San Diego State University
Electrical and Computer Engineering
College of Engineering

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ENERGY COMMISSION

Enabling Technologies for Deploying Second-Life EV Batteries in Grid Storage Applications

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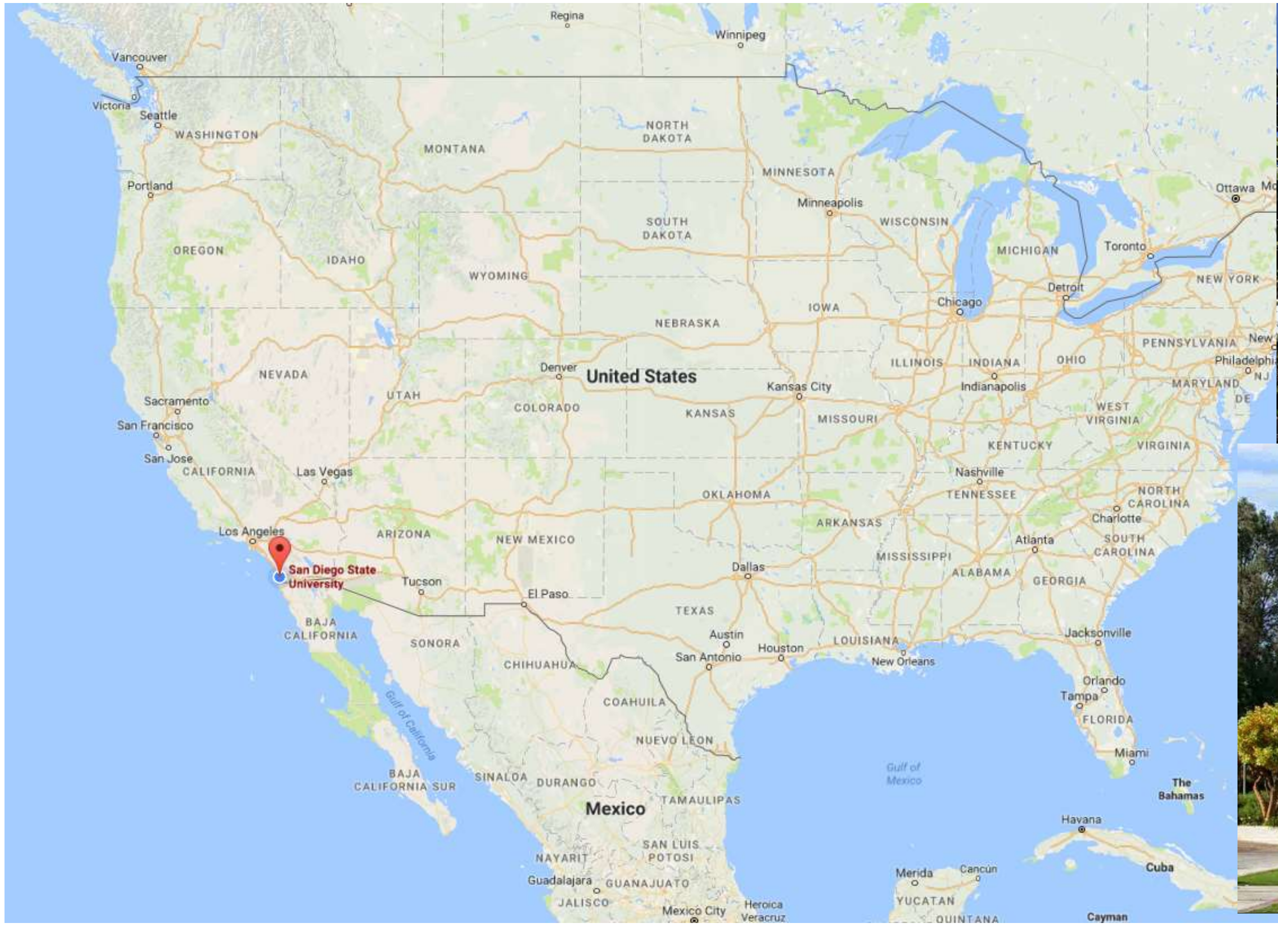
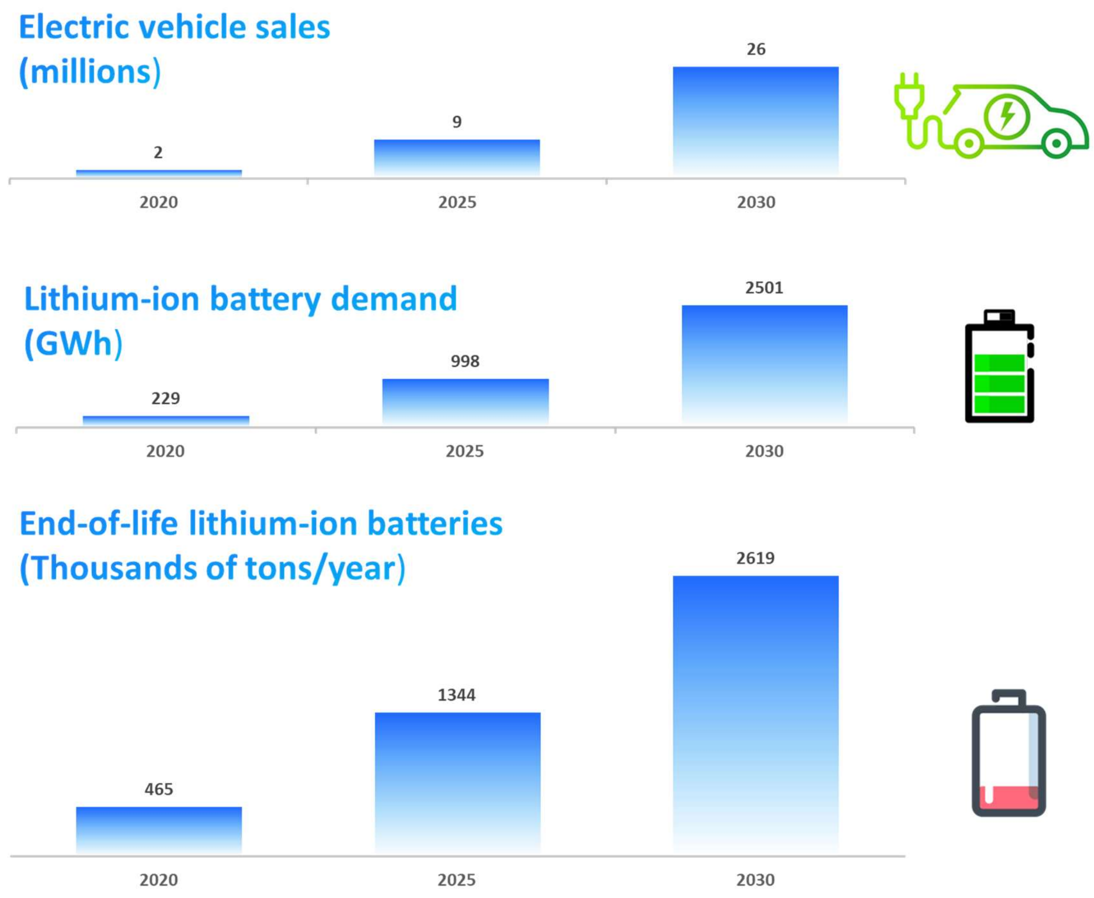


Outline

- **Needs of energy storage in renewable energy systems**
- **Second-life batteries**
- **Aging of second-life EV batteries**
- **Energy storage system design with SLBs**
- **Standards for the use of second-life EV Batteries**
- **Recycling of EV Lithium-Ion Batteries**
- **The project is to answer three questions:**
  - Can spent EV batteries be used for storage applications?
  - If yes, how can they be used?
  - How can the system be designed to be safe, reliable, and cost effective?

Electric Vehicle & Battery Growth

- **EV battery market has 750GWh, $126+ Billion USD in 2023 (14M+ vehicles produced)**
    - Assuming $150/kWh and 60KWh battery pack per vehicle -> $9, 000 /EV
- **15 % (HEV + EV) Penetration annually**
- **It will likely triple to reach US$300 billion by 2030, or 2.25 TWh**



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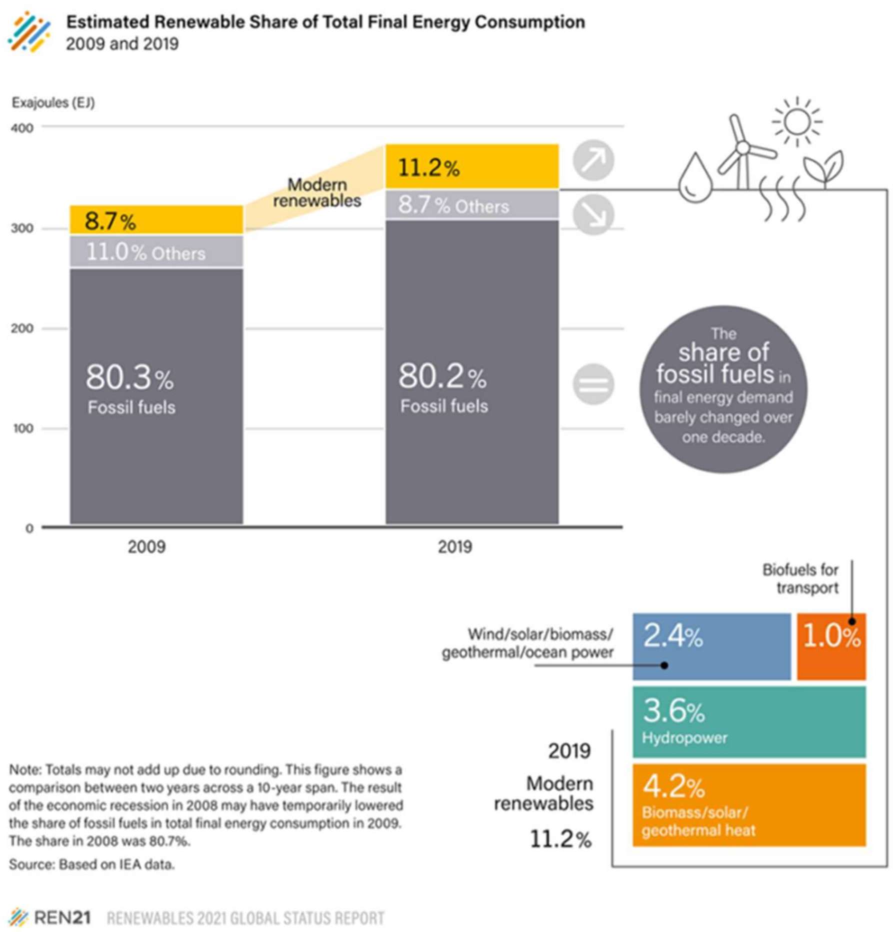
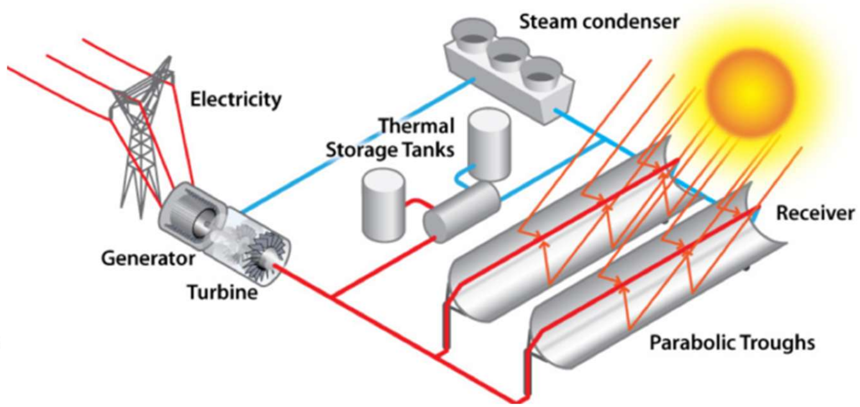
Source: Global Battery Alliance; World Economic Forum; McKinsey analysis

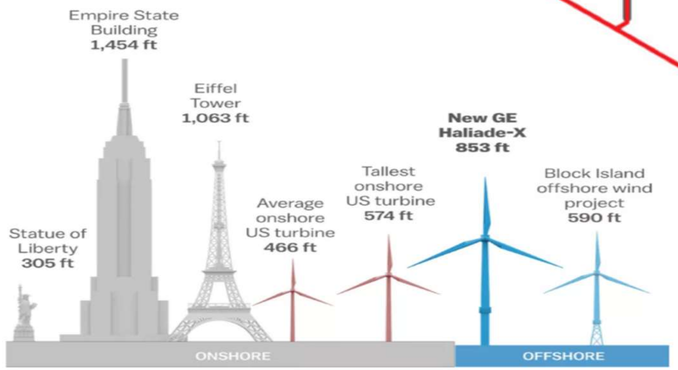
Demand for EV batteries reached more than 750 GWh in 2023, up 40% relative to 2022.

Renewable Energy Growth



- **Added together, lithium-ion batteries will reach 7 TWh/year by 2030 or US$ 1 trillion**





https://www.c2es.org/content/renewable-energy/#:~:text=At%2Da%2Dglance,percent%20from%202000%20to%202020).

Second-life EV batteries

- **Second-life EV batteries include those that**
  - are discarded EVs due to degraded conditions;
  - in-warranty replacements;
  - road accidents;
  - test vehicle batteries; and
  - unsold batteries.
- **These batteries may have energy for other purpose before being recycled. Use of these batteries in Grid BESS**
  - extend the life cycle of batteries after their first life in EVs
  - improve the environment
  - reduce EV ownership cost by selling them for second-life use
  - reduce the cost of BESS in renewable energy systems

Barriers to Use Second-Life EV Batteries

- **Reliability, cost, and safety are of great concerns.**
- **The following hurdles must be addressed:**
  - Proper removal from EV, transport, storage, testing and selection of second-life batteries for storage applications;
  - Quick, simple and accurate battery health estimation of every cell within the BESS after deployment in grid storage;
  - Dynamic battery management systems that can minimize degradation and optimize usage;
  - A thermal management system;
  - Fire hazardous mitigation/prevention, certification, permit, and meeting all other safety related standards.

