures of the cells both when stacked and during single cell tests.

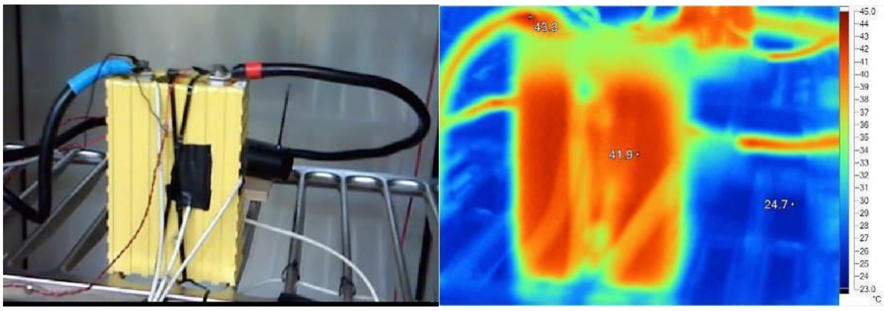


Figure 89: Temperature distribution on battery cell

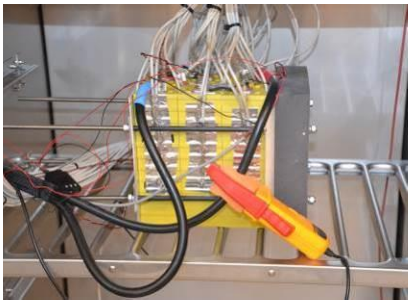


Figure 90: Cell Pack test in climate clamber

The cells to be used for single cell tests can be seen in Figure 91 during the first full charge before they are made ready for climate tests.

Figure 91: Initial charge of 40Ah Lithium-Ion cells for single cell degradation tests

The received cells for single cell tests varied some in voltage upon arrival..
After initial charge to 3.65 V and rest for 24 hours, the voltage of 3 cells differs from the rest of the cells, which can be seen in Figure 92. These cells are not used for the battery tests.

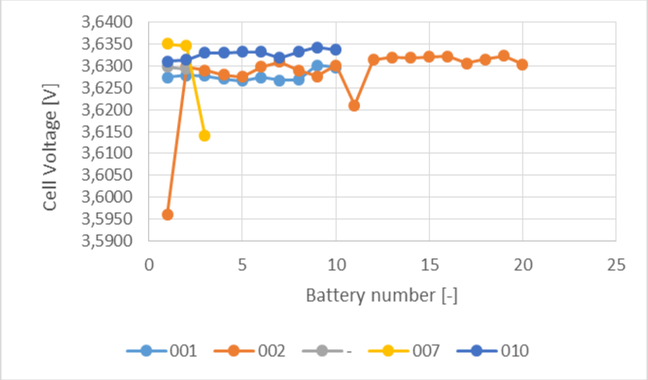


Figure 92: Cell voltages 24 hours after charge to 3.65 V

Figure 93: Pictures of some of the battery cells during test in test chamber

Lithium-ion batteries are electro-chemical devices, and apart from the intended chemical reactions some unintended side reactions takes place as a result of the battery cell design. Side reactions as for instance: electrode passivation layer formation, lithium plating, electrolyte decomposition and binder decomposition may all occur during normal use of the battery cell, thus degrading the cell by decreasing the cell capacity and increasing the internal impedance of the cell. This degradation, which is also called aging, depends on usage pattern, the environmental conditions at which the battery cell is used and the battery cell design. A lithium-ion battery cell degrades whether in operation (charge & discharge action) or not (storage).
So, when a battery cell type is chosen, it is desirable know how to operate it in a way which yields a long life of the battery pack and therefore the best pay back of the investment made. Especially when investing in large batteries like in a BESS system. Many battery cell specifications indicates an expected lifetime at

temperature=25°C, Charge rate=1C, Discharge rate=1C and 100% DoD. This information is far from enough to determine the optimum operation conditions, and if the desired lifetime information cannot be provided by the battery supplier, a degradation test or lifetime test must be performed.

A comprehensive lifetime test is performed in the BESS project and the results are given in the sections below.

Usually, the lifetime is stated as the number of cycles, which can be performed before the remaining capacity has dropped to 80% of the initial capacity, but the lifetime could be defined as any capacity loss depending on the battery application. In this report, a capacity loss of 20% is applied to define the battery lifetime for the purpose of comparison.

Annex 4.1.1 Overall test matrix

The test comprised cell aging at cycling (operation = charge or discharge) and at storage (no operation) condition. Hence, a test matrix for both conditions is shown in Table 42 and Table 43 below. The matrix is based on literature studies and DTI experience suggesting that the capacity loss at cycling due to aging is a function of Ah-throughput or equivalent cycles. This function is influenced by the stress factors listed below:

- Temperature
- Charge rate
- Discharge rate
- DoD (Depth of discharge)
- SoC (State of charge)

In addition the impact of the following parameters are tested:

- 100% DoD from 100% SoC at 1C charge and 1C discharge rate (Test as shown in Datasheet)
- Cell capacity
- Dynamic load pattern from primary reserve operation

Cycle test matrix					
Test focus	Temperature	C-Rate chg	C-Rate dis	DOD_rated	SOC_max
Temperatur	45	**0,5**	**1**	**50%**	**75%**
	35				
	25				
	10				
	0				
	-10				
C-rate	25	0,25	1	50%	75%
		0,75			
		1			
		1,5			
		0,5	0,5		
			0,75		
			1,5		
			2		
	10	0,25	1		
		0,75			
		1			
		1,5			
DoD	25	0,5	1	10%	75%
				40%	
				60%	
				75%	
SoC	25	0,5	1	50%	50%
					60%
					85%
					95%
Datasheet	25	0,5	1	100%	100%
60Ah cell	25	0,5	1	50%	75%
100Ah cell	25	0,5	1	50%	75%
180Ah cell	25	0,5	1	50%	75%
Load pattern	25	Max. 1C	Max. 1C	N/A	N/A

Table 42: Test matrix for cycling test. Temperature is the temperature in the test chamber. C-rate chg. is the charge rate (charge current). C-rate dis. is the discharge rate (discharge current). DoD_rated is the depth of discharge in percentage of nominal capacity. SoC_max is the maximum state of charge in percentage of nominal capacity from where the tests are performed.

The nominal capacity of the tested cells is 40 Ah and thus DoD_rated=50% and SoC_Max=75% means that the cell is charged with 30 Ah from fully discharged to reach 75% SoC. Then the cell is discharged with 20Ah and afterwards cycled between 25% SoC and 75% SoC.

The settings near the top of Table 42 marked in bold (25°C, Chg-rate = 0.5C, Dis rate = 1C, DoD rated = 50%, SoC max = 75%) is the reference cell, which is tested at reference conditions. The matrix is designed to keep all stress factors constant and equal to the reference except from the stress factor, which is tested, so when testing SoC the stress factors: Temperature, Charge rate, Discharge rate and DoD-rated is kept constant and equal to the reference, whereas SoC_ max is altered between 50% SoC and 95% SoC.

The reference settings is selected on the basis of the cell type chosen for the tests and possible operation patterns for stationary batteries on the electrical grid. In addition the test results from the reference cell will be applied as reference in the battery degradation model presented later.

Rather than testing redundant cells, the test matrix is designed with “additional” points for each parameter in order to make it robust. Discharge rate for instance has four points to characterize this parameter, and five point when the reference point is added. If one of these cells fail during test or show a strange behaviour, there is still four points left for characterization.

Storage test matrix		
Test focus	Temperatur	SOC
Temperature	45	70%
	35	
	25	
	10	
	0	
	-10	
SoC	45	95%
		85%
		35%
		10%
	25	95%
		85%
		35%
		10%

Table 43: Test matrix for storage test

Annex 4.2 Test description

The cells for test are 40 Ah prismatic lithium iron phosphate cells from CALB. Before test the cells are mounted in a test fixture as shown in Figure 94. The fixture makes an easy connection to the cell and the temperature sensor, and prevent the cell from swelling in case of gas development.

