Multi-functional use of battery storage in micro-grid

WP4 Fraunhofer IFF Report

ACES project

Adaptive Control of Energy Storage

Final Version

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1.0 (Final)	Released	2021-04-13	Release by WP4 Fraunhofer IFF Lead

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[1] RULES OF PROCEDURE FOR THE EUROPEAN FORUM FOR MEMBER STATES (EFMS) ON PUBLIC POLICIES FOR SECURITY AND RESILIENCE IN THE CONTEXT OF CRITICAL INFORMATION INFRASTRUCTURE PROTECTION, Version 3.0 FINAL – May 2011 "Traffic Light system"

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Acronyms

Word/abbreviation / acronym	Explanation
ACES Project	Adaptive Control of Energy Storage project
ACES Service Provider	is meant to be the operator of energy storage services comprising energy / battery management, order processing and billing. The ACES Service Provider causes OPEX which is necessary to calculate the economic value of an ACES business application. The ACES Service Provider expects remuneration of OPEX plus profit.
ACES Service Receiver	is meant to be a user of energy storage services provided by the ACES Service Provider. The ACES Service Receiver pays the bill and thus covers CAPEX, OPEX and profit in the business model of the specific ACES application.
ACS	Adaptive Control System
aFRR	Automatic Frequency Restoration Reserve
AMS	Automatic Measurement System
B2B	Business-to-Business
Battery Owner	is meant to be the party which invested into ACES technology, where the main share of investment will be related to the battery. The Battery Owner causes CAPEX which is necessary to calculate the economic value of an ACES business application. The Battery Owner expects ROI including coverage of CAPEX (interests, depreciation) plus profit or any other value.
BMS	Battery Management System, A battery management system (BMS) is any electronic system that manages a rechargeable battery (cell or battery pack), such as by protecting the battery from operating outside its safe operating area, monitoring its state, calculating secondary data, reporting that data, controlling its environment, authenticating it and / or balancing it. (Barsukov and Qian 2013)
BO	Battery Owner
BRP	Balance Responsible Party
Billing System	Shall be the complete software package including all necessary services provided by MINcom Smart Solutions to achieve the required ACES goals. This comprise services like: TS (Tariff Service), BS (Billing Service), print services, file transfer services for bills and credit notes provided to the ACES demo sites.
BS	Billing Service
CAPEX	Capital Expenditure
DER	Distributed energy resource
DSO	Distribution System Operator
DSOA	DSO Aggregator
EEG	Erneuerbare-energien-gesetz (German renewable energy sources act)
EEX	European Energy Exchange

EUR	Euro
EMS	Energy Management System. Generally, this is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system. It also is used by systems which control the dispatch and thereby energy flows (charging, discharging of batteries) between the battery storage system and the electrical grid it is connected to.
ERP	Enterprise Resource Planning
EV	Electric Vehicle
FCR-D	Frequency Containment Reserve – Disturbance
FCR-N	Frequency Containment Reserve – Normal
FMS	Facility Management System
ICT	Information and Communication Technology
kVAr	Kilovolt-ampere reactive power
kW	Kilowatt
kWh	Kilowatt hours
kWp	Kilowatt Peak - The optimal power delivery from a solar cell, int0 the best possible environment. In Sweden a solar panel typically delivers 800-850 kWh/year for every 1 kWp.
mFRR	Manual Frequency Restoration Reserve
MINcom	Short for MINcom-Smart-Solutions GmbH
MTTI	Mean Time To be Informed – receive information about an event
MTTR	Mean Time To Repair
MVP	Minimum Viable Product
MW	Megawatt
MWh	Megawatt hour
OPEX	Operational Expenditure
OS	Operating System
PCR	Primary Control Reserve
PQ	Power Quality
PtH	Power to Heat
PV	PhotoVoltaic
RES	Renewable Energy Sources
REST	Representational State Transfer: a software ar-chitectural style that de-fines a set of constraints to be used for creating Web services. [Wikipe-dia – Representational state transfer. 2019]
ROI	Return on Investment
SCR	Secondary Control Reserve

SEK	Swedish krona
SME	Small Medium-sized Enterprise
SWOT	Strength – Weaknesses – Opportunities – Risks
TCR	Tertiary control reserve
TRL	Technology Readiness Level
TS	Tariff Service is a part of the Billing System
TSO	Transmission System Operator
UPS	Uninterruptable Power Supply
USD	United States Dollar
VAT	Value Added Tax
VPP	Virtual Power Plant

1. WP2 - Battery Storage Hardware Development

Grid services with electrical energy storage systems

In general, there are many of use cases for energy storage systems (ESS) depending on technical environment, technical needs and economical goals. One field of interest is "grid ancillary services (AS)". In Germany, four main categories are defined by grid codes, which can be covered mostly by ESS. A fifth category with additional future services can be imagined for energy storage systems or electric vehicles especially - see Figure 1.

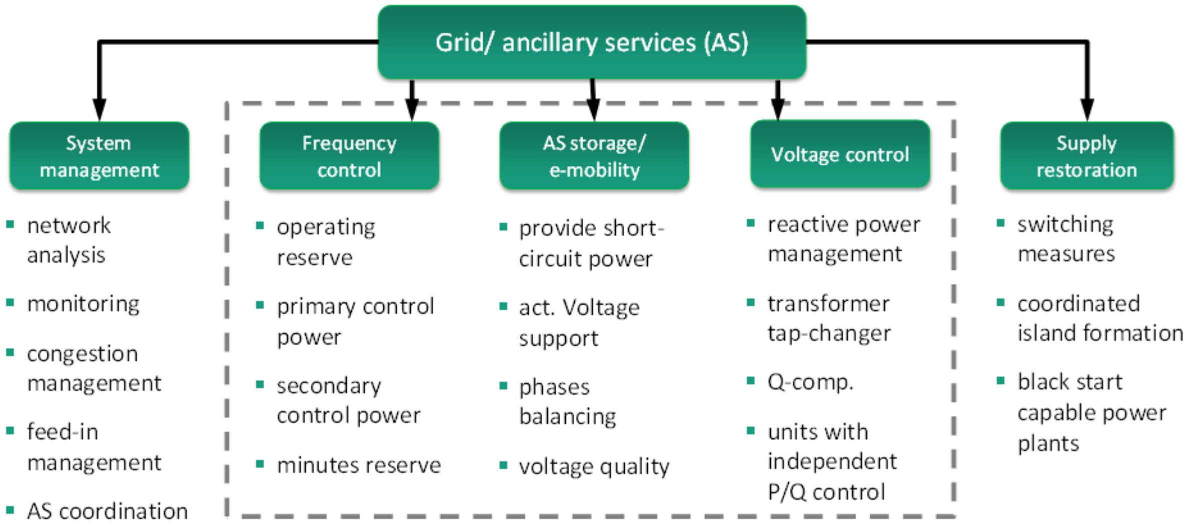

Figure 1 Overview of different grid services

Modern loads, generators and electrical storage systems work with power electronic converter systems. Benefit of such systems with power electronic are the flexible and dynamic control of active and reactive power, the phase-selective active and reactive power control and distortion reactive power as regulating variable for system operation. Through this technical operation point of these devices, several effects in the distribution grid can be realized to deliver grid services. The following table shows the achievable effects for grid operation related to the regulating variable.

Table 1 Technical control mechanisms and their effects in power supply system

Regulating variable	**Effect in the distribution grid**
Active power control	• Charging curve according to renewables, tariff, etc. (Power setpoints according to schedule) • Frequency support (Power setpoints according to local frequency measurement) • Voltage support (Power specification according to local network voltage)

	• Short-circuit power supply (Power specification according to local network voltage)
Reactive power control	• Voltage support (cos (phi) / reactive power setpoints according to local grid voltage)
Phase-selective active power control	• Phase symmetry (active power withdrawal according to phase voltage)
Distortion reactive power	• Voltage quality (active filters according to harmonics)

In order to remain a safe and reliable energy supply, in addition to the transmission and distribution of electrical energy as core function, a variety of services for maintaining the functionalities are defined by the network operator. These services include:

- the frequency maintenance,
- the voltage maintenance,
- the system management as well as
- the restoration of supply

and are summarized in German grid codes under the term "grid ancillary services (AS)". The frequency control is to be viewed as a tool for balancing feed-in and consumption and is further divided into the 4 areas of primary control reserve, secondary control reserve, minute reserve (tertiary control reserve) and balancing group.

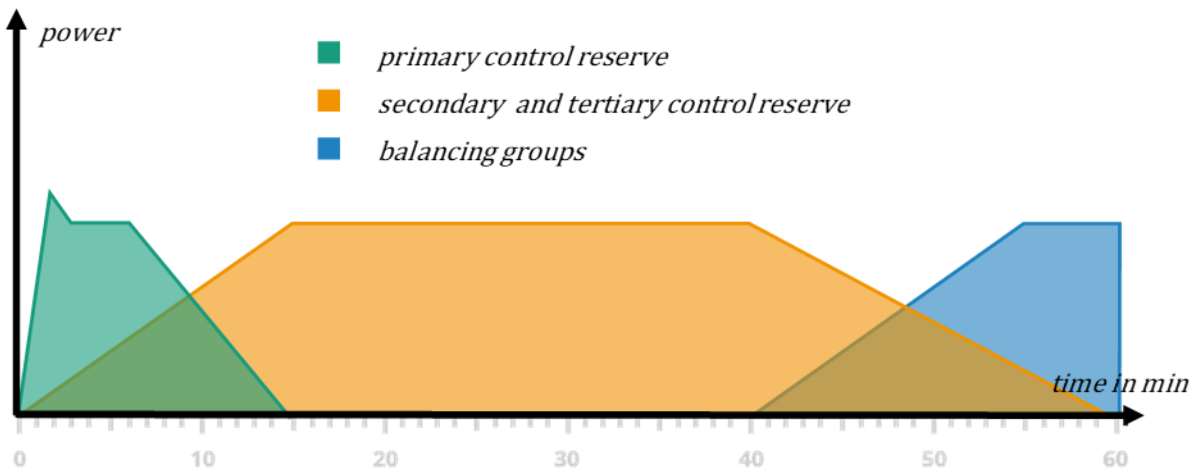

Figure 2 Requirements on primary, secondary, tertiary reserve operation window

If the energy supply and demand do not match, a change in the power frequency is caused. This effect can be explained by the change of rotation speed of the synchronous generators in the grid if there is an unbalance between load and generation in the grid.

In case of higher load, rotation speed is decreasing and grid frequency is falling accordingly. On the other hand, less load than generation in the grid causes an increase of rotation speed of the synchronous generators in the grid and frequency is rising. The rotating machine masses in the grid is damping this function and is well known as the spinning reserve, which is an essential value for grid stability.

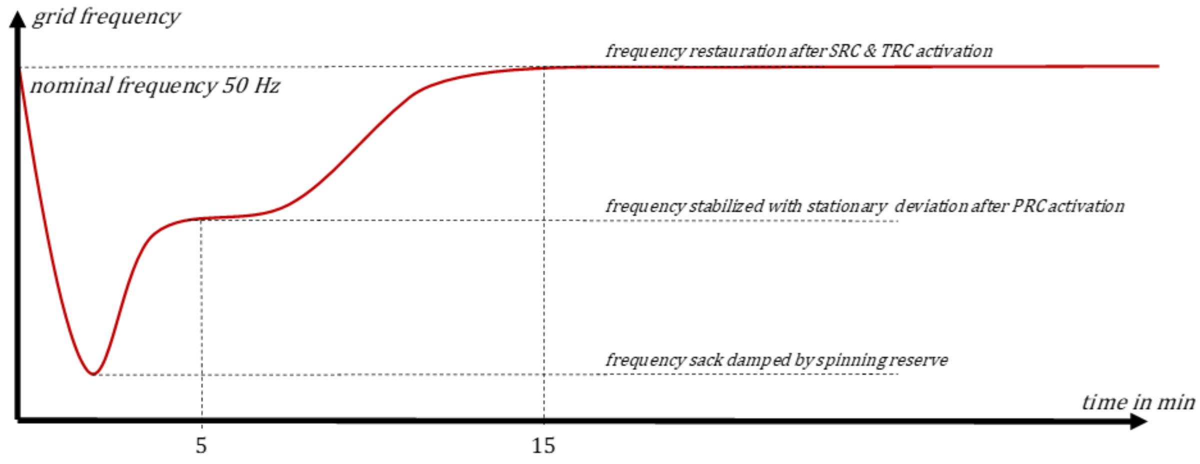

Figure 3 Requirements on primary, secondary, tertiary reserve operation window

In the following, the primary control reserves (PRC) is activated, which is provided across all control areas by every feed-in unit involved, according to the principle of solidarity. The task of the PRC is to restore the balance between generation and consumption and to stabilize the grid frequency with a maximum quasi-stationary deviation of 200 mHz. The return to the nominal frequency is implemented by calling up the secondary (short term) and tertiary (long term) control reserve.

In order to guarantee a permanent provision of primary control power by storage units, as it is intended by the system described, it must be ensured that the storage system is able to absorb or release its prequalified amount of energy in any case and thus itself moved as close as possible to the loading condition of 50%. The storage unit therefore takes part in the energy market and charges or discharges, depending on the amount of energy requested, in order to level its state of charge and be able to meet this requirement.

1.1 WP2A – Battery Management System

Generic functional requirement of the BMS

Lithium-based battery cells became the most common chemistry of battery cells in the past years. The benefits are the high power and energy density, the high number of cycles and its dynamic performance. The most critical challenge is the safety of the cell. A mistreatment could easily damage single cells or even cause a thermal runaway that could end in a chain reaction destroying the whole BESS and other nearby devices as the released thermal energy is about six times higher than stored electrical energy.

Therefore, a BMS (battery management system) is needed for proper operation of BES. Its key functions (Figure 4) are protection, diagnostics, performance management, control of auxiliary devices and interface provision.

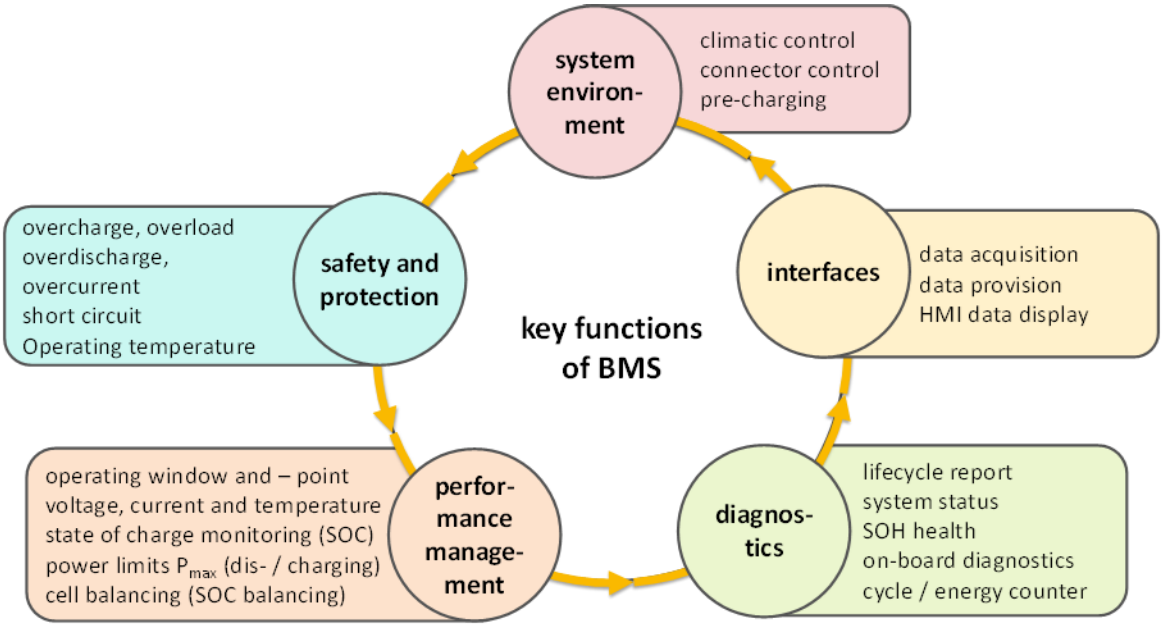

Figure 4 The general key functions of a BMS

A main challenge is the accuracy of cell diagnostic (Figure 5). All functions depend on the measurements of cell voltages, cell currents and cell temperature. Based on these data sets, the SOC (State-of-Charge) and the SOH (State-of-Health) as well as all other values are calculated. The accuracy of SOC or SOH calculation has an enormous impact on operation reliability that is directly related to use cases and economic operation. The operation strategies depend on the quality of the BMS including the accurate identification of the BESS system state and the optimal use of the storage capacities. In order to avoid a fast aging of the storage system, gentle treatment and maximum system efficiency must be balanced.

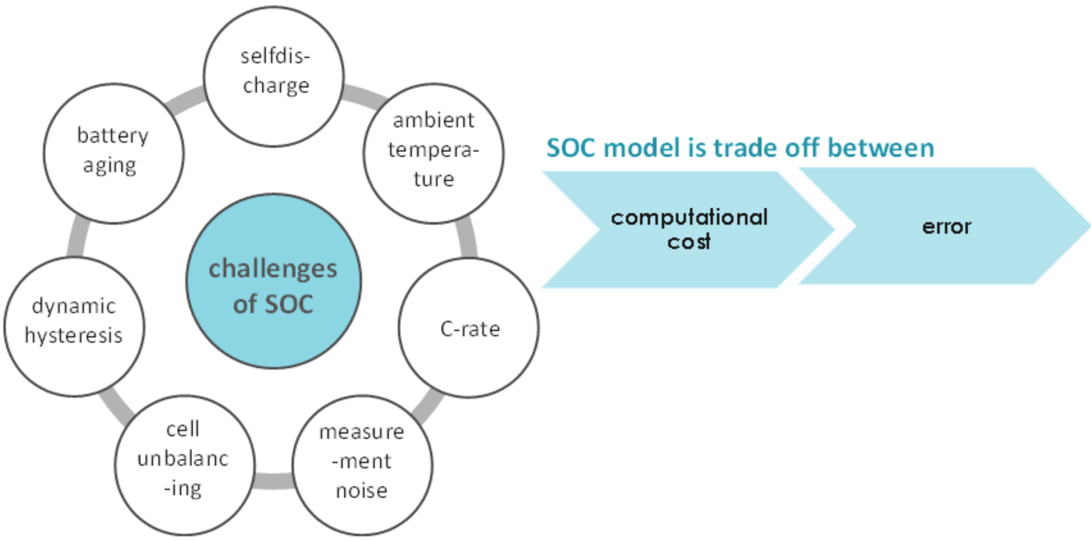

Figure 5 Challenges of SOC modeling

Stationary battery systems feature modular construction (Figure 6). Depending on use case and operation strategies, storage systems differ in dimension and system design. Small stationary BESS, up to 50 kWh, could consist of single battery-string that is serial connection of view battery modules, set up by serial and/or parallel connection of single battery cells. The battery modules are the smallest units on system level. They have an autonomous BMS with important meaning for operation. The modules are connected in series, usually. On the next higher level, the energy management system (EMS) is connected to single module BMS and communicates with the overall control unit, called BESSM (battery electric storage system management). This is processing all system data and controls / manages the different components of the system.

