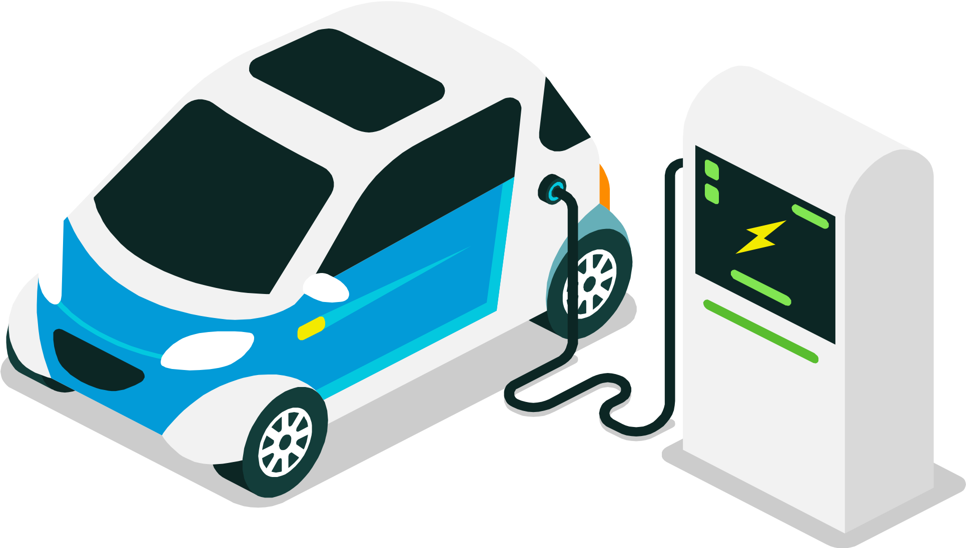
ACM Summer School 2025

Electric Vehicle Performance Optimization



Smart power Electronics Laboratory
SPEL
Let's create a green future together

INDIAN INSTITUTE OF TECHNOLOGY GANDHINAGAR
भारतीय प्रौद्योगिकी संस्थान गांधीनगर

Dr. Pallavi Bharadwaj
Smart Power Electronics Laboratory, IIT Gandhinagar

My Journey

Bachelors in Engineering, EE, Delhi College of Engineering 2012

Masters in Engineering, EE Indian Institute of Science, 2014

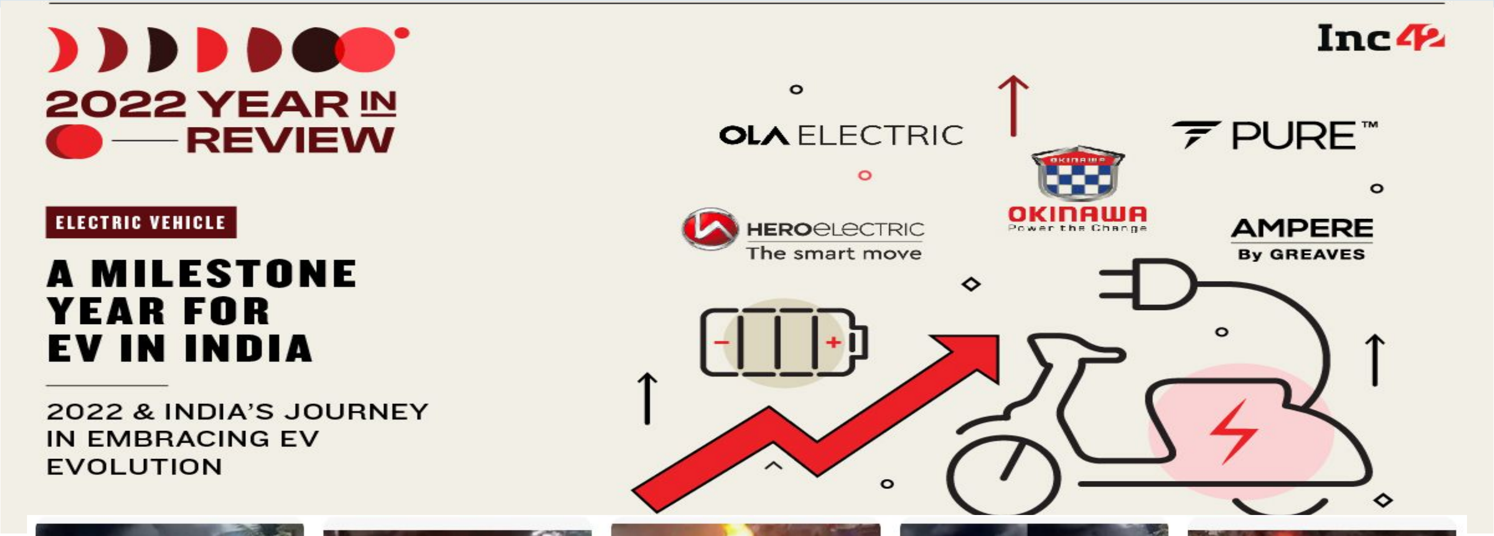
Doctor of Philosophy, Power Electronics, EE, Indian Institute of Science, 2019

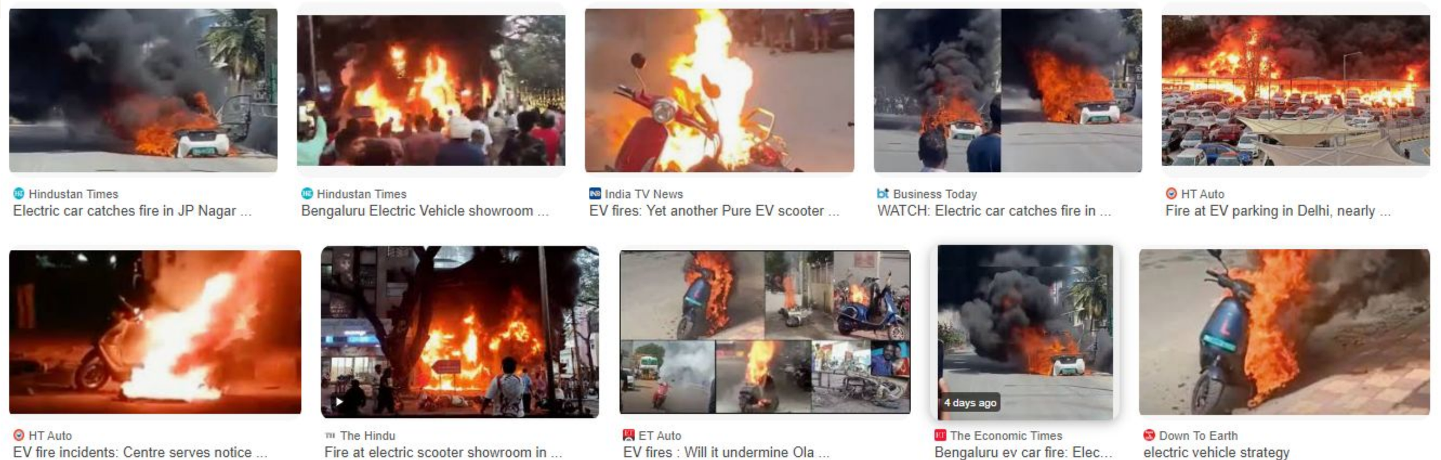
Postdoctoral Research, EECS Massachusetts Institute of Technology, USA, 2020-2021

