Battery Systems – Development of Modular Solutions and their Applications in Electric Cars and Stationary PV Systems

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Agenda

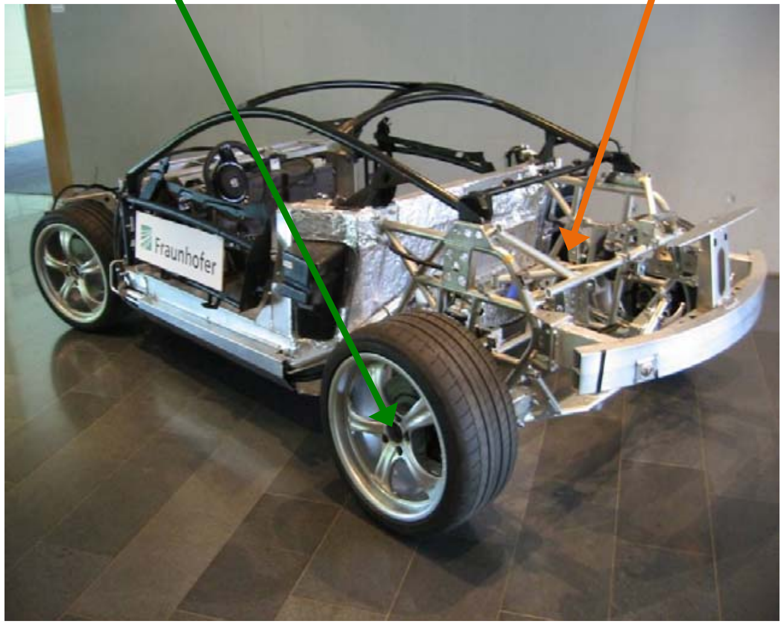
- Battery systems in electric mobility applications
  - Battery module and system design
  - Energy and battery management
- Grid integration
- Battery systems in stationary applications
- Conclusions

Battery systems for a passenger car and a public transport demonstrator

Wheel-hub motor
(including power electronics)

Battery 28 kWh

Battery 42 kWh



Fraunhofer E-Concept Car Typ 0
FrECC0 (Photo Fraunhofer IFAM)

AutoTram®
(Photo Fraunhofer IVI)

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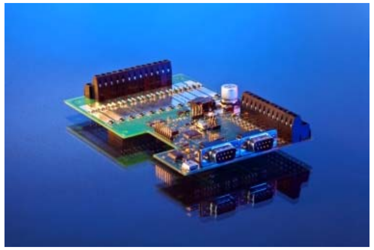
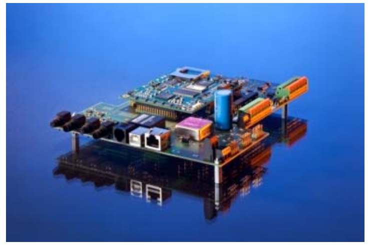
Battery system – Design

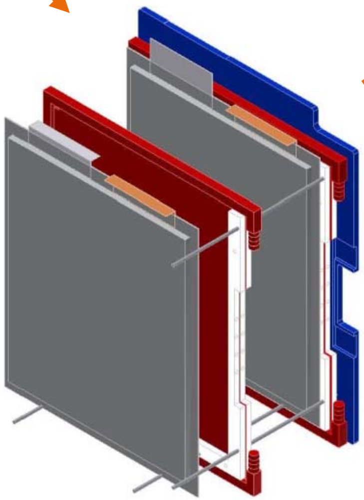
Cells → Modules → System

M-BMS



C-BMS (EMS)





231x179x289 mm

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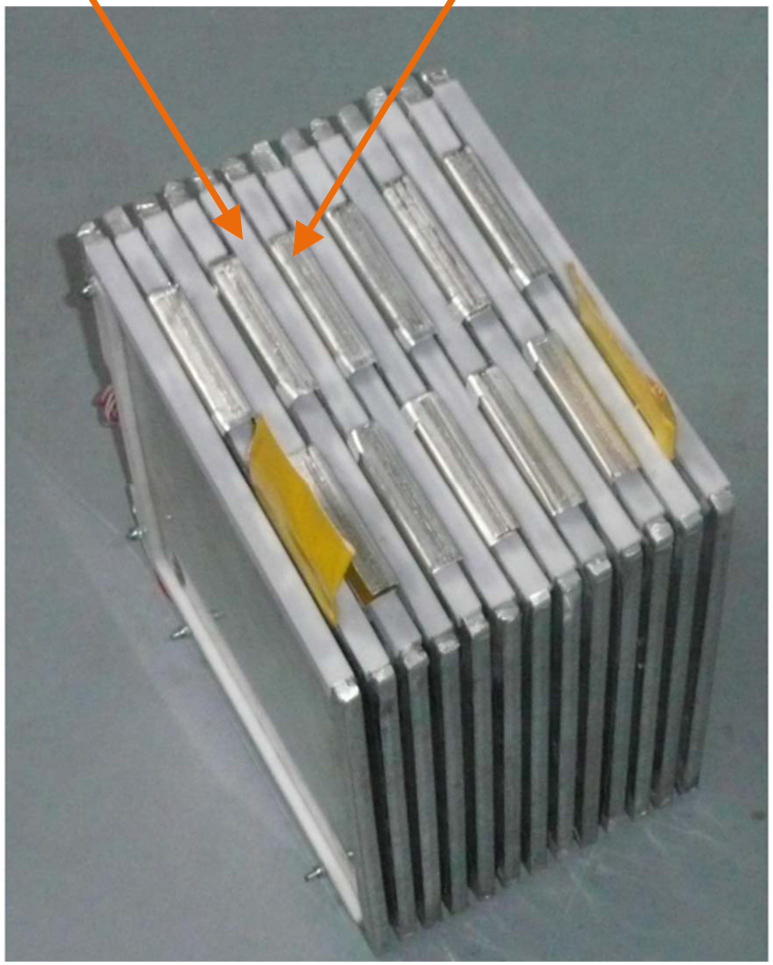
Battery module – Connection methods

- Cell interconnectors
  - ➢ Laser welding
  - ➢ Ultrasonic welding
  - ➢ Spot welding
  - ➢ Gluing
- Mechanical stability of cells
- Thermal connection of cells via cooling plates
- Module data:
  - ➢ 12 cells à 3.6 V and 40 Ah
  - ➢ Rated voltage 43.2 V
  - ➢ Rated current 105 A cont., 200 A peak
  - ➢ Maximum heat generation of 360 W at 40 °C cell temperature



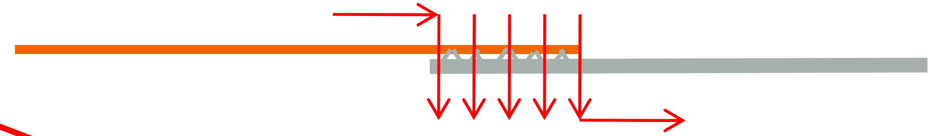
Interconnectors – measurements of resistance

Only one line of contact !!!

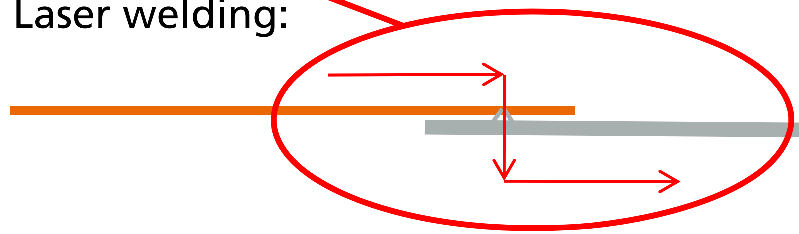
Potential for optimization

Type of connection	Result [mOhm]
Laser welding type 1	0.03629
Laser welding type 2	0.03558
Ultrasonic welding	0.02996
Gluing type 1	0.03693
Gluing type 2	0.03684

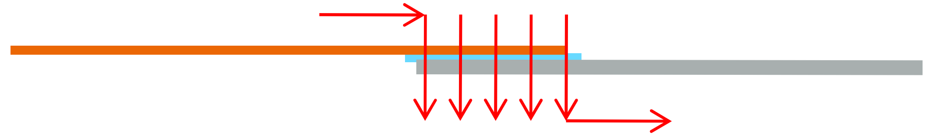
Ultrasonic welding:



Laser welding:



Gluing:



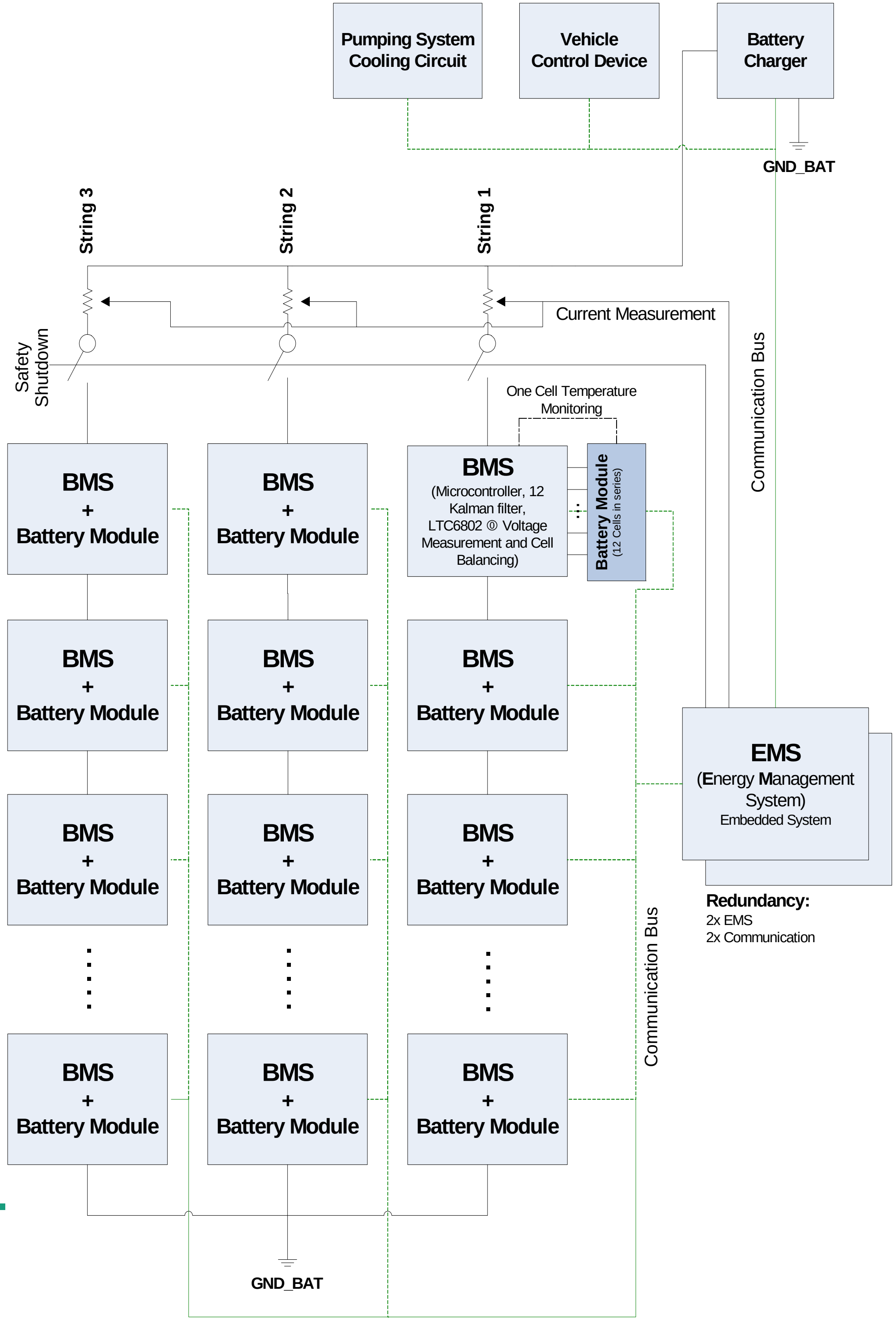
Energy and battery management – Architecture