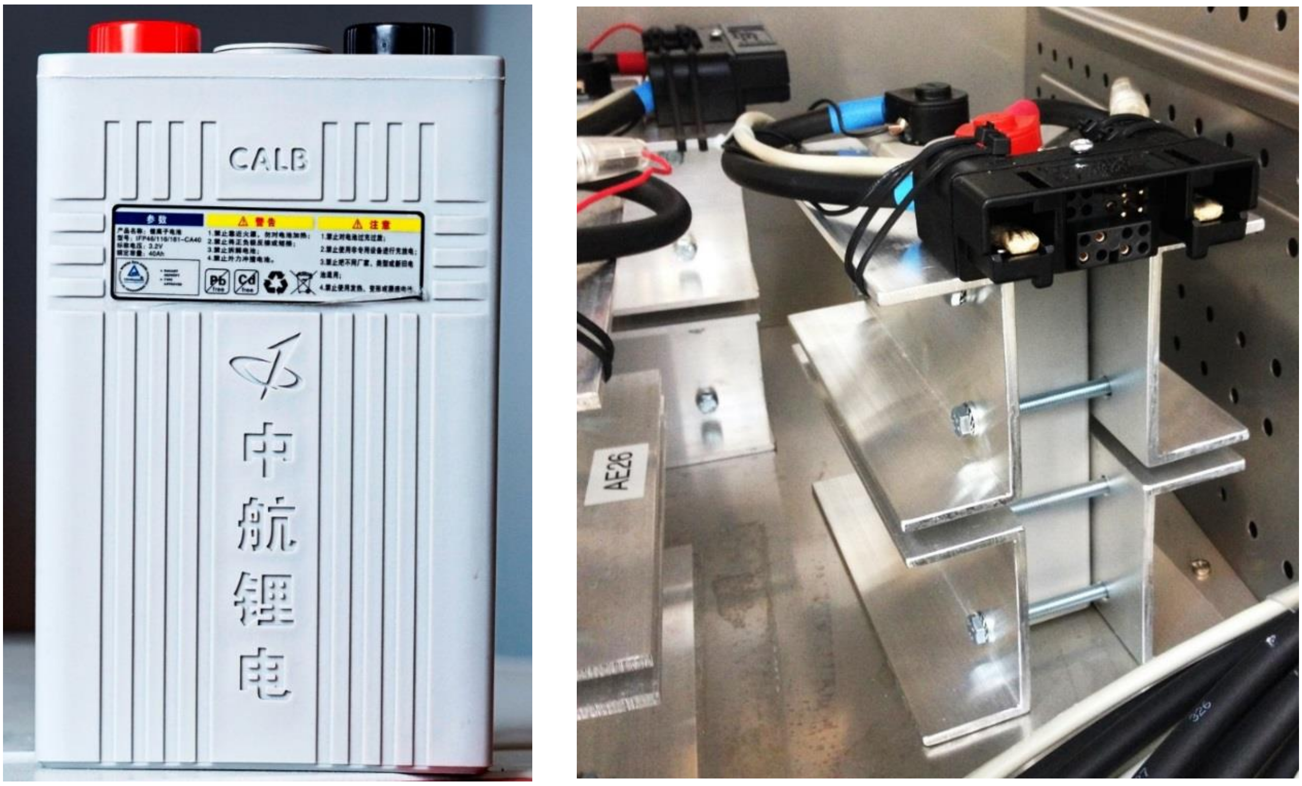


Figure 94: CALB cell and test fixture

Constant ambient temperatures are provided by five Binder chambers with forced airflow. The heart of the test setup is a battery test system, which is a Maccor 4000 test system as shown in Figure 95. For each cell, a program is written in order to perform each specific test.

Figure 95: Binder chambers and Maccor 4000 Battery tester in the background

Annex 4.2.1 Test protocol

The overall test procedure is as follows

7. Performance test
8. Initialization
9. Performance test
10. Cycle / storage test
11. Performance test
12. Repeat item 4 and 5 until end of test

Annex 4.2.2 Performance test

The performance test characterizes the cell by measuring capacity and internal resistance at 25°C.

1. Discharge at 1C to low voltage limit
2. Rest
3. Charge at 0,5C to I = C_{20} at high voltage limit
4. Rest
5. Discharge at 1C to low voltage limit
6. Rest
7. 2C pulse test at every 10% charge step
8. Rest
9. 2C pulse test at every 10% discharge step
10. Rest
11. Charge to 10% SoC for cycling cells and specified SoC for storage cells

Annex 4.2.3 Initialization

Initialization is performed in order to “kick start” the cell after storage for some time. It is well known that during the first cycles of a new cell, the capacity increases.

1. Discharge at 1C to low voltage limit
2. Rest
3. Charge at 0,5C to I = C_{20} at high voltage limit
4. Rest
5. Repeat item 1 to 4 for 10 times
6. Rest
7. Charge to 10% SoC for cycling cells and specified SoC for storage cells

Annex 4.2.4 Cycle test

The purpose cycle test is to degrade the cells according to the specified test conditions.

1. Discharge at specified C-rate to low voltage limit
2. Rest
3. Charge at specified C-rate to specified nominal SoC
4. Rest
5. Discharge the nominal Ah amount as specified at specified C-rate
6. Rest
7. Charge the nominal Ah amount as specified at specified C-rate
8. Repeat item 4 to 7 for at fixed Ah amount
9. Rest
10. Charge to 10% SoC for cycling cells and specified SoC for storage cells

The rest times are selected so that comparable cells, like the four cells running SoC tests, are tested for the same time and therefore will be kept at the specified temperature for the equal amount of time. For instance, the SoC test cell charging to 50% SoC will do this faster than the cell charging to 95% SoC. Hence, the rest time for the 50% cell is increased accordingly.

The efficiency of Lithium-ion battery cells are quite high, but still less than 100%. To compensate for this loss, the cells are charged a little more than discharged. As shown in Figure 96, both the maximum and the minimum voltage measured during cycling are falling over the first 127 cycles, which means that the compensation is not adjusted correct. After each performance test the compensation is readjusted to make the cells stay within the specified limits.

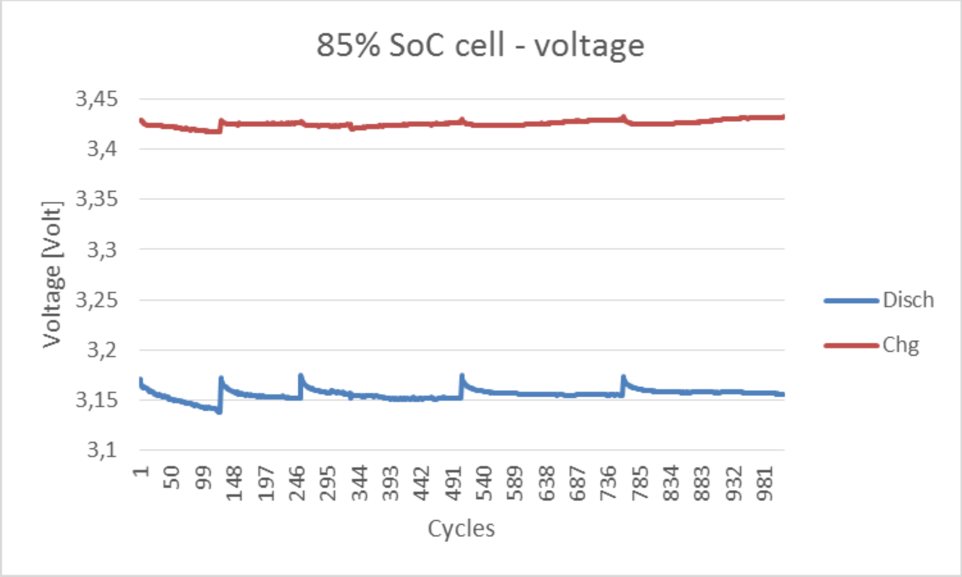


Figure 96: Max. and min. voltage levels from cycling of 85% SoC cell test

Annex 4.2.5 Degradation test results

A brief overview over the test results is given in Table 44 and Table 45 below.

Storage test matrix					
Test focus	Temperatur	SOC	Days	Cap loss	Avg. loss
Temperatur	45	70%	293	14%	4,7%
	35		174	5%	2,6%
	25		553	5%	0,9%
	10		230	1%	0,6%
	0		499	3%	0,7%
	-10		56	1%	1,1%
SoC	45	95%	252	16%	6,3%
		85%	243	14%	5,7%
		35%	242	11%	4,4%
		10%	242	9%	3,8%
	25	95%	587	8%	1,4%
		85%	611	10%	1,6%
		35%	553	3%	0,6%
		10%	613	3%	0,4%

Table 44: Storage test results overview

Cycle test matrix								
Test focus	Temperature	C-Rate chg	C-Rate dis	DOD_rated	SOC_max	E Cycles	Cap loss	Avg. Loss
Temperatur	45	**0,5**	**1**	**50%**	**75%**	1149	33%	2,9%
	35					830	12%	1,5%
	25					1149	14%	1,2%
	10					765	12%	1,6%
	0					765	18%	2,4%
	-10					194	8%	3,9%
C-rate	25	0,25	1	50%	75%	639	7%	1,1%
		0,75				638	9%	1,4%
		1				638	9%	1,4%
		1,5				681	9%	1,4%
		0,5	0,5			681	6%	0,9%
			0,75			617	7%	1,2%
			1,5			639	11%	1,8%
			2			637	15%	2,4%
	10	0,25	1			766	11%	1,4%
		0,75				765	12%	1,6%
		1				765	12%	1,6%
		1,5				766	11%	1,4%
DoD	25	0,5	1	10%	75%	1305	15%	1,2%
				40%		1226	15%	1,3%
				60%		1102	17%	1,6%
				75%		1242	8%	0,7%
SoC	25	0,5	1	50%	50%	382	3%	0,8%
					60%	382	4%	1,1%
					85%	383	6%	1,6%
					95%	384	7%	2,0%
Datasheet	25	0,5	1	100%	100%	512	6%	1,1%
60Ah cell	25	0,5	1	50%	75%	211	3%	1,3%
100Ah cell	25	0,5	1	50%	75%	486	3%	0,7%
180Ah cell	25	0,5	1	50%	75%	292	2%	0,6%
Load pattern	25	Max. 1C	Max. 1C	N/A	N/A	287	6%	2,0%

Table 45: Cycle test results overview

The impact of each stress factor is examined in the following chapters.

Annex 4.2.6 Degradation during storage

Lithium-ion batteries degrade when in operation (cycling) and when left inactive on the shelf (storage). In the latter case, it is well known from the literature that the degradation at storage depends on the battery temperature and the state of charge (SoC). The different influences can be seen below.

Temperature during storage

The storage capacity loss at different temperatures is shown in Figure 97 and the relation between capacity loss and temperature is shown in Figure 98.

