TECHNISCHE UNIVERSITÄT DRESDEN

Chair of Energy Storage Systems

Investigation of multi-use applications of a PV Park with hybridized large-scale battery storage and power-to-gas plant

Tim Biermann, Thilo Bocklisch
Chair of Energy Storage Systems

7. Online-Workshop Energiespeichersysteme / 7th Energy Storage Systems Workshop
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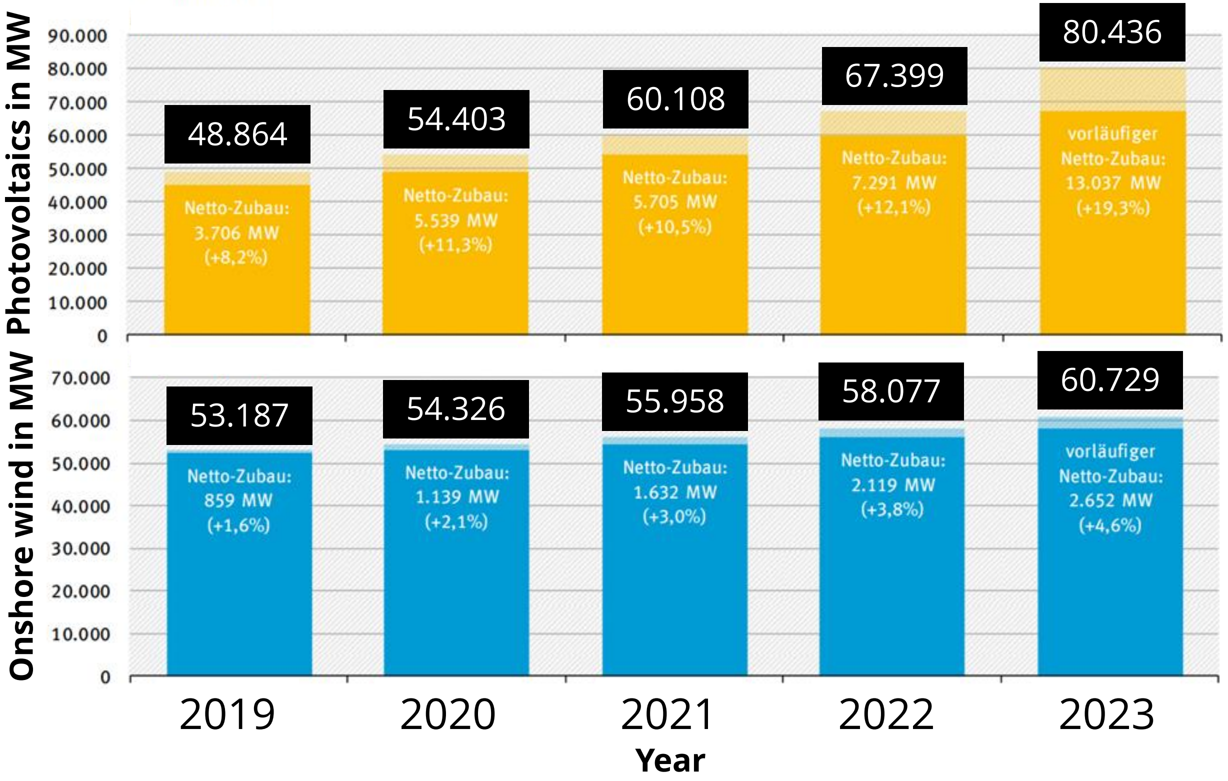
Agenda

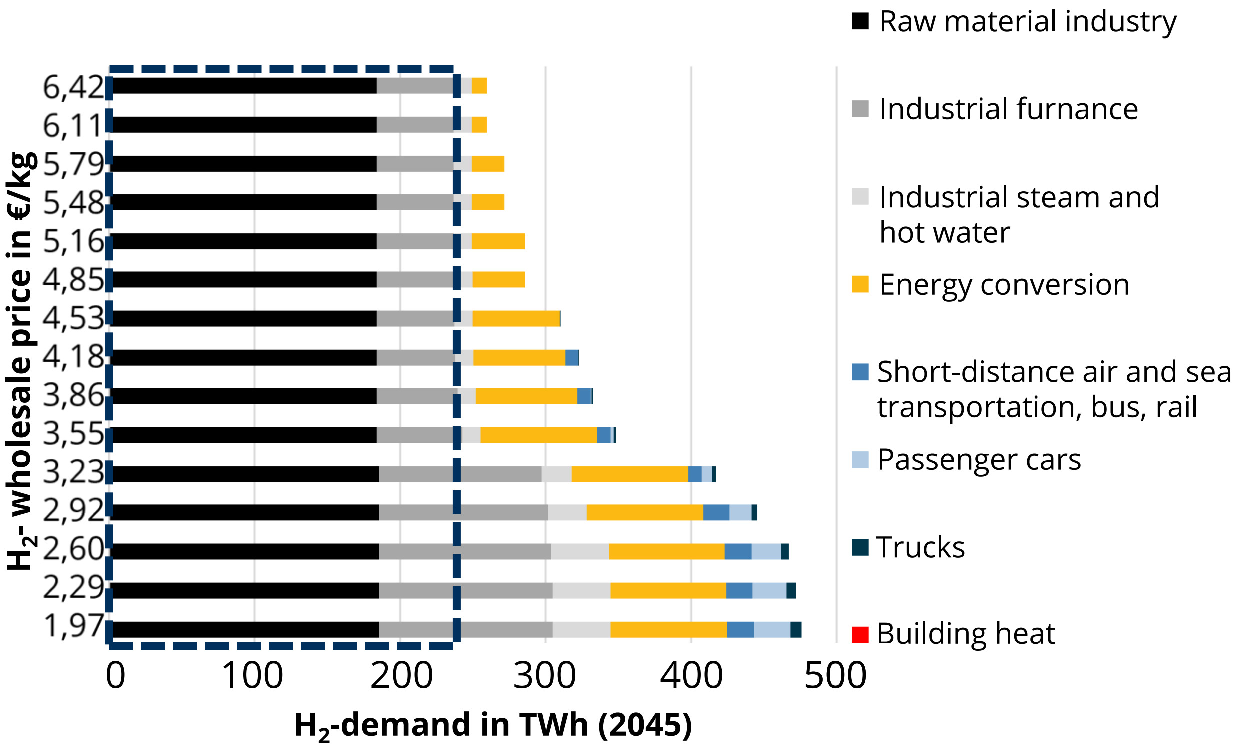
1. Motivation
2. System description and multi-use applications
3. Energy management concept
4. Simulation-based investigations
5. Summary and outlook

1. Motivation

Transformation of the energy system



Development of the installed power of PV and onshore wind in Germany [1]



Price-dependent hydrogen demand in Germany in 2045 [3]

→ Target 2030: **215 GW** PV and **115 GW** wind (onshore) installed power

→ Sharp increase in fluctuating electricity production

→ **System flexibilization and sector coupling**

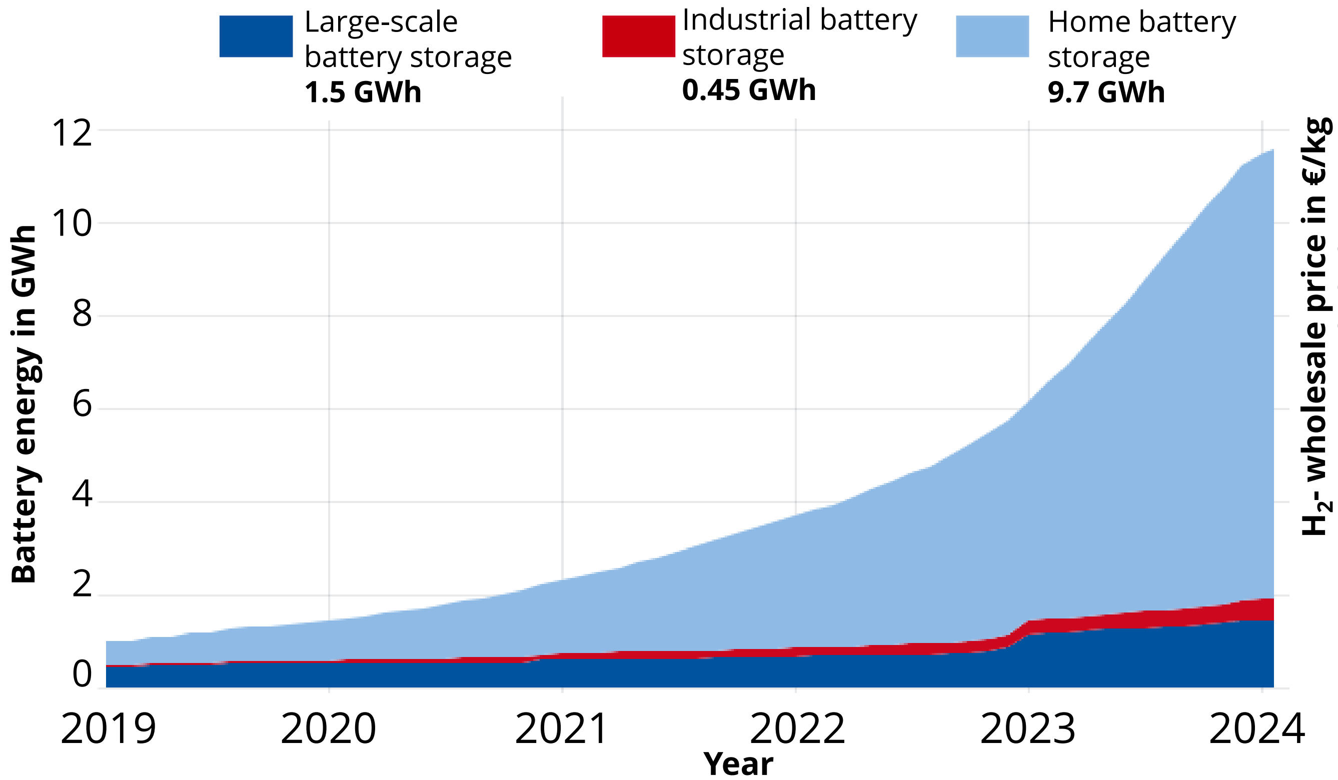
→ From today's perspective, no other economic options than hydrogen (and derivatives) in the industrial sector

→ This requires **60 GW** of electrolysis capacity to cover German demand

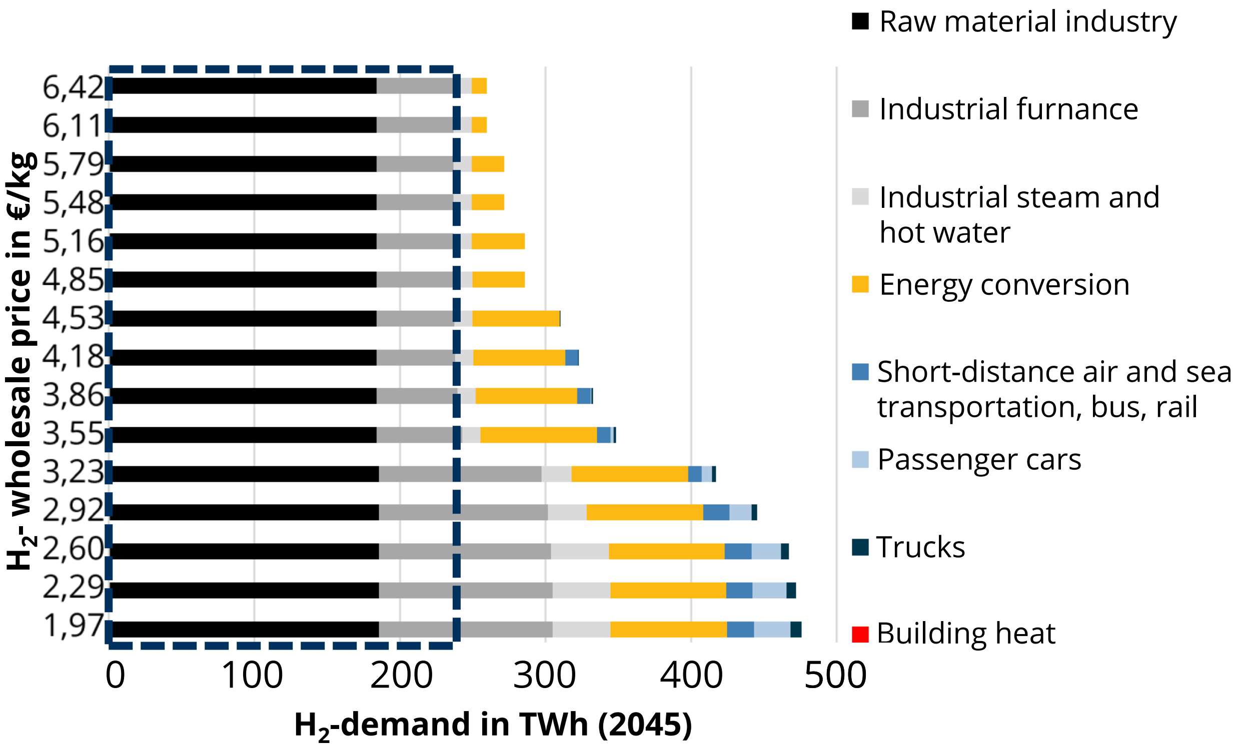
→ Currently **~173 MW** electrolysis capacity installed in Germany [4]

