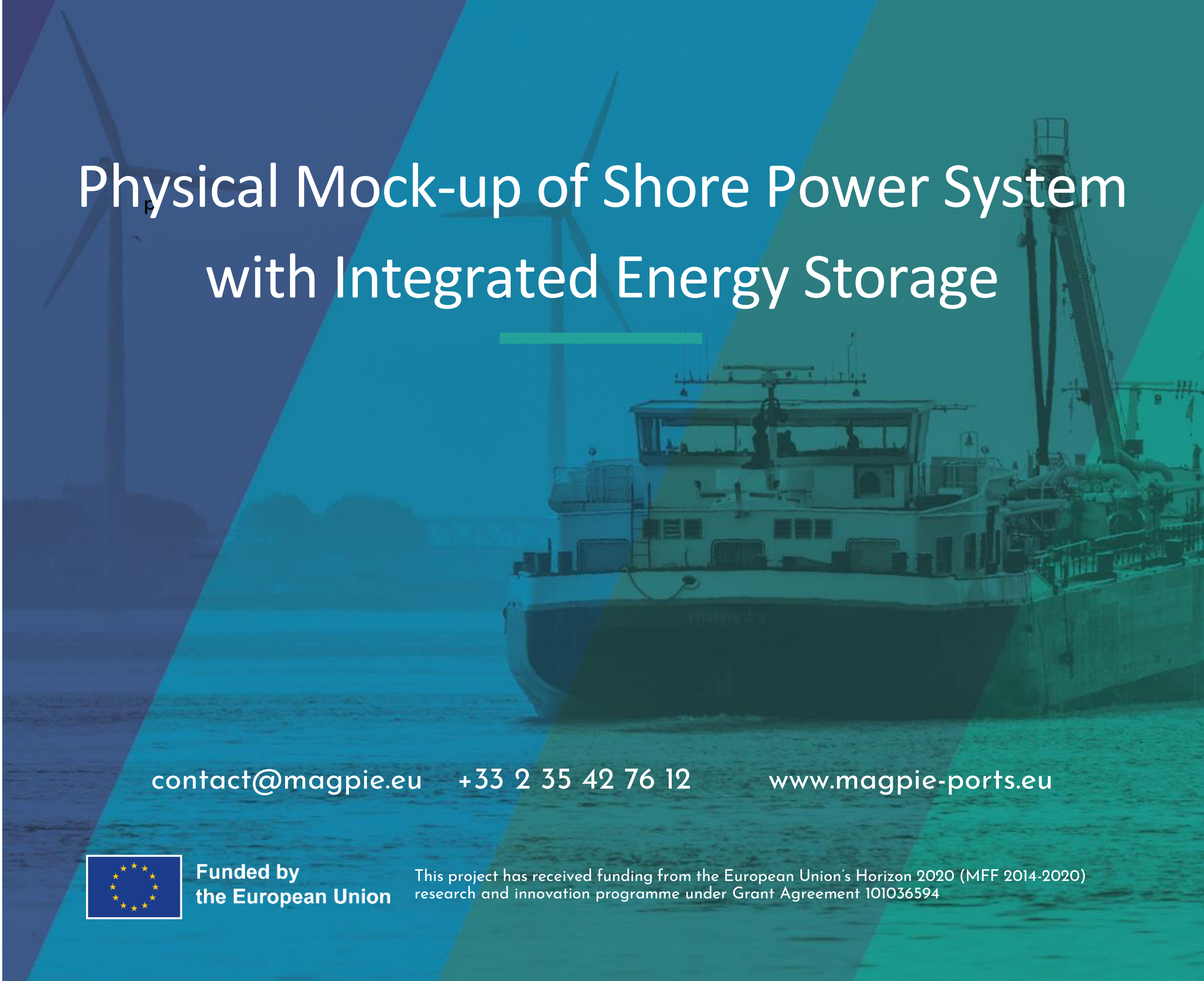
MAGPIE

SMART GREEN PORTS

Physical Mock-up of Shore Power System with Integrated Energy Storage



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D3.15 - Physical Mock-up of Shore Power System with Integrated Energy Storage

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Abbreviations

AS	Ancillary Services
BESS	Battery Energy Storage System
DSO	Distribution System operator
EMS	Energy Management System
FCR	Frequency Containment Reserve
GHG	Greenhouse Gasses
KPI	Key Performance Indicator
HMC	Heerema Marine Contractors
MTU	Market Time Unit
PoR	Port of Rotterdam
PTU	Program Time Unit
pu	Per-unit
RES	Renewable Energy System
RSP	Rotterdam Shore Power
SoC	State-of Charge
WF	Wind Farm

Executive Summary

The MAGPIE R&D project is working towards the European Green Port of the Future, which includes energy supply chains, such as shore power. The shore power peak shaving demonstrator (Demo 3) sets out to increase utilization of an existing shore power hub facility in the Port of Rotterdam, aiming to reduce the costs and greenhouse gas emissions.

To support this demo, the technical viability was demonstrated of peak-shaving of the electricity demand of the crane vessel Thialf of Heerema Marine Contractors (HMC) when connected to shore power, by means of an onboard Battery Energy Storage System (BESS). The use-case of this pilot also included balancing of the demand (behind-the-meter) with renewable electricity produced by a local wind farm.

For this use-case peak-shaving was first simulated, based on measured vessel data provided by HMC and historic weather data, and then tested in a down-scaled physical mock up at the SWITCH field lab in Lelystad, The Netherlands. Tests were conducted with and without considering renewable generation, with different limits for the grid demand.

The simulations provided a working principle for peak-shaving of the vessel demand, such that the 15-minute grid demand did not exceed a pre-set limit, while also respecting the maximum instantaneous maximum power level of the shore power facility. This shows that peak-shaving with the onboard battery system would allow to apply shore power without the risk of overloading this installation or exceeding the contracted grid demand. Suitable ranges for the grid limit resulted from the simulations and were tested in the mock-up.

The field tests in the mock up (pilot settings down-scaled with a factor 100) showed that for a maximum vessel demand of 65 kW during the test period, peak-shaving can effectively reduce the 15-minute averaged grid demand to 60 kW. The battery state-of-charge remained well above the allowed minimum level that was set to 80% of the nominal capacity of 57.6 kWh, with only a modest lifetime consumption of 0.10 equivalent full-cycles per day. For the full-scale pilot, this is equivalent to 0.50 daily cycles, due to the relatively smaller battery size of 1.17 MWh (equivalent to 20% useable capacity of 57.6 kWh, upscaled a factor 100). This 60 kW grid limit setting, equivalent to 6.0 MW for the pilot scale, can be considered as optimal specifically for this data set. A tighter setting of the grid demand of 55 kW (equivalent to 5.5 MW) proved to be ineffective due to temporary depletion of the battery. Fine-tuning of the grid limit may still be considered, as a more lenient setting strongly reduces the battery lifetime consumption and the risk of temporary depletion.

Balancing the vessel load with local renewable electricity was tested and showed to reduce the need for peak-shaving by discharging the battery, while recharging it primarily from local renewable electricity. However, as sufficient wind power may not always be available when needed, e.g., due to low wind conditions or temporary outages of the wind farm, this balancing will probably not allow to set a tighter grid limit.

For determining the grid limit at pilot scale more accurately and assessing the cost savings, additional simulations are recommended, based on concurrent data of the vessel electricity demand and wind farm production over periods of several months. These should include detailed design characteristics of the pilot, such as the useable battery capacity, ramp rates and ageing models, as well as the available net metering data, e.g. considering latencies.

The tests have demonstrated demand peak-shaving in realistic conditions using a battery system and considering local renewable generation. It has also provided insight in aspects of the battery design and operational settings of the battery and the EMS that determine whether peak-shaving can be effective. These findings enable more accurate simulations to assess the benefits and risks, both for the current pilot and future shore power facilities.

1. Introduction

The MAGPIE R&D project is an international collaboration, working towards the European Green Port of the Future. The project is divided in 10 main work packages which include energy supply chains, digital tools, 10 demonstrators for maritime, inland water, road and rail transport, non-technological innovations and the development of a Masterplan for European Green Ports. As one of the demos on energy supply chains, the shore power peak shaving demonstrator (Demo 3) sets out to increase utilization of a shore power hub facility, aiming to reduce the costs and greenhouse gas emissions.

1.1 Demo 3: Shore power peak shaving pilot

Background

Shore power is the supply of electrical power to a ship moored in port to replace the onboard generation of electricity, which in most cases uses diesel generators. The obligation to apply shore power from 2030 onwards for vessels above 5,000 gross tonnages calling at EU ports is one of the measures of the "FuelEU Maritime Regulation"[1] put in place for the EU maritime sector to meet its climate targets. The objectives are to: 1) reduce emission of Greenhouse Gasses (GHG), and 2) improve air quality in port and surrounding areas.

One of the key challenges for shore power is the large and fast variation in load levels, especially for crane vessels and passenger vessels. As a result, the shore power supply infrastructure will be under-utilized most of the time, which leads to high operational costs. Local electricity storage can provide flexibility, in particular by means of peak shaving of the energy demand from the grid, in order to reduce these costs. Secondly, peak shaving can also help to relieve the limitations in the available grid capacity.

Concept

The shore power hub demonstrator is built upon an existing shore power facility of the joint venture Rotterdam Shore Power (RSP) in the Port of Rotterdam (PoR) that provides electrical power to two large crane vessels. This facility also connects to a nearby onshore wind farm of 9 wind turbines. The generated wind power reduces the demand from the grid, while excess wind power is supplied to the public grid. The concept of this demo has been described in the MAGPIE Deliverable D3.14 Report (Jullens & Wiggelinkhuizen, 2023).

As an integral part of the shore power pilot, a Smart Energy System is envisioned, developed by project partner Distro, that schedules and controls the energy supply to and from the local storage unit and enables a multi-user local marketplace. The control is based on grid capacity, availability of green energy and the requirement concerning when the local storage should be full and ready for a vessel alongside.

In the course of the project, it became apparent that the original plan to integrate the battery system in the existing onshore shore power facility was not feasible within the available budget and time of this project. For new facilities however, integrating a battery system in the onshore facility may still be a valuable option. As an alternative solution, the vessel owner and operator Heerema Marine Contractors (HMC) is developing a solution to integrate a battery system on board of their crane vessel Thialf. As a consequence, the battery system is only connected to shore power when the vessel is moored at the quayside, and no power can be fed back towards the public grid. This mainly leads to a different use

[1] Regulation - 2023/1805 - EN - EUR-Lex

of the battery when the vessel is not moored at the quay, while its operation for demand peak shaving when connected to shore power remains unchanged.

Main objective

The MAGPIE Shore Power Peak Shaving demonstrator sets out to "Increase utilization of a shore power hub facility to reduce costs and emissions by shaving the peaks using stored energy".

This high-level ambition is achieved by pursuing:

- To demonstrate the effect of locally stored energy on relieving the electricity grid and infrastructure loading caused by large, low frequent power demand variations
- To demonstrate the contribution of locally stored energy on the grid stability considering both large load demands for shore power and temporal excess of green electricity
- To simulate the grid dynamics in a controlled environment including the smart energy system controlling the charging and discharging of locally stored energy.

Key Performance Indicators

The project (in WP8) has defined Key Performance Indicators (KPIs), of which the following are relevant for demo 3:

- CO2 emissions per demo per year
- Emissions of other pollutants (e.g. NOx, SOx and organic) per demo per year
- Energy use (joule) per demo per year
- CAPEX, OPEX
- No. jobs and type of employment
- Amount of added value

Table 1.1 provides an overview of the innovations and how these can impact the KPIs. Most impacts identified thus far are positive (green) and relate to several KPIs, while the negative impacts (orange) are directly related to Battery Energy Storage System (BESS) costs.

Table 1.1: Innovations and possible impacts on KPIs; positive (in green) and negative (orange) impacts

Innovations KPIs	Use local renewable energy	Peak shaving	Grid support
CO_2 emission per demo per year	Reduce thermal generation in battery		
Energy use per demo per year	Reduce energy procurement costs	Reduce renewable energy curtailment	Lower peak load on grid
CAPEX, OPEX	Reduce energy procurement OPEX: BESS cycling	Reduce grid fees CAPEX: BESS ramping capabilities	OPEX: BESS cycling
Amount of added value	Improve Renewable Energy System business case	Enable further upscaling Improve security of service	Additional market revenues Improve security of service

The assessment of most KPIs is defined in MAGPIE WP8, (TNO, 2021) (Houwelingen, et al., 2022), however, some KPIs require additional calculations, such as emission reduction when local renewables replace electricity supplied from the grid that is a mix of thermal generation and renewables. The KPI assessment is part of follow-up tasks in the MAGPIE project.

Energy management strategies

A comparison of three strategies to schedule the operation of a battery system at RSP has been made in a recent master thesis study (Weenk, 2023), based on simulations, considering uncertainties in wind energy production. The strategy that combines arbitrage (energy trading) and peak shaving offered the largest cost savings compared to the situation without a battery system. The current setup of the pilot with an onboard BESS does not allow to feed in electricity from the BESS to the grid, which diminishes the revenues for arbitrage, while the calculated cost savings from peak shaving are similar to the case with the BESS installed onshore. As this study has optimized the operation of a single BESS within a 24-hour time horizon and without considering BESS degradation, these aspects are mentioned as topics for further research. Other aspects recommended are to include weather forecasts in the optimization and to allow some violation of certain optimization constraints.

1.2 Mock-up aims and approach

To support the shore power pilot, a small-scale physical mock-up of this pilot will be set-up at the SWITCH field lab of TNO and Wageningen Research in Lelystad in the Netherlands. This enables to test multiple use-cases of the shore power system and to optimize operational strategies of the battery system, before testing these at full-scale in PoR.

In order to support the overall aims of the RSP pilot, the following concrete objectives are defined for the down-scaled mock-up:

- To demonstrate the technical viability of an integrated BESS to provide flexibility services for a shore power system with local renewables generation, in a realistic (down-scaled) environment
- To obtain an energy management strategy for the integrated BESS, that is optimized for operational costs, considering uncertainties in the renewable generation, load profiles, market dynamics and grid limitations

To achieve these objectives, the mock-up will follow a structured approach. The generic approach for the mock-up is provided in the MAGPIE WP3.9.2 task description:

"Detailed design and system development [TNO] – Detailed specifications for the integration of the battery package with the shore power hub. The battery should work as a flexible source during demand peak periods thus allowing to minimize the power required from the electrical grid."

TNO has further detailed this approach, defining three subtasks:

- Supporting analysis on flexibility provision of the demo, based on project specifications and foreseen integration with RSP
- Experimental validation of the RSP pilot physical mock-up to:
  - Demonstrate the viability of deploying peak shaving of the demand

  - Assess capabilities of different operating strategies to increase wind energy utilization and to assure effective peak-shaving of the demand
- Optimizing demo operation and scalability (roll-out plan), based on real-life data from RSP pilot. Lessons learned from SWITCH lab are input for demo RSP optimization.

1.2.1 Research questions

Considering that TNO will provide support to the shore power pilot before the innovation is implemented in PoR, the translation from full-scale pilot use-cases to the small-scale mock-up needs to be performed by means of model simulations. This also holds for upscaling of the results from the mock-up to the full-scale pilot.

The following research questions are defined, where questions 1 and 2 are addressed within the scope of this deliverable, while questions 3 and 4 apply to the broader scope of Demo 3:

Research Questions
1. How to represent the RSP pilot in a down-scaled mock-up system? a. Which aspects need to be included and in what detail, e.g., system performance and reliability, resource and load data variations and uncertainties? b. Which are representative simulation scenarios, based on various possible use-cases? c. How to assess effects of scaling the pilot down to the level of the SWITCH field lab?
2. How to implement and validate the innovations in a down-scaled environment? a. Which are representative test scenarios, measurements and analysis methods? b. How to implement the energy management algorithms? c. How to analyze the test results, considering the limitations of due to the small scale, the different wind resource characteristics and limited duration?
3. What are the pros and cons of locating the battery system, on the vessel or as part of shore power supply facility? a. What are optimal designs and energy management strategies? b. How to compare the two designs (relevant use-cases, KPIs, upscaling potential)?
4. What are the potential gains and bottlenecks of the innovations when upscaling the shore power in PoR to multiple locations and users?

Based on the research questions, the overall approach is further detailed:

- Develop algorithms to schedule and control the shore power system (e.g., decide on when to charge/discharge the battery to the vessel or grid, based on WF generation and RSP load profiles and scenarios provided by RSP). These algorithms will serve as baseline for benchmarking with the Distro local marketplace, which is beyond scope of this deliverable.
- Simulate the mock-up configuration, wherein the above algorithms will be tuned.
- Validate the developed algorithms in a scaled experiment with the mock-up system at the SWITCH field lab. These are implemented in a local industrial computing platform, e.g. a PLC, operating as an Energy Management System (EMS)
- Analyze the results to study different designs, scales and use-cases of shore power systems.

2. Shore power use-cases and scenarios

In order to define scenarios for simulations and field tests, this subsection 2.1 provides a description of the use-cases and specific aims of the Rotterdam Shore Power (RSP) pilot. Based on these use cases, scenarios for simulation and testing are defined in subsection 2.2.

2.1 Energy storage use-cases for RSP pilot

The main innovation in the shore power pilot is the introduction of an energy storage system (ESS) as flexibility source to provide peak shaving of the electricity demand from the grid. This will be realized as a battery system that is installed on-board of the crane vessel and integrated in the vessel's electrical power system. Although the battery system will be applied primarily to reduce the vessel's fuel consumption during operation offshore, this project will only consider situations wherein the vessel is connected to the RSP facility.

In order to assess the impact of this innovation and optimize its operation, a number of use-cases for the RSP pilot are defined. These need to consider different operating conditions:

- the level of activity of the crane
- wind resource (low/high-wind periods)
- electricity costs (market prices and tariff structure)

For future shore power installations that may including onshore BESS, different use-cases can be studied, regarding:

- battery system sizing
- potential multi-user operation as envisioned in the Distro Smart Energy System, i.e., creating a local market place for automated trading of battery capacity and energy.
- battery system operation when the vessel is not present at the quay

As this results in a large number of potential use-cases, the approach is to only conduct experiments for the set-up in which the battery system is installed on the vessel, assuming a pre-determined battery size and centralized energy management system, in line with the planned set up at HMC.

Table 2.1 shows for different locations of the BESS, which objectives are applicable and what is to be considered regarding pilot and mock-up design and deployment.

While demand peak shaving remains the main objective, when installed at the RSP, the battery system can also be deployed to increase the utilization of local renewable generation (considering grid limitations) and tap additional revenues by arbitration and ancillary services provision. This additional functionality will mainly be applied to improve the business case for the battery when the vessel is not connected to the RSP, and will therefore not directly facilitate shore power integration, so this is not in scope of this demo. It is however useful to simulate this functionality for future applications. The situation when the vessel is connected to the RSP is more complicated and will benefit from small-scale mock-up field tests.

Table 2.1: RSP pilot use-cases dependent on ESS location

ESS location / Applicable objectives & considerations	ESS installed on crane vessel	ESS installed at RSP E-house
Primary objectives	• Reduce peak demand • Maximize WF utilization	• Reduce peak demand • Maximize WF utilization / market value
Secondary objectives	• Improve security of supply	• Provide grid support, (when vessel is not connected to RSP)
RSP pilot deployment	• Serving local loads at vessel • Cannot feed-in power to grid • Operated by vessel EMS	• Serve local loads, market & local grid • Can feed-in power to grid • Operated by RSP (coordinated with WF and vessel operators)
Mock-up: vessel at RSP	• Simulations and experiments	• Simulations

2.1.1 Use-cases supporting the RSP pilot primary goals

The two primary goals of the RSP pilot are considered to be **reduction of peak demand** (i.e. peak-shaving) and **maximization of the WF utilization**. Both intend to **reduce the RSP operational costs and emissions**, while **maintaining the quality of service**. Although these goals are linked, maximizing WF utilization focuses on energy at timescales longer than 15 minutes (typically hourly to day-ahead), while peak-shaving focuses on energy and power at minutes to seconds timescale. This can be used to separately develop and simulate operating strategies for different timescales, which are combined as a next step.

USE-CASE DESCRIPTION: PEAK-SHAVING

Operate the BESS to limit the energy demand from the public grid[2] on 15-minute[3] timescale, as well as to minimize momentary peak power.

The objective is to assess how different BESS operating strategies and operating conditions (e.g. vessel power demand levels, WF production levels, prediction uncertainties) affect the effectiveness of the peak shaving and the resulting operational costs.

This assessment requires the following features:

- Real-time tracking of the vessel's power demand and the WF power production
- Fast response to keep the demand below the predetermined (contractual) limit for each 15-minute interval
- Recharging strategy to maintain sufficient energy reserve, while aiming to minimize electricity procurement costs and optimizing battery lifetime

[2] Power exchange through the local grid between WF and RSP substation is exempted from grid tariffs.

[3] Grid tariffs (e.g. monthly) are based both on energy transport (kWh) summed over a month, measured per 15-min. block, plus the maximum average power (kW) per 15-minute block in that month. (these 15-min. block is also known as: Program Time Unit).

This assessment requires the following data:

- Real-time data and short-term prediction of vessel power demand and WF production (typ. up to 1 hour)
- Market prices (Intra-Day and spot market)
- BESS asset status, e.g. availability, available capacity and State-of-Charge (SoC)
- Grid status, e.g. actual disruptions or transport limitations or voltage fluctuations
- Data on communication latencies (both internally and externally)
- Asset response characteristics (e.g. response times, ramp rates, etc.)

USE-CASE DESCRIPTION: MAXIMIZING WF UTILIZATION

Operate the BESS to compensate for mismatches between WF energy generation and RSP energy demand at relevant timescales (i.e. hourly in case of day-ahead market and 15-minutes for short-term/real-time markets), considering uncertainties in WF generation and load forecasting, grid limitations and BESS limitations and OPEX. Apart from dispatching strategies (charging and discharging) this includes optimized BESS capacity scheduling.

Objective is to assess the impact of BESS compensating mismatches between WF generation and load patterns on WF energy utilization, RSP costs and security of service, and to optimize BESS scheduling and dispatching strategies (e.g. central EMS versus decentral marketplace).

This requires the following features:

- WF production and load forecasting
- Optimum bidding (BESS capacity allocation) in Day-Ahead and short-term markets
- Optimum dispatching to compensate WF generation and load profile mismatch

This requires the following data:

- Wind resource forecast data (e.g. from service provider)
- Wind farm characteristics: actual and planned availability and performance
- Load prediction, e.g. day-ahead horizon at 15-min to 1-hour resolution
- Prediction of Day-Ahead and Intra-Day market prices
- ESS asset status, e.g. availability, available capacity and SoC
- Grid status, e.g. planned disruptions or limitations

USE-CASE DESCRIPTION: PEAK-SHAVING COMBINED WITH MAXIMIZING WF UTILIZATION

Combining maximization of WF utilization and peak shaving, applying different strategies (e.g. different priorities, central EMS versus decentral market place).

This requires the following features (in addition to previous lists):

- Optimized trade-off of BESS operation to maximize WF utilization and peak shaving

2.1.2 Use-cases supporting the RSP pilot secondary goals

Two secondary objectives considered for the RSP for the situation of a battery system installed onshore, are **providing grid support** to create additional revenues and **improving security of supply** in case of grid events like outages or transport limitations, while preserving the battery system lifetime and limiting energy losses.

USE-CASE DESCRIPTION: GRID SUPPORT

The BESS provides one or several services to the Ancillary Services (AS) market, such as:

- Frequency support, e.g. in the Frequency Containment Reserve (FCR) market
- Voltage control and maintain/improve power quality

This use-case is only relevant if bi-directional power flow between the BESS and the public grid is possible, which for the RSP requires locating the BESS at the e-house rather than on the vessel. Further, the Ancillary Services-provision is most relevant when the vessel is out at sea, which can be combined with arbitrage to maximize the WF and BESS business case.

This requires (in addition to previous lists) the following data:

- Prediction of short-term market prices, e.g. for offering reserve capacity and power
- Battery system capabilities to fulfil Ancillary service requirements set by the grid code, e.g., response time and accuracy

USE-CASE DESCRIPTION: IMPROVE SECURITY OF SUPPLY

- Mitigate grid congestion by reducing RSP power demand from the public grid on request of the Distribution System Operator
- Ride-through outages of public or local grid
- Improve reliability and voltage quality of vessel on-board grid, particularly offshore

This requires (in addition to previous lists) the following data and features:

- Remote grid operator requests for congestion management (to be coordinated with other objectives for energy shifting and peak shaving)
- Grid forming capabilities of battery inverter, local grid balancing, e.g. through grid frequency shifting, and grid re-synchronization.

2.1.3 Assessing KPIs

Part of the KPIs can directly be assessed, like energy use, costs and quality of service, while others, e.g., direct and indirect emissions and number of jobs, can be derived from these based on external data or assumptions.

KPIs that can directly be assessed require:

- Metering energy flows and losses, e.g. exchange grid, fraction of green energy
- Cost models of RSP, BESS and WF investments, O&M, grid tariffs, interests, insurances
- Energy markets and AS markets net revenues and fees (when non-performing)
- Models for BESS cycle efficiency and lifetime consumption (validated by measurements)

- Monitoring reliability (number and duration of grid outages or events like congestion, voltage dips), quality of service (e.g. Total Harmonic Distortion, voltage level excursions)

KPIs that can be assessed indirectly require also:

- Average emissions for electricity from the grid or supplied locally from diesel genset
- A measure on the contribution to improve grid operation (mitigating congestion, improving frequency stability)
- A measure on the improvement of economic potential (upscaling, number of jobs)

2.2 Scenarios for assessment

2.2.1 Preparations

For each use-case, scenarios are defined and simulated to assess the impact of the innovations and optimize operating strategies. Based on the simulation results, a number of scenarios is selected for testing in the field lab. When defining these scenarios, the following preparations are needed to produce useful results for the RSP pilot:

For the simulations:

- Determine which scenarios (incl. baseline) need to be tested and which to (only) simulate
- Select models, e.g. use/develop in-house, 3rd-party commercial or open-source models
- Find what data is already available to verify the models, and as input for the simulations

For the field lab set-up:

- Address limitations of the mock-up, such as:
    - scale difference: pilot is in the order of 10 MW and mock-up in the order of 100 kW
    - different characteristics between the actual and down-scaled load, which can either be simulated (without hardware) or emulated (e.g. with a controllable load)
- Determine a proper (relative) component sizing
- Determine minimal test duration
- Specify data needs, determine what is available and how to down/up-scale:
    - Wind resource / wind production patterns (predicted and actual)
    - Load patterns (predicted and actual)
    - Electricity market prices and (connection and transport) tariffs
    - Characteristics and limitations of RSP equipment: wind farm, grid supply and E-house (e.g. converters, protection and control equipment), battery system, cabling

2.2.2 Scenarios for primary use-cases

The following scenarios for simulations and field tests are proposed, to assess the RSP use-cases wherein the BESS is operated to maximize WF utilization and reduce peak demand. Scenarios for secondary use-cases, mainly related to the BESS providing grid support, have not been elaborated further. Table 2.2 presents an overview of these simulation and test scenarios.

Table 2.2: Simulation and test scenarios for peak shaving and maximizing WF utilization

Scenario	Assessment	Details
Simulation		
BESS minimizes peak demand from public grid	Compare monthly peak demand of different BESS operating strategies compared to baseline (i.e. without BESS) over 1-year period	Optimization should take into account generation and load uncertainties. Also consider trade-off on costs: BESS OPEX, grid tariffs
BESS optimizes WF utilization	Compare WF utilization increase of different BESS operating strategies compared to baseline (i.e. without BESS) over 1-year period	Optimization should take into account generation and load uncertainties. Also consider trade-off on costs: BESS OPEX, market prices, grid tariffs
BESS optimizes WF utilization and peak shaving of the vessel demand	Combining abovementioned assessment criteria, and assessing the sensitivity of different priorities and strategies to hedge uncertainties	Selected strategies for field tests: 1. Baseline* 1. Central energy management 2. Decentral marketplace * Baseline data can be calculated from experiments with BESS
Field test		
BESS characteristics	BESS available capacity and cycle efficiency, auxiliary power demand, dynamic response, temperature rise, protection	Cycling at different rates and depths of discharge, response to steps and ramping
BESS minimizes peak demand from public grid	Similar as 1st simulation scenario, while also assessing aspects such as actual BESS performance, event response	Capture several periods of consecutive days with different wind generation levels.
BESS optimizes WF utilization and peak shaving of the vessel demand	Similar as 3rd simulation scenario, while also assessing aspects such as forecasting errors, actual BESS performance, event response	Capture several periods of consecutive days with different wind generation levels.

