

# Potential Applications of RV and Diagnosis to Lithium-Ion Batteries

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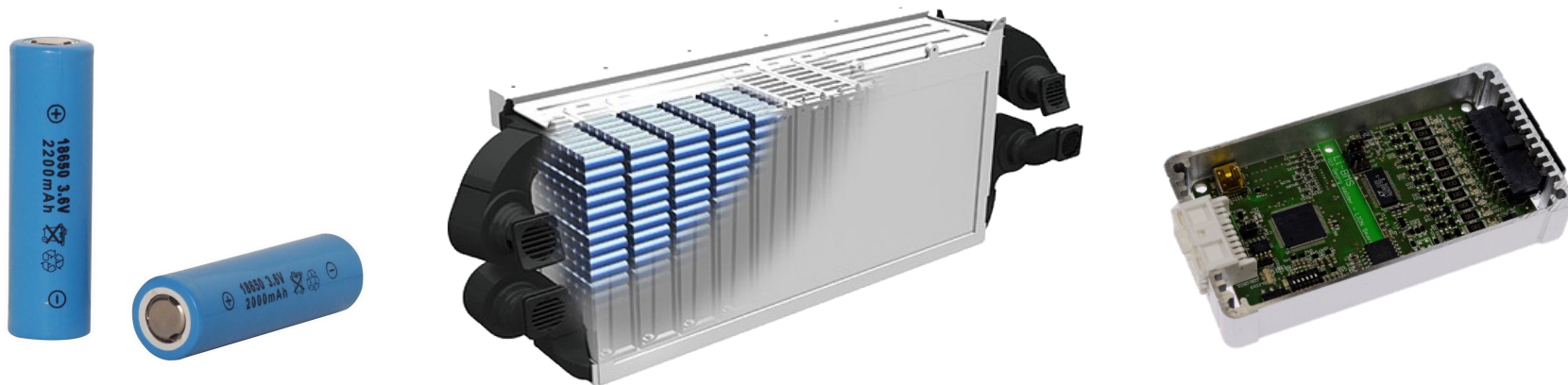
# Introduction

- Ongoing transition towards „green“ economy depends on technologies for electrical energy storage
  - Reliable wind and solar power
  - Self-sustaining residential homes
  - Locally emission-free electric mobility
- EU market for lithium-ion batteries
  - 2012: 0,75 B US\$; 2017: 1,65 B US\$



# Lithium-Ion Energy Storage

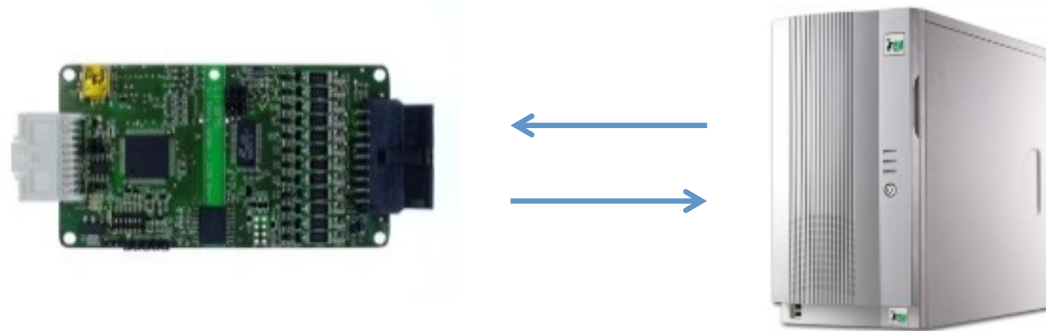
- Lithium-ion batteries among leading technology for electrochemical energy storage
    - 1,000 liters of water at 365 meters elevation  $\approx$  6 kg lithium-ion batteries
  - Safe and efficient operation requires close monitoring of each cell's voltage, current, and temperature values
    - Cell voltage 3.3 V ... 4.2 V, temperature -10 °C ... +40 °C
- ⇒ Battery management system (BMS) to control charging and discharging and protect cells from operating outside safe regions



