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

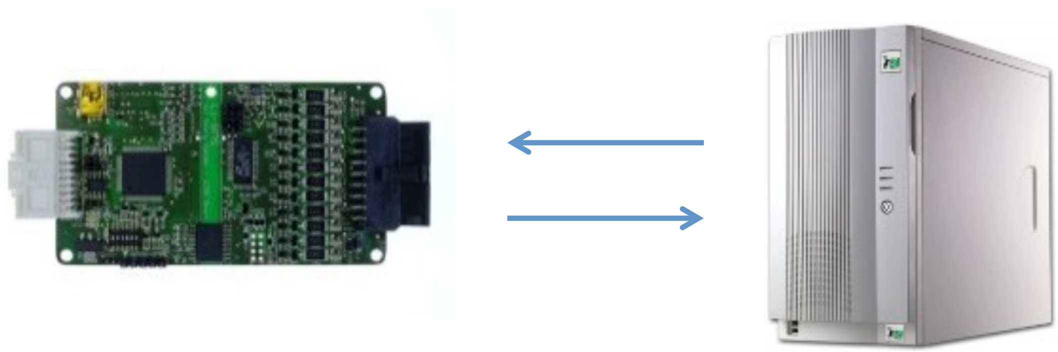
- Lithium-ion batteries among leading technology for electrochemical energy storage
  - 1,000 liters of water at 365 meters elevation ≈ 6 kg lithium-ion batteries
- Safe and efficient operation requires close monitoring of each cell's voltage, current, and temperature values
  - Cell voltage 3.3 V ... 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

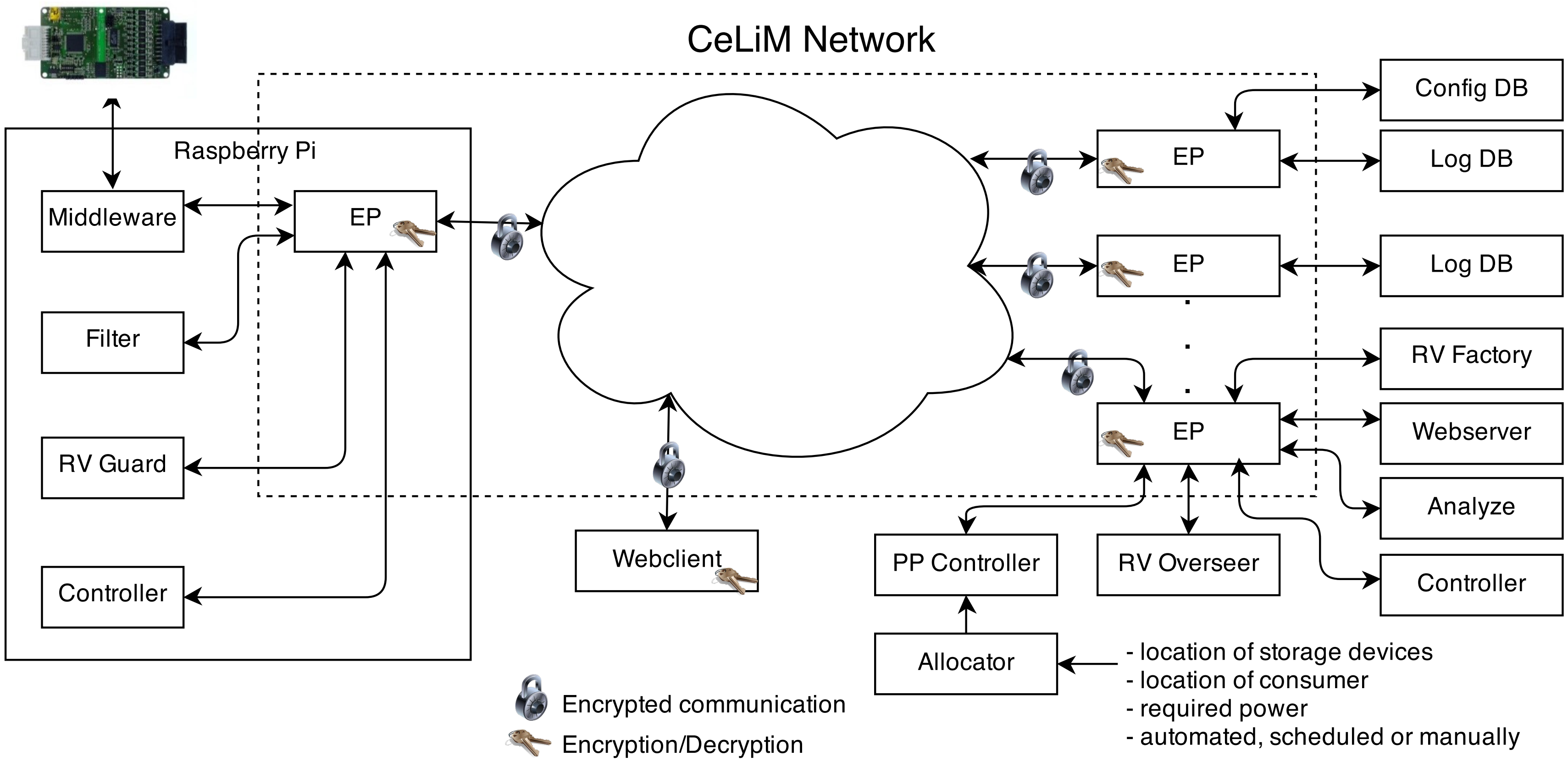
- BMS has limited computational power and on-board memory
- At the same time, increasing need for complex data analyses
  - Kalman-filter methods for estimating the precise state of charge
  - Data mining techniques for analyzing long-term cell aging effects
  - Automated supervision and control capabilities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