3. Shore power mock-up description

This section describes the set-up of simulations and field tests in a down-scaled mock-up to assess peak shaving strategies. The simulation includes modelling, data needs and analysis. The mock-up includes the physical configuration, data needs and procedures for testing and analysis of the results. Simulations have been performed prior to the field tests to determine suitable settings. Using the field test results, simulations can be performed to assess peak-shaving in scenarios that have not been tested, e.g. at full-scale.

3.1 Modelling and simulation

Figure 3.1 presents a high-level block scheme of the simulation models. The greyed-out part generates a production schedule that is optimized to maximize the business case considering trading at the day-ahead market, considering the EPEX SPOT process as a given. The experiments for Demo 3, use historic wind production and vessel load demand data instead. In a later stage, forecast uncertainties in the electricity production can be considered as these affect the battery recharging strategy. The simulated assets include the local electricity generation, storage and emulated vessel load.

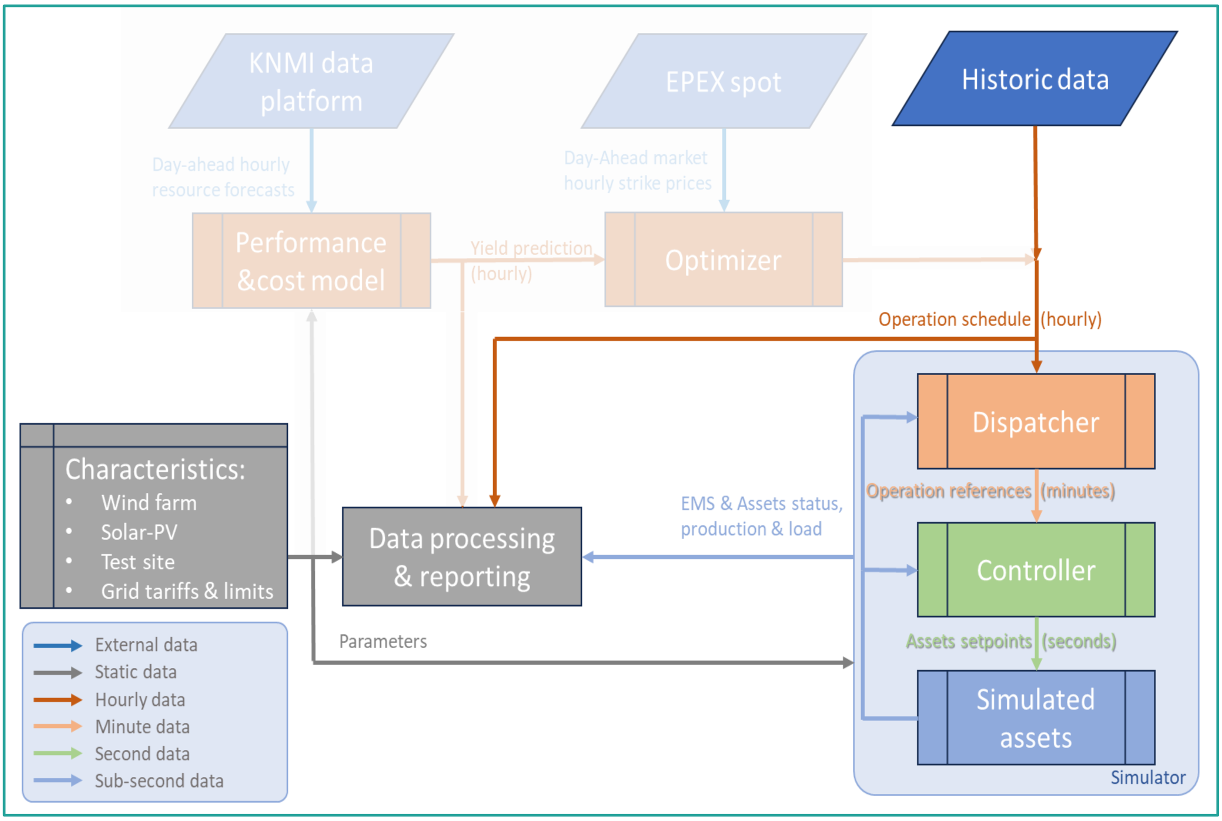


Figure 3.1: Modelling framework and inputs

3.1.1 Model inputs

Table 3.1 lists which input data is applied to perform the simulations. Simulations are performed based on this data and also on down-scaled data to compare the down-scaled mock-up tests at the SWITCH field lab with the actual pilot at RSP.

Table 3.1: Simulation inputs for RSP pilot

Input	Unit	Source	Notes
Wind farm production forecasts	MWh	KNMI forecast data Hoek van Holland; Wind turbine power performance curve	• No access to proprietary forecast data of local wind farm • Ignoring wake effects • Wind speed scaled to turbine hub height
Wind farm production profiles	MWh	Wind turbine power performance curve (Vestas 3.45MW)	Available: • Combined historical meteo data with WT-characteristics Open requests: Historical production data; with this, TNO can synthesize profiles (Weenk, 2023)
Electricity prices	EUR/MWh	EPEX SPOT Public	• Day-ahead market (bidding) • Spot market (re-dispatching)

Load profiles[4]	MW(h)	HEEREMA Marine Contractors	Available:
			• Historical power demand (two 10-day periods)
			• Base load & peak power levels
			• Wish list items (for improving peak-shaving strategies)[5] :
			  • Day-ahead energy demand forecast (hourly)
			  • Short-term energy demand forecast (15-min.)
			  • Short-time demand-flexibility options

Grid tariffs	EUR/MW EUR/MWh	PoR/STEDIN (public), (Weenk, 2023) App. G	• Based on 2024 tariffs
RSP limits	MW(h)	RSP / STEDIN	• Max. demand: 8.3MW • Feed-in to grid not possible

[4] HMC kindly provided measured data from Thialf crane vessel at high sample rate (1 sec.) over two 10-day periods.
[5] Load forecasting and demand-side flexibility are not considered: it is essential to always have the minimum energy available, to guarantee that power consumption limits are respected.

Input	Unit	Source	Notes
Battery design specs[6]	EUR/MWh	Battery / inverter manufacturer data	• LFP (Lithium Ion Phosphate) technology • Sized 3.5MW at 3C (1,167MWh)
Battery OPEX	EUR per cycle	Battery / inverter manufacturer data	• Apply typical lifetime consumption models, internal resistance, cycle efficiencies

3.1.2 Simulation model

The simulation environment consists of an optimizer and a central Energy Management System (EMS). The optimizer produces a sequence of hourly bids at the Day-Ahead energy market (as price-taker) and produces an hourly production schedule to commit to these bids. The user can specify any combination of assets to include, e.g. wind, PV, battery.

The EMS aims at realizing this market bid (i.e. unit commitment), by producing power setpoints for each individual asset, while respecting the operational limits of the assets and the grid connection. This is realized in two steps:

3. For the single energy bid for the current hour at power-plant level, the dispatcher produces power references at 1-minute intervals for each group of assets of this power plant, e.g. a wind farm or solar-PV farm.
4. The controller tracks the power references of the dispatch groups and produces power setpoints for each individual asset at 1-second time intervals.

Annex A.3 provides an overview of the simulation model.

NOTES:

- The user can assign assets with similar characteristics to a single dispatch group, in which the power reference is evenly distributed between the assets, considering different sizing. Dispatch groups are a means to specify dispatch limits and priorities.
- The EMS allows for defining up to four grid connection points. Each grid connection point can be defined with its own limits in energy supply and demand (at Program Time Unit interval, i.e. 15-min.) and instantaneous power supply and demand limits. The assets within a single dispatch group should be connected as the same grid connection point.
- Besides unit commitment, the dispatcher can operate in several other modes, as shown in Figure 3.2. Most important for this project are "peak-shaving consumption" (case 3) and "curtail consumption" (case 2), while "unit commitment" is defined as case 4. This figure also shows the logic that determines the operational state. The state for "Production peak-shaving" is not applicable for this test and therefore not yet implemented.
- In case no energy bid is provided, the EMS falls back to a default state "Pass on Pref" (case 0) wherein local generation is enabled while the battery system is being fully recharged.

[6] HMC has provided the main battery system design specifications

3.1.3 Peak-shaving strategy

The strategy for peak-shaving of the power demand of a vessel that is connected to the shore power facility aims at limiting the average power over each 15-minute period within a prescribed limit, that is set in the contract with the grid operator as 'peak power demand' and determines the capacity tariff. At the same time, the momentary power demand needs to stay within the physical limits of the shore power facility.

The peak-shaving is realized by means of an on-board battery system and is based on a prognosis of the demand over the current 15-minute period. This prognosis is a weighted average of the average demand over the previous 15-minute period and the accumulated energy demand within the current 15-minute period and is updated every minute (EMS time step). The same prognosis is applied to determine how much room is available for recharging the battery within the current 15-minute period.

In peak-shaving mode, the amount of energy supplied by the battery is determined to compensate for the expected amount of energy that is exceeding the limit. In case when the accumulated energy demand already exceeds this limit during the current 15-minute period, the battery also starts to supply power, trying to fully compensate the demand.

In case local generation is considered, in case of RSP by a wind farm, the same peak-shaving strategy can be applied, provided that the grid connection contract and metering infrastructure allow that the local generation compensates the RSP demand.

State transitions when starting and ending peak-shaving mode differ. When starting peak-shaving, the battery has to respond rapidly in order to effectively limit the energy demand within the remaining time of the current 15-minute period. When ending peak-shaving, the battery setpoint can change more smoothly from discharging to zero power and, if allowed, to recharging. This reduces the ramp rate at the grid connection and reduces the risk of again exceeding the limit, leading to oscillating behaviour between these operating states.

Annex A.4 provides a detailed description of the peak-shaving implementation.

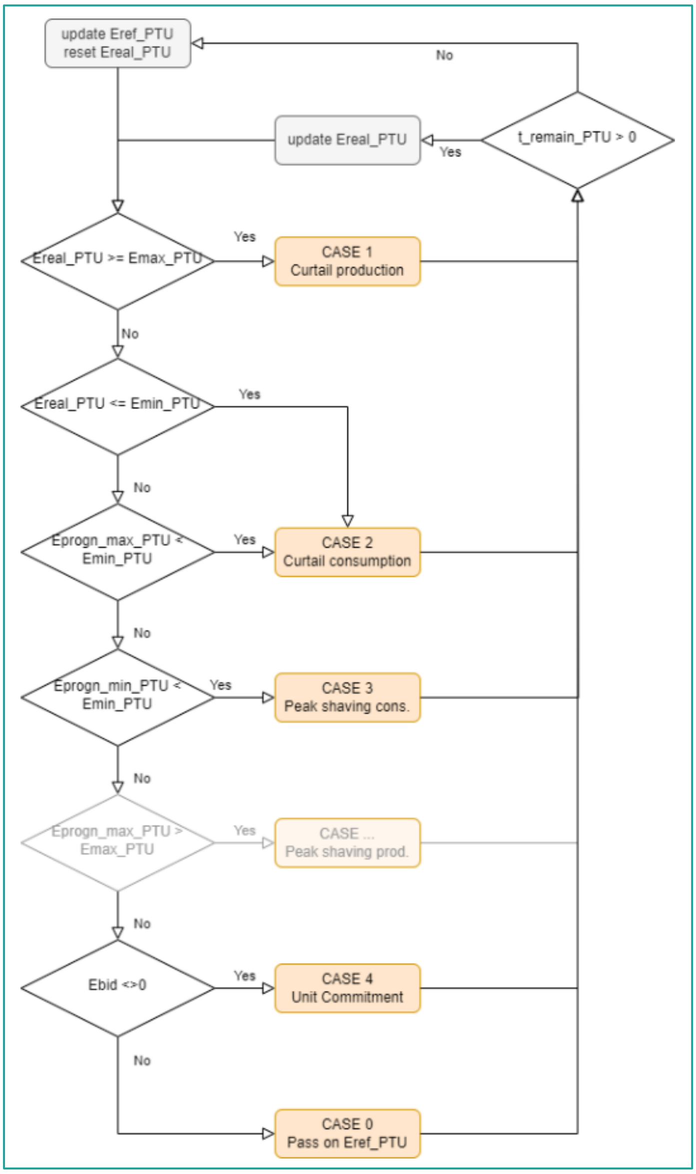


Figure 3.2: EMS dispatching operation modes

3.1.4 Using simulation results for field lab experiments

During the preparation of field tests, desktop simulations have been conducted to determine suitable EMS settings and to select useful test cases, considering:

- Relative sizing of the assets in the down-scaled set-up (explained in section 3.2.2)
- Setting appropriate limits for the grid demand
- Pre-processing and selecting suitable periods for measured vessel power demand (see also Annex B.1)
- Generating data sets for unit-testing of the EMS, implemented in the real-time platform

During and after conducting field tests, simulations have been conducted to study the effect of specific features, e.g. response times, ramp rate limitations, which cannot be modified in the field lab. Having verified the simulation model with field test data, simulation results can be translated to pilot-scale, although due to the large scale difference, these can only provide an indication of the expected behaviour. Simulation results are provided in section 4.1.

3.1.5 Simulation cases

The following simulation cases have been conducted for different limits of the grid demand and of the local energy provision from wind. The main aim was to investigate the effects of these settings on the peak-shaving and to select useful settings for the experiments. Table 3.2 states the values for the three main parameters for the pilot [MW] scale and the mock-up [kW] scale. The simulation (and parts in the EMS and controller) uses normalized values in per-unit with 1.0 [pu] corresponds with 10 [MW] at pilot scale and 100 [kW] at mock-up scale. Negative values indicate a demand and positive numbers indicate supply. More details on the simulation cases are provided in Annex B.2.2.

Table 3.2: Simulation cases

Parameter	Cases				
Wind farm rated power: varied in steps between 60kW and 0kW					
Pilot scale [MW] (# WTs approx.)	31 9	6 2	2 <1	1 <1	0 0
Mock-up scale [kW] (# WTs)	N/A	60 6	20 2	10 1	0 0
Grid demand limit (15-min. averaged power): varied in steps between -75kW and -55kW					
Pilot scale [MW]	-7.5	-7.0	-6.5	-6.0	-5.5
Mock-up scale [kW]	-75	-70	-65	-60	-55
RSP power demand limit: fixed at -80kW					
Pilot scale [MW]	-8.0				
Mock-up scale [kW]	-80				
Battery specs	**Rated**	**Setting**	**Rated**	**Setting: SoC 80-100%**	
Pilot scale	3.5MW		1.17MWh (3C)		
Mock-up scale	60kW	35kW	57.6kWh (1C)	20%: 11.5kWh	

3.2 Field lab experiments

Field tests have been conducted at the SWITCH Fieldlab of TNO and WUR in Lelystad, which includes a small wind farm, a solar-PV farm and battery system and a grid connection. All assets are centrally monitored and controlled. For the MAPGIE experiments an emulation of the vessel load based on measured historical data was added to this central controller.

3.2.1 Switch experimental set-up

Figure 3.3 shows the assets at the SWITCH field lab of TNO and Wageningen Research, located in Lelystad in The Netherlands. Asset specifications and a simplified schematic of this field lab are given in Annex A.

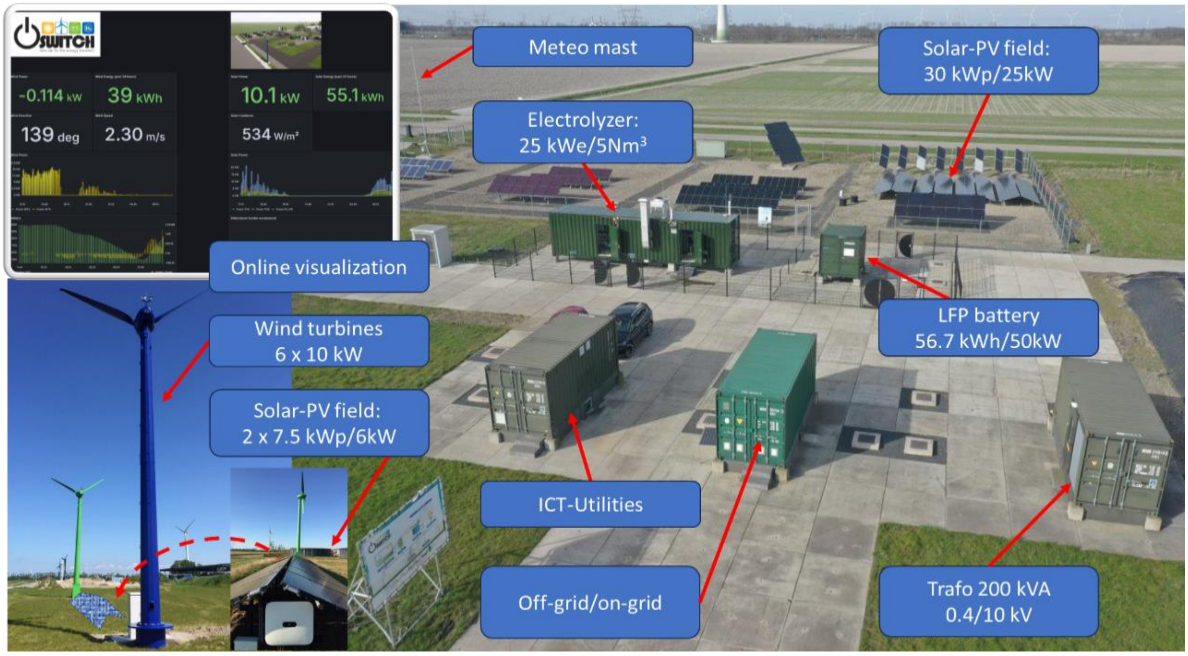


Figure 3.3: Overview of assets at SWITCH field lab

The mock-up of the RSP demo uses the following assets at the SWITCH field lab:

- 6 wind turbines (6 x 10kW)
- 3 solar-PV arrays, East-West oriented (30kWp/25kW, 2x7.5kWp/6kW)
- Battery system, operating in grid-connected mode (57.6kWh/50kW)
- Monitoring system that measures the status and performance of the assets, power flows and local meteo resources and stores this in a database (Wind Data Management System), while live data can be viewed remotely through a Grafana dashboard.
- A central Energy Management System (EMS) and control system that provides the power setpoints to the assets, based on asset status, measured power and external inputs.
- A low-voltage collection grid that is reconfigurable and is connected to the public grid. Using the battery system's grid-forming capabilities, it can also operate in off-grid mode, maintaining the power balance through frequency droop control, but this is not part of the test plan for this project.

The physical and contractual grid limits at the SWITCH lab are not limiting the operation. Therefore, to mimic the limits at the RSP pilot, these limits have been down-scaled and implemented as parameters in the EMS and control system.

The external inputs, that largely determine how the experiment behaves, are:

- A pre-determined emulated load profile, retrieved from measurements at the full-scale demo, which is added to the measured grid demand and provided to the EMS
- An hourly production schedule, based on the day-ahead production forecast, a performance and cost model of the assets, and known hourly spot prices. However, for these experiments, the default schedule is set to produce at maximum available power.

Figure 3.4 shows the actual field lab and simplified functional schematic of the test set-up.

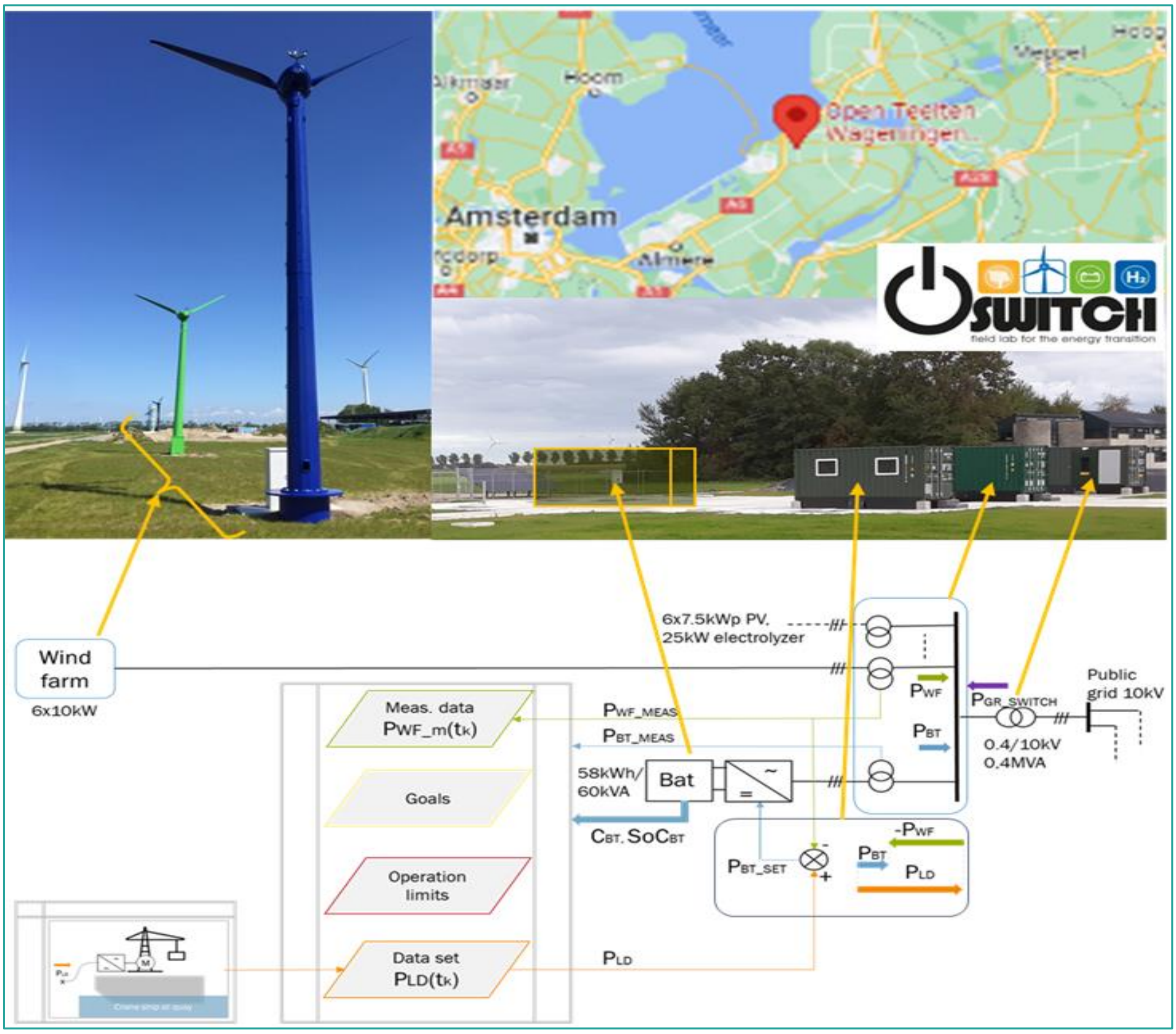


Figure 3.4: SWITCH Fieldlab and simplified schematic of RSP mock-up

Figure 3.5 shows a simplified structure of the EMS, control and monitoring systems. For the MAGPIE tests the market optimization has been disabled (the greyed-out part), so that the default production schedule applies. A functional description is provided in Annex A.2.

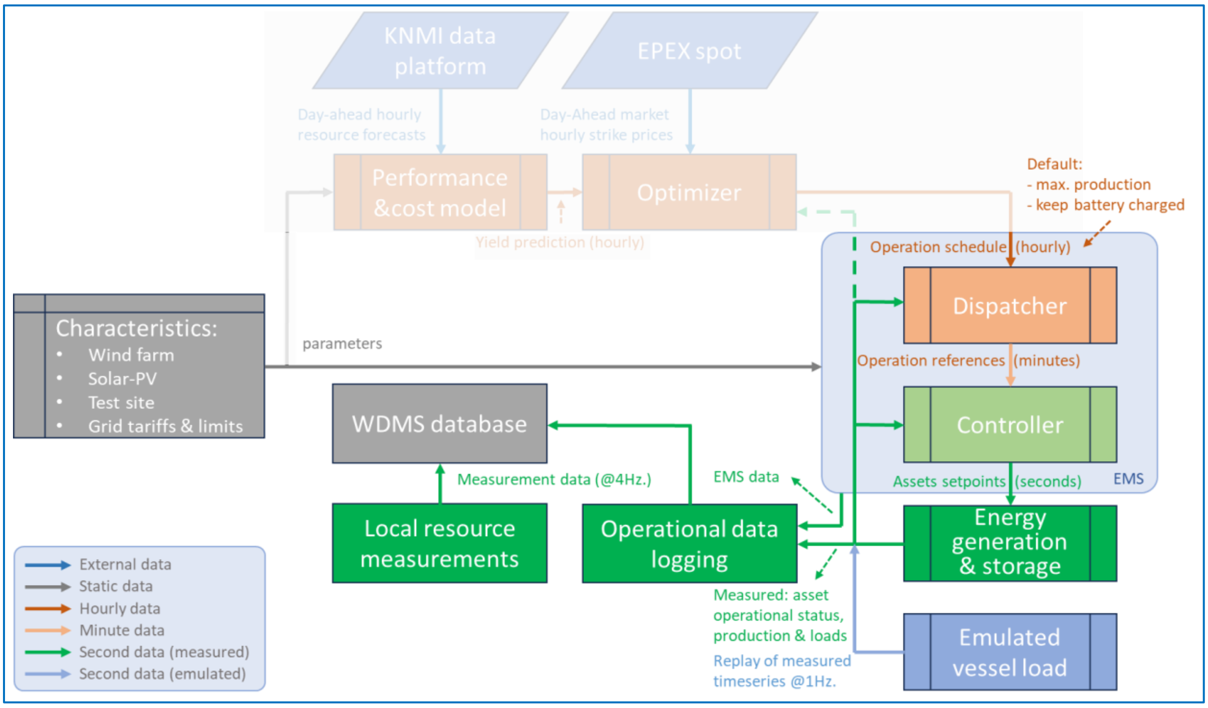


Figure 3.5: Schematic of SWITCH field lab energy management and monitoring system

3.2.2 Down-scaling

A down-scaling factor of 100 is chosen for the mock-up to represent the pilot. Some adaptations were made trying to match differences in the relative sizes of the assets at the mock-up with those at pilot scale. For instance, the wind farm relative size compared to the battery size at the mock-up is much smaller than in the pilot-scale, see also Figure 3.6.

Another difference is the higher allowed charging and discharging rates in the pilot compared to the mock-up. At pilot scale the charging power is 3.5 MW while the battery capacity is 1.17 MWh, which equals a so-called C-rate of 3 (or 3C). To make the relative sizes comparable, the useable battery power in the mock-up has been limited to 35kW and the usable battery capacity has been reduced to 20% by limiting the minimum SoC to 80%. Part of the battery capacity in the RSP pilot might be reserved for providing back-up power in case of temporary loss of the shore power connection, thereby limiting the useable capacity for peak shaving, but this is not considered in the mock-up experiments. Table 3.3 summarizes the applied scaling.