- EMS (C-BMS): Energy management system as central control unit of battery pack
- BMS: Decentralized battery management system for each single battery module

→ Determination of state of charge and state of health for each single cell possible

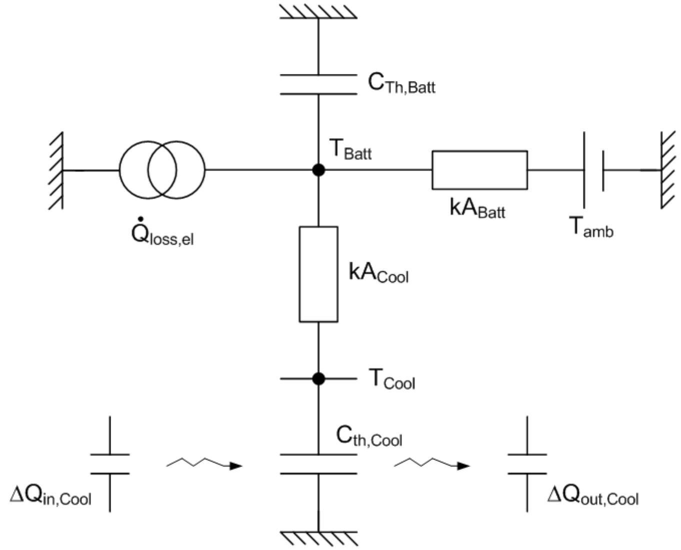
→ Slightly higher costs for processors, but some kind of frontend for data acquisition is necessary anyway

→ Additional energy demand for quick processor is negligible (decrease of efficiency of battery system approx. 0.05 %)

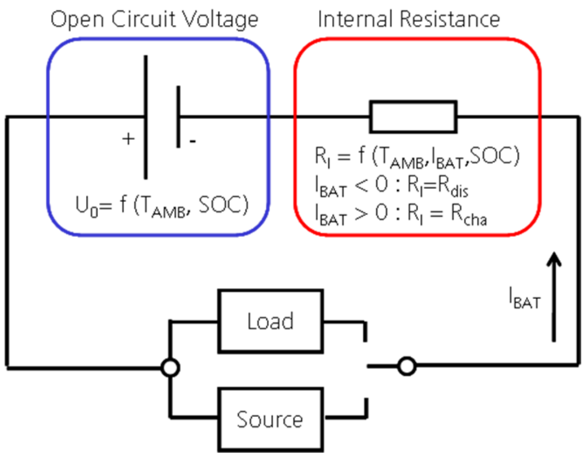


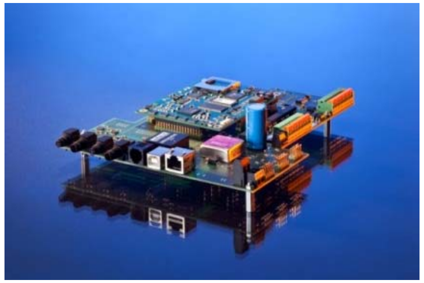
Model based battery management

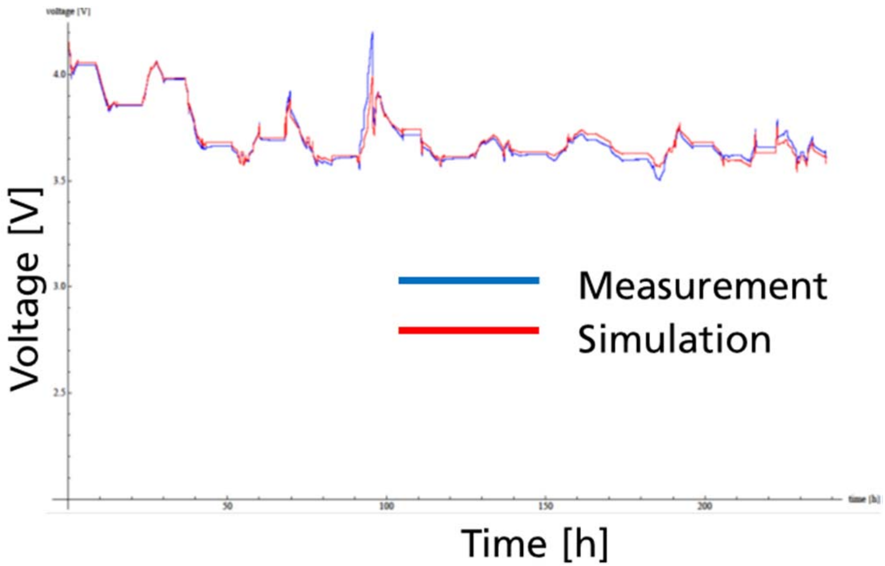
Thermal model

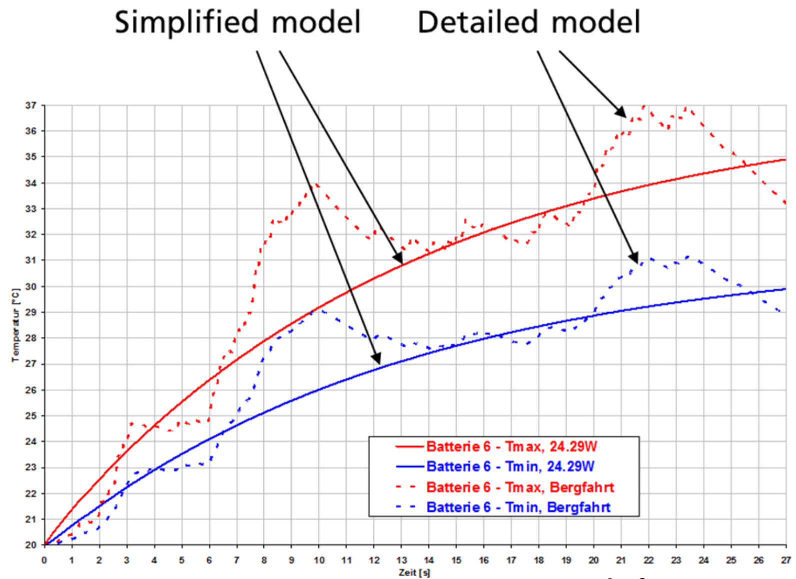


Electric model









Source: Fraunhofer IZM

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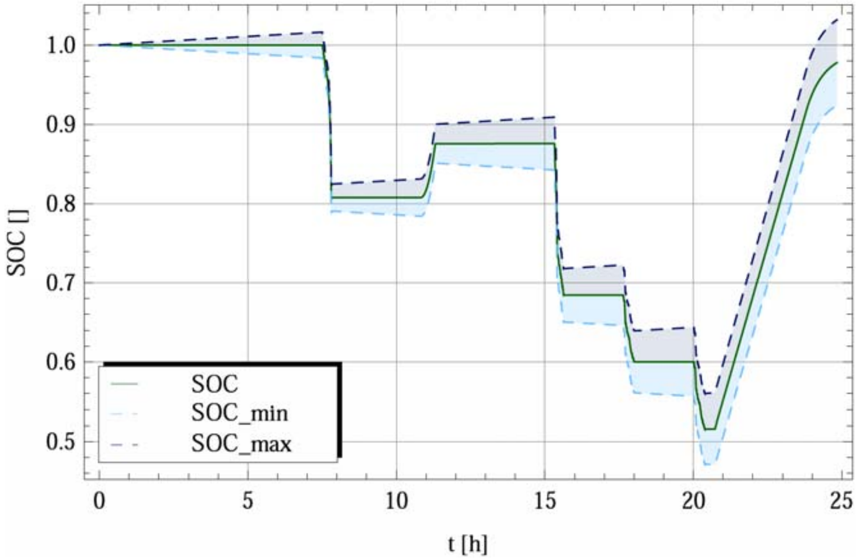
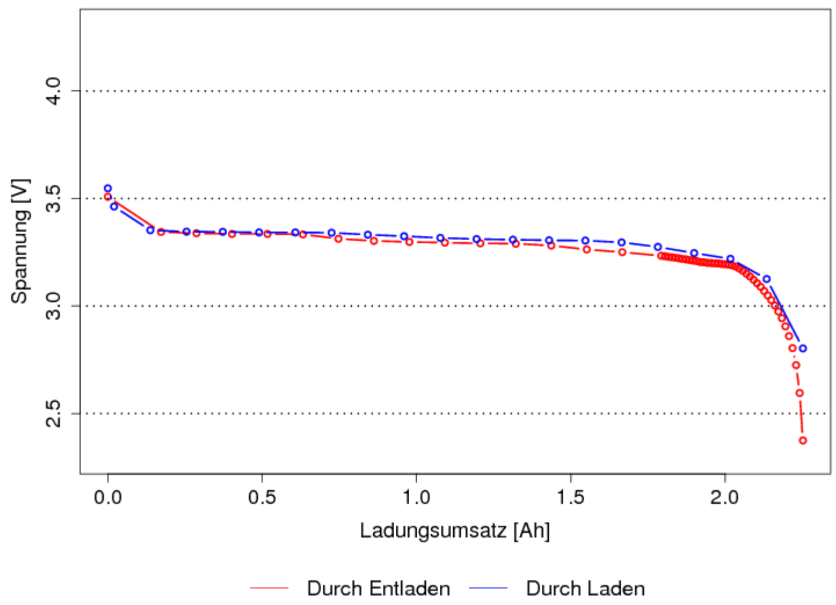
State of charge determination

- Ah counter: Integration of measurement errors
- Most conventional approaches:
  - ➢ Use of some kind of OCV correction in combination with Ah counting
    - → Recalibration of the SOC value via OCV consideration needs resting phases
- Flat OCV characteristic with hysteresis for $LiFePO_4$





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Parallel Bayesian filters

I, V, T

State of charge

Process model

$$SOC_{k+1} = SOC_k + \frac{(I_{batt} - I_{loss})\Delta t}{C_N \cdot SOH}$$

Measurement model

$$V_T = V_0 + R_i \cdot I_{Batt}$$

SOC →

← SOH

State of health

Process model

$$SOH_{k+1} = SOH_k$$

Measurement model

$$SOH = \frac{\Delta Q}{\Delta SOC * C_N}$$

SOC, SOH

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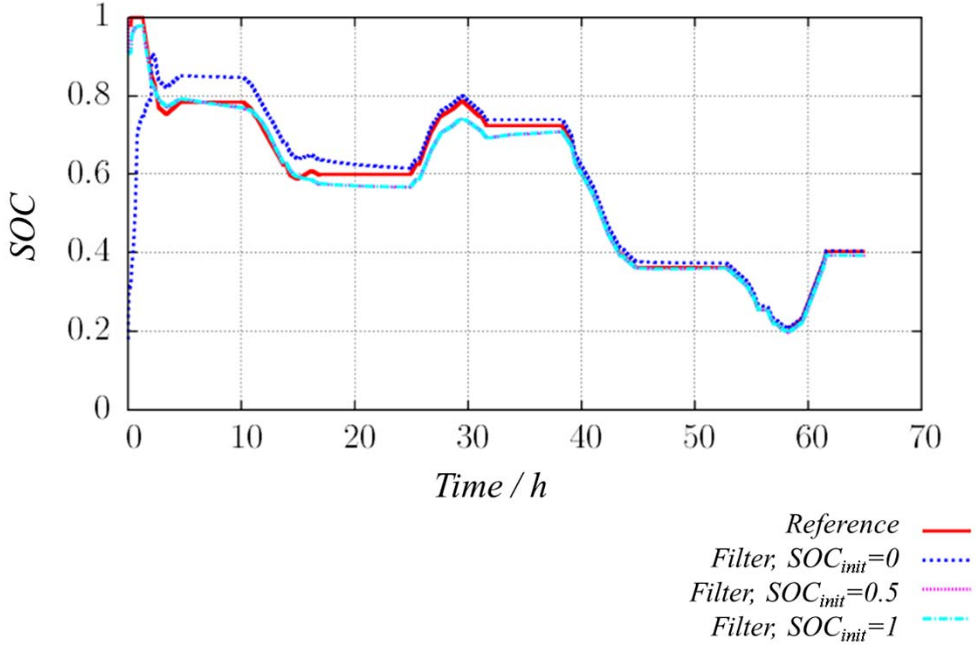
Bayesian filter for state determination – Examples