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

Aging of Second-life EV Batteries

Tested Batteries

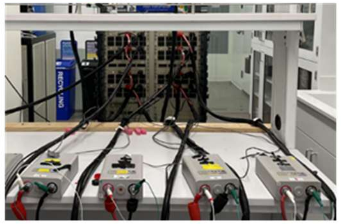
1

BYD LFP Battery Modules (270Ah 3.2V)

- Four BYD LFP battery modules and cells tests

2

CALB LFP Battery Cells (100Ah 3.2V)



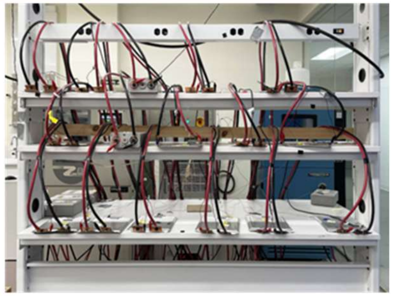
- Four battery cell aging test - 9000 cycles
- The influence of long-time resting on the battery SOH

Nissan Leaf Gen1 Battery Packs (32.8Ah *3.8V) *2P*96S = 24kWh

- 100 Battery Packs SOH investigation
- Tested two battery packs
- Aging test for two battery cells -- 7000 cycles

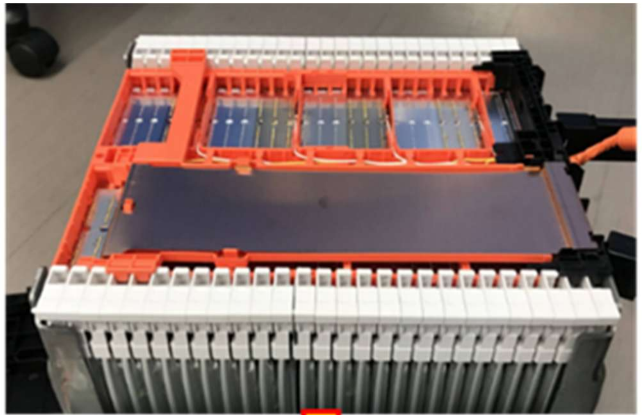
Nissan Leaf Gen3 battery packs (56.3Ah *3.75V)*3P*96S = 62kWh

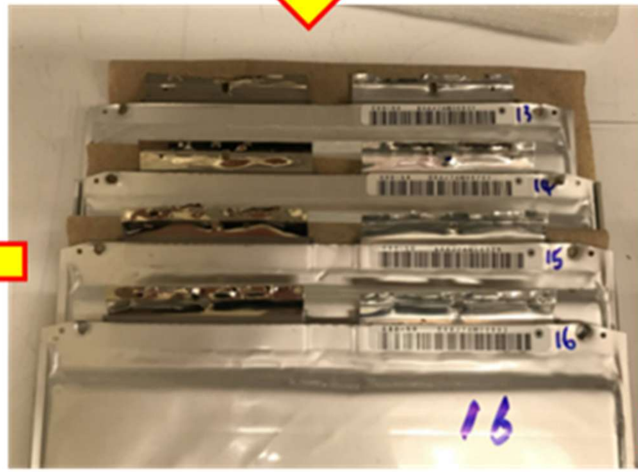
3P*4S

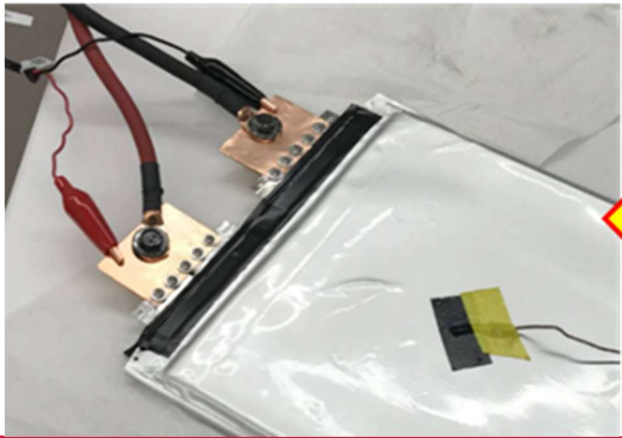


- Tested 24 retired battery packs
- Aging test for a battery module - 1000 cycles
- Aging test for 24 battery cells at different working conditions

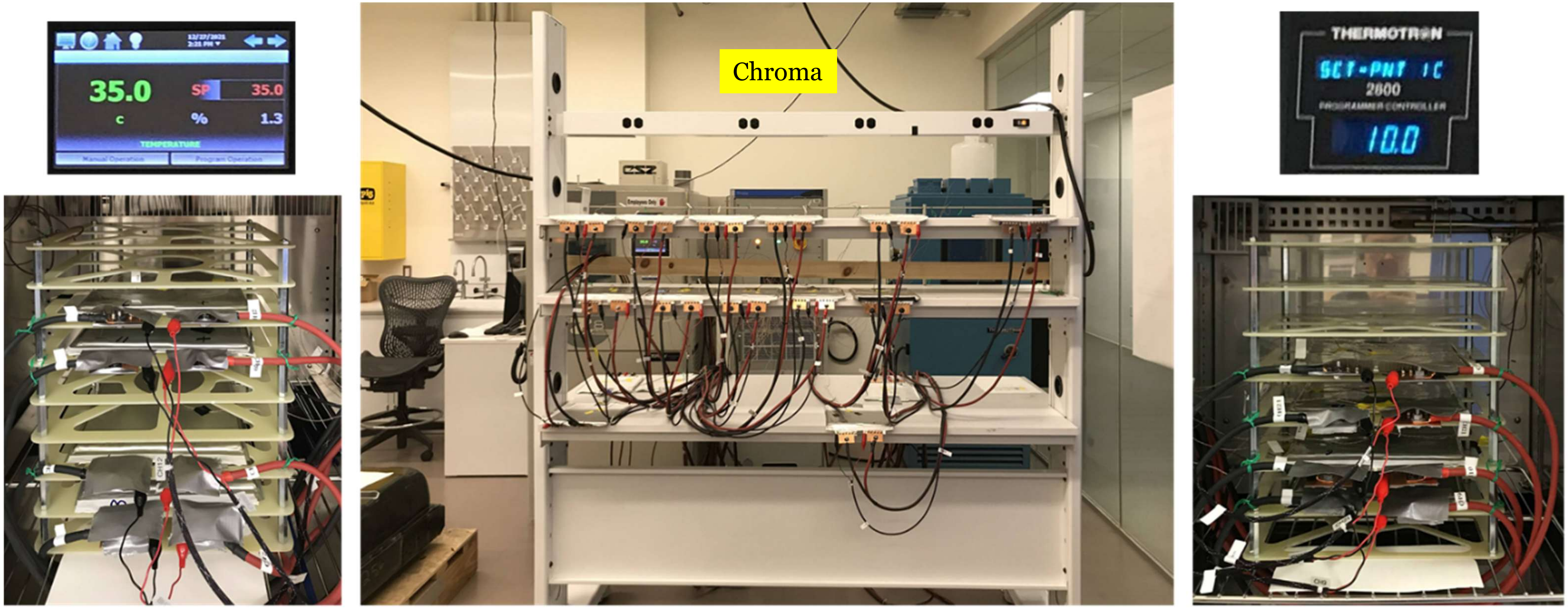
Leaf Gen3: Pack to Module to Cell







Temperature Testing – Leaf Gen3

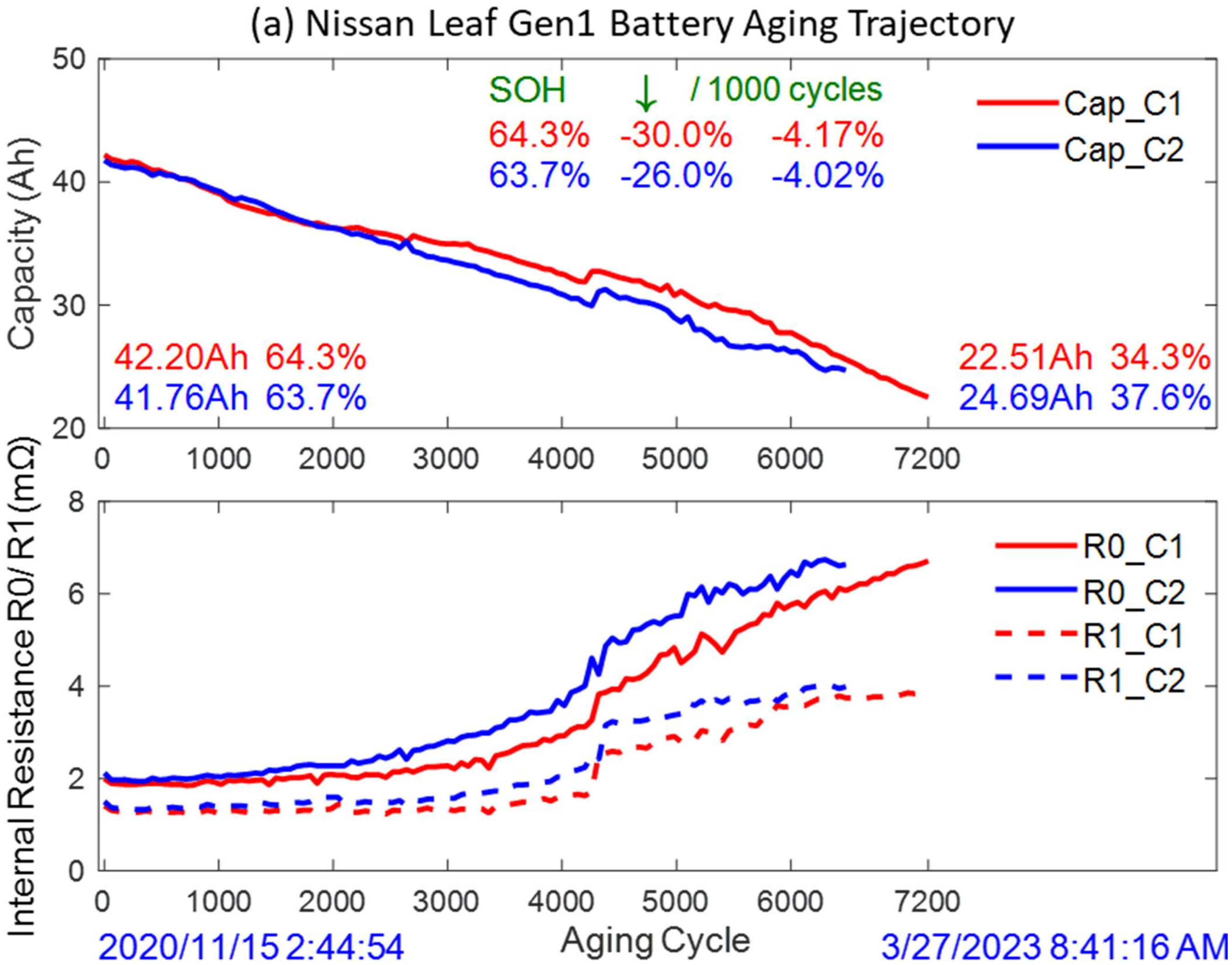


(a) CSZ +35°C (b) Room Temperature 23°C (c) THERMOTRON +10°C

Aging Test Results:

Nissan Leaf Gen 1

20 months aging test, 5640 cycles
– equivalent to 19 years of second life service



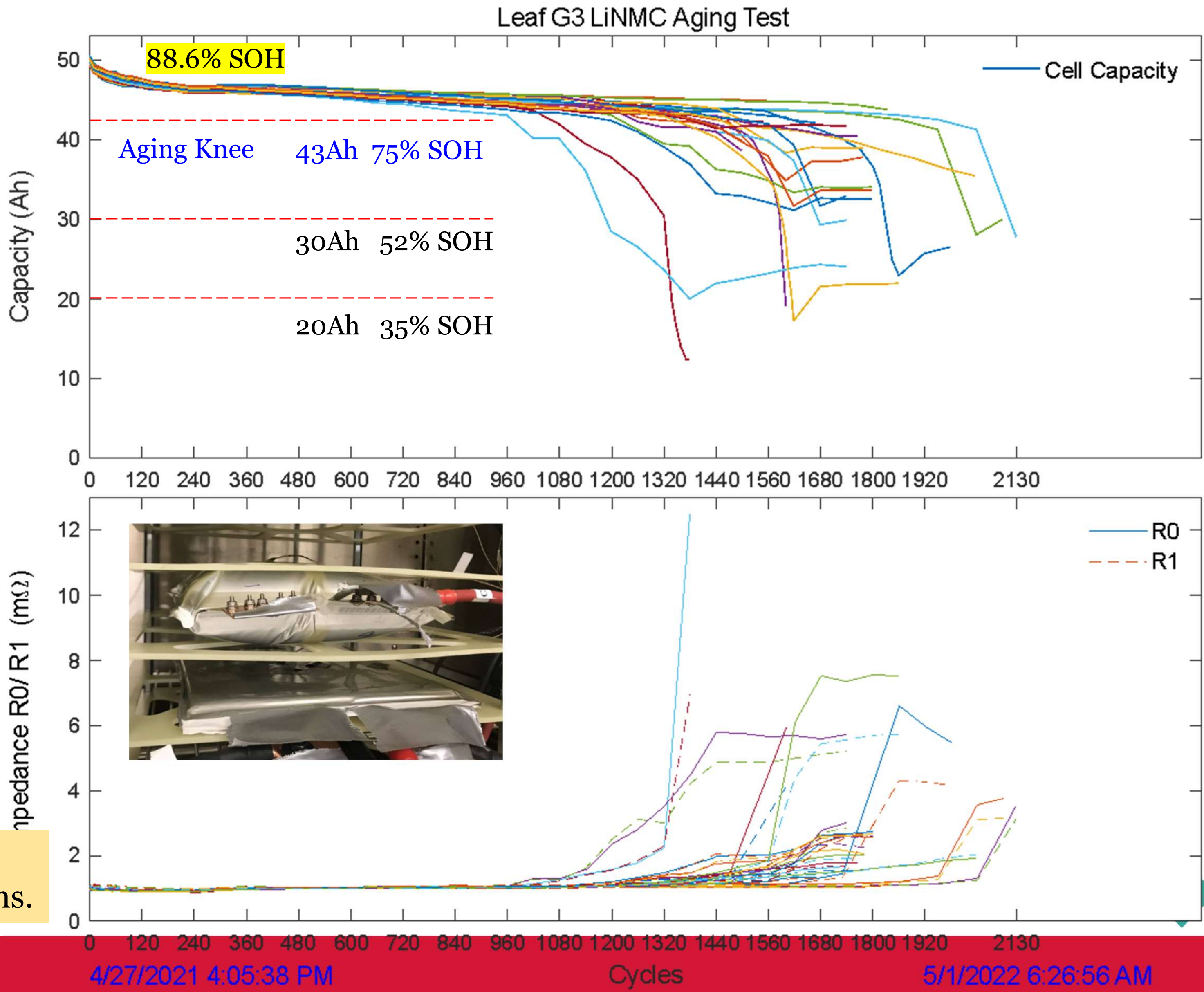
Aging Test Results:

Nissan Leaf Gen 3

Optimal Working Condition
:

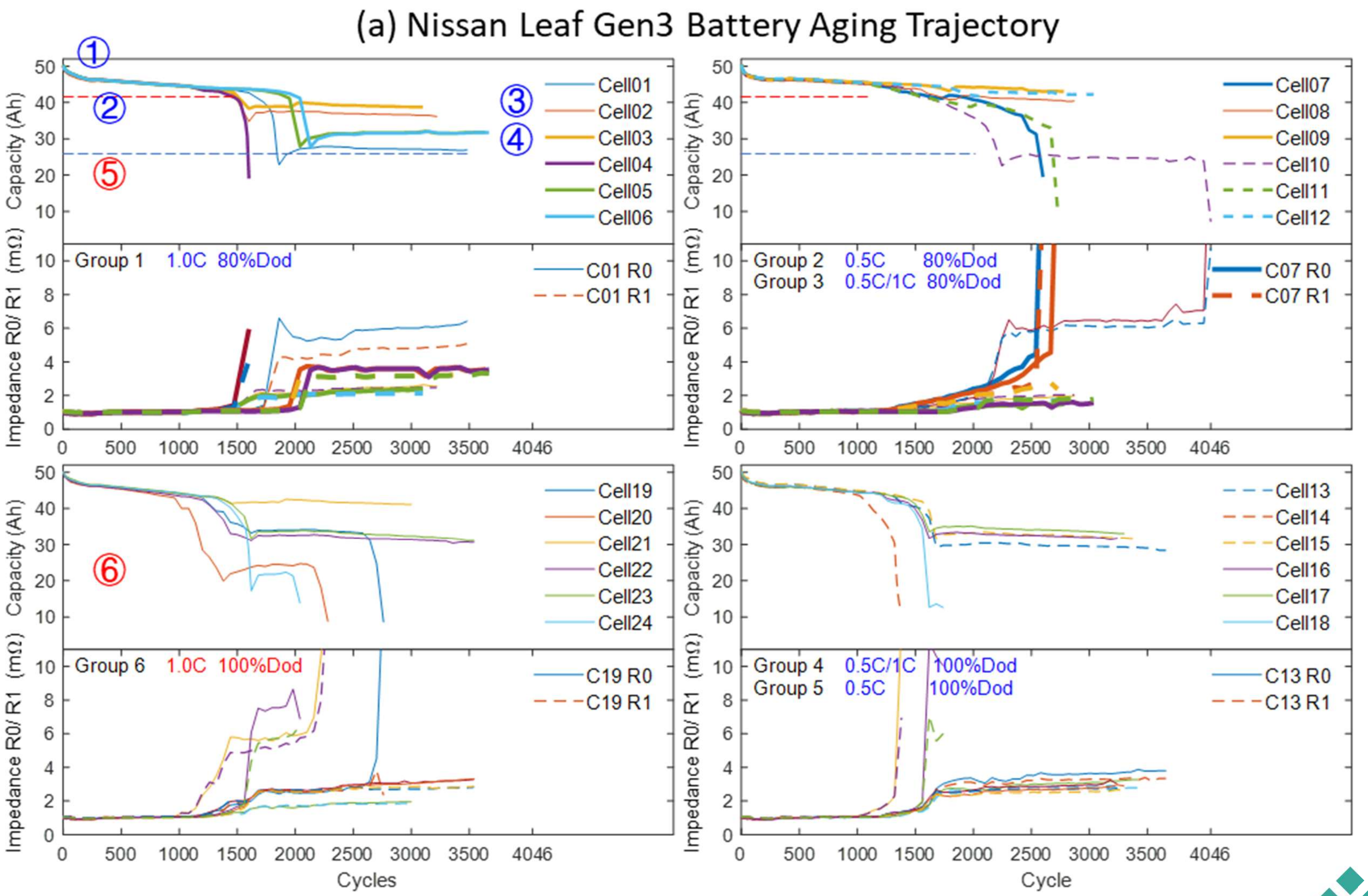
- <=0.4C rate (4 hour BESS)
- Temperature: 15°C~27°C
- Dod: 80% 10%~90% SOC

Higher energy density, lower cycle life, and more sensitive to working conditions.



Leaf Gen 3

Performance under different Testing Conditions



Leaf Gen 3 Aging Summary

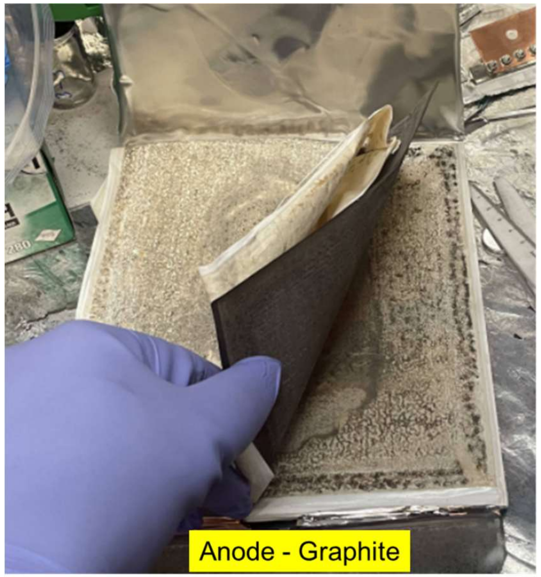
- 24 Nissan Leaf G3 batteries completed 2000~2400 aging cycles
- 15 months of testing
- Divided into 6 groups for different testing conditions
- Soon after they reach the aging knee, the capacity degrades very quickly
- Batteries working at harsh conditions (Group 6) reached the aging knee after 1200~1500 cycles (1C, 100% DoD)
- Batteries working at better conditions (Groups 1, 4, 5) reached the aging knee after 1500~2000 cycles (0.5C/1C, 100%DoD)
- Batteries working at good conditions (Groups 2, 3) reached the aging knee after 2000 cycles (0.5C, 80% DoD)

Leaf Gen 3 Aging Summary

- The aging knee can be stopped as soon as the cycle conditions are improved, i.e., current<0.4C rate, and Dod<80%.
- Even though the battery capacity has dropped to 50%~60% nominal value, they can still be cycled another 500 times with improved working conditions.
- If the battery aging knee is detected in the early stage, e.g., when battery capacity has dropped to 75%~80% of its original/nominal capacity, then the battery pack should be retired from the EV and diverted to BESS purpose.
- The battery pack's working conditions should be strictly confined, and their expected service life should be at least 1000~2000 cycles / 4~6 years before the capacity drops to below 50%, and the second-life degradation speed is expected to be 10%~20% per 1000 cycles.

End of Life Batteries

- **Nissan Leaf Gen 3**
- **Dead after 2000 aging cycles**
- **Dissembled to understand the failure mechanism**
    - The battery material is still wet, which means the electrolyte was not dried out.
    - There is a lot of graphite ripped off the anode copper sheet, suggesting anode graphite material failure, this may be the reason for the dead battery.
    - Nothing special can be found on the cathode material by the naked eye.



Second-life EV Batteries – Summary

Step	 • Nissan Leaf Gen1 24 kWh LiMO2	 • Nissan Leaf Gen3 62 kWh LiNMC	 • Electric Forklift LFP 100Ah battery	 • Electric Bus LFP 270Ah battery
1: Initial SOH	60%~67%	89~97%	Cell: 89% SOH Pack: 50%~60% SOH	Cell: 79% SOH Pack: 52% SOH
2: Balance State	< 5% minor	< 5% minor	30% serious	27% serious
3: Capacity degradation speed ▪ *Fast / Vehicle* ▪ *Slow / BESS*	20% / 1000 cycles 4% / 1000 cycles	20% / 1000 cycles 3.6~5.9% / 1000 cycles	9.3% / 1000 cycles 5.0% / 1000 cycles	Balance Issues exist
4: Aging Knee	No aging knee	Aging knee at 75% SOH (1500 cycles)	No aging knee	
5: Estimated 2nd life	10~15 years 3000~5000 cycles 10 years / 3000 cycles high performance	10 years 3000 cycles 80% Dod <0.4C-rate	30 years 9000 cycles 100% Dod 0.5C charge/ 1C discharge	>10 years 3000 cycles Enhanced balance system is needed

Storage System Architecture Using Second-Life EV Batteries

Using the pack as a storage unit

- **Multiple packs connected in series and/or parallel using various power electronics converters.**
- **Advantages:**
  - Easy to obtain
  - Easy installation
  - Low cost for grouping the system
- **Disadvantages:**
  - Cells inside the pack may be unbalanced – need to address balancing issues
  - No access to cell monitoring
  - Access the CAN messages of the onboard BMS is not possible – a GATEWAY is necessary

Disassemble the pack and obtain battery cells

- **Advantages**
  - Cells can be grouped based on their SOH
  - Bad cells are discarded for recycling
  - Maximize the new BESS capacity and longer life span
- **Disadvantages**
  - Labor intensive to disassemble packs
  - Damage can happen during disassembling
  - Dangerous for the disassembly process itself
  - Difficult to test and store the cells
  - A new BMS is needed for the new BESS
  - May not be cost-effective

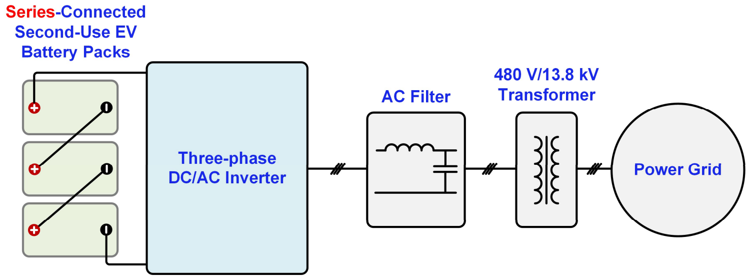
SDSU System Deployed at UCSD Warehouse

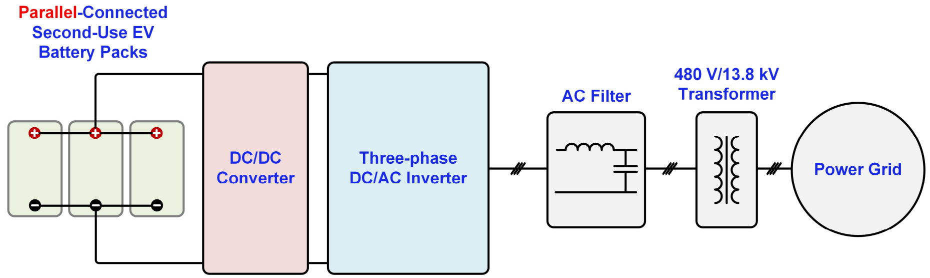
- Six Nisan Leaf Gen 3 packs
- Total 372 kWh nominal
- Used packs as is
- No balance issues

Installed at UCSD Warehouse

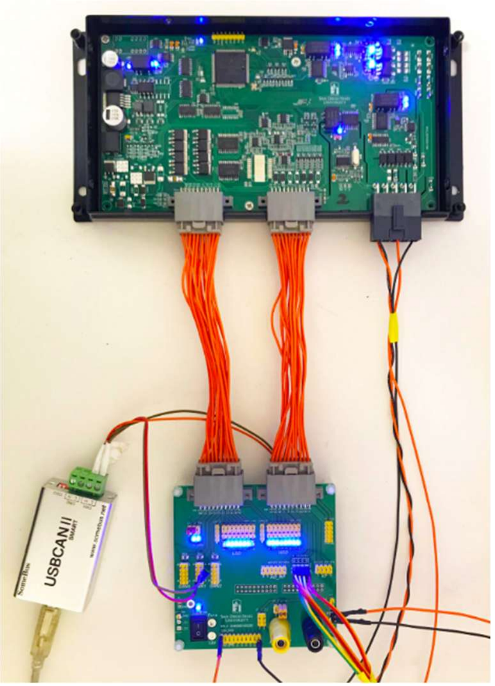
System Design Considerations

- **EV battery packs are typically 300-400V**
- **Single pack connected to inverters will only support 208V/3-phase grid.**
- **While the minimum DC-link voltage required for a 480V/3-phase grid is 750V (= 480 * $\sqrt{2} * 1.1$)**
  - Option #1: two to three packs needs to be connected to series
  - Option #2: Connect each pack or paralleled packs with a DC-DC, and the output of the DC-DC could be fed to an inverter



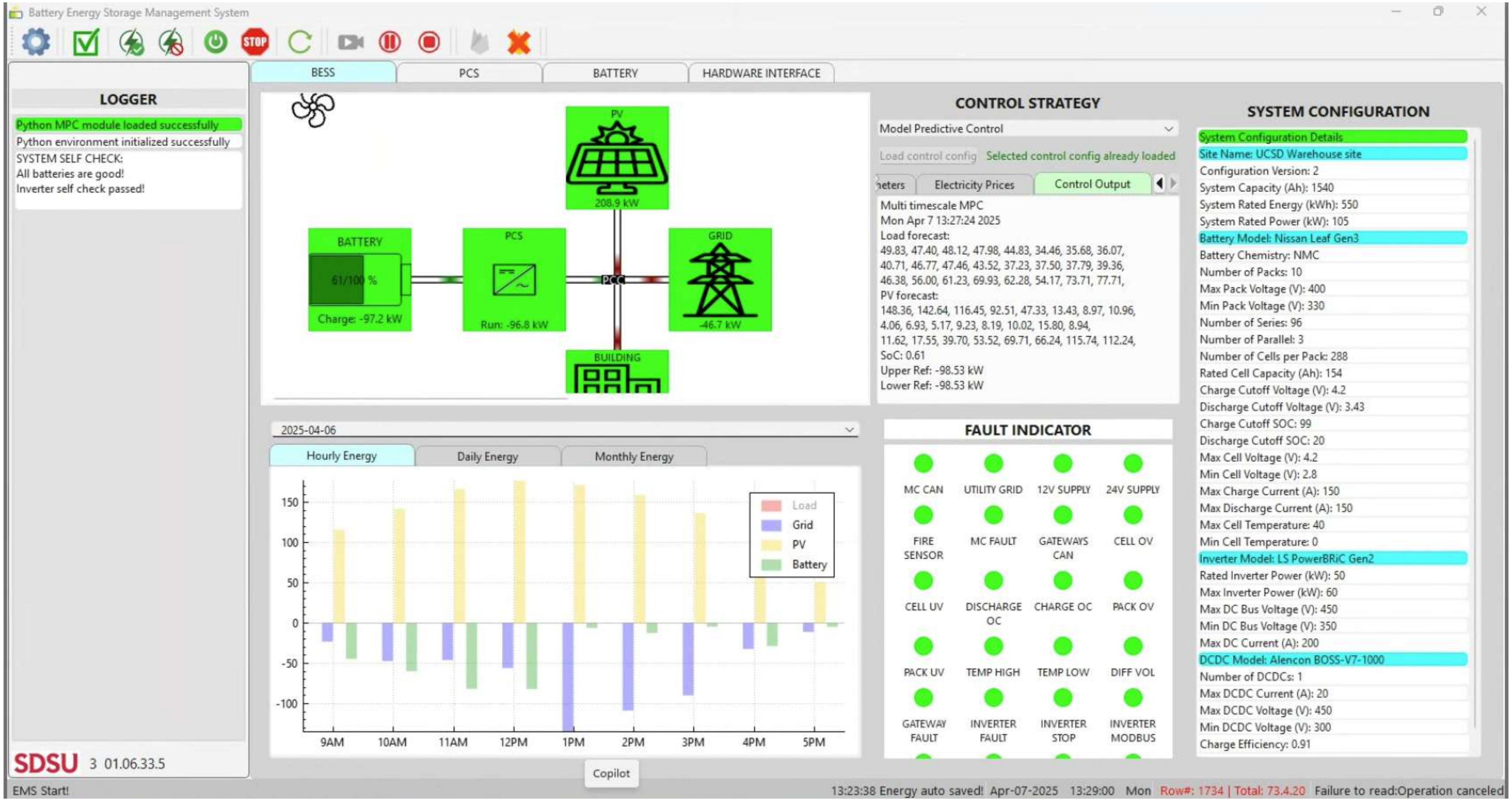


BMS Gateway Design and Manufacturing



- The BMS-Gateway is designed to work between each Nissan Leaf Gen 3 battery pack and the main controller of the BESS.
- Fourteen BMS-Gateway were produced and will be used in the pilot test and laboratory test.