Table 3.3: Summary of scaling

Quantity	Pilot-scale	Mock-up scale	Comment
Power	10MW	100kW	Set as per-unit base power
Battery power	3.5MW	±35kW	Actively limiting 60kVA inverters
Battery useable capacity	100% of 1.17MWh	20% of 57.6 kWh = 11.7 kWh	Set min. SoC to 80%
Wind farm	9x3.45MW: 31MW	6x10kW (+37kW PV)	PV added to partly compensate smaller size

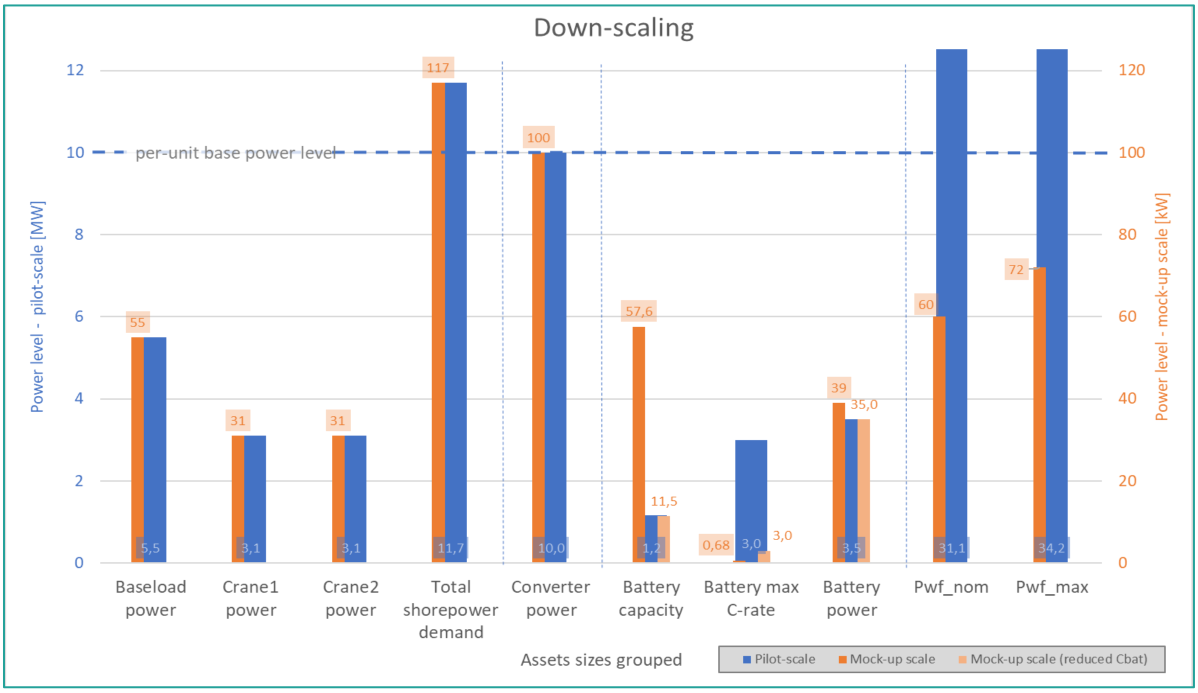


Figure 3.6: Relative sizes of the assets, considering the scaling factor

3.2.3 Experiment plan

Table 3.4 lists the sequence of field tests. The first battery tests were needed to determine the main performance characteristics for different operating conditions, cycle efficiency, charge current limits and system dynamics. No long-term aspects (such as degradation) have been considered in the characterization tests due to time and scope constraints. Instead, the number discharge-recharge cycles combined with the depth-of-discharge is taken as a measure for battery lifetime consumption in the tests with peak-shaving.

Table 3.4: Proposed sequence of field tests

Description	Results	Duration
BESS characterization		
Initial cycling at 0.5C	Cycle efficiency	1 week
Cycling at different C-rates	Cycle efficiency Loss and thermal models	1 week
Test sequence		
Peak-shaving – strategy: BESS recharging whenever possible	Grid demand profile without and with peak shaving, estimated costs	1 week
Peak-shaving – strategy: BESS recharging considering load forecast	Grid demand profile without and with peak shaving, estimated costs	1 week
Peak-shaving – strategy: BESS recharging max. use of wind power	Improved wind energy utilization versus higher grid costs (or load curtailment)	2 weeks

3.2.4 Experiment preparation

Preparations for the experiments included developments in the EMS and control system algorithms, selection and processing of input data and setting parameters.

As the SWITCH field lab was established recently, a number of features for MAGPIE were implemented and tested in the course of the project. These included the peak-shaving and battery recharging algorithm[7], emulation of the vessel power demand and battery characterization. For testing, this functionality of the EMS and control system, the assets' responses were emulated in real-time using desktop simulation data, which allowed for a 1-to-1 comparison with simulation results.

The measured vessel power demand, provided by HMC has been analyzed and pre-processed. This included selecting data, i.e. omitting periods in which the vessel's thrusters were active for longer than a few seconds, and removal of outliers. Next, the data was characterized, considering the daily average load and the number of occurrences and energy content of power levels exceeding certain limits. Annex B.1 provides more details. These limits, and other settings of the EMS, are set as parameters, listed in Annex B.2.4.

Table 3.5 lists which inputs were applied to perform the field tests, in addition to the input needs for simulations.

Table 3.5: Data input applied in field tests

Input	Source	Details
Emulated load profiles	Measured timeseries provided by HMC (typical days / crane operations)	Measured power levels at 1 sec. resolution
Battery SoC and available capacity	Battery BMS and PMS	Data is continuously logged
Power flows, accumulated energy	power measurements: WTs, PV, battery system and grid exchange	Data is continuously logged
Day-Ahead and Intra-Day market prices	EPEX SPOT	Day-Ahead strike prices are retrieved automatically
DA and short-term wind farm production forecast	NWP, nearby meteo station data, SWITCH meteo mast, WT status	Sources need to be combined into production forecasts

[7] The battery recharging power is determined by the headroom that is available in the prognosis over the current PTU, which includes the momentary local wind power. Thus far, no wind power forecasting is implemented that could contribute to a better utilization of the locally produced green energy to recharge the battery.

3.2.5 Test sequence

Table 3.6 lists the details of the applied test sequence at the field lab.

Table 3.6: Test sequence

Test No.	Test period (UTC)	Vessel data period	Load down-scaling [-]	Power limit RSP [pu]	Peak-shaving limit DSO [pu]	Remarks
1	08/11/2024 12:13 12/11/2024 19:20	26/02/2024 12:43 01/03/2024 19:49	80 à 90 à 100*	1.0	0.55	Max. battery recharging after peak-shaving. Local generation included: Wind and PV
2	12/11/2024 20:42 17/11/2024 00:57	01/03/2024 19:44 05/03/2024 23:59	100	1.0	0.55	Battery recharging power made dependent on load prognosis included: Wind and PV
3	17/11/2024 07:31 19/11/2024 07:30	03/03/2024 00:00 04/03/2024 23:59	100	0.85**	0.65	Without generation
4	19/11/2024 07:40 21/11/2024 07:39	03/03/2024 00:00 04/03/2024 23:59	100	0.80**	0.60	Without generation
5	21/11/2024 13:13 23/11/2024 13:12	03/03/2024 00:00 04/03/2024 23:59	100	0.80	0.55	Battery recharging strategy: more conservative setting*** Without generation
6	26/11/2024 12:09 28/11/2024 14:55	01/03/2024 19:44 04/03/2024 23:59	100	0.80	0.55	Local generation included: Wind and PV
7	28/11/2024 14:55 02/12/2024 19:10	01/03/2024 19:44 05/03/2024 23:59	100	0.80	0.55	Local generation included: Wind only

* Initial down-scaling 80 of vessel load to quickly test both peak-shaving & power limitation. Down-scaling 80 à 90: at 8/11/2024 20:31:39; 90 à 100: at 9/11/2024 11:06:04.

** Maximum power limit was reduced, using updated information on actual limits of Thialf vessel connection at RSP

*** Battery is recharged only in case of sufficient margin between load prognosis and load limit. Margin was enlarged from 0.05 pu to 0.20 pu

Remarks

The first test in this sequence was conducted to check the proper functionality of the energy management and control systems. The vessel load was temporarily increased to quickly test the peak-shaving of the momentary power demand and the 15-minute averaged demand, with more frequent occurrences where the load exceeds the limits.

In the course of this test sequence, the power demand limit has been reduced from 1.0 pu to 0.80 pu, as new information was provided about the actual power limit at the RSP: 8.0MW.

To perform an assessment of the peak-shaving, different settings have been applied:

- 15-minute averaged load limit (between 0.65 pu and 0.55 pu)
- Enable/disable compensation of the vessel demand with local generation (wind and PV)

The results were analyzed to assess whether peak-shaving is effective (i.e. preventing depletion of the battery) and at what costs (energy losses and battery lifetime consumption).

4. Results

4.1 Simulation results

Figure 4.1 shows the result of a simulation over a 48-hour period, without considering any local electricity generation. The first four subplots show EMS data updated each minute, while the lower four subplots show 1 second-data of the controller. The sign convention considers supply to the grid as positive and demand from the grid as negative.

The first subplot shows the energy exchange with the grid for each Market-Time Unit. As the (market) optimizer is not activated in the simulation (or the field tests), all energy bids **Ebid** and scheduled energy **Esched** values are zero. **Emeas** is the actual measured net energy demand from the grid, which in this simulation case consists of the vessel load and battery load/supply. The hourly accumulated demand roughly varies around -0.5 pu.

The second subplot shows the same measured energy accumulated each (15-minute) Program Time Unit. This is the measurement interval to determine the peak power, which determines a substantial part of the grid tariff. The yellow line represents the allowed peak power level, set for this simulation case of -0.55 pu. It shows that this value is not exceeded during the simulation period.

The third and fourth subplot show the behaviour of the EMS over time. The EMS allows the battery to recharge, showing negative values for **Pref_EMS_pu** (in red) as long as there is sufficient margin left between the **prognosis** of the energy **Emeas** over the current PTU and the limit. On the other hand, if this prognosis indicates that **Emeas** is likely to exceed the limit, peak-shaving kicks in. Also visible in the **Dispatch case** when switching from 0 (no peak shaving) to 3 (demand peak-shaving), see Figure 3.2 for the definitions. When **Emeas** actually exceeds the limit, direct demand curtailment (Dispatch case 2) will be initiated (although this does not occur in this particular simulation run). Peak-shaving will produce a positive reference power **Pref_EMS_pu**, which in combination with the **Dispatch case** signal commands the controller to set the battery to discharge.

The fifth subplot can be used to study the controller response, e.g. dispatching between assets, and adapts its behaviour depending on the **Dispatch case**, but it is not detailed here.

The sixth subplot shows that the battery not only discharges when the EMS commands peak-shaving, but also in case when the momentary power demand exceeds the RSP power limit, thus preventing overload of the RSP converter and transformer. This plot (purple) also shows that the base vessel load (purple) is close to the peak-shaving limit, set for this case. A slight increase in the vessel base load will lead to much more frequent peak-shaving activity with the risk exceeding the grid demand limit due to temporary battery depletion.

The seventh subplot shows (yellow) that battery recharging stops when reaching full charge, as shown in subplot eight. Please note that the minimum state-of-charge is set to 80% and the energetic efficiency, both for discharging and recharging, is set to 95%. Battery ageing is modelled, considering linear capacity reduction from 100% to 80% with the number of equivalent full cycles.

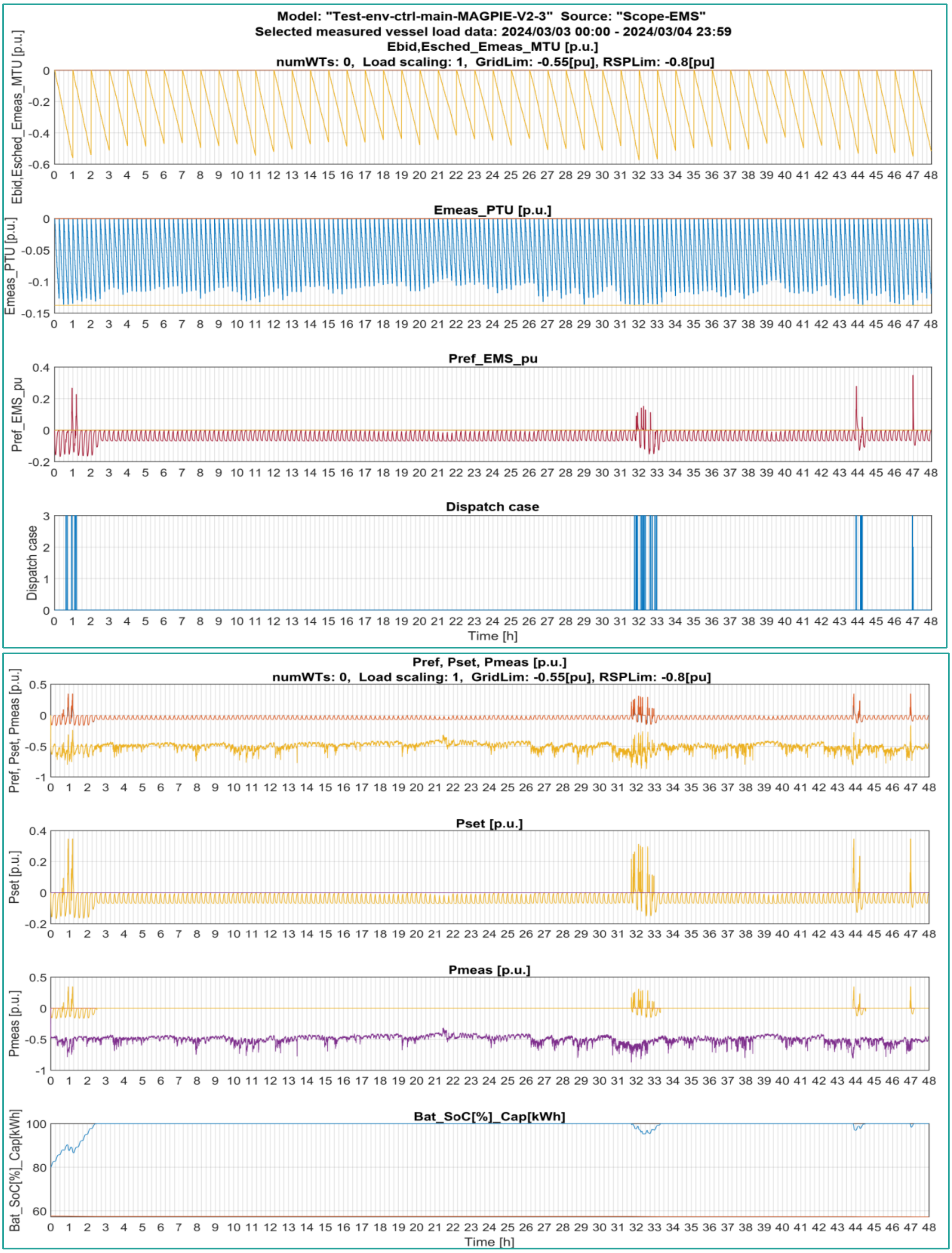


Figure 4.1: Simulation results for grid limit of -0.55pu, showing signals of EMS (top) and Controller (bottom)

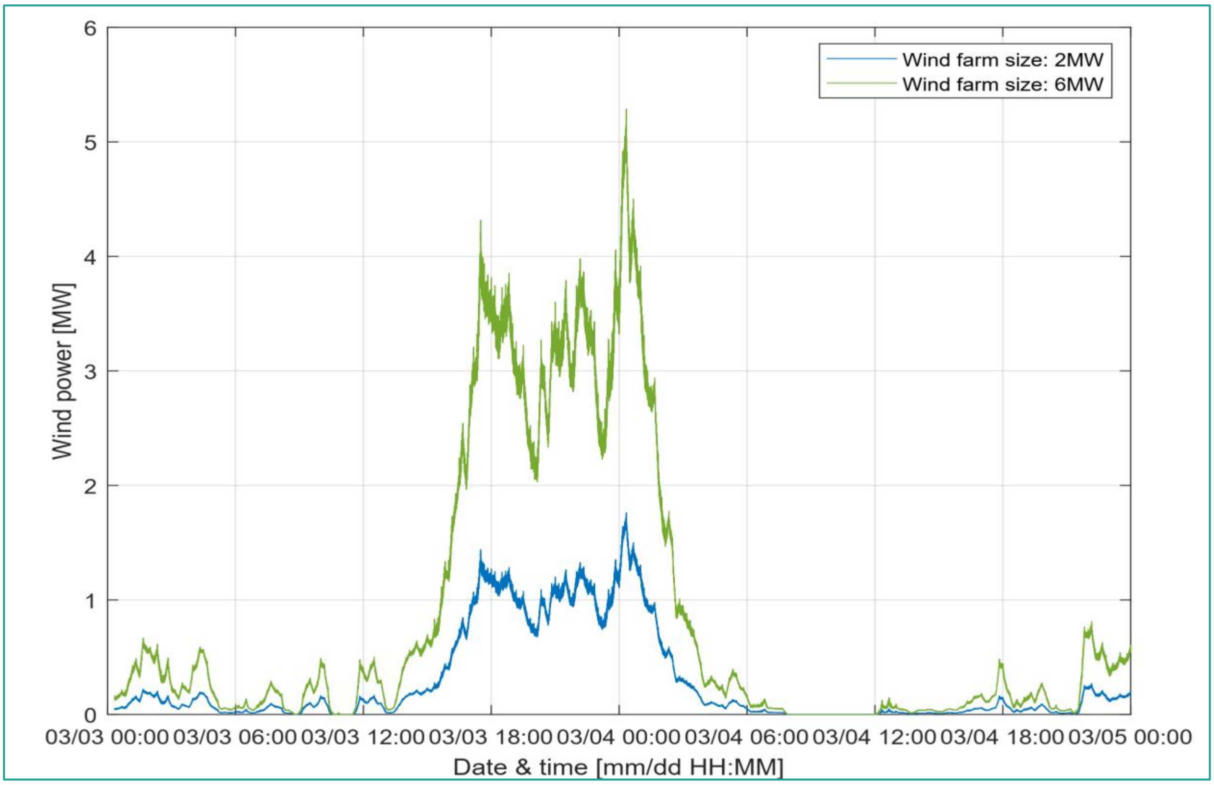


Figure 4.2: Simulated electricity production for 2MW and 6MW size wind farm

The simulated electricity production from a local wind farm Figure 4.2 is applied to compensate the vessel load (behind-the-meter) and thereby reduce the net grid demand. Figure 4.3 shows the effect of this compensation on the peak-shaving. The 2MW and 6MW at pilot-scale is equivalent to 2WTs and 6WTs of 10kW at mock-up scale, as stated in the figure headings. The limit for the maximum 15-minute peak load remains unchanged.

The local production results in fewer occurrences where demand peak-shaving is needed. Also more energy is available to recharge the battery, although in this simulation the battery recharging power is limited at high state-of-charge to keep the battery temperature at modest levels, preventing early degradation.

Despite a relatively large installed wind farm capacity, low electricity production levels can still occur due to periods with very low wind speeds (March 4 between 0h and 12h) that coincide with periods of higher vessel load, peak shaving still remains needed. This can be seen in the two subplots of Figure 4.3 wherein the signal **Dispatch case** is equal to 3.

Figure 4.4 shows the high sensitivity of the peak-shaving activity to the setting of the 15-minute peak load limit. This limit (starting from Figure 4.1) has been enlarged in steps of 0.05pu (or 0.5MW at pilot-scale).

A more compact way to present the results is to select the total energy demand per PTU and sort these along the vessel demand, as shown in Figure 4.5. It shows the effect of peak-shaving when the vessel load exceeds the prescribed grid limit (at the left side of the x-axis), showing the grid demand is reduced, compared to the vessel demand, while at lower vessel load levels (towards the right side of the x-axis), the grid demand is mostly larger than the vessel load as the battery needs to recharge.

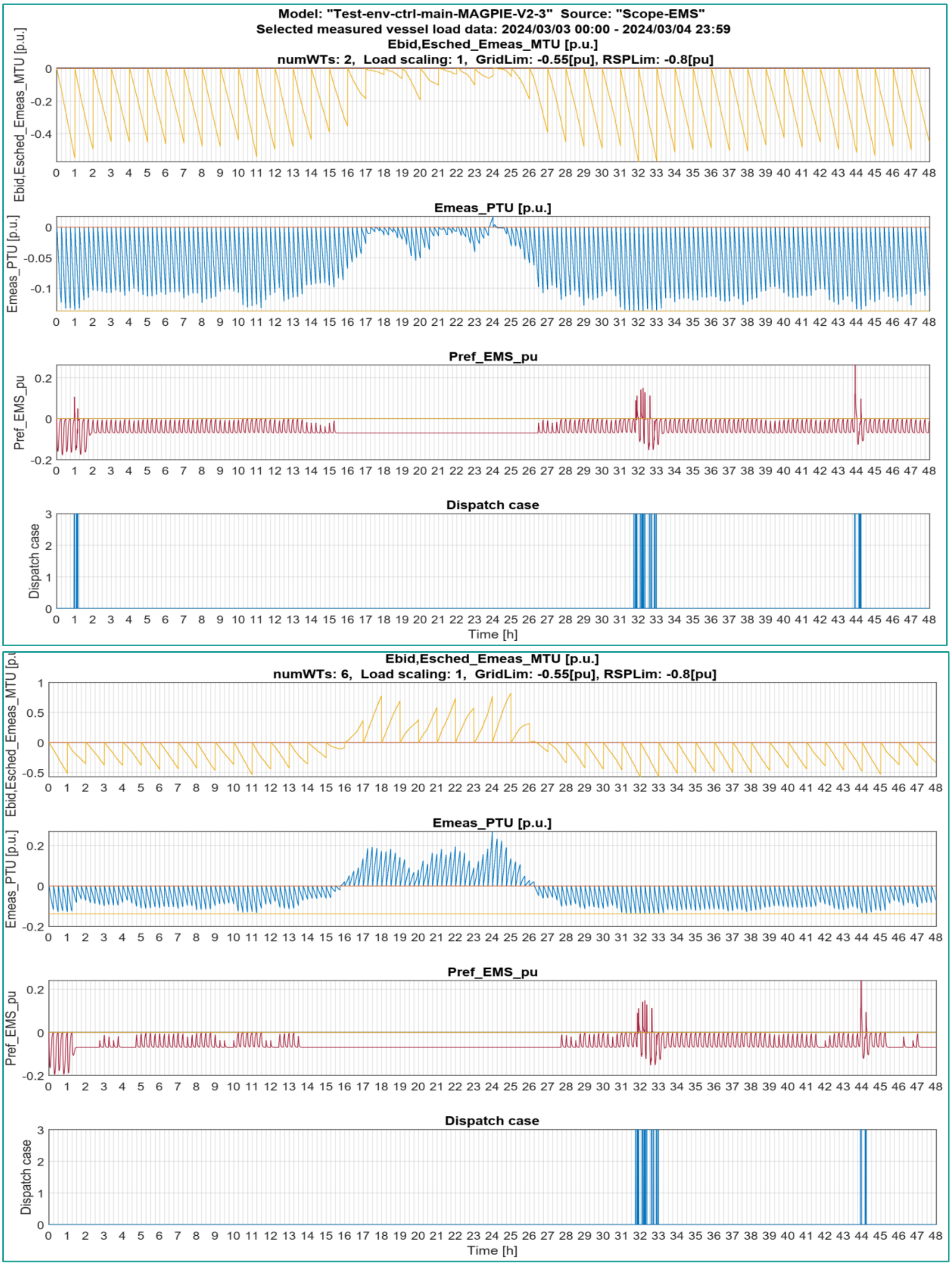


Figure 4.3: Simulation results with different sizes of local electricity production (top) 2MW, (bottom) 6MW

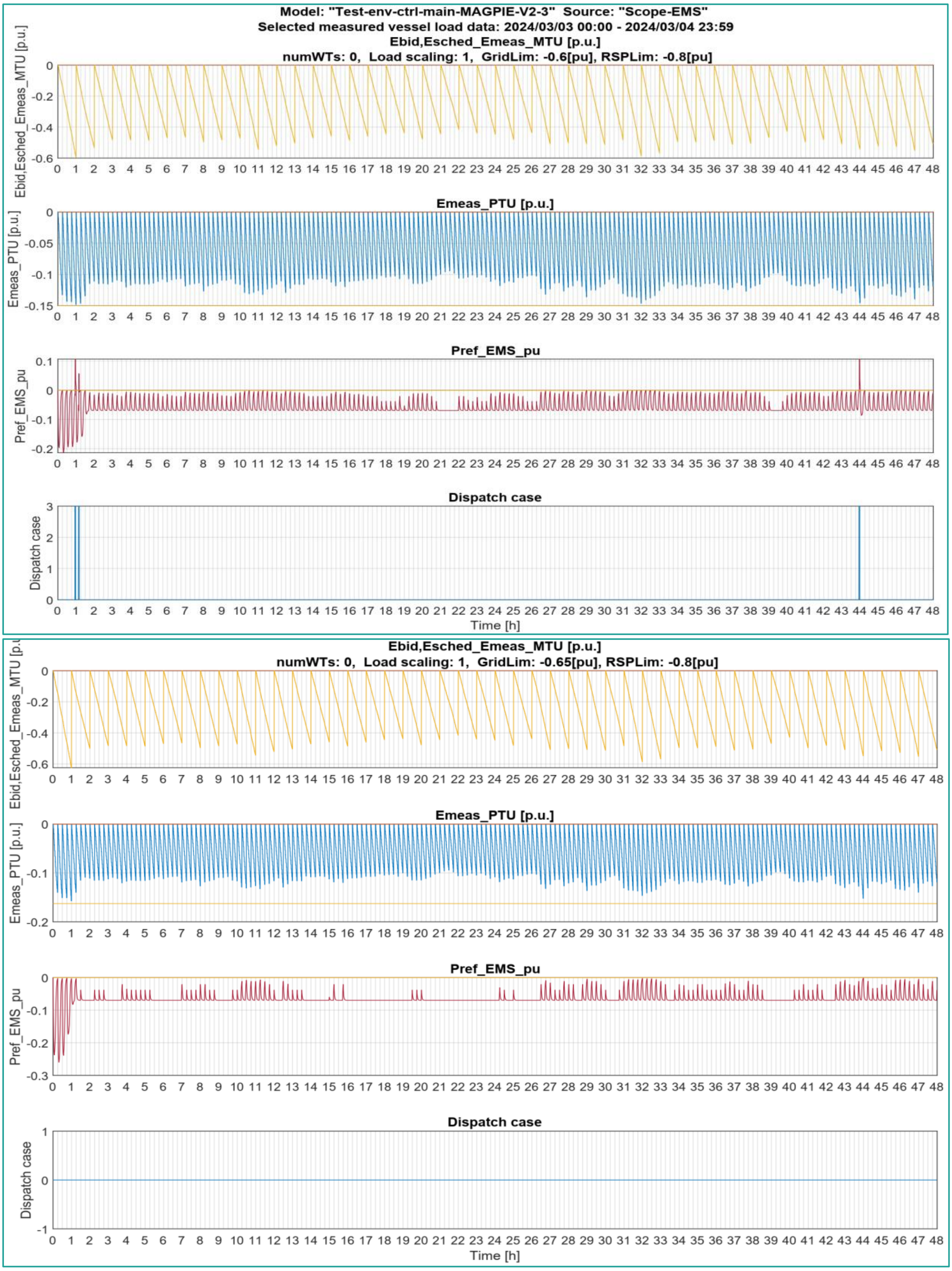
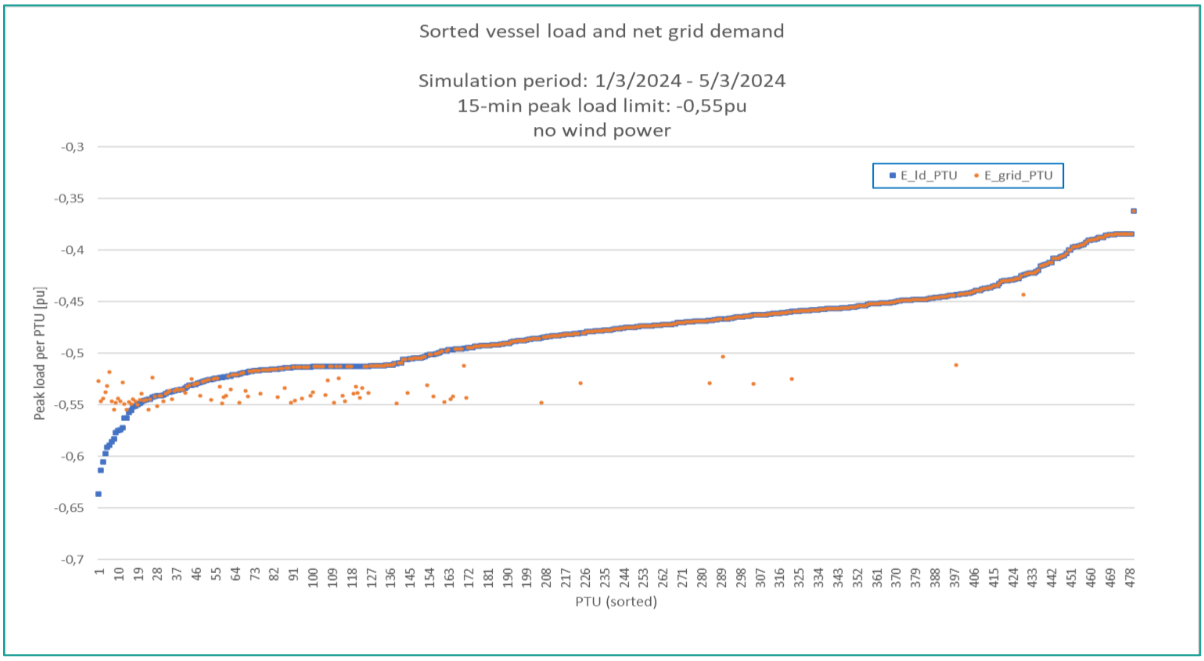


Figure 4.4: Simulation results with different settings for 15-min. peak grid demand



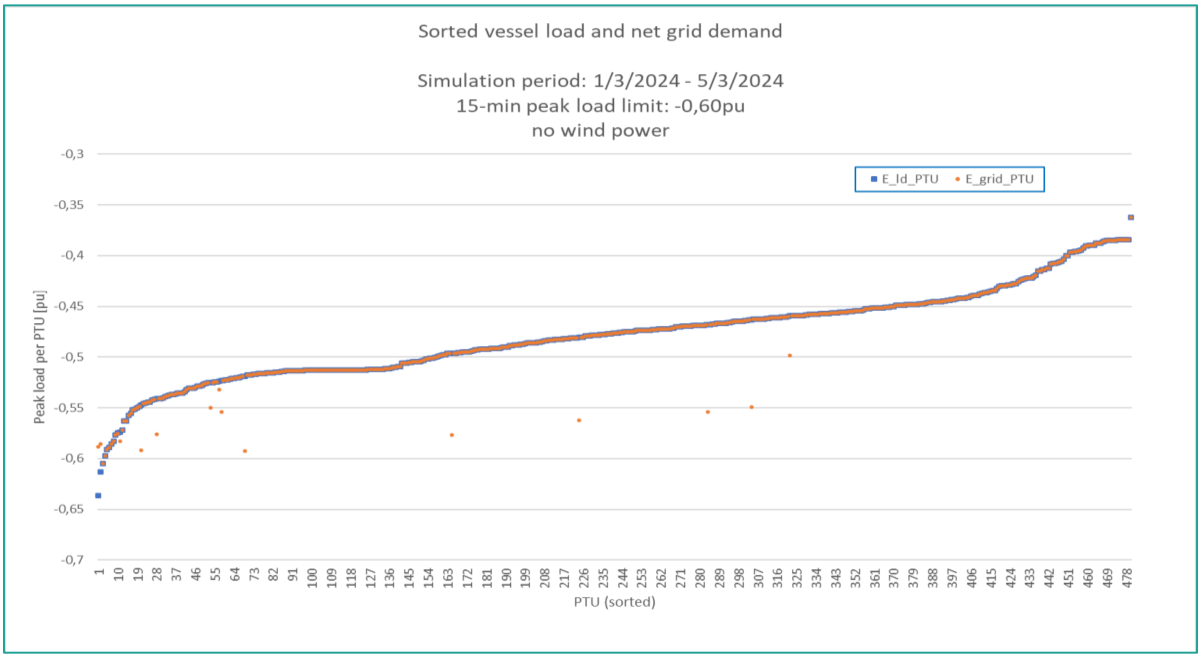


Figure 4.5: Sorted vessel load per PTU (blue) with resulting grid demand (orange) for two simulation cases (peak load limit -0.55pu and -0.60pu)

Despite the short time period of these simulations, some conclusions can be made for the set-up of the field tests:

- setting the 15-minute peak load limit at different levels within the range of 0.55 up to 0.65 pu seems appropriate (unless tests show different outcomes that simulations)
- testing with local wind production should cover different wind conditions to show that peak-shaving is also effective in periods of low production; see whether battery recharging during periods of sufficient production from wind is possible.