## Towards Advanced Battery Monitoring

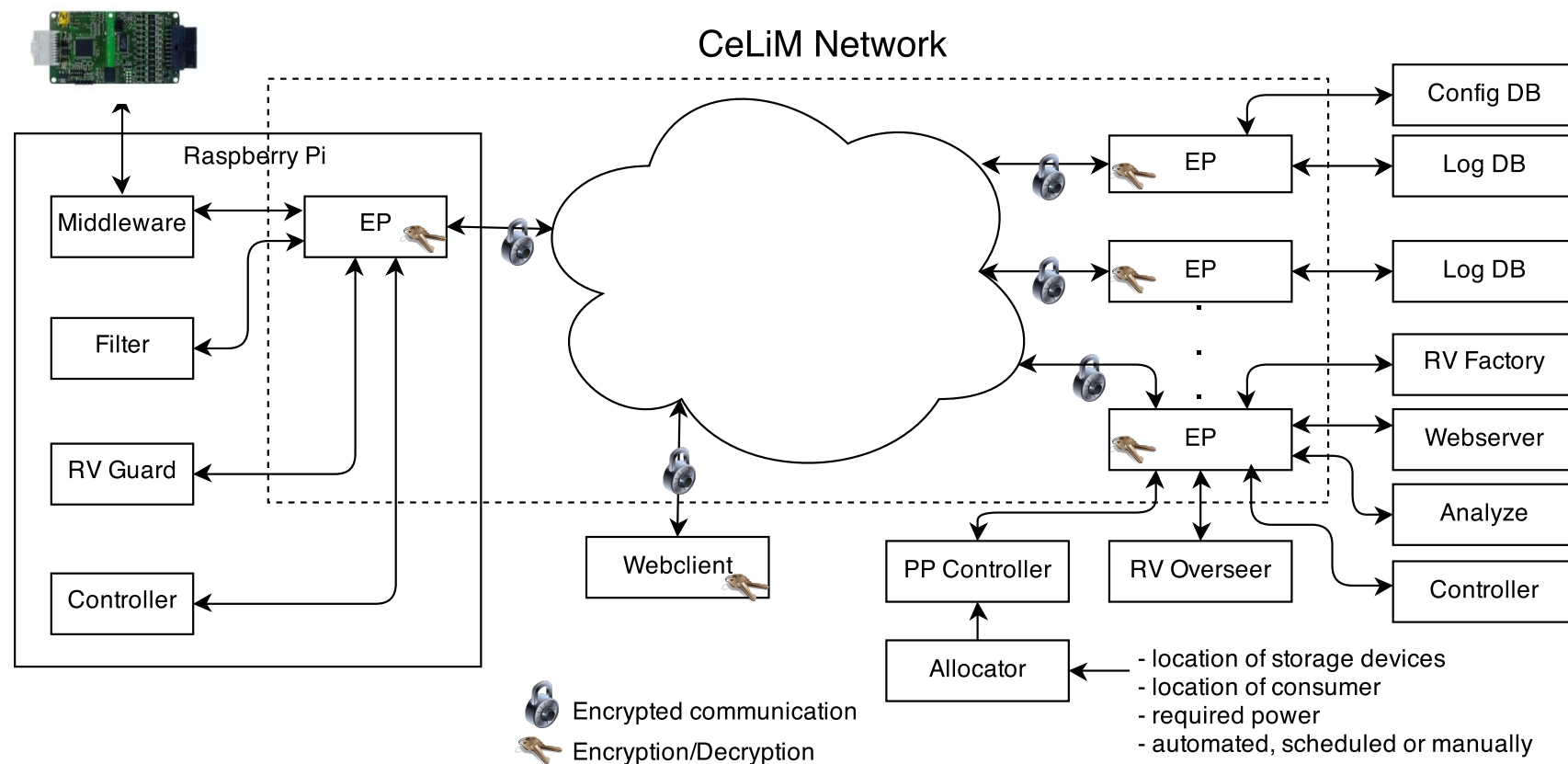
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- BMS has limited computational power and on-board memory
  - At the same time, increasing need for complex data analyses
    - Kalman-filter methods for estimating the precise state of charge
    - Data mining techniques for analyzing long-term cell aging effects
    - Automated supervision and control capabilities for power storage manufacturers, utility companies, and e-fleet managers
- ⇒ Server-based data collection, monitoring and control capability for lithium-ion battery packs



# CeLiM System Prototype

- Simultaneous logging of high-volume, fine-grained data streams
- On-the-fly analysis, verification, and event generation