Modular Energy Management System



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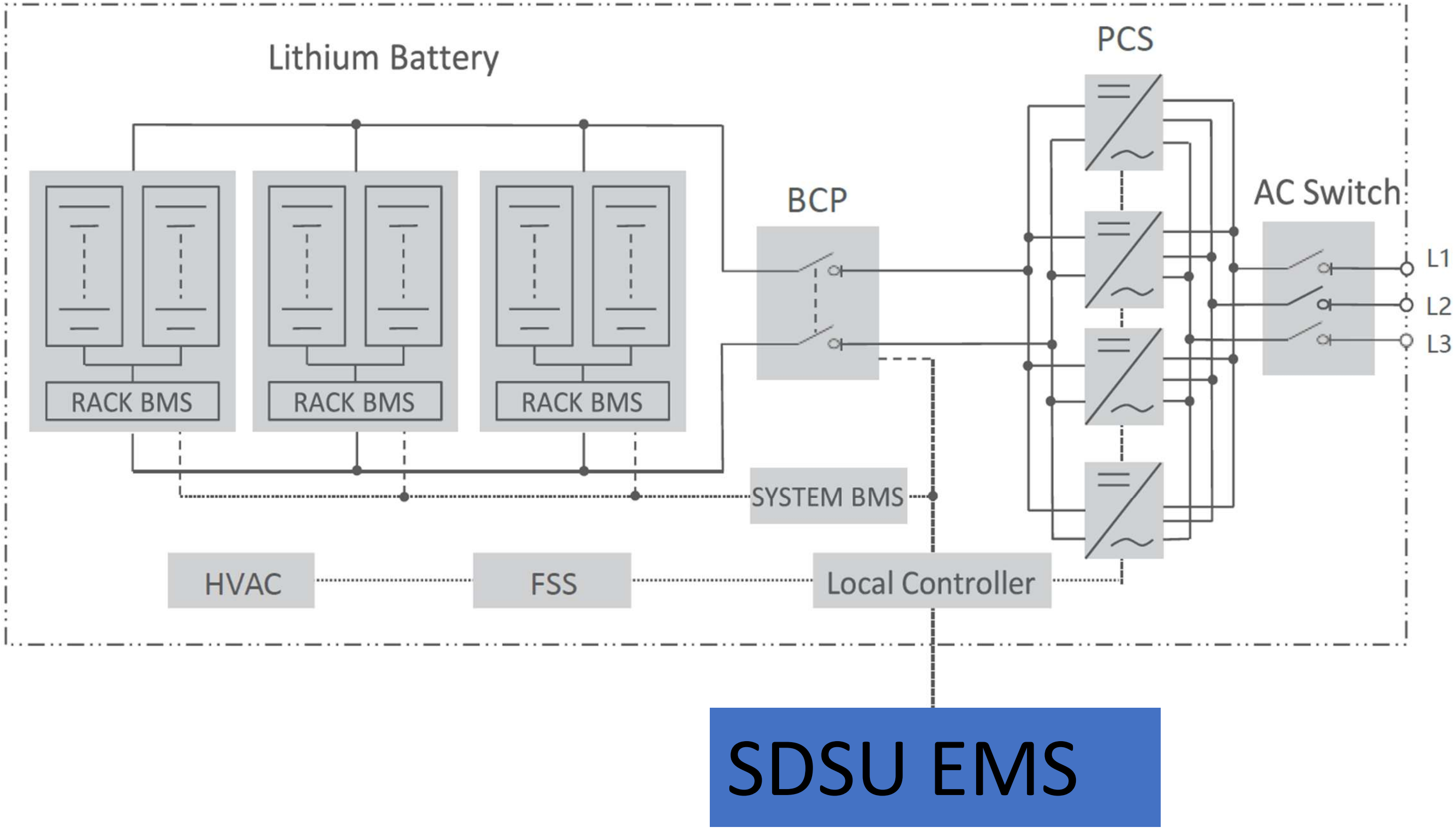
The goal of MEMS: minimize the electricity bill and extending life of battery

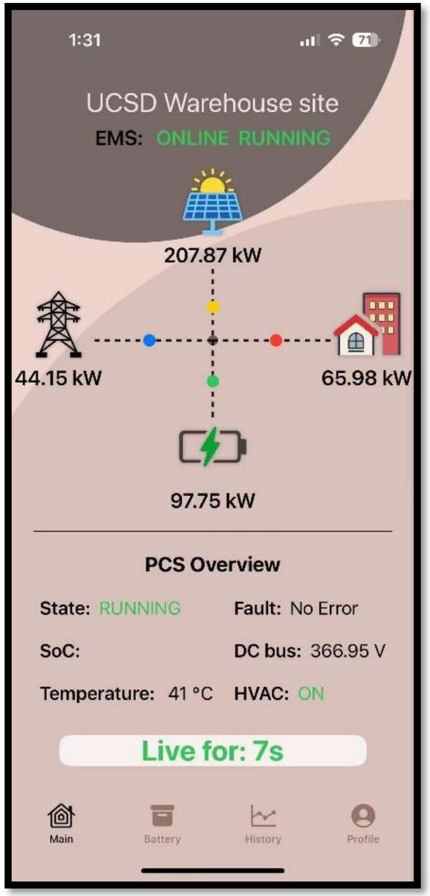
New ESS with our EMS

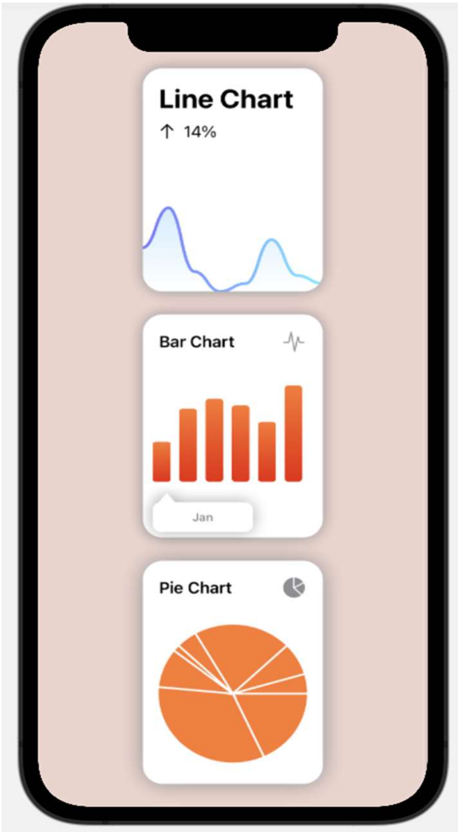
- 556kWh
- 250kW
- 480V
- SunGrow System
- Samsung SDI Mega
- 3.68 V / 100 Ah cell



Funded by the California Energy Commission.

Phone App for Realtime Monitoring





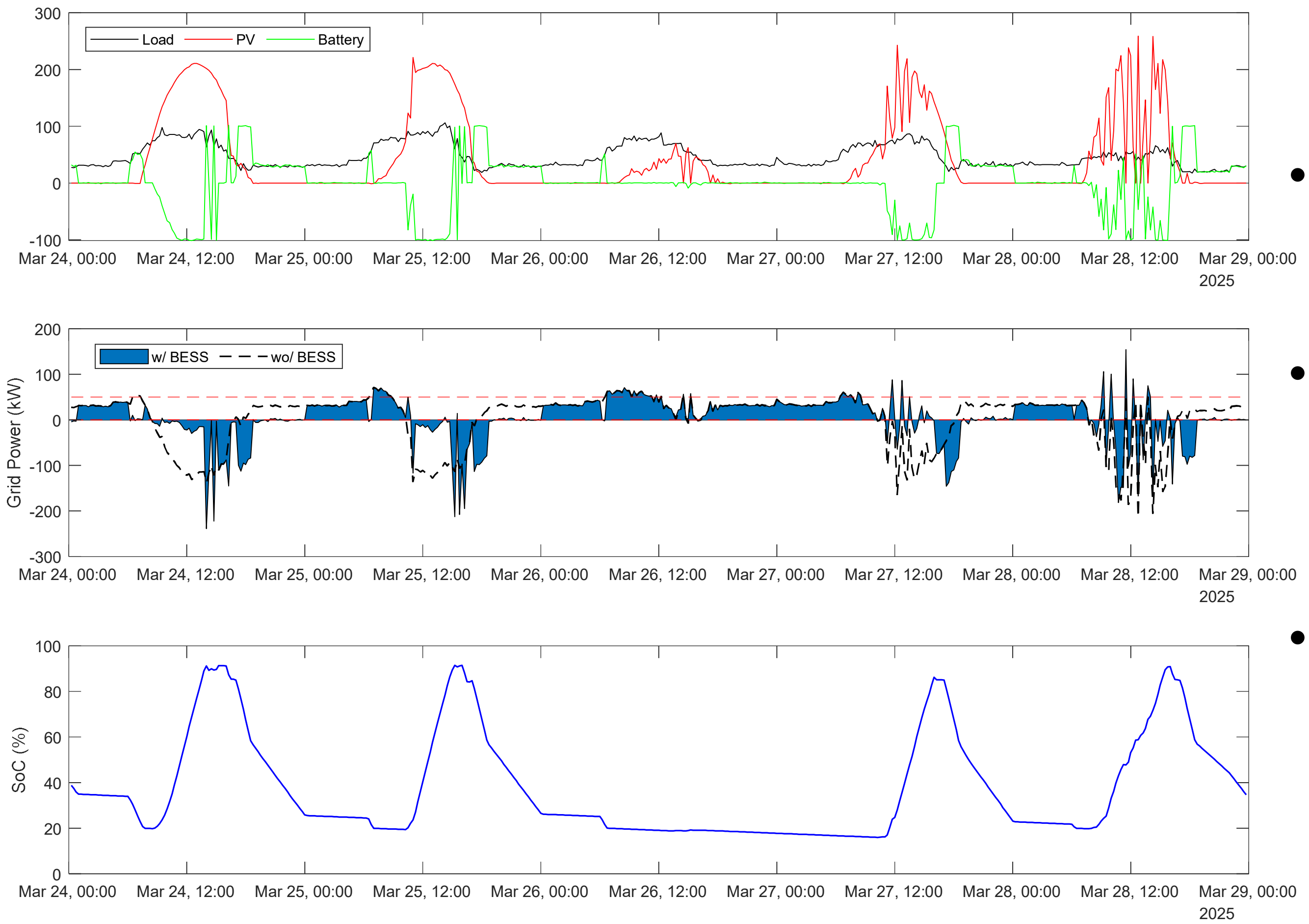
iPhone APP

Coded using Swift and Xcode for IOS

Functions:

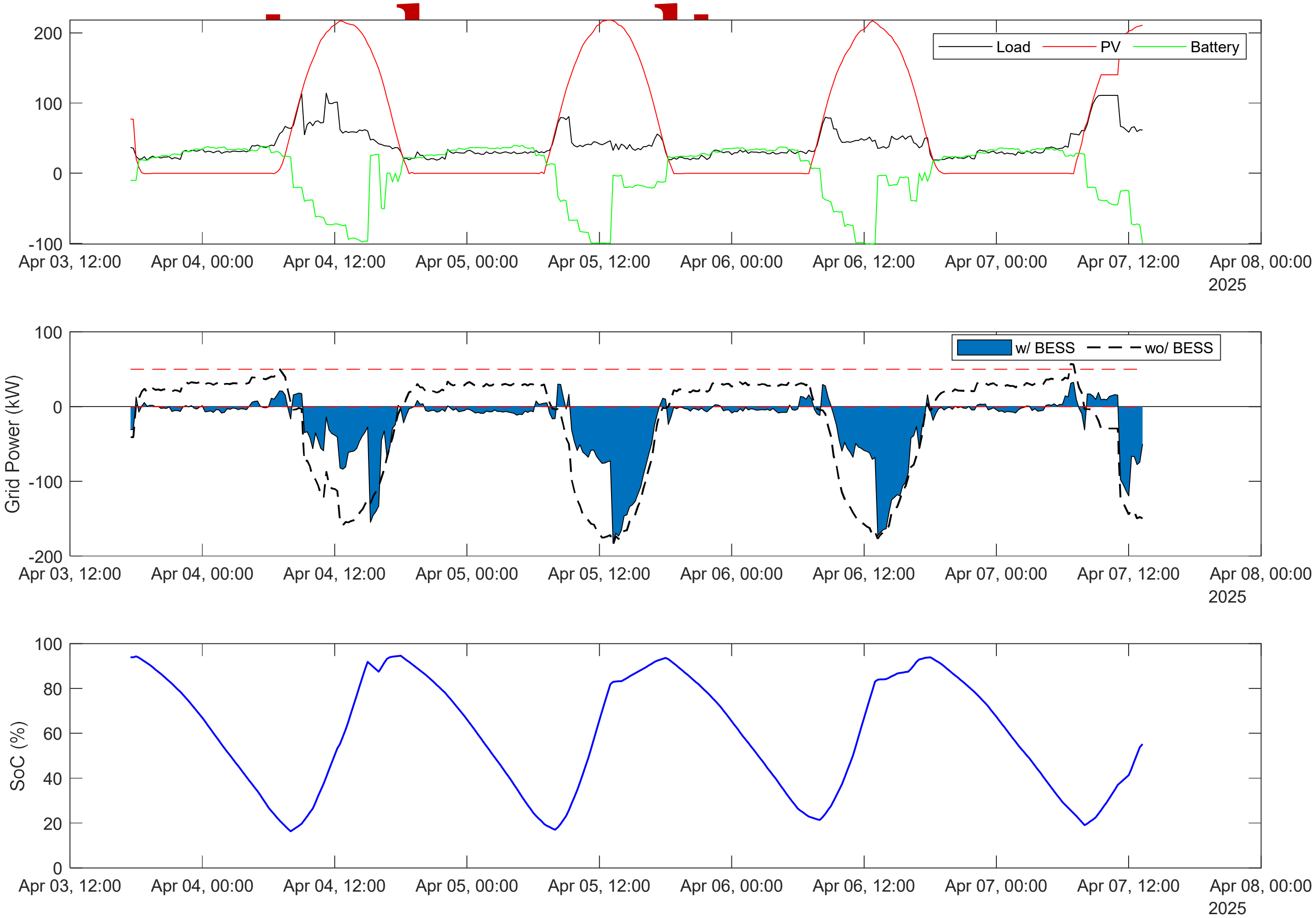
- Switch time period to see present and past amount of power stored/delivered
- Realtime data and status display
- Analysis: Present the histogram of power generated
- Emergency button: Turn off the system in an emergency.
- Core users (control functions) and viewers