4.2 Field test results

Detailed results of the field tests that have been performed, according to the test sequence in Table 3.6 are shown in Appendix B.3, while a summary is provided here. In total 7 tests have been performed, which have been divided into 3 groups (see column "purpose"), as shown in Table 4.1.

Table 4.1: Overview of field tests performed at mock-up

Test nr.	Duration [hours]	Grid limit [pu]	Purpose	Comment
1 2	100 100	0.55 0.55	Functionality testing and tuning	Ineffective peak-shaving due to immediate battery recharging
3 4 5	48 48 48	0.65 0.60 0.55	Sensitivity of grid peak-demand limit	Improved recharging strategy; Local RES not considered
6 7	51 100 (93 analyzed)	0.55 0.55	Effect of local RES (wind farm); repeatability	Discarded data after hour 93 due to (too) high vessel demand

The results from test 1 and 2 are not analysed further, as the battery recharging strategy needed improvement. This strategy (immediate recharging after peak-shaving was de-activated) led to unnecessary re-activation of peak shaving, resulting in ineffective limitation of the grid peak demand (i.e. exceeding the pre-set limit) and excessive (micro) discharge-recharge cycles.

4.2.1 Data quality and processing

The data from the tests includes measurements of all physical power flows relevant for the analysis, as well as SCADA signals: power setpoints to the battery, battery status signals, e.g. State-of-Charge and internal EMS signals. All signals have been logged continuously at 4Hz., synchronized though a NTP time-server in the Local Area Network.

To calculate the grid demand, the battery power measured at the AC-side of the AC/DC-converters has been combined with the emulated vessel load (directly provided to the EMS SCADA) and the measured local renewable energy production. The separately measured battery auxiliary power (with the air-conditioning as main consumer) has been discarded, as this will probably not scale linearly with the battery size, and the onboard battery may have different types of auxiliaries.

Note: As the field lab has been established only recently, the power measurement chains have not been recalibrated. This considers the following types of equipment:

- Carlo Gavazzi EM24 power meter (class 0.5), directly in the power circuit
- WAGO 750-495/040-000 power measurement card (class 0.5) with current transformers

The EMS running at the SWITCH field lab has a mechanism to synchronize with 15-minute and hourly intervals of the local standard time (UTC). However, during the tests, this synchronization had an offset of one minute, which is corrected for future tests. For the data post-processing this was corrected by applying the same time shift when calculating the energy sums and averages. This does not affect the assessment of the peak-shaving.

4.2.2 Analysis of results

Figure 4.6 shows the grid peak power demand from the vessel (red dots) and the resulting demand with peak-shaving applied (blue dots). The horizontal position is set to the grid demand limit (with tighter limit towards the right), while the vertical position equals the peak demand measured over all 15-min. intervals during the testing period. The axis units are normalized (per-unit), with 100 kW set to 1.0 pu for the mock-up scale (and 10MW for the pilot scale). Dots in the green area fall within the grid limit, while in the red area the preset grid limit is exceeded.

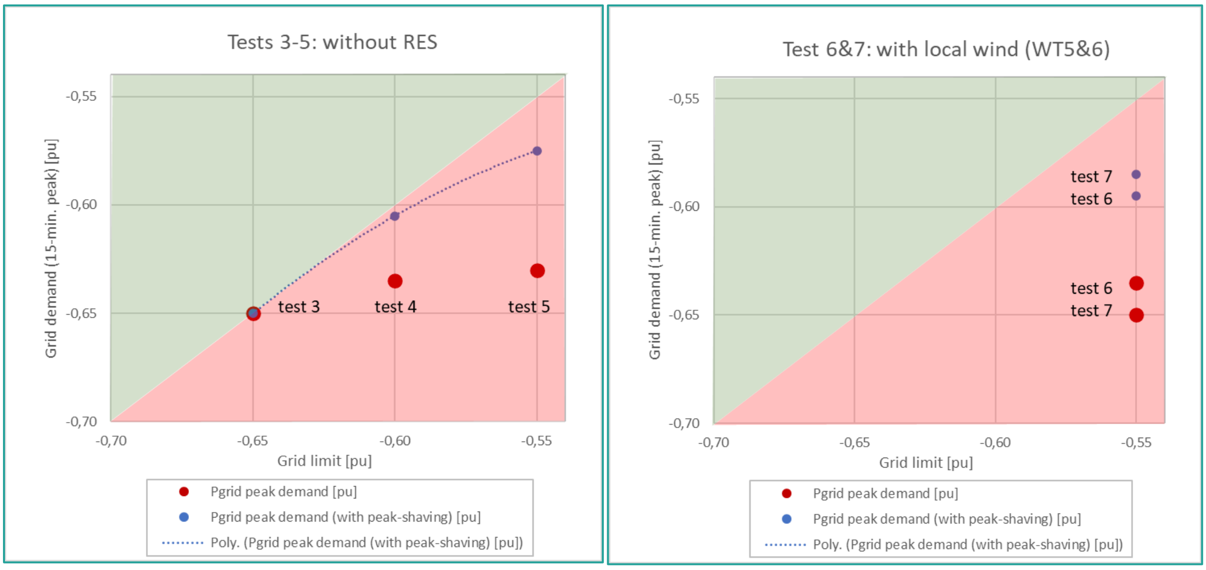


Figure 4.6: Grid peak power demand without and with peak-shaving

The left figure shows the result of three tests using identical vessel load data and different grid limit settings. The overlapping dots at (-0.65pu, -0.65pu) result from test 3 wherein the vessel load did not exceed the grid limit. However, peak shaving was activated once, as the prognosis indicated a risk of the average load in the current 15-min. interval would exceed this limit. For the grid limit set to -0.60pu, peak shaving showed to work effectively (test 4), while for a tighter limit of -0.55pu (test 5) the load demand reduction was not sufficient to stay within this limit, although the load was reduced further than for the other tests. As the vessel load exceeded the grid limit more frequently and more severely, the battery was depleted after a period in time due to insufficient headroom for recharging.

The right figure shows two tests (test 6 and 7) with identical settings, i.e. the most tight grid limit setting from previous test but with the load being partly compensated (behind the meter) by two wind turbines of 1kW each, and therefore potentially compensating the load with 20kW (0.20pu). However, the wind conditions during the test were not favourable, i.e. often below the cut-in speed of the wind turbines. Another issue was a brief but heavy storm that occurred during test 6, which caused the wind turbines to stop. During this test the wind turbines compensated over 40% of the load, but for most of the time the wind production was zero. During test 7 only 1% of the load was compensated on average, with a peak at 8%. These test were still useful to assess the effect of the wind turbine volatility, but the measured production profile does not resemble that of a large wind farm (31MW at pilot-scale). This calls either for longer test periods, or using historic wind farm production data. Test 6 and 7, and test 5 (most right dots in the left plot) used different subsets of the vessel load data but still the results are well in line with each other.

Figure 4.7 shows histograms of the 15-minute-averaged peak grid demand for three cases: the vessel load (red), the vessel load combined with local generation (blue) and the vessel load combined with the onboard battery (green). It shows that the maximum vessel load in red (0.685pu) was not compensated by the local electricity supply (0.680pu) due to poor wind conditions, shown in blue. This maximum load occurred within the last 12 hours of the test wherein the vessel load level increased (measurements from March 5, 2024), leading to a depletion of the battery capacity, such that no effective reduction occurred (grid demand 0.635pu). Until that moment (before Dec. 2 14:15), the vessel load was reduced to 0.585pu, compared to the limit set at 0.55pu. Due to the limited battery capacity, peak-shaving can only be effective for peak loads that occur rarely, with sufficient time and headroom (margin between vessel demand and grid limit) to allow the battery to recharge sufficiently in between occurrences. Therefore, it is important to know the characterisation of the vessel load distribution over longer periods in time for implementation of peak-shaving.

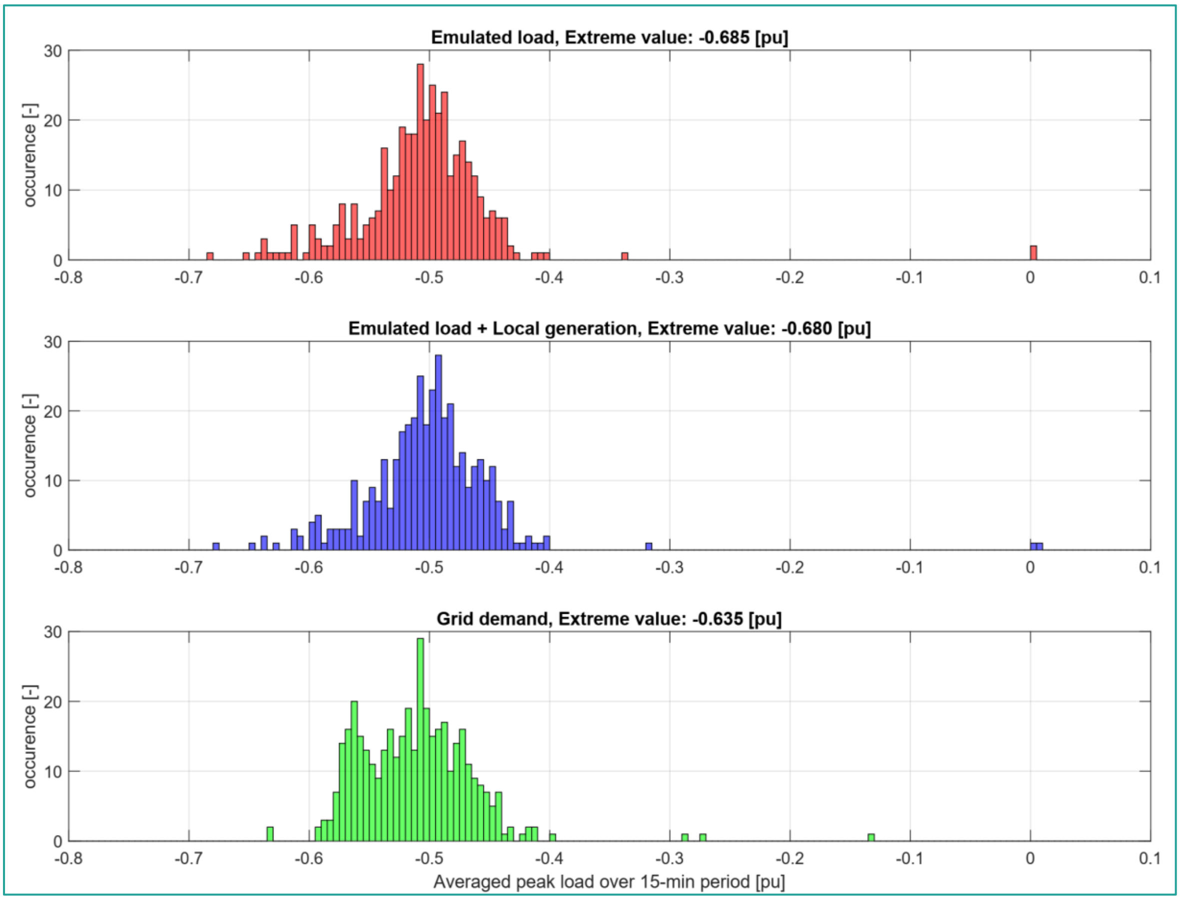


Figure 4.7: Histogram of 15-minute averaged vessel load and grid demand of test #7

Figure 4.8 shows the minimum battery state of charge (SoC) that was measured at any moment in time during the tests. The 80% limit for the usable SoC range set as the battery capacity (56.7kWh) is relatively large compared to the planned battery size at pilot scale (1.16MWh). The 20% usable capacity (11.5kWh) matches roughly the 100-times down-scaled capacity of the pilot. Please note that at pilot scale only a part of the nominal battery capacity will be reserved for peak-shaving, which requires to limit the useable SoC range at mock-up scale proportionally. The battery discharge and recharge power was limited as well (35kW), in line with the planned 3.5MW at pilot-scale.

In the left figure, the minimum SoC of nearly 100% corresponds to test 3 in which only a single occurrence of peak shaving occurred. The maximum discharge of 35kW over a single EMS timestep (1 minute) equals 35/60kWh. When normalized to the nominal battery capacity of 57.6kWh, this results in 100% (35/60/57.6) = 1%.

With the grid limit set to -0.60pu (test 4), the minimum SoC is 95%, so well above the minimum level, which allows to deploy the battery effectively for peak-shaving. With the limit set to -0.55pu (test 5) the battery SoC reaches the minimum limit, resulting in temporary unavailability for peak-shaving. During this period, the vessel load exceeded the grid limit and could not be compensated.

While in the right figure the battery SoC remains above the minimum limit, the grid limit is exceeded, indicating that other factors also determine whether peak-shaving is effective. One factor is the decision strategy to activate peak-shaving and the battery recharging strategy (both based on a rolling prognosis of the 15-min. grid demand), which is a trade-off. A second factor that is identified is the limited ramping limit, which is explained in Appendix B.3.3, Figure B.22.

Considering all tests, it can be concluded that the tightest limit (-0.55pu) leads to the risk of depletion of the useable battery capacity and should thus be relaxed.

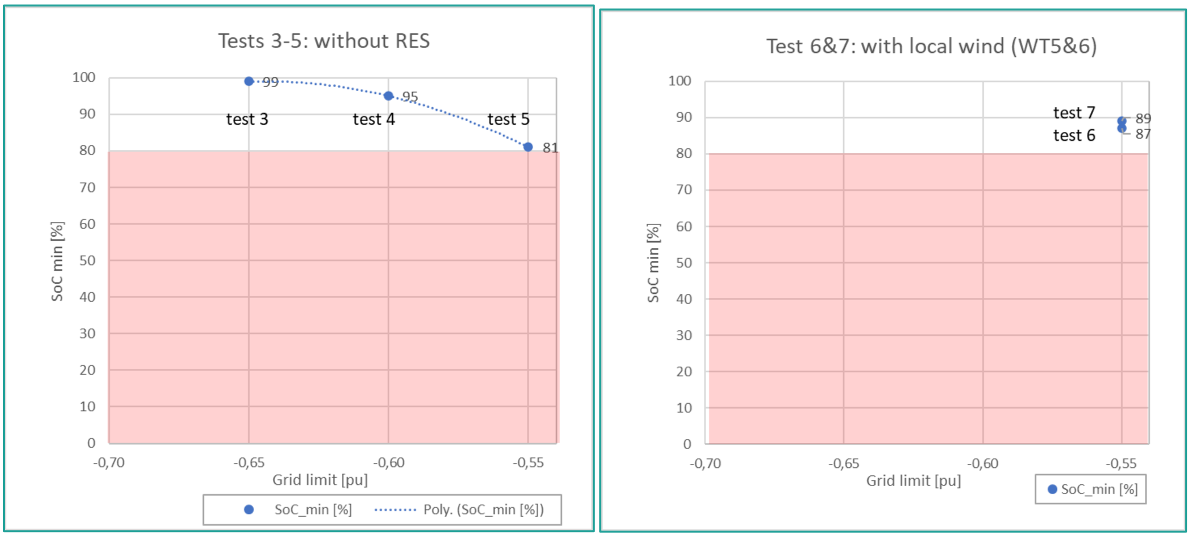
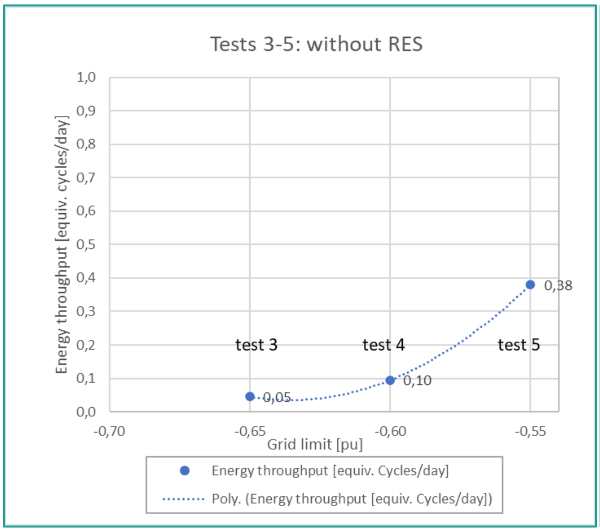


Figure 4.8: Minimum battery state of charge

Figure 4.9 shows a measure of the battery usage by counting the energy throughput. This measure sums the measured energy provided when discharging the battery and the measured energy consumed when recharging (both counted positive). The energy totals[8] are scaled by dividing by two and by the nominal battery capacity. (i.e. one full discharge followed by one full recharge counts for one cycle.), both divided by two.

[8] Please note that the energy is measured at the AC-side and that AC/DC conversion losses have not been considered and neither the effects of a battery management system and of battery degradation which are likely to reduce the useable capacity.



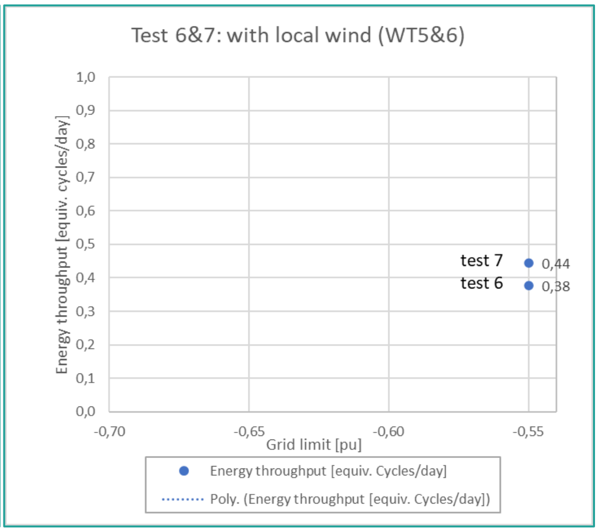


Figure 4.9: Daily normalized energy throughput of battery

As expected, the battery use increases with the need for peak-shaving from 0.10 (test 5) up to 0.44 (test 7) equivalent full-cycles. Please note the steep increase in battery usage (and resulting energy losses and battery lifetime consumption) when setting a tighter grid limit. This effect, together with the risk of battery depletion (or equivalent enlarged battery sizing) are main factors in the system design.

4.2.3 Evaluation of KPIs

The evaluation of KPIs, as defined in Table 1.1, based on the tests, is limited to qualitative statements or a bandwidth for the improvement for a subset of KPIs. This is due to the short duration and small scale of the mock up. A more accurate and complete quantitative evaluation of KPIs, i.e. what would be the expected improvements (compared to the reference case of the vessel connected to RSP for a period of several months without the battery system installed), requires an assessment over a longer time period, to cover different combinations of measured vessel loads and wind farm production levels. This evaluation will take place during the validation of the actual pilot. Another aspect, which is relevant when conducting additional simulations, is to model battery system ramping limits according to the design specifications of the pilot, as this accurately predicts the capabilities to limit the momentary power demand and the 15-minute power shaving, and how to correctly tune the peak-shaving algorithm.

Grid fees (based on contracted grid peak demand)

Based in the given the battery sizing, the tests indicate that a reduction of the contracted peak demand is possible to a level of roughly 0.60pu, provided that sufficient battery capacity is reserved for peak-shaving. However, relaxing the grid peak demand to about 0.65pu leads to fewer occurrences where the vessel load exceeds the grid limit, which strongly reduces the battery utilization and related lifetime consumption, as well as the risk of temporary depletion of the available energy in the battery. In both cases, this is still a significant reduction of the contracted grid demand, compared to the current level, and related costs.

Apart from the maximum of the 15-minute peak demand, also the distribution of the 15-minute peak demand changes, with more frequent occurrences of load levels near the contracted peak level. This would be an advantage in case of a "use-it-or-lose-it" policy that the grid operator might follow in future.

Utilization of renewable energy

When connected to the RSP, the vessel average demand with or without the onboard battery does not change significantly, as the only difference is caused by the battery losses, which are relatively low. When assuming that this load level is independent from the local wind farm production, the utilization remains the same. However, the onboard battery would enable that the vessel remains connected to RSP during periods of high demand, assuming effective peak-shaving of the 15-minute demand (preventing grid tariff increase) and momentary demand (preventing overload of the RSP connection rating of 8.5MW that would cause disconnection). This would reduce the operating hours of the onboard diesel generators and increase the utilization of wind energy, reducing fuel costs and GHG emissions.

4.2.4 Upscaling of results to RSP pilot

The mock up tests have demonstrated how peak shaving can be implemented and provided insights in design aspects and operational settings of the battery and of the EMS. Considering that the battery system technology of the RSP pilot is similar to the mock up, no significant discrepancies in the functional behaviour are expected, so the mock-up tests provide a good indication that peak shaving for the optimum grid limit setting of 6.0MW can be effective at full scale. As said, the wind farm production of the mock up strongly differs from the RSP pilot, which requires simulations to properly assess the impact of balancing the RSP pilot load with renewable electricity. However, the effect of strong wind production variations could be assessed, which the battery system was able to follow. While local wind production does not provide sufficient certainty to reduce the grid limit, the mock-up tests showed it reduces the number of peak shaving occurrences and contributes to recharging the battery, which reduces energy procurement from the grid.

Besides the large scale difference with the mock up, the RSP pilot aims at implementing a battery system that is an integral part of the vessel energy provision. This might put limitations on the battery system design and operation that are not known when conducting the mock up tests. Another aspect is the real-time availability of the required metering data, as this needs to be provided by the grid operator. In the mock-up all measured data and SCADA data is made available to the EMS in real-time, but this might not be the case for data from third parties at the RSP pilot.

5. Conclusions

To support the pilot at Rotterdam Shore Power (RSP) pilot, Demo 3 of the MAGPIE project, the technical viability was demonstrated of peak-shaving of the electricity demand of the crane vessel Thialf of Heerema Marine Contractors (HMC) when connected to shore power, by an onboard Battery Energy Storage System (BESS). The use-case of this pilot also included balancing of the demand (behind-the-meter) with renewable electricity produced by a local wind farm.

For this use-case peak-shaving was first simulated, based on measured vessel data provided by HMC and historic weather data, and then tested in a down-scaled physical mock up at the SWITCH field lab in Lelystad. The battery power limit and useable capacity were adapted to match the vessel load, while tests were conducted with and without considering renewable generation and with different limits for the net grid demand. Seven field tests have been conducted with a total duration of over 20 full days (491 hours).

The simulations provided a working principle for peak-shaving of the vessel demand with suitable ranges for setting the grid limit, which were applied in the field tests. The field tests results showed that peak-shaving can effectively reduce the vessel 15-minute averaged grid demand within the limit of 0.60pu. This setting (equivalent to 60kW for the mock up scale and 6.0MW for the pilot scale) can be considered optimal for this data set, as the battery minimum state-of-charge of 95% (equivalent to 80% at pilot scale due to the smaller battery size) remained well above the limit. The battery lifetime consumption is small, with 0.10 equivalent full-cycles per day (equivalent to 0.50 at pilot scale). Setting a tighter limit for the grid demand of 0.55pu led to temporary depletion of the battery, resulting in ineffective peak shaving, while also the battery utilization steeply increased to 0.44 (1.8 at pilot scale) equivalent full cycles per day.

Fine-tuning of the grid limit may still be considered, as a more lenient setting of 0.65pu strongly reduces the number of occurrences of peak-shaving and thereby the battery lifetime consumption and the risk of temporary depletion, while still reducing the contracted grid capacity and related grid fees for the contracted grid demand.

Balancing the vessel load with local renewable electricity reduces the need for peak-shaving, but will probably not allow to set a tighter grid limit, as sufficient wind power may not always be available when needed. However, momentary peak loads that exceed the power rating of the shore power connection of 8.5MW for the Thialf can only be compensated by the onboard battery system and not by onshore wind power.

Lessons learned in the field test were that the battery power ramp rate limitations prevented the effective limitation of short power peaks that exceeded the shore power capabilities, although this limitation had only a very small effect on the peak-shaving of the 15-minute averaged peak demand. The test period with balancing the vessel demand with local wind power proved to be too short to make a quantitative assessment.

Determining the grid limit at pilot scale more accurately and assessing the cost savings requires additional simulations over periods of several months, based on concurrent data of vessel electricity demand and wind farm production. Secondly, the peak-shaving and battery recharging strategy need to be evaluated with more detailed characteristics at pilot scale. For this, also additional simulations are recommended, based on these characteristics, in particular the useable battery capacity, ramp rates and ageing models, as well as the available net metering data, e.g. considering latencies.