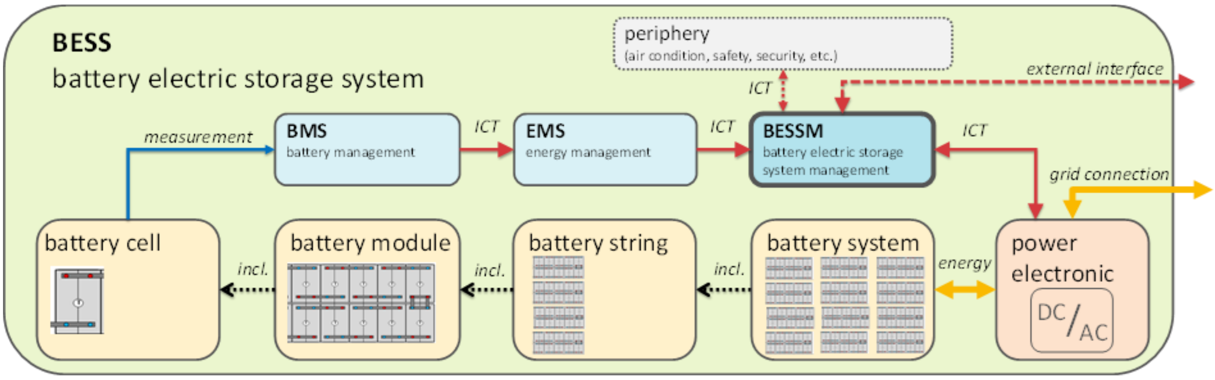

Figure 6 Scheme of modular construction of BESS

The BESS will be integrated in the ACES-system using the requirements and configuration needs of the BESSM. All system critical functions and requirements are fulfilled by the BESSM. Furthermore, every needed data is measured by the system and can be used. Additional, safety functions needed for battery applications come with the BESSM, so that interfaces and communication protocols will be implemented in the ACES-system.

1.2 WP2B – Batteries & Health Sensors

Generic functional requirement of the batteries for the demos

Concept of battery stack integration into the test environment

The idea of usage of the NPS (Nanoplasmonic Spectroscopy) sensors is to get additional information directly from the inside of the cell. A gain of quality of cell information such as SOH (state-of-health), SOC (state-of-charge), temperature etc. could be expected. Therefore, the NPS – test system of Insplorion should be implemented inside of a commercial ICT structure of a battery energy storage system (BESS). The system was planned with a BMS measuring the cell voltage, cell current and cell temperature determining the SOC, SOH and cell conditions in reference to the NPS-sensor measuring.

The energy controller is reading and processing the system information and controls the power electronic converter (charger), which is regulating the energy flow, charging and discharging, of the BESS. The energy controller delivers and processes the BESS system information and is reacting to the control commands of the external ACS (adaptive control system) which takes the role of the system control in the electrical micro grid (Figure 7).

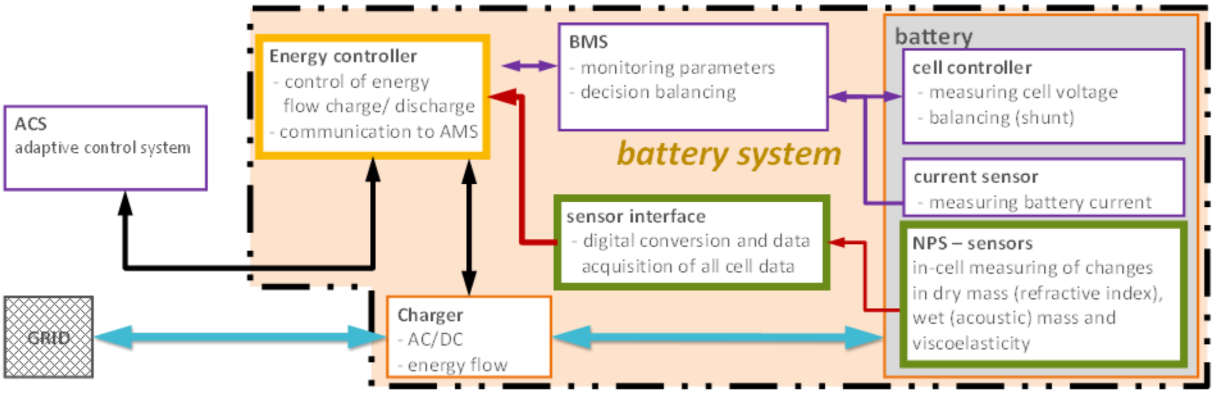

Figure 7 Concept of ICT-structure of adaptive control energy system with NPS-sensors

For the realization of the NPS-Sensor-test-environment an electrical and ICT concept was developed. The concept was the base for the preparation of the test equipment including the electrical parameters as current, voltage and measurement equipment with needed accuracy. Nevertheless, the configuration of the cell stack has influence on additional equipment such as the requirements of the needed BMS and the interfaces for monitoring and control of the test application.

Concept of battery stack with NPS sensors and interfaces[2]

In this project a battery pack with 8 cells, all equipped with one NPS sensor each, will be produced. The minimum lifetime of the NPS sensor probes should exceed one month. The NPS sensors will have all the necessary electronics and hardware for reading off the optical signal. The optical components will consist of one light source, one detector, one optical splitter and an optical switch capable of switching between the 8 fibre optic probes to control which battery cell that is measured at each moment of time. The physical dimensions of the optical hardware unit will be ca. 2 dm^3.The NPS sensors will communicate with the ACS through a RS-485 connection and a Modbus protocol.

The sensors will be implemented in batteries delivered by AGM Batteries, who already have an established connection to Insplorion.

In terms of interfaces, the NPS sensors will only be connected to the ACS as the scope is to demonstrate the NPS sensors capability as sensing rather than act on the batteries.

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[2] *Author Insplorion: David Nilebo / Elin Langhammar*
https://www.insplorion.com/sv/products/insplorion-acoulyte/
https://www.insplorion.com/en/technology/nanoplasmonic-sensing-2/

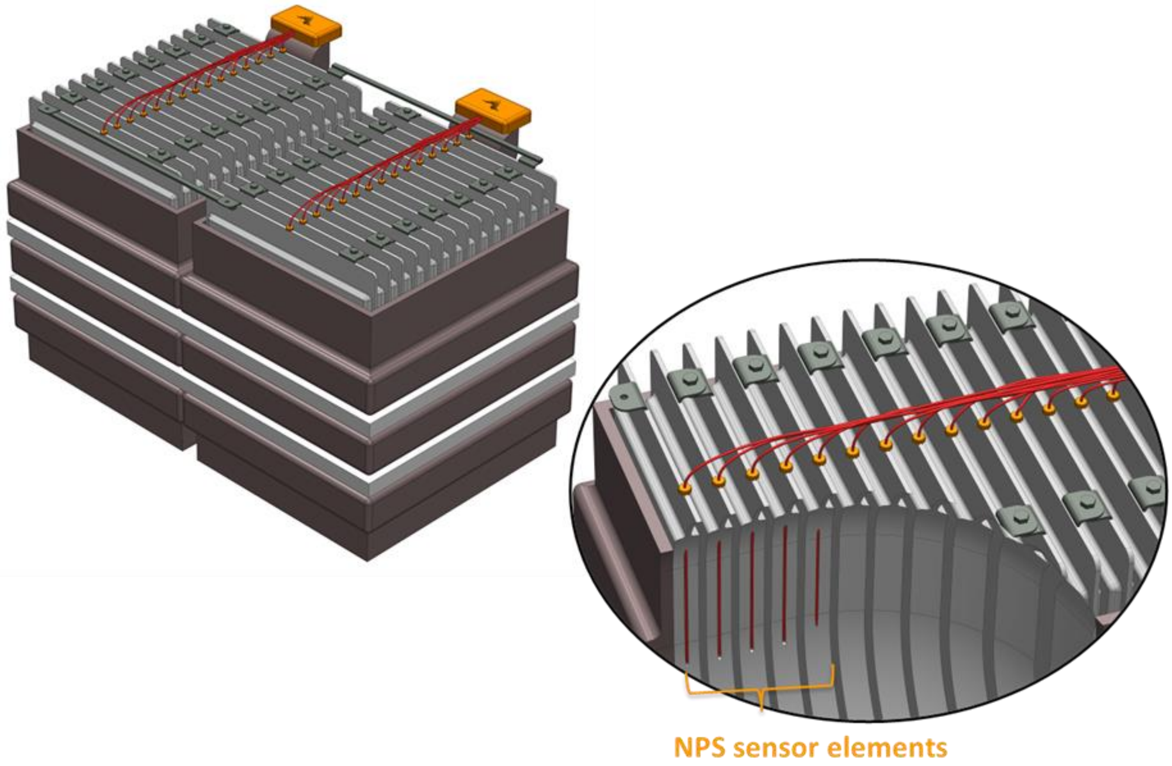

Figure 8: Sketch of the demonstrator battery pack with NPS sensors in each cell.

The NPS sensors can potentially be valuable in all of the Business Use Cases defined in the ACES project. Accurate SoC, and SoH estimations will help to control the battery performance and to control that the safety margins are not exceeded. For each Business Use Case, the SoF (State of Function) can be defined as a combination of SoC, SoH and the function that is to be made. The SoF helps us understand whether a certain task is available or not, and if the potential damage of the battery is covered by the revenue from service provided to the end-customer.

The NPS sensors will be evaluated in the Demonstrator 1a together with an identical battery pack without sensors. The two battery packs will be cycled in identical ways, and the purpose is to show the differences in the NPS signals and the traditional voltage and current signal, as well as compare the actual performance differences between the two battery packs in terms of capacity and power density.

1.3 WP2C – Power Electronics & Measurement technology

Power electronic characteristics and usage

A numerous of loads, and especially the renewable energy generation units such as wind turbines and photovoltaic plants, are equipped with the power electronic converters as is the charger unit for BESS. Depending on the location of installation, requirements on weight, charging capacity, functionality, costs and the used technique the circuit characteristics are quite different. An assortment of typical charger circuits is shown in Figure 9.

Circuit a), b) and c) are AC/DC-converters with the following qualities:

a) B2U - input rectifier
   - Continuous high level of odd harmonics
   - Low development effort and costs

b) B2C - H-bridge
   - four quadrant chopper, bidirectional operation
   - active Power Factor Correction (PFC) possible
   - Higher development effort and costs

c) B6C - full bridge circuit
   - four quadrant chopper, bidirectional operation
   - active Power Factor Correction (PFC) possible
   - Higher development effort and costs

For the DC current control, a DC/DC converter follows the AC/DC converter; examples are d), e) and f):

d) Bidirectional DC/DC converter
   - High efficiency
   - No galvanic separation
   - Need RCCB all current sensitive

e) DC/DC converter with HF - transformer
   - lower efficiency
   - galvanic separation
   - Higher development effort, weight and costs

f) Bidirectional DC/DC converter with HF - transformer
   - lower efficiency
   - galvanic separation
   - Many elements, higher development effort, weight and costs

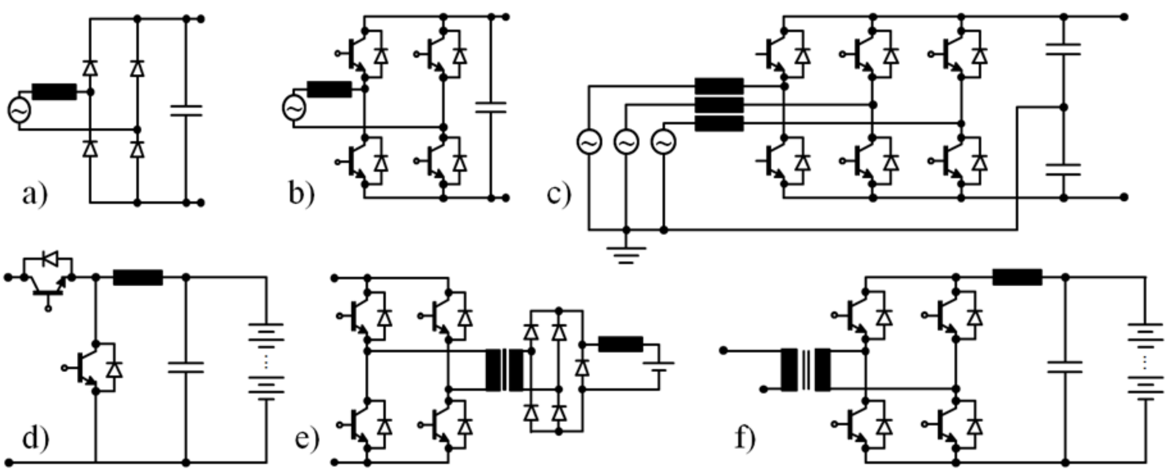

Figure 9 Power electronic topologies used in typical charger circuits
a) B2U input rectifier, b) B2C H-bridge, c) B6C full bridge circuit,
d) Bidirectional DC/DC converter, e) DC/DC converter with high frequency transformer,
f) Bidirectional DC/DC converter with high frequency transformer

The different BESS and DUT's (device under test) used in the project did differ in power electronic configuration. The functionalities researched and used in the project did focus on active and reactive power control. The DEMO Sides do fulfil the technical requirements for evaluation of the theoretical use cases, operation strategies and test scenario.

Power quality measurement installation concept in demo side

The power quality device should measure at different measuring points to fulfil the ACES functions developed in the project. Therefore, the PQ-measurement (metrum PQX3) is installed in a demo side environment. In the demo side, a micro grid application is designed to test and evaluate the ACES algorithm. Therefore, a bidirectional 200kVA battery test bench for a load profile replication is taken, which allows the operation with generation and consumption in the grid. In the lab environment, the standard loads and installation are running as stochastic loads. A 20kVA/28kWh BESS is used to realize the practical evaluation of the ACES algorithm. The PQX3 records three measurement points of loads, storage and micro gird connection point with their reactive and active power flow and calculates a real time system forecast used for the ACES controller.

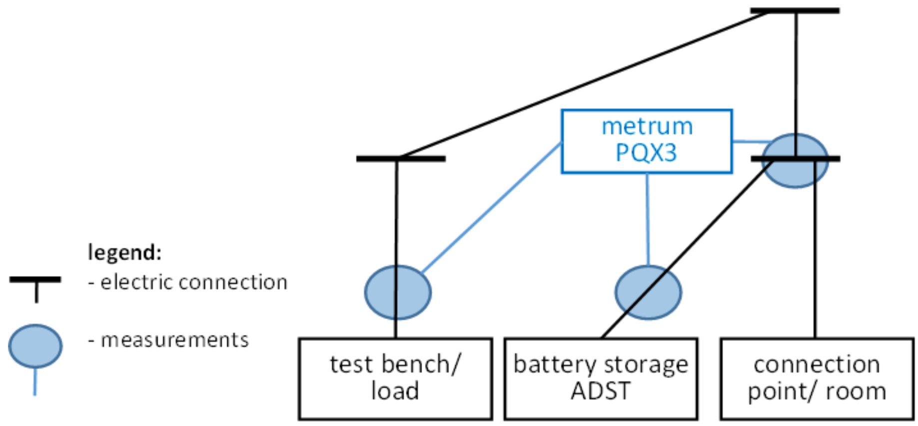

Figure 10 PQ-measurement installation in the demo side of ACES

2. WP4 DEMO 3: Germany (Fraunhofer)

2.1 Pre-study & data gathering & analysis for requirement specification

One of the main challenges of the ACES-system is the ICT structure, especially integrating the different components with their interfaces, functionalities and system requirements. Nevertheless, different converters are needed and a central data storage was developed an IFF-demo to handle the communication and information requirements of the system. Some of the components, such as PV-generation, wind-generation and loads where classified as passive components, so the system integration was limited data acquisition. An active control or impact on their operation profile was not planned. Components such as electric vehicles, hydrogen fuel cell, electrolyzer and especially the BESS do need bidirectional interfaces for monitoring and control. Additional important requirements for the communication to the active components in the ACES system are availability, resilience, reliability and performance of the communication structure.

In general IT-structure all data transfer should run through the centralized component pictured as data base in Figure 11 including the needed services realizing the interfaces with the specific protocols, which are more detailed described in the further chapters. The PQ-measurement device (Metrum) has a separate role in the ICT-structure, because of the additional task in the ACES-system and the resulting requirements.

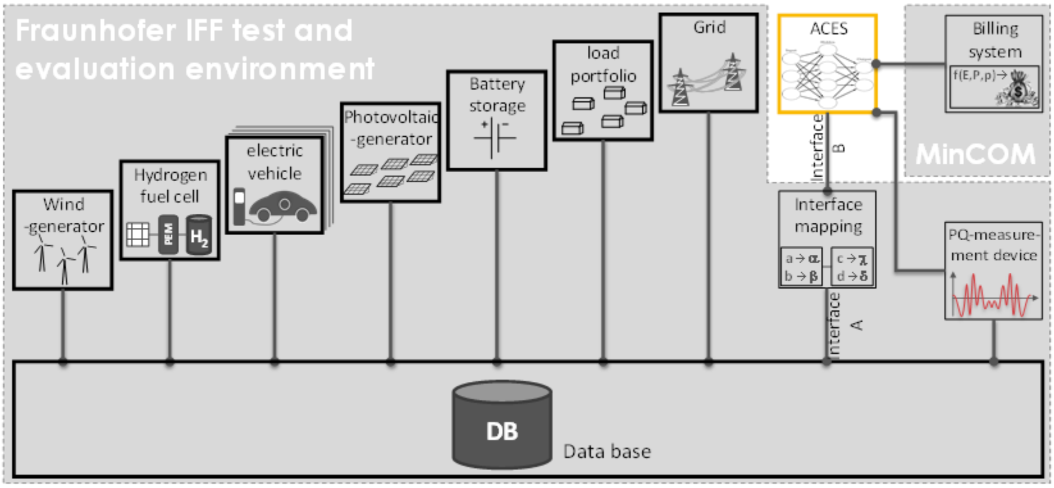

Figure 11 General overview of planned demonstrator ICT structure and integrated components

The implemented PQ-system of metrum fulfils two important rolls. The high precisely and dynamic measurements for the local complex infrastructure of loads, generation and storage is done by the PQ-device such as the real time load forecast for the ACES-algorithm. The requirements and functionalities are detailed in the report of metrum.

The resulting communication structure was realized as shown in the example for the BESS integration in Figure 12. The processing, monitoring and control such as the central data management and the system integration of the billing system services of MinCOM was realized in the ACES component developed by EMBRIQ. Detailed description can be fuound in the reports of Embriq, MinCOM and in relation to the IFF-demonstrator in the further chapter.