Assistant Professor, Department of Energy, Aalborg University, Denmark, 2022

- Joined IIT Gandhinagar on 10/10/2022

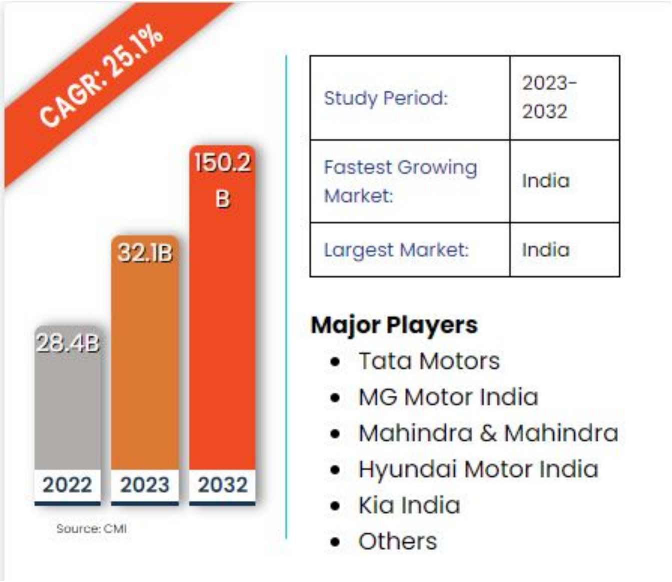
Motivation

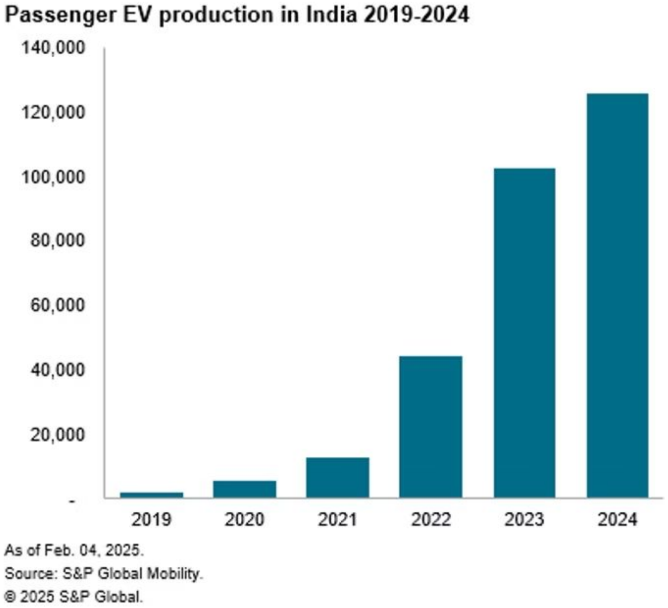

2022 YEAR IN REVIEW
ELECTRIC VEHICLE
A MILESTONE YEAR FOR EV IN INDIA
2022 & INDIA'S JOURNEY IN EMBRACING EV EVOLUTION
Inc42
OLA ELECTRIC
PURE™
HEROeLECTRIC The smart move
OKINAWA Power the Change
AMPERE By GREAVES


Hindustan Times
Electric car catches fire in JP Nagar ...
Hindustan Times
Bengaluru Electric Vehicle showroom ...
India TV News
EV fires: Yet another Pure EV scooter ...
Business Today
WATCH: Electric car catches fire in ...
HT Auto
Fire at EV parking in Delhi, nearly ...
HT Auto
EV fire incidents: Centre serves notice ...
The Hindu
Fire at electric scooter showroom in ...
ET Auto
EV fires : Will it undermine Ola ...
4 days ago
The Economic Times
Bengaluru ev car fire: Elec...
Down To Earth
electric vehicle strategy

Need for Reliable and Safe Electric Vehicles

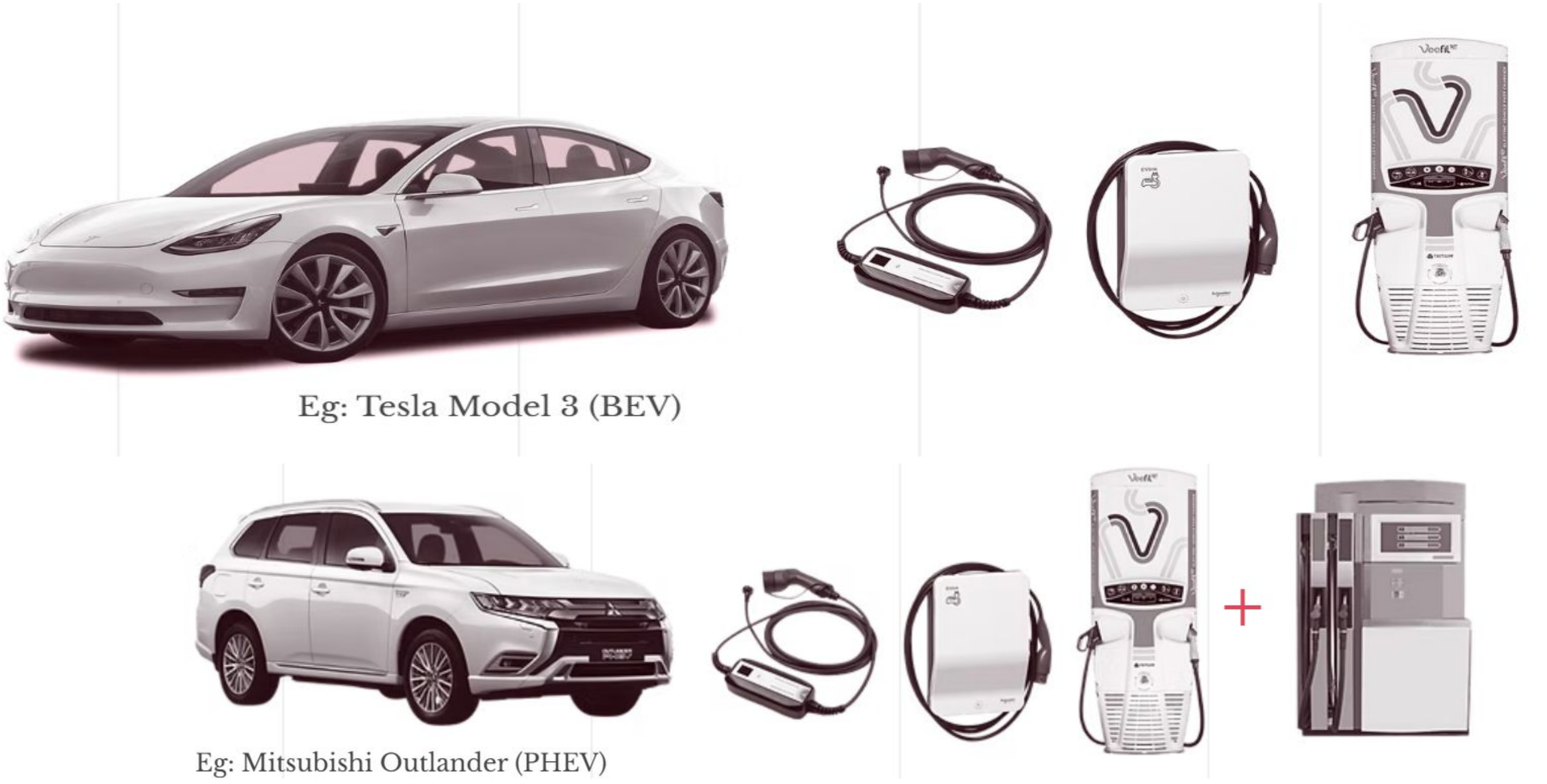
The Indian electric vehicle (EV) market is experiencing significant growth and is projected to be a major player in the global EV landscape.