The tests have demonstrated demand peak-shaving in realistic conditions, using a battery system, and considering local renewable generation. It has also provided insight in aspects of the battery design and operational settings of the battery and the EMS that determine whether peak-shaving can be effective. These findings enable more accurate simulations to assess the benefits and risks, both for the current pilot and future shore power facilities.

In summary:

1. Down-scaled tests showed that peak shaving of the vessel electricity demand with an on board BESS lowers the grid demand and allows for a reduction of the contracted 15-minute peak load
2. Lowering the current peak load by peak shaving to approx. 0.6pu (6.0 MW) proves to be most efficient for this data set, considering that this reduction can be achieved without the risk of depleting the battery
3. The battery utilization when peak shaving at this grid limit is modest, with 0.10 equivalent full cycles per day (0.50 cycles at pilot-scale), which is not expected to cause fast degradation
4. Simulations based on several months of data vessel load and wind production data and with more detailed design specifications are recommended to determine the grid limit and potential cost savings more accurately. The limited data set that has been used to perform simulations demonstrates that peak shaving works for certain grid limit settings. As next steps, Heerema will implement the battery on the vessel and conduct the actual pilot for several months.
5. Possible enhancements to increase the use of local wind power and reduce the electricity procurement costs can be to apply forecasting of the local wind production and provide live indicators of the potential cost savings by allowing short-term flexibility in the crane operation.

References

Houwelingen, R., Backers, R., Hein, C., Jansen, M., Pruyn, J., Streng, M., & Zubin, I. (2022). *Baseline evaluation and prioritization of demo-specific scenarios, MAGPIE D8.2 deliverable report.* Retrieved from https://www.magpie-ports.eu/wp-content/uploads/2024/12/D8.2-Baseline-evaluation-and-prioritization-of-demo-specific-scenarios-final.pdf

Jullens, J., & Wiggelinkhuizen, E. (2023). *Conceptual Design of Smart Energy System - MAGPIE Deliverable 3.14.*

TNO. (2021). *Measurement requirements, method and KPIs framework, MAGPIE D8.1 Deliverable report.*

Weenk, T. (2023). *Smart Grid-Integrated Vessel through a shore power system.* Electrical Engineering, Mathematics & Computer Science - Intelligent Energy Systems. Delft: TU Delft. Retrieved from http://resolver.tudelft.nl/uuid:eedf3cb6-6079-4a86-bf2b-3b4043227a09

Annex A Fieldlab Description

A.1 Hardware

Table A.1 lists the assets used for the tests and **Figure A.1** shows how these are connected and measured.

Table A.1: List of Fieldlab assets

Name	# / ID	Description	References
Wind turbines WUR	4 WT1-4	BestWind BW10, stall-regulated, rated 10kW *Not to be curtailed under normal conditions*	BestWatt Datasheet
Wind turbines TNO	2 WT5-6	BestWind BW10, pitch-controlled, rated 10kW Remote power control	TNO_WT_docs
Battery system	1	8x LFP battery MG 7.2kWh each BMS.: mg-master-lv-24-48v-1000a-rj45-m12-4155 Inverter: 6x Victron Quattro 10kVA each Pwr. Mgt. Syst. Modbus Interface: Victron Cerbo GX	MG LFP 280Ah MG-BMS Victron-Quattro Victron-CerboGX
Energy meters TNO	8	Carlo Gavazzi EM24	CG_EM24
Energy meters WUR	9: Bat, gr.1-8	WAGO 750-495_000-001	Data sheet
Controller	1	National instruments Compact RIO 9041	NI-CRIO9041

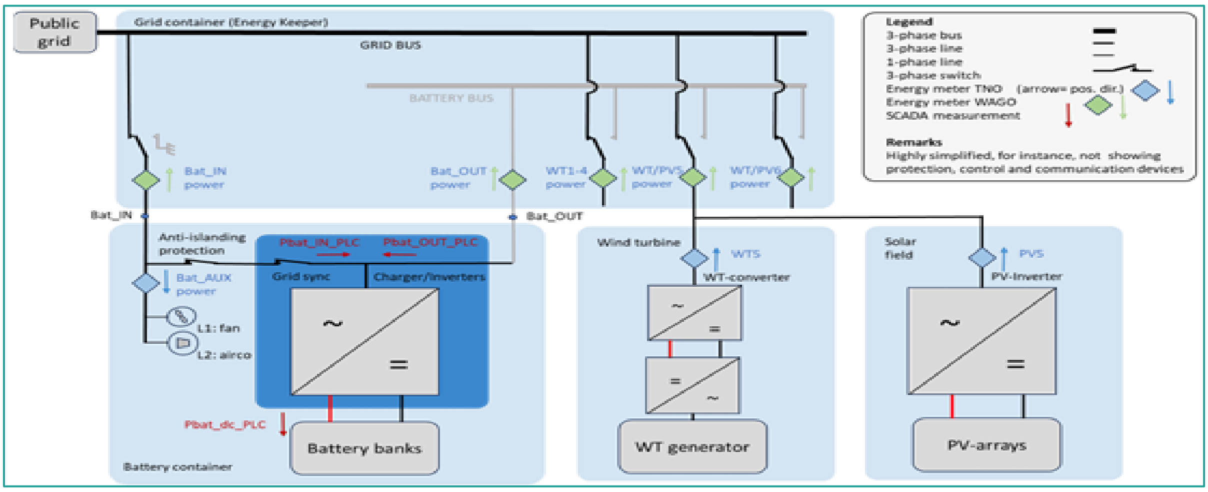


Figure A.1: *Simplified schematic of assets interconnection and measurements*

A.2 Energy Management System

The EMS performs a number of high-level tasks, also indicated in the schematic in **Figure A.2**:

- Optimize field lab operation schedule, based on weather prediction and market prices, modelled plant behaviour and inputs from remote/local plant operator, grid operator;
- Calculate power references per asset (group) to meet the optimized production schedule, considering the actual asset status (from Asset Management System and grid operator);
- Control power production per asset to track the power references, while respecting operational limits of the assets and the grid.

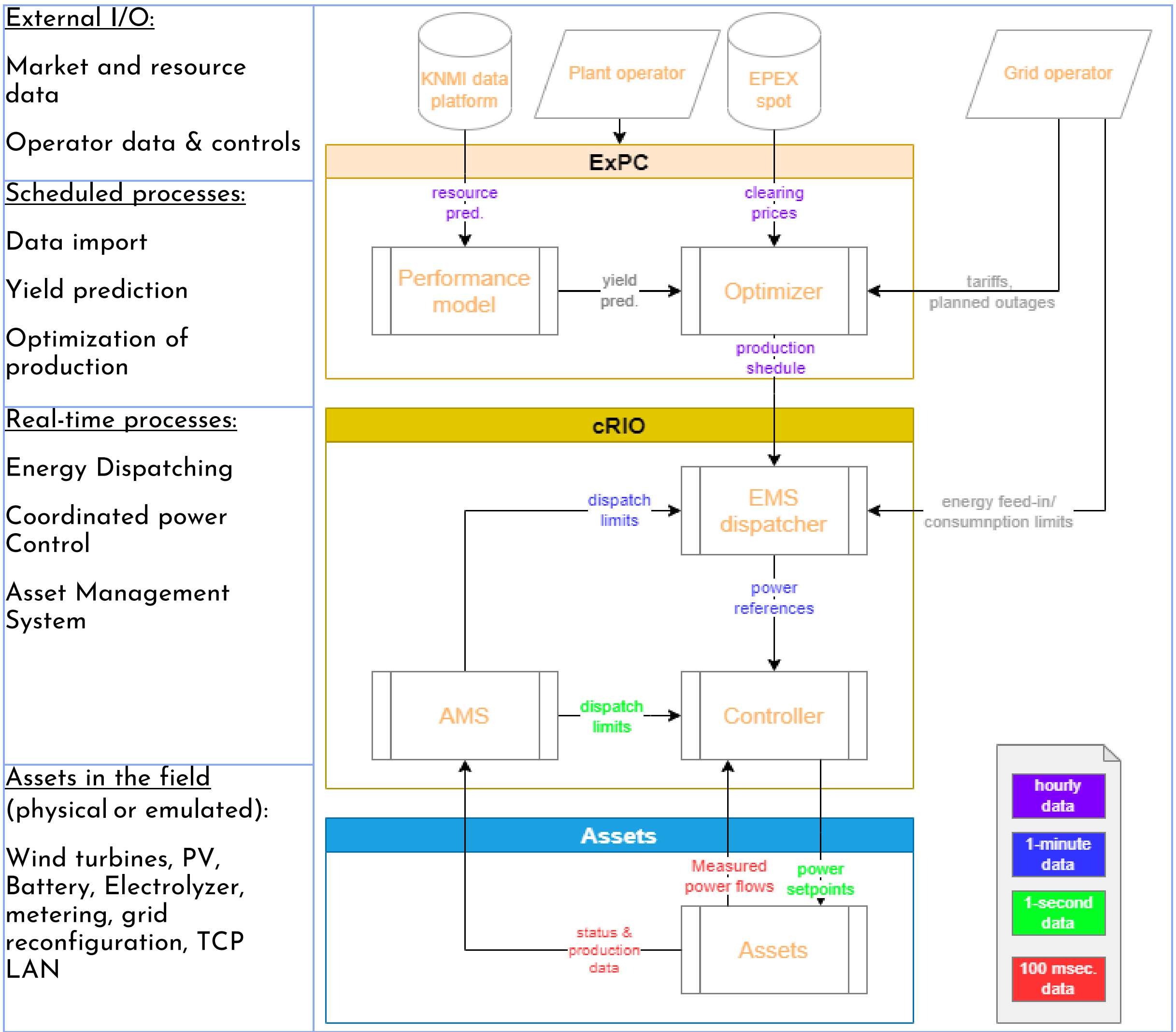


Figure A.2: Simplified schematic of the EMS

Notes on EMS dispatcher and Controller implementation

- The dispatcher and controller are both real-time processes that combine signals that are provided at different time intervals:
  - scheduled energy target at current hourly period resolution (Market Time Unit), provided by the optimizer
  - dispatch limits for power and energy exchange with the grid, provided (typically) at 15-minute intervals (Program Time Unit)
  - measured power flows and status of the assets (momentary)

To secure the correct timing with all other connected platforms, the EMS dispatcher, Controller and the Asset Management System (AMS) are implemented in a single real-time platform (NI-Compact RIO), which also holds a central Modbus data register.

- For simplicity, the TNO monitoring and data visualization system are not shown here.
- Also not shown in the scheme is the protection system (WAGO PLC) to safely disconnect and reconnect assets to either the public grid bus or to a local battery bus, and which assures local power balance by frequency shifting at the battery bus.

Notes on the EMS tasks

- The EMS keeps track of the produced and consumed energy at plant level and can redispatch power to meet the production schedule, e.g. in case of forecast errors equipment outages, or to prevent violation of grid power and energy exchange limits.
- During the tests for demand peak-shaving, the production optimizer was set inactive, i.e. producing zero bids. In this situation the EMS allows full renewable production, while keeping the battery fully charged, if sufficient energy is available, considering the maximum momentary power demand and contracted energy demand from the grid.

Notes on the Controller tasks

The Real-Time Controller (RTC) needs to achieve that the scheduled energy bid to the market as well as the scheduled consumption of local loads are met, while respecting the operational limits and external conditions, and handling events. For instance, the RTC should consider the limited battery capacity, battery cycle losses and ageing, and electrolyzer safe operation limits. Typical events that the RTC should handle are equipment or communication failures, a mismatch of the actual resource with the predictions and electricity feed-in or consumption limits imposed by the grid operator. Grid limitations are set at each 15-minute period, the so-called Program Time Unit (PTU).

The RTC performs a number of tasks to achieve this:

First task is fetching the setpoints that have been written into the Modbus server by the EXPC for the current hour, which consist of the:

- energy bid to the Day-Ahead (energy) market (either production or consumption)
- scheduled operation (energy consumption) of local loads, e.g. electrolyzer
- scheduled operation of the battery (charged or discharged energy)

Second task is to keep track of these hourly targets (e.g. energy offered to the market) and adjust the energy setpoints at a 15-minute basis, while considering grid limitations. This usually requires re-dispatching the setpoints, e.g., due to forecast errors. Currently this is implemented based on a set of dispatch priorities per asset group from a configuration file, which also specified (static) limits for electrical energy exchange with the grid. Other information used for re-dispatching are operational limits that are calculated based on the asset status acquired from various SCADA signals, such as operating mode, alarms, battery state of charge.

Third task is to translate these energy setpoints are translated to power setpoints for each individual asset, which are currently updated each minute.

Fourth task of the RTC is to track these active power setpoints by comparing these to the measured power and writing power setpoints to the Modbus server each second. Similar as for the second task, the asset limitations and grid power exchange limits are considered. Also similar is that the controller prioritizes certain assets, which in this case considers dynamic limitations (e.g., the battery can respond faster than the WTs or electrolyzer).

The current RTC implementation distinguishes between fast assets (PV and battery) and slow assets (electrolyzer and TNO wind turbines) and assets that are not controlled (WUR turbines, operating under a performance contract).

A.3 Simulation model

The simulation model, implemented in MATLAB/Simulink™. The top-level diagram in **Figure A.3** shows the main components and how these are interconnected. The blocks within the yellow area are compiled to the real-time target running at the field lab, while the other three are only used in the offline Simulink development environment.

Model blocks

This setup shows the following model blocks (from top to bottom):

- "EMS_model" performs the dispatching of the production schedule, producing 1-minute power setpoints for the controller
- "Controller_Model": performs the tracking of the 1-minute power references and produces 1-second setpoints
- "Asset_Management_System_Model": Processes incoming asset status signals and calculates (status-dependent) dispatch limits per asset
- "Simulate_optimizer": The optimizer providing the hourly setpoints (already-calculated optimization results are simply read from a file)
- "Simulate_Modbus_server": Simulates writing and reading back data from the Modbus server. All registers addresses are linked to the central Modbus configuration file.
- "Simulate_assets": Simplified model that simulates the response of several assets to incoming setpoints, e.g. the changing battery state-of-charge, the allowed power setpoints as well as (accelerated) ageing due to battery (dis)charging

Inputs:

Escheduled: Setpoints supplied from the EXPC, specifying the scheduled energy flow per asset for over the current hour.

Emeas: Energy measurements retrieved from the energy meters in the field.

Status_for_EMS and Bat_SoC_Cap: Asset status from the assets' PLCs

Param: Parameters (user-set) that determine the controller's behaviour.

Outputs:

Pset: Active power setpoints to each individual asset, which is updated each second.

Status_controller: Includes heartbeat and cycle counter, which the EMS can use to respond on events like communication errors.

Signal sampling times and dimensions

The colours represent the sampling times: blue = 60 sec., green = 1 sec. and red = 0.1 sec.

The signal dimensions can be linked as follows:

- (11): individual assets: 6xWT + 3xPV + 1xbattery + 1xElectrolyzer
- (11x2): min and max setpoint limits per asset
- (12): 1xEnergy bid to the market + Energy scheduling for each of the 11 assets
- (10): Number of asset groups, each with different dispatch priorities and capabilities: 1: WTs1-4 WUR, 2: WT5, 3: WT6, 4: PV1, 5: PV2, 6: PV3, 7: Battery, 8: Electrolyzer, 9/10: spare.

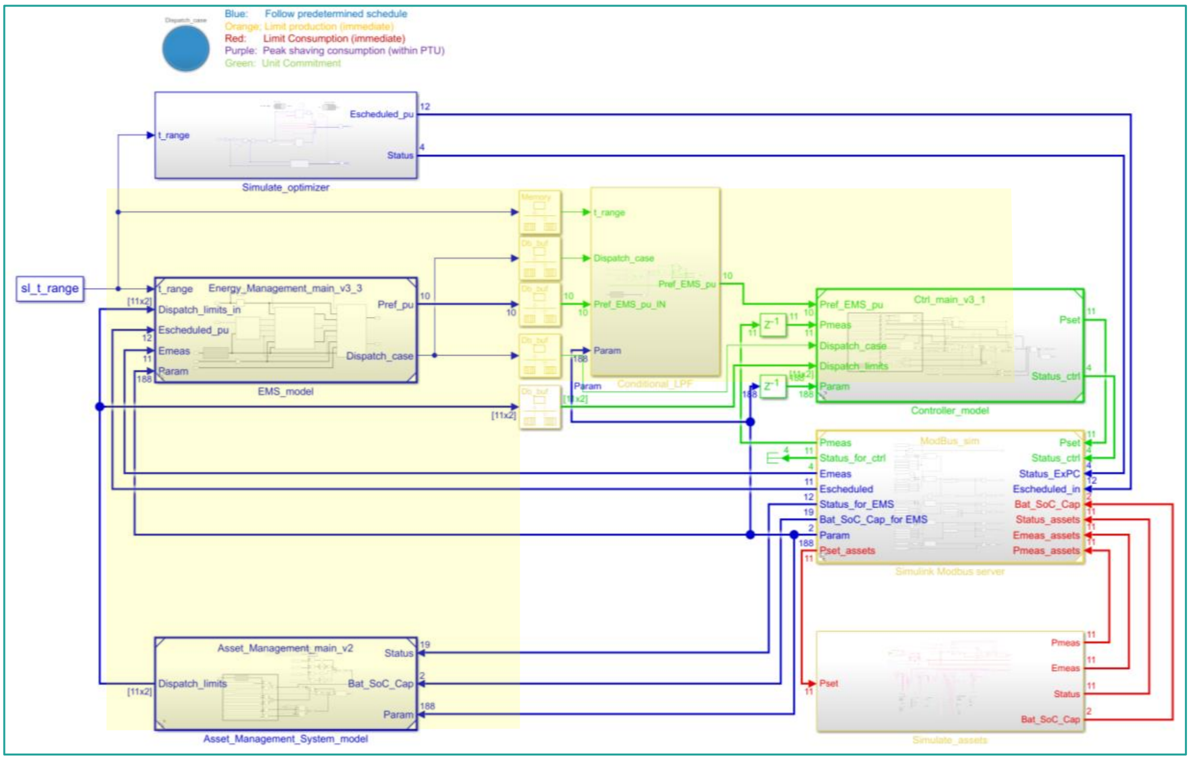


Figure A.3: Top-level block diagram if simulation model

Notes

- The diagram shows that all communication it routed through the Modbus register, except for a for two signals "Dispatch_limits" and "Pref_EMS [pu]". This is possible, as the "EMS_model", the "Controller_Model" and the "Asset_Management_System_Model" will be implemented in the same cRIO platform.
- A number of functions are not yet implemented, such as the handling of events on the short-term directly by the controller ("Status_for_ctrl" is not connected to the controller).
- The sample rate transition blocks have been located outside of the three model blocks for practical reasons, related to the compilation process. This also holds for the two unit-delay Z^{-1} blocks. These delay blocks are only required in this Simulink environment to prevent algebraic loops due to the Simulated Modbus server model.
- Small offsets in the starting time can be applied by the user
- A conditional Low-pass filter of the reference power to the controller has been inserted to smoothens stepwise variations that can occur during specific operational state changes of the EMS.

Model configuration

The model configuration, determined by the parameter values in the signal **Param**, is explained in detail in Appendix B.2.4. The parameters hold settings for:

- Priorities for re-dispatching energy and for tracking a power reference
- Grid electrical energy and power exchange limits
- Asset characteristics, such as battery discharge and recharge rates

A.4 Demand peak-shaving logic

Figure A.4 shows the internal structure of the EMS dispatcher block, which includes simple logic to decide on the energy dispatching method, which is detailed in **Figure A.5**. The dashed lines are enable signals that only enable one of the five dispatch function blocks.

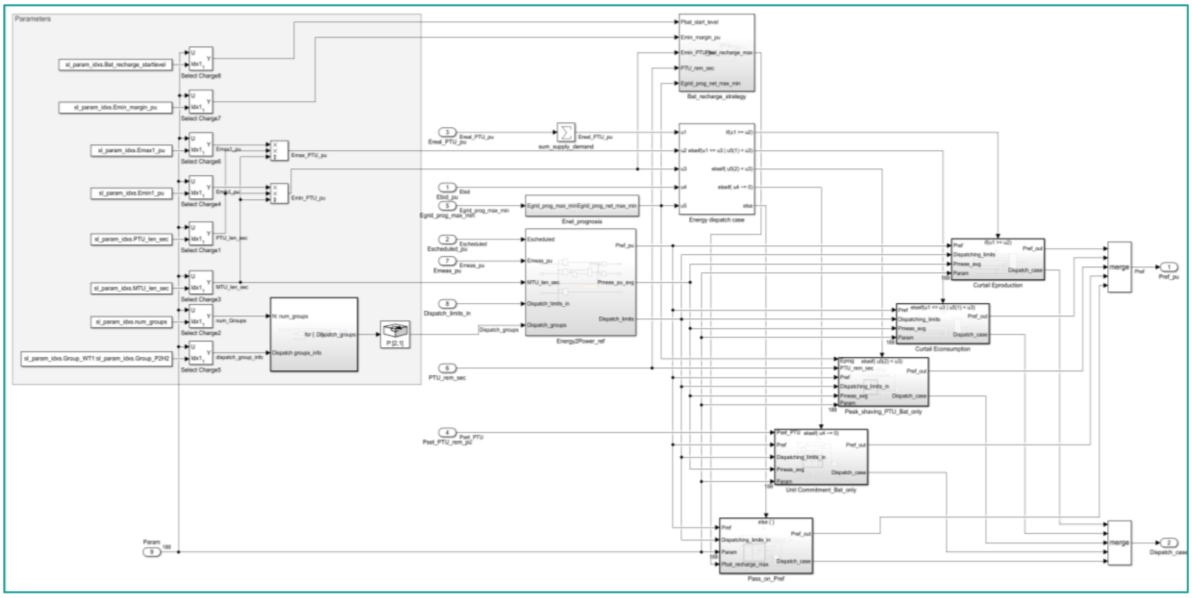


Figure A.4: EMS dispatcher internal structure

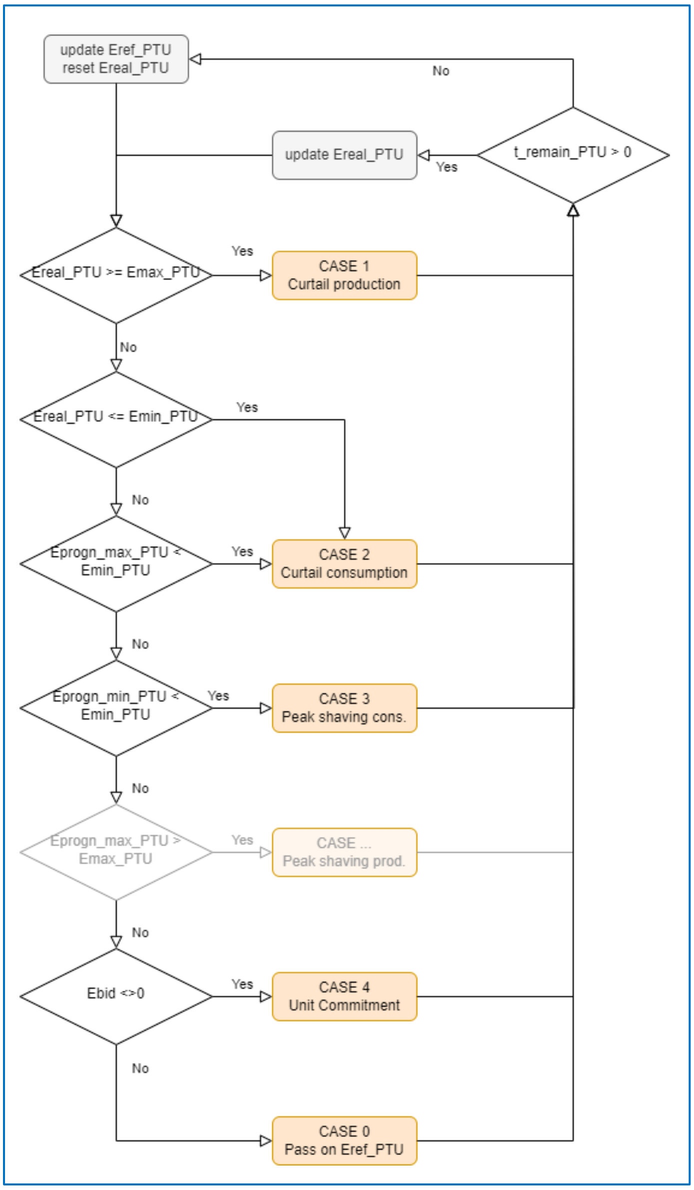


Figure A.5: Energy dispatching logic

The dispatching logic defined in the block "Energy dispatch case" decides which of the five dispatch cases (case 0 .. 4) to apply:

First, the logic decides whether direct curtailment, either supply (case 1) or demand (case 2) is required, by comparing the supplied or consumed energy thus far within the PTU with the user-set limits. As next step, based on the comparison between the prognosis of the energy at the end of the current PTU with the limits, peak shaving (case 3) is applied. As for the current experiments only demand peak shaving will be applied, and supply peak shaving is not yet implemented. In other cases, the dispatching aims to meet the scheduled energy bids (Unit Commitment, case 4), unless the bid is set to zero (case 0). In case 0 the scheduled energy references received from the ExPC are directly forwarded as power reference to the controller. This can be applied for the characterization of assets (battery, electrolyzer), to force their operation to follow a predefined pattern.

The two output signals of the block "EMS_Unit_Commitment_setpoint", which are the selected dispatch case and the power references, are provided to the controller. In case of dispatch case 0, the controller only performs feedforward of the power references without feedback control.

Direct curtailment

The curtailment of the supply considers the priorities of each asset, starting with the reducing the production (or increasing the consumption) of the assets with the highest priority setting (1) for supply reduction. Until the reduction target of the total production is met, this is repeated for assets with lower priorities. Curtailment of the demand obviously works similarly, although that priority setting can differ from supply curtailment. For instance, production form wind and solar PV assets can be reduced, but the result of lifting the curtailment does not guarantee a similar increase in the production.

For assets with identical priorities the energy curtailment is evenly distributed, while assets with their priority set to 0 are exempted from curtailment.

Peak shaving

The peak shaving is enabled based on a prognosis of the energy supply and demand at the end of the current PTU. **Figure A.6** shows a simulation result with the prognosis in the upper subplot, which lies between the blue and red. When the prescribed limit, shown as the red dashed line, is exceeded, the peak shaving starts, as shown in the lower subplot.

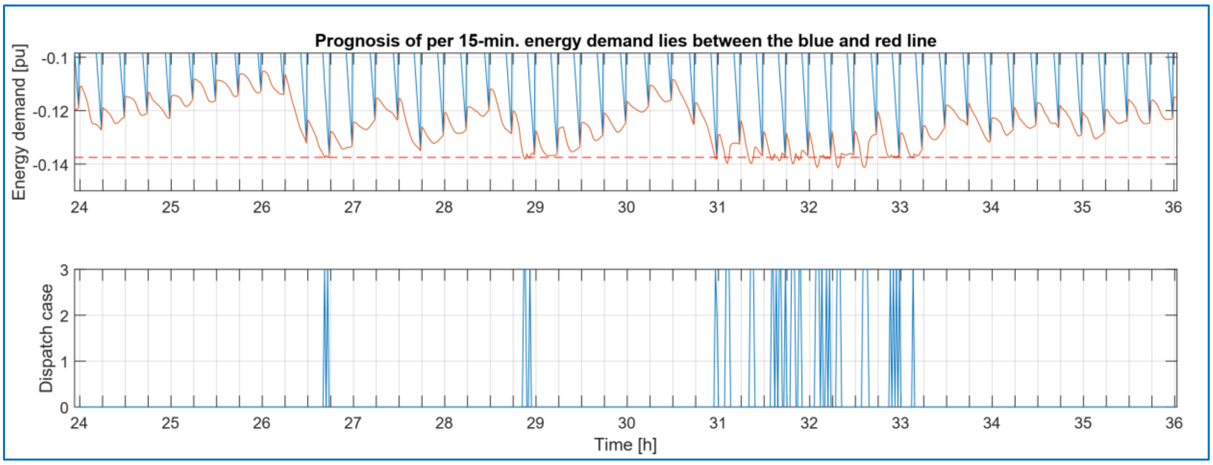


Figure A.6: Prognosis of the energy supply and demand per PTU

The prognosis of the grid demand at time t_k is calculated as:

$$Eprog\_grid_{max,min}(t_k) = Eprog\_dmd_{max,min}(t_k) + 0.5 * \{Eprog\_sup_{max}(t_k) + Eprog\_sup_{min}(t_k)\}$$

With:

$$Eprog\_dmd_{max,min}(t_k) = \max, \min\{ Ereal_{k-1} * \left(1 - {t_k}/{T_{PTU}}\right), Esched_K * \left(1 - {t_K}/{T_{MTU}}\right)\} + Ereal(t_k)$$

K = current MTU (Market Time Unit, 1-hour bids over a single day: 1 .. 24)

k = current PTU (Program Time Unit, 15-minute measurement periods: 1 .. 96)

T_{PTU} = length of PTU = 900 [sec]

T_{MTU} = length of MTU = 3600 [sec]

t_k = time [sec], starting from the current PTU, i.e. 0. 60, …, 900 sec

t_K = time [sec], starting from the current MTU, i.e. 0. 60, …, 3600 sec

$Ereal_{k-1}$ = measured energy <u>demand</u> [kWh] over previous time period PTU(k-1)

$Esched_K$ = scheduled energy <u>demand</u> [kWh] over current time period MTU(K)

$Ereal(t_k)$ = measured energy <u>demand</u> [kWh] from start of current period PTU(k)

Notes

$Eprog\_sup_{max,min}(t_k)$ is calculated similar as $Eprog\_sup_{max,min}(t_k)$.