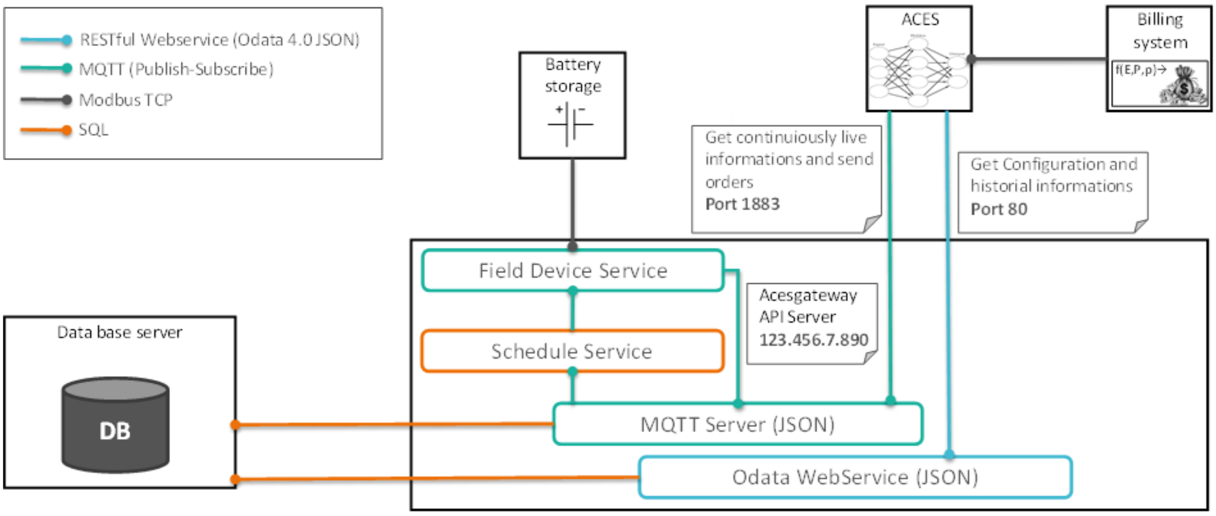

Figure 12 ICT structure for German Demonstrator example of BESS system integration

2.1.1 ACES Algorithm for cell analyzing - Examples of methods to count charging cycles in account to aging.

Characterisation and modelling of the BESS in ACES system

The ACES-system relies on accurate forecasts of the operation and characterization of the components in the complex energy system. The BESS as storage component plays an important role in the system and needs to be characterized proper. The IFF brings the expertise, experience and know-how with system structure and operation of different BESS in a wide range of power and capacity classes, starting from several kilowatts up to megawatts. In the defined use-cases the main criteria for BESS operation are increase of reliability, increase of power quality, load shaping and economic aspects. Especially for the last named aspect, the systems cycle life plays an important role in this considera-tion. Even if an economic surplus is based on high system usage, an overwhelming use of the storage system reinforces cell aging end ends up in shorter system lifetime. Thus the aging do have a significant influence to the control algorithm and calculated schedule of the BESS operation in the ACES system. For the ACES system, an analysis of different cell cycle valuation methods was done to identify the best balanced method between computational performance and accuracy for the aging impact of BESS operation.

Full cycle equivalent and types of cycles

When determining the cycle life, usually only full cycles are considered. A well-known procedure is the calculation of the Full Cycle Equivalent (FCE).

$$FCE = \frac{1}{2 \cdot C_{\text{Stor}}} \cdot \sum_{i=1}^{n} |E_i|$$

This method is limited to the energetic balancing and puts the total converted energy E_i in relation to the storage capacity C_{Stor}. The resulting value corresponds to a mode of operation with exclusively maximum cyclical depth and is regarded by the specialist elite as a common means of ageing estimation.

However, a complete and uninterrupted charge and discharge process rarely occurs in real use. For a better lifetime estimation, different types of cycles should be introduced. In ACES, the following cycle types are considered:

Sub-cycles: A sub-cycle is a time-related process consisting of loading and unloading, each with an energy conversion below the design capacity of the system. A subcycle is considered completed, provided that the original state of charge is reached again.

Half cycles: A half cycle is a monotonous process which describes a loading or unloading process. The energy conversion can correspond both to the full rated capacity (without specifying the cycle depth) and to a part of it (indication of the cycle depth required). Two consecutive half cycles of the full rated capacity thus form a full cycle.

Cycle depth: With the aid of the depth of discharge range $DODr$, the extent of a partial or half cycle is described. The information is given in relation to the rated capacity and can be between 0% and 100%.

Guarantee cycles: guarantee cycles are equivalent to the cyclic life of an electrochemical store specified by the manufacturer and usually take the form of full cycles. It is ensured that the end-of-life criterion ($C \leq 0{,}8 \cdot C_N$C≤0.8 · C_N) is not reached during the passage through the specified number of cycles.

Depth of cycling consideration

A more realistic estimation can be made by using the procedure described in "Method for determining the ageing of a battery"[3]. Due to the fact, that the active material used in the cells corresponds to cycle depth and thus more unwanted side reactions take place, the lifetime consideration is not limited to full cycles. For cycles with different discharge depths, adequate numbers are defined and thus the different ageing contributions are taken into account. The distribution (see Figure 13) according to „Selection and Performance-Degradation Modeling of LiMO2/Li4Ti5O12 and LiFePO4/C Battery Cells as Suitable Energy Storage Systems for Grid Integration With Wind Power Plants: An Example for the Primary Frequency Regulation Service"[4] is used as a basis for the different cycle depths in ACES. The measured values shown correspond to the guarantee cycles if the charging/discharging is limited to the assigned cycle depth. The function of the guarantee

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[3] O. Bitsche, B. Spier, C. Ashtiani and R. Lagerstrom, "Method for determining the ageing of a battery". Germany/EU Patent EP 1 450 173 A2, 08 25 2004.

[4] M. Swierczynski, D. I. Stroe, A.-I. Stan, R. Teodorescu und D. U. Sauer, „Selection and Performance-Degradation Modeling of LiMO2/Li4Ti5O12 and LiFePO4/C Battery Cells as Suitable Energy Storage Systems for Grid Integration With Wind Power Plants: An Example for the Primary Frequency Regulation Service," IEEE transactions on Sustainable Energy, Bd. 5, Nr. 1, pp. 90-101, 2014.

cycle number N as a function of the cycle depth $DODr$, as shown in following equation, was determined by data fitting.

$$N = c_1 \cdot (DODr)^{c_2}$$

From the functional relationship, it follows that the coefficient c1 corresponds to the number of guarantee cycles provided by the manufacturer with a $DODr$ of 100 %. Due to this, an easy transferability to other lifetime values is ensured. With the help of the determined equation and the usual manufacturer specification of guaranteed full cycles, a corresponding number of virtual warranty cycles N can be determined for each cycle depth $DODr$. Figure 13 shows the resulting course of the cycle distribution (fitting function) and the underlying measured value distribution of the cycle service life.

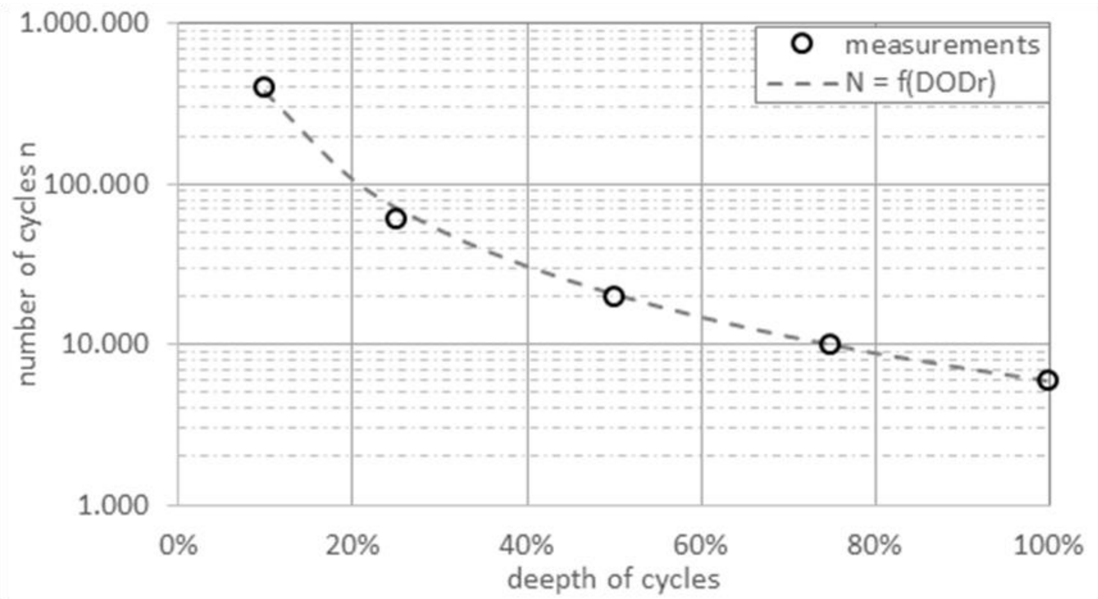

Figure 13 Cyclic battery life of Li accumulators in relation to discharge depth[5]

For the further considerations the cycle depth is defined by $m = 10$ equidistant areas w with a range of 10 % each. Based on this distribution, a weight h_w, which is based on the results of the distribution function, can be determined for all n_w cycles for $0 \le n_w \le N_w$ and the corresponding discharge depth $DODr_w$, so that a representative ageing fraction A_w can be determined for each area w.

$$h_w = \left.\frac{1}{N_w}\right|_{DODr_w}$$

The total ageing state A then results from the sum of the weighted cycle numbers.

[5] S. Balischewski, "Multifunktionaler Einsatz von Batteriespeichern in elektrischen Verteilnetzen - optimale Auslegung und Betrieb", Dissertation, Magdeburg, 2020, http://dx.doi.org/10.25673/32637

$$A = \sum_{w=1}^{m} A_w = \sum_{w=1}^{m} n_w \cdot h_w$$

Principle of half cycle

Beside the cycle weighting, their determination is decisive for a meaningful estimation of service life. For the determination of the individual partial cycles with different cycle depths, the path over the half-cycles can be chosen according to **Error! Reference source not found.Error! Reference source not found.**, whereby each continuous and monotonous curve segment is counted as a half-cycle with corresponding depth of charge/discharge.

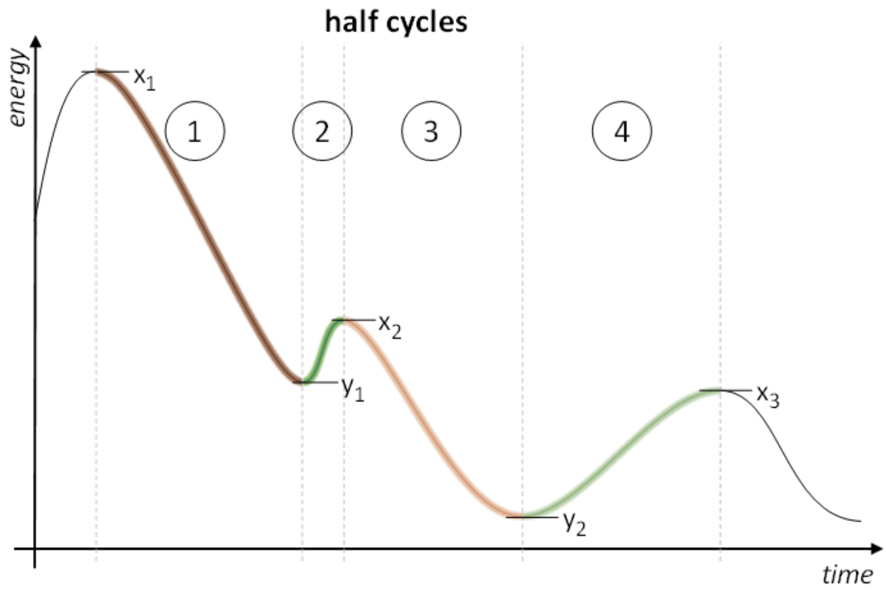

Figure 14 Counting of half cycles[6]

Principle of the Rainflow Counting Algorithm

In order to perform a more advanced evaluation, the Rainflow counting method according to "ASTM E1049-85(2017): Standard Practices for Cycle Counting in Fatigue Analysis,"[6] was combined with the previously described weighting as a function of the cycle depth in this project. The Rainflow Counting method originates from materials science and was developed for the analysis of vibrational stress of components, which in reality almost without exception occurs with varying amplitude, and a service life estimation based on it. The name is derived from the rainwater flows over pagoda roofs, on which this method is based. While using this method, a series of reversal points is built from a temporal load sequence and then the occurrence of closed hysteresis (derived from the stress-strain diagram of materials science) is determined, which are defined as fundamental damage events. At this point, the analogy between materials and battery cells, on

[6] "ASTM E1049-85(2017): Standard Practices for Cycle Counting in Fatigue Analysis," ASTM International, West Conshohocken, PA, 2017.

which the transfer of the process to battery ageing is based on, becomes very clear. Regarding storage systems, these hysteresis can be interpreted as cycles with corresponding cycle depth. Areas not covered by this are included as residuals in the further counting and thus add up to a stretched cycle over time (see Figure 15). This represents a significant improvement in determining the storage aging.

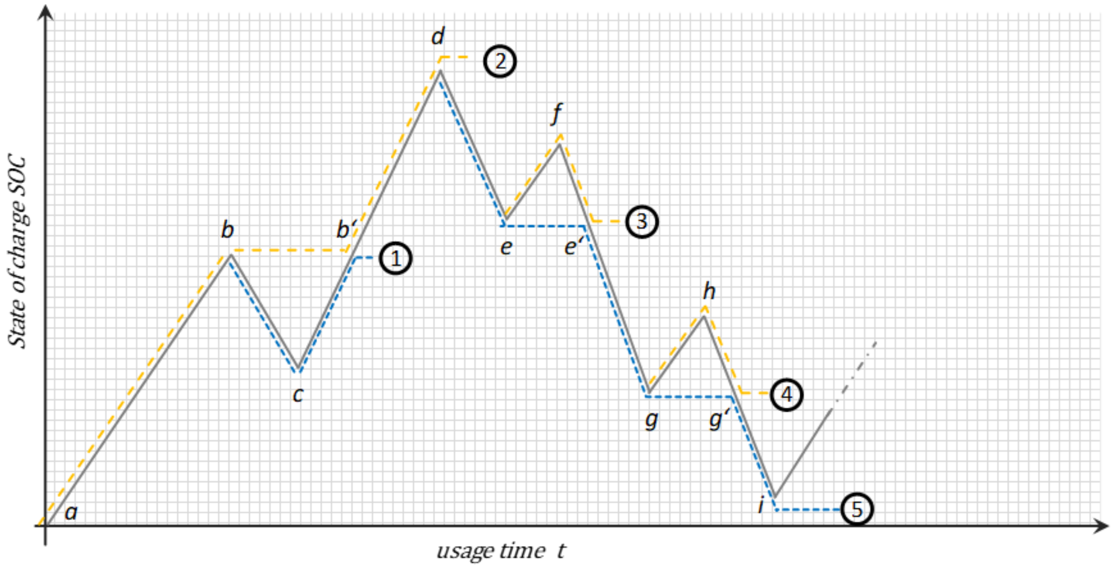

Figure 15 Principle of Rainflow counting to determine cyclic ageing[6]

The curve in Figure 15 shows the determination of the cycles very well. Starting from a starting point (t=0), the curve is first graphically searched for recurring minima (valleys) and then for maxima (peaks). A cycle is considered as "complete" when the level of former minimum (or maximum) has been reached or fallen below again (or exceeded at maximum). Starting from the minimum a, the value is compared with the following minimum c. However it is not less than or equal to the value of a, so that the cycle is continued via points b and b'. Since none of the following minima reaches the value of a, cycle 2 is counted as a half-cycle with the cycle depth (value) 0.5·(*d-a*). The included points *b,c,b'* form a self-contained cycle and are considered as partial cycle 1 with the value b-c. Following the same pattern, a half cycle 5 can be determined via *d,e,e',g,g',f*, which is interrupted several times by the closed subcycles 3 (*e,f,e'*) and 4 (*g,h,g'*). Due to the extraction of these occurring intermediate cycles, extended (half) cycles interrupted by the intermediate cycle can be identified as such and accordingly assigned to a cycle depth with a higher weight. These results in a more realistic distribution of the cycles compared to the originally propagated half-cycle count.

2.2 Specification of client's needs, goals and functional requirements

Business model for charging of electric vehicle's fleet [7]

For implemented and tested demonstration solution at Fraunhofer IFF, the possible use case scenario can be application of stationary battery storage system as supporting component in the charging infrastructure of electric vehicle's fleet. The developed business model is a theoretical example.

In the coming years there is expected a tremendous growth in the usage of electric vehicles (EV). The result will be an increasing amount of EV charging operations, where requirements for charging management strongly depend on frequency, power demand and time of charging. A high simultaneity factor of the charging processes together with inherent high and constant load demands can lead to a higher stress on grid assets and in extreme situations to violations of grid operation constraints. The costs to guarantee availability of charging capacity according to mobility requirements on the one hand and the need to protect the assets of the charging infrastructure on the other have to be calculated and covered by the EV user. Intelligent load management using batteries for load balancing including also the ability to invoice charging services would be suitable and beneficial to owners of said charging infrastructure.

The following business model has been specified, which can be demonstrated to potential owners / investors of charging infrastructures at Fraunhofer IFF in Magdeburg. In Figure 16 the principle layout of the demonstration scenario is described. The roles of the chosen business scenario are defined as follows:

Owner (investor): Logistic company – we used a real German company called DB-Schenker

Operator: Logistic company

User (beneficiary and receiver of invoices): (i) cost account of DB-Schenker's fleet, (ii) subcontractors extending the fleet of DB-Schenker, (iii) employees, (iv) visitors & guests.

The assets used are (i) roof top PV, (ii) battery, (iii) MV/LV micro- grid and the connection to the public energy network, (iv) 1 … n charging station, (v) mini CHP, and (vi) 1 … m EVs. The software for energy management, charging operations and the billing / accounting solution shall be provided as a service and thus shall be a part of OPEX.

[7] Please note: the business model describing e-car charging in this demo is a theoretical example.

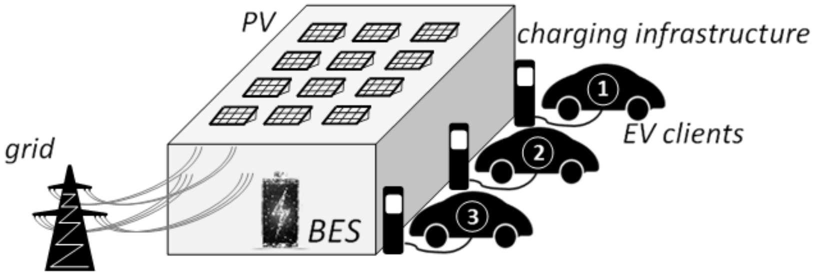

Figure 16 Demonstrator FhG IFF (Magdeburg) logistic company with own EV fleet and charging infrastructure

The system can be classified as MicroGrid. It generates its own cheap energy from PV and CHP. The generation characteristics cannot be controlled or can only be controlled to a limited extent for the CHP unit. PV is dependent on meteorological factors and is a strongly fluctuating and difficult to predict variable. The generation curve of the CHP is subject to seasonal and day-dependent fluctuations. Electricity generation can be better predicted. The site-specific electricity demand consists of office buildings including personnel, production - printing plants, logistics - electric vehicles. The charging processes of visitors and logistics service providers must also be taken into account.

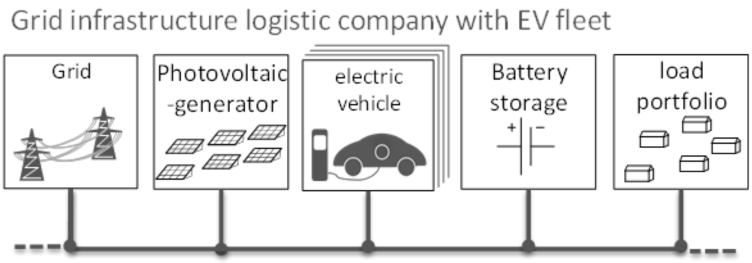

Figure 17 ACES managed components of the demo scenario at FhG IFF in Magdeburg

A battery storage is used to offer several functions in the MicroGrid. The following ACES business use cases can be demonstrated by this application:

- **Avoidance/reduction of peak loads:** For commercial user in Germany, the electricity price consists i.a. of energy price and power price. The power price is based on the maximum peak power of a billing period. This can extend over a year, a quarter or a month. Typically, it is one year. In negative scenario, the simultaneous charging of electric vehicles and peak consumption may lead to a one-off large peak load, which causes very high fixed annual costs. Therefore, the economic potential of battery storage application for peak load reduction/ avoidance results from the local power price.
- **Avoidance of grid feed-in:** There is a lower remuneration for the energy feed-in into the grid than the electricity purchase costs. Own generation needs to be matched to the electrical demand. The economic potential results from the difference between the electricity remuneration according to feed-in tariff and the electricity purchase costs.