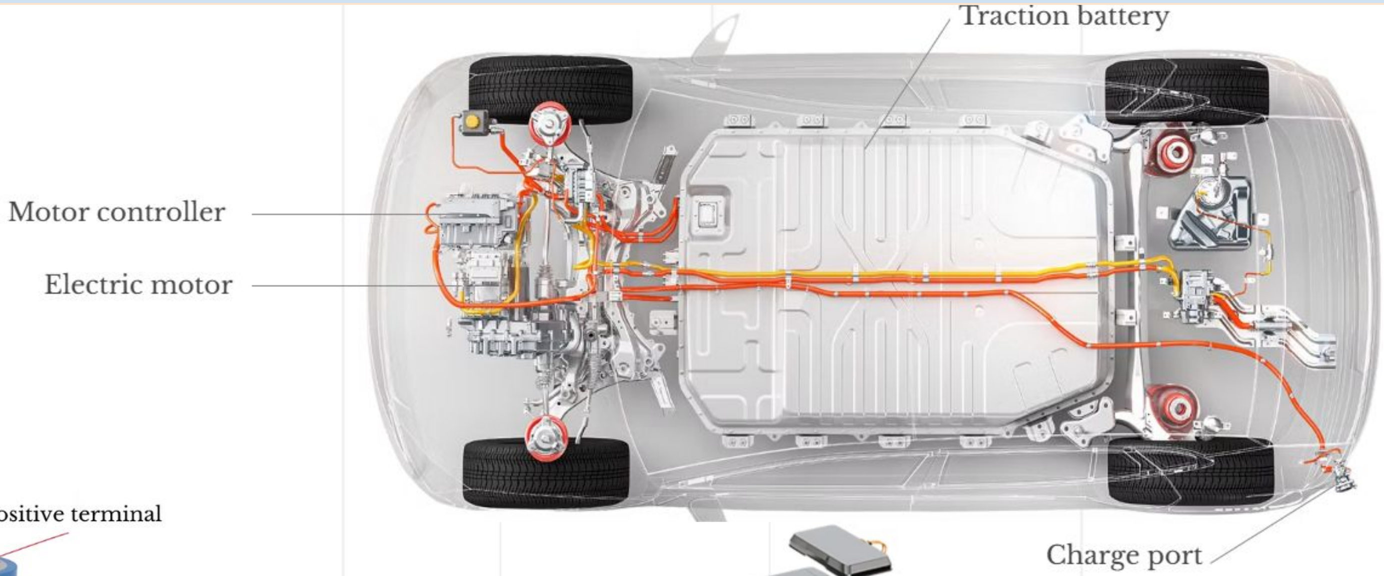
Source: https://www.custommarketinsights.com/report/india-electric-vehicle-market/
https://www.spglobal.com/automotive-insights/en/blogs/2025/03/india-ev-market-trends-future

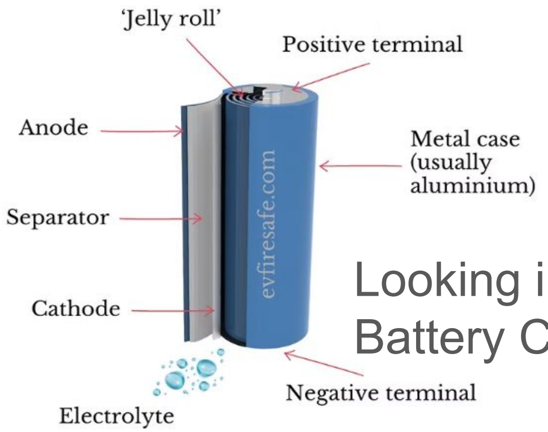
Common EV Types



Source: https://www.evfiresafe.com/what-is-an-ev

What is inside an EV?