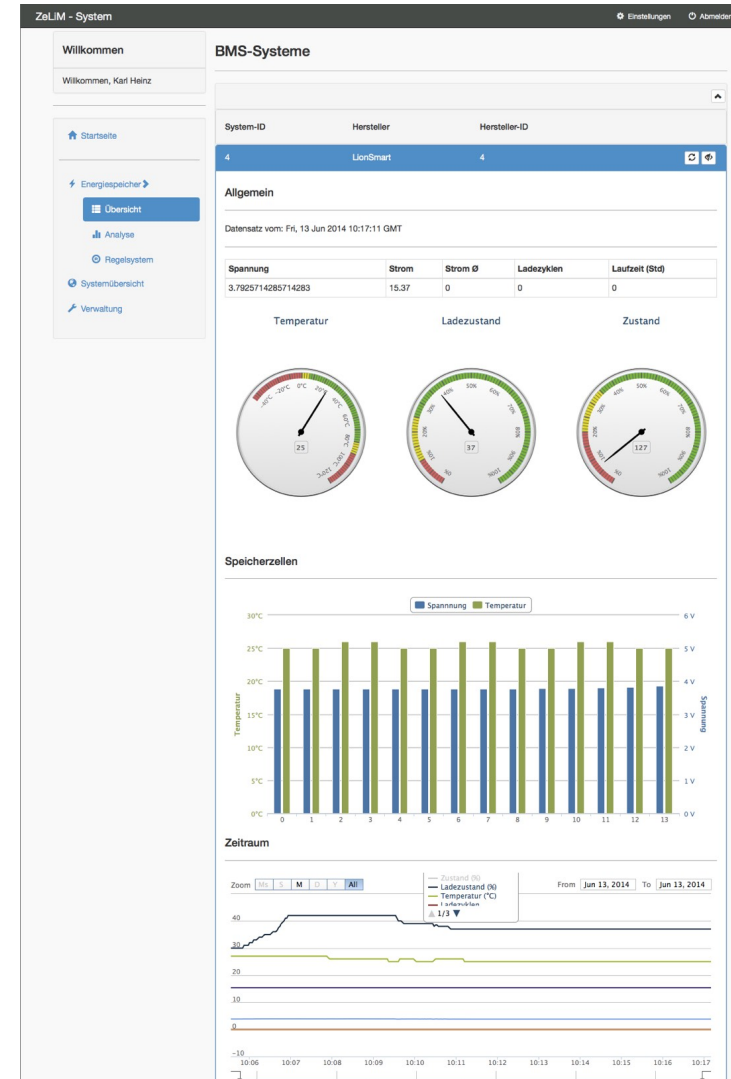
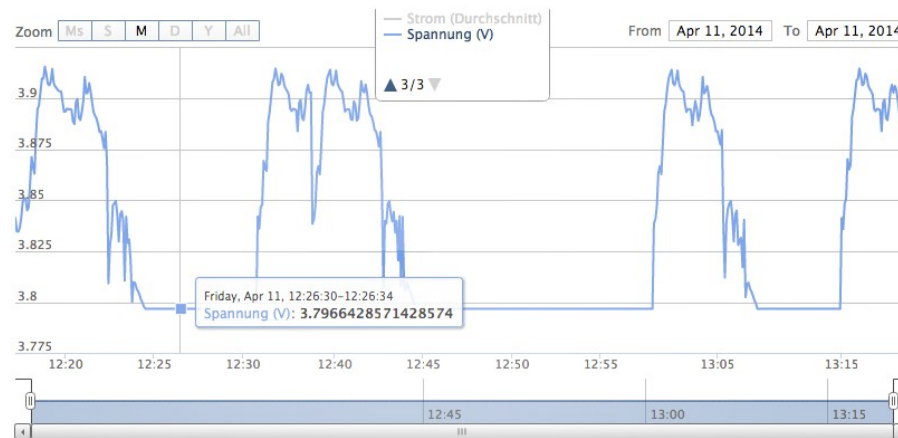


# CeLiM System Example

```

- <battery>
  - <cell id="c1">
    <type>18650</type>
    <voltage unit="V">3.7</voltage>
    <capacity unit="mAh">1575</capacity>
  </cell>
  - <par id="p1">
    - <measure>
      <value>voltage</value>
      <unit>V</unit>
    </measure>
  </of>
  <id>c1</id>
  <count>53</count>
</of>
</par>
- <module id="m1">

```





## Effizienzhaus Plus in Berlin, Germany

- Self-sustaining residential home with PV
- Stationary lithium-ion battery with 43,2 kWh, 7.420 cells (second-life use) in 70 modules
- Battery management system monitors voltages and temperatures in modules

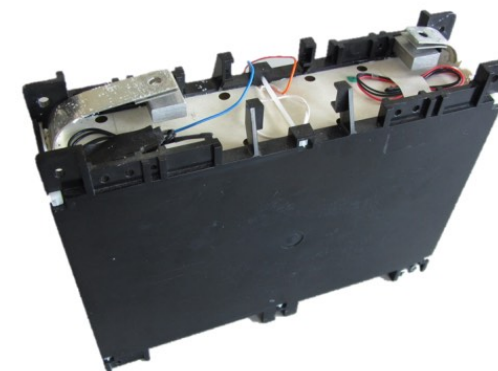
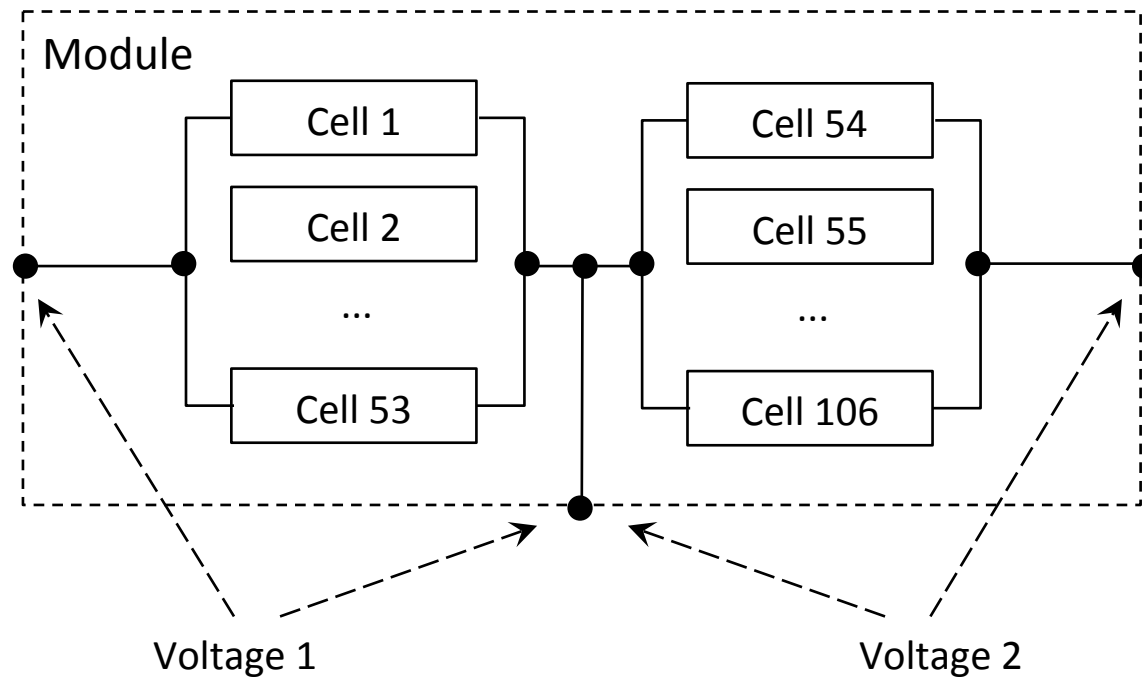