- **Sale of electric energy at the charging stations:** At the charging stations, electrical energy from the company's own production facilities is mainly to be sold. This presupposes that there is overproduction that covers the demand or is stored in the battery buffer to be sold to the charging station user. It is also possible to charge the vehicles in a controlled way in order to adapt the consumption to the generation – see Figure 16.
- **Resale of electrical energy:** If the demand cannot be covered by own production, it is purchased from the grid and resold.
- **Avoidance of reactive power costs:** The reactive power consumption is invoiced by the grid supplier. This reactive power can be provided by compensation systems. It is also possible to use inverters (PV or battery) for this purpose. In the future, electric vehicles or DC charging stations can also be used for this purpose.

For the proposed business use cases a billing solution has been implemented by the project partner MINcom Smart Solutions. The detailed description on how the above services will be invoiced or accounted is given in the Work Package 5 Report: "Deployable Storage-to-Cash Solution".

2.3 Specification of Adaptive Control parameters & functionality

Requirement analyses out of use cases und story lines

In ACES project different use-cases, story lines and business models were identified to define the requirements on the ACES-algorithm and the needed infrastructure and test and evaluation environment. For the Demonstrator environment a main challenge was the realisation of flexibility to build up realistic generation, load and storage behaviour to test and evaluate the ACES system. For the demo side setup a portfolio of different characteristic profiles and system models for loads, generation and storages where available (Figure 18). In next step by prioritized use cases a technical set up was defined.

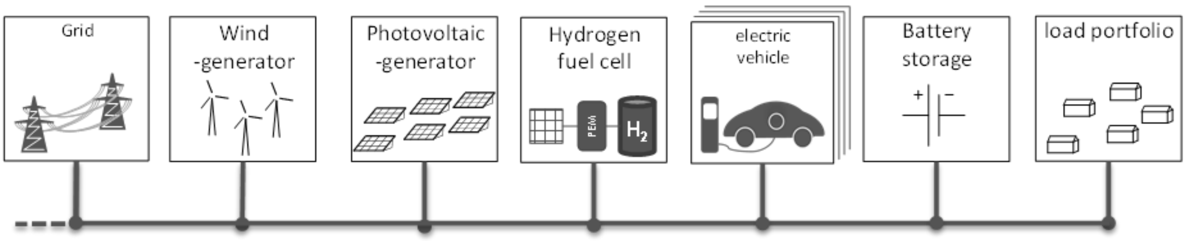

Figure 18: imageable components' in a demonstrator set up of a complex micro grid

The following example scenario gives an example of requirement analyses.

Description of story line and demo case which should be realized for the algorithm development (eg. hotel with weak power supply and generation)

- **Peak shaping and peak shaving**
    - The battery/ storage schedule is calculated from ACS algorithm and communicated to the battery system.
    - The battery/ storage state is communicated to the ACS system as input for adaptive calculation/ control
    - All system safety functions are realized by the battery/ storage system. If the control command is outside operation window, the command is ignored and information is reported/ communicated to ACS system
    - All measurements and test relevant data are stored and if possible evaluated online or evaluated later manually
    - Additional grid measurements are taken by metrum power quality instruments for documentation of grid impact
- **Reactive power**
    - The battery/ storage schedule is calculated from ACS algorithm and communicated to the battery system
    - The battery/ storage state is communicated to the ACS system as input for adaptive calculation/ control
    - All system safety functions are realized by the battery/ storage system. If the control command is outside operation window the command is ignored and information is reported/ communicated to ACS system
    - All measurements and test relevant data are stored and if possible evaluated online or evaluated later manually
    - Additional grid measurements are taken by the metrum power quality instruments for documentation of grid impact

Out of the defined story line and scenario the environmental conditions for the technical conditions and requironment are difined.

Requirement analyses out of technical characteristics

In the scenario load shaping in a micro grid infrastructure with generation, load and storage the requirements on technical equipment and the algorithm can be explained as seen (Figure 19). In the pictured graph, a load schedule (red) is supposed to be harmonized within a load band P_{max} and P_{min} (black doted). Therefore, the algorithm is calculating the schedule for the BESS (orange). The shaped load schedule is inside the limit (green doted). Out of this theoretic analysis the three cases, (1) charging, (2) idle and (3) discharging, do occur.

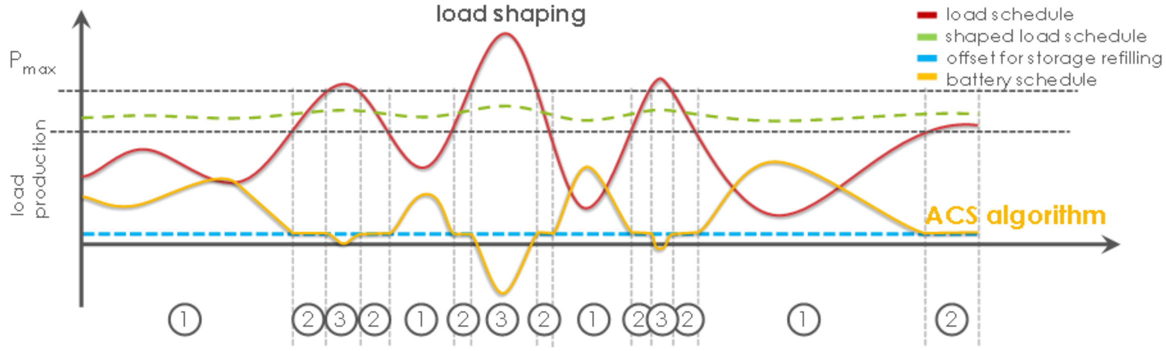

Figure 19: exmplae graph of a scenario run at a demonstrator showing power levels of load, battery use and resulting load shape

The resulting function of long-term schedule analyses gives information about the storage capacity, power and system dynamic requirements. Realistic schedules are much more complicated so the resulting algorithm, such as the ACES algorithm is much more complicate. For this reason the used measurement devices and system components are of high measuring accuracy and high sampling rates. In combination with an integrated load forecast algorithm, developed in ACES project, the BESS schedule should be optimized.

2.4 Installation & testing energy storage system

2.4.1 Overview of the different test and evaluation environments

The Fraunhofer IFF has different test and evaluation environments, which were build up or modified for the ACES demo site implementation.

The overview and technical specification of demonstrators for NPS-sensor and battery cell investigations and BESS control algorithm applications at Fraunhofer IFF Magdeburg are given in

Table 2: Overview of demonstrators at Fraunhofer IFF Magdeburg

Demo	Name	Type	Specification
Test bench for single cells NPS-sensor environment			
NPS-1	80W 2-Channel Battery test bench for single cells and small stacks	Test environment for small battery stacks and battery cells	Bidirectional DC-source with test and measuring application, ICT – interfaces and test shedules and interface for simulation environment (MATLAB) Channel 1: (DC-voltage-range U = 0 V-9 V, DC-current I = 0-5 A, DC-power P = 0-45 W) Channel 2: (DC-voltage-range U = 0 V-12 V, DC-current I = 0-3 A, DC-power P = 0-36 W)
Evaluation and test environment for PQ-measurement and ACES-algorithm			
PQ-1	15kW Battery test bench for cells stacks	Test environment for different cells stacks and battery	Bidirectional DC-source with test and measuring application, ICT – interfaces and test shedules and interface for simulation environment (MATLAB) (DC-voltage-range U = 0 V-360 V, DC-current I = 0-120 A, DC-power P = 0-15 kW
PQ-2	200kW Battery test bench for cells stacks	Test environment for different battery stacks	Bidirectional DC-source with test and measuring application, ICT – interfaces and test shedules and interface for simulation environment (MATLAB) (DC-voltage-range U = 9 V-900 V, DC-current I = 0-600 A, DC-power P = 0-200 kW
PQ-3	20kW stationary battery system SRS 2025	Commercial stationary battery system	Bidirectional stationary battery system for low voltage grid application (3-phase, AC-Power P = 20 kW, nominal battery capacity E = 25 kWh)

2.4.2 Installation of infrastructure and physical environment of demo site BESS operation with ACES algorithm

Demonstrator for NPS-sensor operation optimized BMS functions

The component **NPS-80 W Battery test bench** is a bidirectional power supply (voltage range 9/12 V; max. current 4/3 A; max. power 80 W). The BMS, EMS and controlling software is not included in the test system. The interfaces allow the implementation in different systems and simulation environments such as MATLAB, LabView etc. The Fraunhofer IFF has different kinds of battery cell packs with BMS, which can be utilized to test other battery system devices. It allows praxis tests of the storage behaviour, the BMS system, ICT and interfaces to the external controller as well as the integration of sensors and measurement. The system allows high flexibility to configure different cell-chemistries and utilize them with precise low current schedule. The high dynamic and bidirectional functionality also allows charging and discharging profiles for single cells and small cell stacks.

- Measuring of electrical parameters and behaviour for especially small current
- Measuring/ testing/ implementation of ICT devices and interfaces (Modbus TCP, CAN-Bus)
- charging and discharging profiles for single cells and small cell stacks

Demonstrator for BESS operation with ACES algorithm

The component **PQ-1 15 kW Battery test bench** is a bidirectional power supply (voltage range 360 V; max. current 120 A; max. power 15 kW). The BMS, EMS and controlling software is not included in the test system. The interfaces allow the implementation in different systems and simulation environments such as MATLAB, LabView etc. The Fraunhofer IFF has different kinds of battery cell packs with BMS, which can be utilized to test other battery system devices. It allows praxis tests of the storage behaviour, the BMS system, ICT and interfaces to the external controller as well as the integration of sensors and measurement. The system allows high flexibility to configure different BESS systems, connecting battery storages. The high dynamic and bidirectional functionality also allows the emulation of load and generation profiles.

- Measuring of electrical parameters and behaviour
- Measuring of thermic behaviour
- Measuring/ testing/ implementation of ICT devices and interfaces (Modbus TCP, CAN-Bus)
- Emulation of load, generation or storage profiles

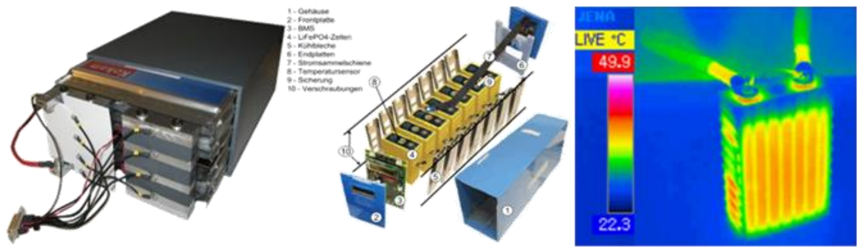

Figure 20 various battery stacks and battery chemistries as DUT

The component **PQ-2 200 kW Battery test bench** is a bidirectional power supply (voltage range 9-900 V; max. current 600 A; max. power 200 kW, efficiency >92%, accuracy 0,1%). The test bench consists of the bidirectional DC source, an external test environment with climatic control and test bench application with different interfaces and evaluation and automation functions. The system could be used to emulate different load or generation profiles and model even high dynamic behaviour.

- Measuring of electrical parameters and behaviour
- Measuring of thermic behaviour
- Measuring/ testing/ implementation of ICT devices and interfaces (CAN-Bus)
- Emulation of load, generation or storage profiles

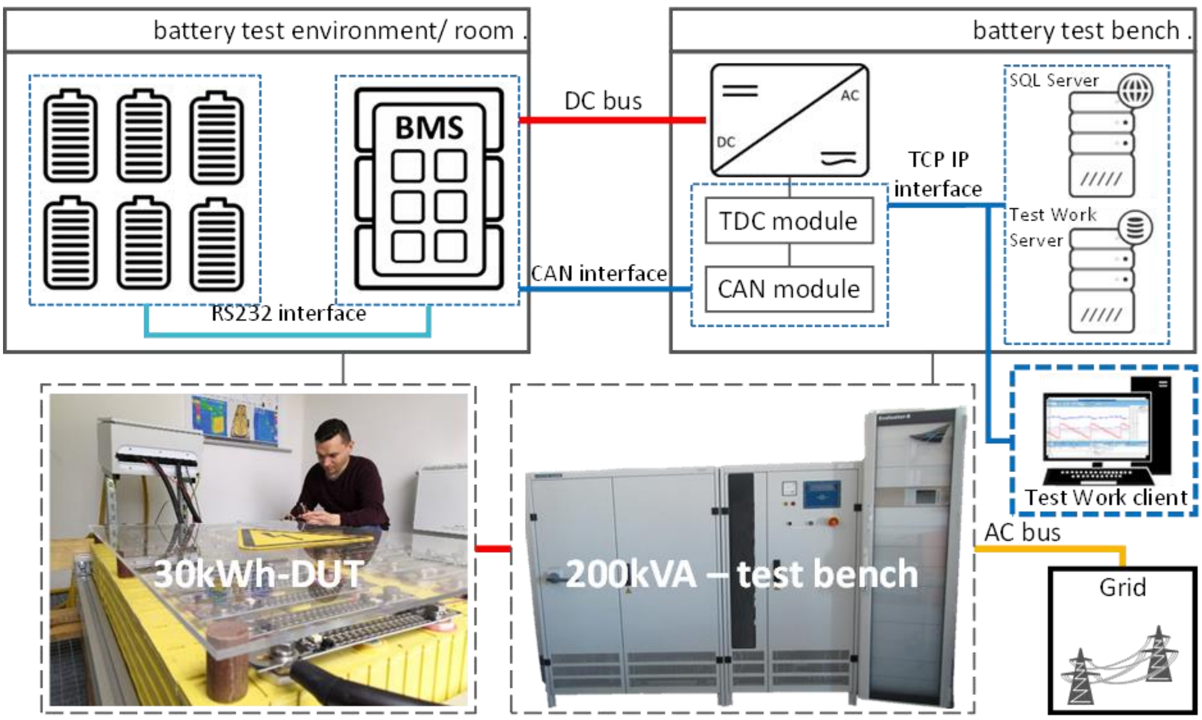

Figure 21: image of Fraunhofers battery test bench

The **PQ-3 20 kW/25 kWh stationary battery system** can be used in several battery applications. As seen in the sketch below the system can be integrated in a local micro grid to fulfil different services. For individual usage, the MODBUS TCP interface can be used. It allows the ICT integration in own energy management controlling systems. The safety function ensuring that the battery system is operating only inside the allowed working range to not stress the battery cells is managed by the system itself. Critical or wrong operation modes are avoid/blocked by the **EMS** and in second instance the **BMS** controller. The storage has different operation modes. It can work in island mode and on-grid mode. For load management and reactive power management the storage fulfils the requirements. It can be used as UPS, but with a short voltage gap only. The storage will be used to test the Business Use Cases defined by the ACES Project and will be integrated in the test and development environment of the PQ-measurement and the ACES controller. The operation icludes dynamic reactive and active power schedules.

- Energy storage for compensating divergence of generation and loads
- Providing active and reactive bidirectional schedule
- Testing/ characterizing of electrical parameters and behaviour of BESS
- Measuring/ testing/ implementation of ICT devices and interfaces (CAN-Bus)
- Testing and evaluate the ACES algorithm for BESS
- Emulation of load, generation or storage profiles

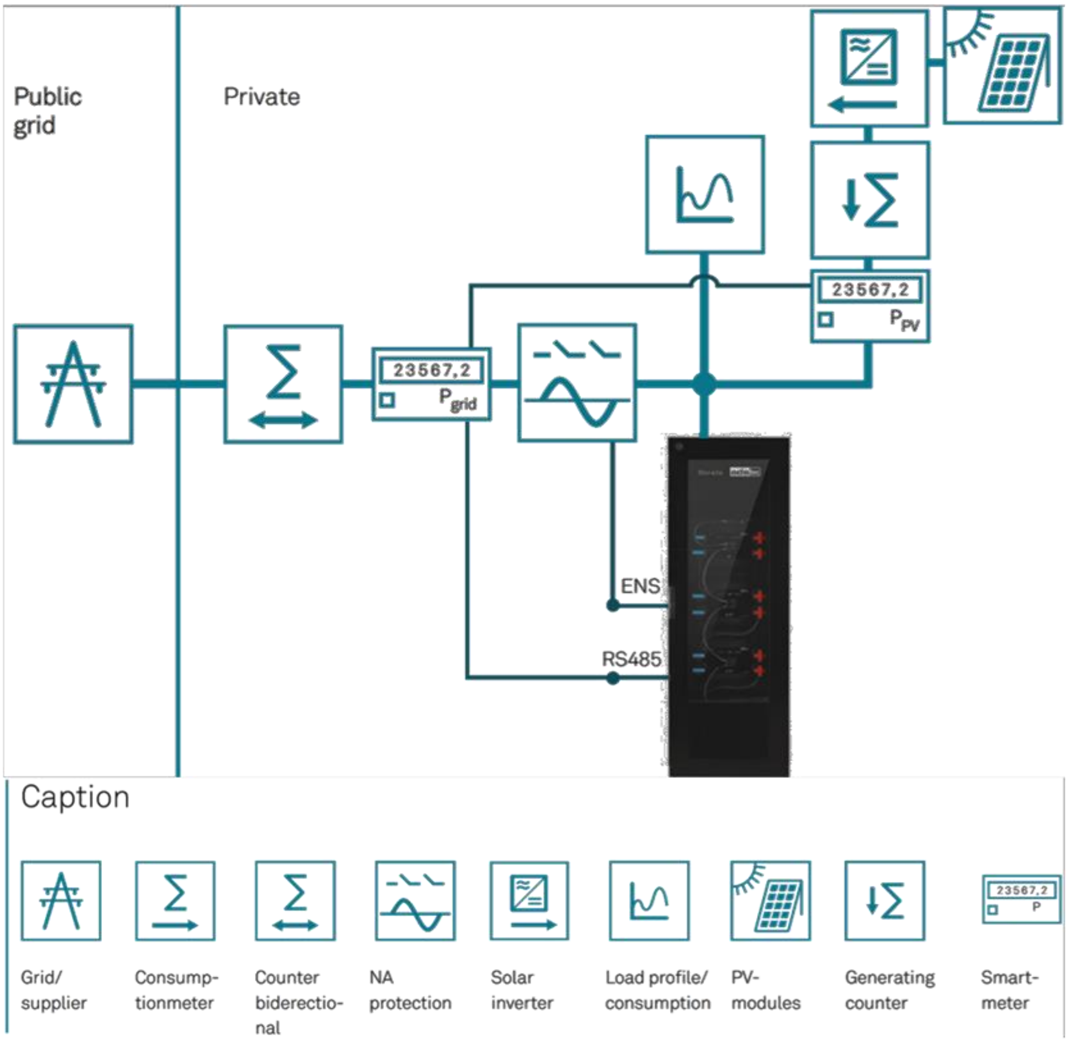

Figure 22: system description of BESS of demo side[source: ADS-TECH Datasheet/ specification]

2.4.3 Functional testing of monitoring and controlling of Battery Energy Storage

For the functional test of the installed energy storage battery system, as an active component of the ACES demonstrator, a monitoring and control program was implemented. Parallel to the Modbus Poll communication solution offered by the manufacturer, a program in Node-RED environment was implemented. It is a flow-based visual programming tool for connecting hardware devices, APIs and online services.

Connection's logic

Figure 1 Read Logic shows the basic principle of reading a value. The logic is subdivided into nodes, which have a specific function depending on the color and image of the node. The first node of each row sends a read command to the Modbus server (energy storage) according to the stored cycle time (1000 ms). The received object is first converted into a processable format (yellow node) and then assigned the corresponding unit (orange node). Finally, the determined value is output in the interface (blue node).