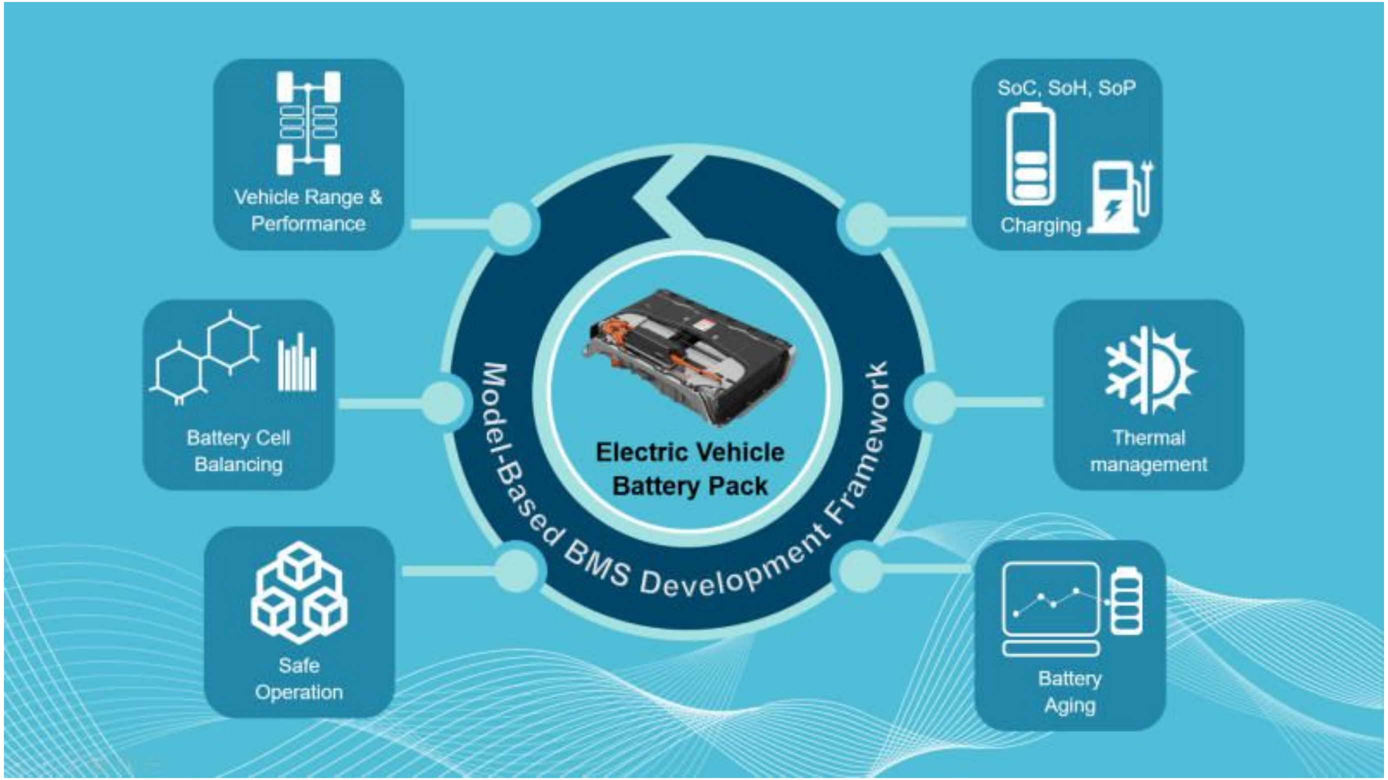


Looking inside a Battery Cell

Battery modules making a pack placed inside EV

Source: https://www.evfiresafe.com/ev-hv-cable-components

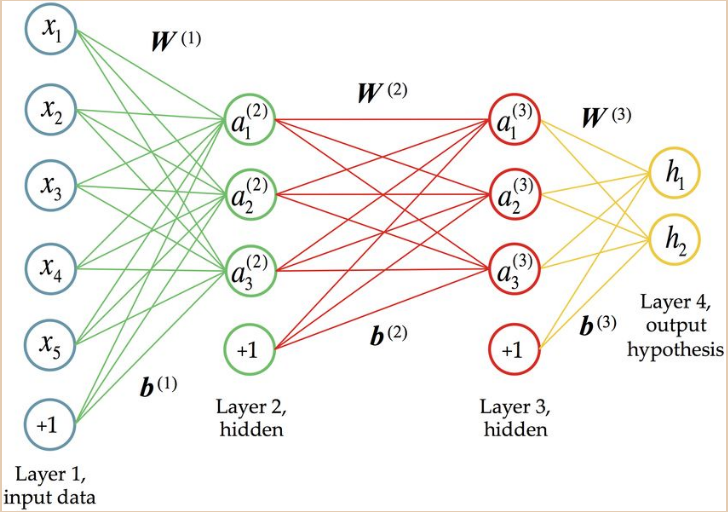
Battery Performance Optimization Requirements



Source: Siemens Software, accessed 2023.

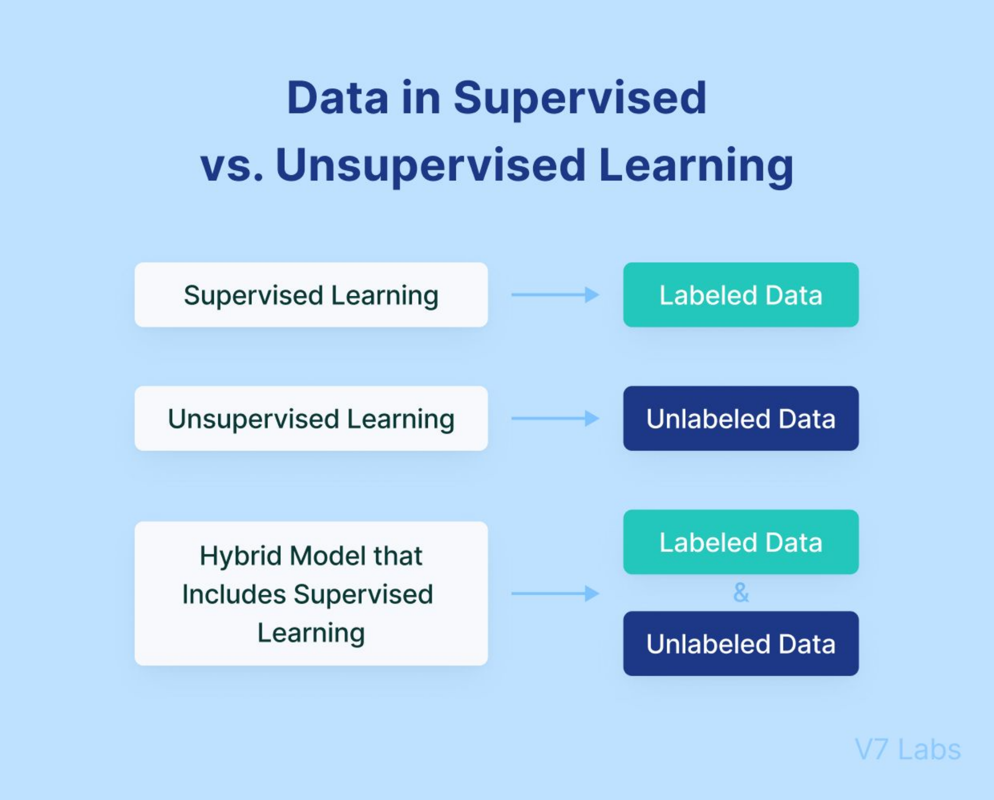
Data driven vs Physical models

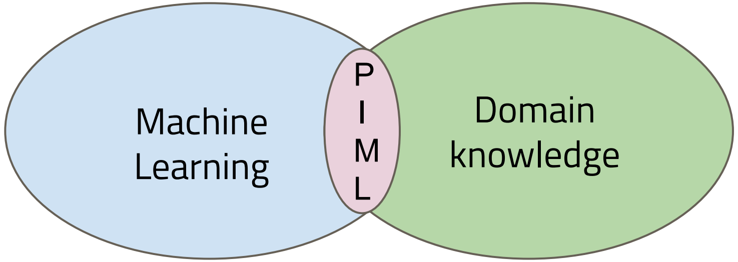
- Data driven models are preferred over physical models.
- Physical models offer slightly more accuracy but struggle in real time prediction due to their complexity
- Data driven methods are easier to implement and use in a wide variety of cases



Source: Sheehan, Sara & Song, Yun. (2016). Deep Learning for Population Genetic Inference. PLOS Computational Biology. 12. e1004845. 10.1371/journal.pcbi.1004845.