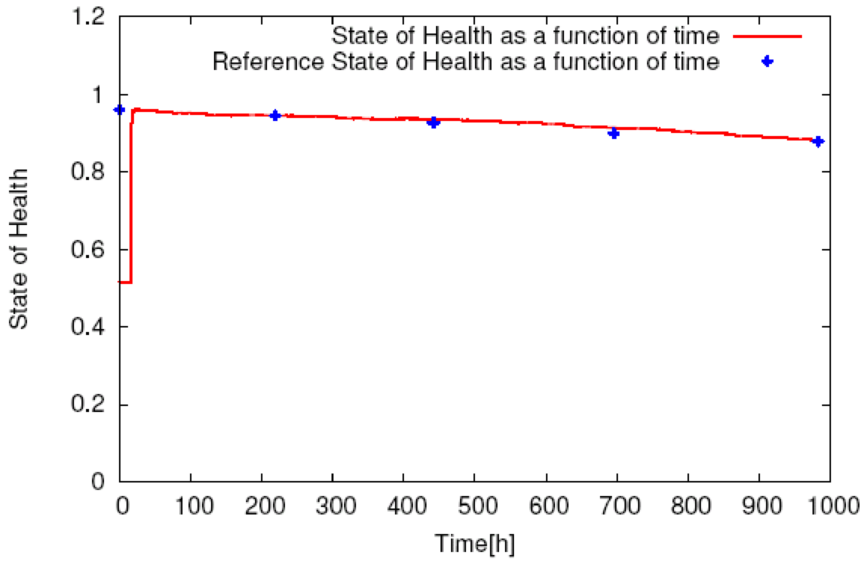
State of charge for $LiFePO_4$

Extended Kalman filter approach



State of health for NMC

Particle filter approach



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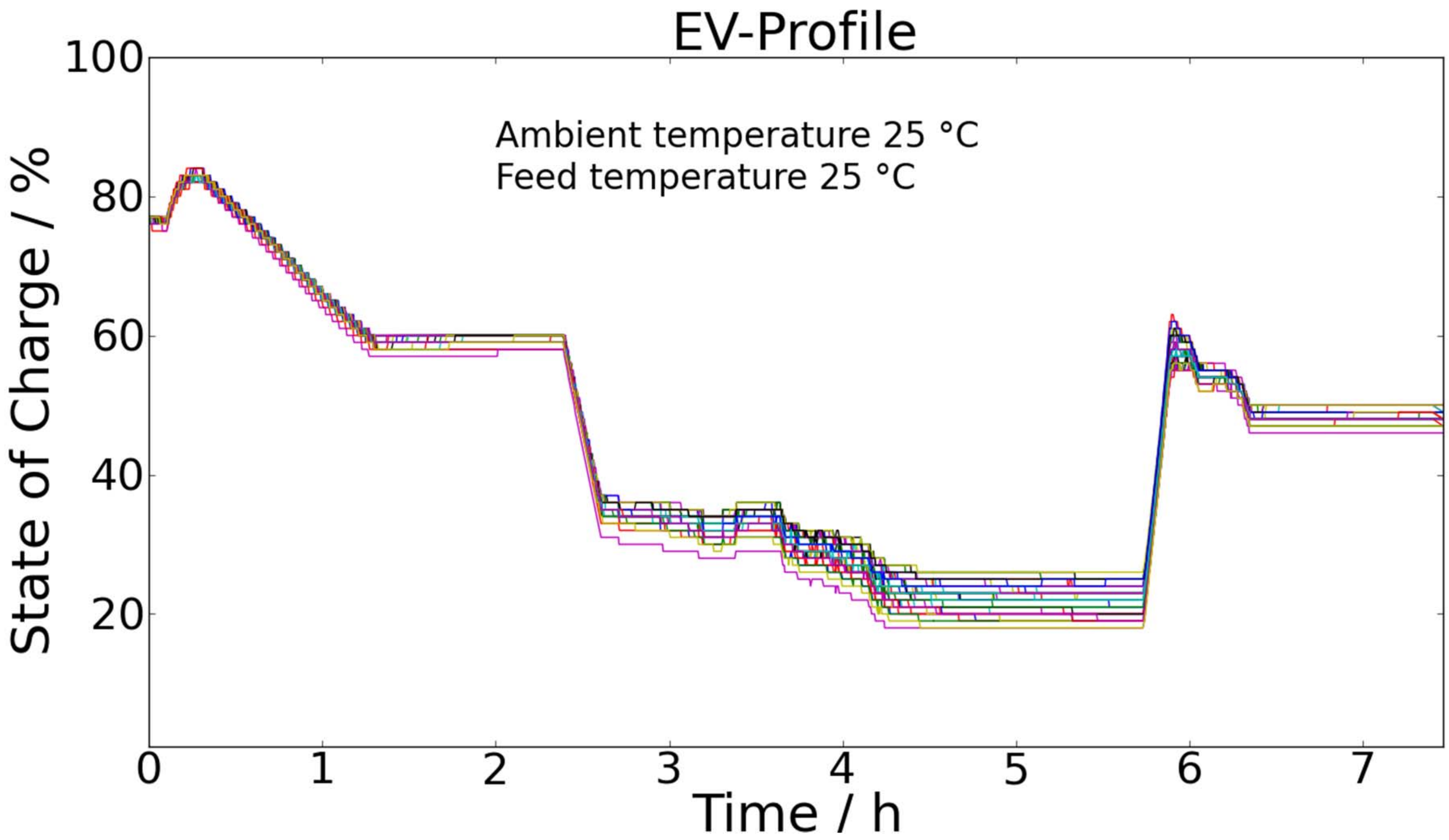
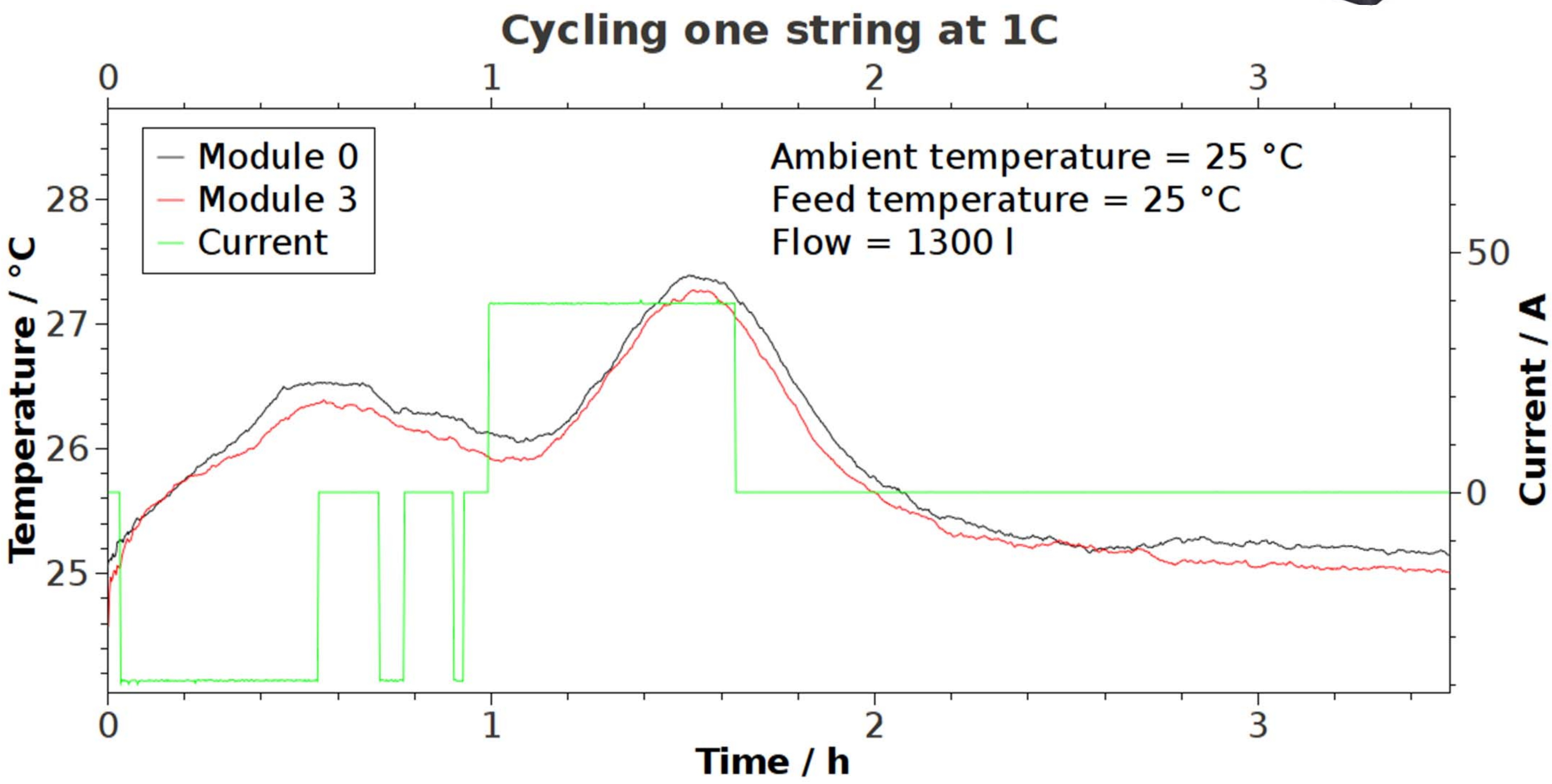
Battery pack testing

State of charge values of cells within one string



Battery pack testing

Temperature distribution within the pack



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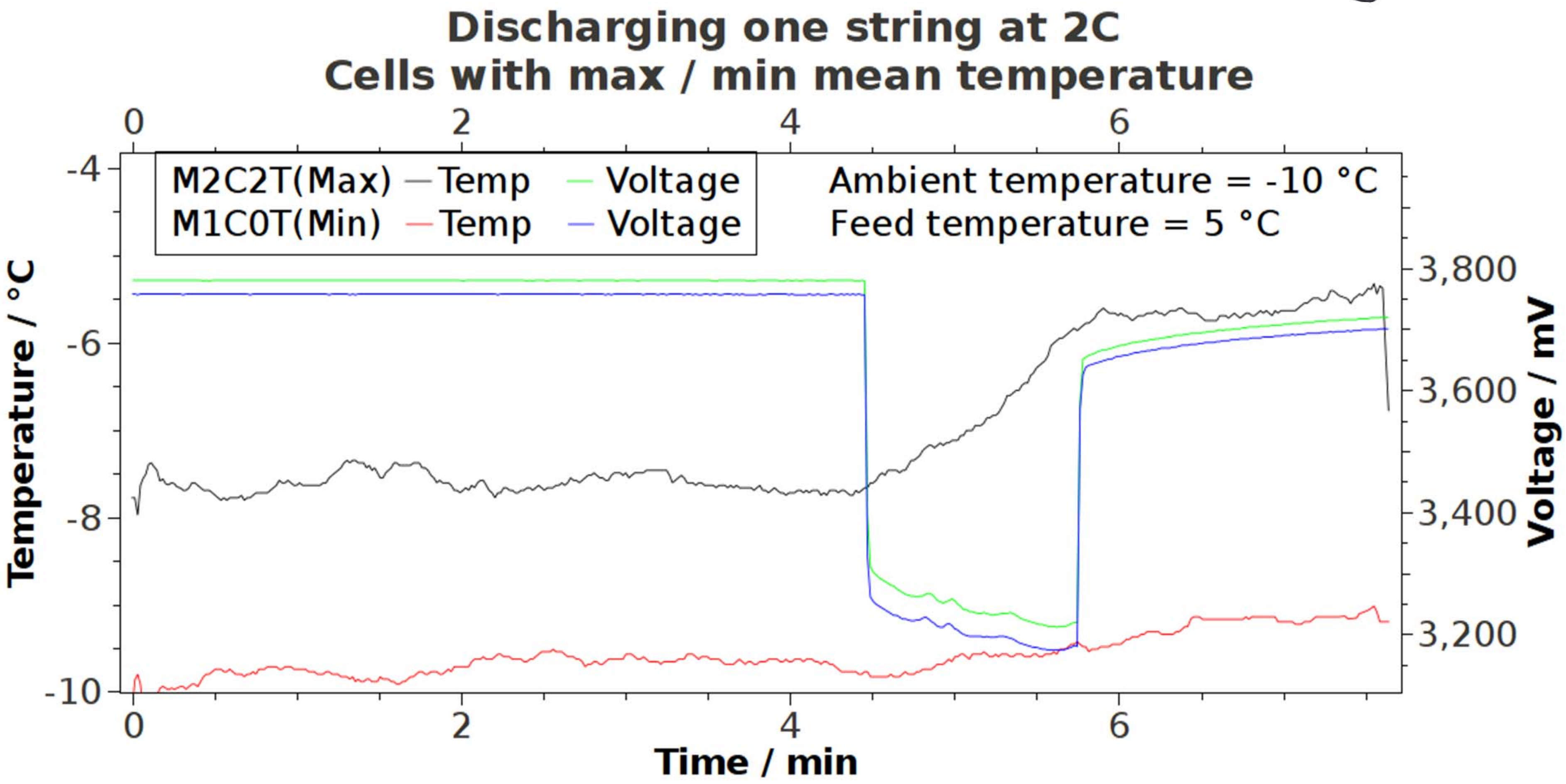
Battery pack testing
Temperature distribution within the pack