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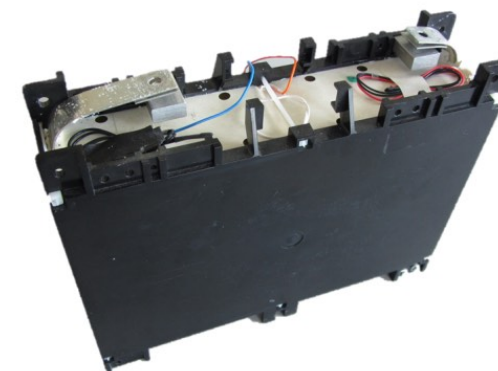
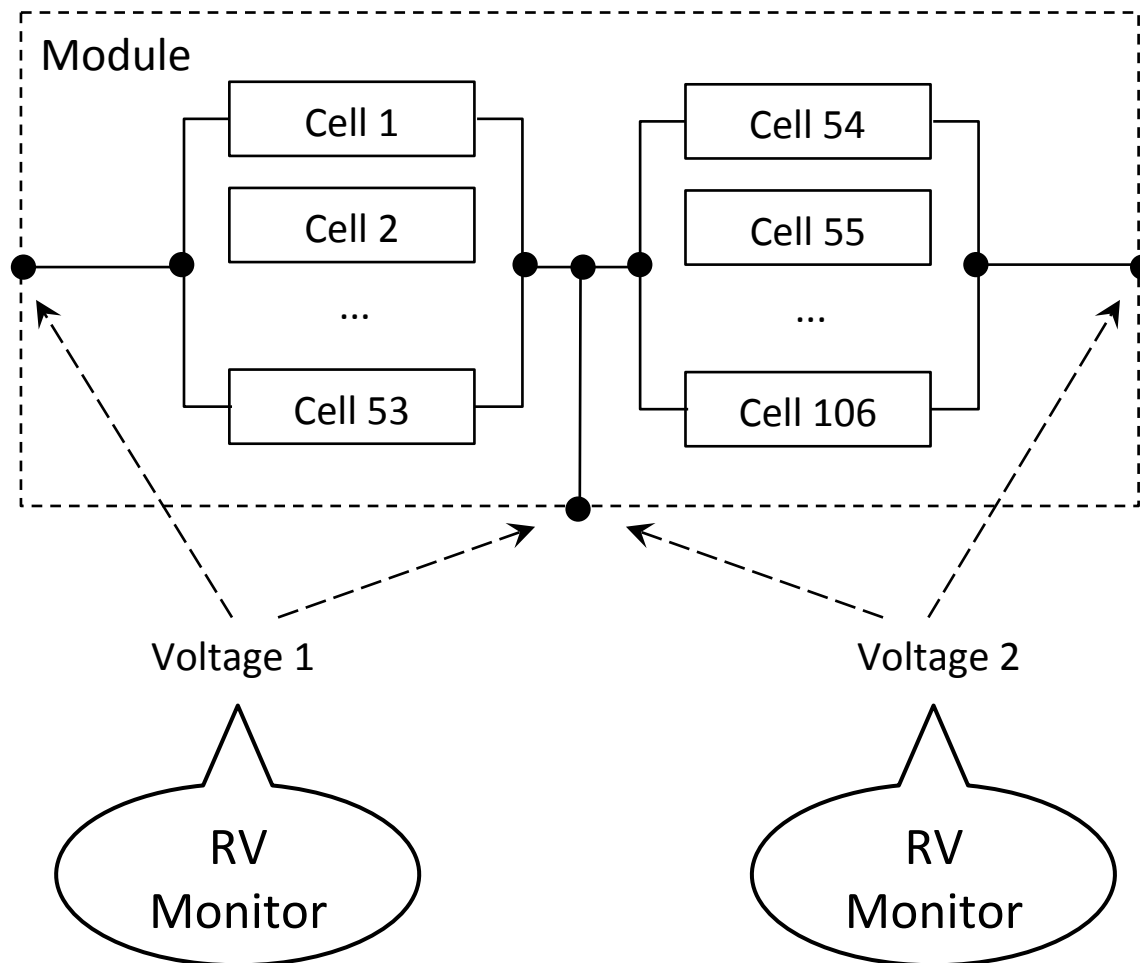