Temperature: Vary
SoC 70%

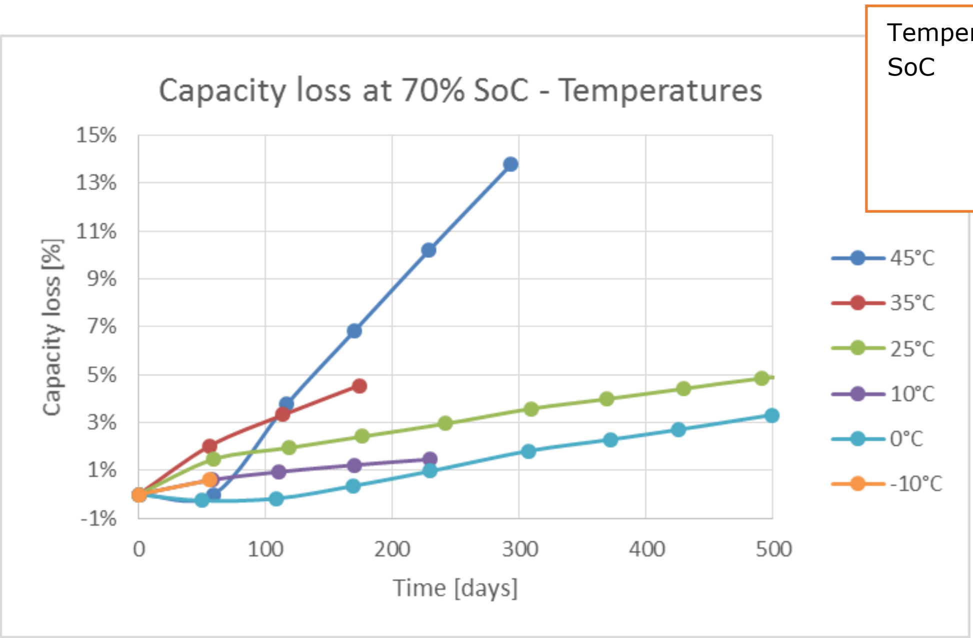


Figure 97: Capacity loss during storage at 70% SoC - different temperatures

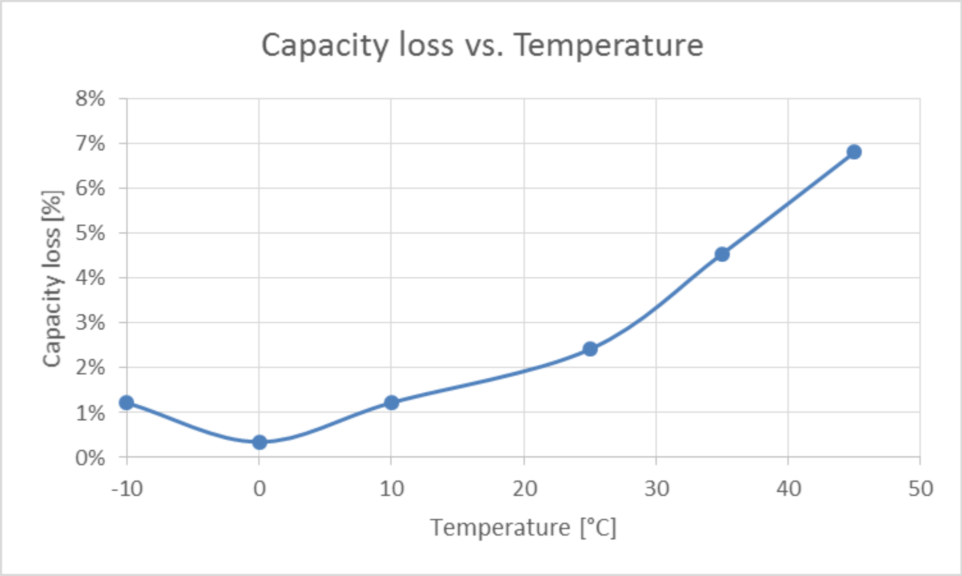


Figure 98: Capacity loss during storage versus temperature after 170 days

The temperature relation was expected to be an exponential function, with higher losses at higher temperatures, which is not the case. Another surprising result is that the slope of the loss curve at 0°C in Figure 97 is almost identical to the slope of the loss at 25°C. Hence, the optimal temperature to store these batteries when not in use at is between 0°C and 10°C.

State of charge during storage

The storage capacity loss at different state of charge is shown in Figure 99 at 25°C and at 45°C in Figure 101. The relation between capacity loss and state of charge is shown in Figure 100 for 25°C and Figure 102 for 45°C.

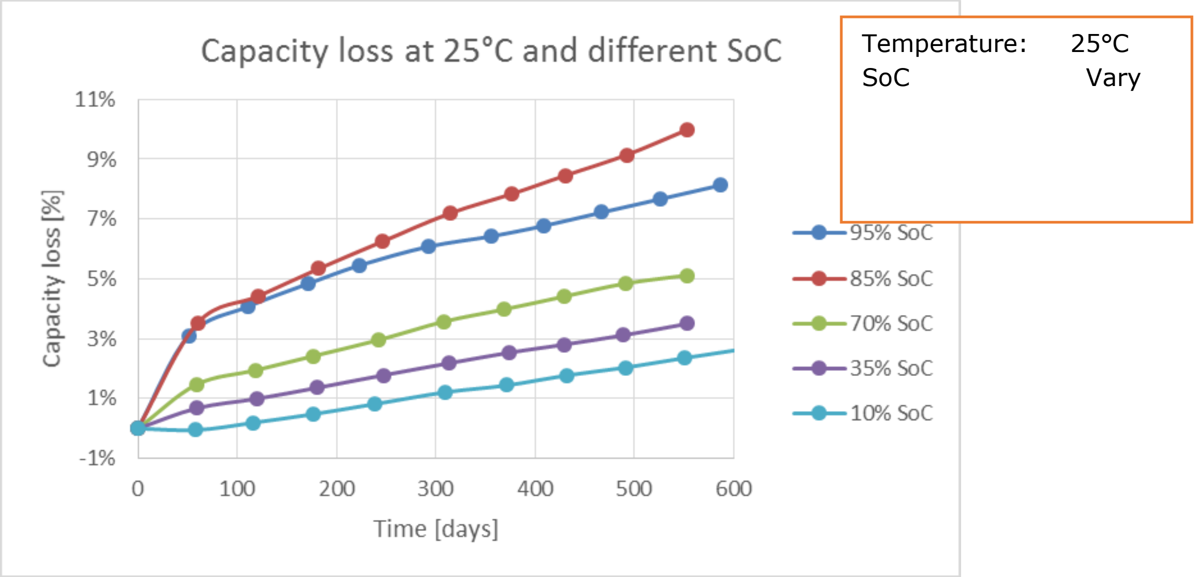


Figure 99: Capacity loss during storage at different state of charge and 25°C

If the loss curve for 85% SoC is removed, there is a neet exponential relation between capacity loss and state of charge at 25°C. It is, however, obvious that the optimal way to store the battery is at low state of charge provided all loads are disconnected.

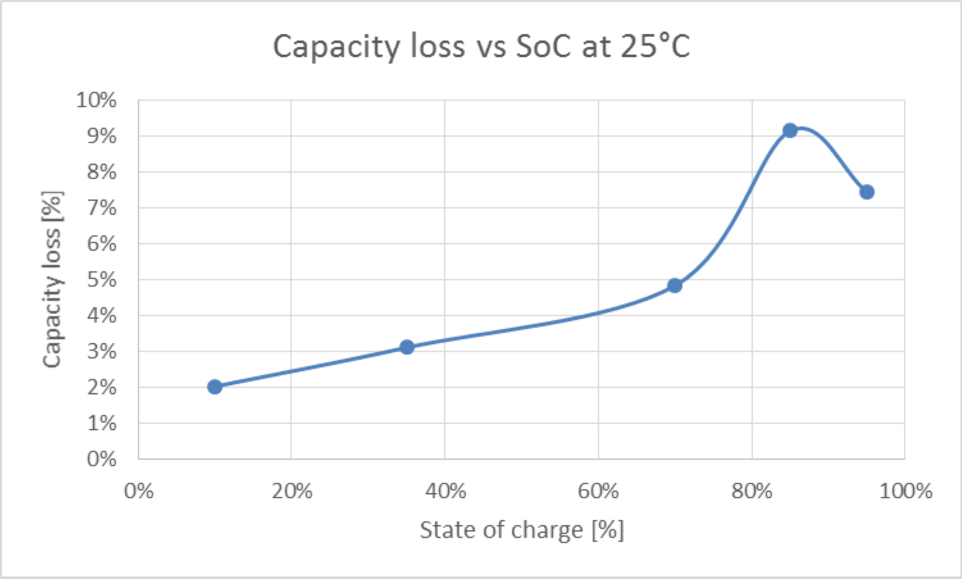


Figure 100: Capacity loss during storage versus state of charge at 25°C

Temperature: 45°C
SoC Vary

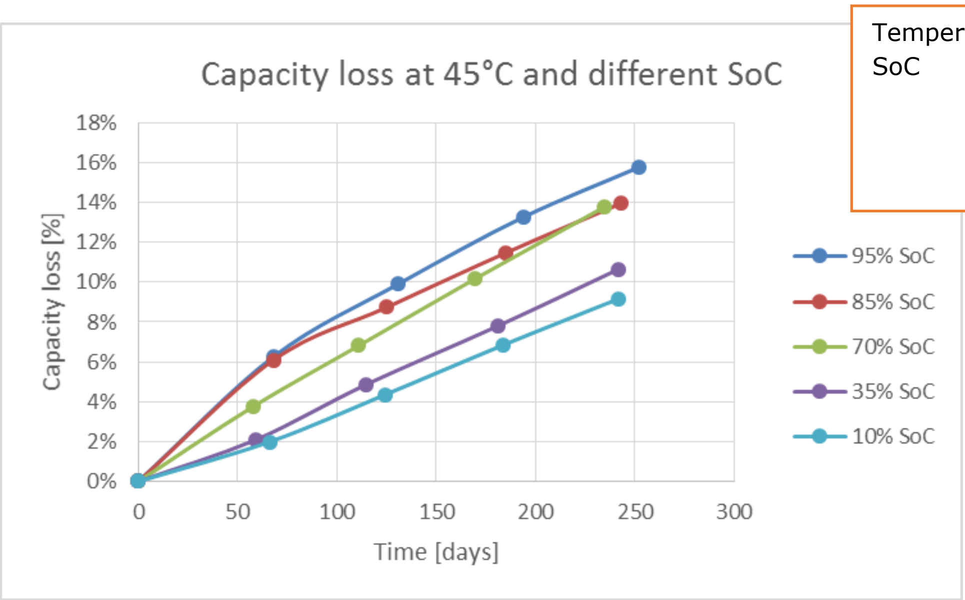


Figure 101: Capacity loss during storage at different state of charge and 45°C

The relation between capacity loss and state of charge at 45°C is an exponential function including the loss at 85% SoC. Although the degradation is highly accelerated at 45°C compared to the degradation at 25°C, the optimal way to store the battery is still at low state of charge.