$Eprog\_sup_{max,min}(t_k)$ is zero, unless local generation is taken into account. The factor 0.5 is meant as a conservative measure when extrapolating the local energy production thus far to the expected production over the current measurement period PTU.

The prognosis of the energy supply, for peak shaving of the energy supply, is calculated in a similar way. In the current tests peak shaving of the supply does not happen as the vessel cannot feed power into the grid.

The actual peak shaving of the demand only considers re-dispatching energy through the battery, as the vessel demand is considered to be inflexible. The battery reference (respecting the momentary power dispatch limits and ramp rate limits) is calculated as:

$$Pbat\_ref(t) = Pbat\_meas_{avg}(t_k - T_{EMS}) + \Delta Pbat(t_k)$$

Where:

$$\Delta Pbat(t_k) = \max\{0, Edmd_{lim} - Eprog(t_k)\} \,/\, \{\frac{T_{PTU} - t_k}{3600}\}$$

$Edmd_{lim}$ = prescribed energy demand limit per PTU [kWh]

(used for peak load assessment)

$Pbat\_meas_{avg}$ (tk - T_{EMS}) = battery power [W]

(averaged over the previous EMS time step)

T_{EMS} = EMS time step 60 [sec]

Annex B Experiment settings

This section describes the settings of the Energy Management System, the input data and the prediction models and optimization strategies.

B.1 Input data

The vessel power demand, measured at 1-second intervals, consists of a base-load and superimposed demanded the two cranes, and is provided by HMC, cf. Table B.1, Figure B.1 and Figure B.2.

Figure B.3 shows the baseload demand between 4 and 5.5MW and extremes between 8 and 12MW, so exceeding the maximum RSP 10 MW limit. Figure B.4 provides more insight how often the load exceeds the grid limit, which is currently 8.5 MW. It shows that the demand only exceeds the grid limit for a few minutes per day, and therefore the accumulated energy for which the power exceeds the grid limit is also small. When lowering the grid limitation in 0.5 MW steps, it shows that below a 7.5 MW the time (and accumulated energy) become significant, keeping in mind that the average power level over a 15 min. period considered as the peak load. For simulating peak-shaving, different grid limitation levels will be considered.

Table B.1: Measured vessel load data

Start date/time	End date/time	Remarks
2024-01-08 00h	2024-01-18 00h	No baseload data present, only crane load
2024-02-25 00h	2024-03-06-00h	Shore power demand constructed from base load and crane loads. Until 29feb, base load of both cranes is (mostly) zero, while later on the base load is about 220 kW per crane. Propose to set a minimum base load for the cranes. Thruster demand is not considered and therefore subtracted from the total demand

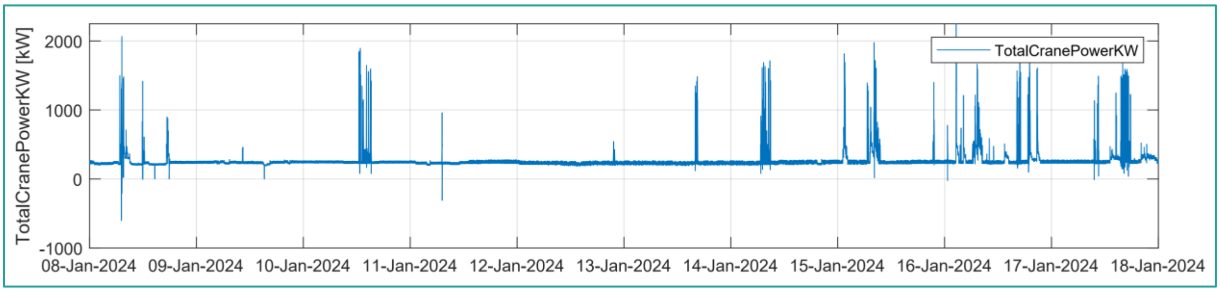


Figure B.1: Vessel load data, January 2024

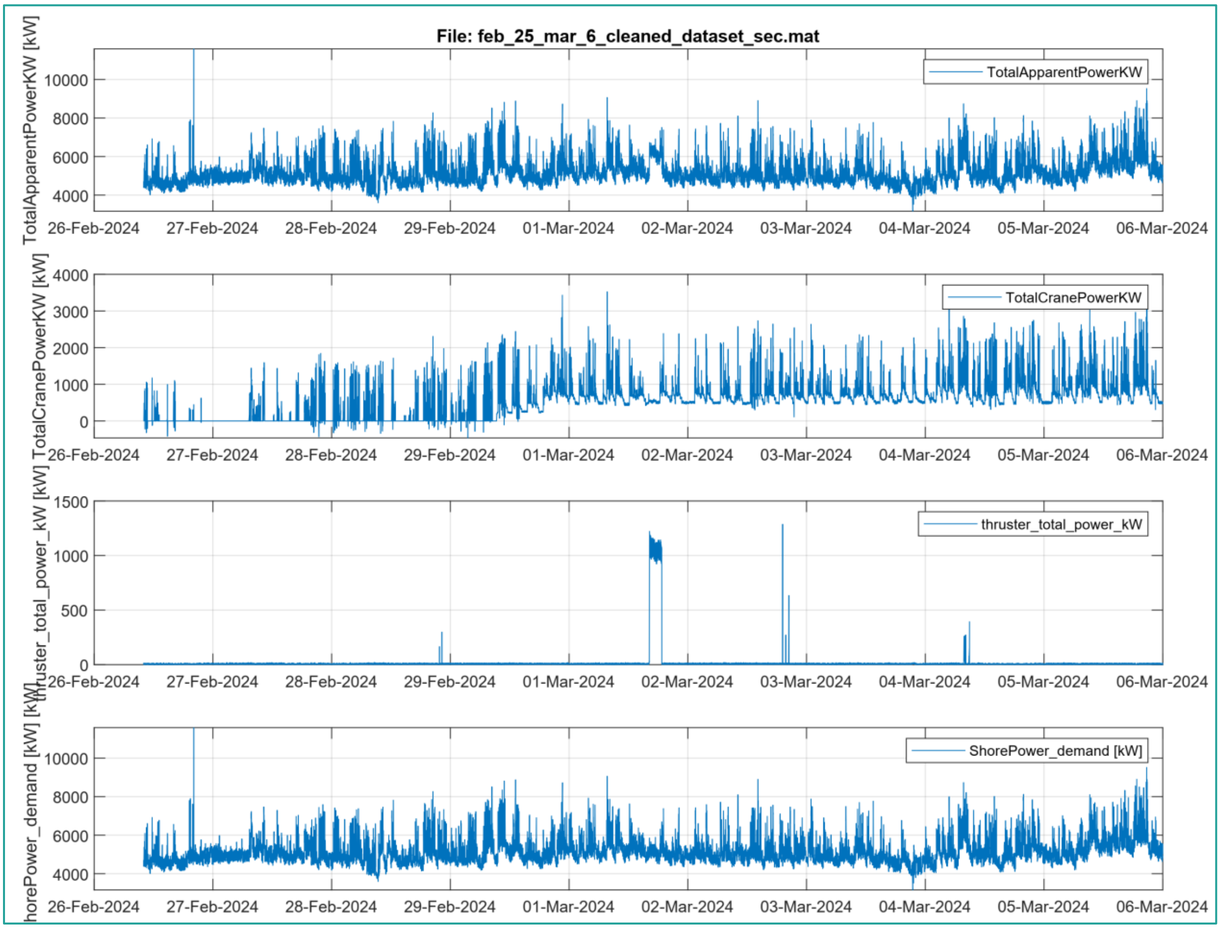


Figure B.2: Vessel load data, February2024-March2024

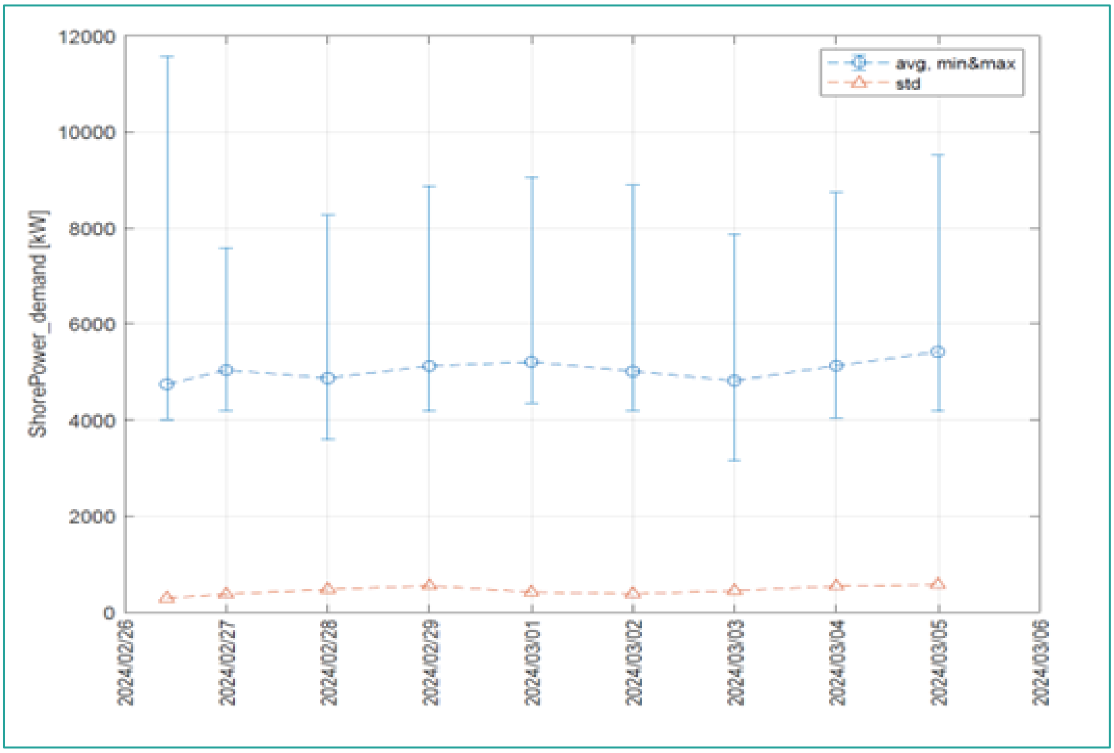


Figure B.3: Vessel load data daily statistics

Figure B.4: Vessel load data daily statistics

Figure B.5 shows the simulated power of a single 3.45MW wind turbine based on the wind data during the actual simulation period, measured at the KNMI meteo station "Hoek van Holland", as no measurement data at the wind farm site is available. The KNMI data is measured at a lower height (10 meters) than the wind turbine hub height, which leads to an under-estimation. However, the wind speed coastal location of the KNMI meteo station is higher than at the inland location (at similar height). Therefore, it is decided not to apply scaling until additional data becomes available. This results in a mean wind speed of 9.03m/s over the period January 2024 to July 2024 and a capacity factor for a single wind turbine of 58%. The second-data has been produced by linear interpolation of the 10-minute data with added white Gaussian noise, scaled to the measured 10-minute wind speed standard deviation.

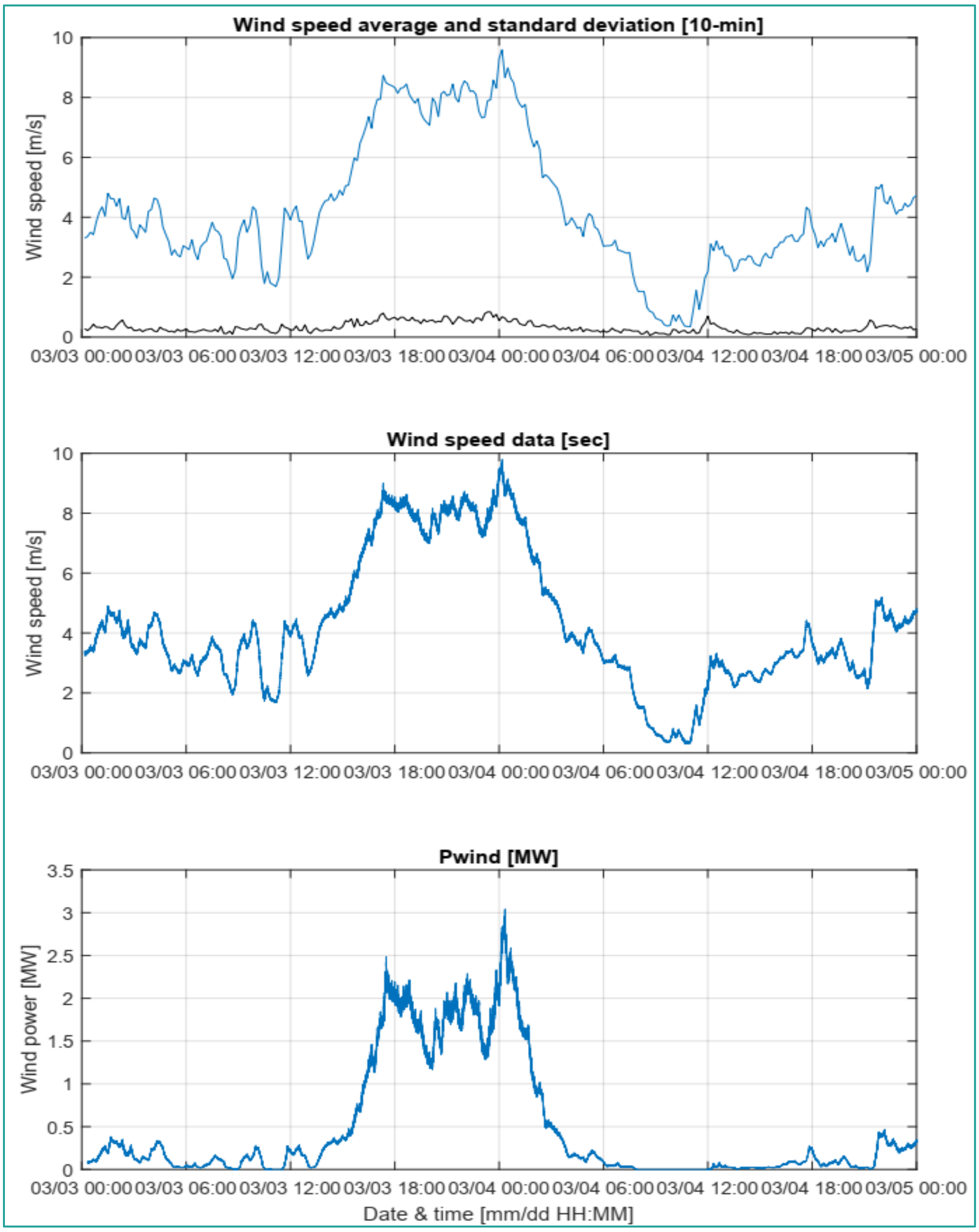


Figure B.5: Simulated wind power of single 3.45MW turbine

B.2 Experiment settings

B.2.1 Down-scaling

Table B.2 lists the limits at the pilot scale at the PoR and at the down-scaled mock-up, with a down-scaling factor of 100 applied.

Table B.2: Pilot and Mock-up limits

Quantity	Pilot	Mock-up	Remark
Vessel base load	5.5 MW	55kW	Average demand at grid-side of shore power converter
Vessel crane load	3.1 MW	31kW	Maximum load demand per crane, 2 cranes in total = 6.2MW
Battery system	3.5MW @3C	57.6kW @1C	Limit mock-up battery power to +/-35kW (equivalent C-rate between +/-0.61C) Limit mock-up battery SoC range to 35/3 = 11.7kWh (equivalent SoC range between 80% and 100%)
Wind farm	31 MW	60kW	Pilot: 9x3.45MW Mock-up: 6x10kW*
Shore Power converter limit	8 MW	80kW	Physical limit of shore power converter: immediate curtailment
Grid demand	8.5 MW	85kW	Contracted grid capacity (measured per 15-min.)

*: The wind farm size of 60kW at SWITCH is much smaller compared to the pilot-scale wind farm of 9x3.45MW = 31MW with a down-scaling factor of 100 (310kW).

B.2.2 Simulation cases

A number of simulations have been defined with different settings for the wind farm production levels and the contracted grid demand. The purpose is:

- to determine what minimum level is contracted grid demand is achievable and what is the effect of balancing the demand with the locally produced wind energy on the performance of the battery in terms of guaranteed reserve capacity and cyclic ageing.
- to determine suitable settings for the contracted grid demand for the field tests

Simulations are also performed after the field tests to tune the models and determine what can be concluded from the tests at pilot-scale.

Table B.3 lists the applied parameter ranges in the simulations. Due to the limited duration of simulations, all relevant combinations of wind farm power and grid limits can be covered. The wind farm sizing is varied to emulate different power production levels, requiring more or less activity for demand peak-shaving.

Table B.3: Applied ranges for wind power and grid demand limit in simulations

Sim case ID	Wind farm Pnom [pu]	Vessel load data period	Load down-scaling [-]	Power limit RSP [pu]	Peak-shaving limit DSO [pu]	Remarks
100	0	03/03/2024 00:00	100	0.80	0.55	Assumed max. peak-shaving need
102	0.2	04/03/2024 23:59			0.55	
104	0.4				0.55	
106	0.6				0.55	
110	0				0.60	
112	0.2				0.60	
120	0				0.65	no peak shaving occurred: no need to further increase grid limit
122	0.2				0.65	
140	0				0.575	
146	0.6				0.575	
100	0	01/03/2024 00:00	100	0.80	0.55	
110	0	05/03/2024 23:59			0.60	

B.2.3 Test cases

Depending on the wind conditions, a wind farm power level between 0 and 20kW seems appropriate to show the effect of peak shaving. Initial simulations showed that at higher wind power levels the load was always compensated within the allowed grid demand limit, so that peak shaving did not occur using the current load data set.

During a first series of tests none of the generation assets were included to compensate the vessel demand, so to maximize the need for peak-shaving for a given load demand and grid limit. Irrespective of the rated wind power, the battery system should be able to effectively perform peak shaving in rare cases when no wind power is produced. In a second test run all local generation assets wind and solar-PV were included, see Table B.4.

Because of to the varying resource conditions during this test, various levels of residual load occurred with different needs for peak shaving, mostly well-below 20kW.

Assessing the performance of the peak shaving at pilot scale, provided that suitable grid limits have been determined during field tests in the down-scaled mock-up, requires simulations over longer periods, typically a 4-month period in which the vessel is docked.

Table B.4: Applied ranges for wind power and grid demand limit in field tests

Parameter	Cases				
Wind power					
Pilot scale [MW]	9.7	2	0		
Mock-up scale [kW]	60 (wind) 37 (PV)	20 (wind)	0		
Grid limit					
Pilot scale [MW]	-5.5	-6.0	-6.5	-7.0	-7.5
Mock-up scale [kW]	-55	-60	-65	-70	-75

B.2.4 EMS settings

Table B.5 explains the parameter EMS settings applied in the tests, together with applied values set for generic parameters. Asset-specific settings are listed in Table B.6 and Table B.7.

NOTE: The contracted energy (parameter Emin1_pu and Emin1_pu) setting (default -0.85pu) is adapted to determine whether smaller contracted energy amounts are achievable with peak-shaving.

Table B.5: Listed EMS settings

Parameter name	Description	Value (INT16)	Real-world value & unit
(1) Status (note: number between brackets denotes relative index or index range of a parameter)			
New_param	Flag indicating new parameter values.	1	1 [-]
(2-6) Timing parameters			
MTU_len_sec	Market Time Unit (of selected market, e.g. Day-Ahead market)	3600	3600 [sec]
PTU_len_sec	Program Time Unit (i.e. grid metering period)	900	900 [sec]
t_step_sec	step time of EMS (unit commitment, peak shaving)	60	60 [sec]
t_step_modbus_sec	step time of Modbus	100	0.1 [sec]
t_step_ctrl_sec	step time of controller	1000	1 [sec.]
(7-25) Limits to energy and power exchange at connection points: 1: at grid connection point, 2-4: Behind-The-Meter connection points (max. 3)			
Emin1_pu .. Emin4_pu, (4 parameters) Emax1_pu .. Emax4_pu (4 parameters)	Limits to energy exchange at connection points: (numbering refers to 1: grid connection point, 2-4: Behind-The-Meter connection points)	-85; -85; 0; 0 500; 100; 0; 0	-0.85;-0.85; 0; 0 [pu] 5.0; 1.0; 0; 0 [pu]

Parameter name	Description	Value (INT16)	Real-world value & unit
Pmin1_pu .. Pmin4_pu, (4 parameters) Pmax1_pu .. Pmax4_pu (4 parameters)	Limits to power exchange at connection points: (numbering refers to 1: grid connection point, 2-4: Behind-The-Meter connection points)	-500;-100; 0; 0 500; 100; 0; 0	-5.0;-1.0; 0; 0 [pu] 5.0; 1.0; 0; 0 [pu]
dPmin_pu_sec dPmax_pu_sec	Power ramp rate limitations (simply set uniform limits for all connection points)	-10 10	-0.01 [1/sec] 0.01 [1/sec]
(26-29) PI(D)-Controller parameters			
flt_tau_sec	Filter time constant to (1st order LPF / HPF) used for power reference tracking to split slow and fast-responding assets	6000	60 [sec.]
ctrl_Pgain	power reference tracking proportional gain	20	0.2 [-]
ctrl_Igain	power reference tracking integration time constant	1	0.01 [sec.]
ctrl_Dgain	power reference tracking derivative gain (currently not used)	0	0.0 [1/sec.]
(30-41) Asset connection point: 1: (public) grid connection, 2-4: Behind-The-Meter connections			
num_connections	Number of connection points	4	4 [-]
Connections_<Asset> (11 parameters)	Connection points for each of the 11 assets. Numbering refers to 1: grid connection point, 2.. Behind-The-Meter connections	[1 .. 4], MAGPIE: WT1-6 = 1 PV1-3 = 1 Bat, P2H2 = 2	[1 .. 4] [-]
(41-92) Asset dispatching configuration			
num_groups	Max. number of groups for dispatching	10	10 [-]
Group_<Asset> (11 parameters)	Assign assets to groups for dispatching	[1..10]	[1..10} [-]
priorities_case1_group<n> (10 parameters) priorities_case2_group<n> (10 parameters) priorities_case3_group<n> (10 parameters) priorities_case4_group<n> (10 parameters)	Set priorities for dispatching for each dispatch group (n = 1..10), from: highest (1) to lowest (4) and no dispatching (0); case 1 = reduce energy feed-in case 2 = reduce energy cons. case 3 = reduce power feed-in case 4 = reduce power cons.	[1,2,3,4,0]	[1,2,3,4,0] [-]
dispatch_ctrl_FF_<Asset> (11 parameters)	Control response setting per asset: FF=Power reference feed-forward	[1/0]	[1/0] [-]
dispatch_ctrl_FB_slow_<Asset> (11 parameters)		[1/0]	[1/0] [-]

Parameter name	Description	Value (INT16)	Real-world value & unit
dispatch_ctrl_FB_fast_<Asset> (11 parameters)	FB_slow = slow feed-back control FB_fast = fast feed-back control	[1/0]	[1/0] [-]
dispatch_lim_<Asset>_min (11 parameters) dispatch_lim_<Asset>_max (11 parameters)	Min and max power limits, relative to rated power of respective assets (1 = supply 100% of Prated, -1 = demand 100% of Prated)	[-1 +1] [-1 +1]	[-1 +1] [-1 +1]
(148-159) Asset dispatching configuration			
Pbase_kW	Per-unit base power level	100	100 [kW]
Prat_kW_<Asset> (11 parameters)	Rated power per asset	e.g. WT=10	10 [kW]
(160-185) Battery system			
Crat_kWh_Bat	Nominal battery energy capacity	7200	7.2 [kWh]
Crat_Ah_Bat	Nominal battery charge capacity	2800	2800 [Ah]
Num_Bat	Number of batteries in system	8	8 [-]
SoC_Bat_ini_perc	Initial State-of-Charge setting	90	90 [%]
Bat_Charge_lim_rel_0 .. Bat_Charge_lim_rel_100 (11 parameters)	Define battery charging and discharging limits for SoC: 0%, 10%, .., 100% 1 = 1C discharge, -1 = 1C charge (notes: +/- 1C rated maximum; +/- 0.61 equals +/-35kW)	[-0.61 .. 0.0]	-0.61C .. 0C
Bat_Charge_lim_rel_0 .. Bat_Charge_lim_rel_100 (11 parameters)		[0.0 .. 0.61]	0C .. 0.61C
(186-188) EMS peak-shaving - recharging strategy			
Emin_margin_pu	Margin needed to allow battery recharging	5	0.05 [pu]
Bat_recharge_startlevel	Initial recharging power level, set at PTU start	70	0.7 [pu]
flt_tau_Pref_sec	Time constant of LPF-filter to smoothen Pref	10000	100 [sec]
(189-199) Asset power and energy measurement parameters			
Enable_meas_<Asset>	Include or exclude power and energy measurement	0/1	0/1 [-]

Table B.6: Dispatching and controller settings: Optimizing market value (blue): MAGPIE peak-shaving (red)

Asset ID	Description	Dispatching Energy / Power: Prio 1..4* = highest .. lowest, Prio 0 = no re-dispatching	Control action: P_{ref} Feed-Forward, Slow response, Fast response, 0=off
WT1	Wind turbine WUR	Group 1, Energy: 4 / 0, Power: 0 / 0	0/FF*** / 0/FF***
WT2	Wind turbine WUR	Group 1, Energy: 4 / 0, Power: 0 / 0	0/FF / 0/FF
WT3	Wind turbine WUR	Group 1, Energy: 4 / 0, Power: 0 / 0	0/FF / 0/FF
WT4	Wind turbine WUR	Group 1, Energy: 4 / 0, Power: 0 / 0	0/FF / 0/FF
WT5	Wind turbine TNO	Group 2, Energy: 2 / 0, Power: 3 / 0	0/FF + Slow / 0/FF
WT6	Wind turbine TNO	Group 3, Energy: 2 / 0, Power: 3 / 0	0/FF + Slow / 0/FF
PV1	PV solar field	Group 4, Energy: 3 / 0, Power: 2 / 0	0 / 0 -> *power set to zero*
PV2	PV next to WT5	Group 5, Energy: 3 / 0, Power: 2 / 0	0 / 0 -> *power set to zero*
PV3	PV next to WT6	Group 6, Energy: 3 / 0, Power: 2 / 0	0 / 0 -> *power set to zero*
Bat	Battery system	Group 7, Energy: 1 / 1, Power: 1 / 1	FF + Fast / Fast + Slow**
P2H2	Electrolyzer system	Group 8, Energy: 4 / 0, Power: 0 / 0	FF / FF -> *not operational yet*
	Emulated load	Group 8, Energy: 4 / 0, Power: 0 / 0	FF / FF

*: for WT1-4 Prio 4 means that curtailment is only allowed as a last resort measure, to prevent production exceeding the contractual limits at WUR site.