1. Motivation

Transformation of the energy system



Cumulated battery storage capacity in Germany (all battery technologies, MaStR)[2]



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- → Currently **~173 MW** electrolysis capacity installed in Germany [4]

1. Motivation

Reference projects

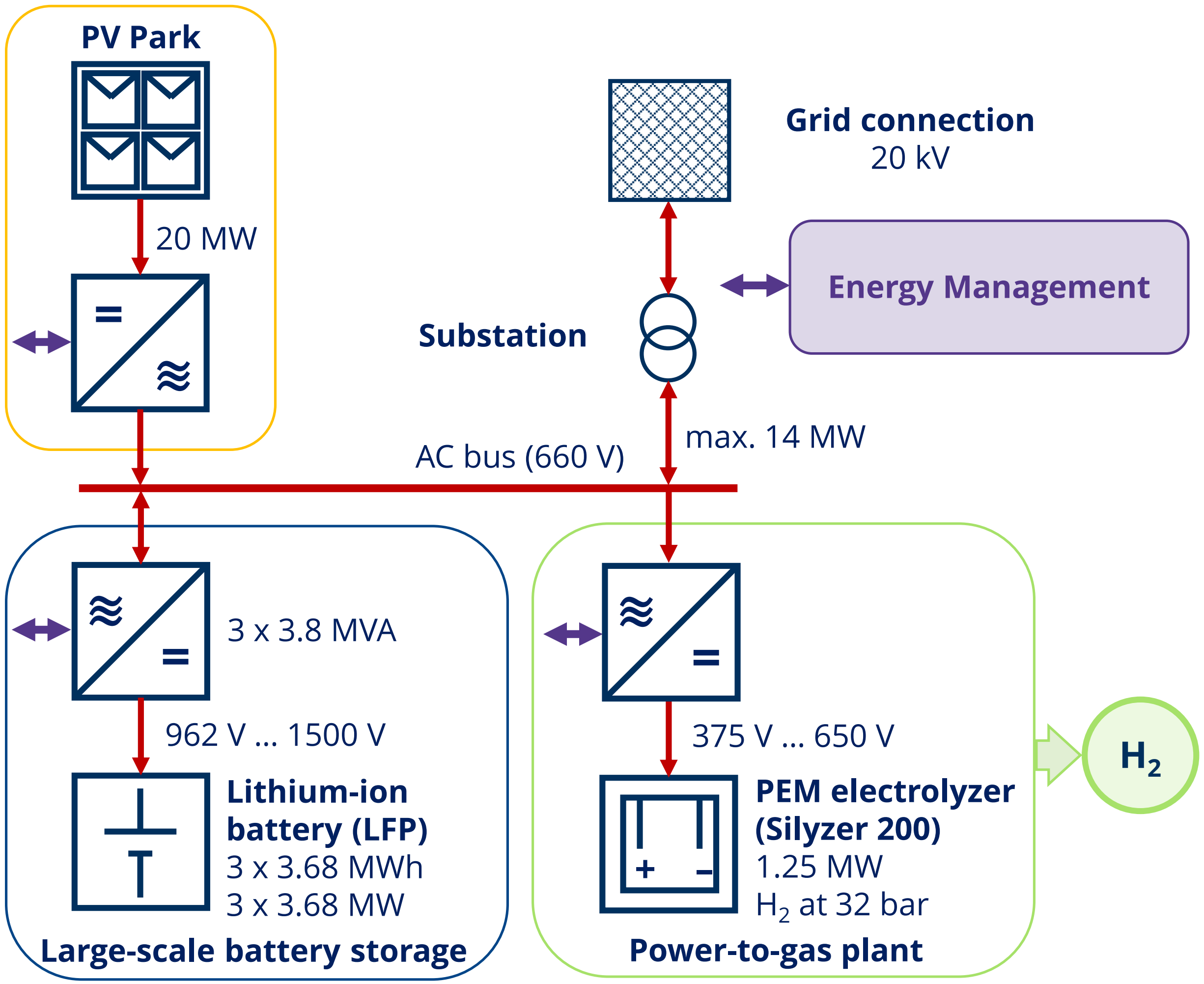
- **Energiepark Wunsiedel, Germany (2022)**[5]
  - 8,75 MW PEM electrolyzer (Siemens Silyzer 300) for gas grid feed-in and truck trailers
  - 8,4 MW / 10,2 MWh lithium-ion battery storage
  - Cooperation with the University of Bayreuth → Optimization-based energy management concept with ageing modelling (currently no publications)
- **Puertollano Green Hydrogen Plant, Spain (2022)**[7]
  - 20 MW PEM electrolyzer (Nel ASA) for industrial sector (ammonia production)
  - 5 MW / 20 MWh lithium-ion battery storage + 100 MW PV park
- **HH2E Lubmin project, Germany (planned for 2025)**[9]
  - 50 MW alkaline electrolyzer
  - 200 MWh battery storage + PPA‘s with offshore wind and PV parks
  - Optimize operation of PtG plant → continuous hydrogen production

Energiepark Wunsiedel, Bavaria, Germany [6]

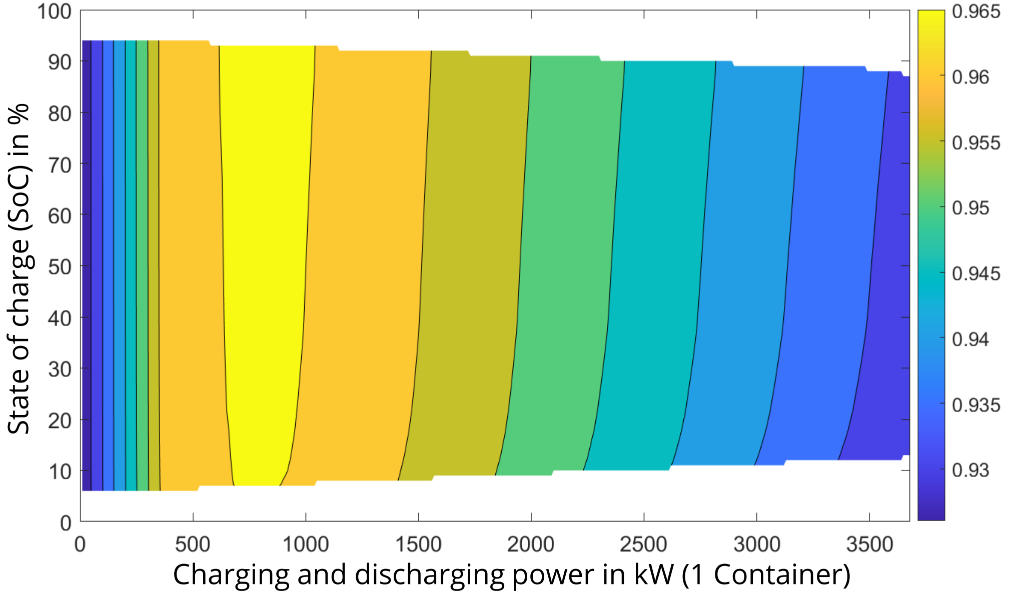
Puertollano Green Hydrogen Plant, Spain [8]

2. System description and Multi-use applications

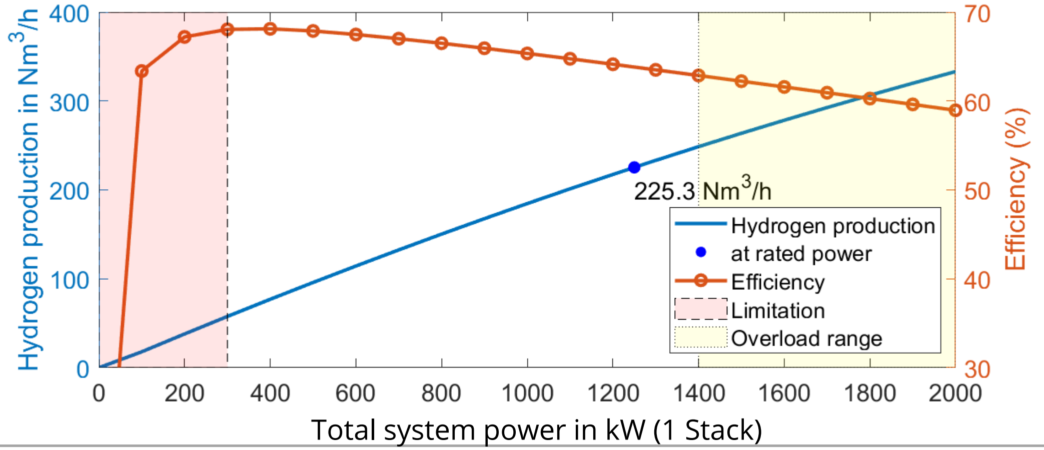
System description



Roundtrip efficiency of large-scale battery storage (without BoP)



Characteristics of Siemens Silyzer 200 [10]



2. System description and Multi-use applications

Multi-use applications for large-scale battery storage (LSBS) and power-to-gas plant (PtG)

Grid services | System services

Large-scale battery storage	Power-to-gas plant
• Peak-Shaving • Participation in the spot markets • Capacity Firming • Frequency Containment Reserve (FCR) • automatic Frequency Restoration Reserve (aFRR) • Congestion management (e. g. Grid booster), Black start capability, Synthetic instantaneous reserve • Voltage maintenance, Reactive power compensation, Uninterruptible power supply (UPS) • **Optimize operation of PtG plant** (Operating range, efficiency, full load hours)	• Hydrogen production • Participation in the spot markets • Frequency Containment Reserve (FCR) • automatic Frequency Restoration Reserve (aFRR) • Participation on the natural gas market via gas grid feed-in

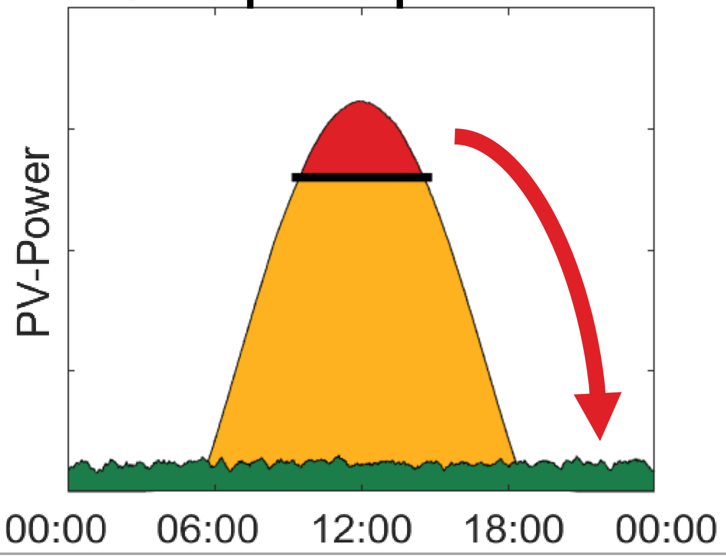
[11] [12] [13] [22] [23]