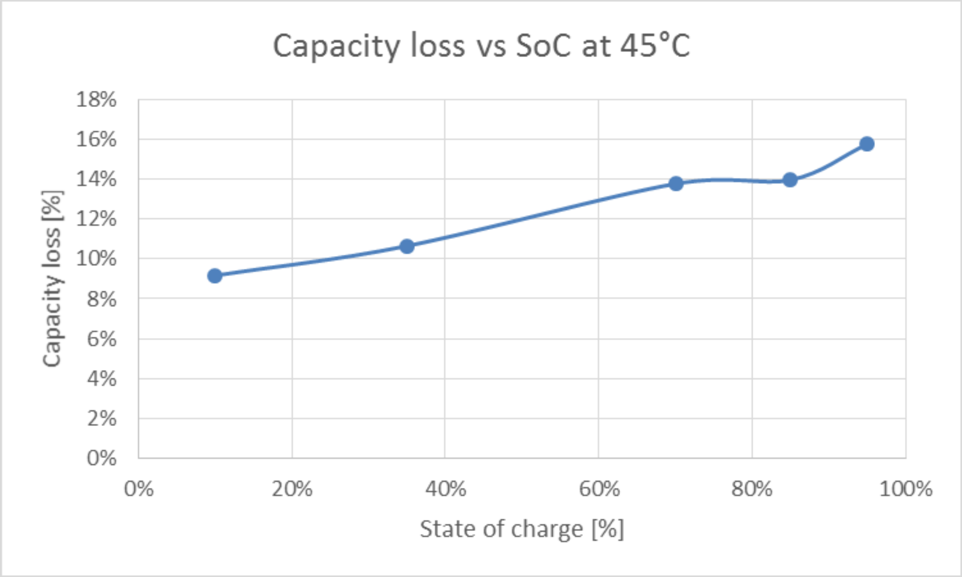


Figure 102: Capacity loss versus state of charge at 45°C

Annex 4.2.7 Optimum settings for a long storage life

The yearly capacity loss can be kept below 6%, if the cells are stored at room temperature or below, and if the state of charge is 35% or less. If stored at a temperature between 0°C and 10°C, and the state of charge is 10%, the yearly capacity loss is less than 3%.

The optimum stress factor settings based on the test results, are shown in Table 46.

Storage stress factor optimum		
Stress factor	**Optimum**	**Comment**
Temperature	10°C	Between 0°C and 10°C
SoC	10%	

Table 46: Long life stress factor settings for storage

If the battery is stored for a longer period of time it should be kept at low temperature, low humidity and low state of charge. Normally the self-discharge rate is very low for lithium-ion batteries, but only if all loads, including the battery management system and other safety electronics, are disconnected.

Annex 4.2.8 Degradation during cycling

The influence of the different stress factors are described in the following.

Temperature during cycling

The cycling capacity loss at different temperatures is shown in Figure 103 and the relation between capacity loss and temperature is shown in Figure 104.

Temperature:	Vary
Charge rate:	0.5C
Discharge rate:	1C
DoD	50%
SoC	75%

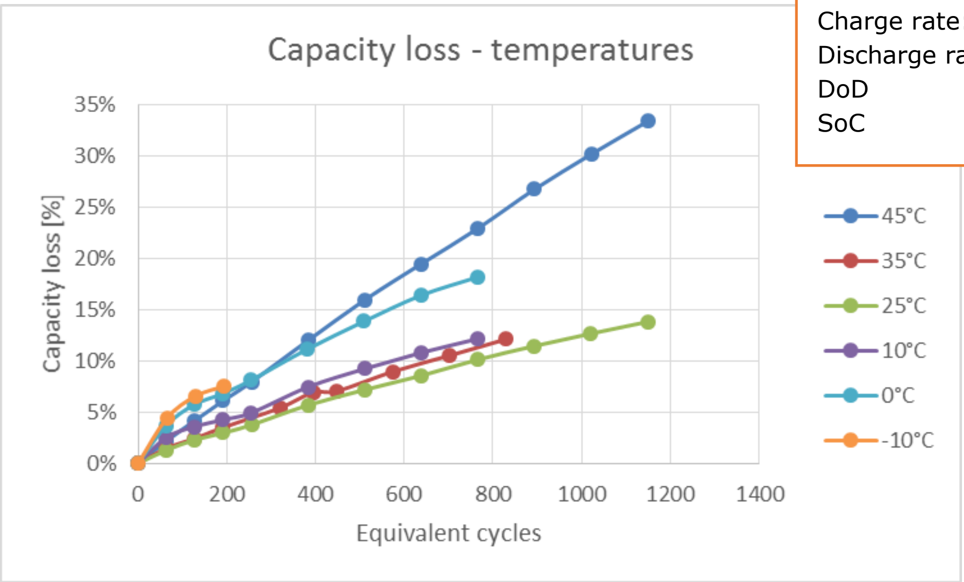


Figure 103: Capacity loss during cycling at different temperatures

The capacity loss at 25°C is the smallest and the loss at -10°C appears to be the largest. However, the slope of the loss at 45°C is steeper than the one of -10°C, so eventually the loss of 45°C seems to become the largest. The relation between capacity loss and temperature at cycling which can be seen in Figure 104 is of polynomial nature, indicating that low temperatures accelerates the degradation as well as high temperatures does.

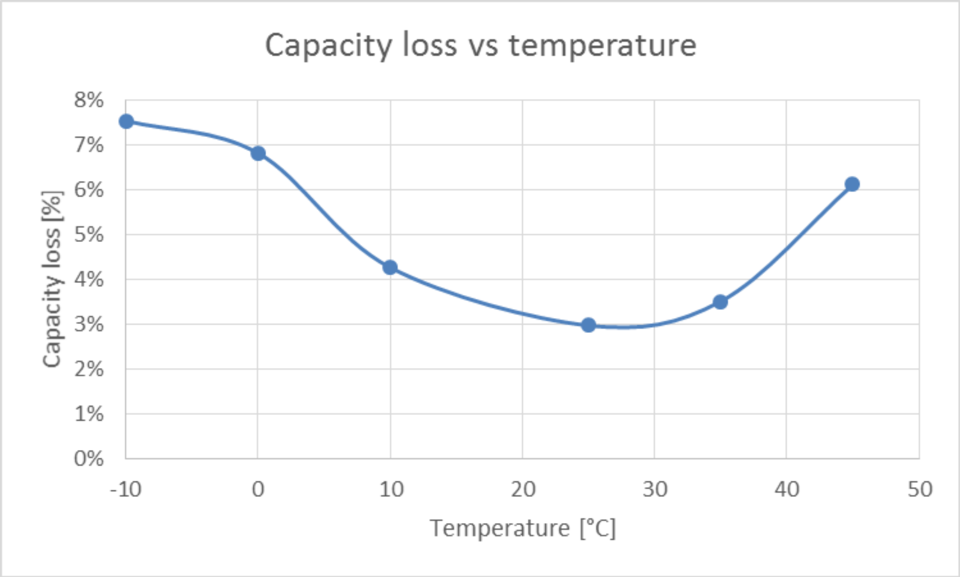


Figure 104: Capacity loss during cycling versus temperature after 192 equivalent cycles

From these tests the optimum cycling temperature is seen to be between 10°C and 35°C with this usage pattern, a discharge of 0,5C and a charge of 1C.