⇒ Server-based data collection, monitoring and control capability for lithium-ion battery packs



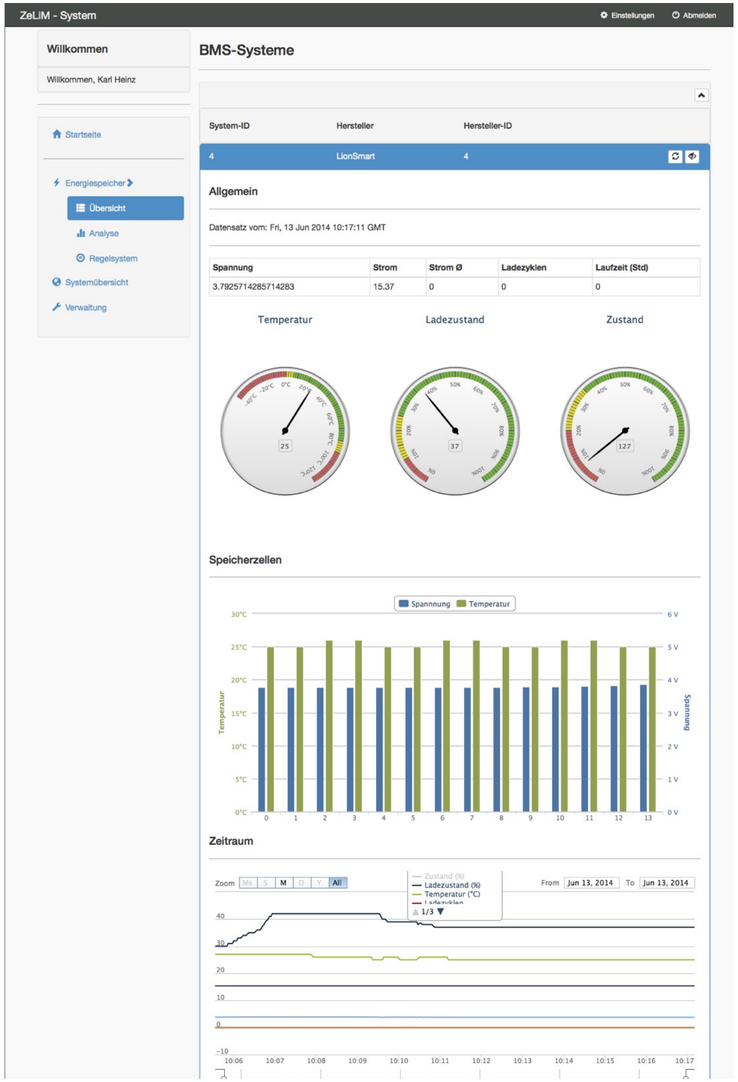
CeLiM System Prototype

- 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

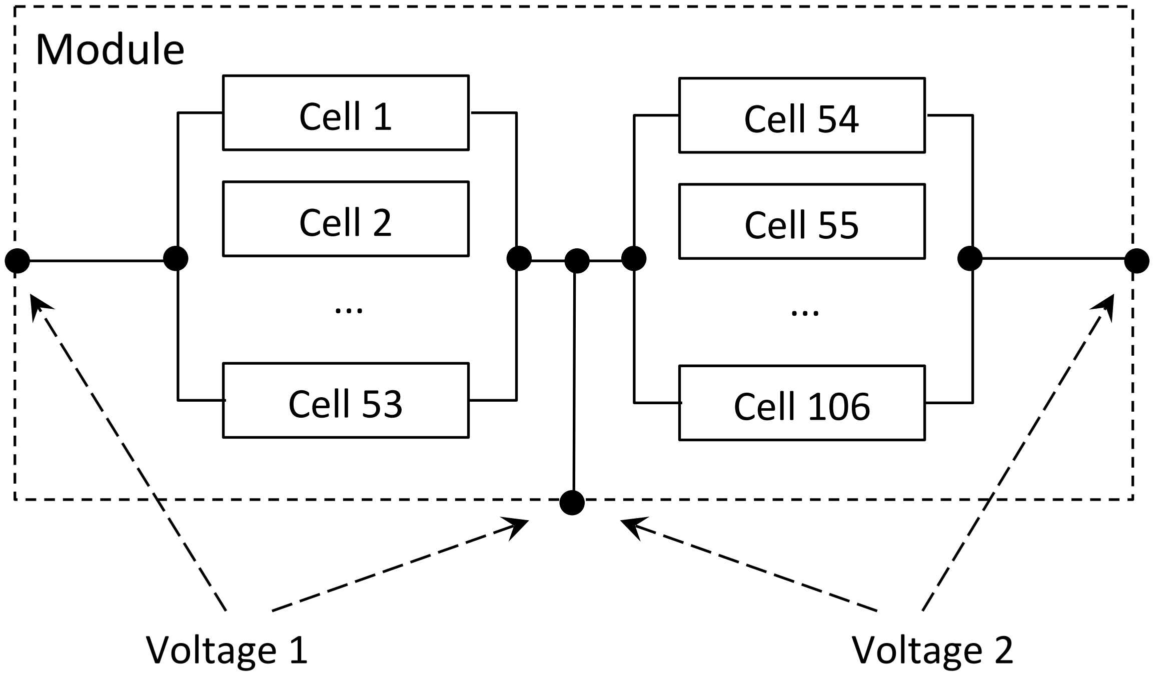
- Self-sustaining residential home with PV
- Stationary lithium-ion battery with 43,2 kWh, 7.420 cells (second-life use) in 70 modules
- Battery management system monitors voltages and temperatures in modules

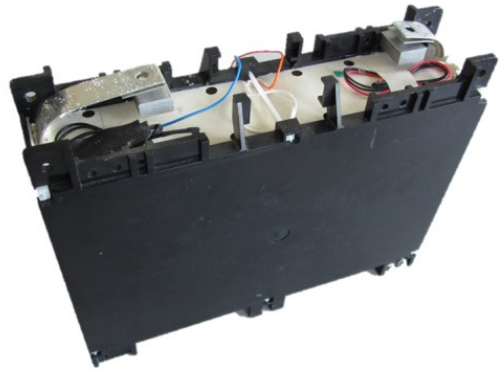
Bundesministerium für Verkehr, Bau und Stadtentwicklung