2. System description and Multi-use applications

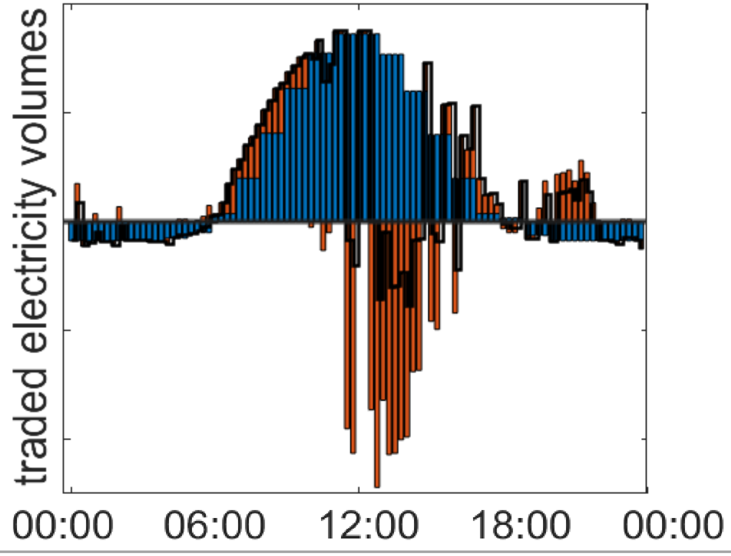
Multi-use applications for large-scale battery storage and power-to-gas plant

Large-scale battery storage	Power-to-gas plant
• Peak-Shaving • Optimize operation of PtG plant • Participation in the spot markets • Capacity Firming	• Hydrogen production • Participation in the spot markets

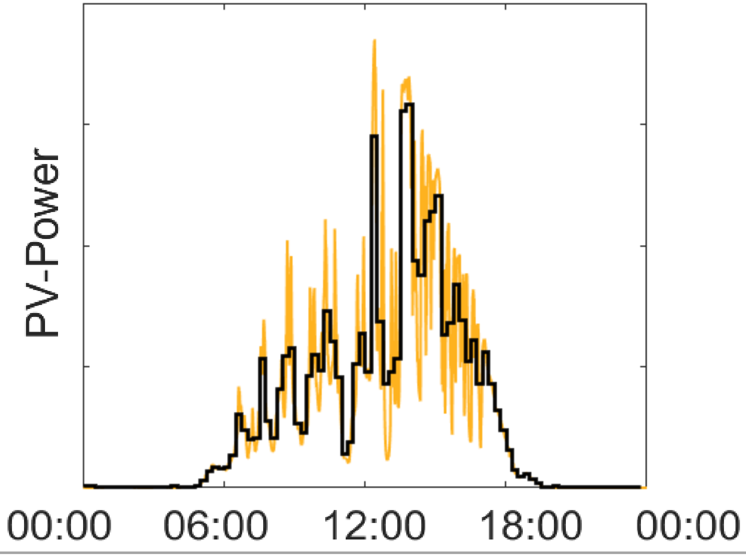
Peak Shaving + Optimization PtG plant operation



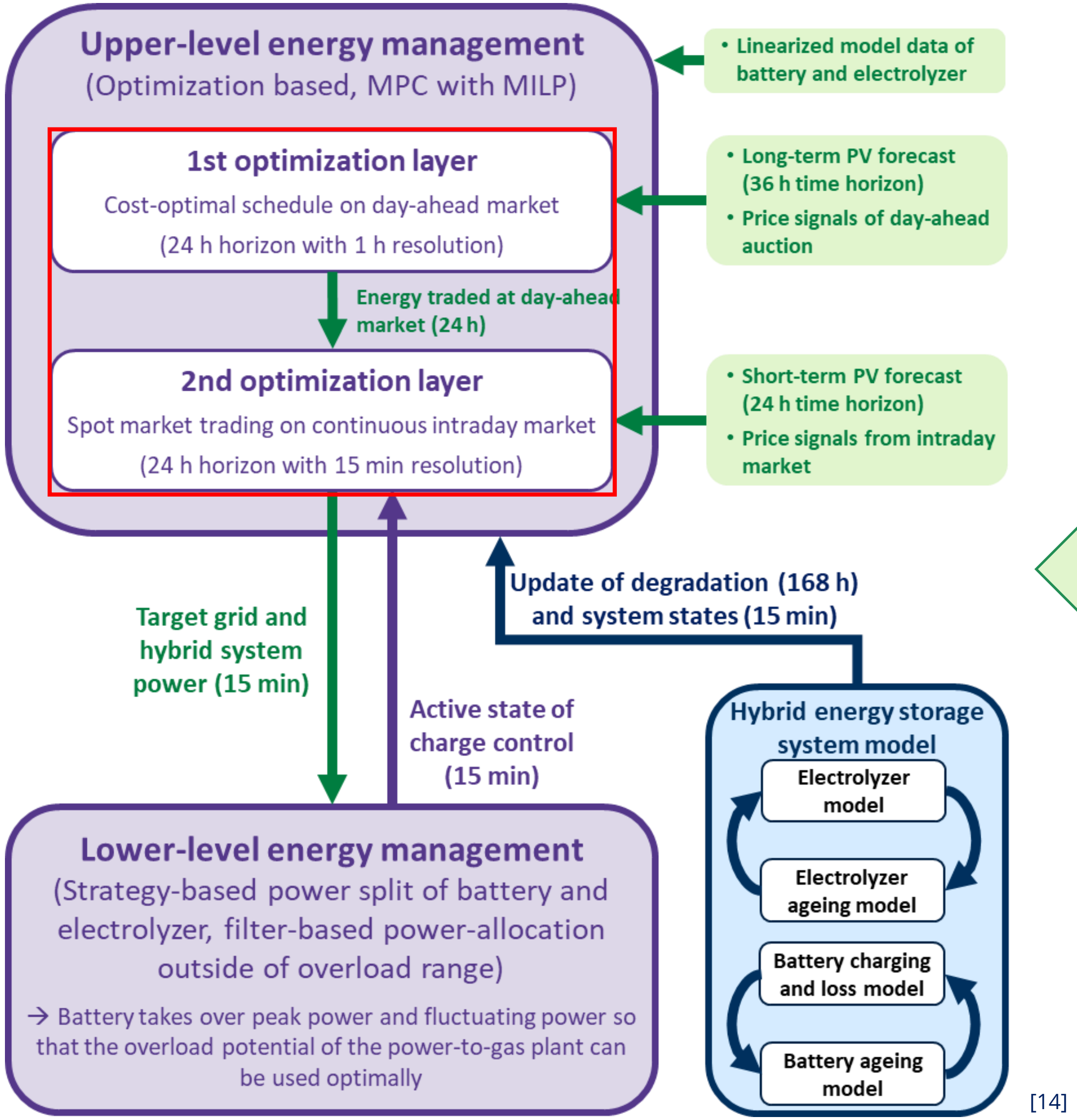
Participation in the spot markets

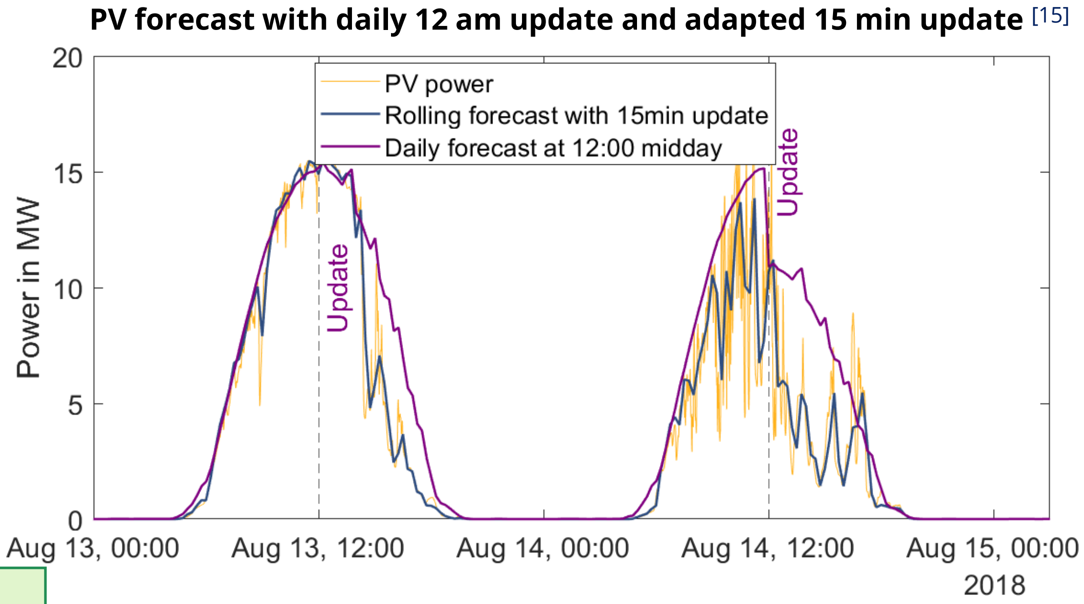


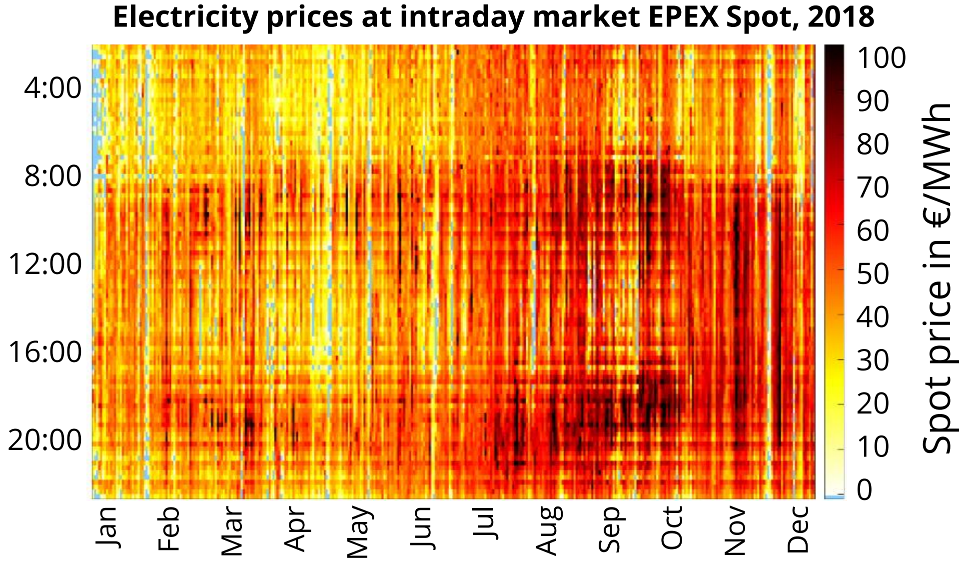
Capacity Firming



3. Energy management concept







3. Energy management concept

Objective functions of the upper energy management level (MPC + MILP)