Annex 4.2.9 Charge rate during cycling

Capacity loss at 25°C cycling

Temperature: 25°C
Charge rate: Vary
Discharge rate: 1C
DoD 50%
SoC 75%

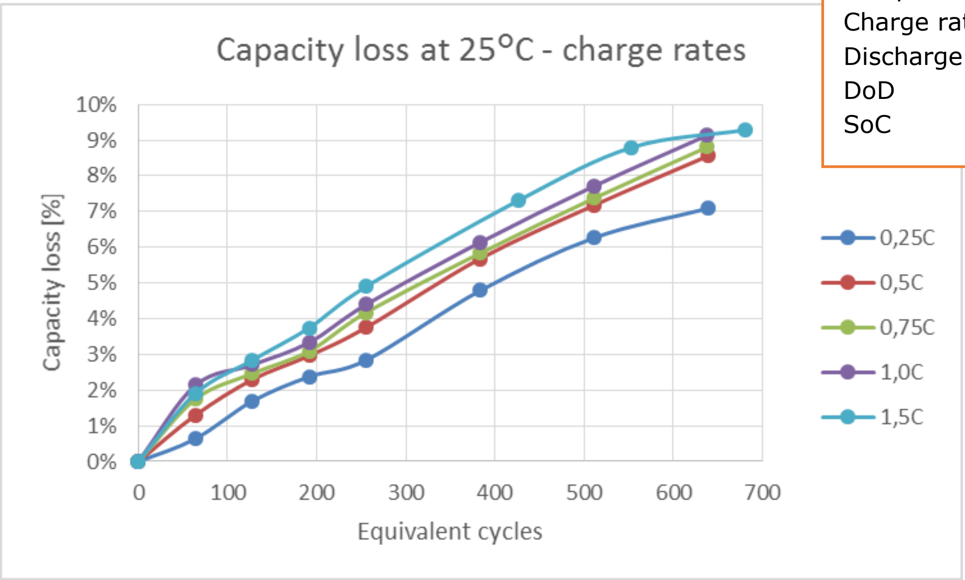


Figure 105: Capacity loss during cycling at different charge rates and 25℃

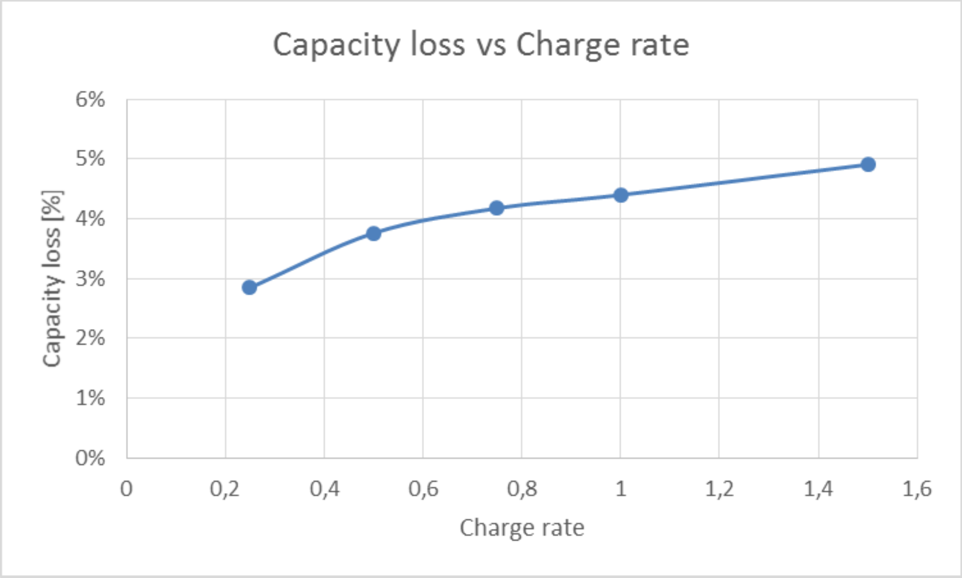
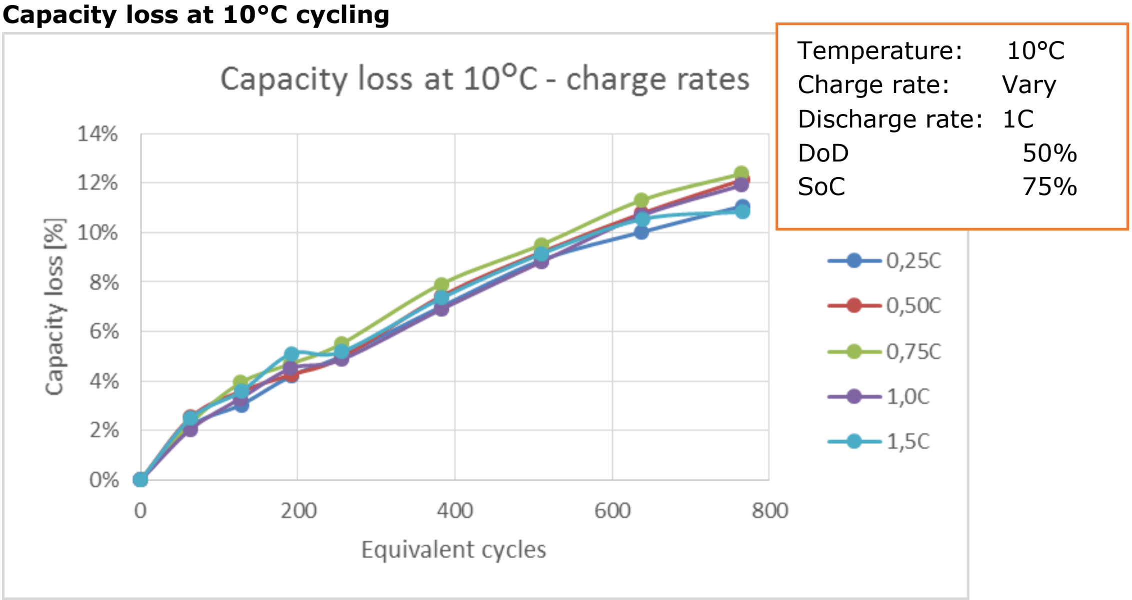


Figure 106: Capacity loss during cycling versus charge rate at 25℃ and 256 equivalent cycles

The capacity loss of all curves stays within a window of 2%, so there is only little difference between the charging rates. As can be seen on Figure 106, the relation between capacity loss and the charge rate is of logarithmic nature at 25°C, and the lowest capacity loss is achieved at low charge rates.

Capacity loss at 10°C cycling



Temperature: 10°C
Charge rate: Vary
Discharge rate: 1C
DoD 50%
SoC 75%

Figure 107: Capacity loss during cycling at different charge rates and 10℃

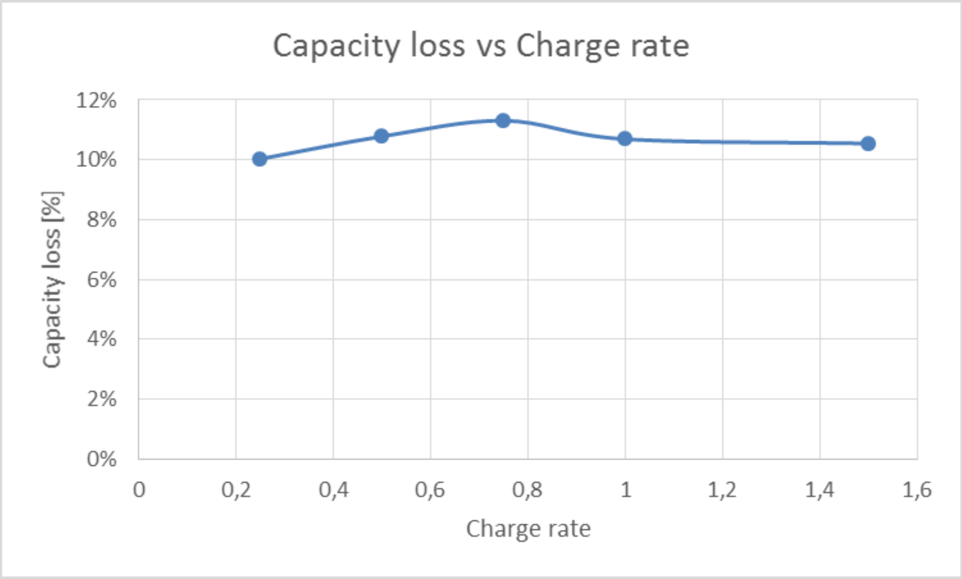
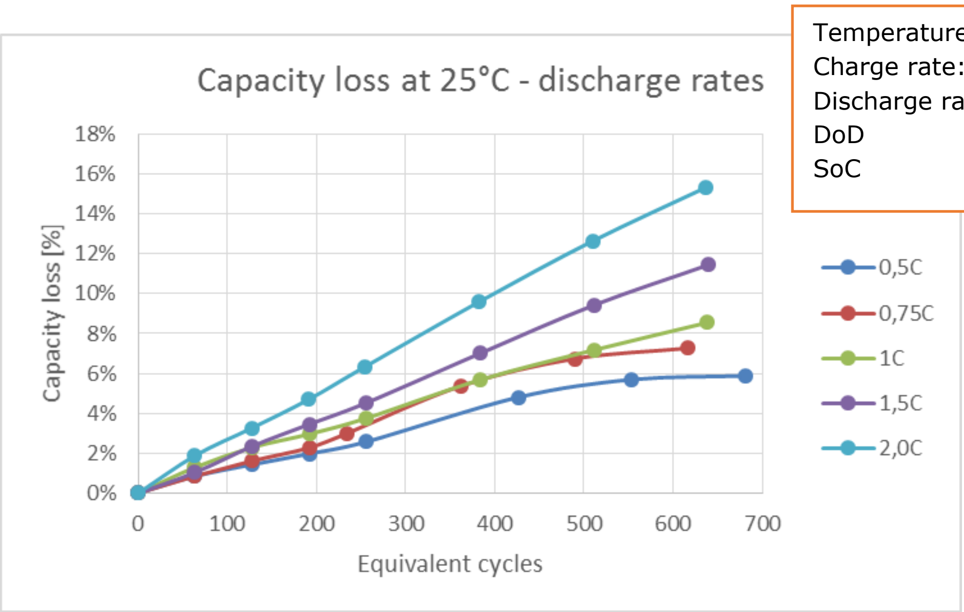


Figure 108: Capacity loss during cycling versus charge rate at 10℃ and 638 equivalent cycles

At 10°C, the difference between the charge rates is so small that they becomes insignificant. The loss is a few percent higher than at 25°C, which comply with the temperature loss curves of Figure 103.