# Faults in Effizienzhaus Plus Modules

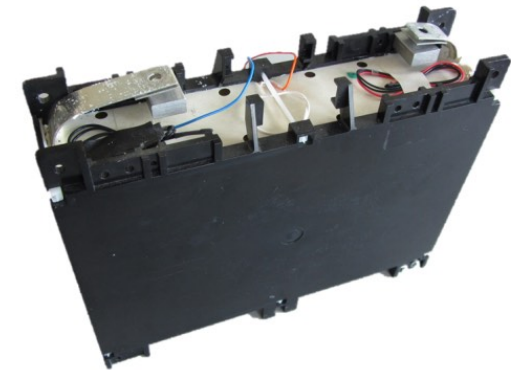
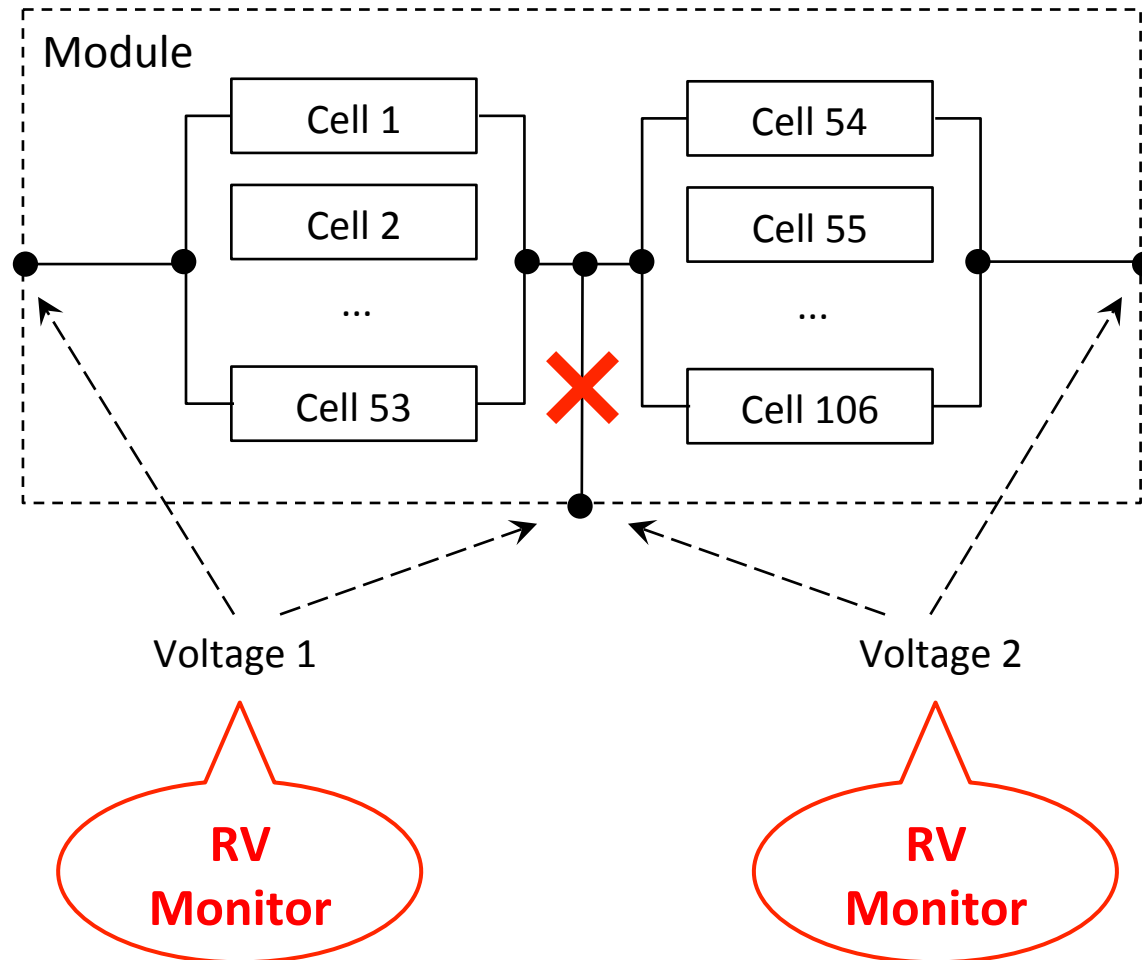