1st optimization level with 1x24 time steps (1 h resolution):

$$\min \sum_{t=1}^{T} \Delta t \cdot \Big\{ -c_{DAM}(t) \cdot P_{DAM}(t) - c_{H_2} \cdot m_{H_2}(t)$$

$$\sum_{s1=1}^{3} c_{cyc,s1} \cdot p_{ch,s1}(t) + \sum_{s2=1}^{3} c_{cyc,s2} \cdot p_{dch,s2}(t) + (a_{cal} \cdot E_{bat}(t) + b_{cal})$$

$$+ c_{PVcurtail} \cdot P_{PVcurtail}(t) \Big\}$$

Profit/costs from electricity volumes on the spot market

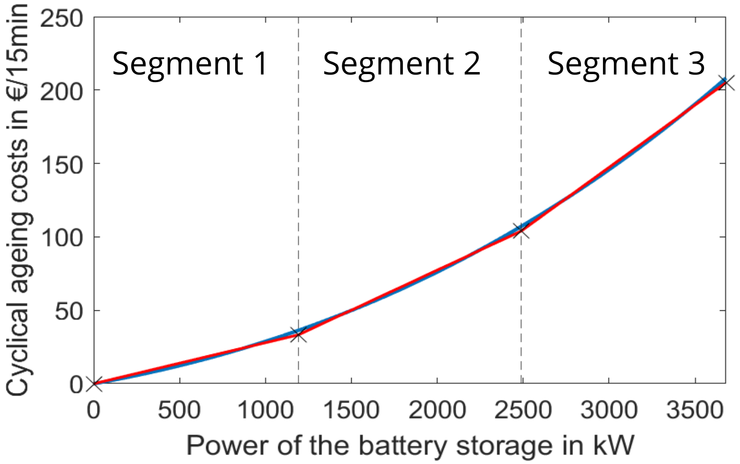
Profit from hydrogen production

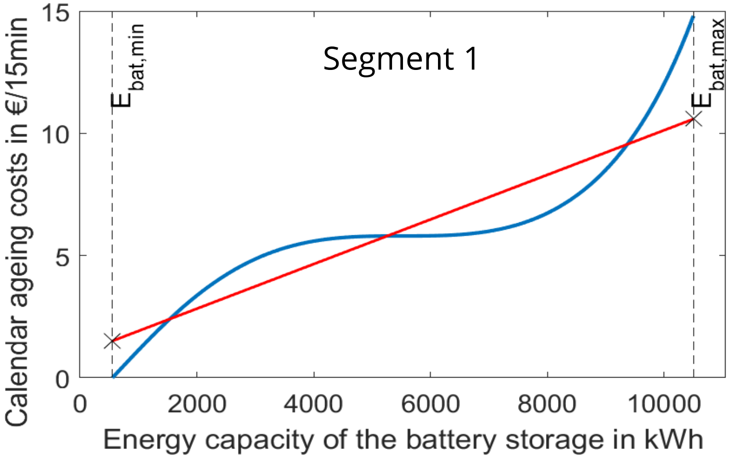
cyclical and calendar Degradation costs Battery [16] [17]

static and dynamic Penalty costs electrolyzer [18]
Penalty costs for curtailed PV power

$c_{DAM/IDM}$	Price signals from Day-Ahead auction/Intraday market
$P_{DAM/IDM}$	Grid power for spot market
c_{H2}	Hydrogen price (**5€/kg**)
m_{H2}	Produced hydrogen in kg
s1,s2,s3	Segment from picewise linearization
$c_{cyc,s123}$, a_{cal}, b_{cal}	Degradation costs in corresponding segment
$p_{ch/dch,s123}$	Charging/discharging power of battery in corresponding segment
E_{bat}	Stored energy in battery storage
BP	Set of allowed operating points for PtG plant
bp	Specific operating point of PtG plant

u_{bp}	current decision variable
$c_{stat,bp}$	Linearly increasing penalty costs for operating points of PtG plant
$c_{elz,dyn}$	Penalty cost for dynamic stress on PtG plant
$P_{elz,dyn,(max)}$	(maximum) Power difference between two timesteps
$c_{PVcurtail}$	Cost for curtailed PV generation
$P_{PVcurtail}$	Curtailed PV generation





3. Energy management concept

Objective functions of the upper energy management level (MPC + MILP)

2nd optimization level with 4x24 time steps (15 min resolution):

$$\min \sum_{t=1}^{T} \Delta t \cdot \Bigg\{ -c_{IDM}(t) \cdot P_{IDM}(t) - c_{H_2} \cdot m_{H_2}(t) + \sum_{s1=1}^{3} c_{cyc,s1} \cdot p_{ch,s1}(t) + \sum_{s2=1}^{3} c_{cyc,s2} \cdot p_{dch,s2}(t) + (a_{cal} \cdot E_{bat}(t) + b_{cal}) + \sum_{bp=1}^{BP\setminus\{0\}} c_{stat,bp} \cdot u_{bp}(t) + c_{elz,dyn} \cdot \frac{P_{elz,dyn}(t)}{P_{elz,dyn,max}} + c_{PVcurtail} \cdot P_{PVcurtail}(t) \Bigg\}$$

- Profit/costs from electricity volumes on the spot market
- Profit from hydrogen production
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- static and dynamic Penalty costs electrolyzer [18]
- Penalty costs for curtailed PV power

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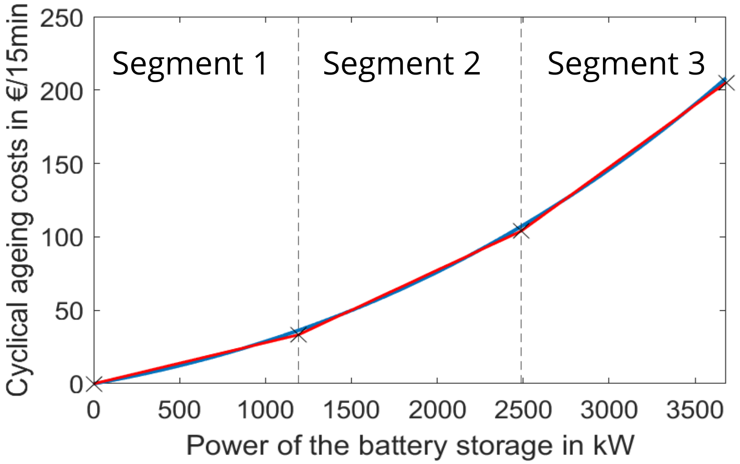
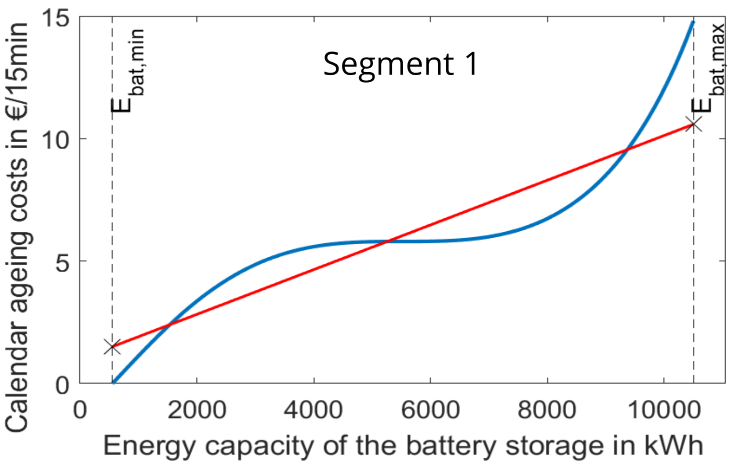
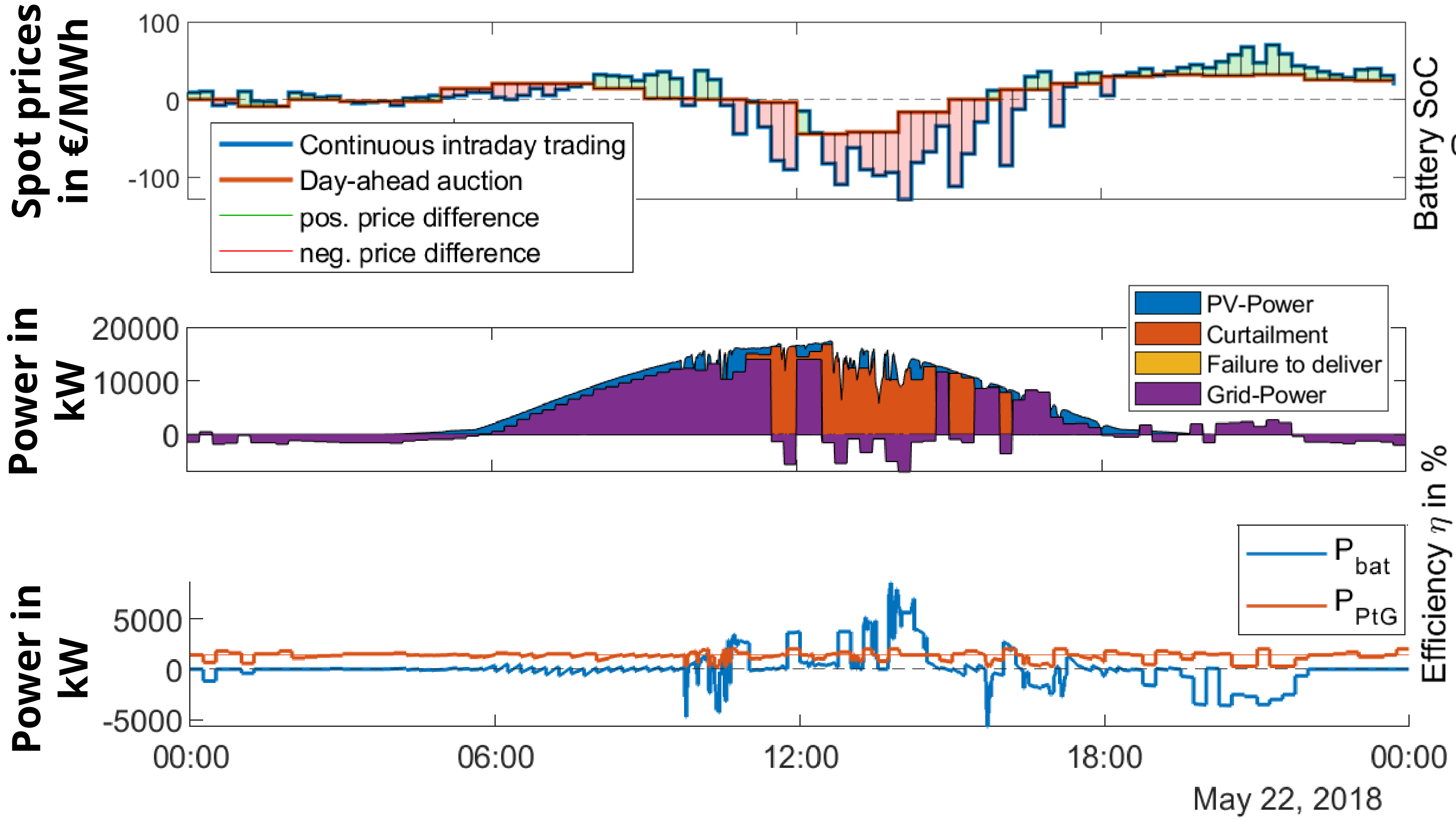


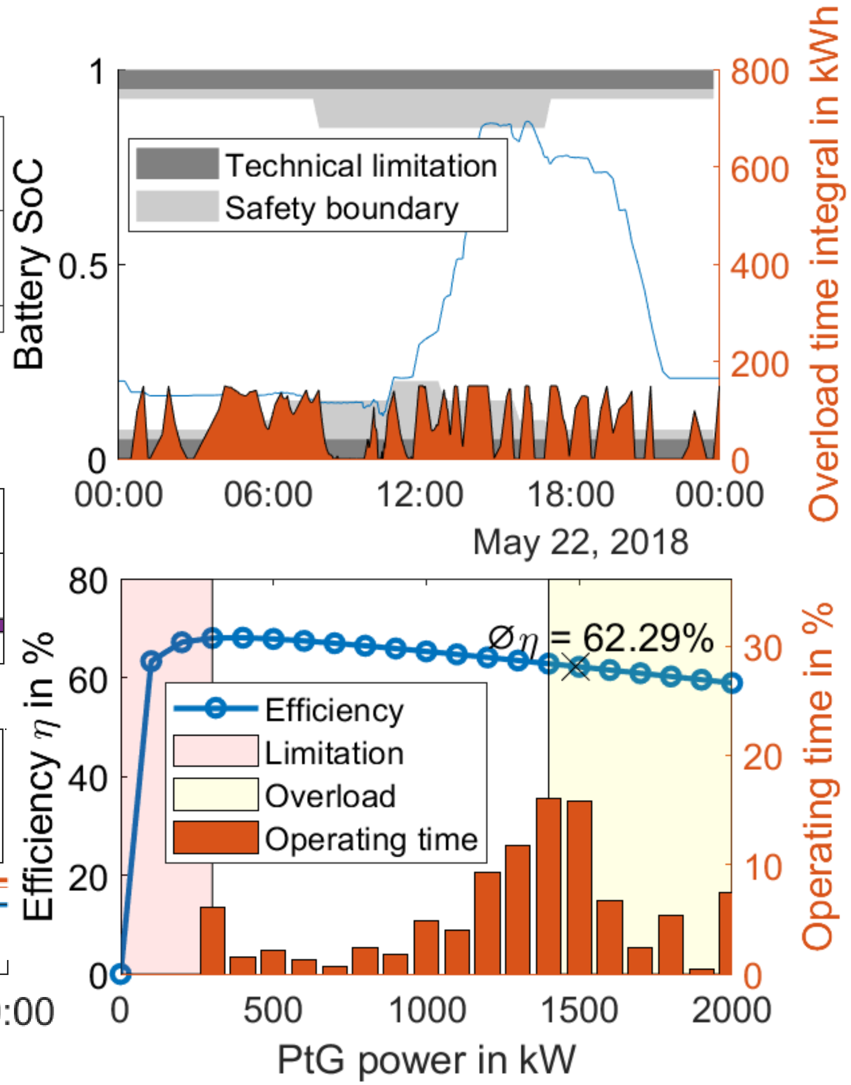


4. Simulation-based investigations

Demonstration of Energy Management Concept

Summer day with negative spot prices (only continuous Intraday market)