Lyapunov control results



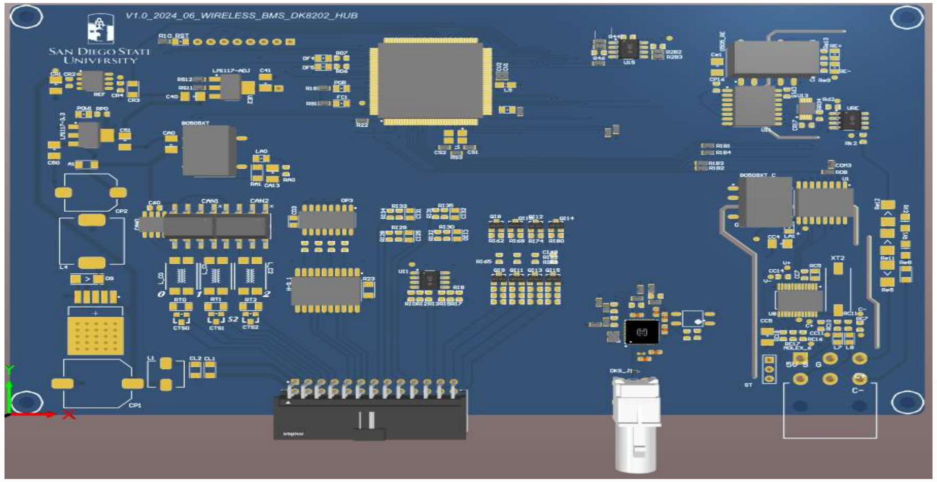
- Lyapunov control tends to charge the battery at maximum power when there is excess PV generation
- Discharges it to the load during the early evening at maximum power.
- As a result, it often drains the batteries around midnight, making them unavailable to support the load further.
- This issue arises because Lyapunov control does not forecast load and PV generation over a long timescale.

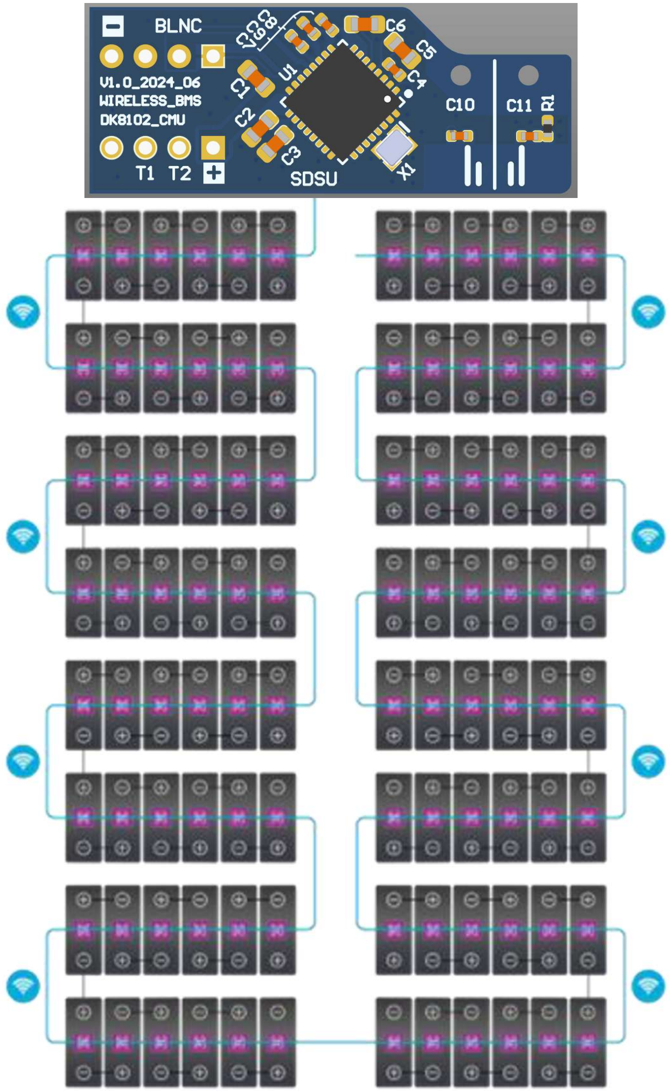
Multi-timescale model predictive



- Multi-timescale MPC predicts load and PV generation for the next 24 hours
- Allowing it to schedule battery power optimally and avoid early battery depletion.
- Multi-timescale MPC demonstrates better performance in reducing grid power usage, lowering both energy charges and demand charges.

Wireless BMS



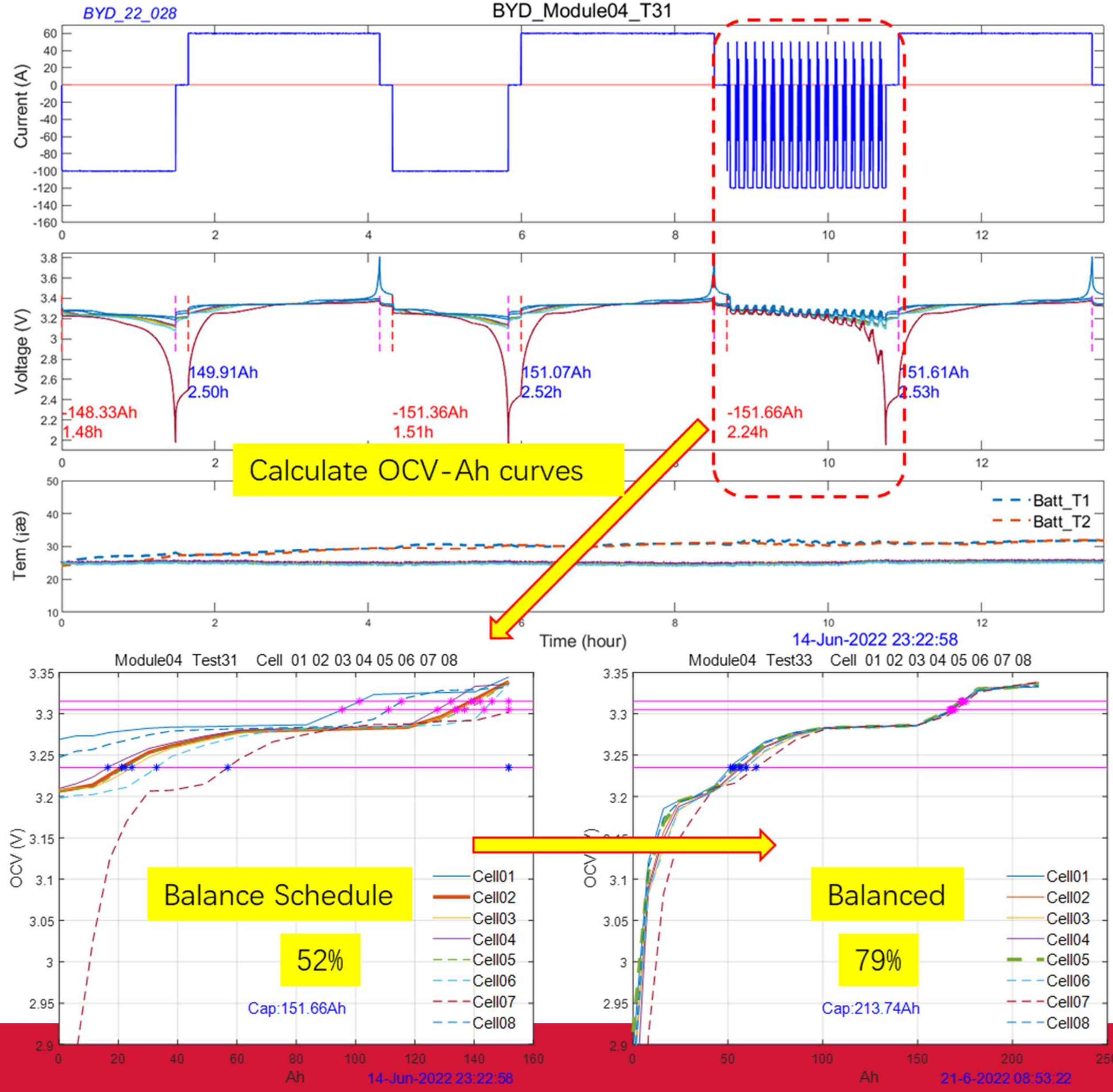


Funded by the CEC, Gotion, and in collaboration with Dukosi.

The Effect of Balancing

- **BYD battery module's capacity recovered from 52% to 79% after balancing**

- First, the OCV-Ah curves of the 8 cells of BYD module4 are calculated based on the dynamic test cycle.
- The relevant distance of the high-ramp of OCV-Ah curves can be calculated, and the balance schedule is defined based on the relevant distance data.
- Each battery cell will be charge or discharged using a defined Ah value, therefore, the high-ramp of the OCV-Ah curves can be overlapped, and consequently the battery is balanced.



Standards

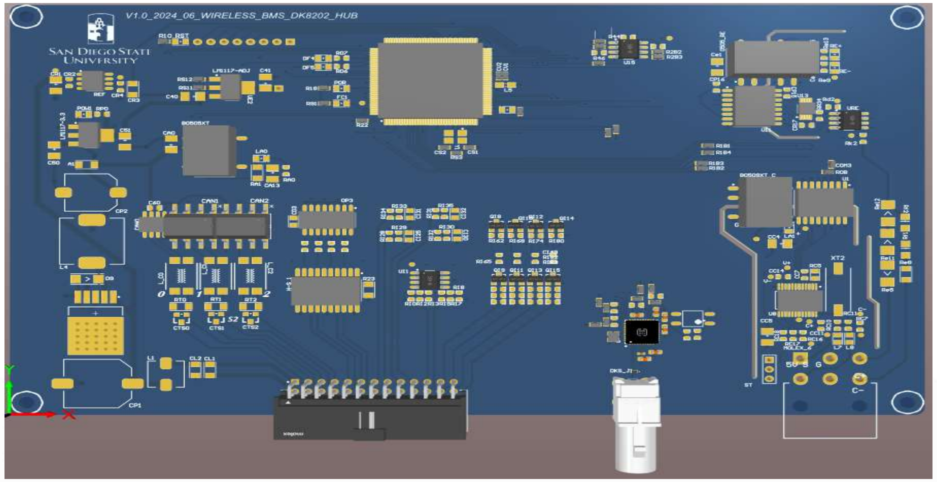
- **For end users/producers**
  - NFPA 1, Fire Code (Also applicable: California Fire Code 2019)
  - NFPA 855 – Installation of Stationary Energy Storage Systems
  - NFPA 70 – National Electric Code (NEC)
  - UL 9540 – Energy Storage Systems and Equipment
- **For producers**
  - UL 9540A – Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
  - UL 1974 - Creating a Safe Second Life for Electric Vehicle Batteries
- **For suppliers**
  - UL 1642 – UL Standard for Safety Lithium Batteries
  - UL 1741, Inverters, Converters, Controllers, and Interconnection System Equipment for DES
  - UL 1973 – Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and LER
  - IEC 62619 – Requirements for Secondary Cells and Batteries for use in Industrial Applications
  - IEC 62933, Electrical Energy Storage (ESS) Systems

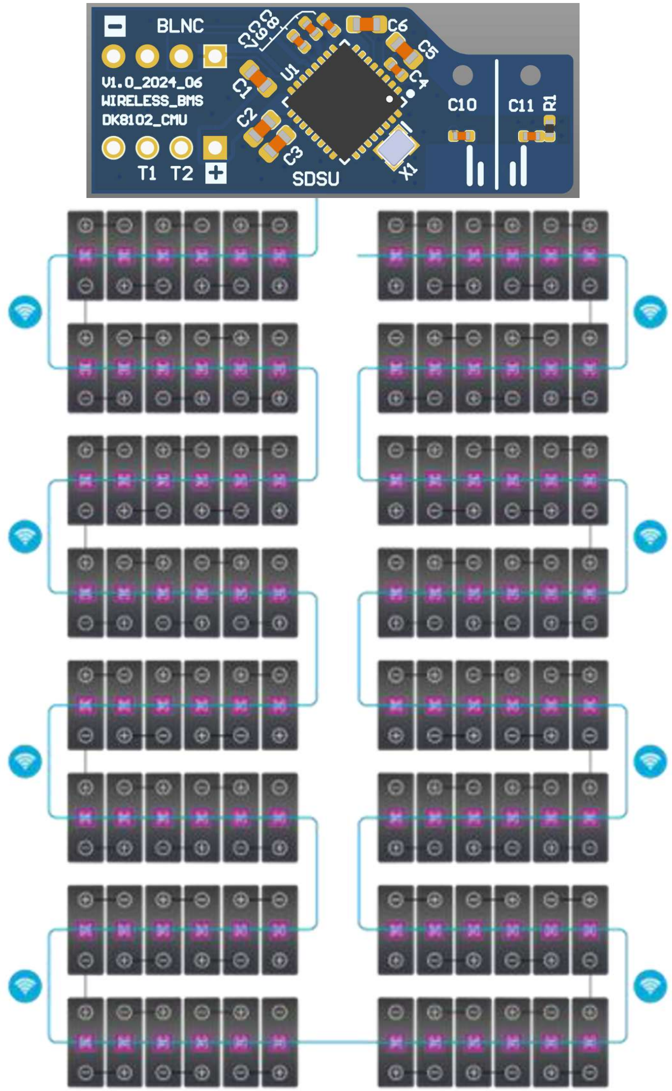
Conclusions

- **EV batteries will start to retire and will be in volume soon**
- **Second-life use can extend the life and reduce environmental impact**
- **Logistics (removing, testing, sorting, storage, transportation, etc.) can be bottlenecks**
- **Safety is another major concern; policy, incentives, and regulations must be in place very soon**
- **To maintain long life in second-life applications**
  - Balance the cells of LFP battery systems
  - Retire at or before knee point for NMC batteries
  - Temperature: 10- 30^{o}C
  - DOD range: 10 – 85%
  - Discharge rate: < 0.25C