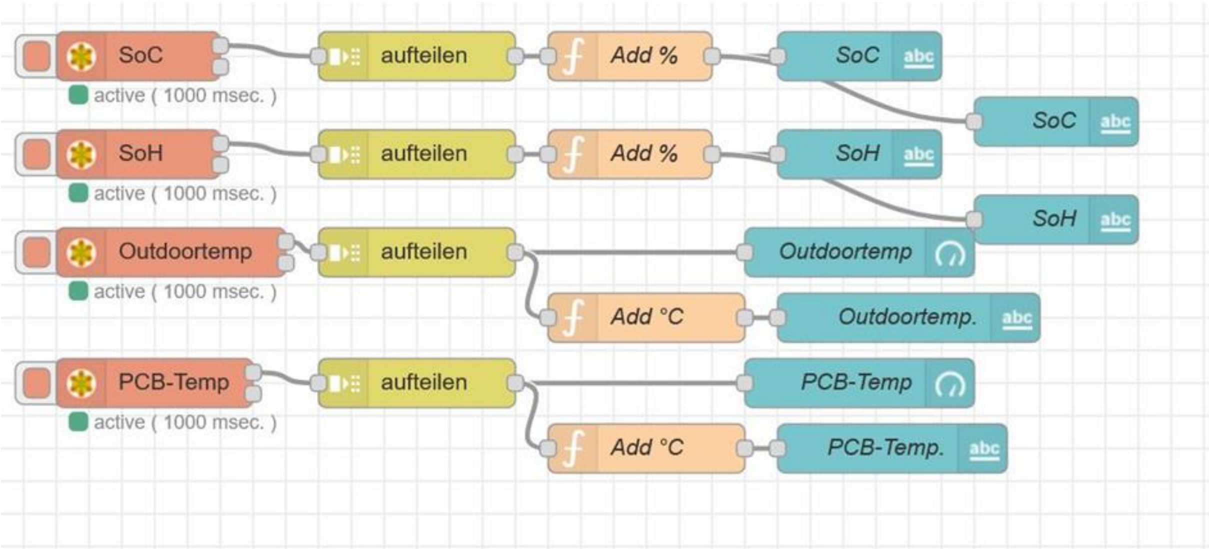

Figure 23 Figure 1 Modbus read logic

Unlike read logic, write logic first requires a value to be obtained from the user for input to the system. The Requested system state node shown in *Figure 2 Modbus write logic* contains a drop down menu with different operating modes for the battery storage. If the user selects a mode, the value stored in the node is sent to the server (SysStReg Write). As with a read command, a request must be followed by a response. This refers to the successful writing of the command into the respective register of the server and is specified by the Modbus TCP/IP protocol.

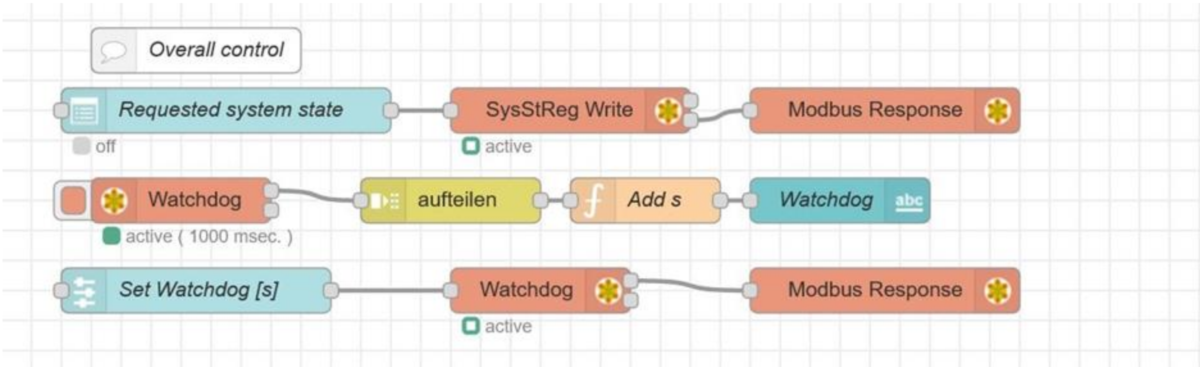

Figure 24 Figure 2 Modbus write logic

Battery Energy Management System

Figure 3 BMS tab with actual SoC, SoH and temperature shows the mentioned output. It provides information outdoor temperature, PCB - Printed Circuit Board temperature, SoC – State of Charge, SoH – State of Health. The value of the temperatures is output color-coded in order to be able to react quickly in the event of an error. The coding changes from green to yellow to red.

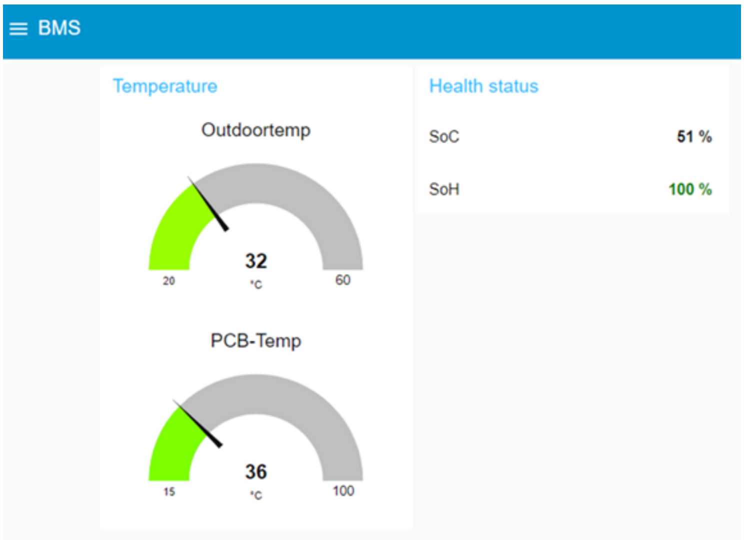

Figure 25 Figure 3 BMS tab with actual SoC, SoH and temperature

In some cases, a converter function is necessary to use the values, because bidirectional quantities like current or power are returned as unsigned integer. However, since the output requires signed integer the read value must be converted. *Figure 3 Converter function* shows the most effective conversion method without relying on the use of external functions.

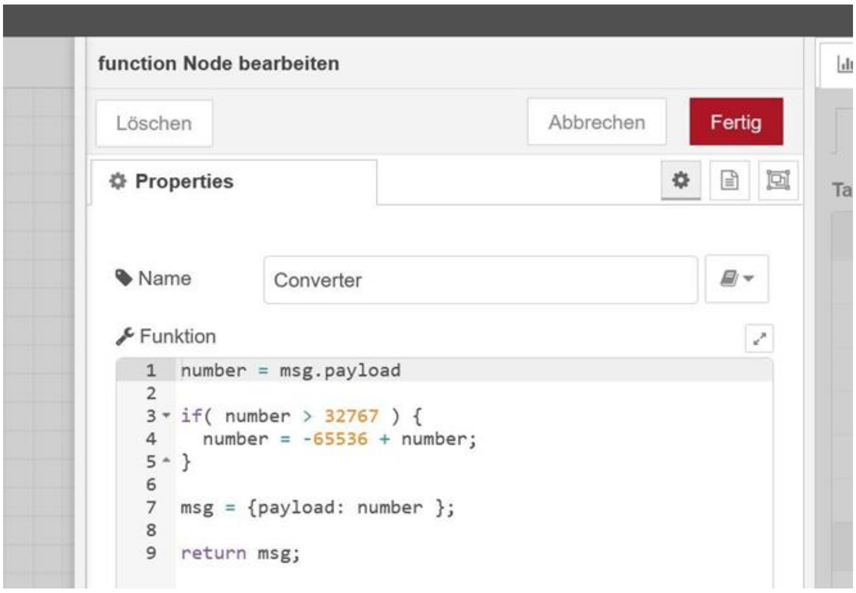

Figure 26 Figure 4 Converter function

The entire program has been divided into sections for clarity, corresponding to the white comment boxes shown in *Figure 5 Overall program part 1* and *Figure 6 Overall program part 2*. In addition to the logic already mentioned, in some cases it is necessary to scale the values, for example in the case of frequency in the node divide by 100.

Figure 5 shows an overview of the function blocks power and frequency monitoring, voltage and current. In addition, the first part of the power request can be seen, in this case for the first phase L1.

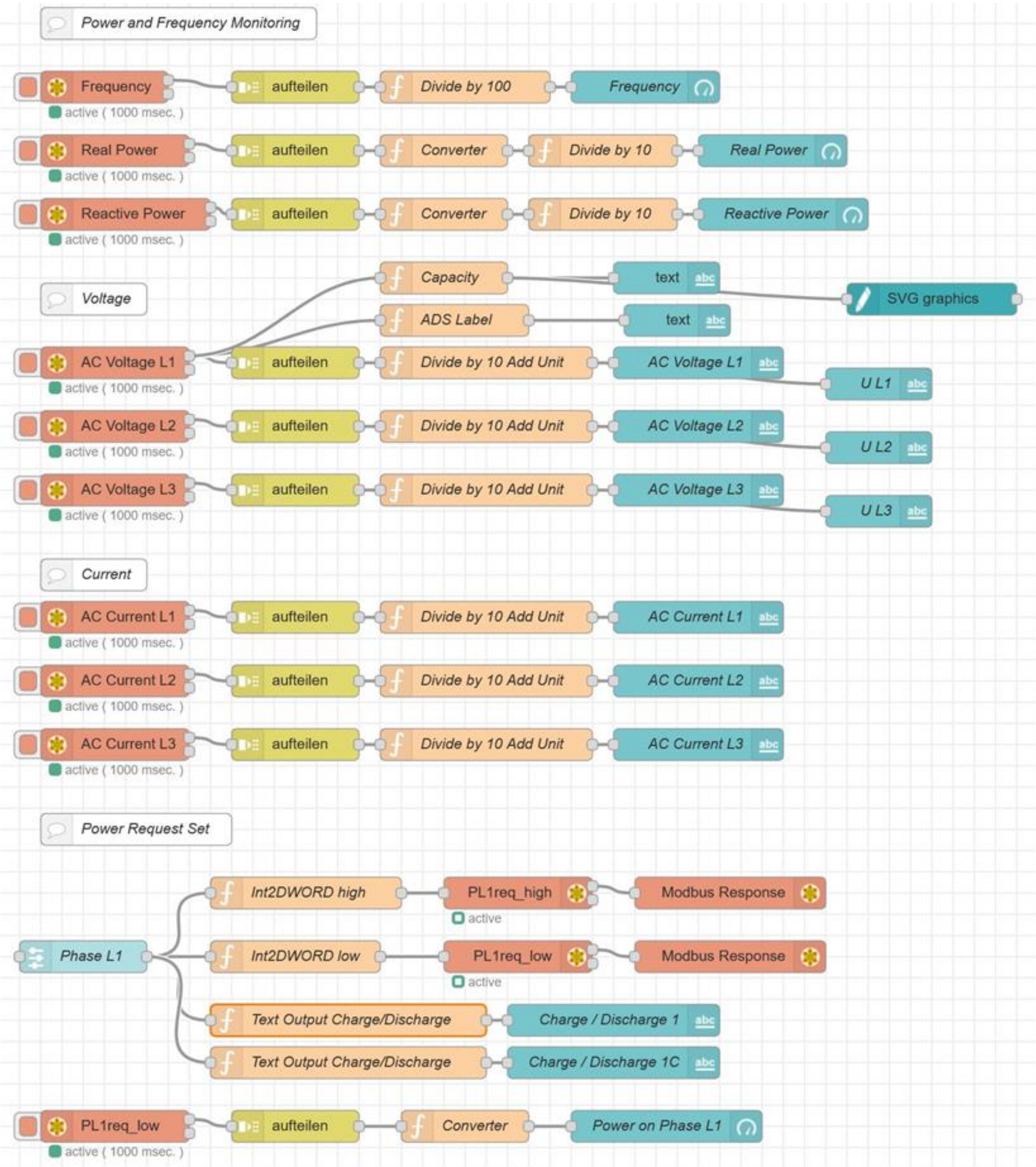

Figure 27 Figure 5 Overall program part 1

Figure 6 Overall program part 2 shows the second part of the program with the power request of the other two phases and the request of the phase angle in the node CosPhi. In addition to the operating mode already mentioned, a watchdog has been implemented to interrupt the sequence in case of an error and prevent serious damage to the battery storage.

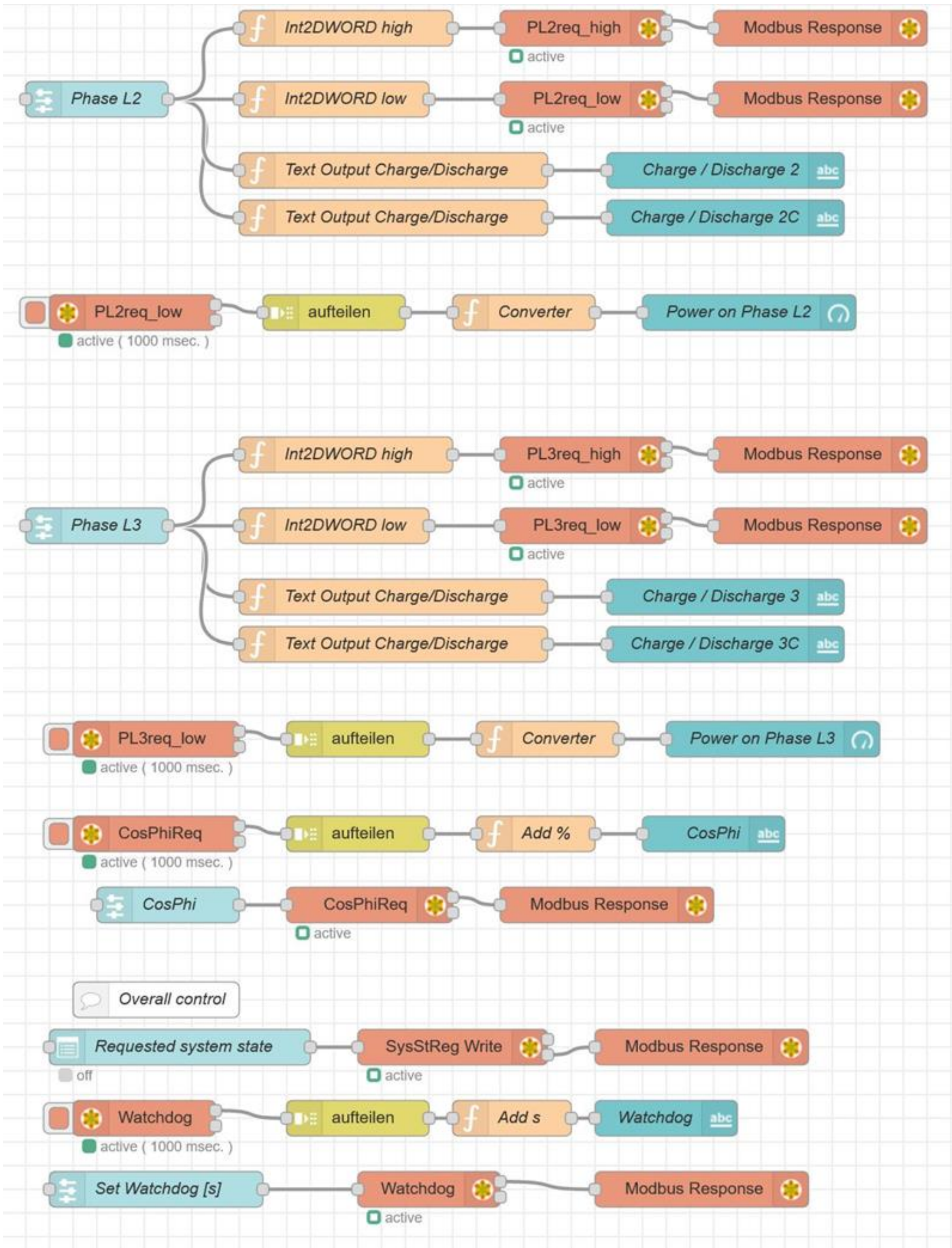

Figure 28 Figure 6 Overall program part 2

Finally, both a charge and a discharge were carried out with the help of the indicated program. As shown in *Figure 7 Monitoring charge* and *Figure 8 Monitoring discharge*, charging and discharging was performed at 5 kW. The surface shows the amount and direction of the current through corresponding fields. Likewise, both charged and measured power can be distinguished.

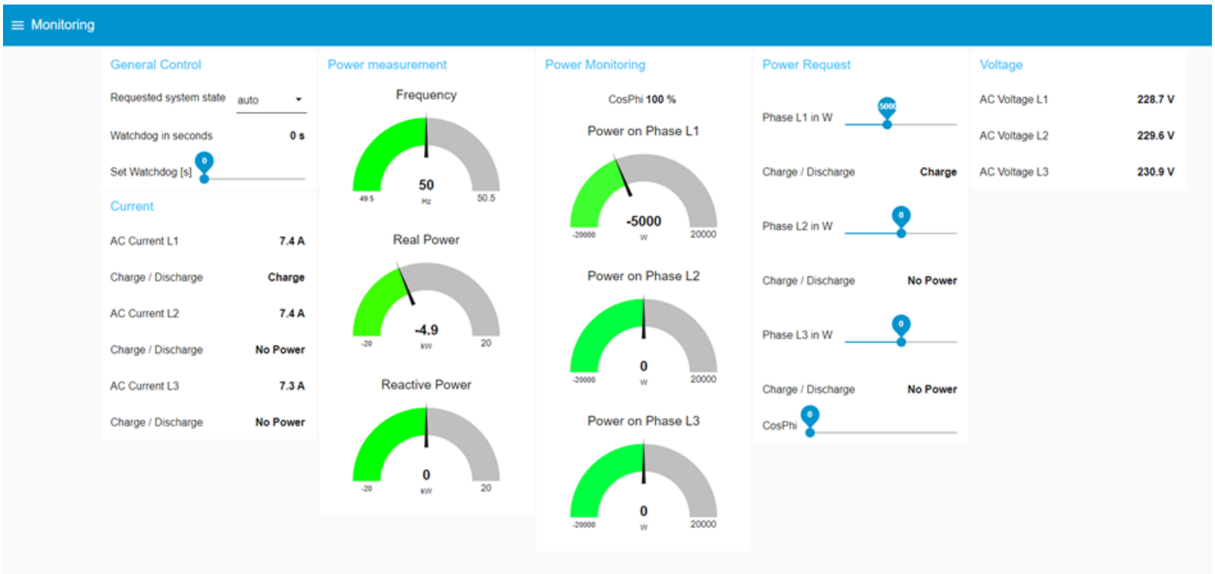

Figure 29 Figure 7 Monitoring charge

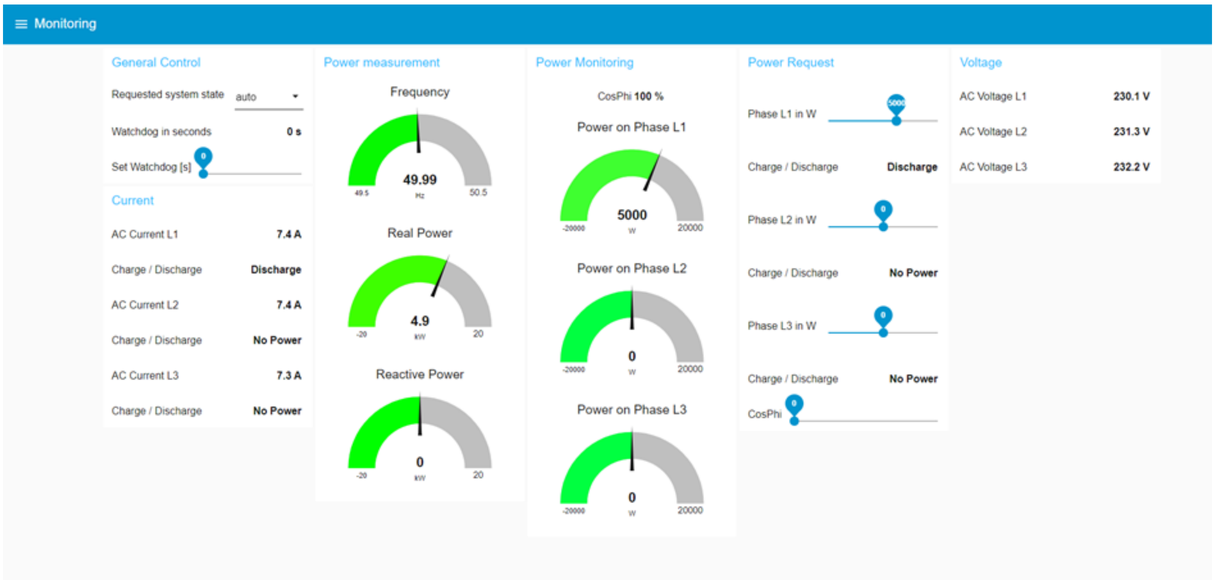

*Figure 30*Figure 8 Monitoring discharge

2.5 Installation and testing of Adaptive Control concept

For testing and demonstration of adaptive control concept of battery energy storage systems the living-lab environment has been designed and erected.