# Faults in Effizienzhaus Plus Modules



# Faults in Effizienzhaus Plus Modules



# Modeling for Diagnosis

- Assume component-based framework
- Each component has *health mode*
  - mode defines a set of dynamical equations

```
type WireHealth = enum
{
    nominal,
    openCircuited
};

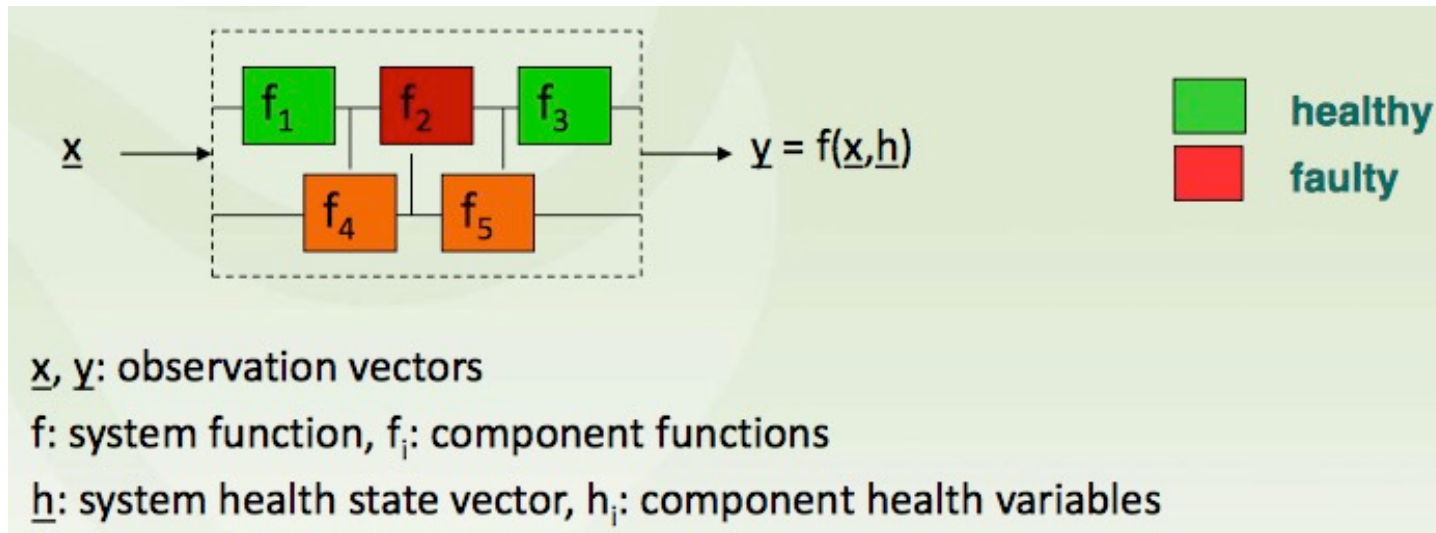
system Wire(float current,
            float terminal1,
            float terminal2)
{
    WireHealth h;

    attribute health(h) = (h == WireHealth.nominal)
    ? true : false;

    switch (h) {
        WireHealth.nominal ->
        {
            resistor(0, current, terminal1, terminal2);
        }
        ResistorHealth.openCircuited ->
        {
            // no constraint
        }
    }
}
```

# Principles of Model-based Diagnosis

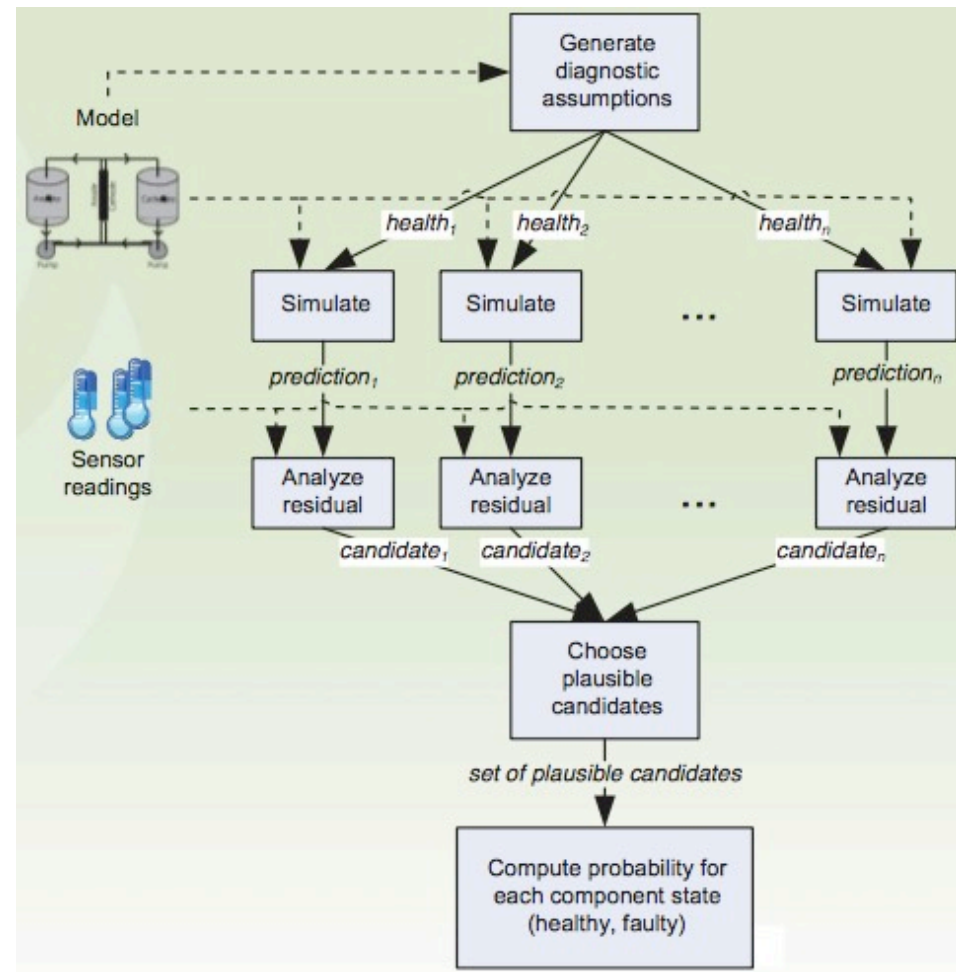
- Identify component(s) that are root cause of failure (error)