Other Research Activities at SDSU

Wireless BMS





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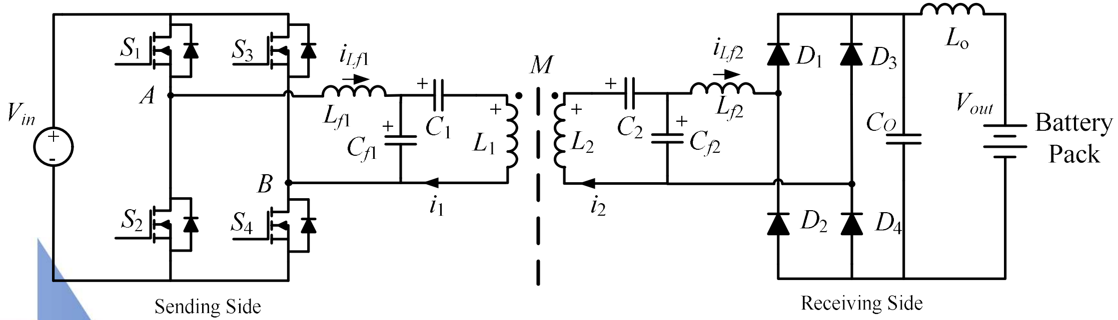
Funded by the CEC, Gotion, and in collaboration with Dukosi.

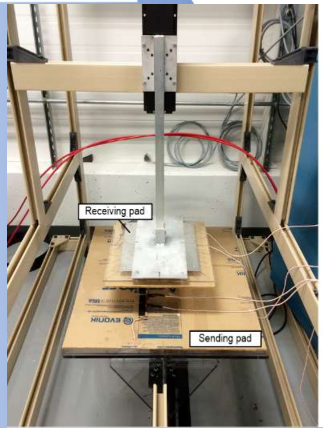
Wireless Charging

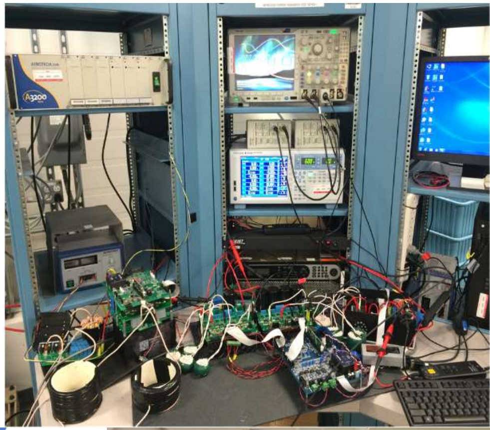


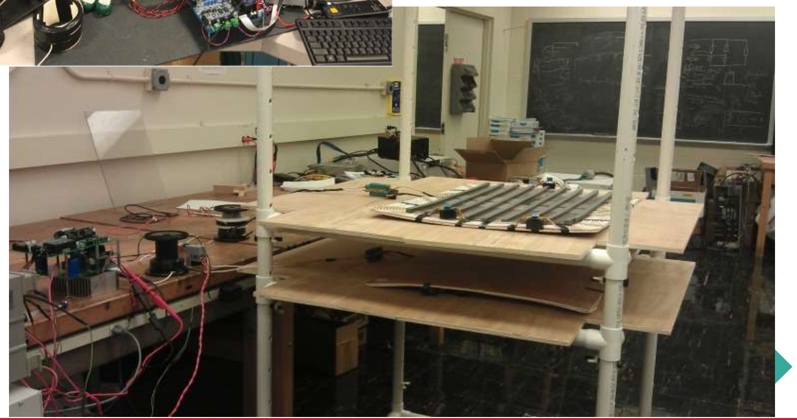
Electric safety is of concern: electric shock due to rain, etc.

Charge station, plug and cable can be easily damaged, stolen

Charge/swap station takes a lot of space and affect the views

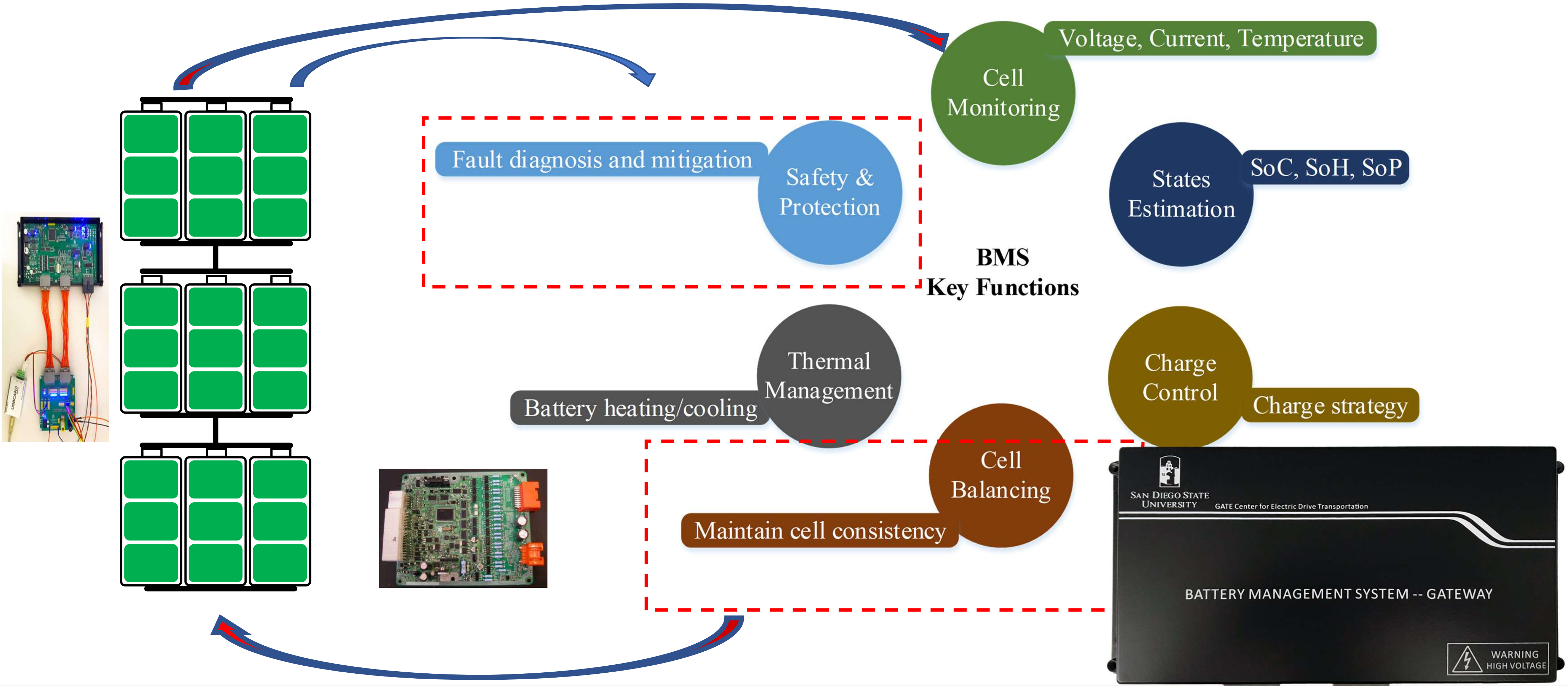






SDSU Projects were funded by the DOE, DENSO, LG, Chrysler, Ford, Hyundai

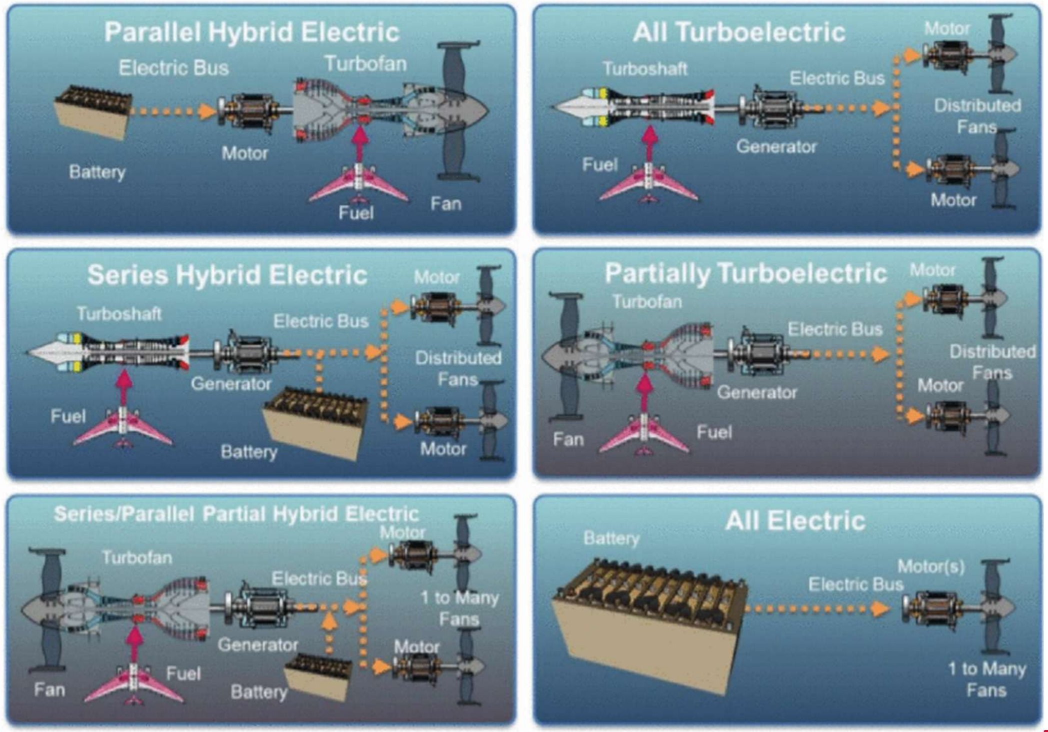
Battery Management Systems



 Projects are funded by the DOE, Ford, Chrysler, Golden Bus, Snovatech, Gotion, DTE

Electric and hybrid airplanes and ships

- 59% GHG emissions of the transportation sector
- EVTOL seems to be ready;
- Long haul large body electric airplane needs breakthrough in energy storage



SDSU Project is in collaboration with Dr. John Hywang, UCSD, funded by NASA ULI

Solid State Batteries

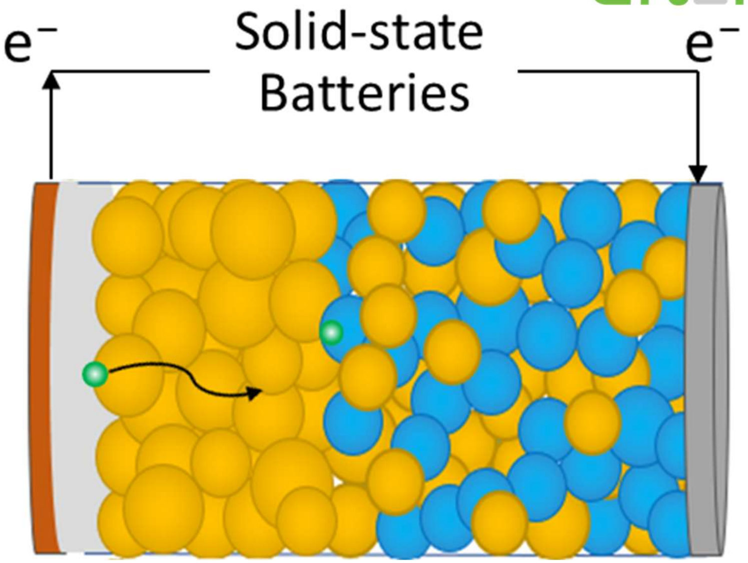
40 Layers
(15Ah)

<1 ATM

5mA/cm^2

-40 to 90ºC

350Wh/kg



- High Safety, not fire hazardous
- Wide operating temperature -40-90C
- High energy density >350Wh/kg
- Cheaper, 25% less cost

cobalt-free, easily sourceable materials

FLEXIBLE

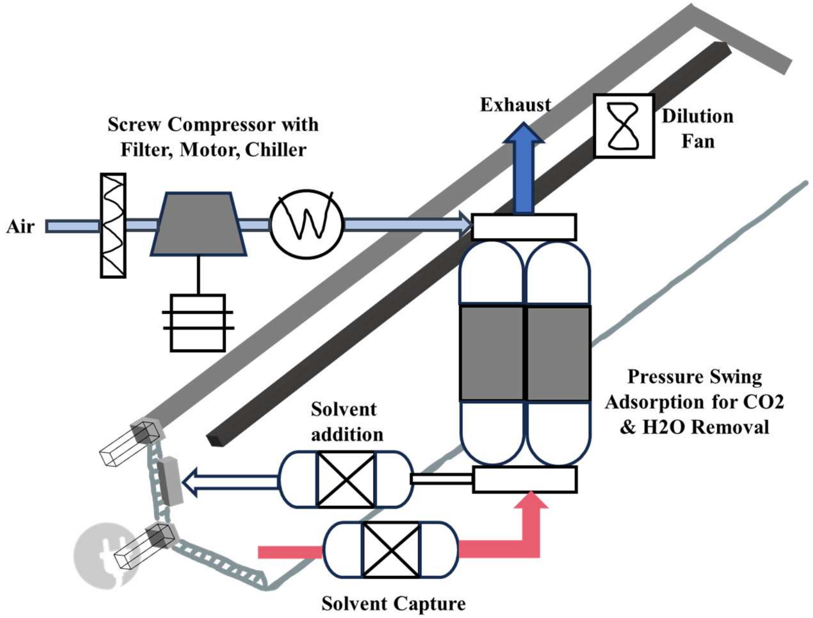
flexible solid electrolyte with extreme low temperature performance