FORSCHUNGSINITIATIVE ZukunftBAU

Plus Effizienzhaus

Faults in Effizienzhaus Plus Modules





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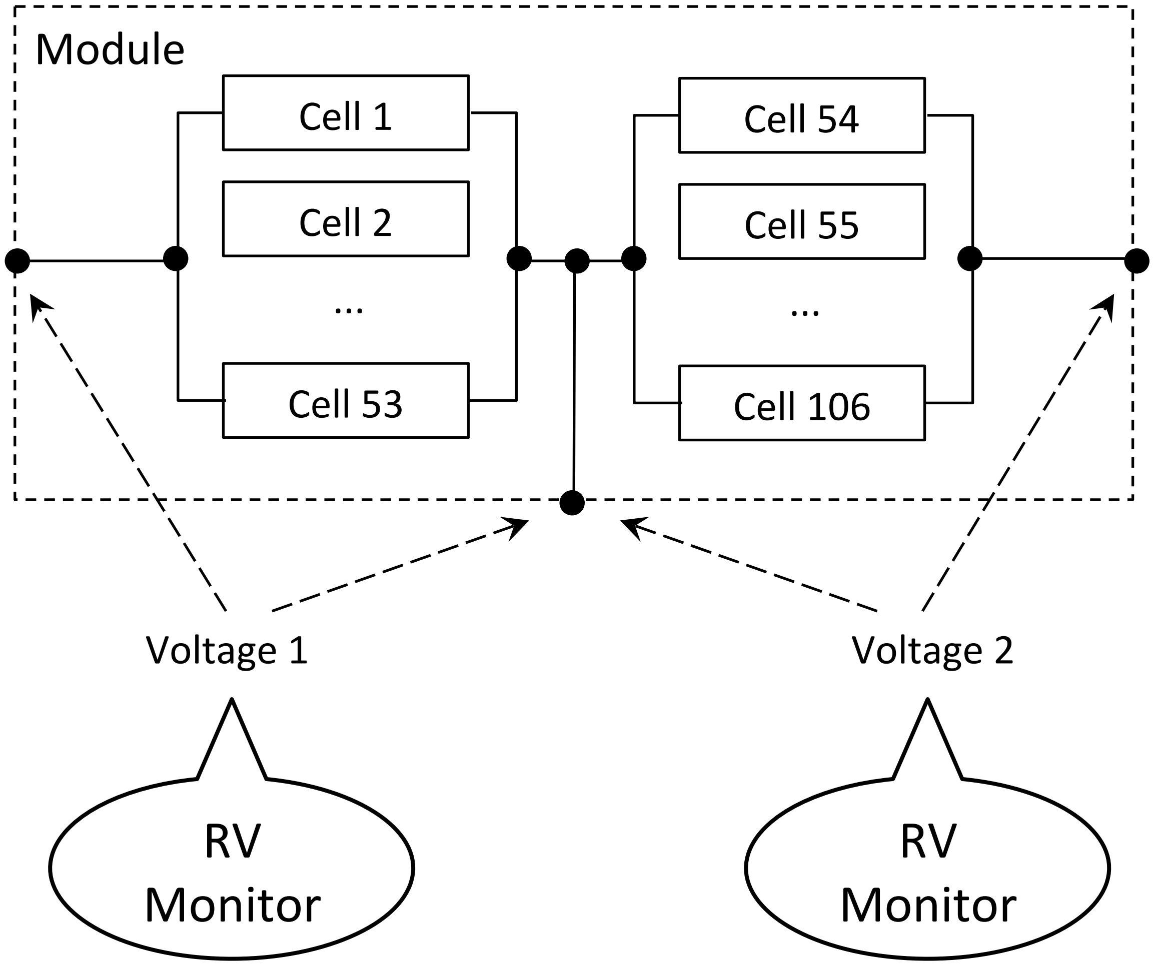
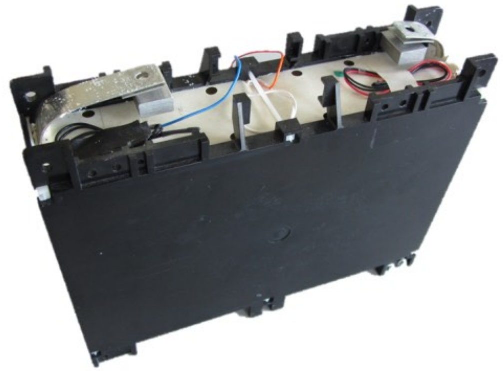
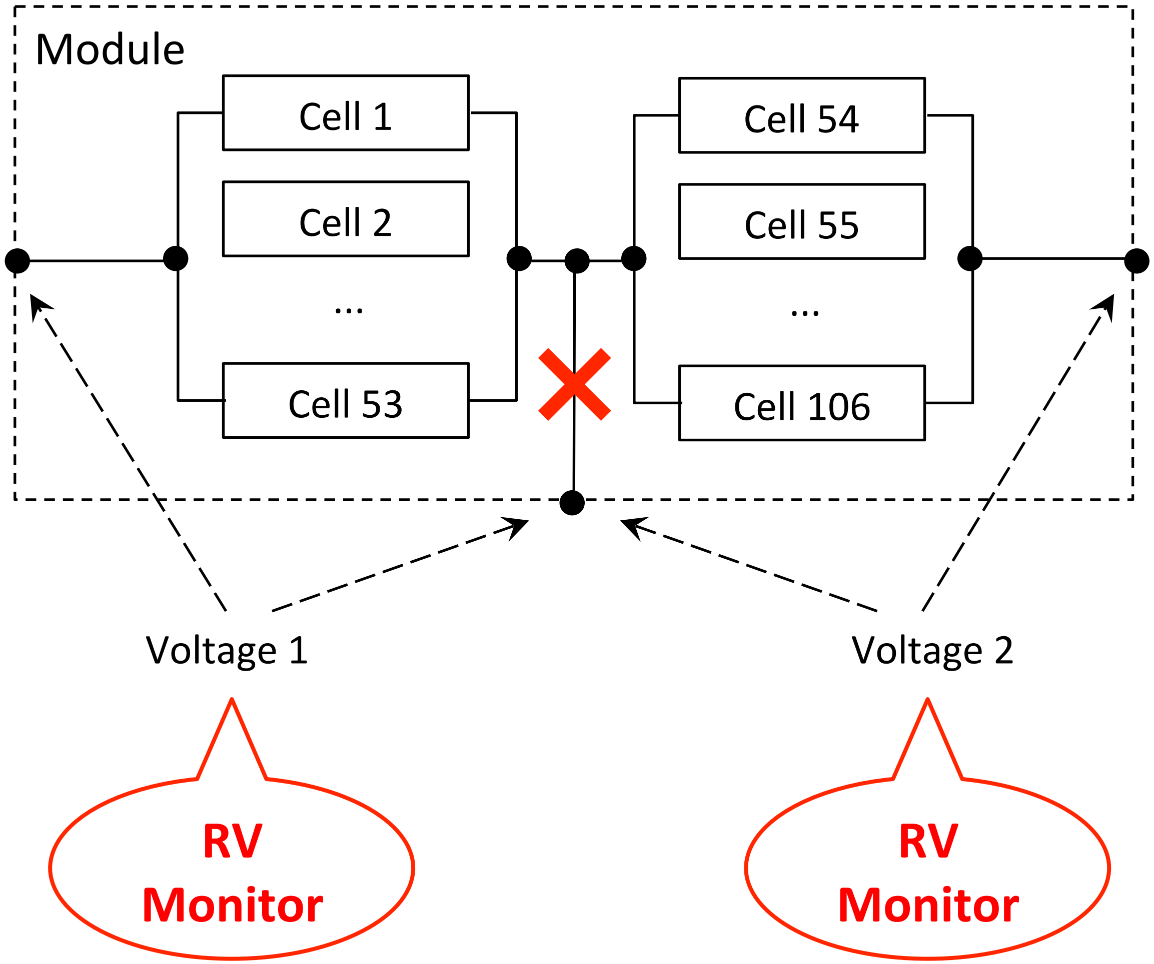