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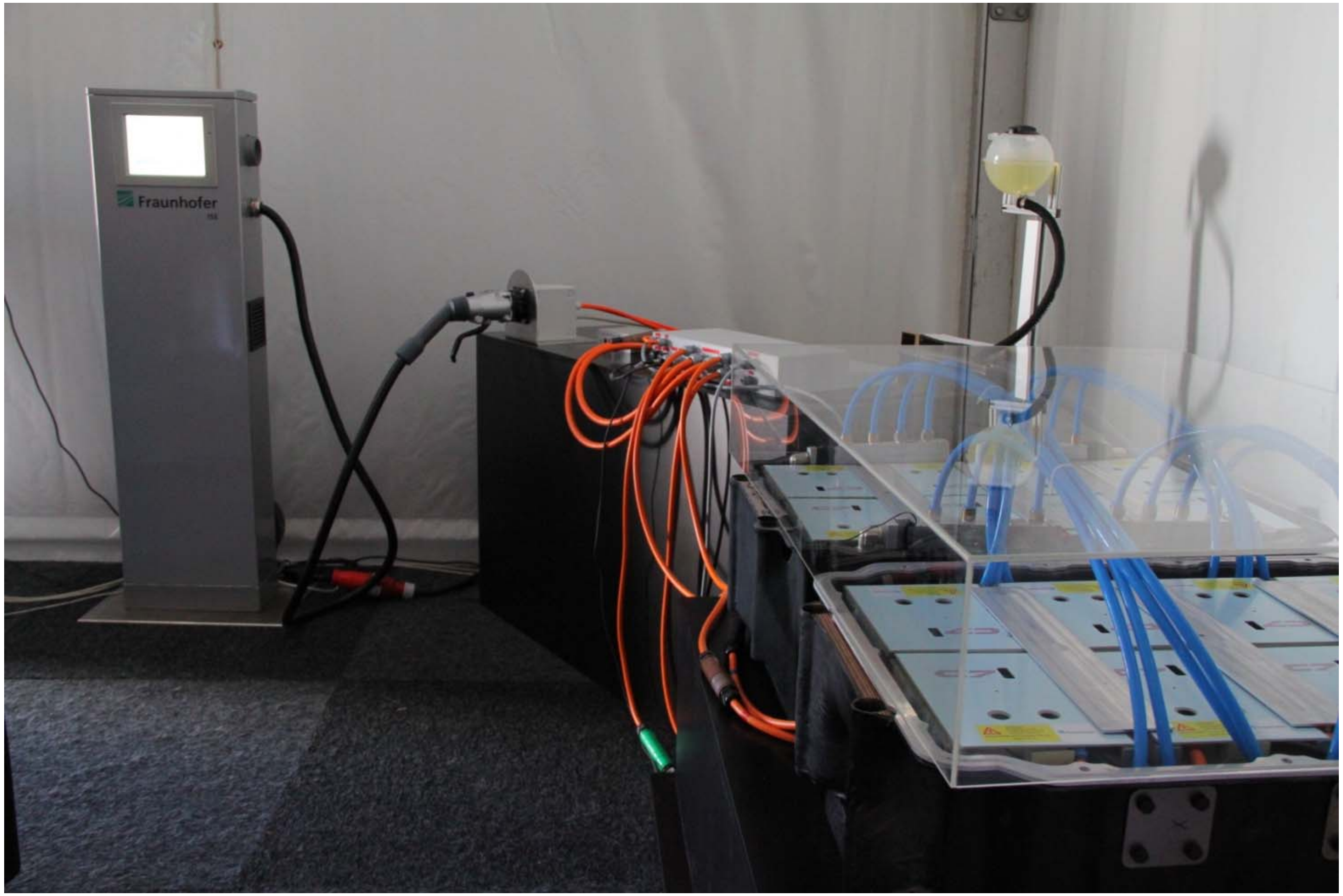
Demonstration of grid integration

- Charging station
  - 22 kW
  - Bidirectional
- Battery system
  - 28 kWh
- E-car manager



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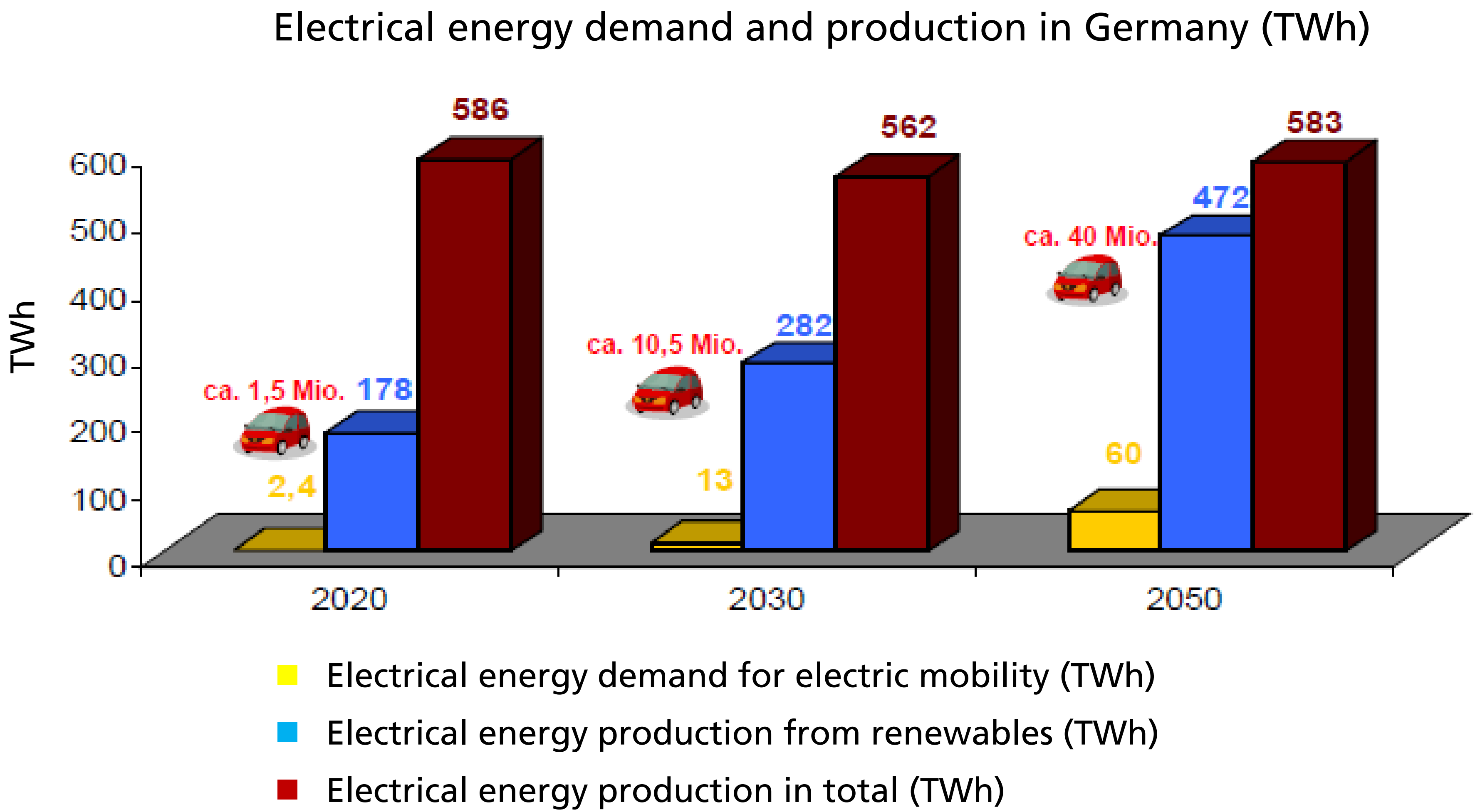
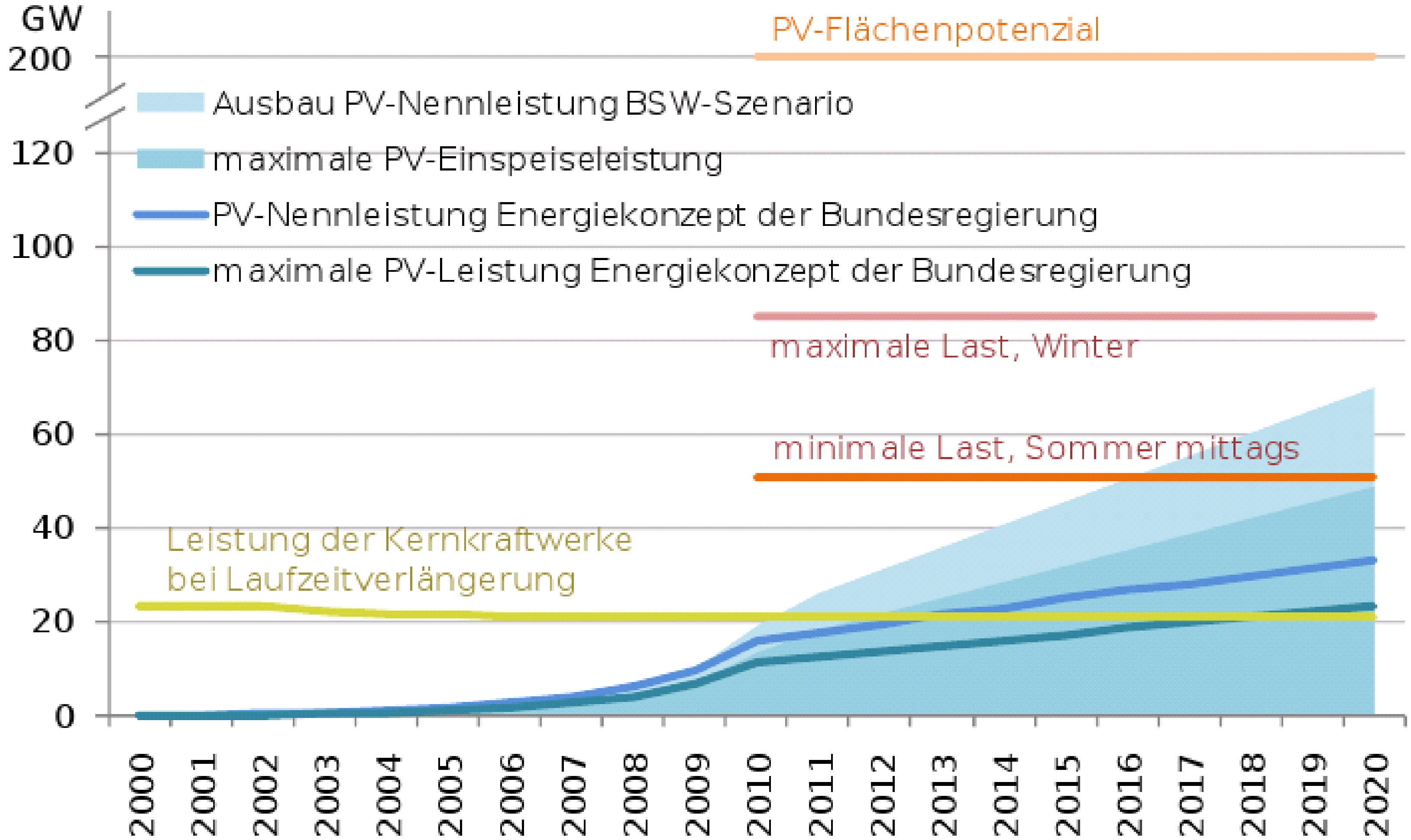
Electric mobility in the grid context