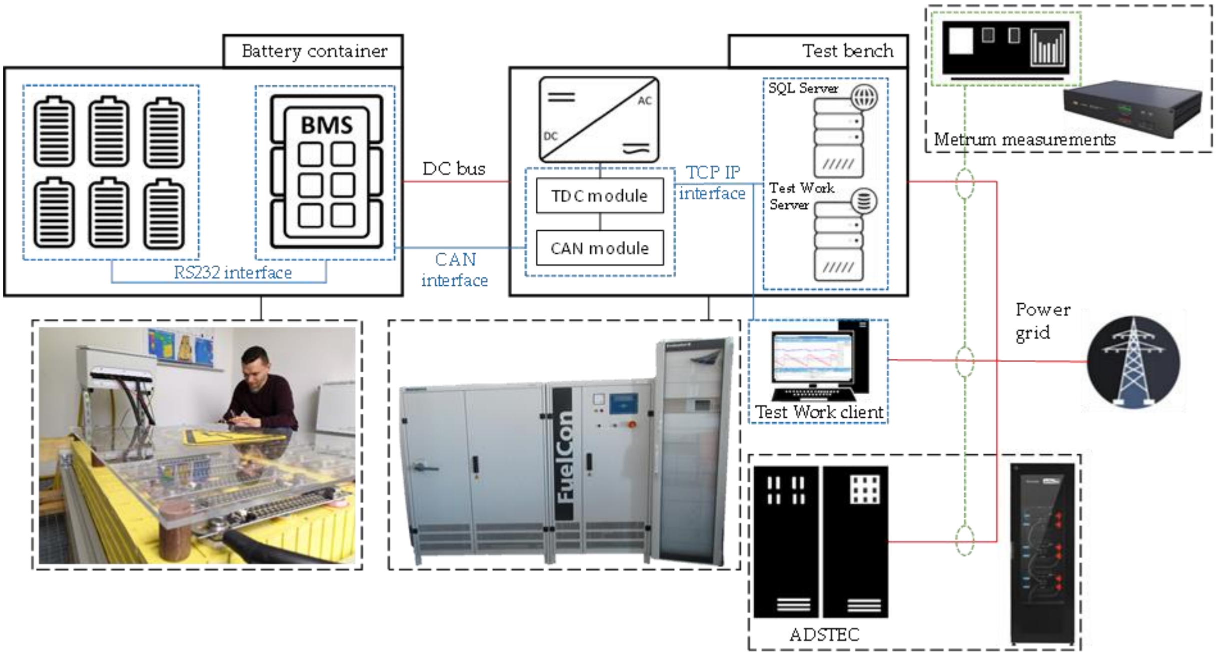

Figure 31 Test and evaluation environment for PQ measurement and ACES algorithm application

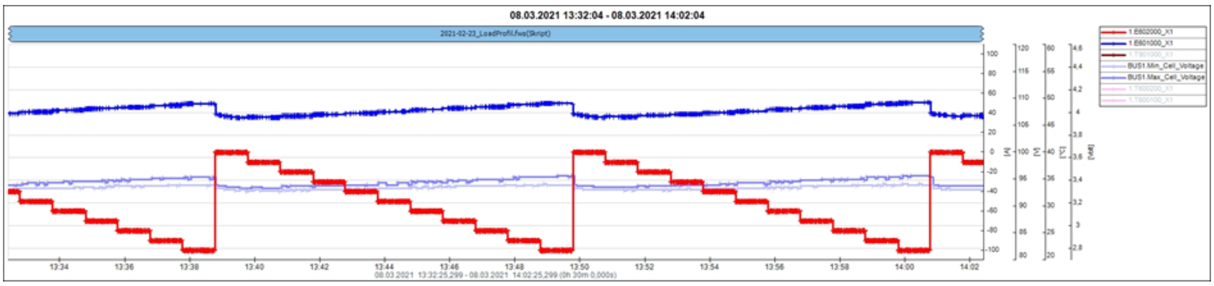

Figure 32 Sequential DC load profile for training an AI for grid control

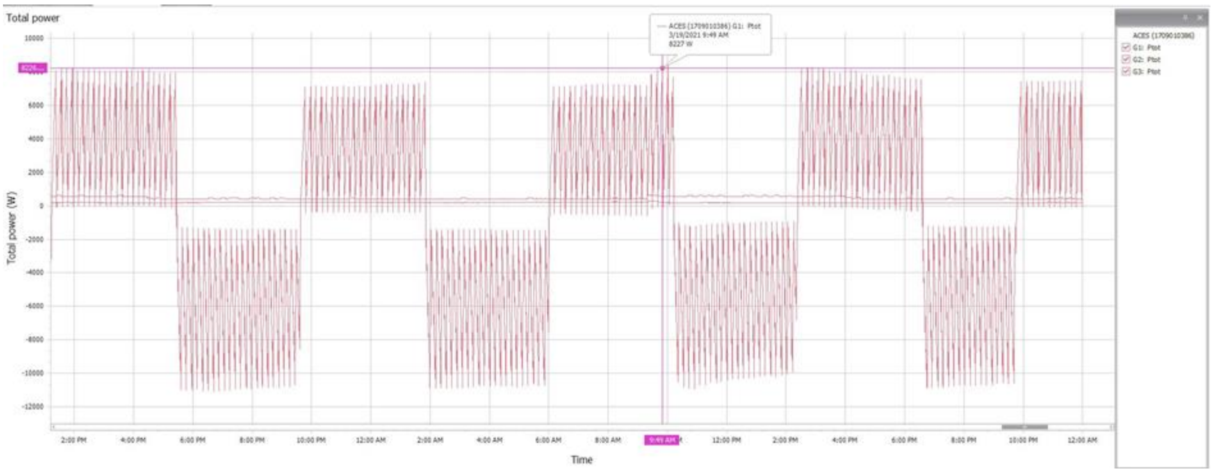

Figure 33 Measurement of DC load profile on AC side via Metrum

2.5.1 Installation of battery cell/pack with NPS sensors

Configuration of the NPS-sensor DUT

For the analyses of the NPS-sensor system, a test environment was defined. During the project, the NPS-sensor technology and the cells had been developed and delivered by the project partner Insplorion. In deviation to the originally planned DUT (device under test) the NPS-sensor system was delivered as single cells with integrated fibre optics connected optical measuring devices and software. For configuration of the test bench, the optical connection had to be realized like shown in Figure 34.

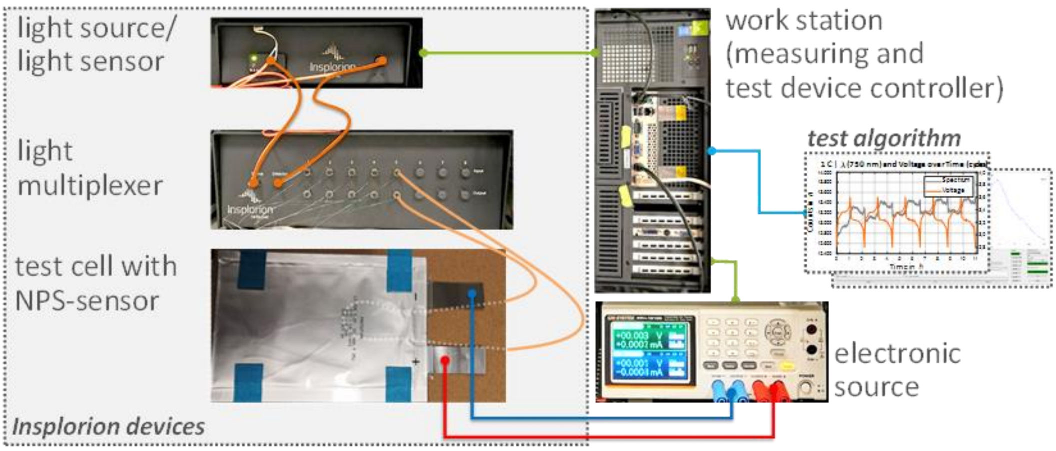

Figure 34 NPS-test configuration at IFF with optical and electrical measurement

The challenge of connecting the DUT is the special fiber optic of 90µm instead of 125µm known from standard telecommunication fiber optics. Additionally the primer coating of the NPS' sensor fiber consist of a special resistant material to ensure its functionality in-side the battery cell. The standard splicing process can be divided in following steps:

- stripping fiber optic cables

- cleaning fiber optic cables
- cleaving fiber optic cables
- splicing fiber optic cables
- coating fiber optic cables

The splicing process needs to be very precise to avoid reflection and attenuation at the joint. Therefore, a fusion splicer was taken which automatically controls the quality of the fiber surface, makes the positioning of the fiber ends and slices them together. Afterwards the quality of the splice is analyzed and pictured (Figure 35). The whole process takes a significant impact on the quality of the resulting splice that has influence on the quality of the measurement of the configuration.

Figure 35 Splicing process of a fiber optic with an automatic fusion splicer

The delivered cells had two ends of 90µm fiber with length of 5-9cm. The diameter of 90µm was too small for standard cleaving tools for 125µm. In addition, the length of the fiber was very challenging, because the automatic fusion splicer did need minimum 7,5 cm for fixation and positioning the fiber during the process. The battery cell was disturbing for this process. So that a mechanical splice method was chosen. In quality check of the cells, a broken fiber on some of the targets was detected. This crack, as seen in Figure 36, appeared at a critical point of the cell. The emitted light in the cell should be seen at the other end of the fiber going through the cell. Splicing the fiber with connector on the target allowed the connection on the Insplorion test devices and the measurement. Details to devices and measuring principle can be seen in Insplorion report.

Figure 36 Fiber optic connection and connection in test stack

Changing the DUT configuration to single cell test configuration also caused the need to design a new test environment with the electrical equipment. The originally test configuration was planned for battery stacks with currents of several amperes. In the resulting configuration, the cell specification (Li-ION 3.2V, 105 mAh) allowed currents less 525 mA and test currents less 30 mA. The test environment was defined as described in the following chapter.

Demonstration and test scenarios at demo site NPS-sensors

The test environment provides the basis for the optical measurement carried out. Since the series of tests involve a certain sensitivity to interference, the test environment was installed in an adjoining area. Essentially, the structure consists of a (1) workstation on which the measurement and test programs are running, (2) the light source and the spectrometer, (3) an optical switch, (4) the DUT (pouch cell with NPS) and (5) the inverter.

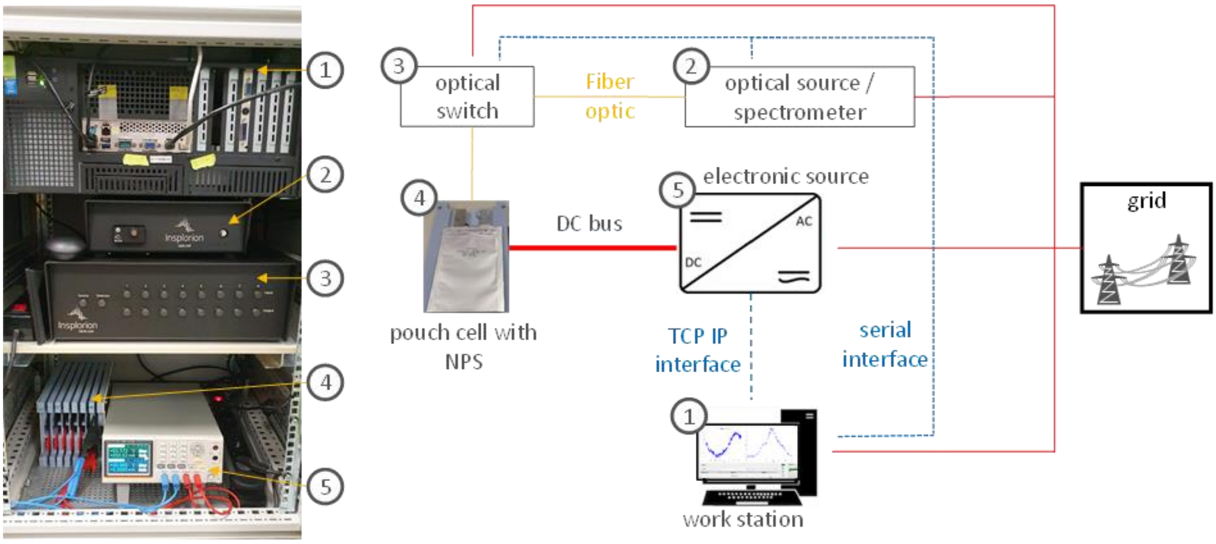

Figure 37 test and evaluation environment for optical measurement of Insplorion pouch cells

For the NPS-sensor evaluation, different test series had been defined. The test had been done with the test cell with NPS-sensors and with the reference test cell without NPS-sensor. During the tests, a dependency/ influence to pressure and temperature had been recognized, so that additional test had been driven to determine the influence on measuring results and accuracy of the NPS-sensors. The measuring method and the dependence on environmental condition and correlation on temperature, pressure, charge and discharge current or SOC can be read in Insplorion report or NPS-sensor specification.

Table 3 selection of test procedure for NPS-sensor evaluation

Test procedure	**Test procedure**	**Description**
TP 1	5 full cycles (cells with NPS) constant volume	several full cycles to determine the main characteristics of the battery
TP 2	5 full cycles (reference cells) constant volume	several full cycles to verify the essential characteristics of the battery with NPS
TP 3	Stair function	The aim is to investigate the stationary accuracy
TP 4	Load change	The aim is to investigate the performance gradient

TP 5	Pressure change	Investigation of pressure dependencies
TP 6	Temperature change	Investigation of temperature dependencies
TP 7	2 full cycle (cells with NPS) constant pressure	Investigation of pressure dependency under current load

TP 1: 5 full cycles (cells with NPS) constant volume

The target cell was mounted in a battery stack, which was tight by screws. The volume is constant during the cycle. The batteries were cycled with five full cycles and 3 different C-rates (1 C, 0.5 C and 0.3 C). The physical quantities (current, voltage, time, temperature and spectrum) were measured during the test period in order to determine the characteristics of the cells. The

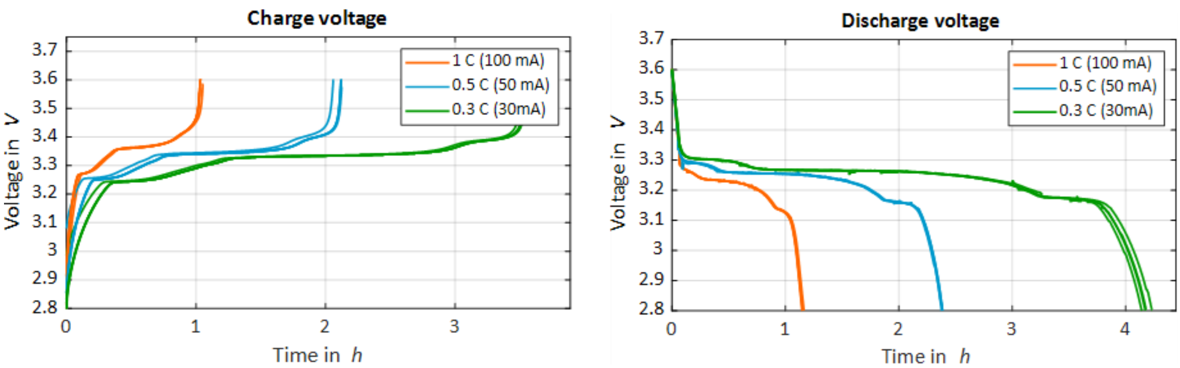

Figure 38 shows the behavior of the voltage for constant charge and discharge of the 5 full cycles for the three different C-rates. The measurement shows the typical characteristic of Li-Ion cells. Based on the electrical measurements further calculation and validations were done and analyzed.

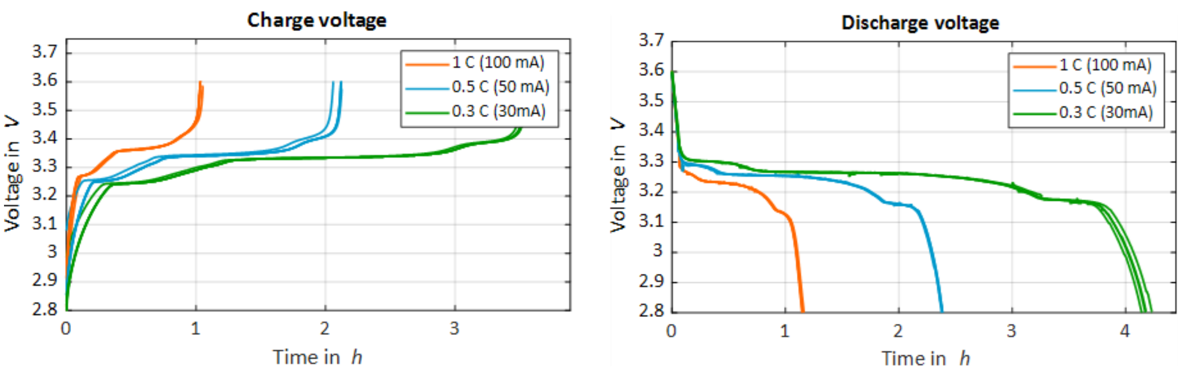

Figure 38 Charge and discharge voltage curves for 5 full cycles (results of procedure 1)

The electrical capacity and the stored energy had been calculated from voltage and current measurement. The tests of the cells with and without NPS-sensor had no measureable difference. In all tests the capacity was with 106 mAh @1 C, 107 mAh @0,5 C and 109 mAh @0,3 C a little higher than manufactural specification.