4. Simulation-based investigations

General conditions for the performance comparisons

Peak-Shaving + Capacity Firming + Hydrogen Production

- Constant electricity prices that favor hydrogen production
- Grid capacity limited to 60 % of the nominal capacity of the PV park (12 MW)
- No requirements for grid power
- PV curtailment as a performance criterion

+ Intraday market

- Time-variable electricity price on the spot markets
- Grid capacity limited to 70 % of the nominal capacity of the PV park (14 MW)
- 0.1 MW minimum bid quantity of grid power through market participation
- PV curtailment as a profitability criterion

4. Simulation-based investigations

Comparison of energy management concepts (end of life simulation)

	Performance criteria (averaged over years)	Peak-Shaving + Capacity Firming + Hydrogen production		+ Intraday market	
		Rule-based + Strategy [19] [20]	**MPC&MILP +** Strategy	MPC&MILP **+ Strategy**	MPC&MILP **+ Strategy&Filter**
	Lifetime (Battery)	7 years 245 days	8 years 231 days	9 years 357 days	10 years 168 days
	Profit	993 568 €	1 174 695 €	1 488 972 €	1 476 608 €
Grid	Failure to provide	-	-	0.2113 %	0.1715 %
Grid	Rel. PV curtailment	1.9156 %	0.6082 %	1.079 %	1.079 %
Grid	Energy feed to grid	17775 MWh	17860 MWh	19207 MWh	19231 MWh
Grid	Energy from grid	-269 MWh	-454 MWh	-6406 MWh	-6784 MWh
LSBS	Energy throughput	6359 MWh	5870 MWh	5413 MWh	5023 MWh
LSBS	Rel. Energy losses	3.83 %	3.77 %	4.31 %	4.1 %
PtG plant	Energy throughput	6634 MWh	7101 MWh	11220 MWh	11189 MWh
PtG plant	Capacity factor	63.76 %	67.02 %	107.33 %	101.22 %
PtG plant	⌀ Efficiency	59.28 %	58.11 %	56.44 %	55.73 %
PtG plant	H_2-production	104 215 kg	110 062 kg	169 192 kg	168 107 kg
PtG plant	Dynamic reduction	98.38 %	96.98 %	88.74 %	82.94 %

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5. Summary and Outlook

Summary

- Discussion of suitable multi-use applications in hybrid configuration
- Conceptual advantages through hybridization approach

→ 3-stage hierarchical model predictive management concept

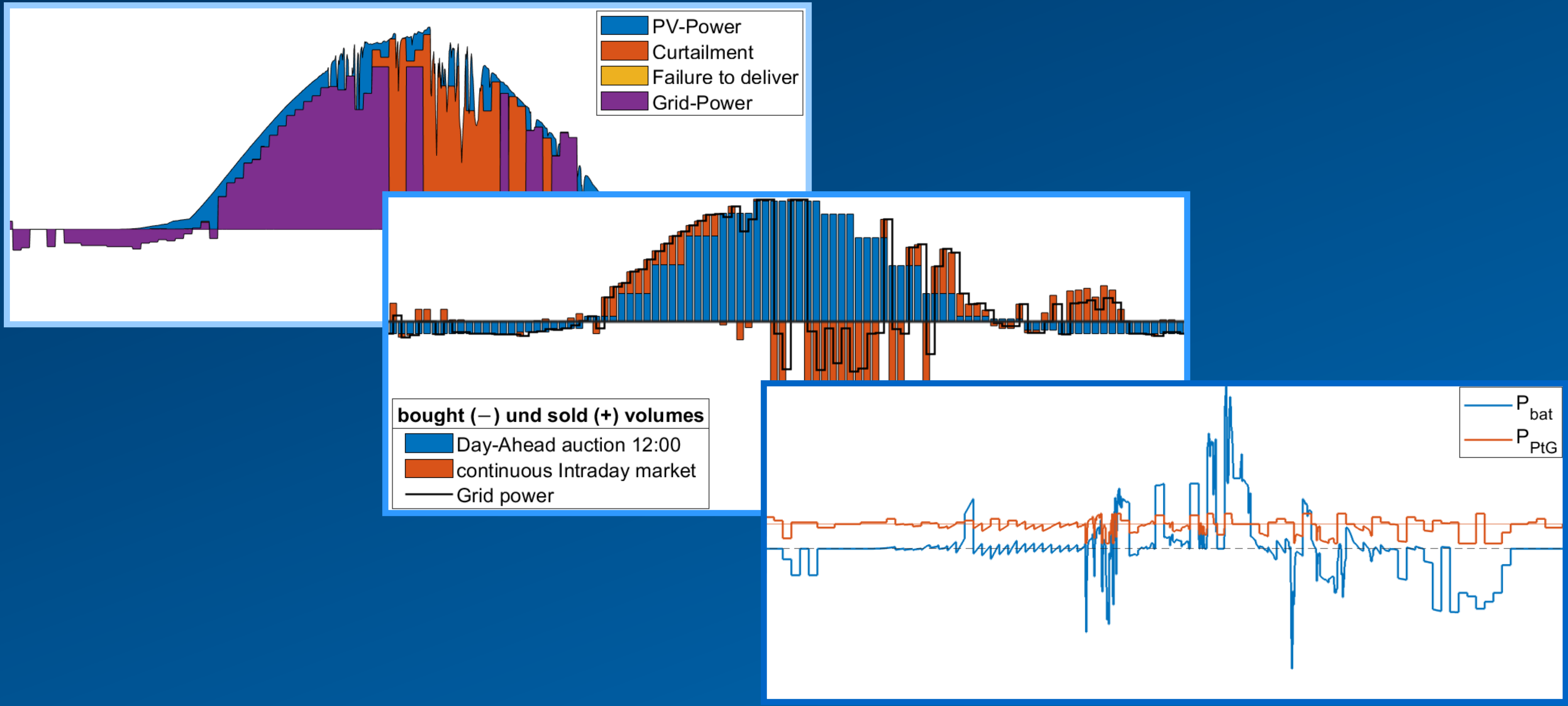
- Results of the simulation-based investigations:

  → Technical and economic advantages in the performance comparison (higher annual profits, lower PV curtailment, longer lifetime)

  → Low-pass filter in lower-level energy management reduces the dynamic stress on the battery by using more flexible operation of the PtG plant → longer lifetime

Outlook

- **Quantifiable ageing model for PEM electrolyzer** → Stress and lifetime assessment
- Improving the long-term PV forecast → Use of extended weather data (DWD)
- Investigate coupling between the two optimization levels to improve trading potential between market levels → (stochastic) price forecast for spot markets
- Investigation/expansion of the lower management level
- Investigate further multi-use cases and generation profiles → Application in the real world



Thank you for your attention!

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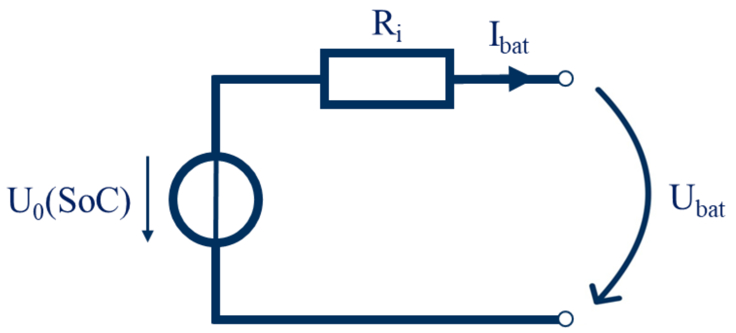
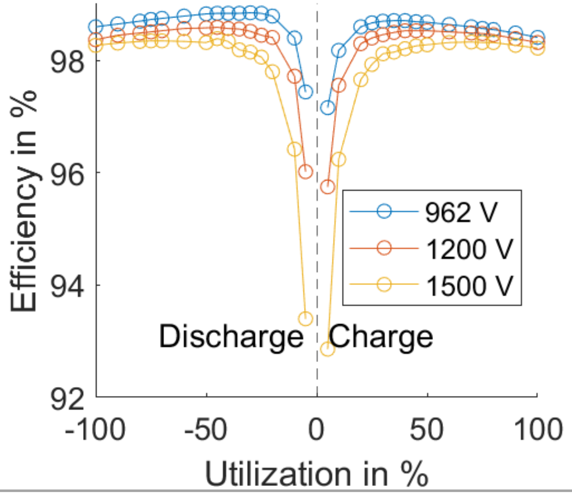
2. System description and Multi-use applications

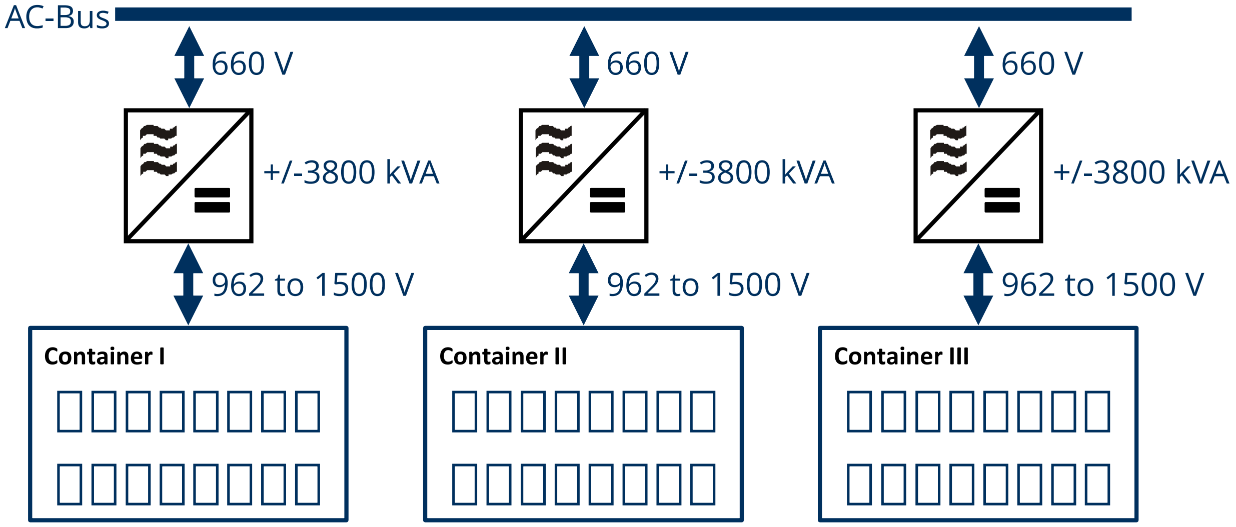
Component modeling - Large battery storage - 1/2

- 3 identical battery containers from the manufacturer Narada, each connected in parallel to the AC bus with a central inverter
- System structure :
  - 16 Racks per container (16P)
  - 15 Modules per rack (15S)
  - 48 Cells per module (24S2P)
- Central inverters are modeled with two-dimensional linear interpolation
- Rint model for battery is modeled with state-of-charge-dependent open-circuit voltage U_{OCV}(SoC) and internal resistance R_i