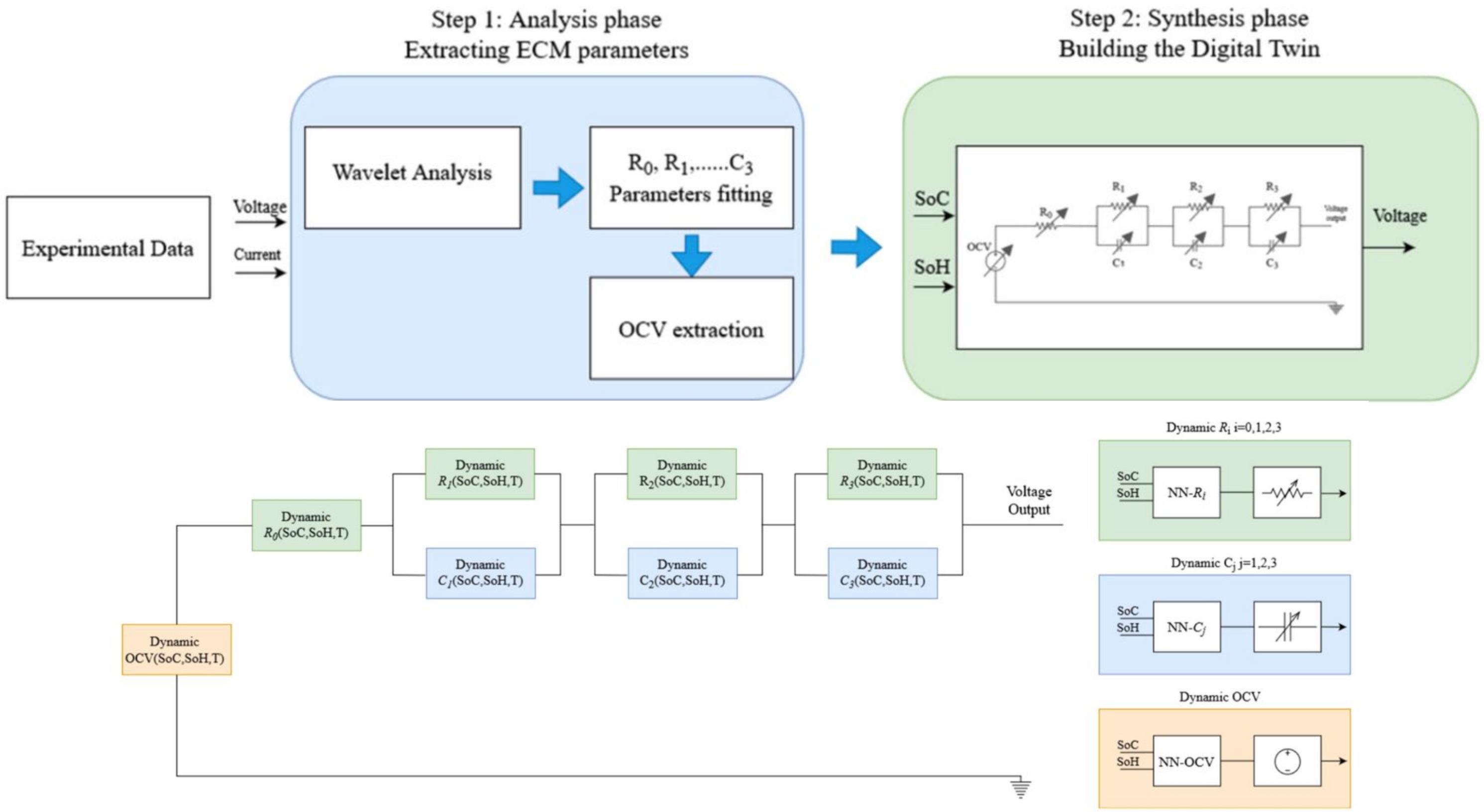
Our approach: taking the best of both worlds





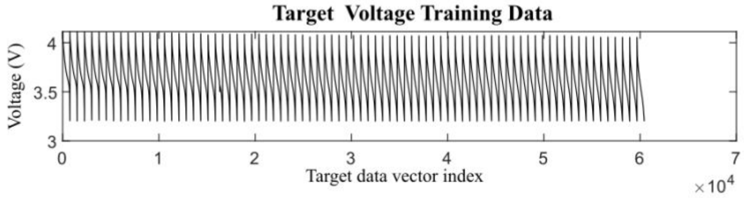
Physics Inspired Machine Learning:
Using physical system understanding to aid ML using pre-established system mathematical models

Methodology for Electrical Battery Model

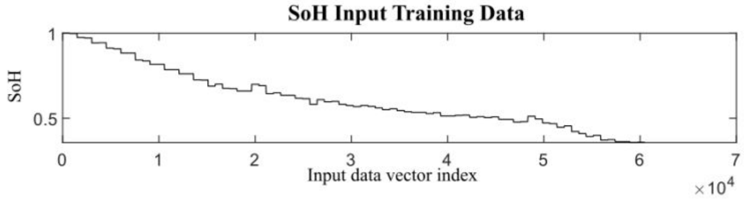


Source: R. D. Fonso, R. Teodorescu, C. Cecati and P. Bharadwaj, "A Battery Digital Twin From Laboratory Data Using Wavelet Analysis and Neural Networks," in *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 6889-6899, April 2024