- Simulation: solve problem  $\underline{y} = f(\underline{x}, \underline{h})$
- Diagnosis: solve inverse problem  $\underline{h} = f^{-1}(\underline{x}, \underline{y})$
- Diagnosis result:  $h_2 = \text{faulty}$ , or  $h_4 = \text{faulty}$  and  $h_5 = \text{faulty}$ , etc.

# Lydia-NG Diagnosis Framework [Feldman et al. '13]

- Run multiple simulations (each simulation reflects different health state)
- Choose simulations that minimize some residual function
- Report diagnosis result as probability of components being healthy/faulty





## Experimental Results

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- Coupling RV monitors with model-based diagnostic framework Lydia-NG [Feldman et al. '13]
- Hybrid model of Effizienzhaus battery pack in Lydia-NG
  - 1128 variables, 212 SPICE circuit simulations
  - 30 minutes runtime, 1 single-fault hypothesis

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- Qualitative model of Effizienzhaus battery pack in Lydia-NG
  - *ok* values propagated if component is correct
  - *faulty* values observed for triggered RV monitors
  - 10 seconds runtime, 6 single-fault hypotheses

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  - *ok* values propagated if component is correct
  - *faulty* values observed for triggered RV monitors
  - 10 seconds runtime, 6 single-fault hypotheses
- Qualitative + Hybrid model (QM used to filter hypotheses)
  - 7 SPICE simulations, 1 minute runtime, 1 single-fault hypothesis

## Conclusions

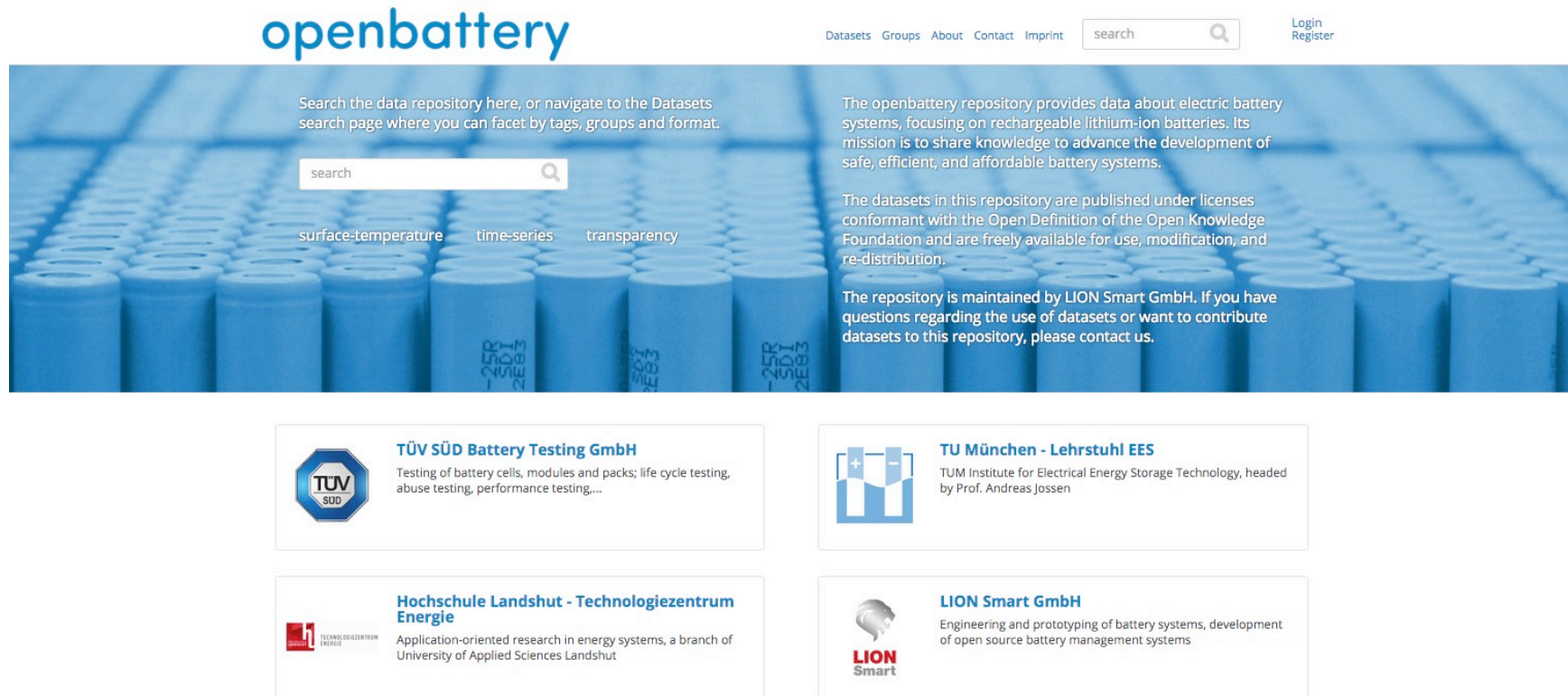
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- Lithium-based electrochemical energy storage requires close monitoring for safe and efficient operation
- Software tool CeLiM for logging, analyzing, and visualizing battery-related data, including on-line monitoring capability using RV techniques
- Outlined and experimentally tested possible coupling of RV with existing model-based diagnosis framework Lydia NG
- Currently working on more general theory for combining runtime verification and diagnosis