Operating parameters	Cell model Narada FE105A	Container 1S16P Racks
Cell type	LFP	LFP
Energy capacity	0,3 kWh	3680 kWh
Charge quantity	105 Ah	3200 Ah
Nominal voltage	3,2 V	1152 V
min. voltage	2,5 V	1008 V
max. voltage	3,65 V	1192 V
max. C-Rate	1	1
Cyclic lifetime	3500 Zyklen	
Weight	2,3 kg	30.640 kg
Dimensions	130 x 36 x 240 mm	20ft ISO HC Container







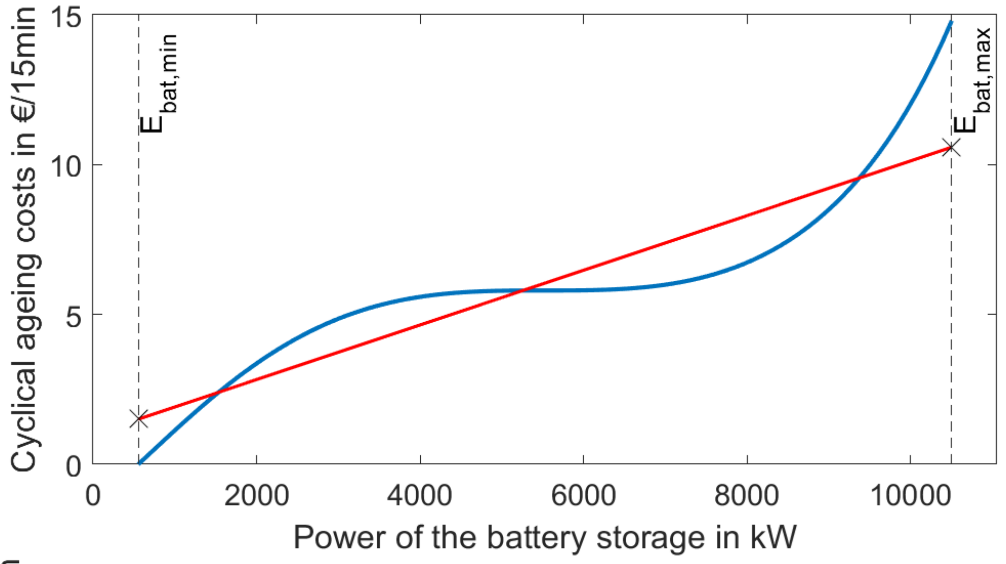
2. System description and Multi-use applications

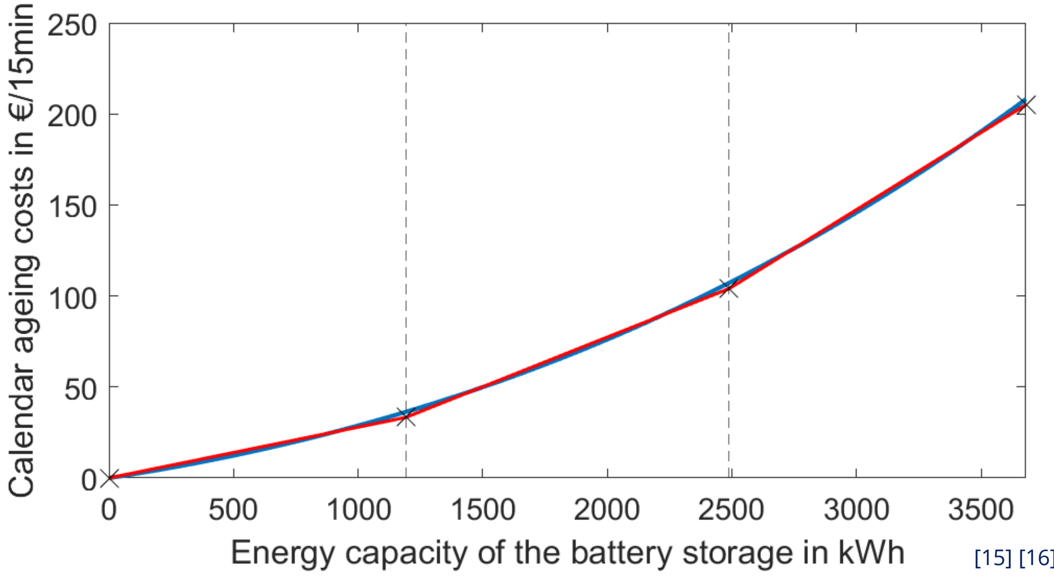
Component modeling - Large battery storage - 2/2

- The semi-empirical ageing models by **Naumann (2018) (2020)**
  - Calendar ageing dependent on charge state duration and temperature
  - Cyclic ageing dependent on C-rate, depth of discharge, equivalent number of full cycles and temperature
- Simplifications and assumptions:
  - Constant temperature T_{ref} = 25 °C
  - End of life (EoL) at 80 % of remaining capacity
  - Capacity loss with EoL is made up of equal parts cyclical and calendar capacity loss
  - Cyclical ageing with a scaling factor of 0.55
  - Constant depth of discharge for cyclical ageing of 0.5
  - Charging and discharging currents are considered equivalent to charging and discharging power

→ Calendar ageing depends on the **state of charge**

→ Cyclical ageing depends on **charging and discharging power**



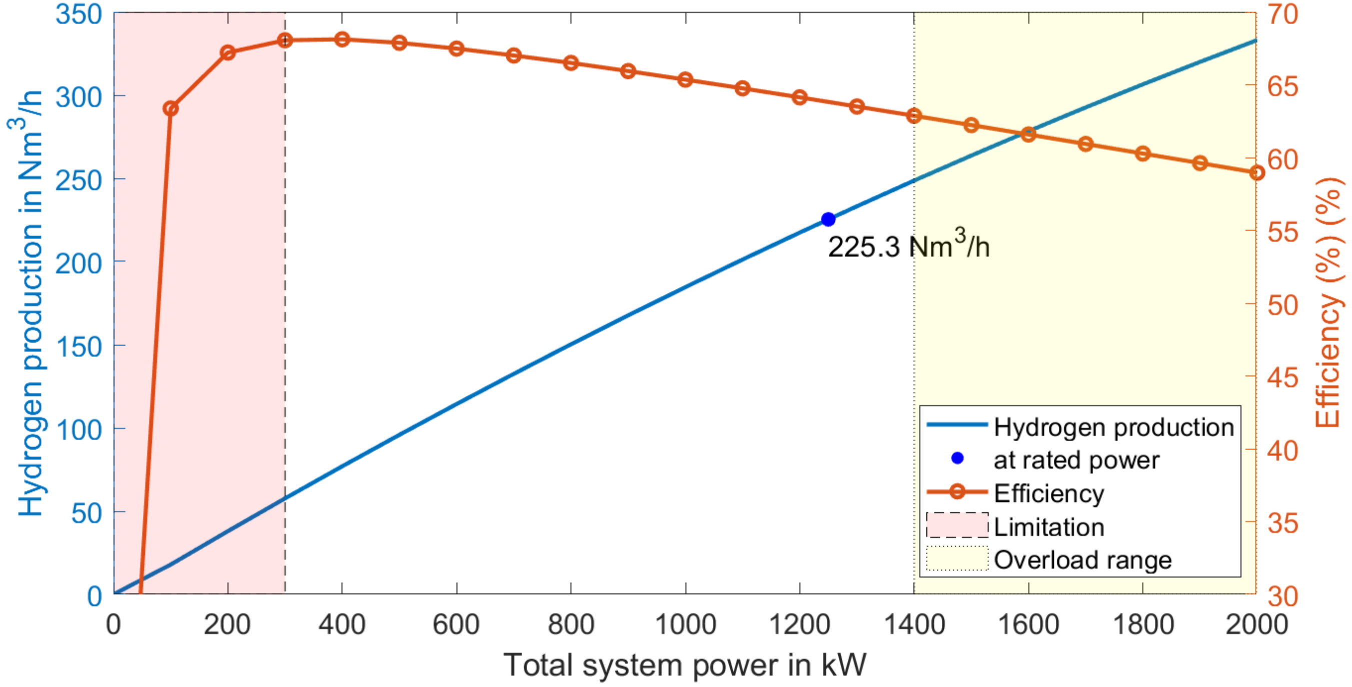


[15] [16]

2. System description and Multi-use applications

Component modeling - Power-to-gas plant - 1/2

- PEM electrolyzer from Siemens from the Silyzer 200 series (2015)
- Characteristics (conversion, overload and start-up behavior) of the overall system were derived and scaled from measurement data of the power-to-gas system of Energiepark Mainz from **Kopp (2018)**



Operating parameters	Value	
Electrolysis type	PEM	
Rated stack power (overload)	1250 kW (2000 kW)	
Dimensions	6,3m x 3,1m x 3,0m	
Start-up time	< 10 s	
Dynamics	125 kW/s (10% of the rated power)	
Operating temperature	60-70 °C	
Output pressure	up to 35 bar	
H_2-production (at rated power)	20 kg/h	225 Nm³/h
Stack lifetime	80.000 h	
Weight	17 t	
Fresh water consumption	1,5 l/Nm³ H_2 or 340 l/h	

- Start-up losses that occur when starting production from idle and are proportional to the start-up power (1,2 kg_{H2} when starting at 1250 kW)
- Constant no-load losses of 9 kW for heaters, transformers, measurement and control technology, lighting and information hub

[13]

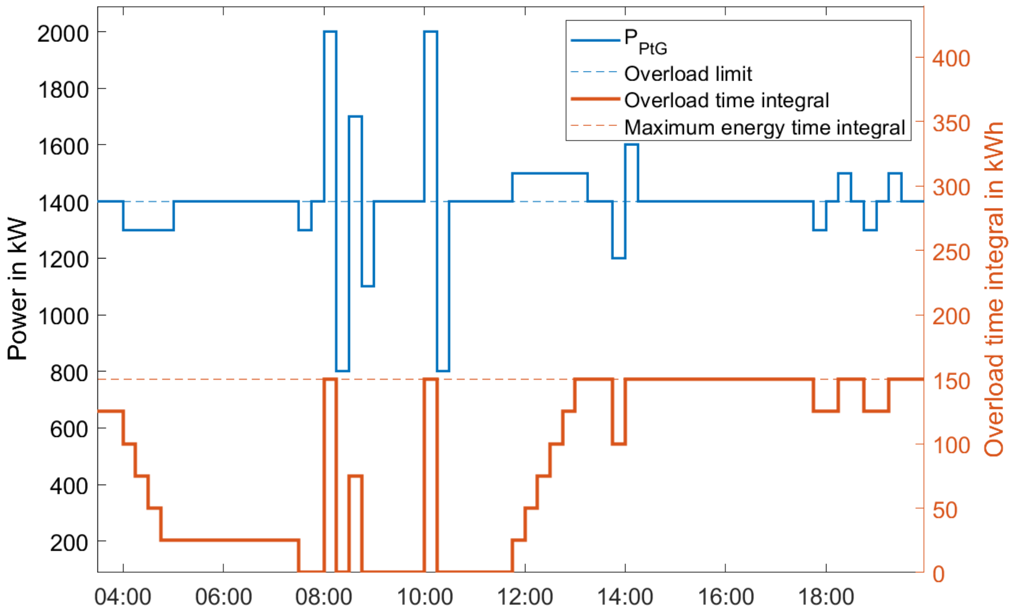
2. System description and Multi-use applications