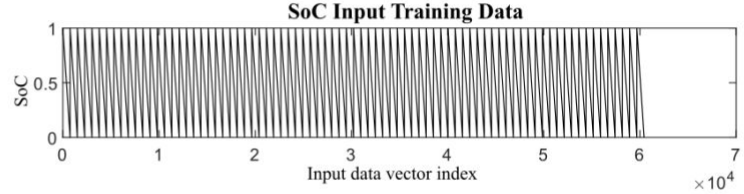
Open Circuit Voltage Estimation



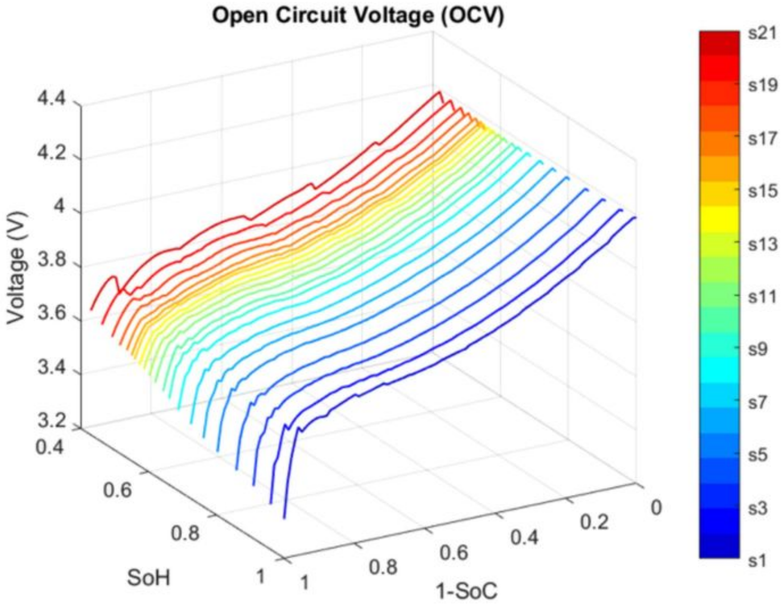
(a) Target voltage training data



(b) SoH input training data

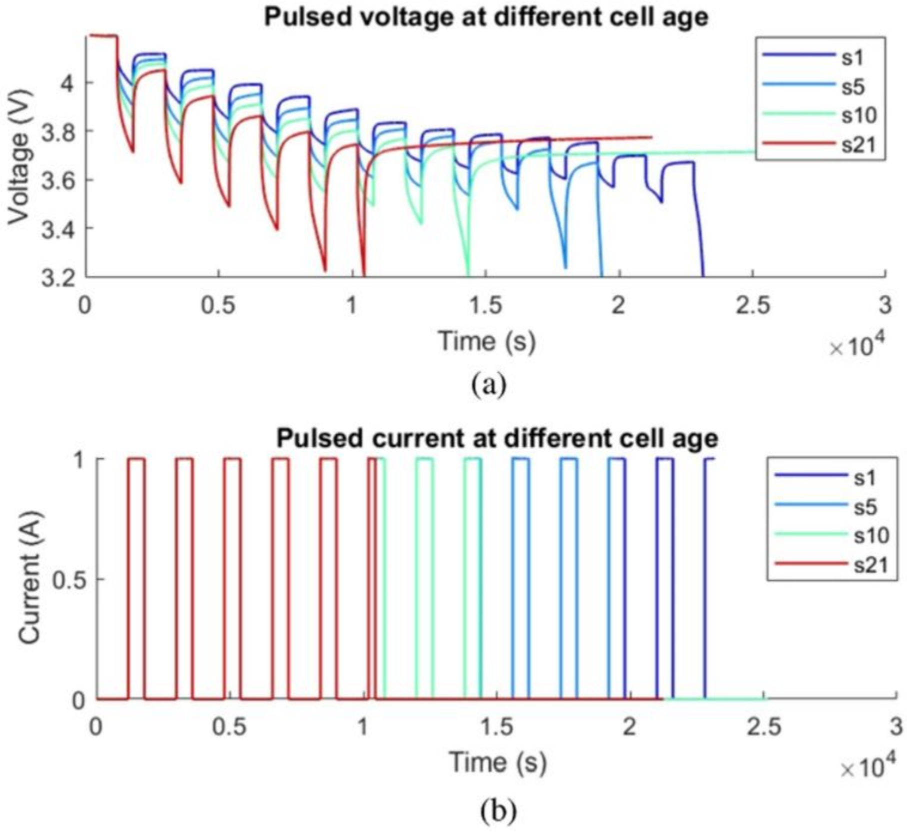


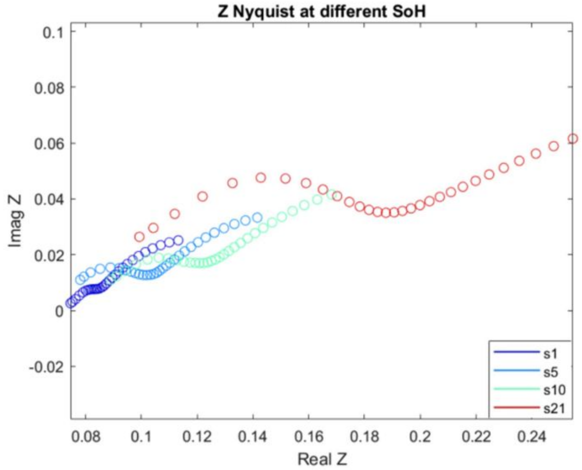
(c) SoC input training data



Source: A Battery Digital Twin Based on Neural Network for Testing SoC/SoH Algorithms by R D Fonso and P Bharadwaj et al., IEEE PEMC 2022.

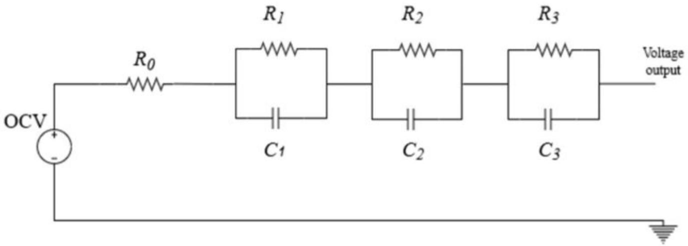
Use of Pulsed Data for Internal Impedance Est.

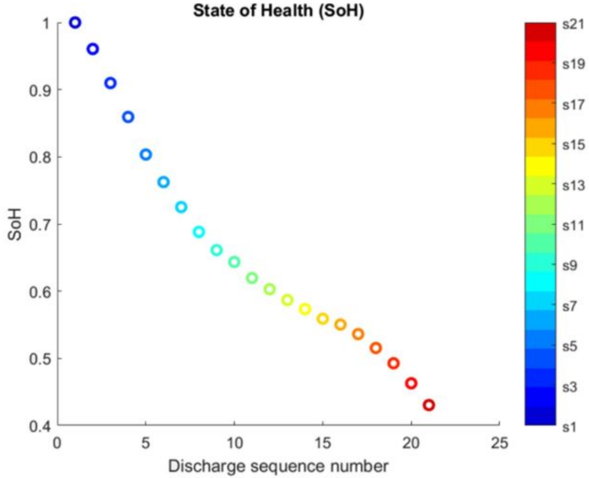


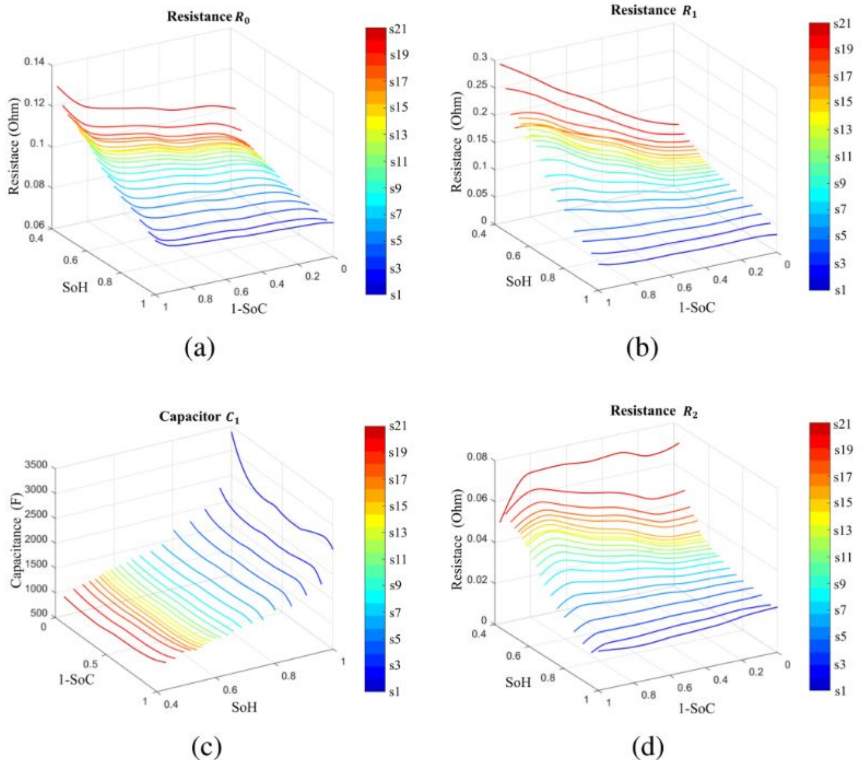


Source: R. D. Fonso, R. Teodorescu, C. Cecati and P. Bharadwaj, "A Battery Digital Twin From Laboratory Data Using Wavelet Analysis and Neural Networks," in *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 6889-6899, April 2024.

Equivalent Circuit Model for LIB

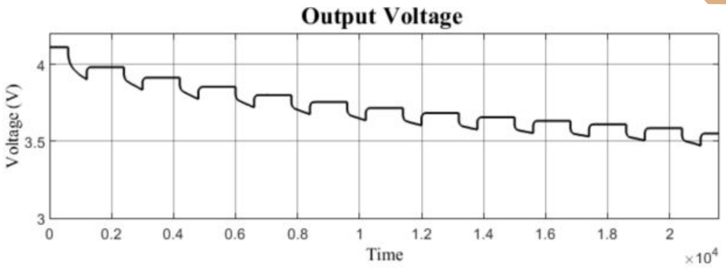




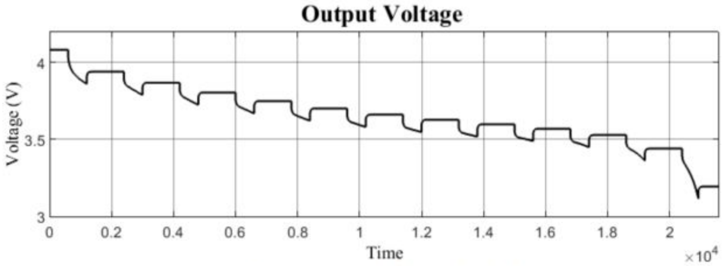


Source: R. D. Fonso, R. Teodorescu, C. Cecati and P. Bharadwaj, "A Battery Digital Twin From Laboratory Data Using Wavelet Analysis and Neural Networks," in *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 6889-6899, April 2024.