Source: M. Wohlfahrt-Mehrens, "Lithium Ionen Batterien: Stand und Perspektiven", VDI-Konferenz Elektrische Energiespeicher, Wiesbaden 2011

Stationary storages: Motivation in Germany
Significant *power fraction* of photovoltaic



Source:
Quaschning
Staffelsein 2011

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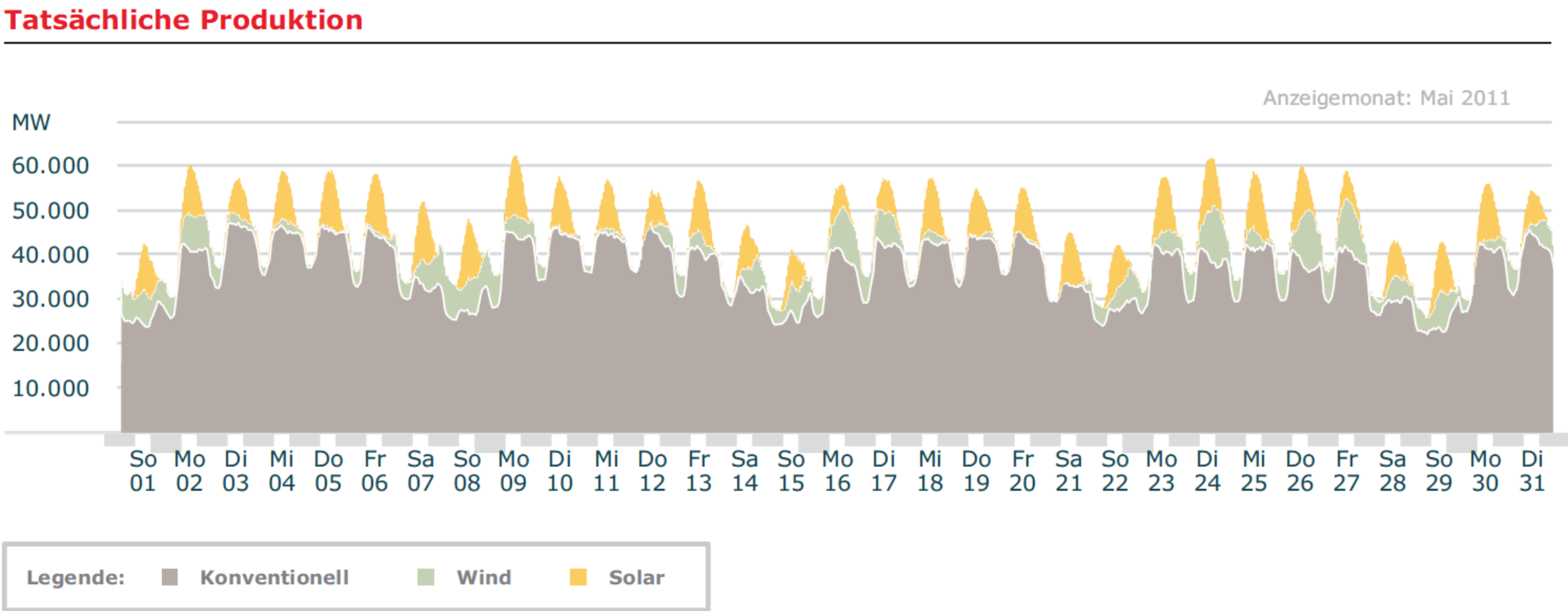
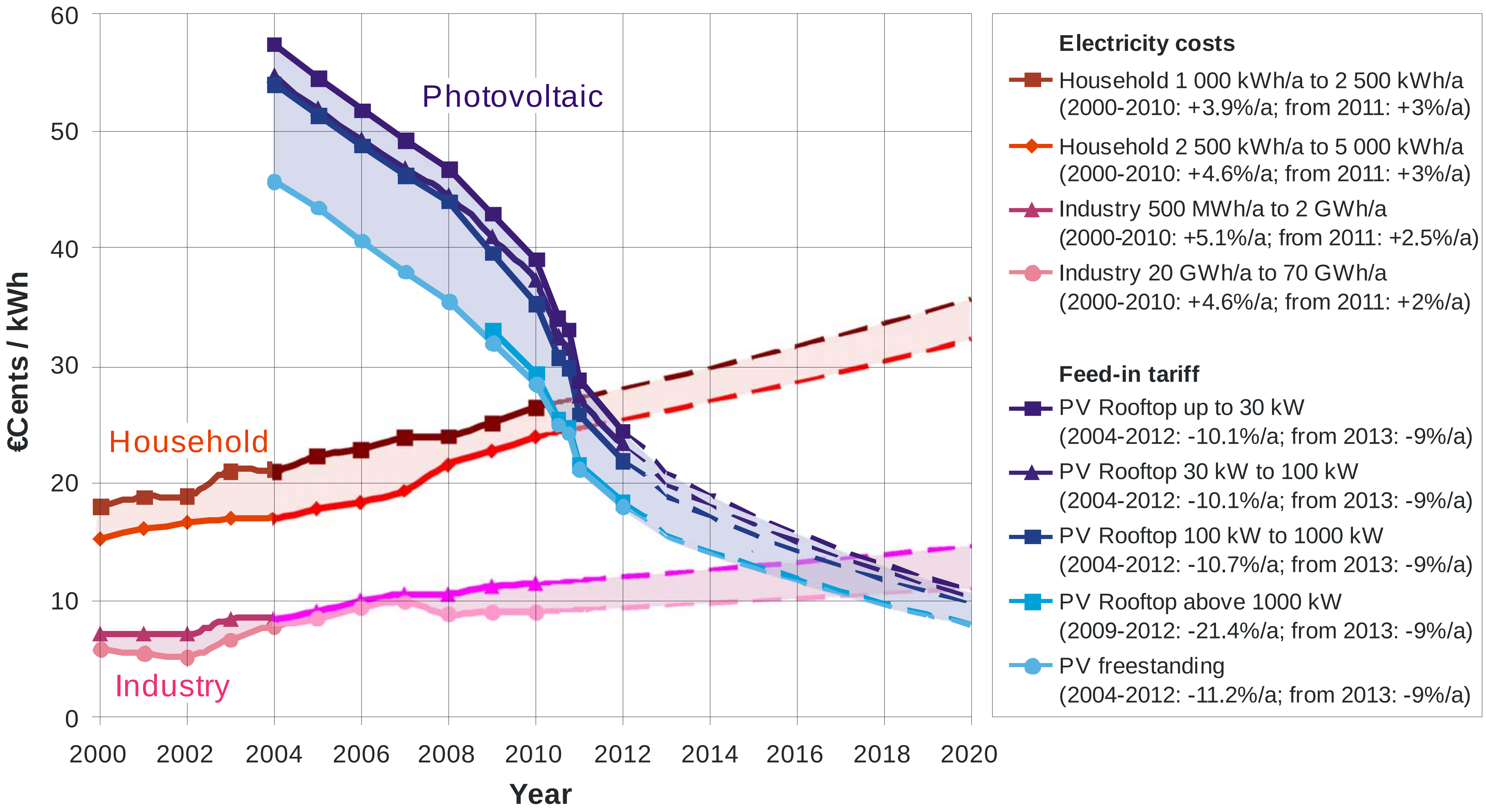
Power production – Germany in May 2011

- PV in Germany end of 2011: ~ 24 GWp installed, approx. 80 % decentralized systems connected to the low voltage grid !!!
- German load curve varies between ~ 50 GW and ~ 80 GW
- PV share of German power generation in 2011: ~ 3 %



Source: B. Burger, "http://www.ise.fraunhofer.de/aktuelles/meldungen-2011/solaranlagen-liefern-spitzenlaststrom"

Electricity costs and feed-in tariffs in Germany



Source: B. Burger, “Energiekonzept 2050”, June 2010, FVEE, www.fvee.de, Update of 05.12.2011

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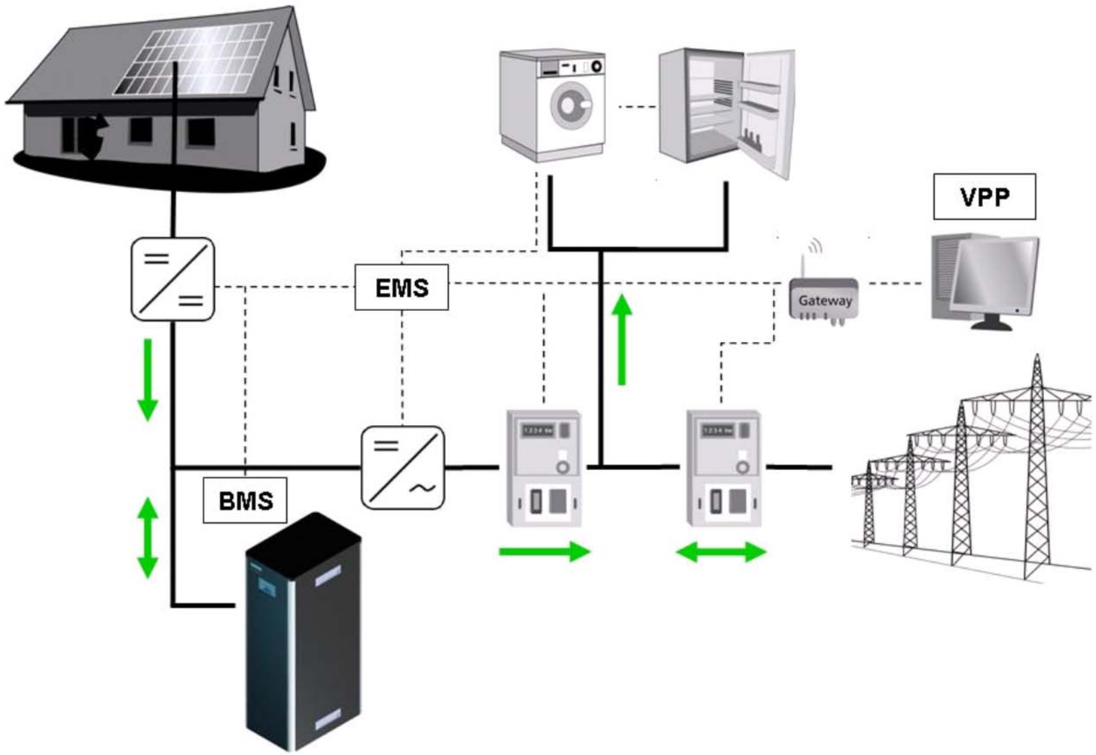
Motivation of a house owner today

Cancelled in the planned revision of March 2012 !!!

- ~~Additional benefit for self consumption of PV energy (rule within the German renewable energy act)~~
- ~ 70 % of self consumed PV energy can be achieved in residential areas (depending on system design and specific user behavior)

→ Beneficial for house owner ✓

→ Beneficial for utility ?