**: in peak-shaving demo the battery is not used for trading (so P_{ref} = 0)

***: in the first tests no balancing behind the meter is considered, i.e. wind power set to 0.

Table B.7: Assets ratings and dispatching limits

Asset ID	Description	Rating (kW)	Rating* [pu]	Notes
WT1	Wind turbine WUR	10kW	0.10	
WT2	Wind turbine WUR	10kW	0.10	
WT3	Wind turbine WUR	10kW	0.10	
WT4	Wind turbine WUR	10kW	0.10	
WT5	Wind turbine TNO	10kW	0.10	
WT6	Wind turbine TNO	10kW	0.10	
PV1	PV solar field	6 kW	0.06	*Controller dispatching: set to 0*
PV2	PV next to WT5	6 kW	0.06	*Controller dispatching: set to 0*
PV3	PV next to WT6	25 kW	0.25	*Controller dispatching: set to 0*
Bat	Battery system	35 kW	0.35	*Note: actively limited (rating is 60kVA)*
P2H2	Electrolyzer system	23 kWe	0.23	*Not yet operational (zero data)*
	Emulated load	117kW	1.17	Data directly fed to controller
Totals Setting	Generation Consumption	60+35 +35+117	0 .. +0.95 0 .. -1.52	Production positive: selected assets Consumption negative incl.. vessel load
Totals rated	Generation Consumption	97 + 60 23 + 60	0.97 .. 1.57 -0.23 .. -0.83	Production: all assets Consumption: all assets, no vessel load

* Per-Unit base power at SWITCH fieldlab: 1.0 pu set to 100 kW

Down-scaling between Rotterdam Shore Power pilot: 1.0 pu set to 10 MW

B.3 Detailed test results

B.3.1 Battery characterization

The battery system characterization focused on the charging and discharging efficiency and accuracy of the internal State-of-Charge measurement, rather than on determining the capacity and ageing. These characteristics have been determined by applying a limited number of discharge-recharge cycles at moderate power levels (C-rate below 0.5C, which is the recommended maximum, equivalent to 28.8kW), as shown in Figure B.6 and Figure B.7.

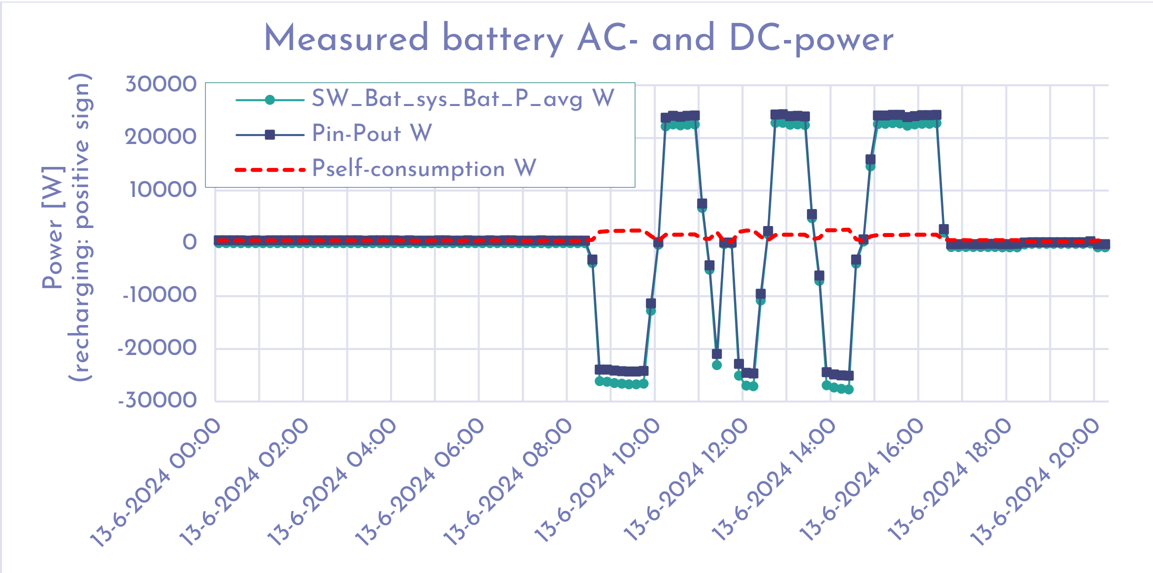


Figure B.6: Battery cycling with constant C-rate

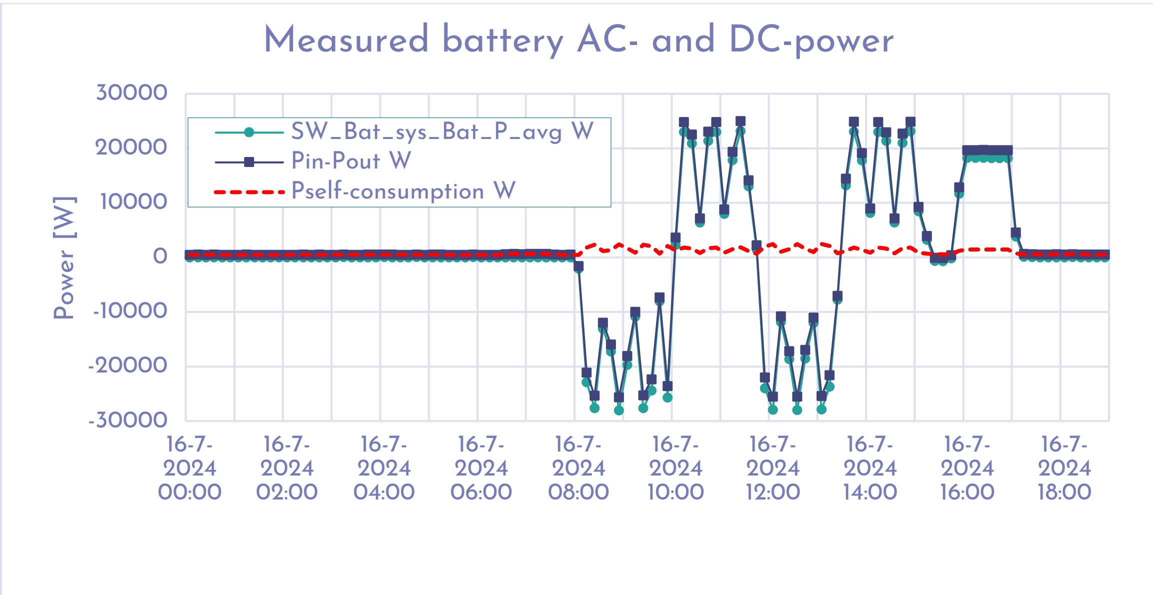


Figure B.7: Battery cycling with varying C-rate

The plots show the DC-power in green (logged battery system SCADA data), the measured AC power in yellow and the estimated self-consumption due mainly due to internal losses in the battery inverter and consumption of equipment connected in the DC-circuit.

During the first test the measured energetic cycle efficiency was about 6%, considering the SoC difference (starting at 100% and ending at 98%). The losses as well as the measured temperatures have been analyzed to determine parameters of loss models for the different components, as well as for the battery thermal model.

B.3.2 Initial tests for demand peak-shaving

Figure B.8 shows the measured signals that are directly related to the EMS and controller.

The first subplot shows the local generation of wind turbines and solar-PV which reduces the grid demand compared to the vessel load, as can be seen in the second and fourth subplot.

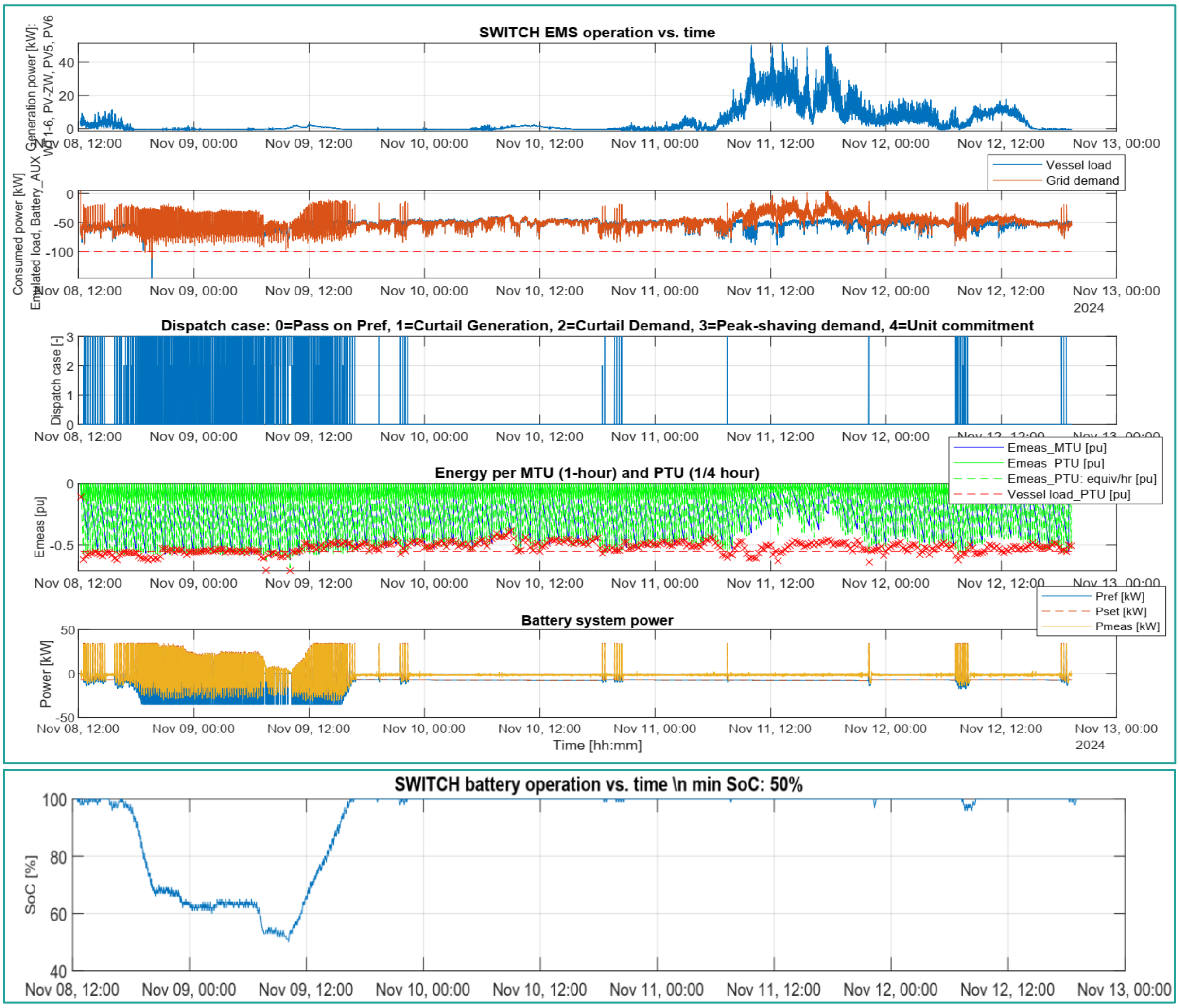


Figure B.8: EMS signals of test #1

The third subplot shows an almost constant activation of the battery for demand peak-shaving over the first hours of the test. This is because the emulated vessel load has been enlarged up to 20% to quickly check the activation of the peak shaving and of the direct curtailment. Also the battery recharging strategy (immediate maximum recharging) needed improvement, as this led to unwanted power fluctuations, higher conversion losses and faster battery lifetime consumption (until reaching full charge on Nov.9, the battery consumption was equivalent to three charge-discharge cycles). Two consecutive improvements were implemented on Nov. 7 12:45 (set ramp rate to recharging power) and on Nov 12 15:33 (calculated recharging power using the energy prognosis).

The fourth subplot shows the vessel's energy demand and the net grid demand, accumulated over each 15-min. period. The two lower subplots show the activity of the battery system. In this first test the battery minimum state-of-charge was limited to 50%, which was later changed to 80% to be in line with the capacity at pilot-scale.

From Figure B.9 it can be observed that the grid demand exceeds the prescribed limit of 0.55 pu. The two data points on Nov. 9 (see arrows) with ah grid demand exceeding 0.60pu coincide with a low battery state-of-charge, such that the battery could not provide sufficient power for peak-shaving. For all other points in time, the peak-shaving limited the grid demand to 0.60 pu.

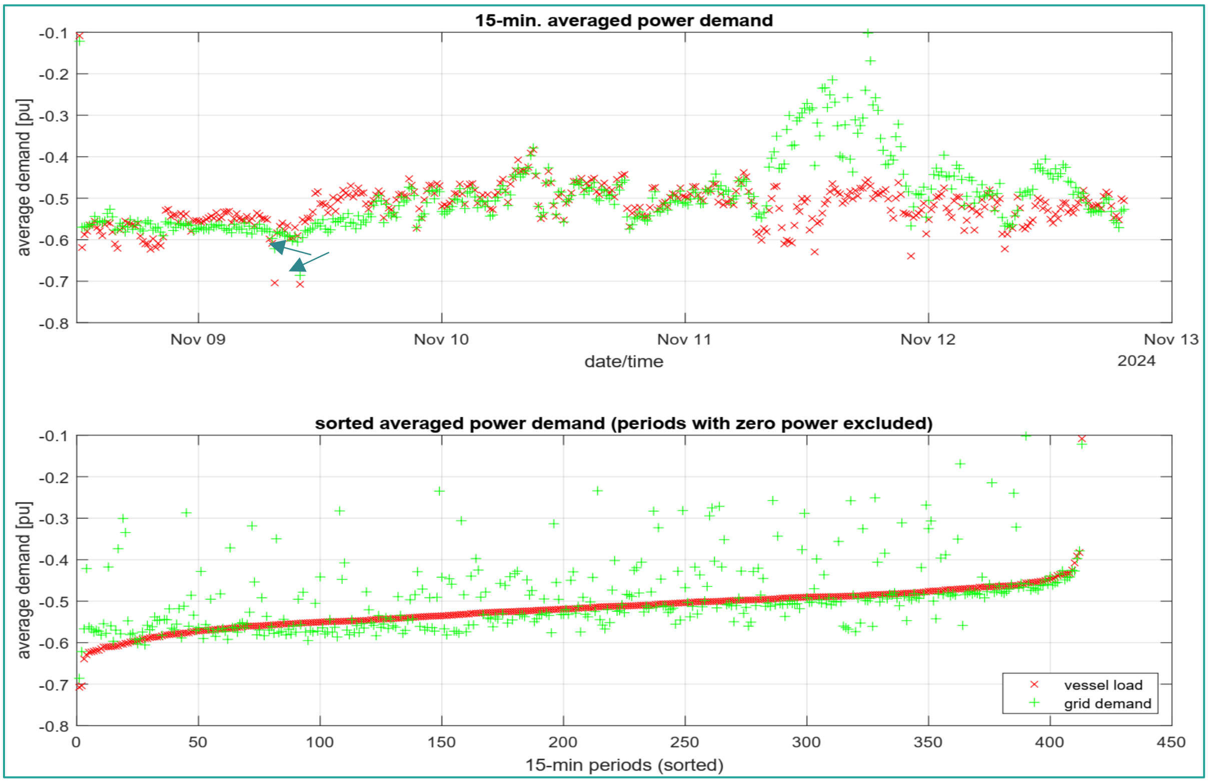


Figure B.9: 15-minute averaged vessel load and grid demand of test#1, in time (top), sorted (bottom)

NOTE: Due to a timing offset in the EMS for determining the start of a new of peak-shaving interval, the measured data needed to be shifted in time (59.5 sec.). This time shift has the same effect as the correction of the offset error, which has been resolved for future tests.

NOTE: According to the Dutch Metering code, the internal clock of the DSO's energy meter is allowed to deviate maximum of ten seconds from the Dutch standard time[9]. The required metering accuracy can be found in[10] (class 0.2S for voltage and current transformers, 0.2s for kWh meters, resulting in a 0.35% accuracy, assuming non-correlated errors)

B.3.3 Improved battery recharging strategy

Figure B.10 shows the measured signals from the second test. On Nov. 14 around 12:00 the total grid demand was temporarily much higher because of an additional consumer that was activated at the field lab for another experiment. As a result, the battery supplied maximum power until its minimum state-of-charge (set to 50%) was reached. The battery was also quickly discharged at the end of the test period, but this was due to an increase in the vessel load (measured at March 5, 2024), in combination with a declining local production at the field lab (see first subplot).

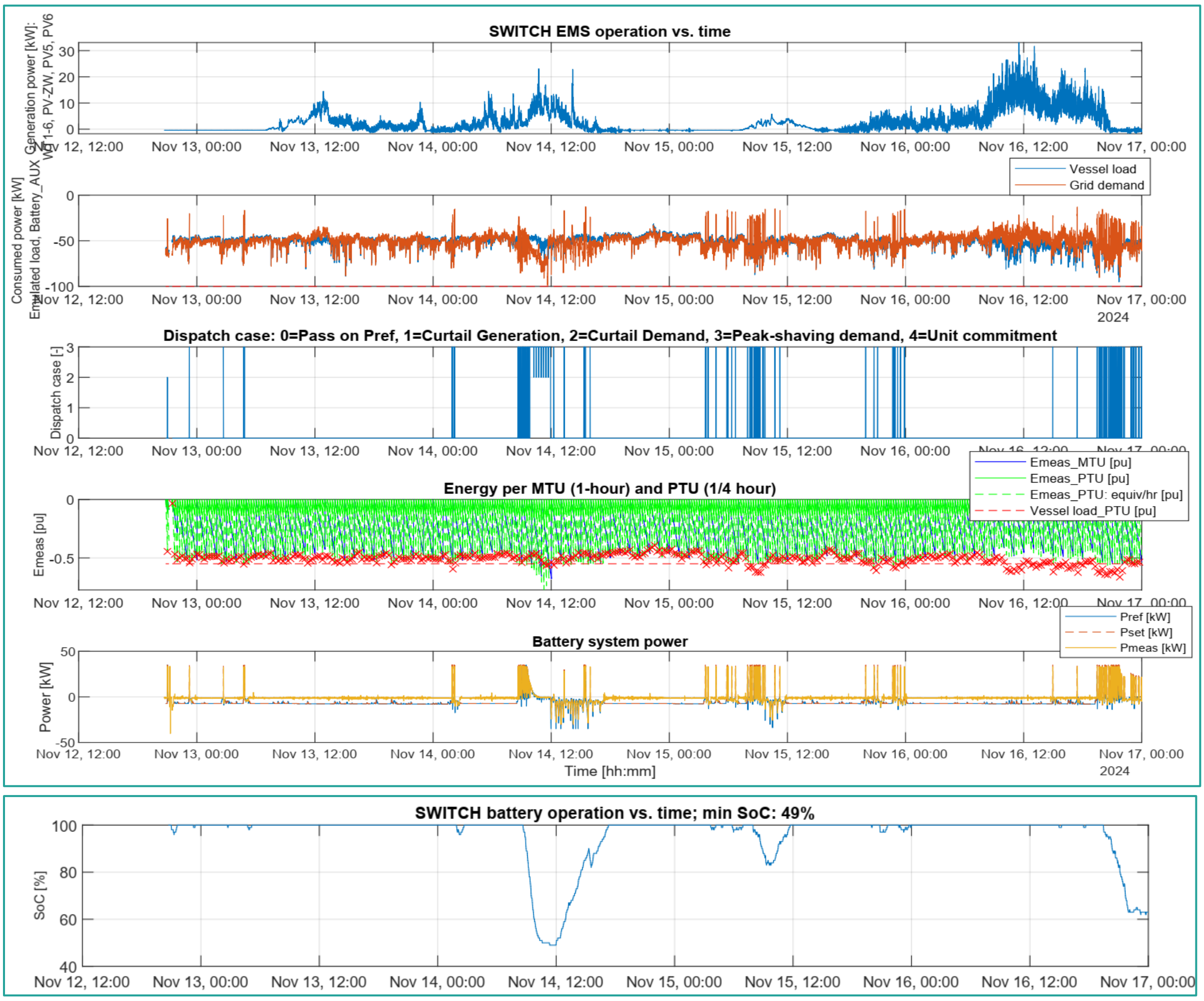


Figure B.10: EMS signals of test #2

[9] wetten.nl - Regeling - Meetcode elektriciteit - BWBR0037946, article 4.3.5 (in Dutch)
[10] wetten.nl - Regeling - Meetcode elektriciteit - BWBR0037946 Table B (in Dutch)

The resulting 15-minute averages grid demand is now limited effectively, except for the eight consecutive data points due to the unexpected additional load, causing a temporal depletion of the battery, as shown in Figure B.11. These data points are considered as outliers as the vessel load in this period is not very high.

Figure B.12 shows another representation of the 15-minute demand, with the vessel load in the first subplot, the vessel load plus the local generation in the second subplot, and the net grid demand (vessel load + local generation + battery) in the third subplot.

It shows that the additional generation causes a shift towards the right of the histogram, when comparing the second and first subplot, but does not effectively limit the extreme load demand. The third subplot shows that, discarding the eight outliers (within the orange circles), the battery reduces the grid peak demand to -0.576 pu. This still exceeds the limit that was set to -0.55pu. Likely causes are the internal ramp rate reduction of the battery system and possible timing issues when the peak demand just exceeds the limit in the final 60-second time step of the EMS. Please note that both the battery ramp rate setting and the EMS update interval can be adjusted.

Figure B.11: 15-minute averaged vessel load and grid demand of test #2, in time (top), sorted (bottom)

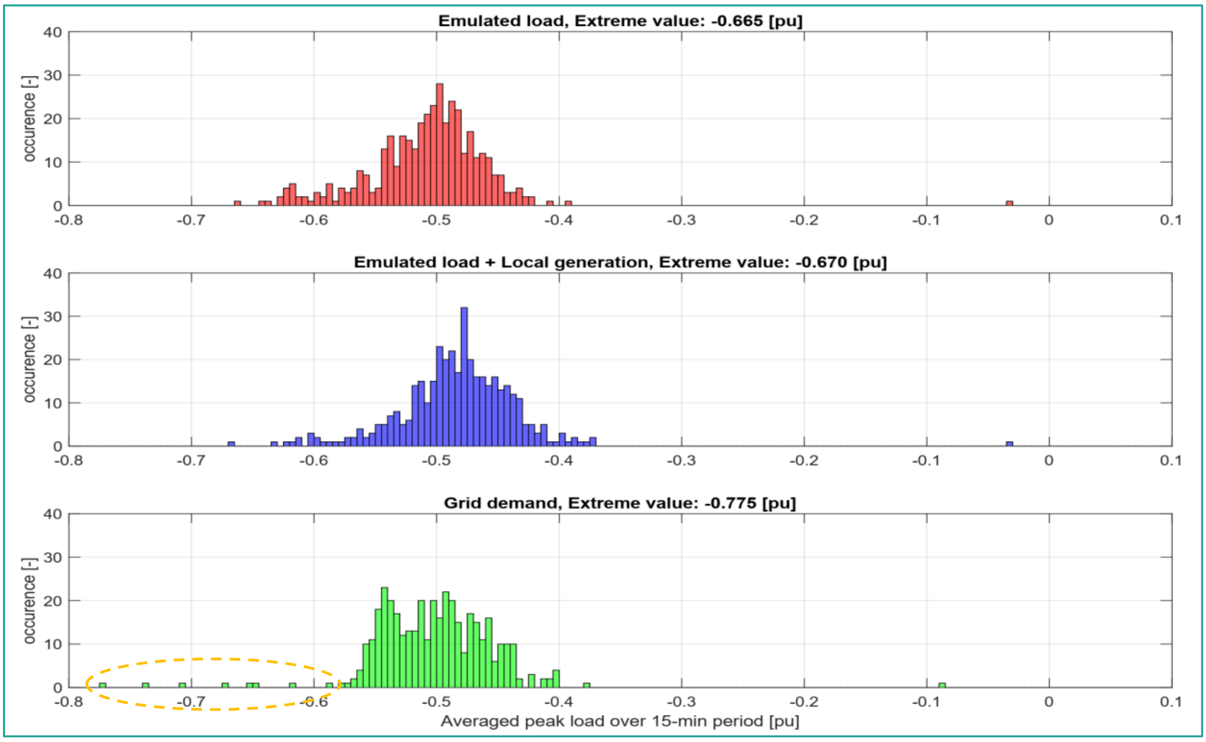


Figure B.12: Histogram of 15-minute averaged vessel load and grid demand of test #2

Figure B.13 shows the results from a test with a limit for the 15-minute grid demand set to -0.65 pu (so allowing a higher net load), without considering local generation to balance the demand. Another difference with the previous tests is that the limit for the momentary power demand was corrected from 1.0pu to 0.8pu, due to updated information from HMC. The results show only a single occurrence of peak-shaving (Nov. 19) during the 2-day test.

This test was repeated with tighter settings of the 15-min averaged grid demand: 0.60pu in test #4 and 0.55pu for test #5. During test #4, see Figure B.14, three periods with peak- shaving did occur, which lead to a reduction of the maximum vessel load demand of 0.635pu to 0.605pu, see shaving did occur, which lead to a reduction of the maximum vessel load demand of 0.635pu to 0.605pu, see also Figure B.15.