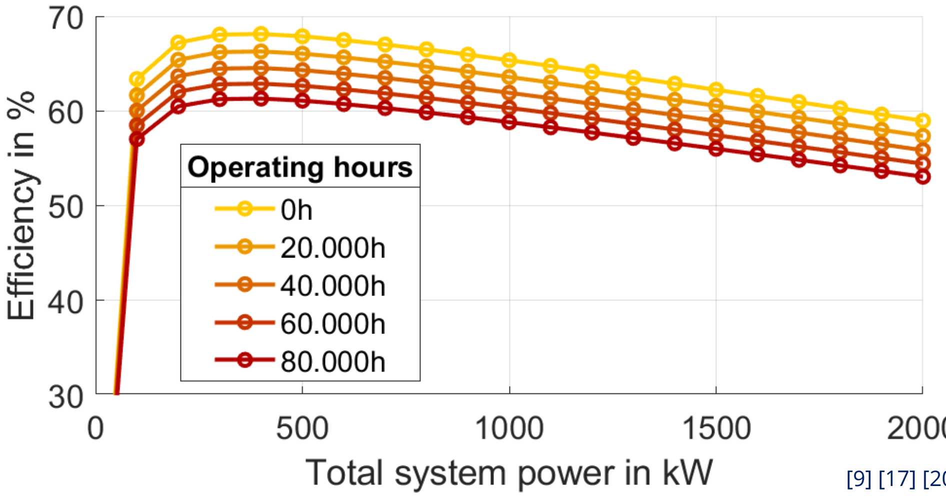
Component modeling - Power-to-gas plant - 2/2

- Overload behavior is determined via an energy integral above the overload power limit and can absorb a maximum of 150 kWh

Load range	Power limit	Description
Rated load	1300 kW	Power can be provided without restriction
Overload limit	1400 kW	From this limit, the integral formation of the overload behavior is active
Maximum power	2000 kW	Maximum power that can be provided as maximum overload durationcan be provided for 15 min
Regeneration	800 kW	Power at which a new overload approval can be issued after 15 minutes

- For the ageing behavior, a combination of static stress based on **García-Triviño (2014)** is used, which is linearly dependent on the degree of utilization of the system and a dynamic component depending on the power difference
- Based on **Fouda-Onana (2016)**, the degradation is modeled using an decreasing efficiency that depends on the number of operating hours

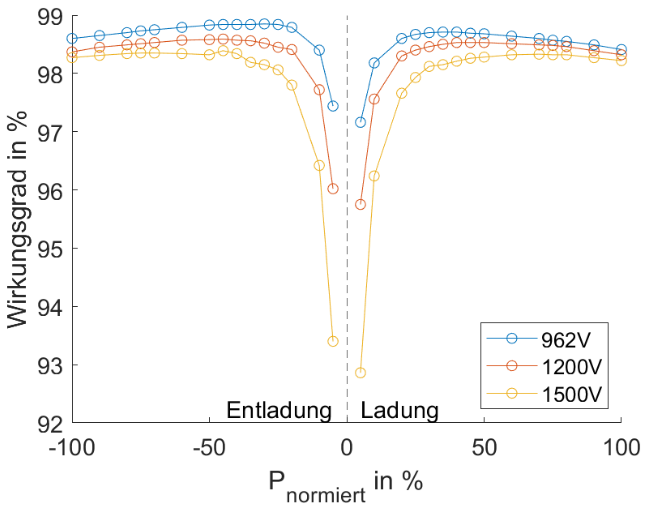




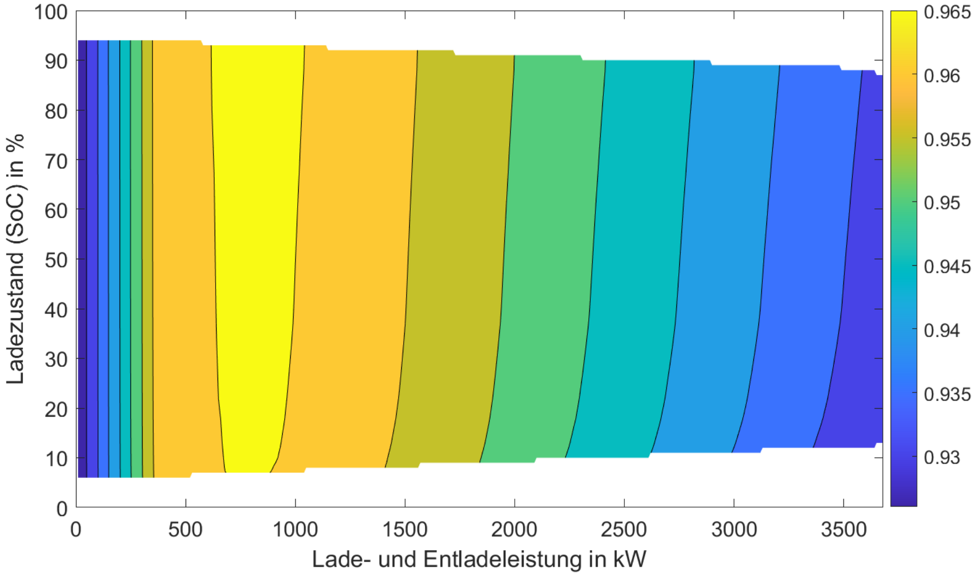
[9] [17] [20]

2. System description and Multi-use applications

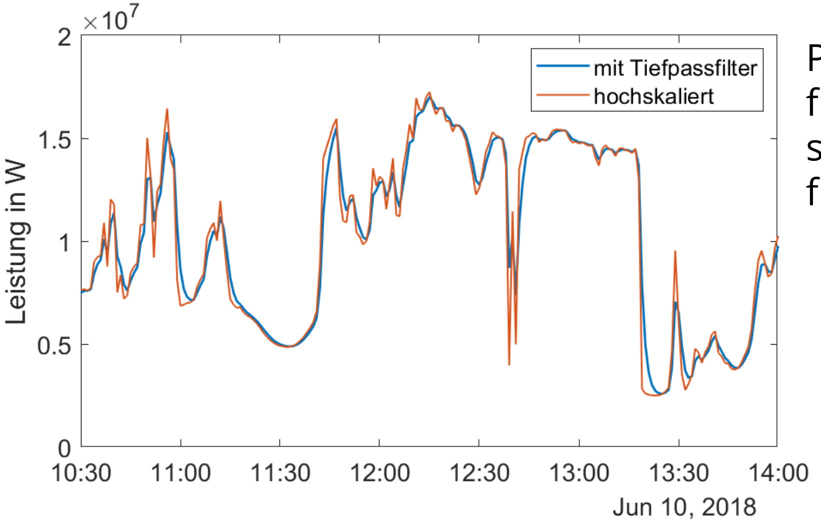
Modeling the components



Inverters with lookup tables and linear interpolation

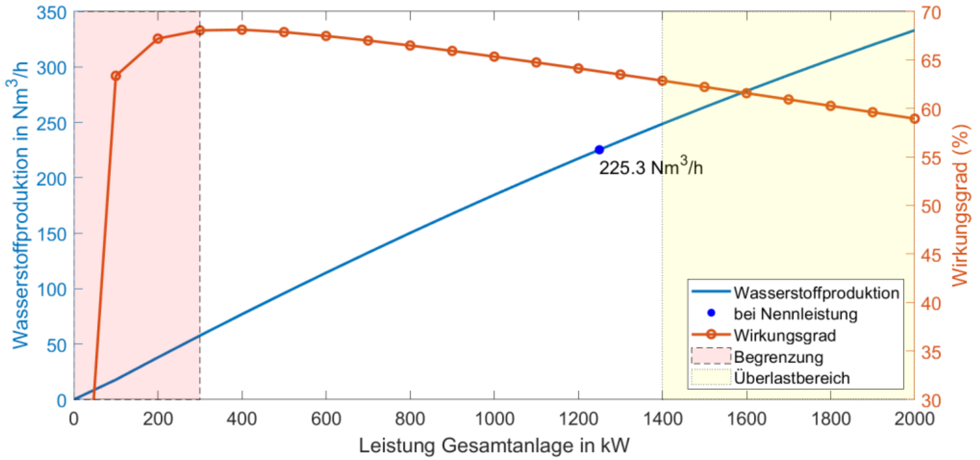


Battery with equivalent circuit model with measured OCV characteristic curve



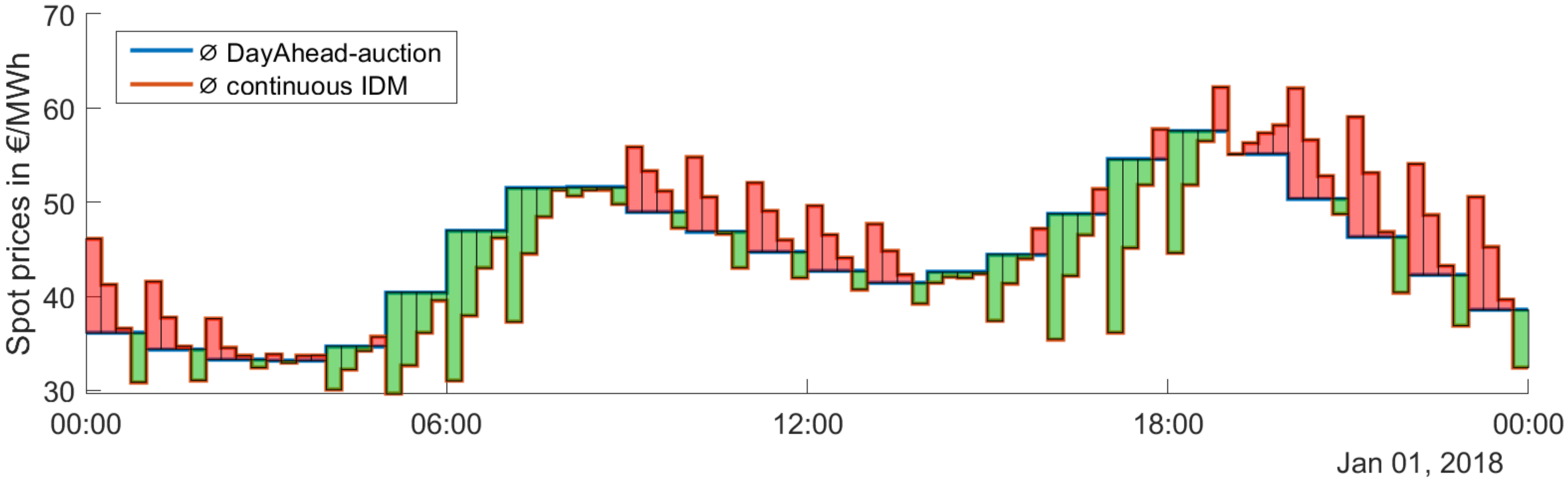
PV park with radiation data from the Lindenberg weather station and spatial smoothing filter

Power-to-gas plant with scaled measurement data from Energiepark Mainz



2. System description and Multi-use applications

Profitable trading options between spot markets



	$Preis_{DAM} - Preis_{IDM} < 0$	$Preis_{DAM} - Preis_{IDM} > 0$
$E_{DAM} < 0$	Sell electricity volumes already purchased at a higher price	
$E_{DAM} > 0$		Buy back electricity volumes already sold at a lower price