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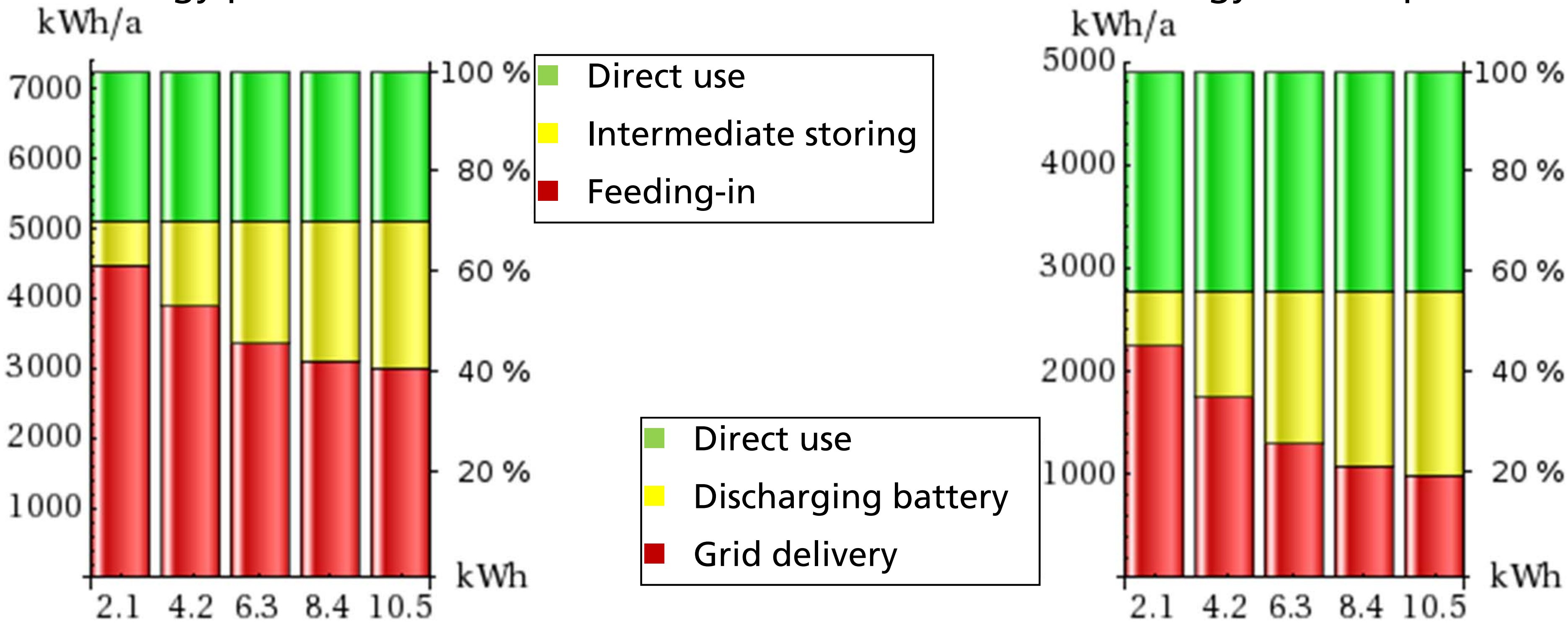
Analysis of energy fluxes (results of system simulation)

- Household: 4900 kWh/year
- PV generator size: 6 kWp
- Lithium-ion battery system: Variation of usable capacity

Energy production Energy consumption



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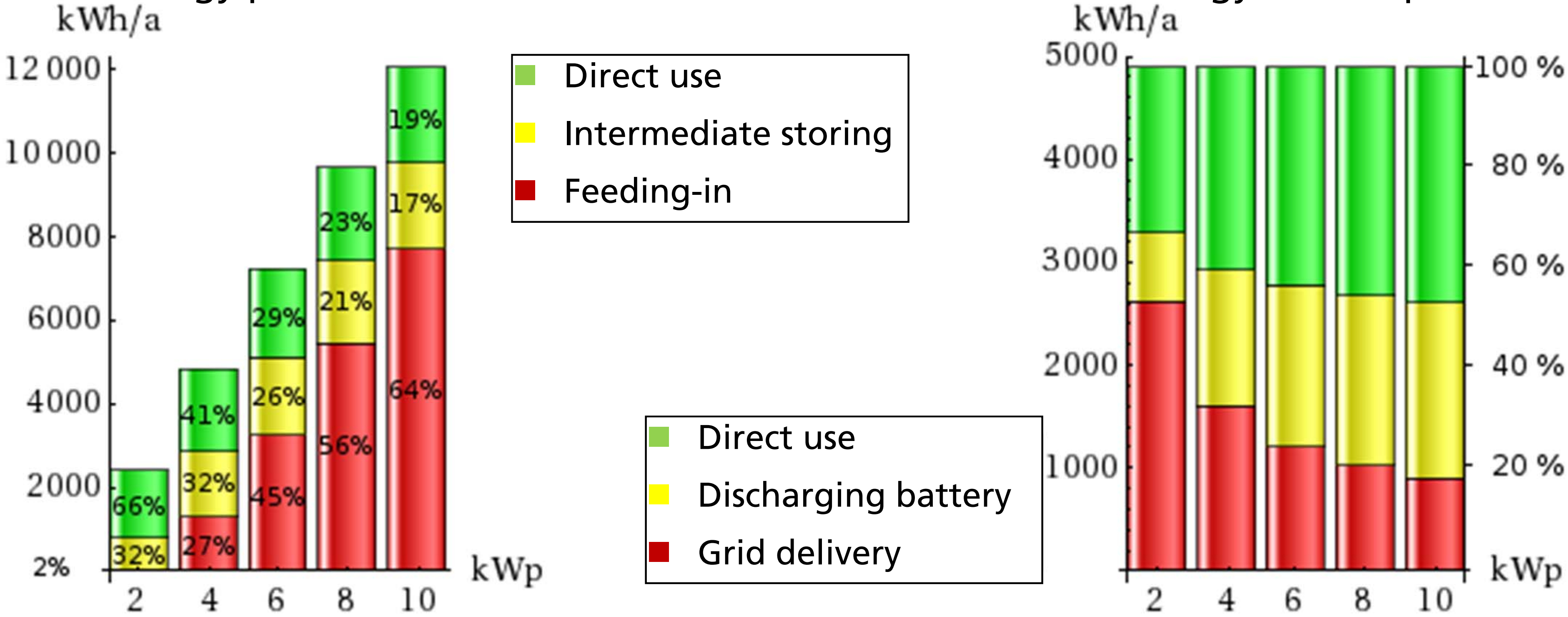
Analysis of energy fluxes (results of system simulation)

- Household: 4900 kWh/year
- Variation of PV generator size
- Lithium-ion battery system: 6,21 kWh usable

Energy production

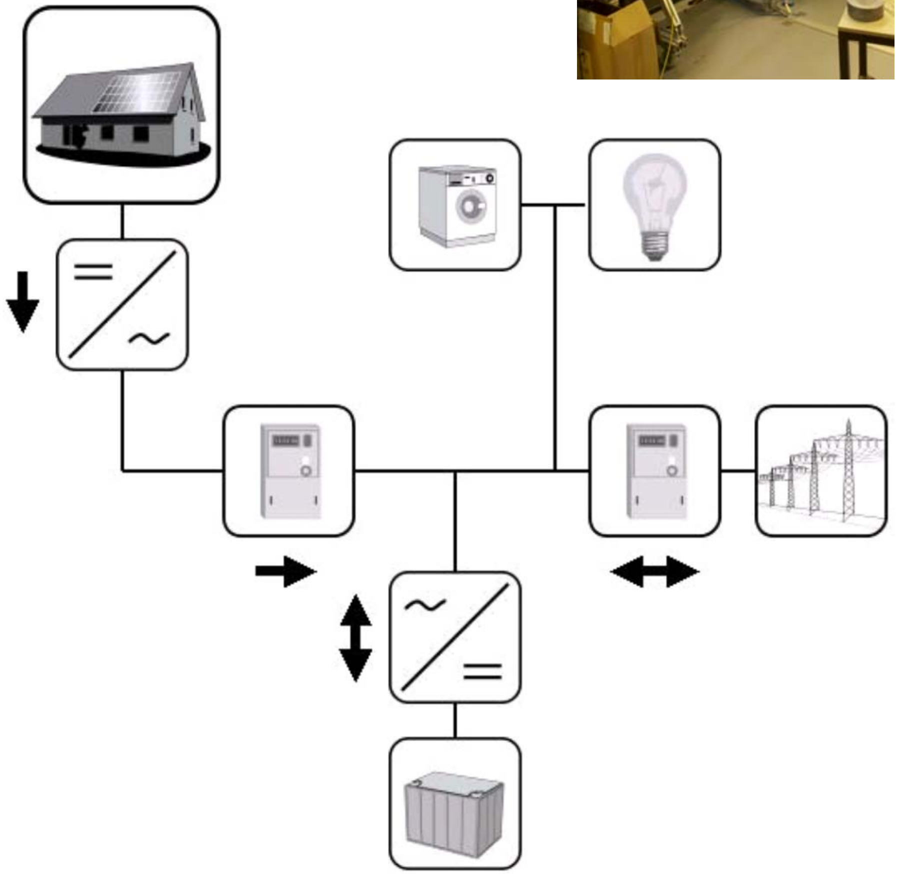
Energy consumption



System concepts and topologies

AC coupled system

- PV generator and battery system coupled with the AC grid via two separate inverters
- High efficient PV inverter
- 24 V / 48 V battery system coupled via an inverter with transformer
- Installed storage capacity scalable almost independently from PV system
- Existing PV systems relatively easy expandable with a battery system
- Battery system can be charged via grid
  - → Intermediate storing of excess grid power possible



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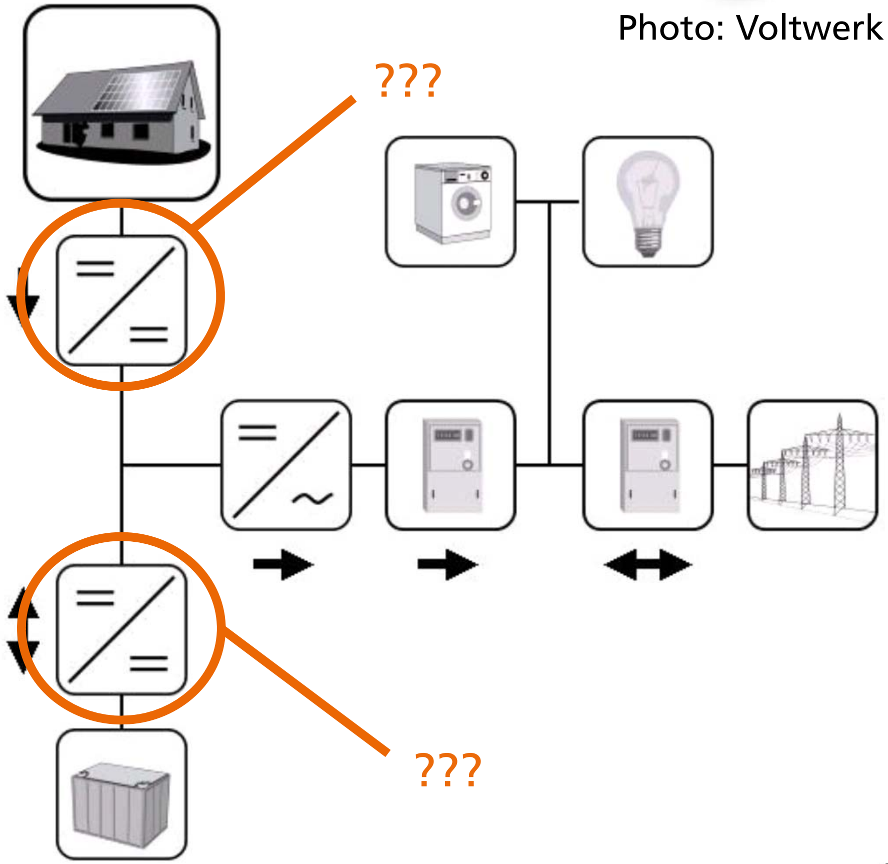
System concepts and topologies


Photo: Voltwerk

DC coupled "high voltage system"

- Transformer-less concept
- Battery system coupled via DC/DC converter directly at intermediate circuit of inverter
- Separate DC/DC converter with integrated MPP tracking for PV generator
- High overall efficiency possible
- High potential for cost reduction
- Market available products: DC/AC bridge not bidirectional
  - → Intermediate storing of excess grid power not possible



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System components and requirements
Power electronics