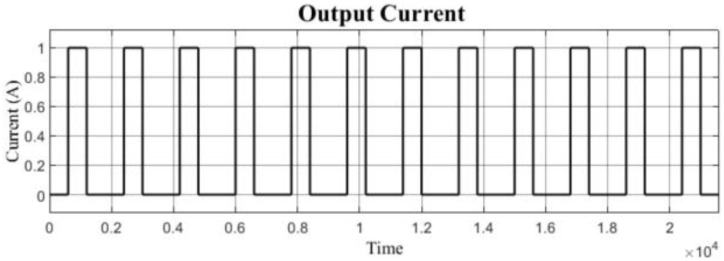
Results for Electrical Output



(a) BDT output voltage, SoH=1



(b) BDT output voltage, SoH=0.9

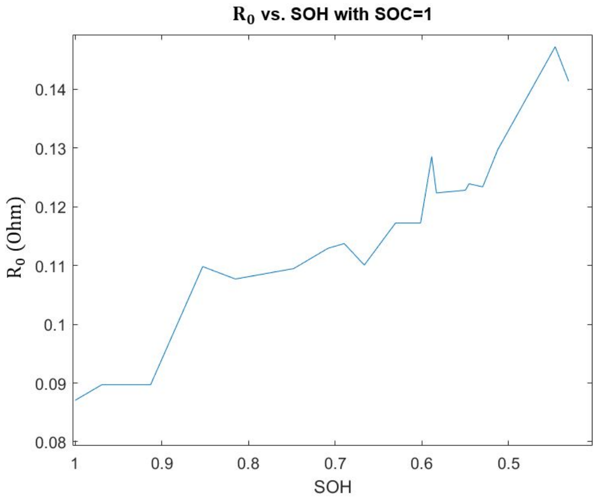


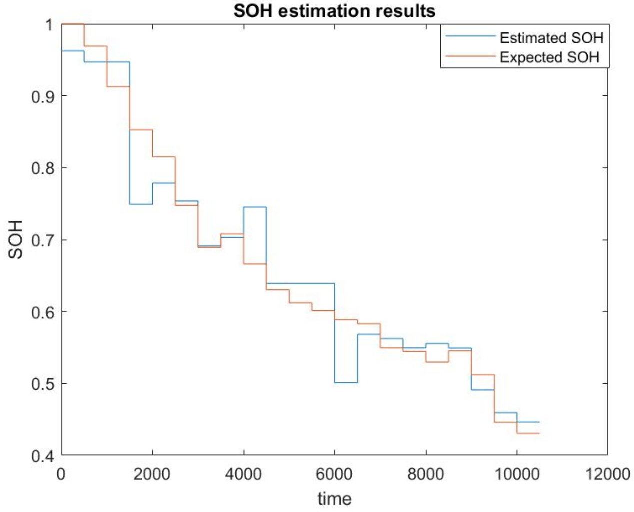
(c) BDT output current

Source: R. D. Fonso, R. Teodorescu, C. Cecati and P. Bharadwaj, "A Battery Digital Twin From Laboratory Data Using Wavelet Analysis and Neural Networks," in *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 6889-6899, April 2024.

SOH estimation from internal resistance

In this work, we trained a NN for the SOH estimation from the parameter R_0.





$0.43 \leq \mathrm{SOH} \leq 1$

Mean absolute relative error
MARE$= 4.25\%$

Aging-aware equivalent circuit model for SOH estimation in lithium-ion batteries – P Bharadwaj, IEEE Intelec 2024

EV Safety

EV Safety Standards in India

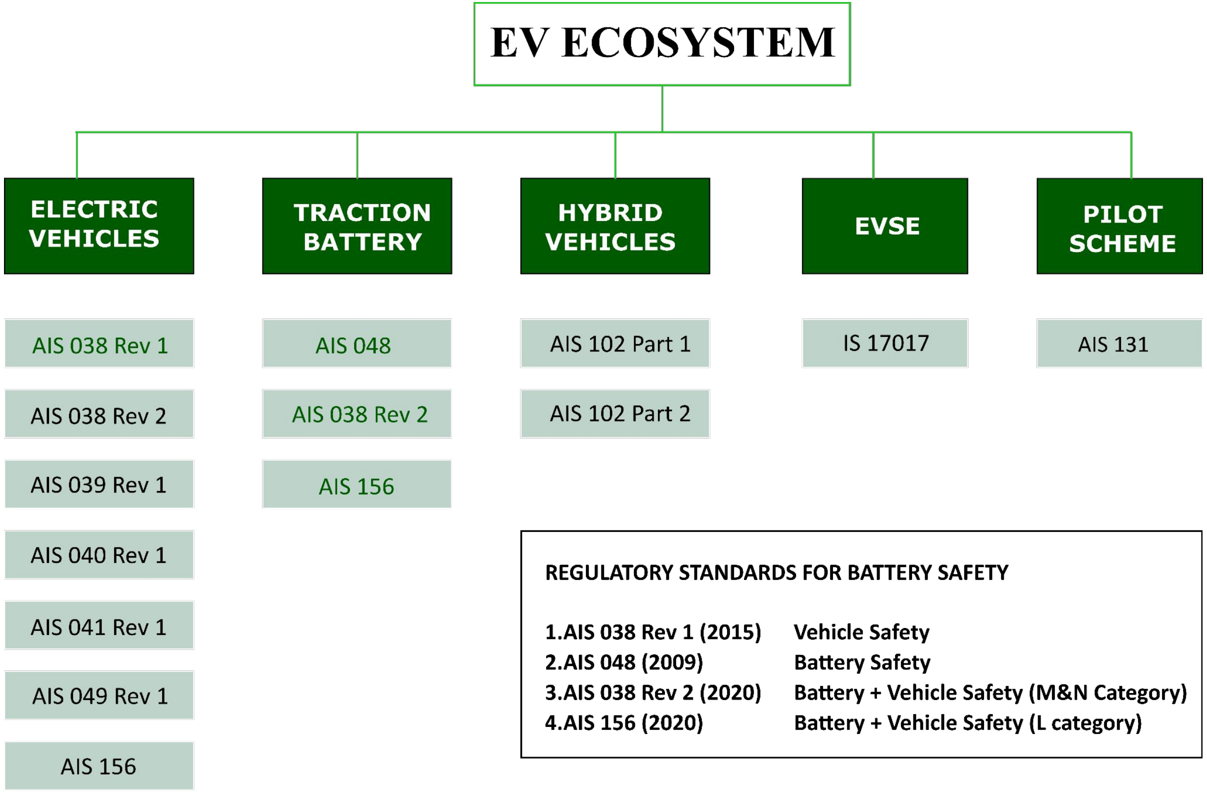


Fig: Battery safety standards in India

Source:https://evreporter.com/battery-safety-standards-in-india-by-arai/

Categories of Electric Vehicles & Safety Requirements

L CATEGORY VEHICLES	M&N CATEGORY VEHICLES
AIS 156 is prepared in-line with UN R136	AIS 038 Rev 2 is prepared in- line with GTR 20 Phase 1 (UN R100 Rev 3)
Vibration Test	Vibration Test
Thermal Shock and Cycling Test	Thermal Shock and Cycling Test
Mechanical drop test for removable REESS	Mechanical Shock
	Mechanical Integrity
Fire Resistance	Fire Resistance
External Short Circuit Protection	External Short Circuit Protection
Overcharge Protection	Overcharge Protection
Overdischarge Protection	Overdischarge Protection
Over-Temperature Protection	Over-Temperature Protection
Hydrogen Emission Test	Over-Current Protection
	Thermal Propagation Test
	Hydrogen Emission Test