2. System description and Multi-use applications

Changing role of Power-to-Gas

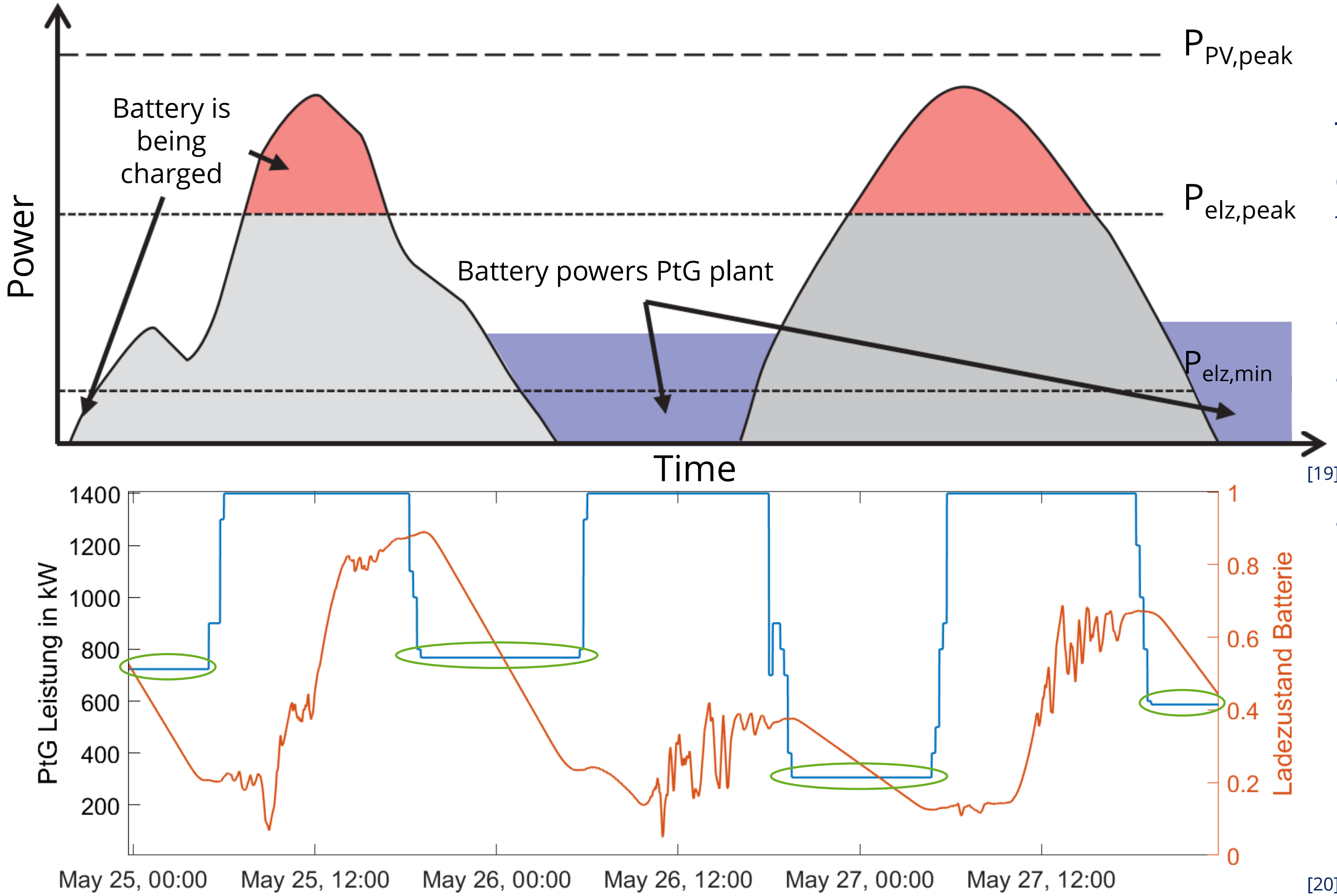
Today	In the future
• **Onsite** hydrogen production due to lack of infrastructure and decarbonization of price-inelastic industry • Close to consumer centers with a high number of full load hours to cover continuous hydrogen demand • Ramp up of Hydrogen economy	• **Offsite** hydrogen production in the vicinity of renewable electricity production • Provision of grid-supporting and market-oriented flexibility • Stabilization of the market value of renewable energies and reduction of grid congestion

Focus on continuous hydrogen production

Focus on providing many services, flexible hydrogen production one of them

4. Simulation-based investigations

Rule-based reference for performance comparison of upper management level



[19] [20]

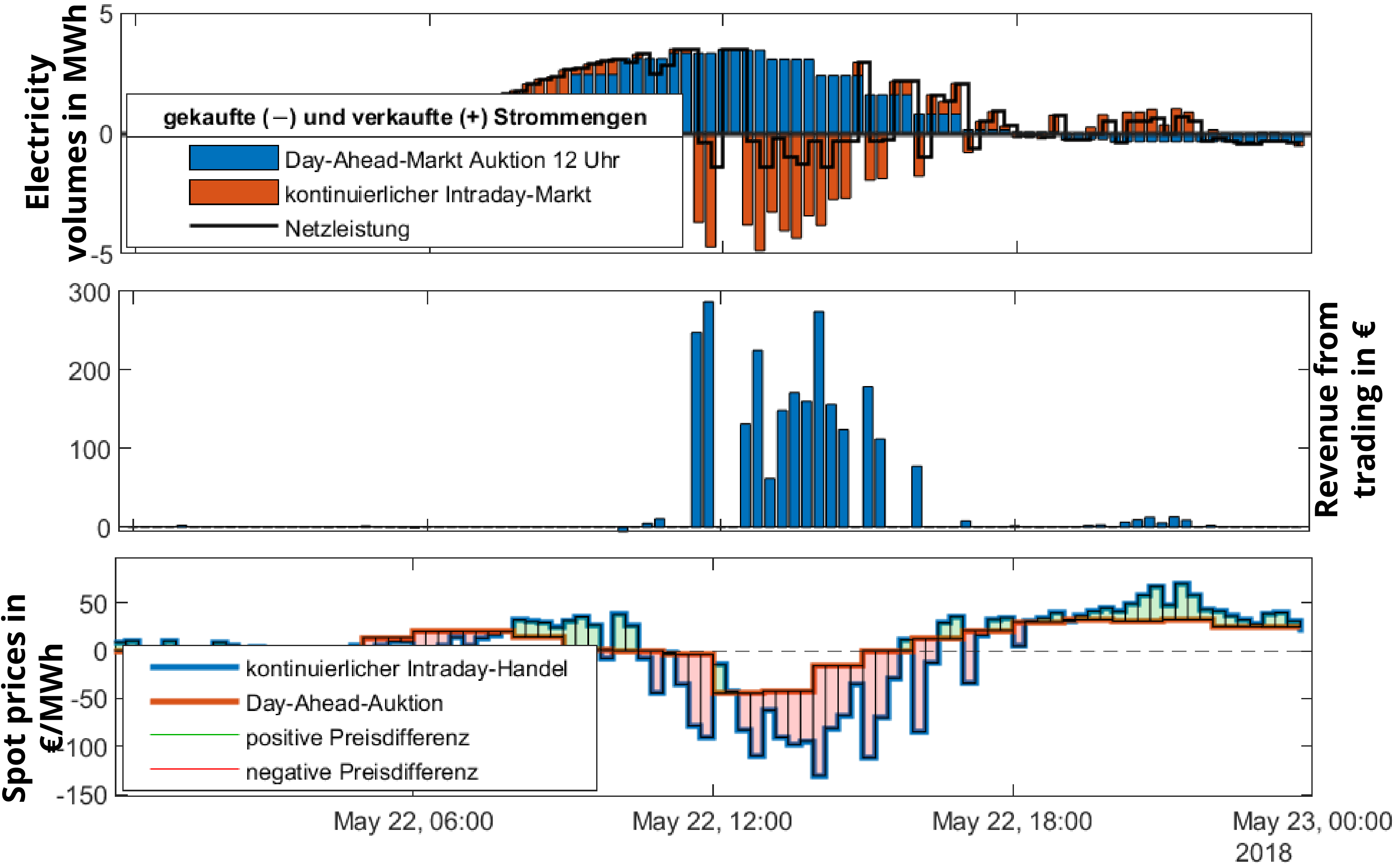
Upper management level - rule-based reference operation

The power of the electrolyzer either corresponds to the PV power or results from the current state of charge of the battery

- Battery takes over peak shaving
- Grid power results between maximum electrolysis power and maximum grid power
- A battery charge level-dependent electrolysis power is calculated daily at 6 p.m. → constant discharge during the night

4. Simulation-based Investigations

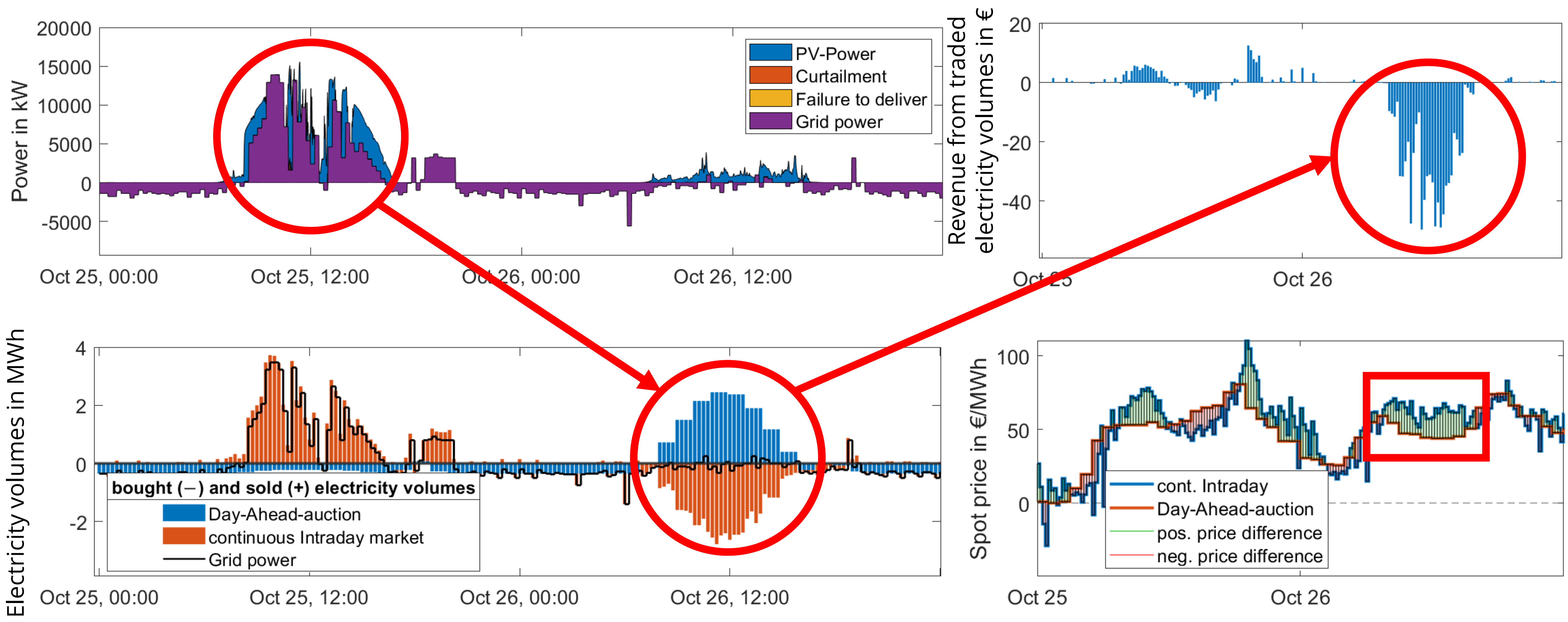
Reference application 2 (MPC+MILP) - summer day with negative spot prices



- Based on the historical PV output, the forecast PV output for the following day is marketed in the day-ahead auction at 12 noon (blue)
- The strongly negative electricity prices in continuous intraday trading between 11 a.m. and 4 p.m. lead to the economic curtailment of local PV generation
- Profitable grid procurement during this period
- Electricity volumes already sold in advance at the day-ahead auction can be bought back more cheaply in intraday trading, allowing revenues to be generated through arbitrage between the market levels

4. Simulation-based Investigations

Flawed Day-Ahead participation



4. Simulation-based investigations

Performance criteria	Formula	Description
Capacity factor Power-to-Gas plant	$K_{elz} = \frac{\sum m_{H_2}}{\sum m_{H_2}(BP_{overload})}$	The capacity factor indicates the degree of utilization of the power-to-gas plant and results from the ratio between the amount of hydrogen produced over the entire period and the amount of hydrogen if the plant had been operated continuously at the overload limit
Average Efficiency Power-to-Gas plant	$\eta_{elz} = \frac{\sum m_{H_2} \cdot e_{H_2}}{\int P_{elz}\, dt}$	The average efficiency results from the ratio between the energy content of the hydrogen produced (the calorific value H_S is used for this) and the energy throughput of the power-to-gas plant
Dynamic reduction Power-to-Gas plant	$DE = 1 - \frac{\int \left(\frac{P_{elz}}{dt}\right)^2 dt}{\int \left(\frac{P_{HESS}}{dt}\right)^2 dt}$	The dynamic load reduction indicates the extent to which the power-to-gas system follows the change in output of the hybrid energy storage system. The higher the value, the greater the dynamic load reduction