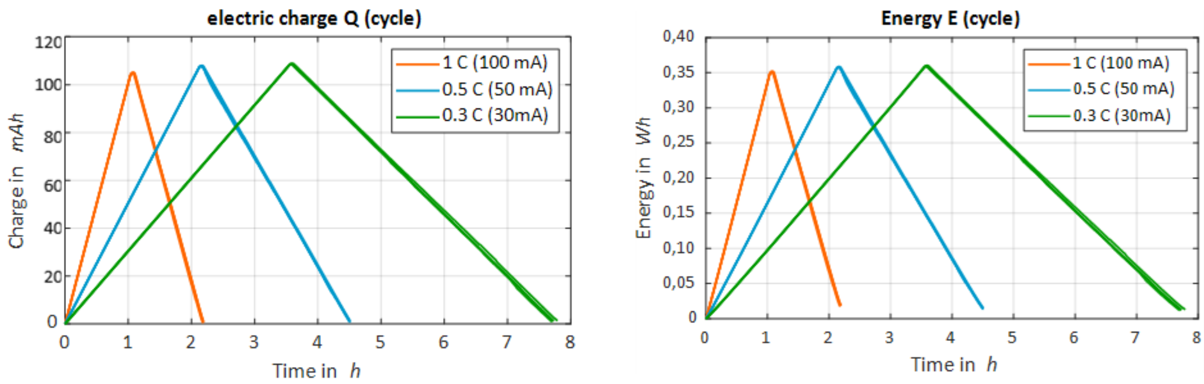

Figure 39 Electric charge and energy curves for 5 full cycles (results of procedure 1)

In further analyses, the graph of open-circuit voltage characteristics was calculated from the mean values of the voltage curves of charging and discharging for the different C-rates (

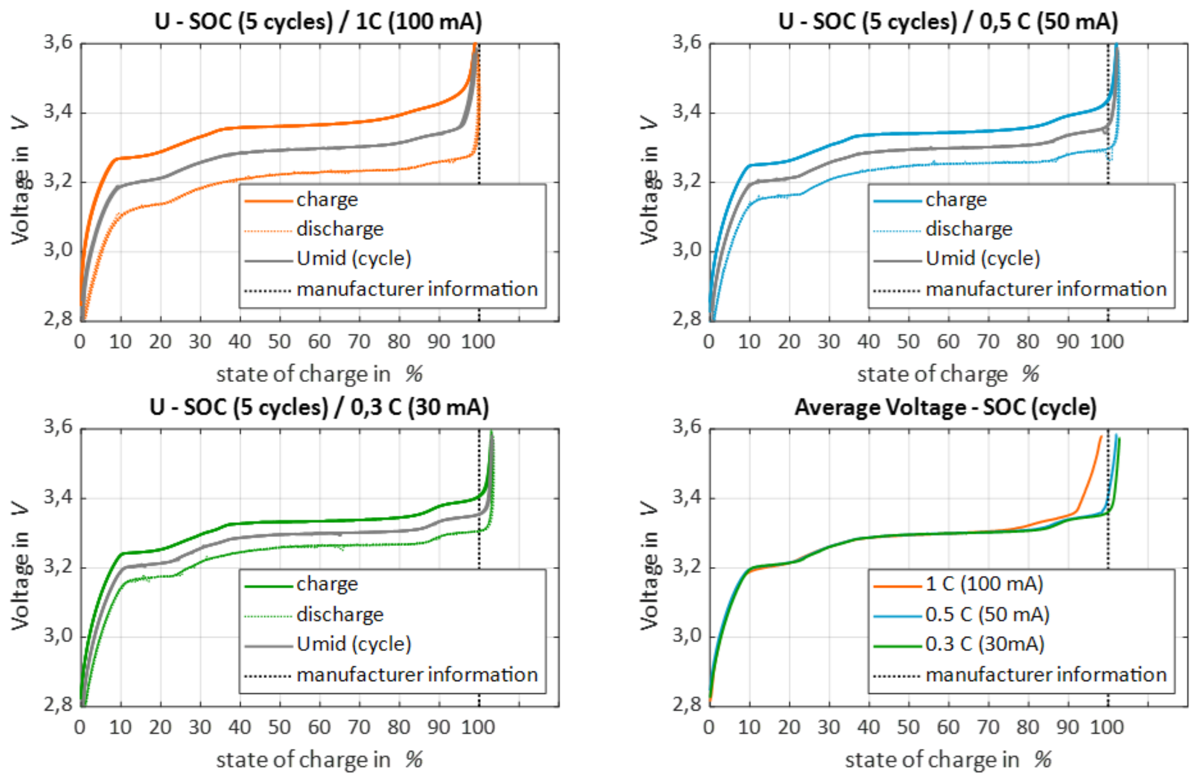

Figure 40). This characteristic is one of the inputs for BMS to determine the SOC regarding the open-circuit voltage. Comparing the three measurement series with different C-rates, no major differences could be identified. Nevertheless, the cells can be characterized by a stable voltage curve.

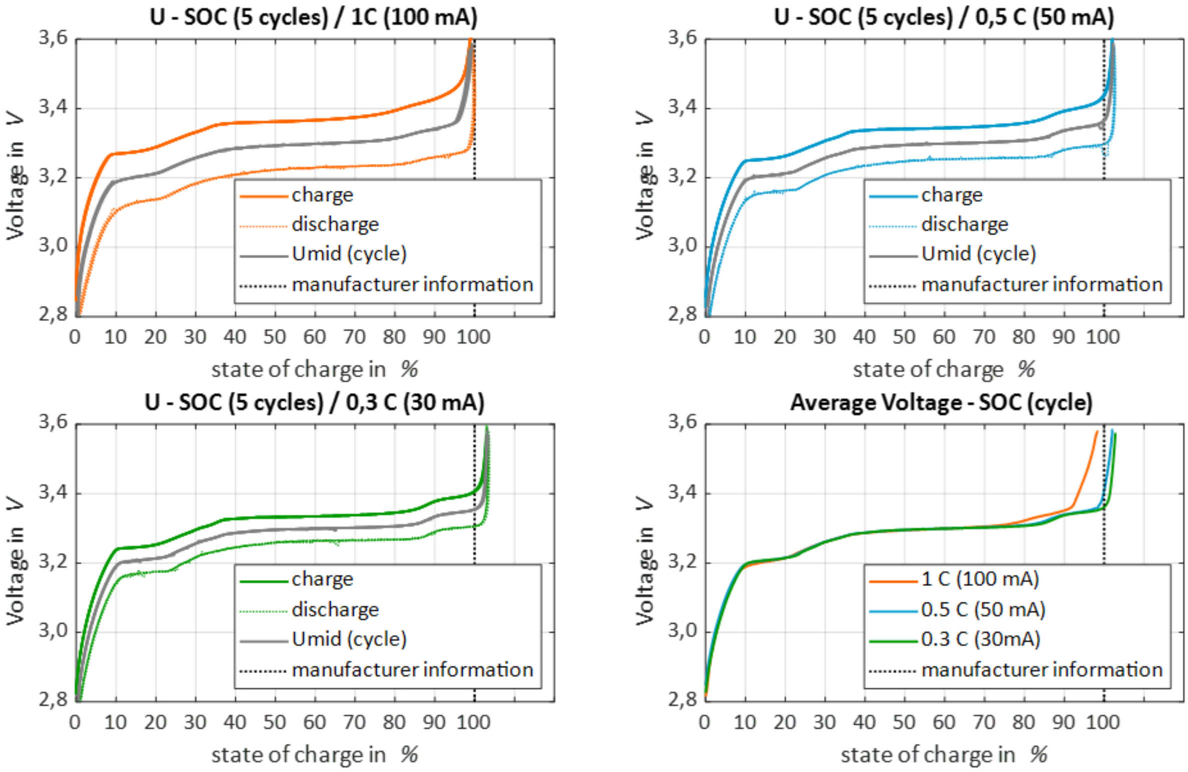

Figure 40 Open-circuit voltage of 5 full cycles (results of procedure 1)

After the electrical analyses, the optical measurement was taken into account. The recorded matrix consists the full spectrum recorded over the measuring time. Most significant are wave length around 750 nm (experience Insplorion). Therefore, in following graph the counts of 750 nm will be analysed. As fibre optics were very difficult to splice (see previous section), in the measurement the noise can be observed.

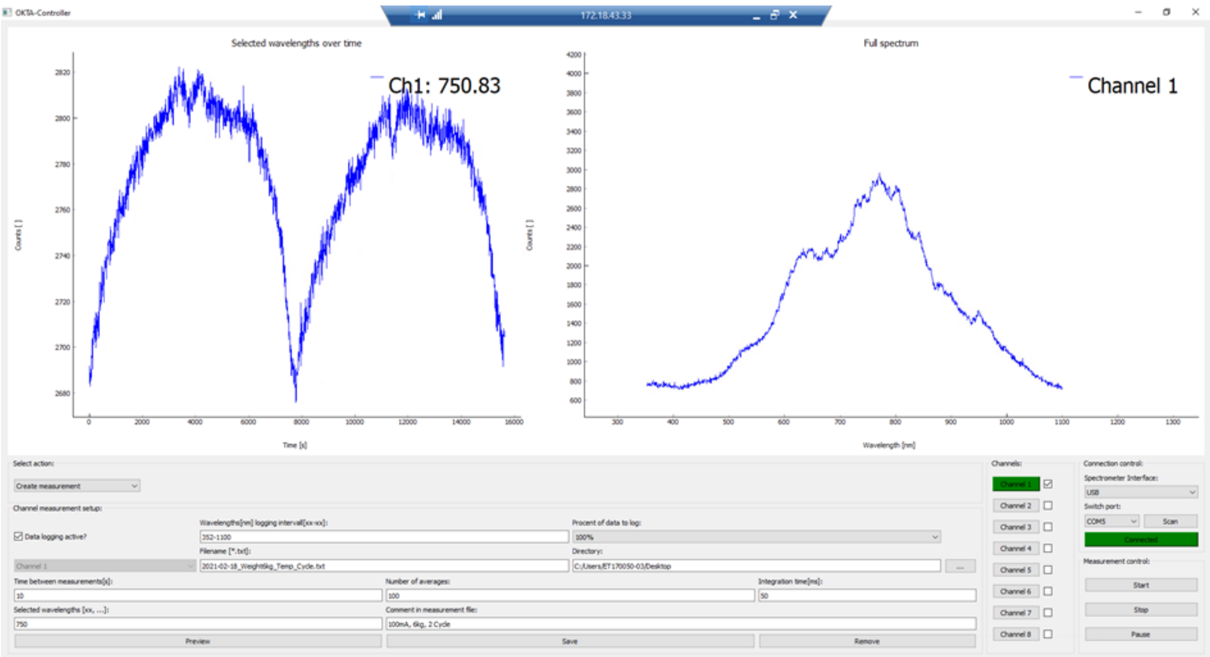

Figure 41 Insplorion OKTA-Controller software, measurement results

In Figure 42 the light intensity, measured in counts, of light wavelength 750 nm is pictured with the voltage. During all measurements, the shape of the curve had a significant characteristic, but during the cycles the measurements had positive or negative slope. It was assumed that besides the dependency of the function to the SOC an additional environmental impact has influence to the function. The three values taken into account where electrical current while charging and discharging, temperature of the cell and pressure on cell.

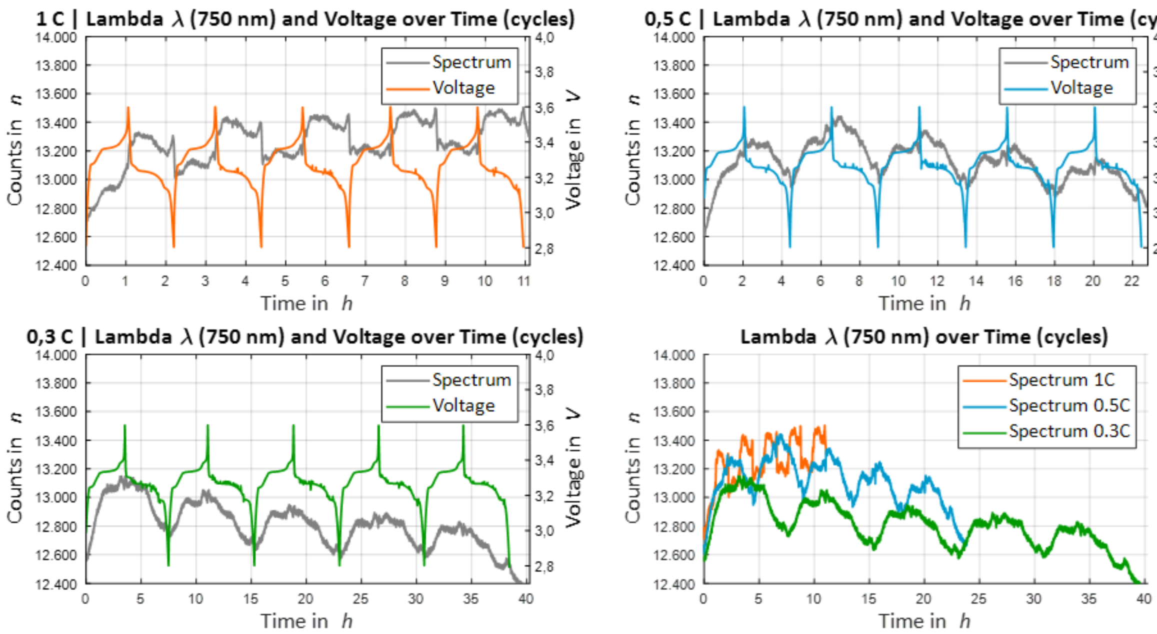

Figure 42 Characteristic of wavelength for 750nm (results of procedure 1)

TP 2: 5 full cycles (reference cells) constant volume

The integration of the sensor could have an influence on cell performance. For that reason, an amount of reference cells had been cycled with same profile as the test cells with NPS sensors. In all electrical tests, no significant difference could be measured. The aging influence was not analysed, cause of missing time capacities. In test application, the cell was mounted in the cell stack with constant volume and constant temperature.

TP 3: Stair function, influence of current on NPS-measurement

In this test function the current was, starting with an initial current of 100 mA, reduced stepwise with steps of 10 mA until -100 mA. The current steps had no significant influence on spectrum measurement in the test scenario. In test application, the cell was mounted in the cell stack with constant volume and constant temperature.

TP 4: Load change, influence of current on NPS-measurement

To increase the stress on the cell and provoke some measurable reaction at the NPS-sensor related to the current, the current direction was changed with each step. The alternating charged and discharged function with 10 mA steps up to a current limit of

+/- 100 mA (1C) did not show significant reaction at the NPS-measurements. In test application, the cell was mounted in the cell stack with constant volume and constant temperature.

TP 5: Pressure change, defined pressure on cell

In this test application, the cell was tested with constant temperature of 23°C, with constant current of 0 A, mounted in a test environment to put a defined pressure on cell. The measurement of the spectrum showed a significant dependency of pressure and measurement as seen in the diagram for wavelength of 750 nm in Figure 43. Increasing the pressure reduced the counts.

The battery with NPS was subjected to an increasing pressure rate gradually and then left alone for a moment. After reaching a maximum pressure of 0.7649 N / cm², the pressure was reduced again gradually. It can be seen clearly that the light signal has a clear pressure dependency. The step of pressure increasing or decreasing is well seen such as the equalising function. Furthermore, it can be seen that the relaxing takes significant longer reducing the pressure. A deeper analysis should be done related to the NPS-measuring technique, the positioning of the NPS and the cell specific construction and the resulting effects under different pressure.

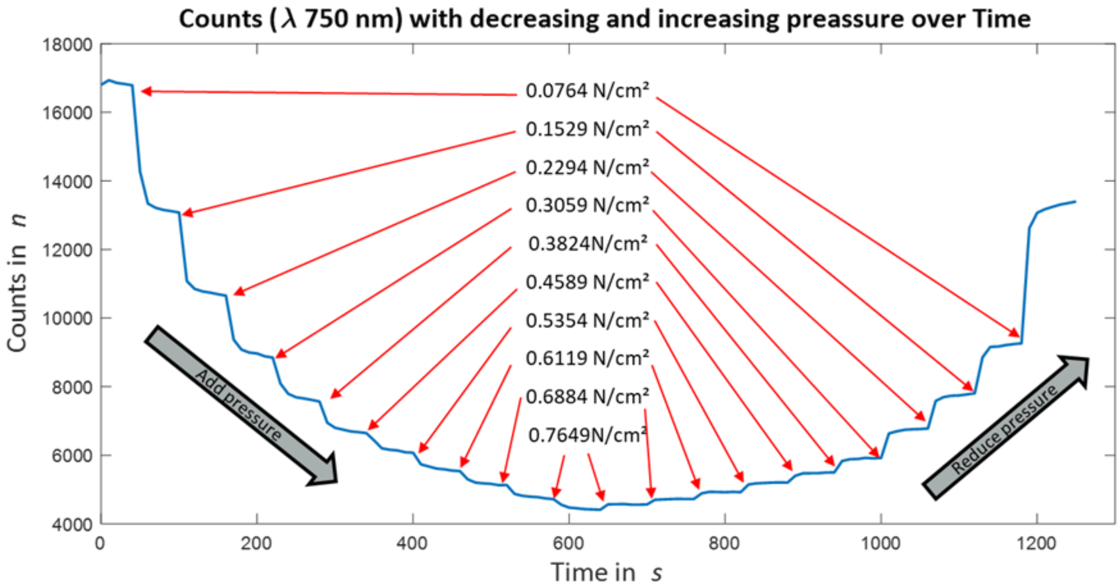

Figure 43 Measurement of the wavelength 750nm for pressure increase and pressure reduction (results of procedure 5)

TP 6: Temperature change, defined temperature change to cell

In this test application the pressure (0,0764 N/cm²) and current (0 A) were constant. The cell was mounted in a test environment to vary and measure the test temperature. For the test, the cell was heated up and cooled down to environment temperature. In

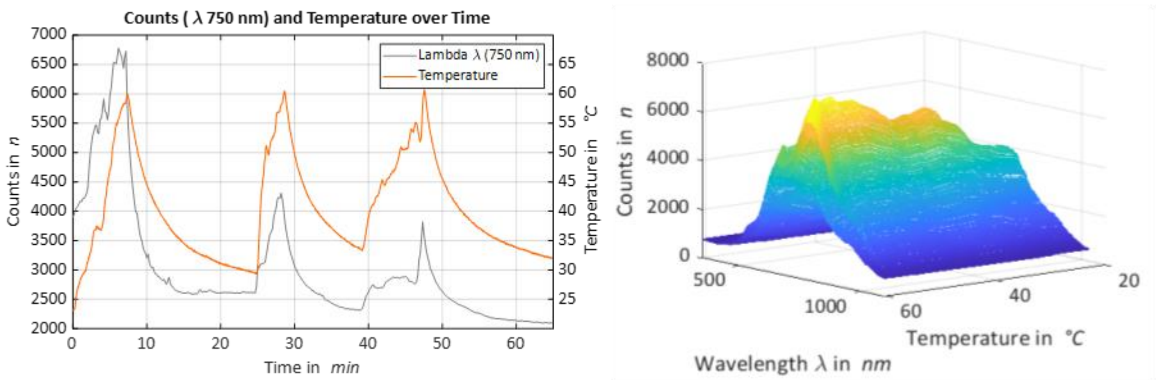

Figure 44 a clear dependency of temperature and NPS-measurements can be recognized. Also, well seen is that the amplitude of the NPS-measurement is decreasing with each cycle. In the 3D-plot of the spectrum dependent to the temperature, the dependency can be recognized over all measured wave length. Further analyses should be done related to the NPS-measuring technique, the positioning of the NPS and the cell specific construction and the resulting effects under different temperatures.