Faults in Effizienzhaus Plus Modules



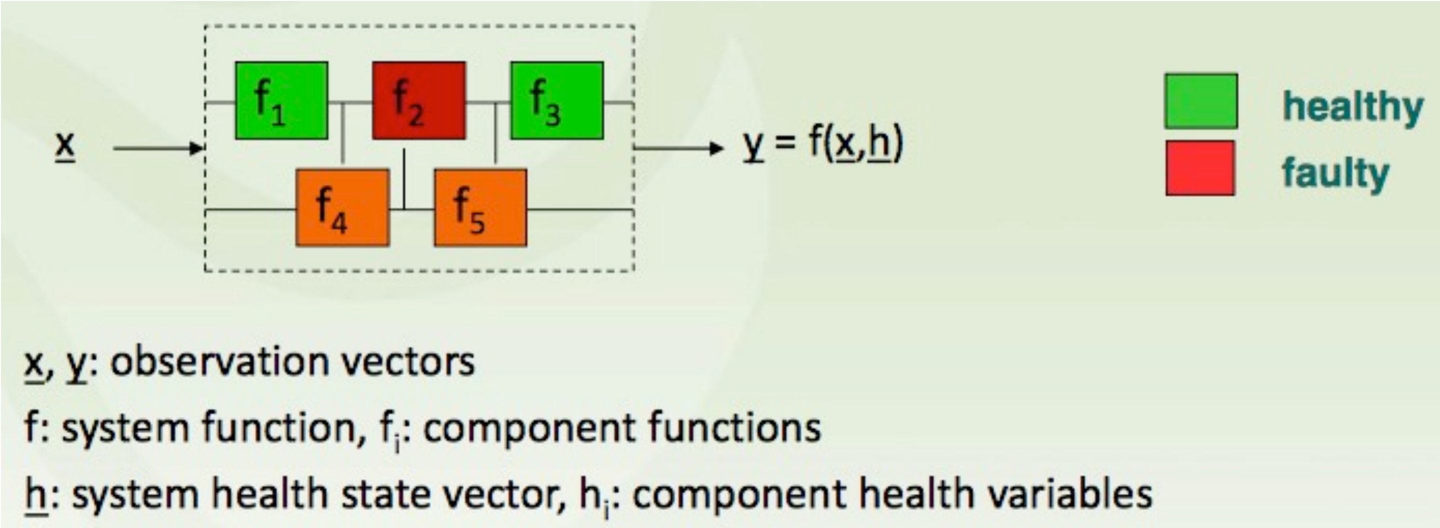
Modeling for Diagnosis

- 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

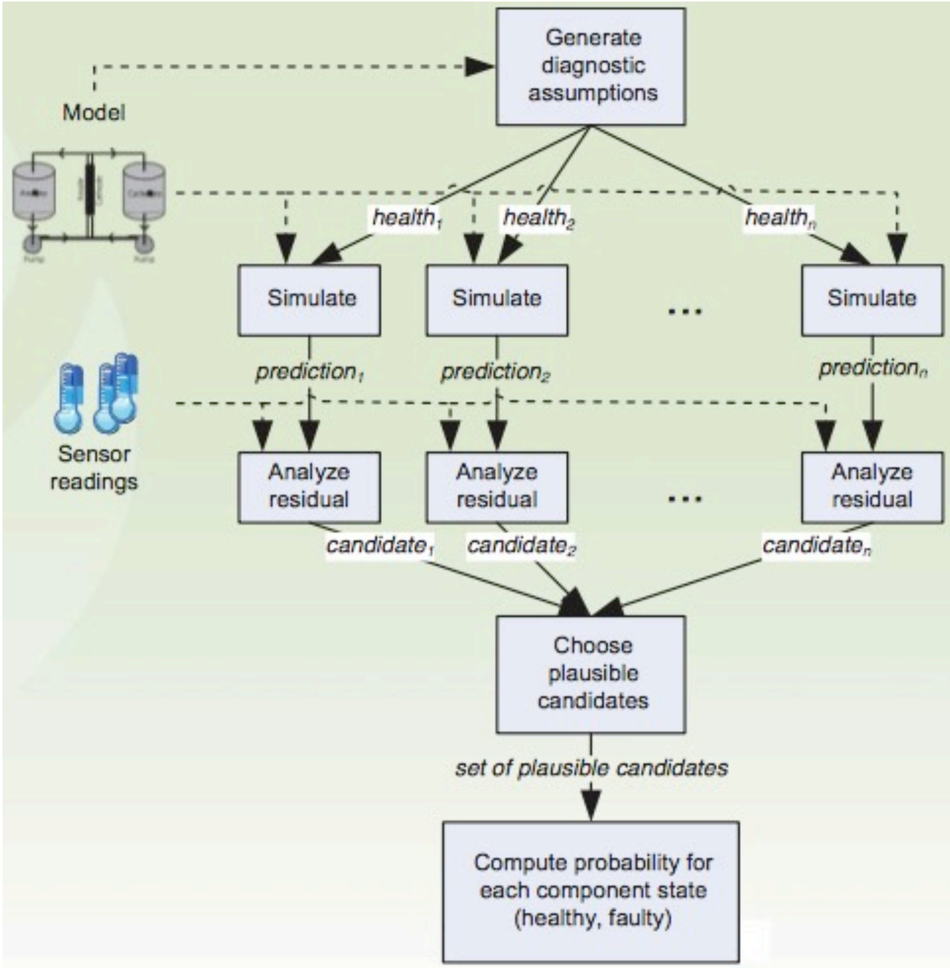
- Identify component(s) that are root cause of failure (error)