# Open Battery Data Platform: [Openbattery.org](https://openbattery.org)

- Freely available measurements (open data commons-licensed)
- Currently ~ 3.7 GB data from different lithium-ion cell types

The screenshot shows the homepage of the openbattery.org website. The header features the "openbattery" logo in blue, navigation links for "Datasets", "Groups", "About", "Contact", and "Imprint", a search bar, and "Login" and "Register" links. The main content area has a background image of blue cylindrical battery cells. It includes a search bar with the text "search" and a magnifying glass icon. Below the search bar are three tags: "surface-temperature", "time-series", and "transparency". To the right, there is a paragraph describing the repository's mission: "The openbattery repository provides data about electric battery systems, focusing on rechargeable lithium-ion batteries. Its mission is to share knowledge to advance the development of safe, efficient, and affordable battery systems." Below this is another paragraph: "The datasets in this repository are published under licenses conformant with the Open Definition of the Open Knowledge Foundation and are freely available for use, modification, and re-distribution." At the bottom, there is a paragraph: "The repository is maintained by LION Smart GmbH. If you have questions regarding the use of datasets or want to contribute datasets to this repository, please contact us." The footer section contains four logos and their descriptions: 1. TÜV SÜD Battery Testing GmbH: "Testing of battery cells, modules and packs; life cycle testing, abuse testing, performance testing,..." 2. TU München - Lehrstuhl EES: "TUM Institute for Electrical Energy Storage Technology, headed by Prof. Andreas Jossen" 3. Hochschule Landshut - Technologiezentrum Energie: "Application-oriented research in energy systems, a branch of University of Applied Sciences Landshut" 4. LION Smart GmbH: "Engineering and prototyping of battery systems, development of open source battery management systems"

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# Open Battery Data Platform: [Openbattery.org](https://openbattery.org)

- Up- and downloads, search, visualization; later also analysis

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Cell type: PD18650NCR - Typ Z  
Number: 36  
Time: 09:49  
Current [A]: 30  
Voltage [V]: 100  
Events: 09:51:43 CID opens/smoke, 09:54:00 stop

[20152901\\_30A\\_100V\\_Z36\\_header.csv](#)

Grid Graph 20000 records

Time	T_01	T_02	T_03	T_04	U_NT	I	U_Zelle
0	24.374	24.9639	24.393	23.3022	-4.0812	0.1384	4.2183
0.01	25.0586	24.7588	24.2427	23.3191	-4.0887	0.1336	4.2209
0.02	24.9015	24.8945	24.2174	23.6135	-4.0861	0.1388	4.2214
0.03	24.8048	24.7075	24.376	23.3529	-4.0891	0.116	4.2224
0.04	24.5905	24.7972	24.4174	23.6369	-4.0855	0.137	4.2185
0.05	24.6637	25.2074	24.1824	23.4543	-4.0856	0.127	4.2229
0.06	24.3327	24.7426	24.2799	23.4314	-4.0849	0.1118	4.217
0.07	24.8871	25.0214	24.3353	23.6654	-4.0803	0.128	4.2157
0.08	24.802	24.8334	24.1206	23.6464	-4.0846	0.141	4.2193
0.09	24.8752	24.6761	24.1454	23.2537	-4.0840	0.1342	4.2178
0.1	24.2883	24.8319	24.1589	23.5368	-4.0850	0.133	4.2154
0.11	24.7952	24.8702	24.1852	23.3033	-4.0860	0.13	4.2224
0.12	24.4259	24.8454	24.4968	23.0245	-4.0857	0.1364	4.2187
0.13	25.0523	24.6227	24.1335	23.581	-4.0863	0.129	4.2196
0.14	25.0032	24.5013	24.331	23.4687	-4.0822	0.1458	4.2194
0.15	24.8933	24.9072	24.1493	23.6729	-4.0869	0.1284	4.22
0.16	24.7318	25.1374	24.1654	23.3291	-4.0897	0.1364	4.2165
0.17	25.0171	25.2988	24.2828	23.5493	-4.0856	0.1374	4.2172
0.18	24.7639	25.1499	24.1191	23.3183	-4.0861	0.132	4.2156
0.19	24.9879	25.0896	24.2847	23.3627	-4.0845	0.1276	4.2188
0.2	24.3561	24.9614	24.2074	23.1947	-4.0850	0.132	4.2196

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