Discharge rate during cycling



Temperature: 25°C
Charge rate: 0.5C
Discharge rate: Vary
DoD 50%
SoC 75%

Figure 109: Capacity loss during cycling at different discharge rates at 25℃

The capacity loss at different discharge rates at 25°C is quite straightforward. Increasing discharge rate results in higher loss, and the relation is exponential. At low discharge rates below 1C, the loss curves flattens out after 400 cycles.

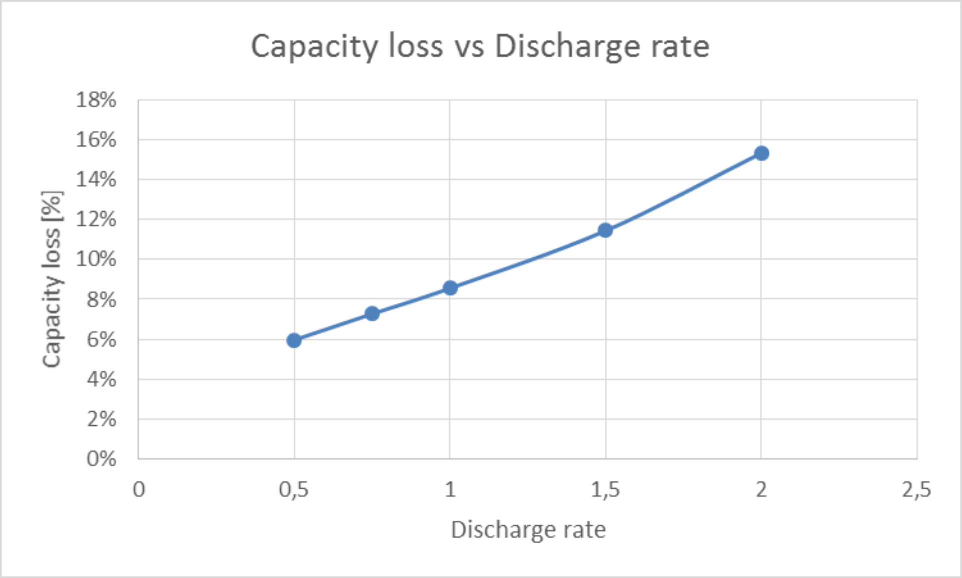


Figure 110: Capacity loss during cycling versus discharge rate at 25℃ and 637 equivalent cycles

Depth of discharge

Temperature: 25°C
Charge rate: 0.5C
Discharge rate: 1C
DoD Vary
SoC 75%

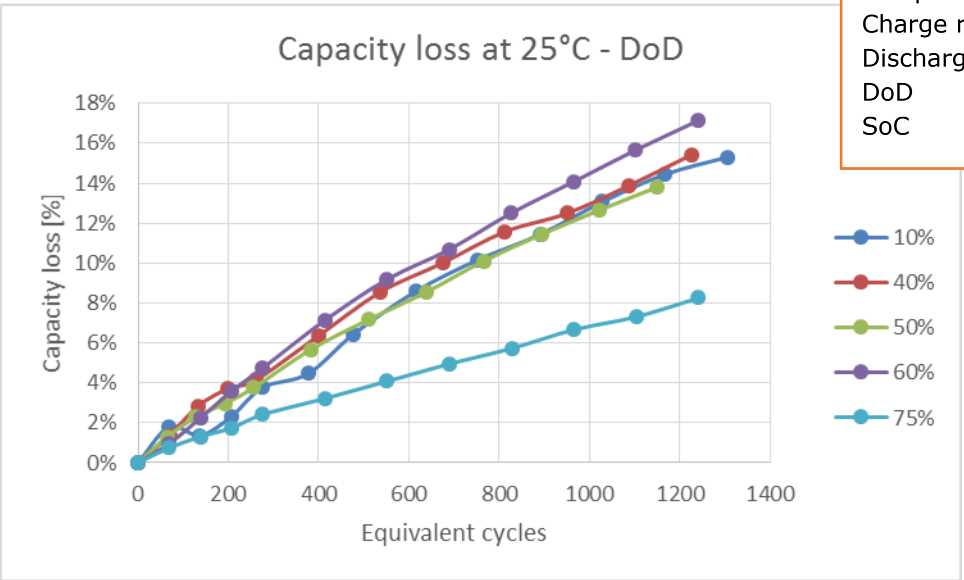


Figure 111: Capacity loss during cycling at different DoD and 25℃

While the loses at 10%, 40% and 50% DoD almost equals the same value, the loss at 60% DoD is 2% higher and surprisingly the loss at 75% DoD is only half the others. Observations from other lifetime tests (DTI tests and litterature) indicate that increasing DoD results in higher capacity loss. These tests, however, was performed from 100% SoC and not from 75% SoC as it was the case in this experiment.
In conclusion, the minimal loss is achieved by emptying the battery in each cycle, and if this is not an option, to keep the DoD below 60%. The result may be different if the test is performed at a higher SoC than 75% SoC like here.

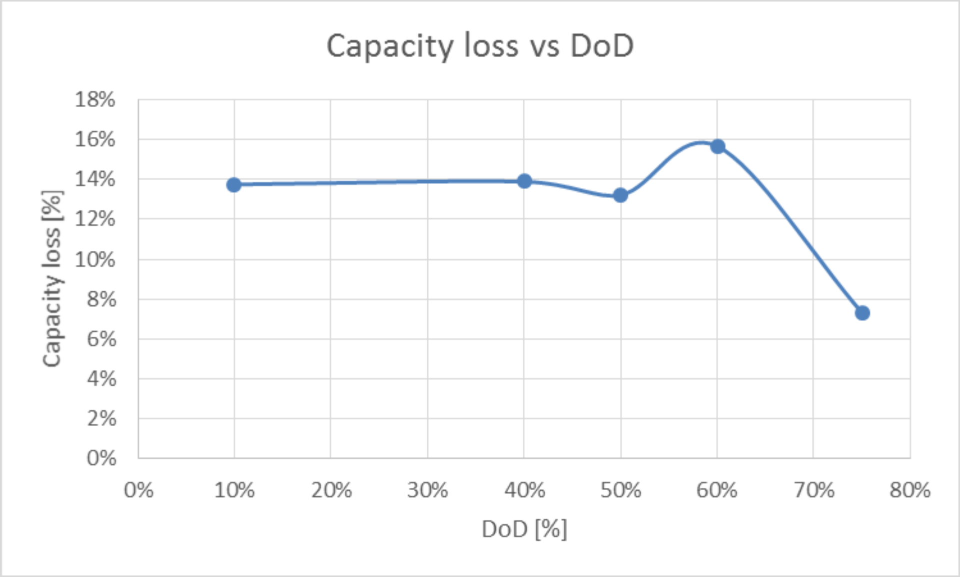


Figure 112: Capacity loss during cycling versus DoD at 25℃ at 1102 equivalent cycles

State of charge

Temperature: 25°C
Charge rate: 0.5C
Discharge rate: 1C
DoD 50%
SoC Vary

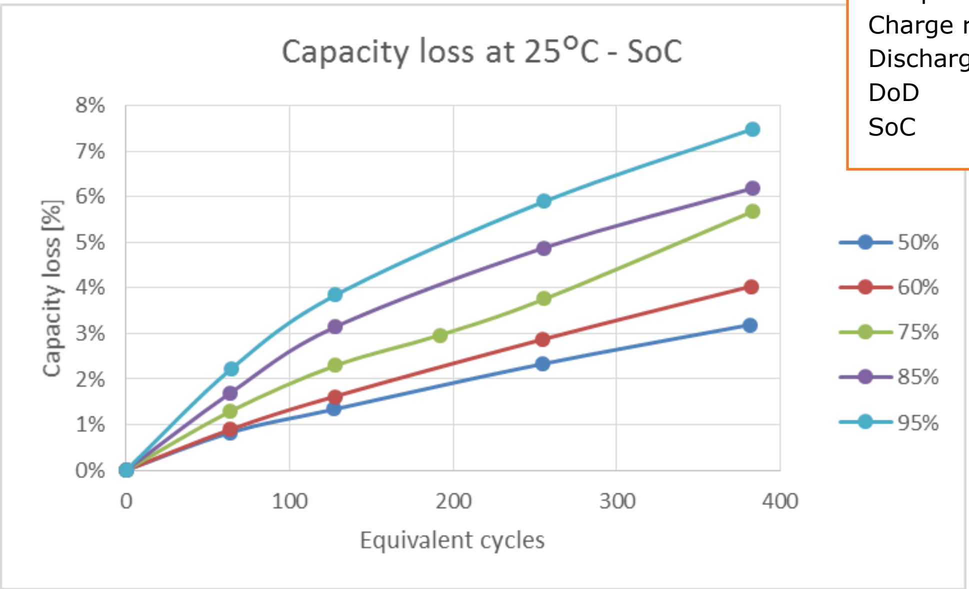


Figure 113: Capacity loss during cycling at different state of charge

The capacity loss at different state of charge at 25°C is shown in Figure 113. The relation between capacity loss and the state of charge shown in Figure 114 is a power function, and the higher SoC the cells are cycled at, the higher the capacity loss results from the cycling.