- 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 = faulty, or h_4 = faulty and h_5 = 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

- 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
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  - *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
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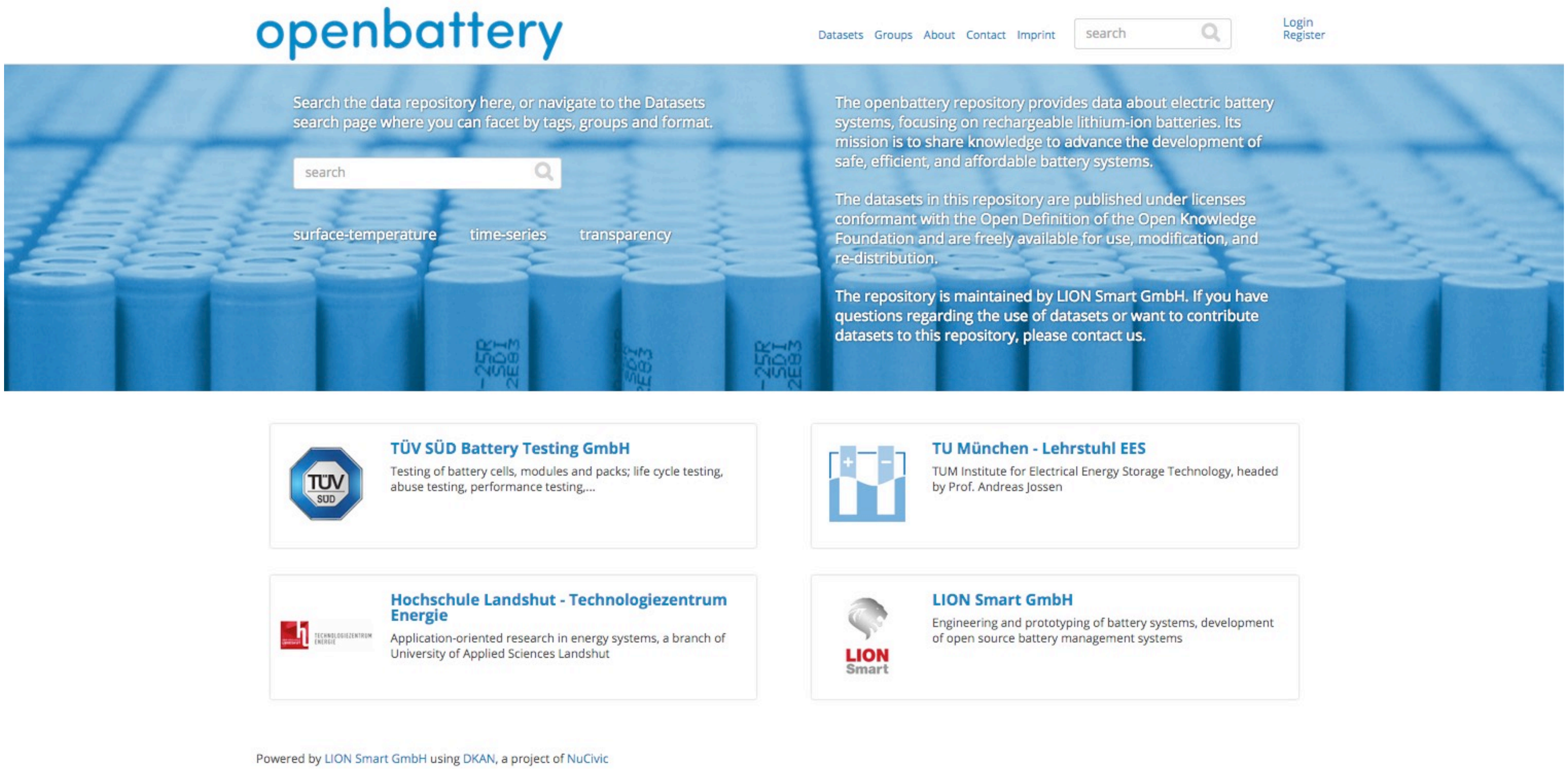
  - 10 seconds runtime, 6 single-fault hypotheses
- Qualitative + Hybrid model (QM used to filter hypotheses)
  - 7 SPICE simulations, 1 minute runtime, 1 single-fault hypothesis