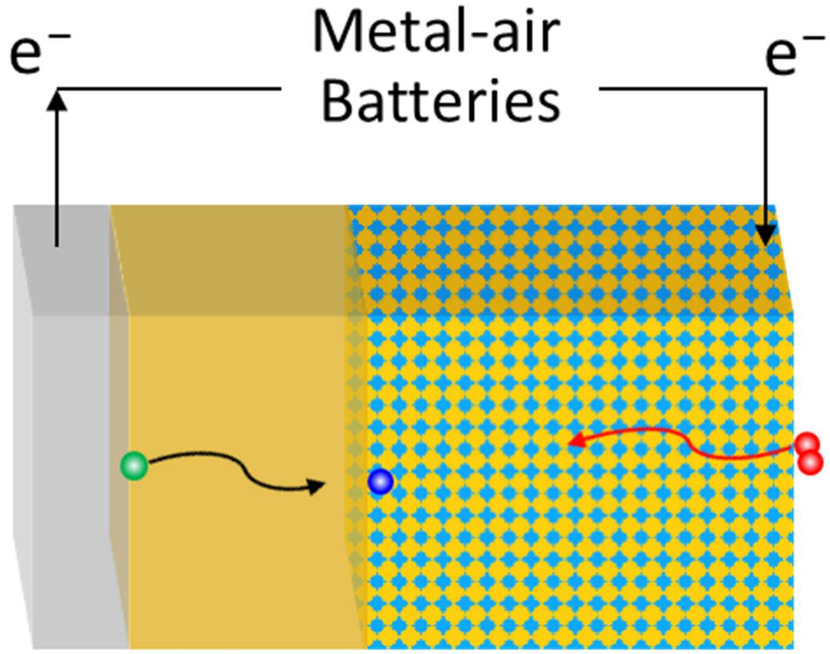
Proven Scalability

industry-leading
16Ah, 3.8 V
50-layer pouch cells

Funded by the CEC and in collaboration with SEI and Dr. Lingping Kong.

Lithium Air Batteries





High energy density over
<u>1000 Wh/kg</u>

SOLiD ENERGIES

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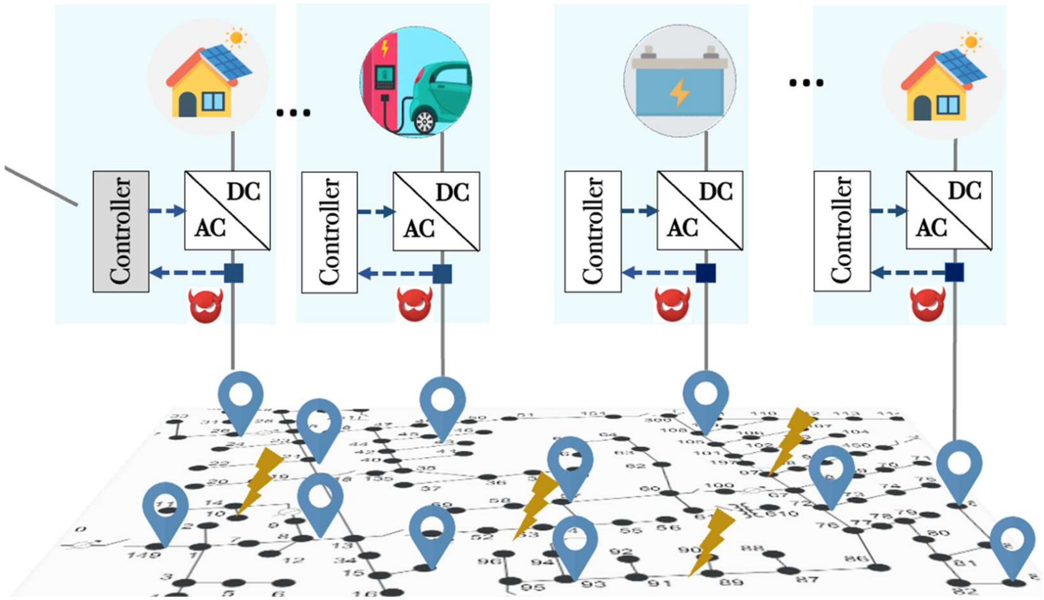
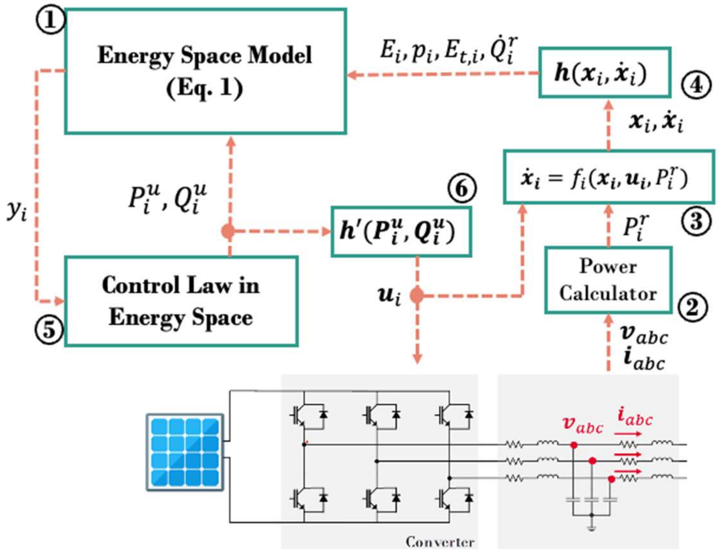
U.S. DEPARTMENT OF ENERGY

SDSU Funded by ARPA-e and in collaboration with Dr. Lingping Kong, SDSU, and SEI.

Cyber Security of Power Systems

- Resilience of power electronics (PE)-dominated power distribution systems is an increased concern
- There exists physical disturbances and/or cyberattacks
- Use unified, energy space-based modeling framework to identify disturbances, cyber attacks, and mitigate the risks

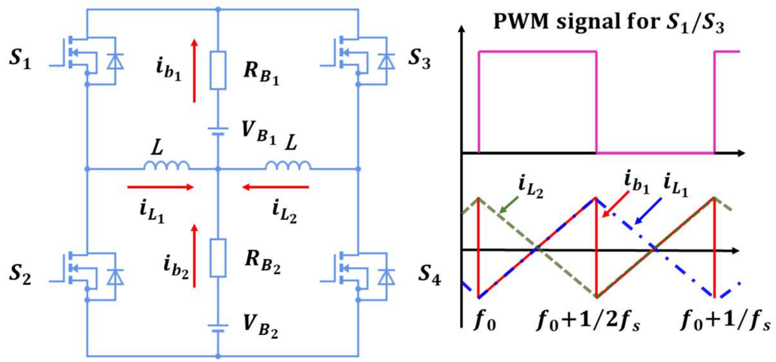


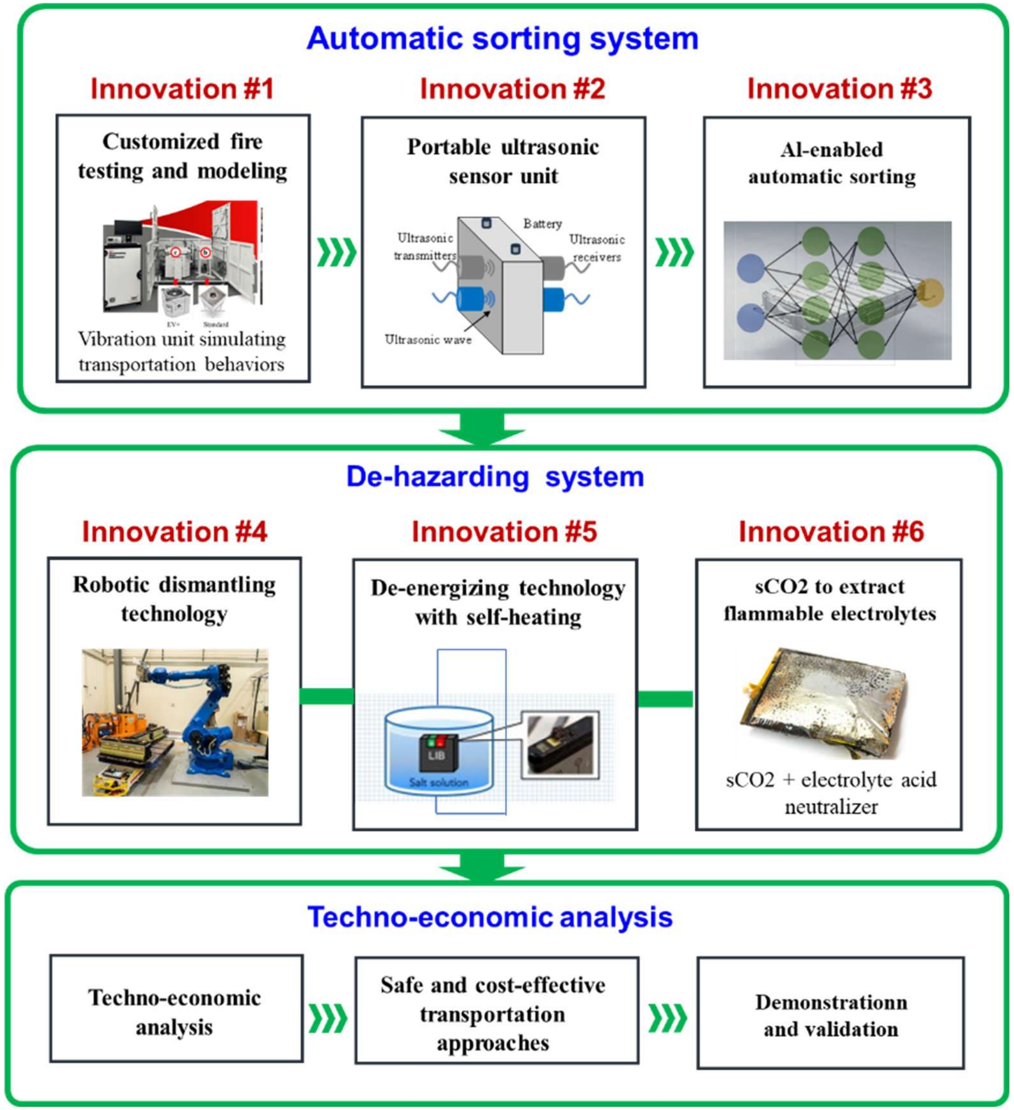


SDSU Funded by the NSF and in collaboration with Dr. Marija Ilic MIT & T. Huang, SDSU.

Battery de-energizing system

- Before recycling, deeply discharge the battery to 0
- 50V to 480V AC, send back to the grid
- 50V to short circuit, heat up the battery and conduct deep discharge





Funded by the DOE and in collaboration with General Motors, UM, etc.

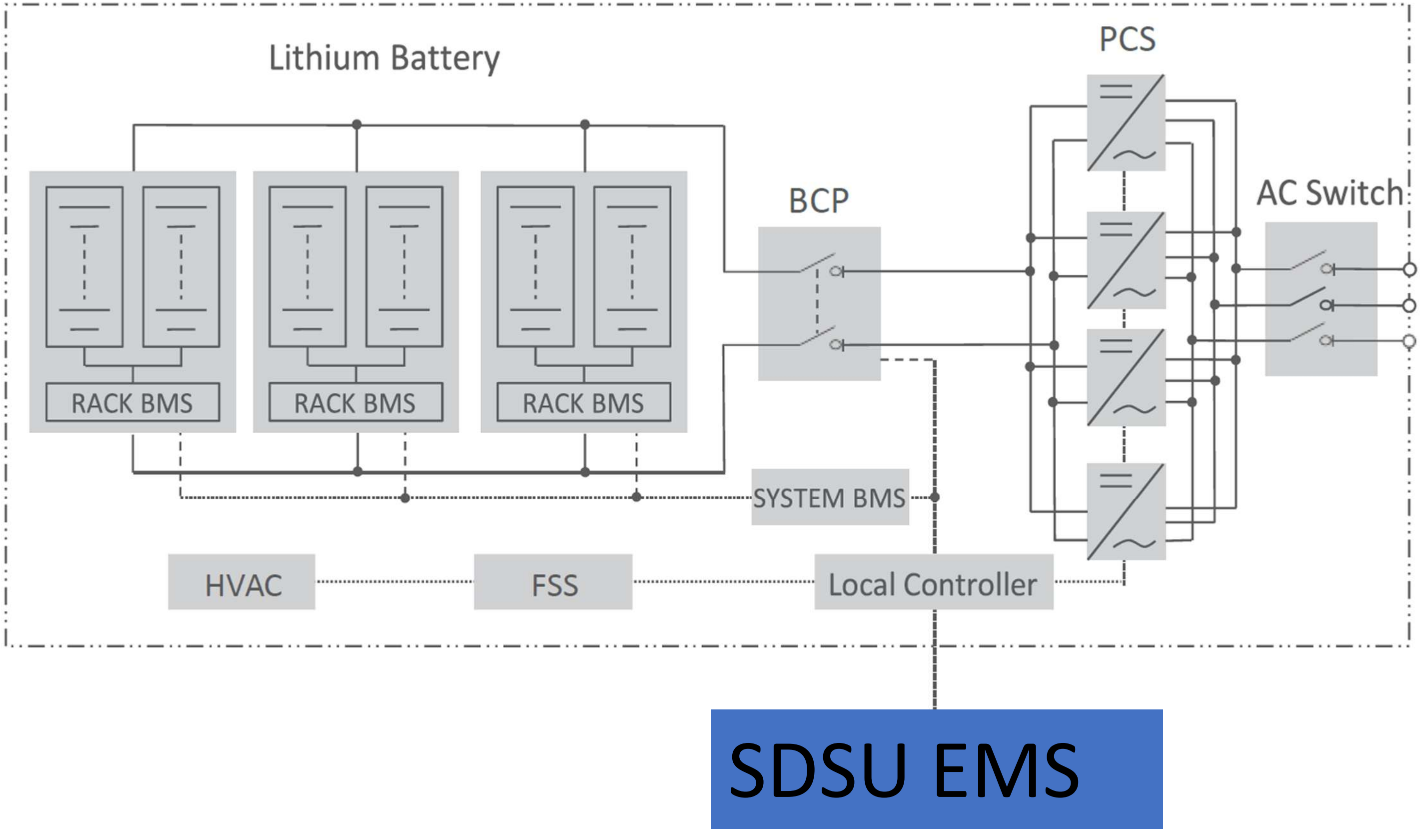
Second-Life EV Battery Summary

Step	 • Nissan Leaf Gen1 24 kWh LiMO2	 • Nissan Leaf Gen3 62 kWh LiNMC	 • Electric Forklift LFP 100Ah battery	 • Electric Bus LFP 270Ah battery
1: Initial SOH	60%~67%	89~97%	Cell: 89% SOH Pack: 50%~60% SOH	Cell: 79% SOH Pack: 52% SOH
2: Balance State	< 5% minor	< 5% minor	30% serious	27% serious
3: Capacity degradation speed ▪ *Fast / Vehicle* ▪ *Slow / BESS*	20% / 1000 cycles 4% / 1000 cycles	20% / 1000 cycles 3.6~5.9% / 1000 cycles	9.3% / 1000 cycles 5.0% / 1000 cycles	Balance Issues exist
4: Aging Knee	No aging knee	Aging knee at 75% SOH (1500 cycles)	No aging knee	
5: Estimated 2nd life	10~15 years 3000~5000 cycles 10 years / 3000 cycles high performance	10 years 3000 cycles 80% Dod <0.4C-rate	30 years 9000 cycles 100% Dod 0.5C charge/ 1C discharge	>10 years 3000 cycles Enhanced balance system is needed

SDSU Funded by the California Energy Commission.