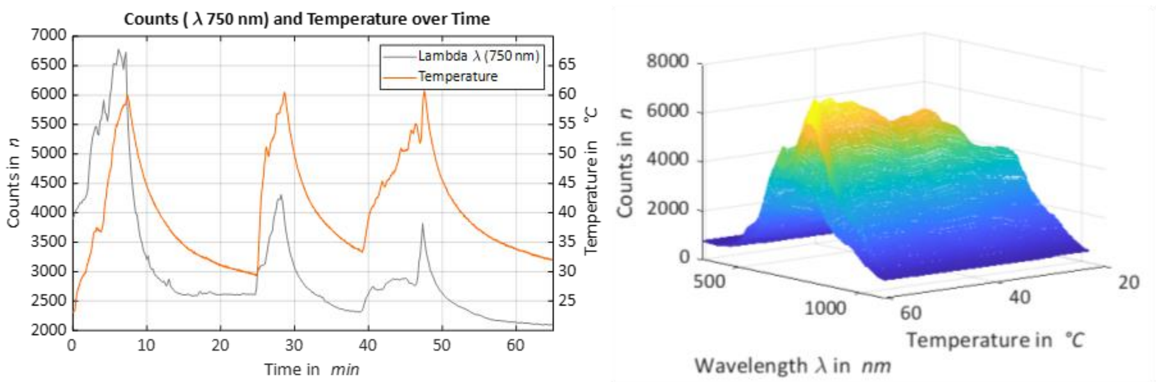

Figure 44 Measurement of the wavelength 750nm for 3 heating-cooling cycles (results of procedure 6)

TP 7: Constant pressure and 2 full cycle

In tests *TP 5* and *TP 6* the dependency of pressure and temperature on NPS-measurement was proven. Therefore, the test of *TP 1* where repeated with constant condition of pressure and temperature to analyse the potential increasing measuring results of NPS-measuring technique for battery cell application. The cells where cycled two times with 1 C in environmental condition of constant temperature 23°C and constant pressure. Therefore, the weight on target cell was defined and increased for the test session from 2 kg up to 10 kg. In Figure 45 the flattening of the function with increasing weight is well seen.

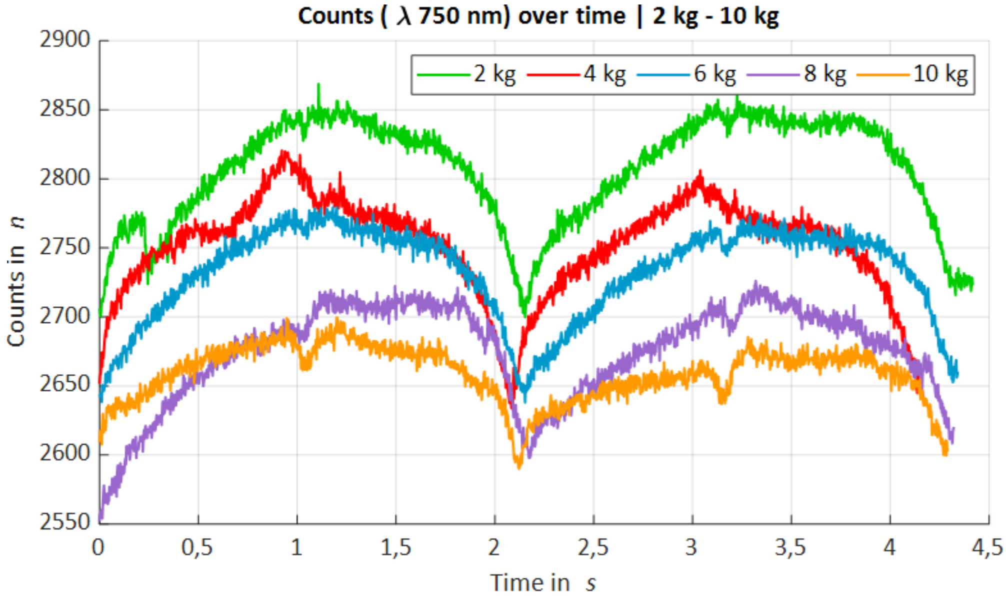

Figure 45 Measurement of wavelength 750 nm for 2 full cycles (results of procedure 7)

In further analyses the NPS-measuring function of the wavelength of 750 nm was related to the stored energy in the cell during charging and discharging of the cell for the different test series with different constant pressure / weights on the test cell. For the diagrams the average function for discharge and charge was taken and the measuring points were plotted to show the fluctuation. The results with constant temperature and weights gave the best measuring results, but there is still a lot of noise in the function. The trend of the function can clearly be recognized, but the fluctuation is that high that no gain of information compared to the electrical measurement system is possible.

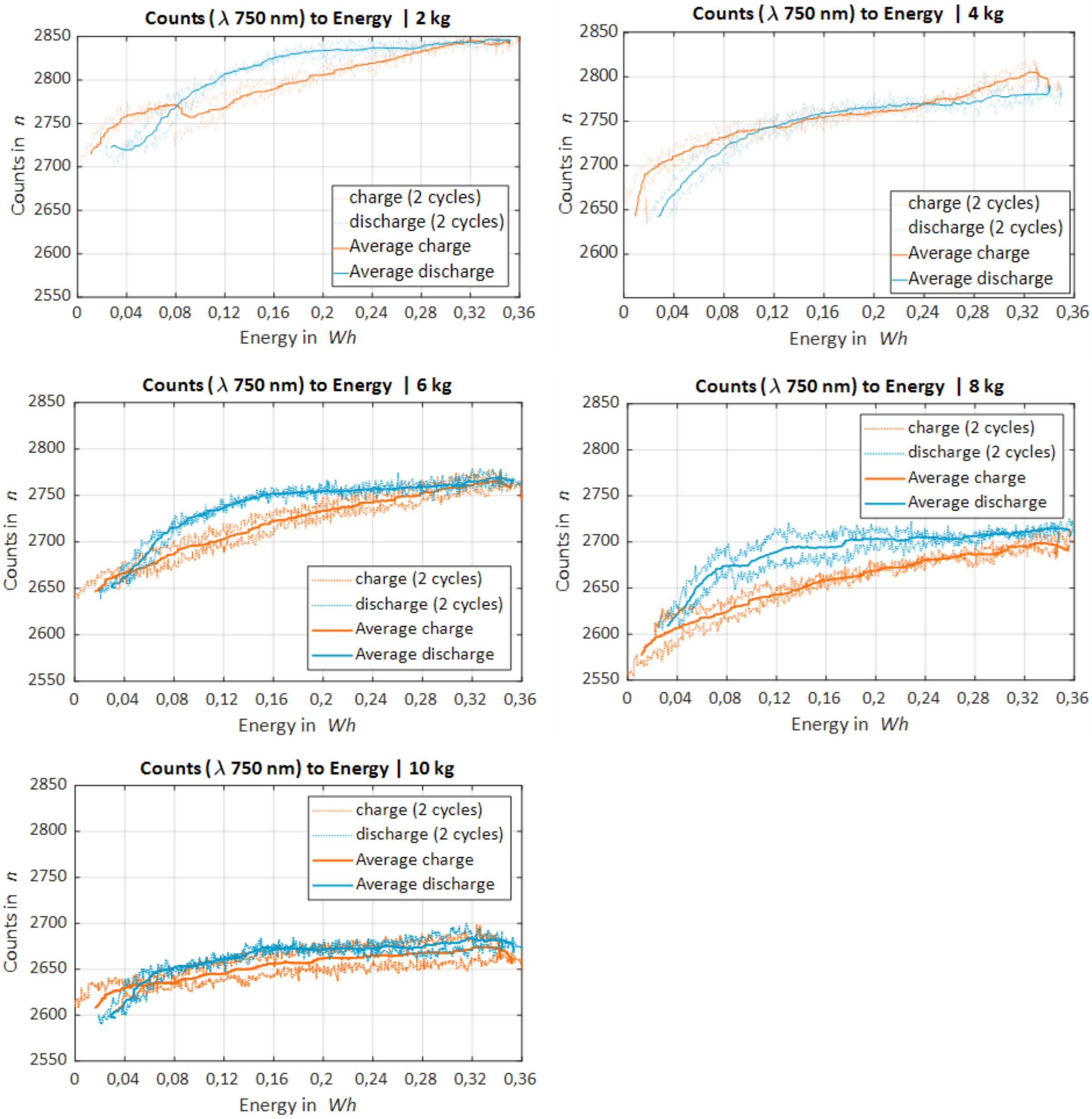

Figure 46 2 cycles NPS-measurements with constant weights related to stored energy in cell

Further analyses should be done related to the NPS-measuring technique, the positioning of the NPS and the cell specific construction and the resulting effects under different pressures and temperature conditions. The potential of the NPS-sensors could not fully be analyzed cause of missing time resources and test targets. Based on these research optimized test environment such as test cell configuration should be used to fully analyze the effects and identify the potential of NPS-sensor technique for additional battery information.

2.5.2 Data collection & piloting Adaptive Control solutions

For the IT system architecture (Figure 47), two fundamentally separate information paths were set up with the respective services. On the one hand, the information is to be read continuously by the field devices and distributed automatically to the interested services. For this purpose, a publish-subscribe pipeline was set up (Figure 48). The advantages here lie in the fast and resource-saving continuous transmission of information from the field devices to the higher-level services, such as the load forecast services. The higher-level services register once to the message broker and specify which information they want to receive. After logging in, the higher-level services receive the information without further action until they log off again. This avoids continuous direct retrieval from the database, since database systems were not designed for this task.

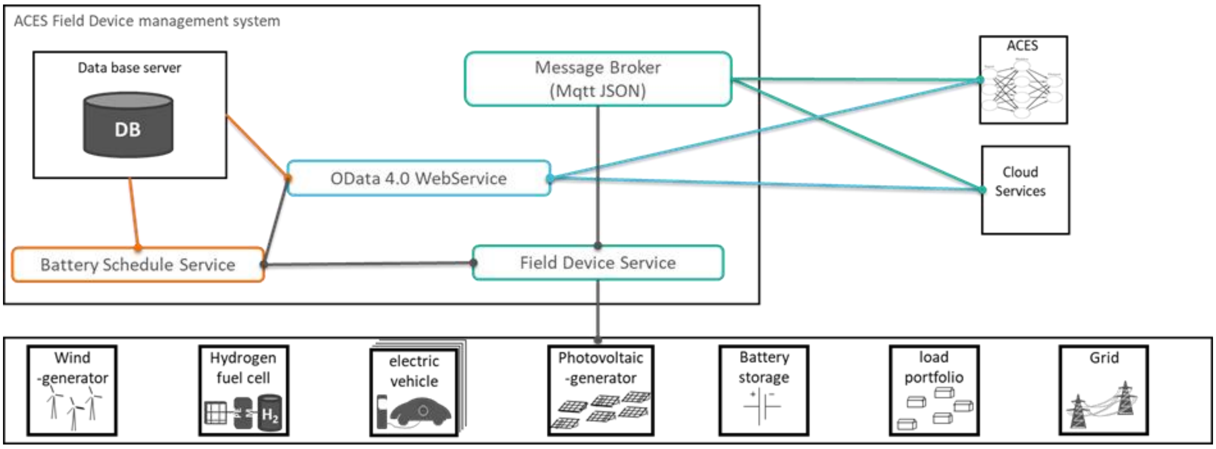

Figure 47 IT system architecture

On the other hand, it should also be possible to retrieve historical information and the parameters of the field devices. For this purpose a second pipeline was set up (Figure 49), which works via an "O-Data web service". The advantages of OData web services lie in the flexible processing of requests. The service can solve individually compiled queries by breaking down the complex query into partial queries and processing them. The content is described using JSON and is thus readable.

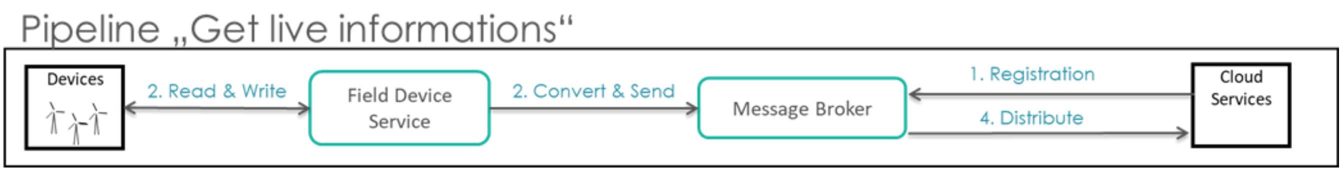

Figure 48 Publish-subscribe pipeline to get live information

Figure 49 Pipeline to get configuration and historical information

In the implemented system solution, it is necessary to call up the parameters and settings for the field devices before establishing the live connection, since interpretation is only possible by combining both pieces of information. In the live transmission, the measurement parameters are only provided with an "identification number" and the values may still have been calculated with a multiplier.

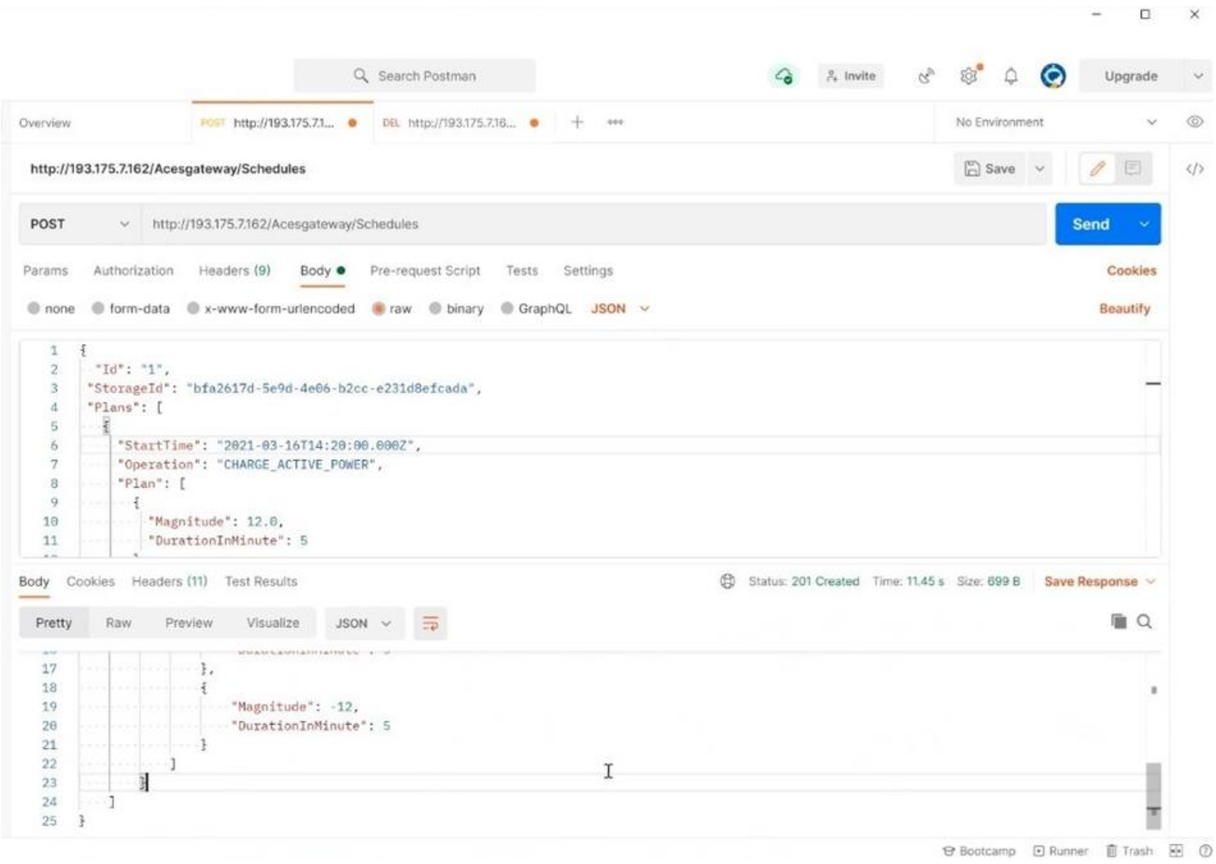

Figure 50 JSON with schedule for battery storage operation

```
2021-03-16 14:12:39,093 [7] INFO  WebApplication2.ScheduleProvider.ScheduleTaskService - 16.03.2021 14:12:39: Sende neuen Befehl an den Batteriespeicher
2021-03-16 14:12:39,358 [7] INFO  WebApplication2.ScheduleProvider.ScheduleTaskService - Value of HoldingRegister 1 2
2021-03-16 14:12:39,390 [7] DEBUG Quartz.Core.JobRunShell - Trigger instruction : DeleteTrigger
2021-03-16 14:12:39,405 [7] DEBUG Quartz.Simpl.RAMJobStore - Deleting trigger
2021-03-16 14:13:06,952 [5] DEBUG Quartz.Core.QuartzSchedulerThread - Batch acquisition of 0 triggers
2021-03-16 14:13:32,593 [5] DEBUG Quartz.Core.QuartzSchedulerThread - Batch acquisition of 0 triggers
2021-03-16 14:13:59,968 [5] DEBUG Quartz.Core.QuartzSchedulerThread - Batch acquisition of 0 triggers
```

Figure 51 Schedule check and reset

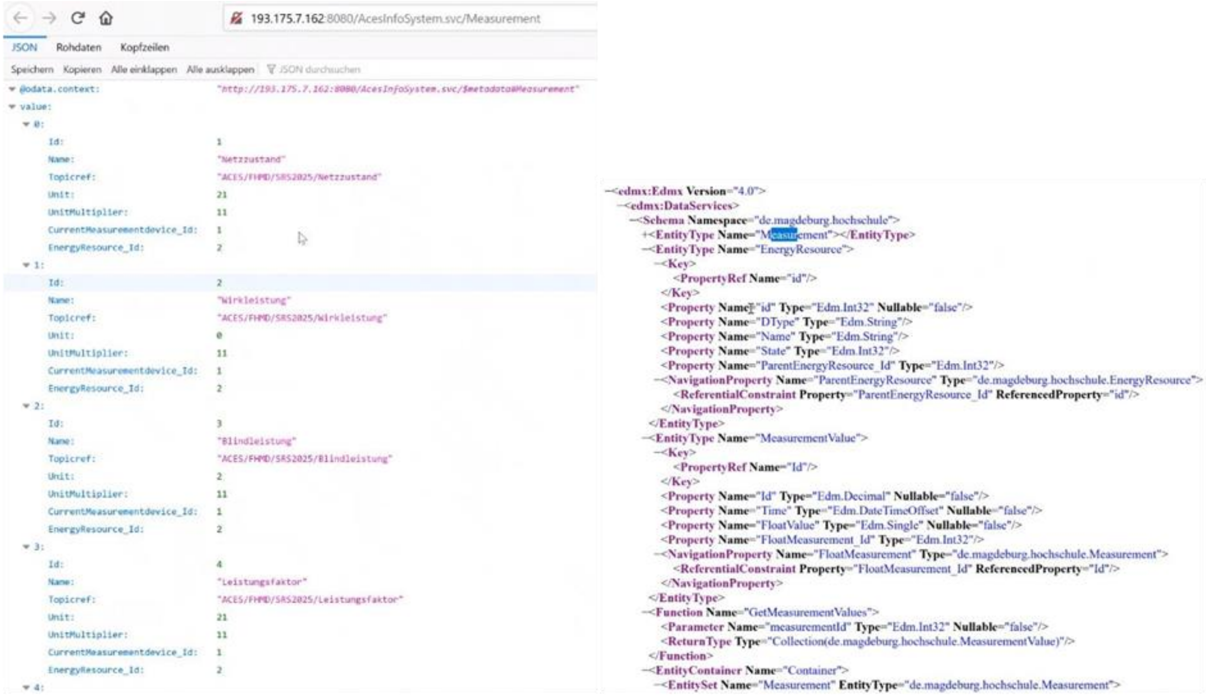

Figure 52 Measurement of battery storage operation according to schedule