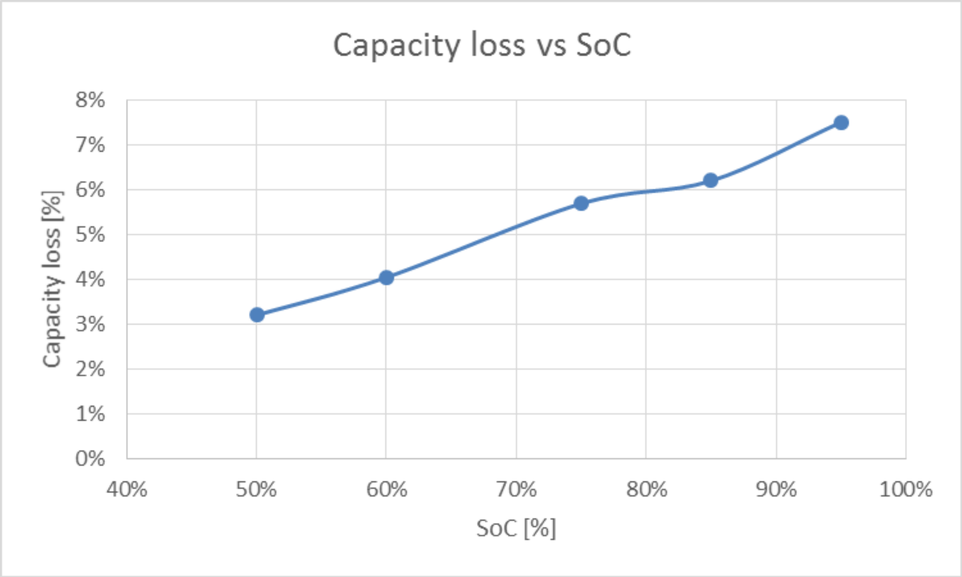


Figure 114: Capacity loss during cycling versus state of charge at 25°C

Comparison between different load patterns

The dynamic load pattern show in Figure 115 is an accelerated test pattern from an average day recorded from the BESS system in Lem kaer, when operated as primary reserve.

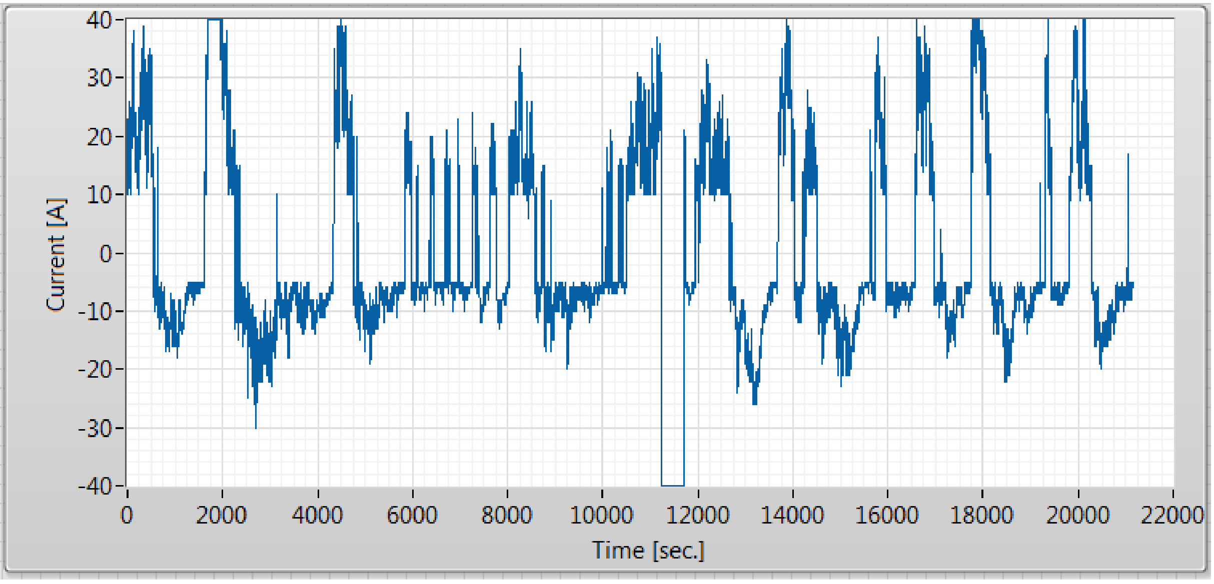


Figure 115: Dynamic accelerated primary reserve load pattern

The capacity loss of the cell running the dynamic load pattern is shown in Figure 116 (Blue curve denoted "Dyn."). The figure also shows the capacity loss of a cell denoted "datasheet" in the test matrix (Green curve denoted Nom.). The cell is charged at 1C to upper voltage limit and discharged at 1C to lower voltage limit. Normally the cell manufacturer test the cell this way in order to provide lifetime data for the datasheet. The last curve (Red curve denoted Ref.) is the same curve as the 25°C curve in Figure 103, which is added as a reference.

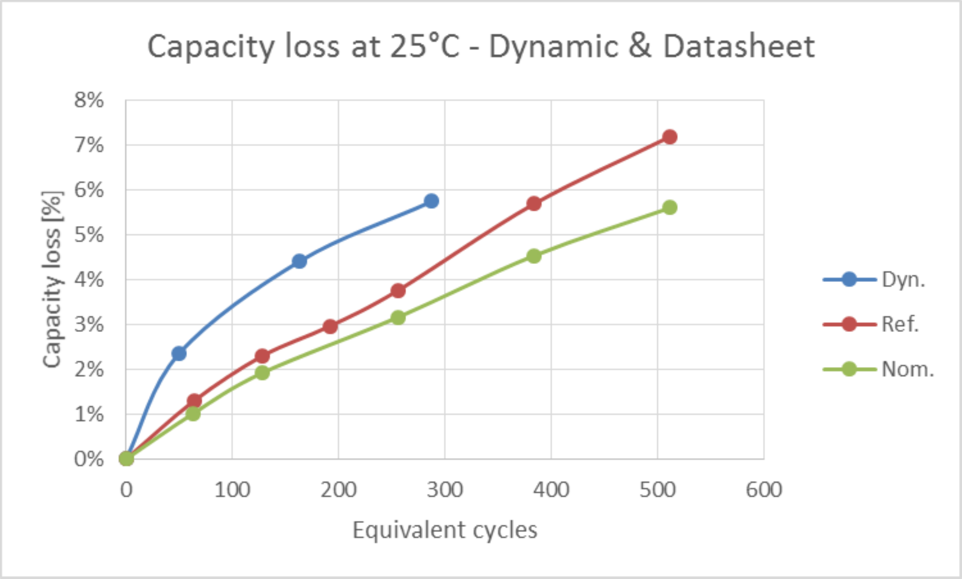


Figure 116: Capacity loss - dynamic load and nominal load at 25℃

Annex 4.2.10 Cycling different cell sizes

Some problems occurred with one of the chambers where some of these cells were kept for test, so the results are limited. The results available suggests that the capacity loss decreases as the cell size increases. Furthermore the loss curves of the 40Ah and 60Ah cells seems sufficient alike, so the test results from the 40Ah cells can be applied on the 60Ah cells as well.

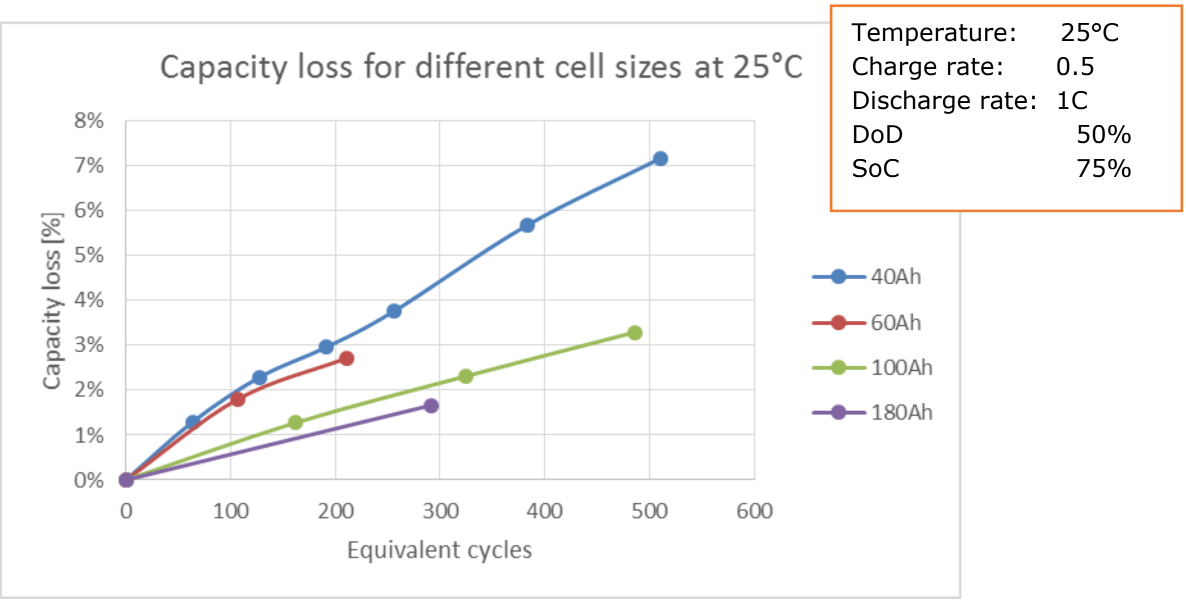


Figure 117: Capacity loss for different cell sizes at 25℃

Annex 4.3 Optimum cycle settings for a long lifetime

Based on the test results, the cycling stress factor settings, which are optimum for the battery lifetime, are shown in shown in Table 47.