New ESS with our EMS

- 556kWh
- 250kW
- 480V
- SunGrow System
- Samsung SDI Mega E3
- 3.68 V / 100 Ah cells



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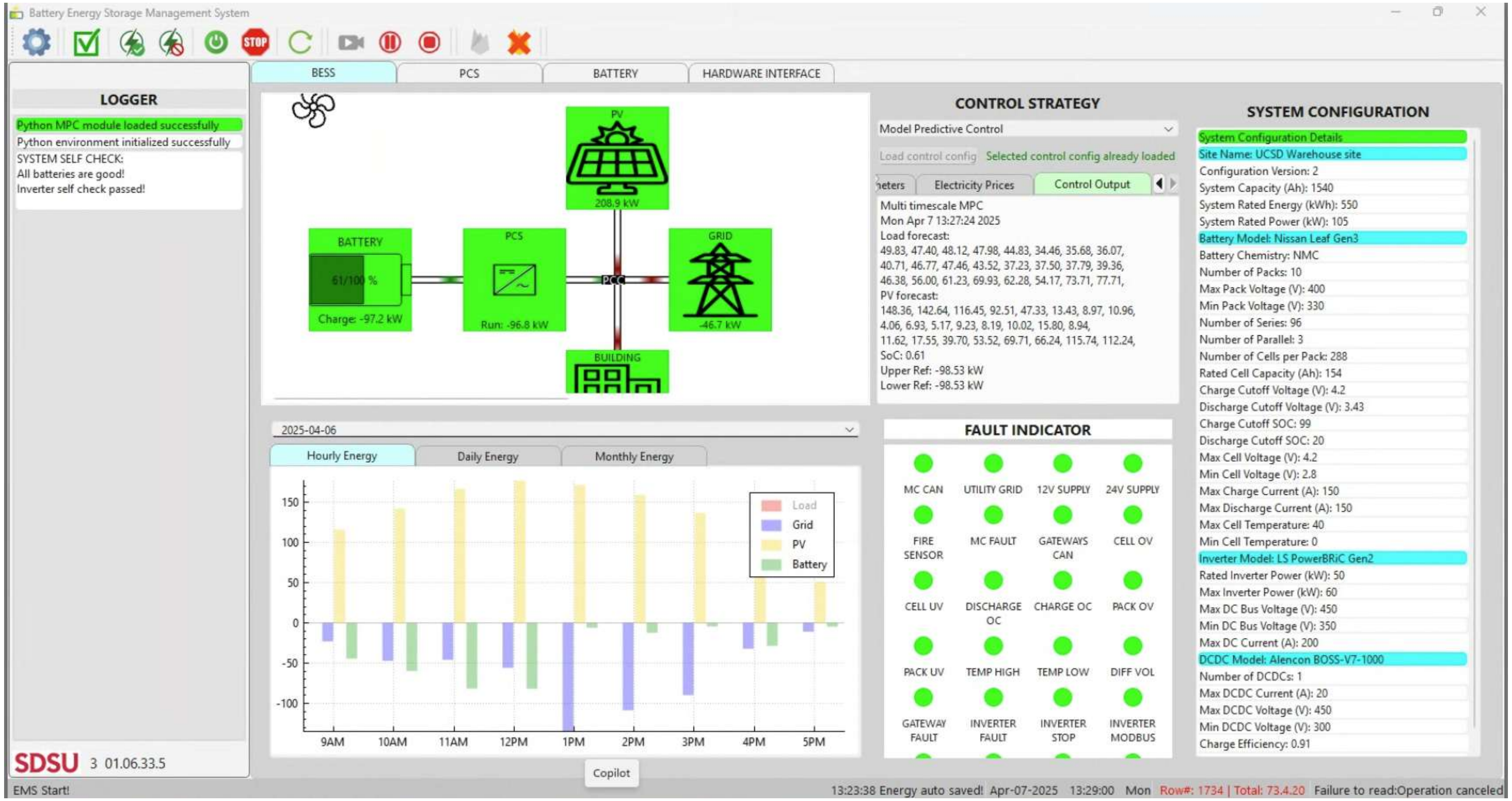
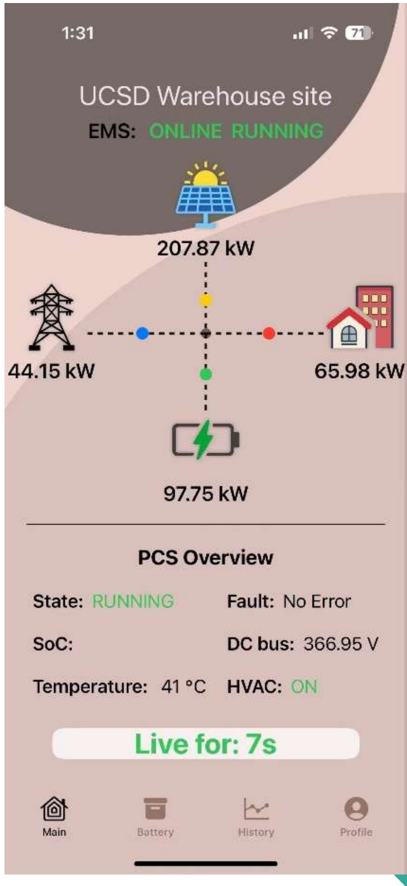
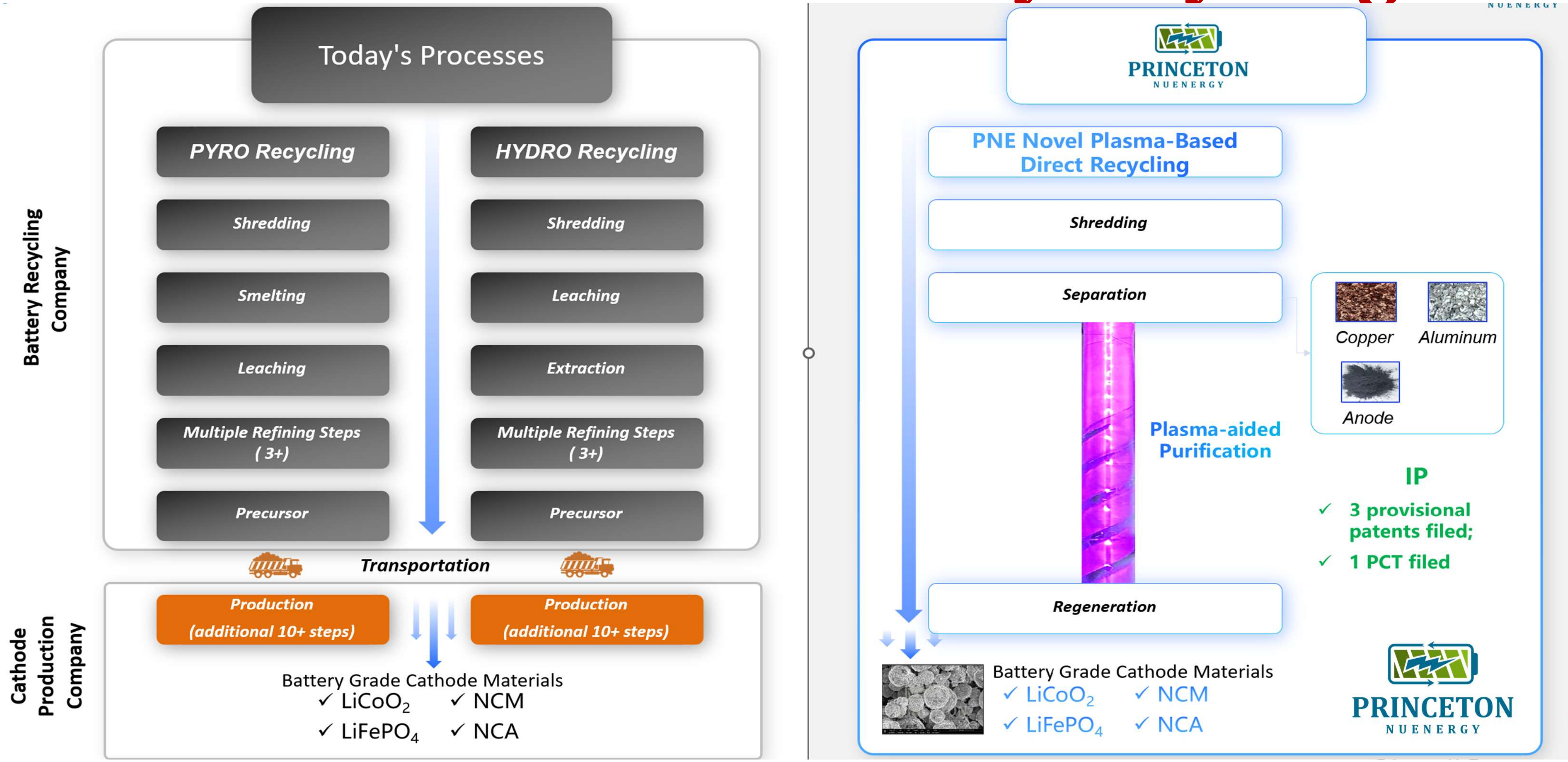
Energy Management System (EMS)



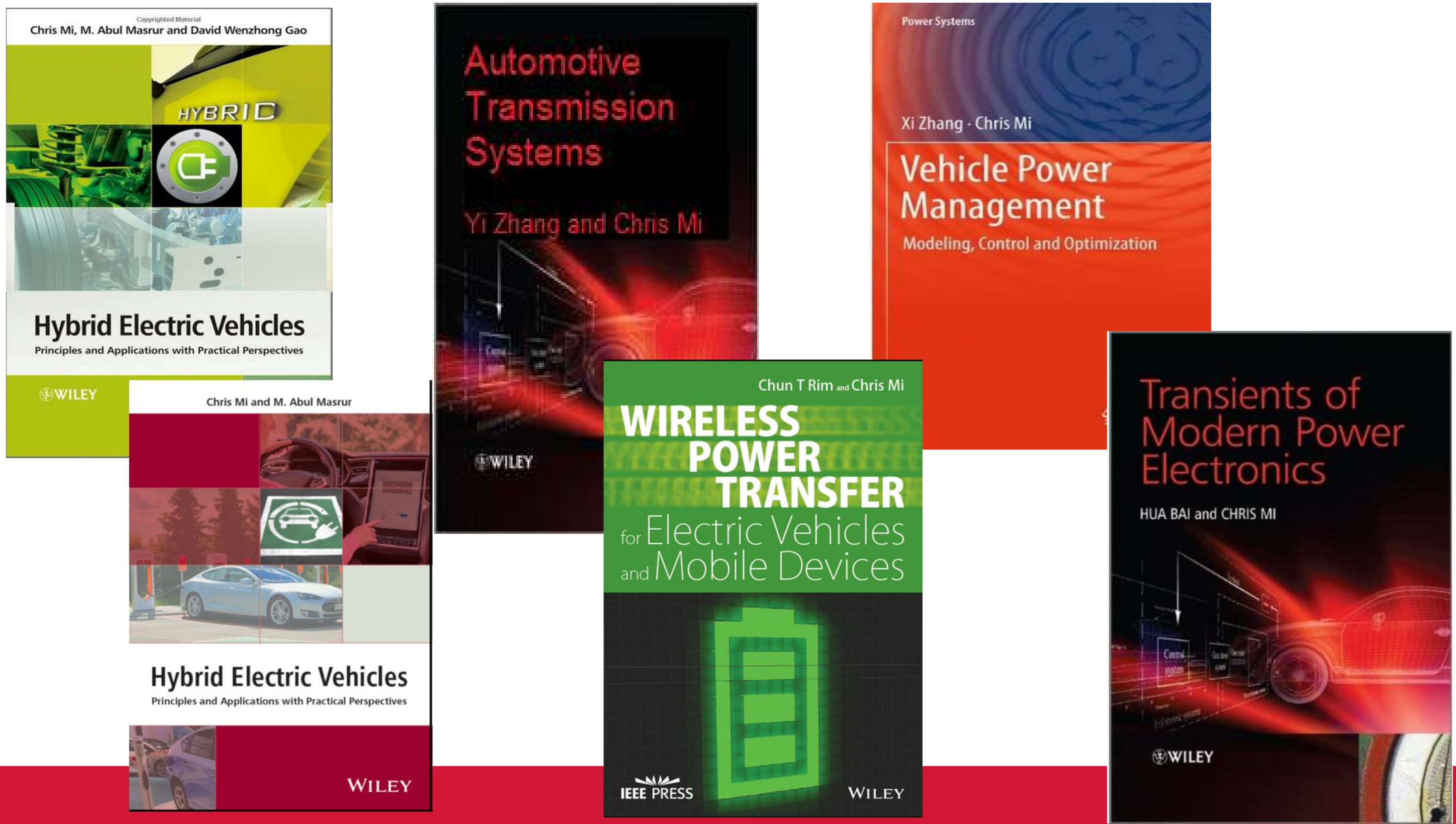


Plasma based direct battery recycling



In collaboration with Princeton NuEnergy

We are committed to conduct research to improve performance, efficiency and safety of electric vehicles



Acknowledgement

- **Thank my students for their hard wo**

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  - Gotion
  - California Energy Commission
  - National Science Foundation
  - NASA
  - Department of Energy
  - Solid Energies

Thank you!