- At least always two components necessary, independently of system topology:
  1. Battery inverter and PV inverter
  2. DC/DC converter with MPP tracking for PV generator, DC/DC converter for battery system and DC/AC bridge
- High efficiencies of all conversion steps
- Communication interface
  - Connection to energy management system
  - Connection to battery system in case of lithium-ion batteries:
    - → Lithium-ion battery systems have always an integrated battery management
- Internal battery management of inverter/charge controller must be deactivated
- Backup functionality:
  - In Germany "nice to have" (so far !)
  - International markets: Important for weak grids

System components and requirements
Standardized communication infrastructure

Network of generators, storages and energy management via

EnergyBus / CiA 454:

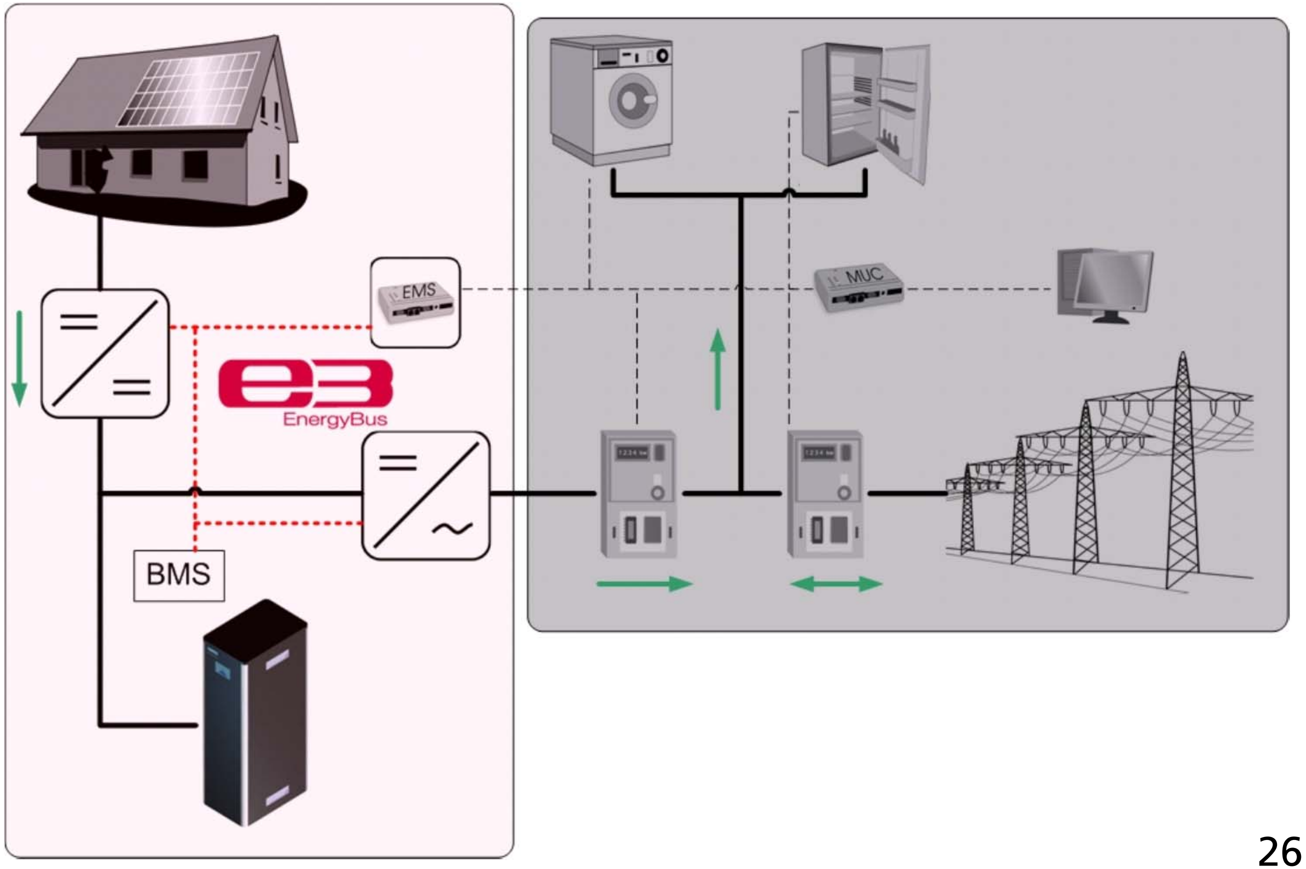
"Energy management systems "

Starting point:

- Light Electric Vehicles !

Current status:

- Extension for stationary systems (on-grid and off-grid)
- Transformation of the "Universal Energy Supply Protocol" UESP, developed at Fraunhofer ISE



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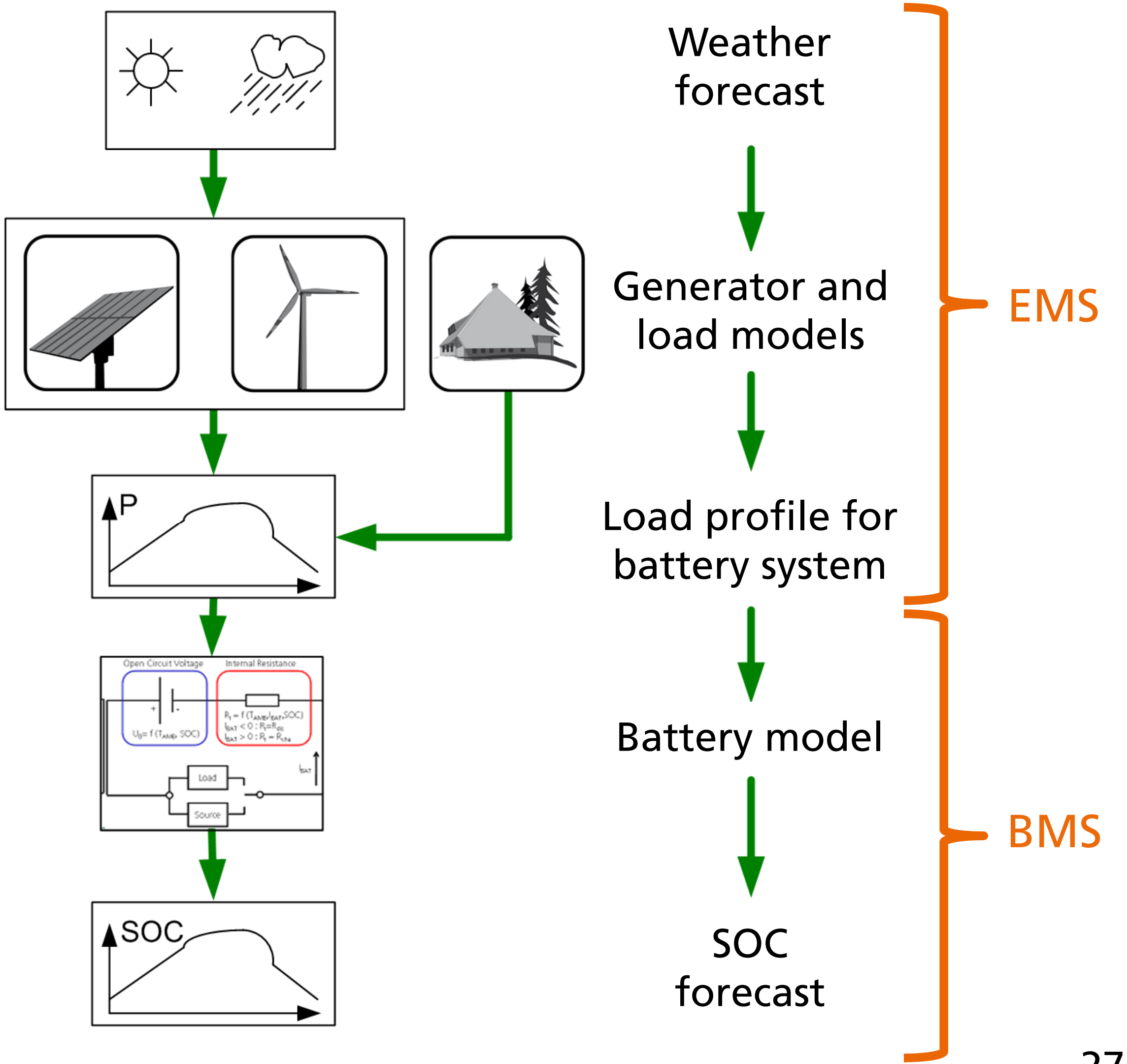
Smart battery management as part of an optimized energy management

- Communication interface between EMS and BMS
- Model based energy management
  - ➢ Load and generation management
  - ➢ Optimized operation of battery system
  - → Control of energy fluxes
- Model based battery management
  - ➢ SOC prediction in dependence on load profile forecast
  - ➢ Efficiencies in dependence on load profile forecast
  - ➢ Information on aging

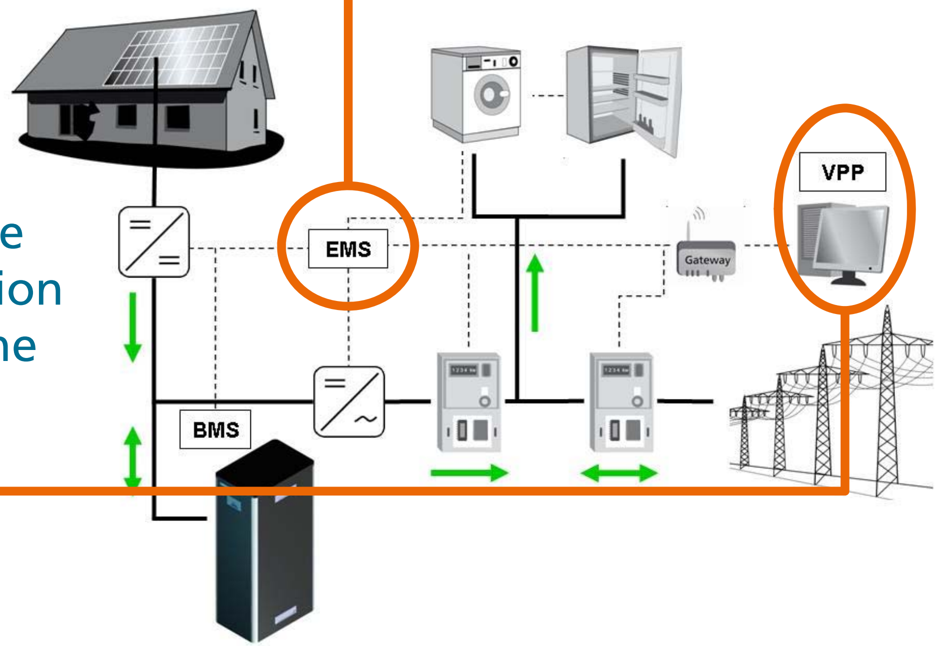


System components and requirements
Energy management

- Home energy management:
  - Optimization of self consumption
  - Communication with battery system (lithium) and power electronics
  - High time resolution for data acquisition of energy fluxes

Self consumption rule of German renewable energy act results in a temporal concentration of PV feeding-in but not in a solution for the high penetration of distribution grids

- Distribution grid management:
  - Approach via flexible tariffs for PV feeding-in
  - Use of “smart metering“ infrastructure



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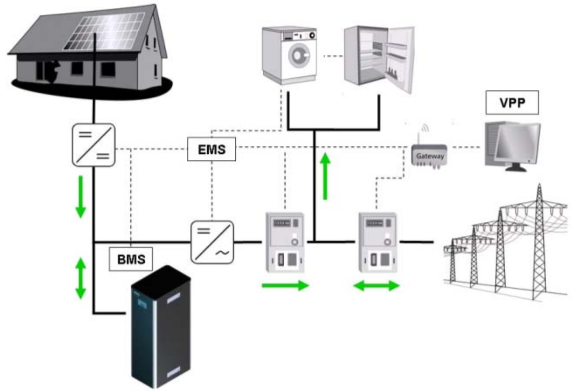
System components and requirements
Residential battery systems