Cycling stress factor optimum		
Stress factor	**Optimum**	**Comment**
Temperature	25°C	Between 10°C and 35°C
Chg rate 25	0.25 C	
Dis Rate 25	0.5C	
Chg rate 10	0.25 C	Between 0.25C-1.5C
DoD	Below 60%	
SoC	50%	

Table 47: Long life stress factor settings for cycling

The optimum temperature is 25°C, but more likely somewhere between 10°C and 35°C. The optimum charge rate and discharge rate at 25°C is 0.25C and 0.5C respectively. The difference between the losses for charge rate at 10°C is almost negligible, but the loss at 0.25C is the lowest.

If the cell is discharged to 0% SoC, the lowest capacity loss was achieved in this test, however, this is normally not desirable, so it is concluded that DoD should rather be kept below 60% for optimum low capacity loss. The optimum SoC level is 50% and maybe even lower.

The capacity loss of the dynamic load pattern is higher than the reference in Figure 116, but the “slopes” are different, so if the curves are extrapolated to 685 equivalent cycles, the curves would intersect, and at higher cycles, the reference cell would yield the highest loss. However, apart from the temperature, the other stress factors are incomparable, so which pattern is the optimum is inconclusive.

The nominal test, which is often indicated in cell datasheets and shown in Figure 116, yields surprisingly a capacity loss less than the reference. This test result is in contradiction with all previously results shown in this report, except from the cell cycled at 75% DoD in Figure 111.

The capacity loss of different cell sizes shown in Figure 117 indicates that increase cell size results in decreasing capacity loss. Although the number of cycles processed is inadequate for two of the cells, it is true for the 40Ah and the 100Ah cell. Since the loss for the 40Ah cell is more than twice as large as for the 100Ah cell, the optimum choice is a large cell.

Annex 4.4 Battery degradation model

The capacity loss is affected more by temperature than any of the other parameters tested. Therefore, the temperature data will form the basis of the degradation model and so the degradation model is of the form:

$$CL(n,T) = A(T)n^{E(T)} \qquad (1)$$

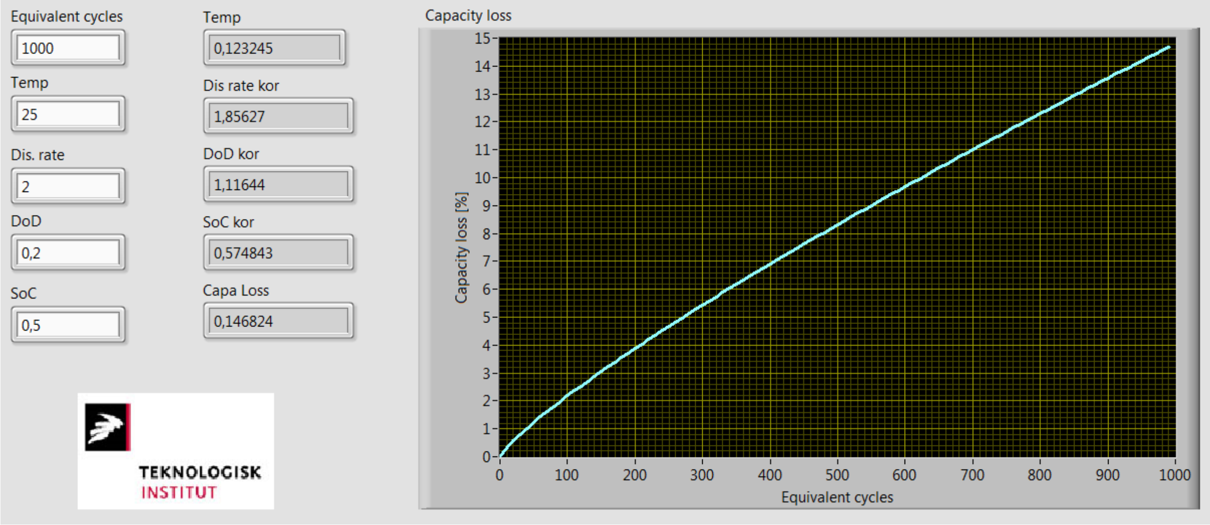
Where CL(n,T) is the capacity loss function of n and T, n is the number of equivalent cycles, T is the temperature and A(T) and E(T) are second order polynomial functions of temperature. Three more stress factores are incorporated in the model, namely Discharge rate f(dr), Depth of discharge f(DoD) and State of charge f(SoC). The result of these functions is a stress factor, which will increase or decrease the outcome of eqauition (1). The model will then be implemented as show in eqauition (2).

$$CL(n,T) = A(T)n^{E(T)}\, f(dr) f(DoD) f(SoC) \qquad (2)$$

For simplicity the most significant stress factors are selected, but if wished the model can be extended with further factors.

The model is implemented in a Labview program as shown in Figure 118 to easyly change parameters and secure that the parameters stay within the model limitations.

The model output was verified against the test results only.



Equivalent cycles: 1000
Temp: 25
Dis. rate: 2
DoD: 0,2
SoC: 0,5

Temp: 0,123245
Dis rate kor: 1,85627
DoD kor: 1,11644
SoC kor: 0,574843
Capa Loss: 0,146824

Figure 118: Battery model as implemented in a Labview program

Annex 4.5 Discussion

Normally the storage capacity loss is an exponential function of temperature. An Arrhenius function to be more specific, since it describes the chemical reaction rate of the most common side reaction, development of a solid electrolyte interface (SEI) between the anode and the electrolyte. Degradation when cycling at temperatures above approximately 15°C is normally governed by the same side reaction but at a higher rate. When this is not the case in this lifetime test, it may be because that other side effects interferes. One suggestion for such a side effect is evaporation of electrolyte, since a bad smell of organic solvents was present throughout the test. Unfortunately the weight of the cells wasn't checked, so this theory can not be verified.

One of the most surprising findings is that full discharge only degrades the battery half as much as if the battery is discharges to lower DoD. There may be a connection with another surprising result. Cycling the battery between 25% and 75% SoC degrades the battery more than if the battery is cycled between 0% SoC and 100% SoC although the same amount of Ah-throughput is processed by the two cells. One theory could be, that all available lithium at the anode is moved to the cathode at full discharge. Then the intercalation at the anode will run more smoothly at the following charge. In the first place however, these tests should be repeated.

Due to some problems with the test equipment a satisfying amount of equivalent cycles was impossible to achieve for a few cells. These cells should be retested in future project. In general the capacity loss rate may well differ over the lifetime as different degradation mechanisms dominate. Hence, it is desirable to keep testing until more than 50% of the capacity is lost. Especially if second life applications could be relevant for the project. Unfortunately very few projects have the time and resources for that sort of tests.

The internal resistance, Ri, are measured by applying a 2C pulse in the performance test. The results of these measurement are not included in this report, since the development in Ri due to degradation is very limited for the CALB cells as for most LFP cells.

Annex 4.6 Conclusion on single cell degradation

A comprehensive degradation test was performed comprising LFP cells at cycling and storage condition, and the capacity loss of each cell as a function of equivalent cycles is shown in this report. To summarize the findings for optimum operation parameters with regard to the battery package lifetime, these parameters are listed in Table 48.

Storage stress factor optimum	
Stress factor	**Optimum**
Temperature	0°C-10°C
SoC	10%
Cycling stress factor optimum	
Stress factor	**Optimum**
Temperature	10°C-35°C
Chg rate 25	0.25 C
Dis Rate 25	0.5C
Chg rate 10	0.25 C-1.5C
DoD	Below 60%
SoC	0,5
Size of cell	180Ah

Table 48: Stress factor optimum for a long cell life

Other regards such as demands for the usage pattern and the investment pay back time must be taken into account, and thus a battery cell degradation model has been establish and implemented in a Labview program, based on the cycling test results.

The cell degradation is found to be a power function of equivalent cycles. A number of stress factors affects the degradation and the four most significant of these, which are temperature, discharge rate, DoD and SoC, are implemented in the model.

Applying the model and extrapolating with regard to the number of equivalent cycles, yields the four scenarios shown in Table 49 below. The column denoted Lifetime is the number of equivalent cycles, which can be performed before the capacity loss has reached 20%.

Temp	Dis rate	DoD	SoC	Lifetime
25°C	0.5C	30%	50%	5500
45°C	2C	95%	95%	330
5°C	2C	95%	95%	170
25°C	0.3C	100%	100%	990

Table 49: Degradation scenarios from model with estimated lifetime measured in equivalent full cycles

Studying the scenarios in Table 49 it becomes obvious that the operation conditions have a huge impact on the battery lifetime and thus the investment pay back. It demonstrates how difficult it is for the battery supplier to specify a lifetime in the datasheet as well. The manufacturer guerantees at least 1000 100% cycles at 0.3C and 25°C. Simulating this test in the model results in 990 cycles as shown in the fourth row in Table 49.

The degradation test performed revealed some new findings, which is not common knowledge according to the literature, and nor is it to DTI.

- Nor is the storage degradation, neither the cycle degradation is an exponential function of temperature. The latter not even at high or low temperatures alone.
- The discharge rate has much more impact on degradation than the charge rate.
- Full discharge degrades only the battery half as much as if the battery is discharges to lower DoD.

- Cycling the battery between 25% and 75% SoC degrades the battery more than, if the battery is cycled between 0% SoC and 100% SoC.

Findings like these reveals the need for more comprehensive tests than normally published in the literature.

The developed model is very useful when designing, operating and predicting the lifetime of a BESS battery pack, but of cause, there is some differences between the conditions in a controlled battery cell test and the conditions for each cell in a large battery pack, not least with regard to the temperature.