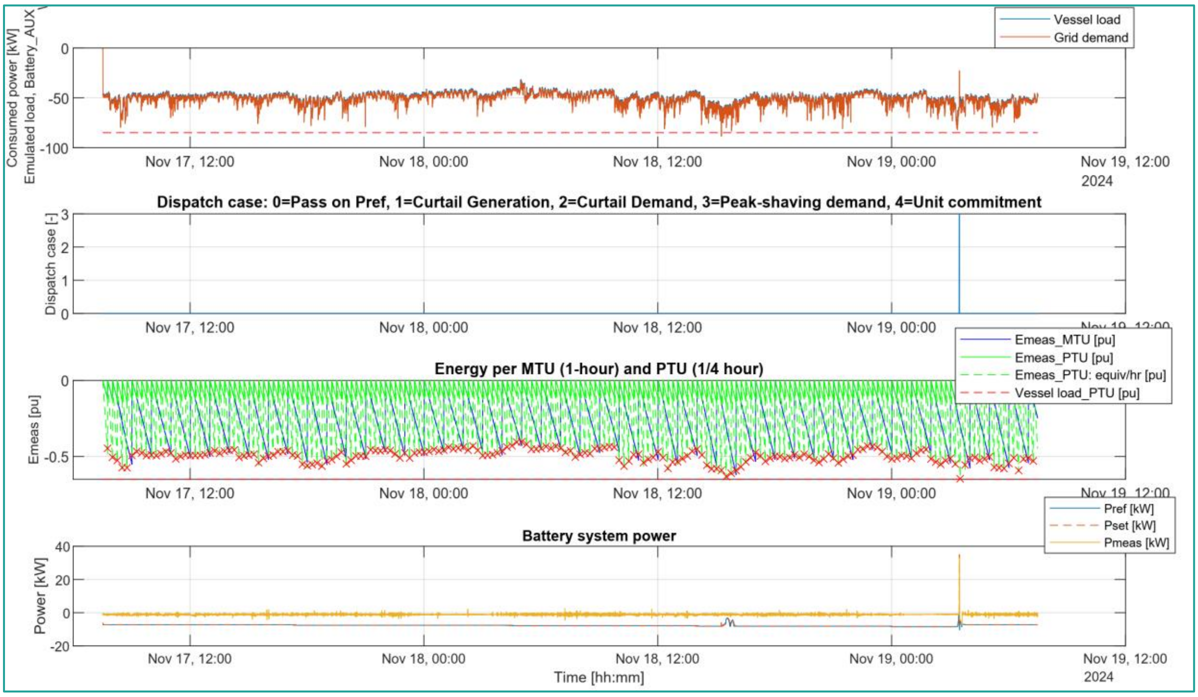


Figure B.13: EMS signals from test #3

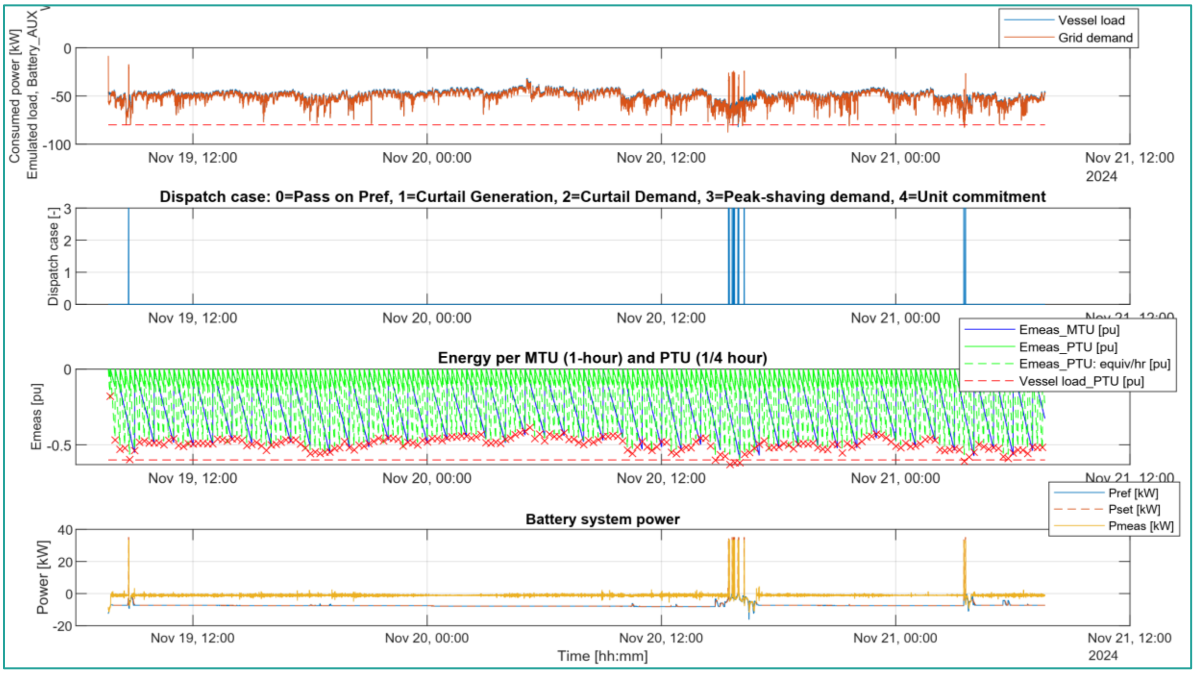


Figure B.14: EMS signals from test #4

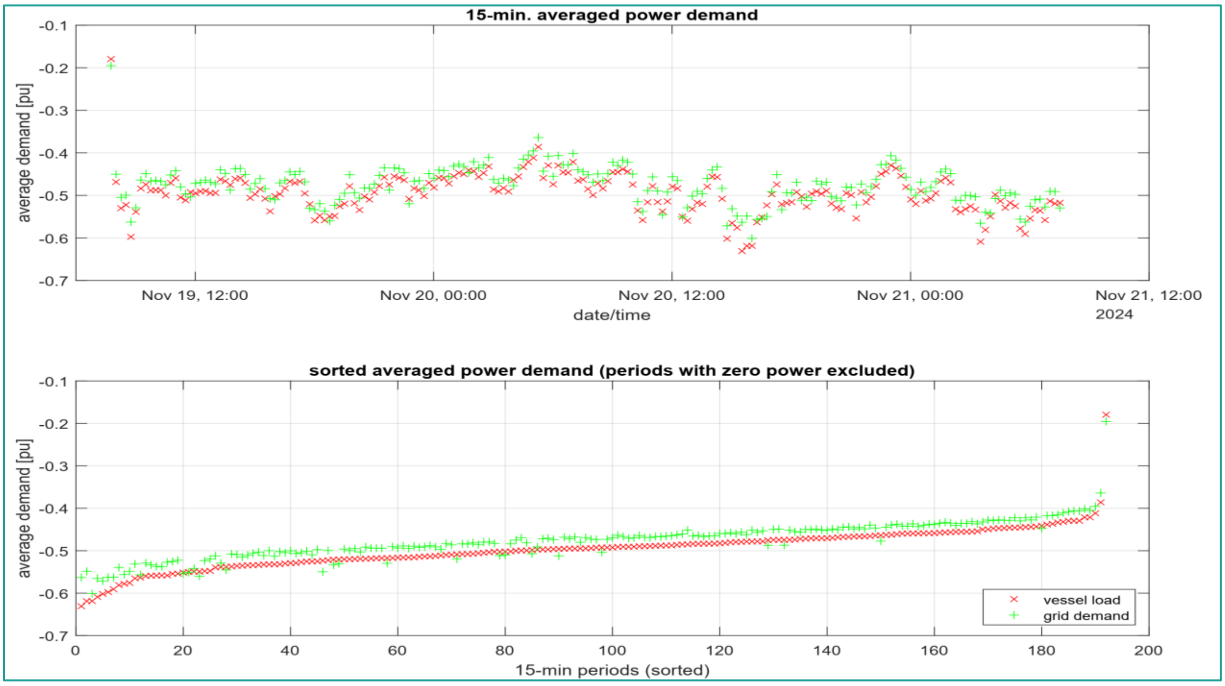


Figure B.15: 15-minute averaged vessel load and grid demand of test #4, in time (top), sorted (bottom)

In test #5, see Figure B.16 and Figure B.17, the maximum 15-min average vessel load of 0.630 pu (slight difference with test #4 can be due to a time shift of the 15-min averaging interval) was reduced by peak-shaving to 0.575pu, while the target limit was 0.55pu.

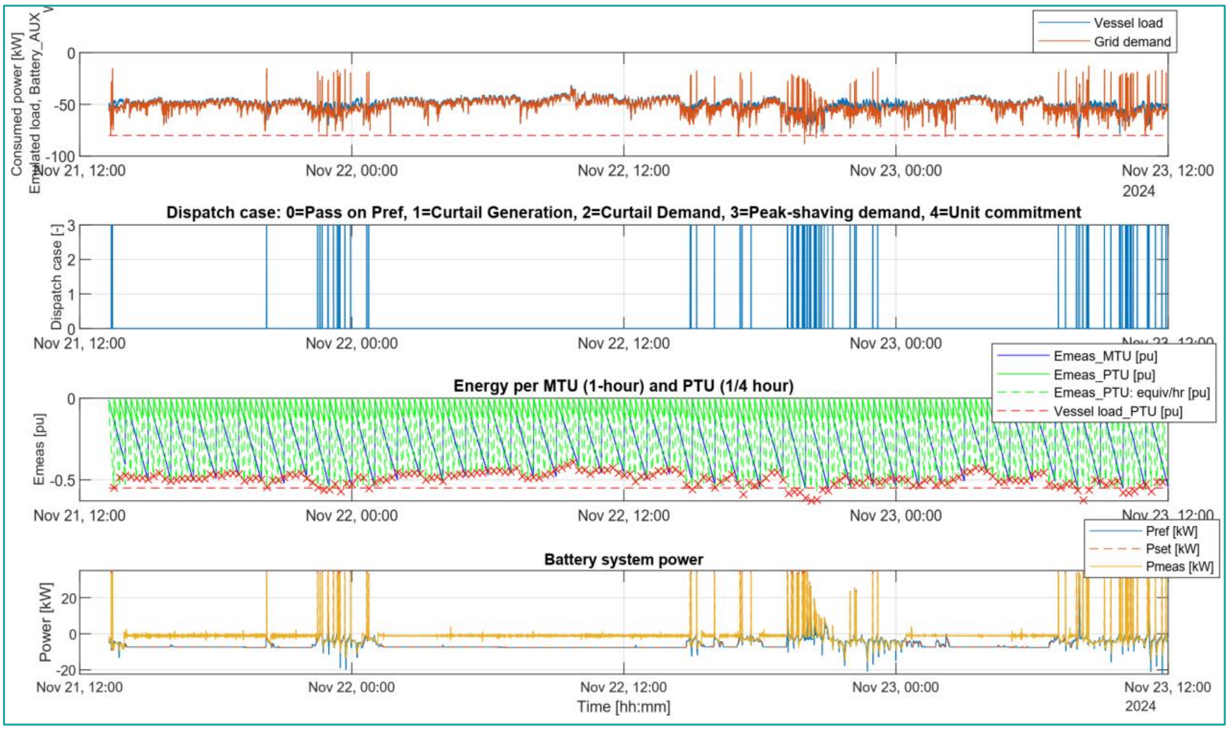


Figure B.16: EMS signals from test #5

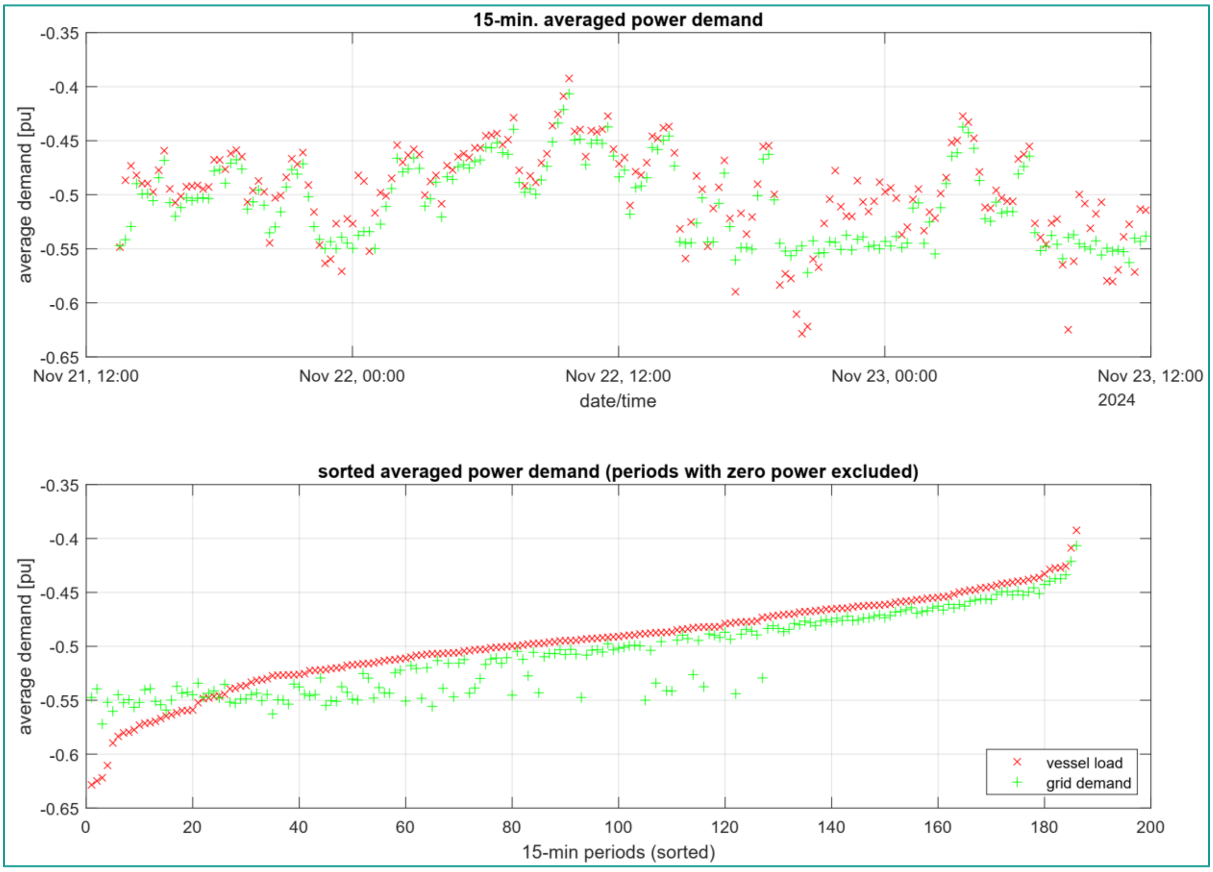


Figure B.17: 15-minute averaged vessel load and grid demand of test #5, in time (top), sorted (bottom)

Although the peak-shaving showed effective, the tight limit setting led to a near-depletion of the battery in the afternoon on Nov. 23, see Figure B.18, considering the minimum state-of-charge set to 80%. Note that the 20% useable cycle depth of the 57.6kWh battery of the mock-up matches with the 1.1MWh nominal battery capacity at pilot-scale.

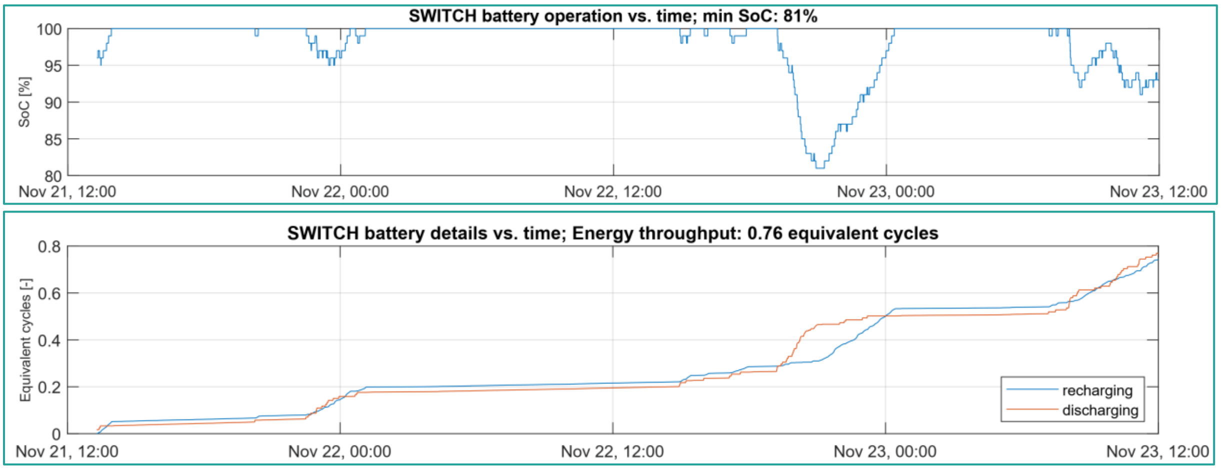


Figure B.18: Battery operation during test #5

The lower subplot shows the accumulated energy for discharging and recharging separately to indicate the battery consumption in terms of the number of equivalent full-cycles. The data is logged from the battery SCADA system, measured at the DC-side, so not including AC/DC converter losses. The curves can be interpreted as a single discharge with a depth of 77% (the end value of the red curve) followed by a recharge with 81% of the nominal battery capacity, or a 0.77 part of a full cycle with an 95% energetic efficiency (77%/81%).

Finally, two tests have been conducted with the same tight limit setting (0.55pu), but with wind energy (two wind turbines of 10kW nominal power each, or 0.2pu) compensating the vessel load. During test #6 several restarts had to be done and was stopped after two days. Test #7 ran for almost 5 days with the same settings as test #6, therefore only test #7 is presented, see Figure B.19, Figure B.20 and Figure B.21.

The maximum vessel load (0.685pu) was not compensated by the local electricity supply (0.680pu) due to poor wind conditions. This maximum load occurred within the last 12 hours of the test wherein the vessel load level increased (measurements from March 5, 2024), leading to a depletion of the battery capacity, such that no effective reduction occurred (grid demand 0.635pu). Until that moment (before Dec. 2 14:15), the vessel load was reduced to 0.585pu, compared to the limit set at 0.55pu.

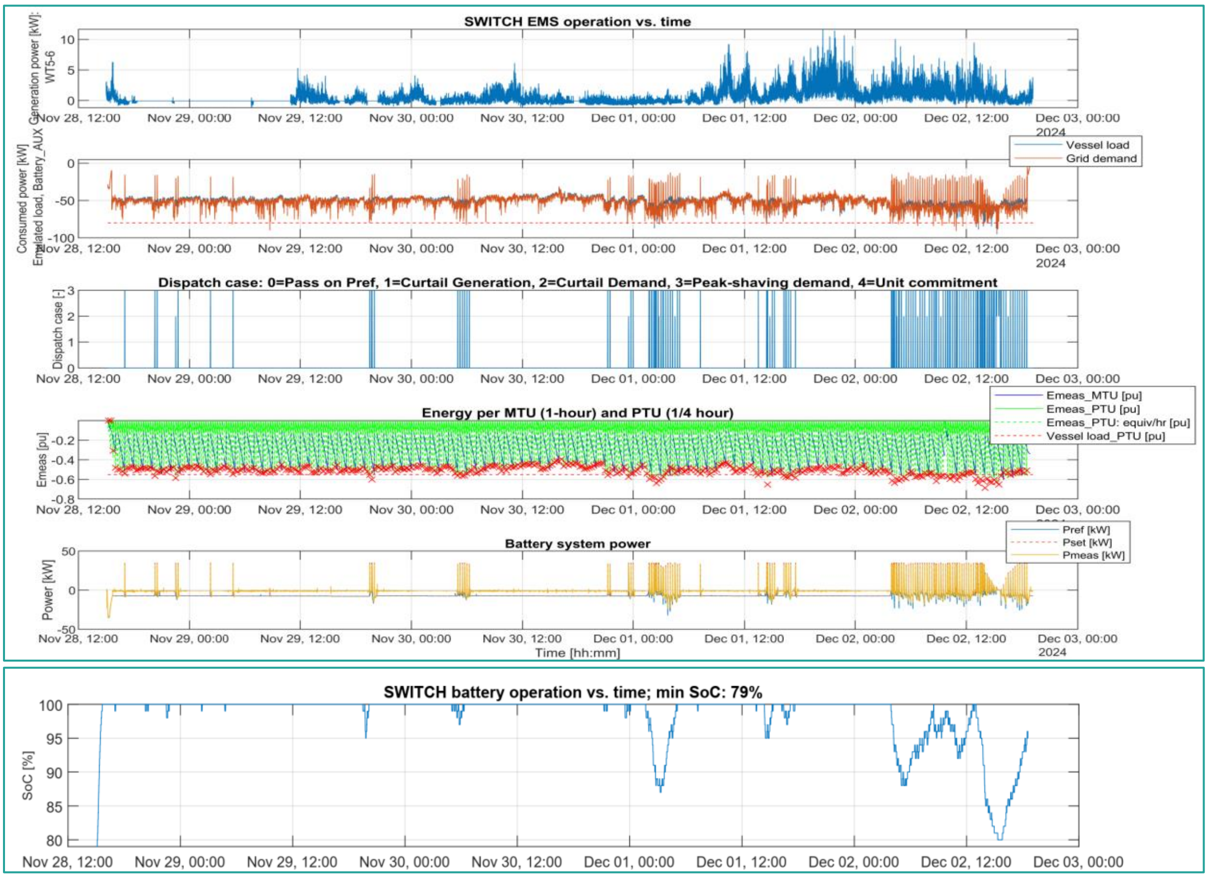


Figure B.19: EMS signals from test #7

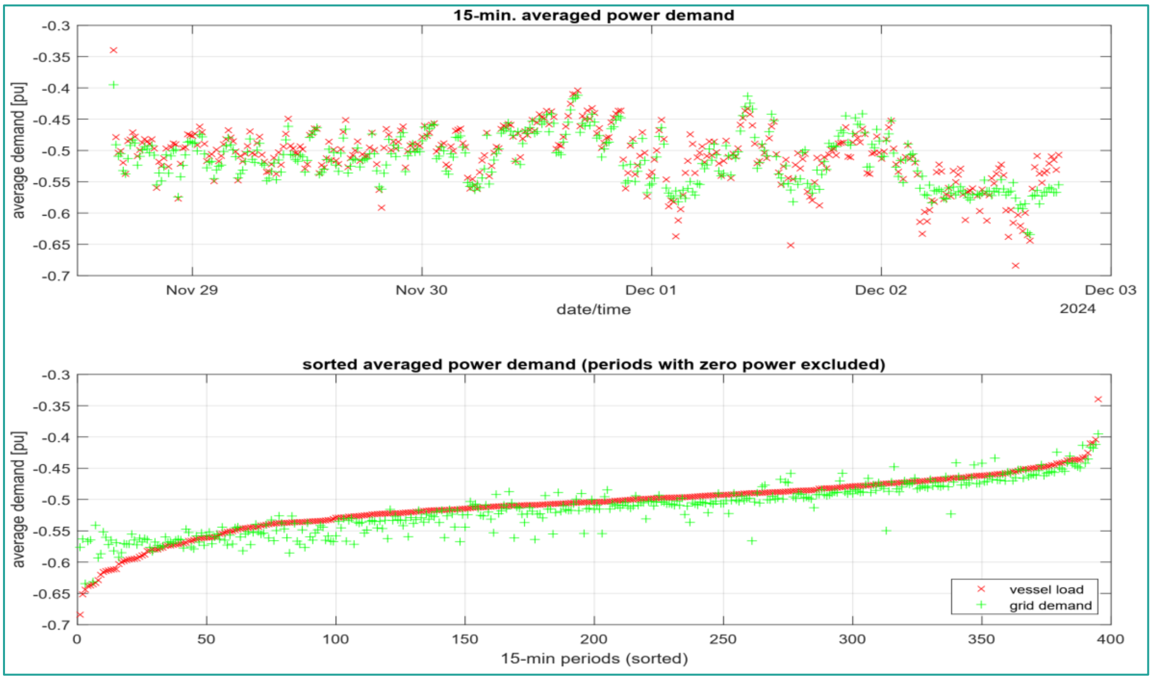


Figure B.20: 15-minute averaged vessel load and grid demand of test #7, in time (top), sorted (bottom)

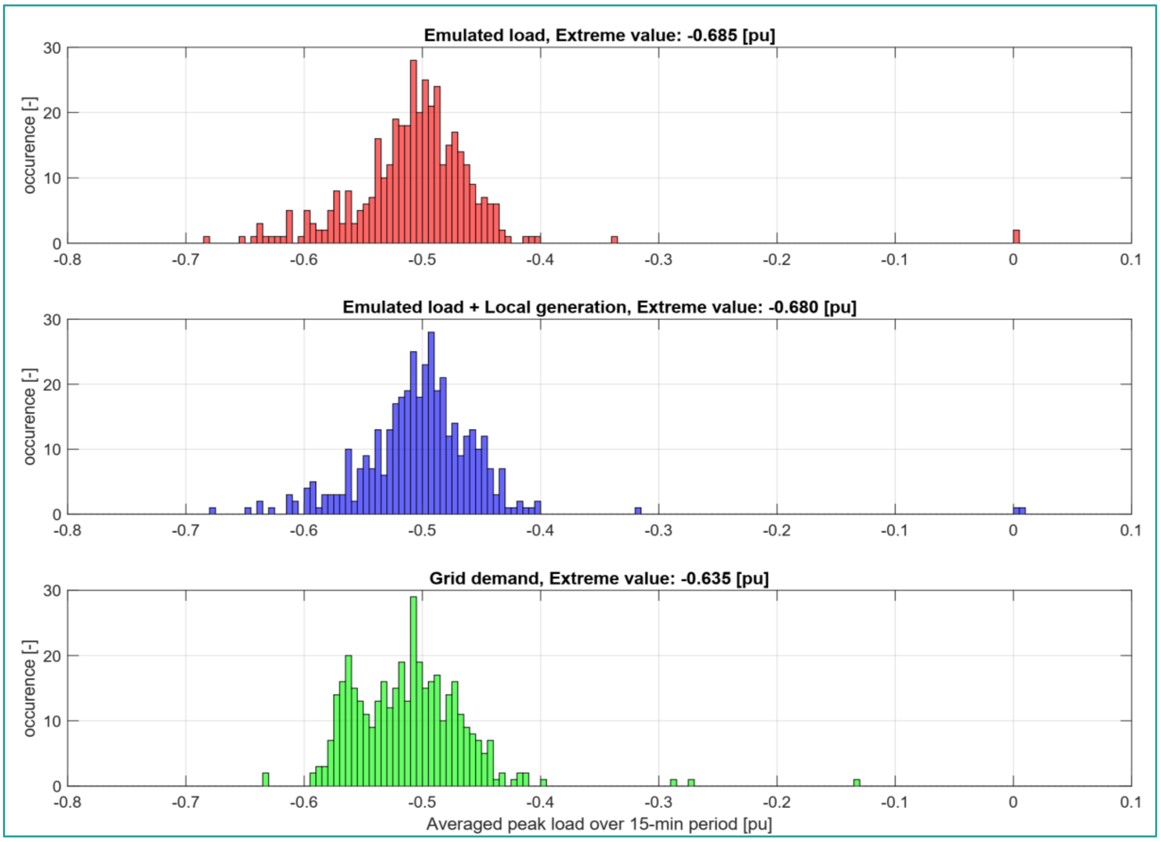


Figure B.21: Histogram of 15-minute averaged vessel load and grid demand of test #7

Figure B.22 shows a short time period of EMS signals to see the effect of the battery ramp-up limit when it is activated. Increasing the ramp-up rate setting can improve the performance of peak-shaving and immediate power reduction, as explained below.

As it takes roughly 30 seconds to ramp up from zero to full power, as can be seen in the lower subplot, the effective energy delivered over one minute when activated is about 25% lower than demanded, equivalent to 25% of 35kW / 60min/hr. = 0.146kWh. For the calculated peak load this means 0.146kWh / ¼ hr. = 0.583kW or 0.00583pu. This deficit is only a problem when peak-shaving is active during the last minute of a 15-minute period, as for earlier periods this is compensated by more frequent activation of peak-shaving later on. This deficit can be compensated by setting this amount as margin to the grid demand limit.

For compensating the momentary peak load, which is needed as 02:17, the battery response is too slow, as can be seen in the lower subplot, where the measured power (yellow) does not follow the setpoint increase (red).

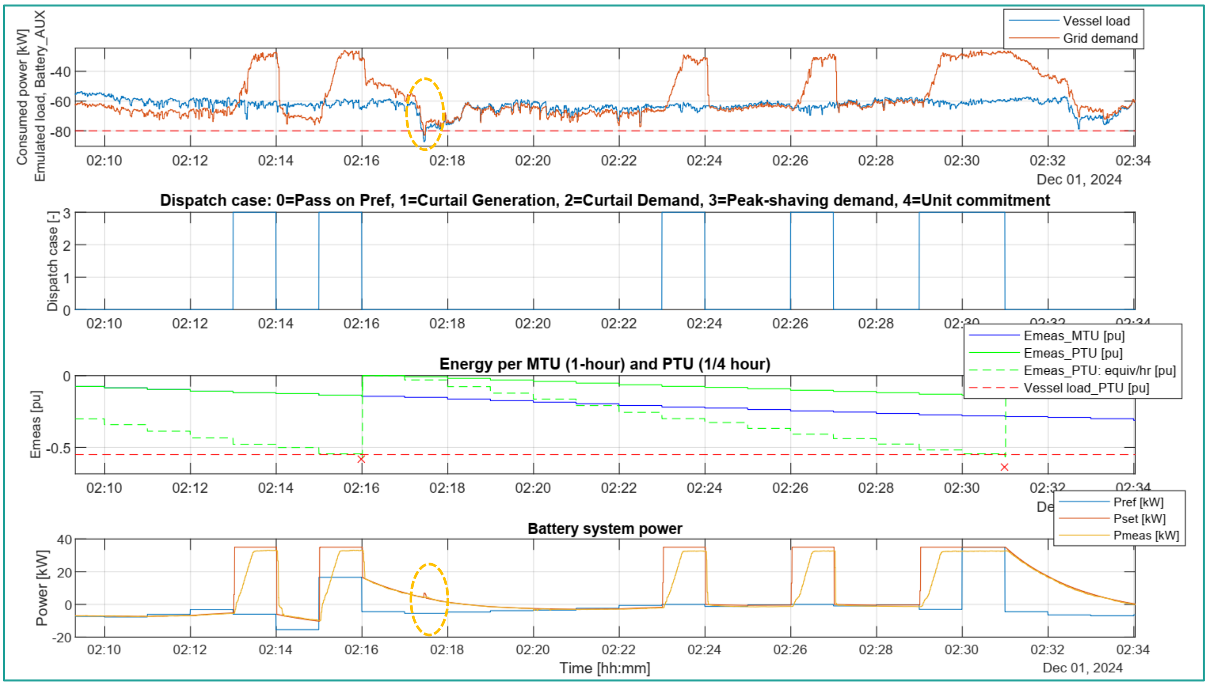


Figure B.22: Detail of measured EMS signals from test #7