- Autonomy time: Typically 12 – 24 hours
- High efficiencies
  - Lead-acid batteries in PV applications up to 86 % (achieved in off-grid systems)
  - Lithium batteries in PV applications approx. 95 % (in PV systems possible)
- High calendar life times
  - Lead-acid batteries in PV applications ≤ 10 years (experience off-grid)
  - Lithium batteries in PV applications approx. 20 years (manufacturer information!)
- Cycle stability: Up to 3000-4000 cycles (for a typical system design in Germany) in grid connected PV applications within a time span of 20 years (!)
  - Lead-acid batteries: DoD of 50 % → 1500-2000 full cycles
  - Conv. Lithium batteries: 6000 cycles at DoD of 60 % (manufacturer information!)
  - Especially for stationary applications developed lithium batteries: 7000 cycles at DoD of approx. 95 % (manufacturer information!)
  - Additional grid services: Up to one cycle per day → 7300 cycles

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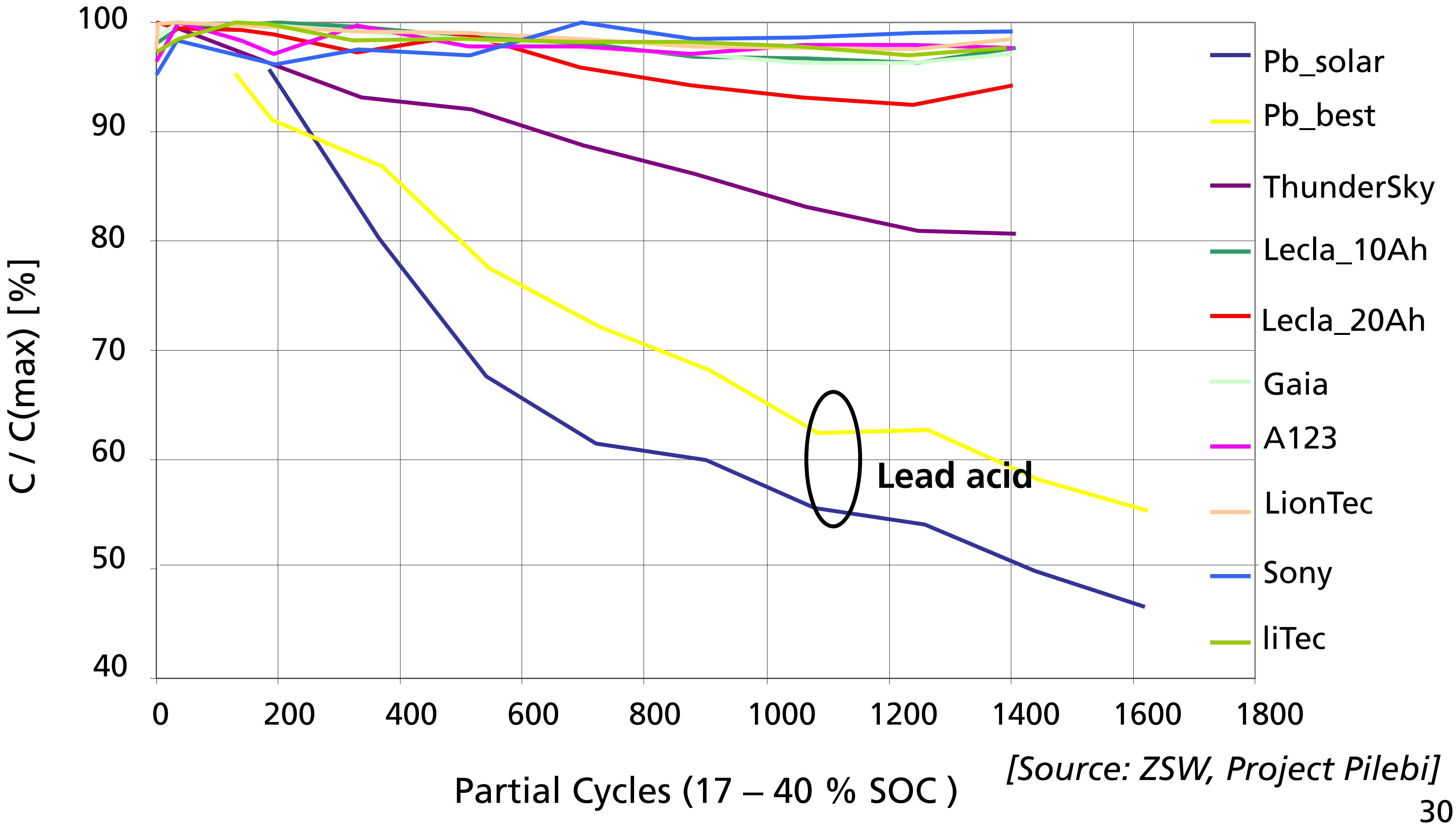
Batteries in PV applications
Partial cycling at low states of charge



[Source: ZSW, Project Pilebi]

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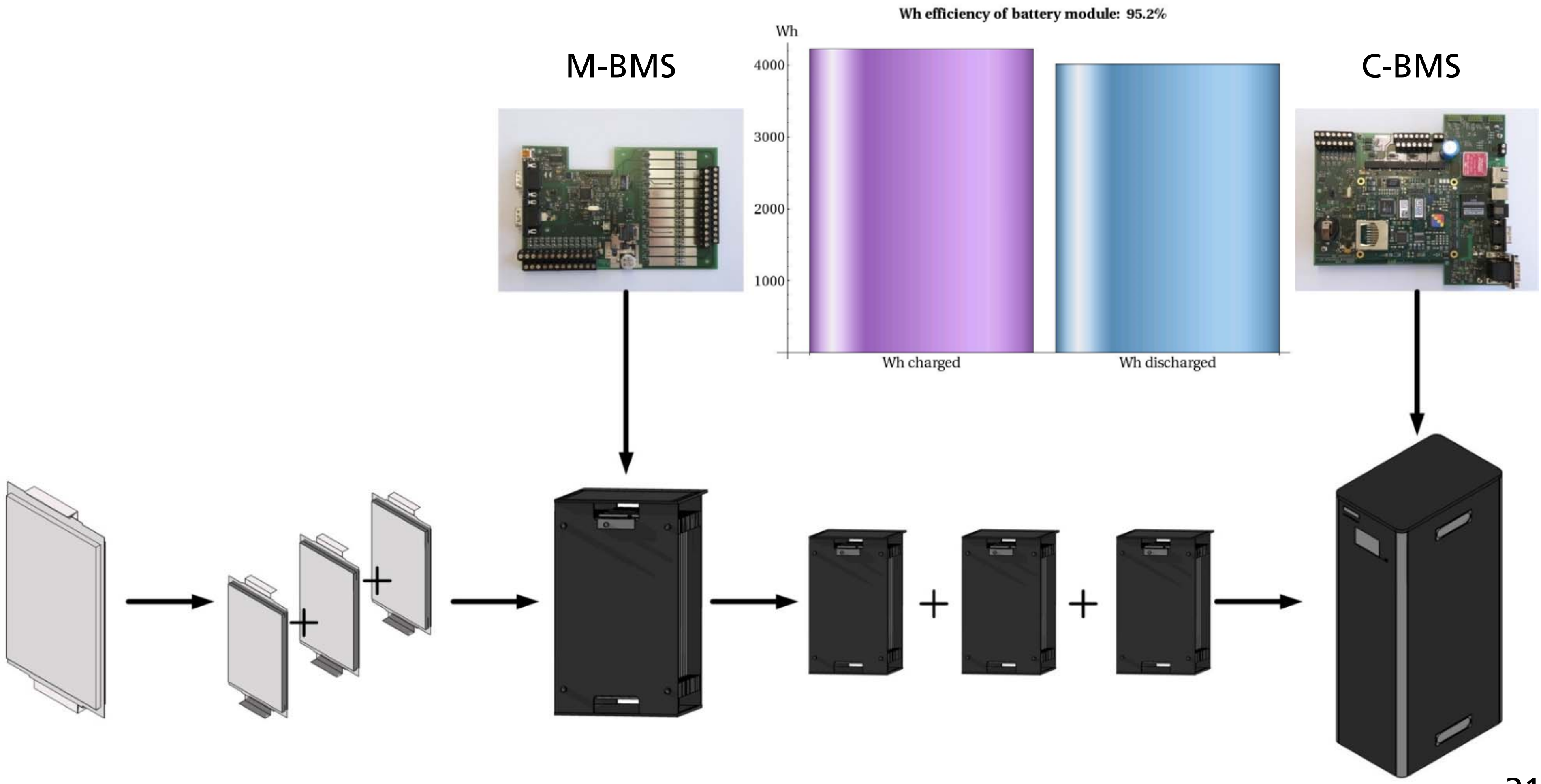
Lithium-ion battery system – Design

Cells → Modules → System



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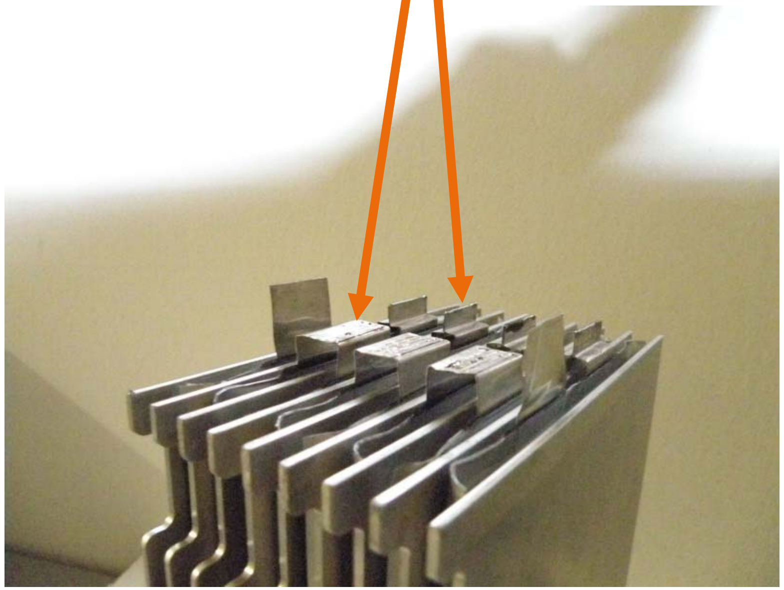
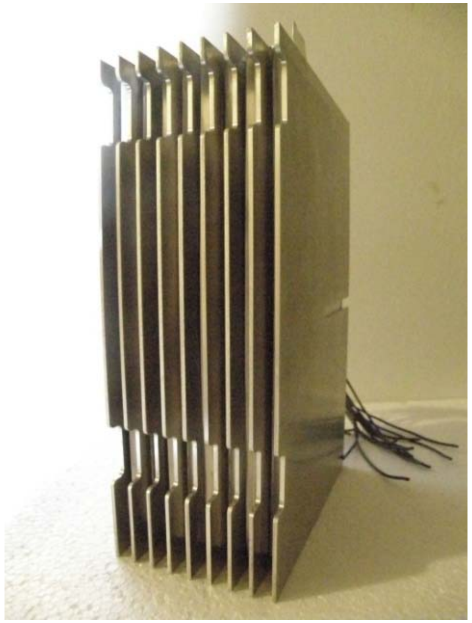
Battery module – For stationary applications

- Optimized design of the modules for simplified combination with market available charge controllers and battery inverters
- Connection method:
  - Laser welding
- Cooling system:
  - Air cooled
- Module integrated battery management





Conclusions

- Development of reliable and efficient battery systems for (hybrid) electric vehicles:
  - **Connection methods:** Laser welding promising alternative for connecting cells
  - **Cooling system:** Design is a trade-off between construction efforts, efficiency, reliability, security and costs
  - **Module battery management:** State of charge and state of health determination of single cells advantageous
  - Integrated **energy management:** Optimized operation of the battery pack
- Stationary applications:
  - 80 % of installed PV in Germany: **Decentralized systems** feeding into the low voltage grid → Need of decentralized storage solutions
  - **Residential applications** in Germany: Purchased energy from the grid can be reduced to ~ 20 % with a justifiable system design (depending on load profiles)
  - Battery storages in combination with an "intelligent" **energy management** enable further large scale grid integration of decentralized PV systems
  - **Standardization of communication** enables easy combination of components of different manufacturers (e.g. battery system, power electronics, EMS)

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Thanks for your attention !!!
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