Conclusions

- 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

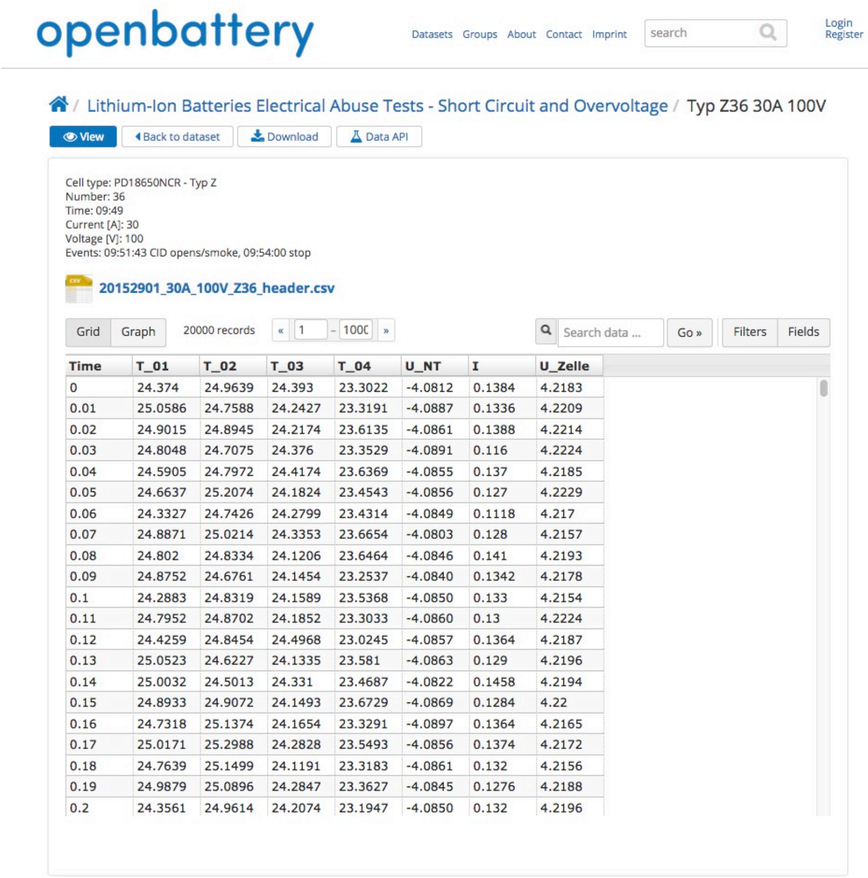
Open Battery Data Platform: Openbattery.org

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



Open Battery Data Platform: Openbattery.org

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



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