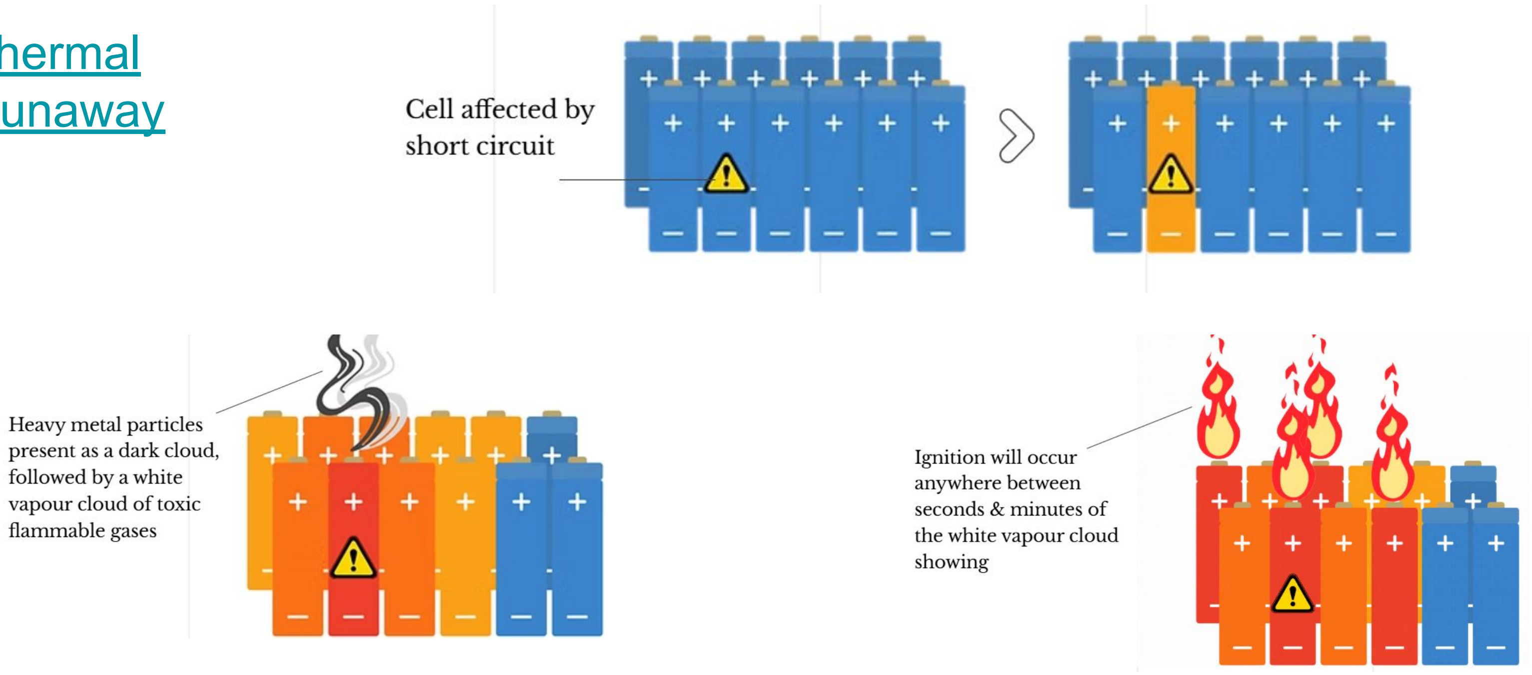
Source: https://evreporter.com/battery-safety-standards-in-india-by-arai/

Causes of Thermal Runaway

Source: Prof Saumyadip Sett’s Guest Lecture on Battery Thermal Management in EV Technology Course, Fall 2023.

Challenges with EV: Fire Safety

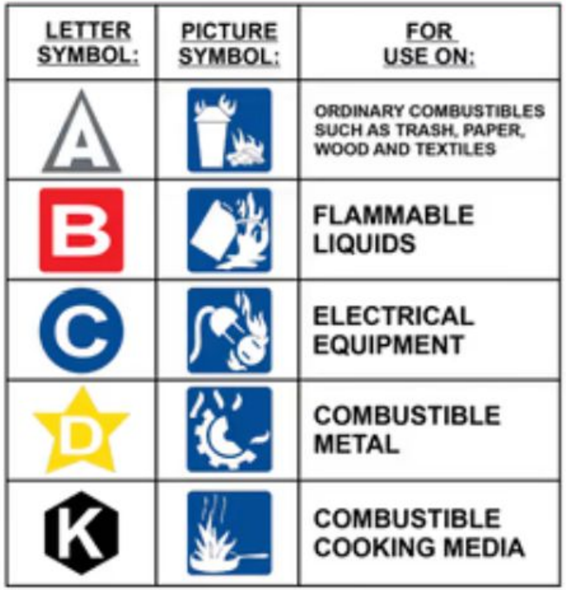
Thermal Runaway



Video Link

Types of Fire

LiB fire is a mixed class fire; conventional agents have no or little effect



LETTER SYMBOL:	PICTURE SYMBOL:	FOR USE ON:
A		ORDINARY COMBUSTIBLES SUCH AS TRASH, PAPER, WOOD AND TEXTILES
B		FLAMMABLE LIQUIDS
C		ELECTRICAL EQUIPMENT
D		COMBUSTIBLE METAL
K		COMBUSTIBLE COOKING MEDIA

Firefighting media	Remark
Water	Requires humongous quantity of water
Water mist	Has been found successful for smaller batteries
Dry chemical	Found to be the least effective
Foam	Achieves reduction in temperature, not effective for extinguishment
Aerosol	Has shown some success esp. in enclosed area
Clean agent	

The fire class of a LiB fire is **contentious** due to the various components which make up the battery; Casing (Class A); separator material, construction material and electrodes (Class D); flammable liquid, electrolyte (Class B); energized electrical apparatus (Class C)

Source: Firetech HCT Ind Pvt Ltd

Challenges with EV Fire Safety?

'Unpredictable Fire' because it has:

- Flames
- Fire – Large, Medium, Small
- Strong and long flares of burning gases
- Explosions (sudden), continuous
- Smoke, soot
- Poisonous, hazardous and HF gases

Source: Firetech HCT Ind Pvt Ltd

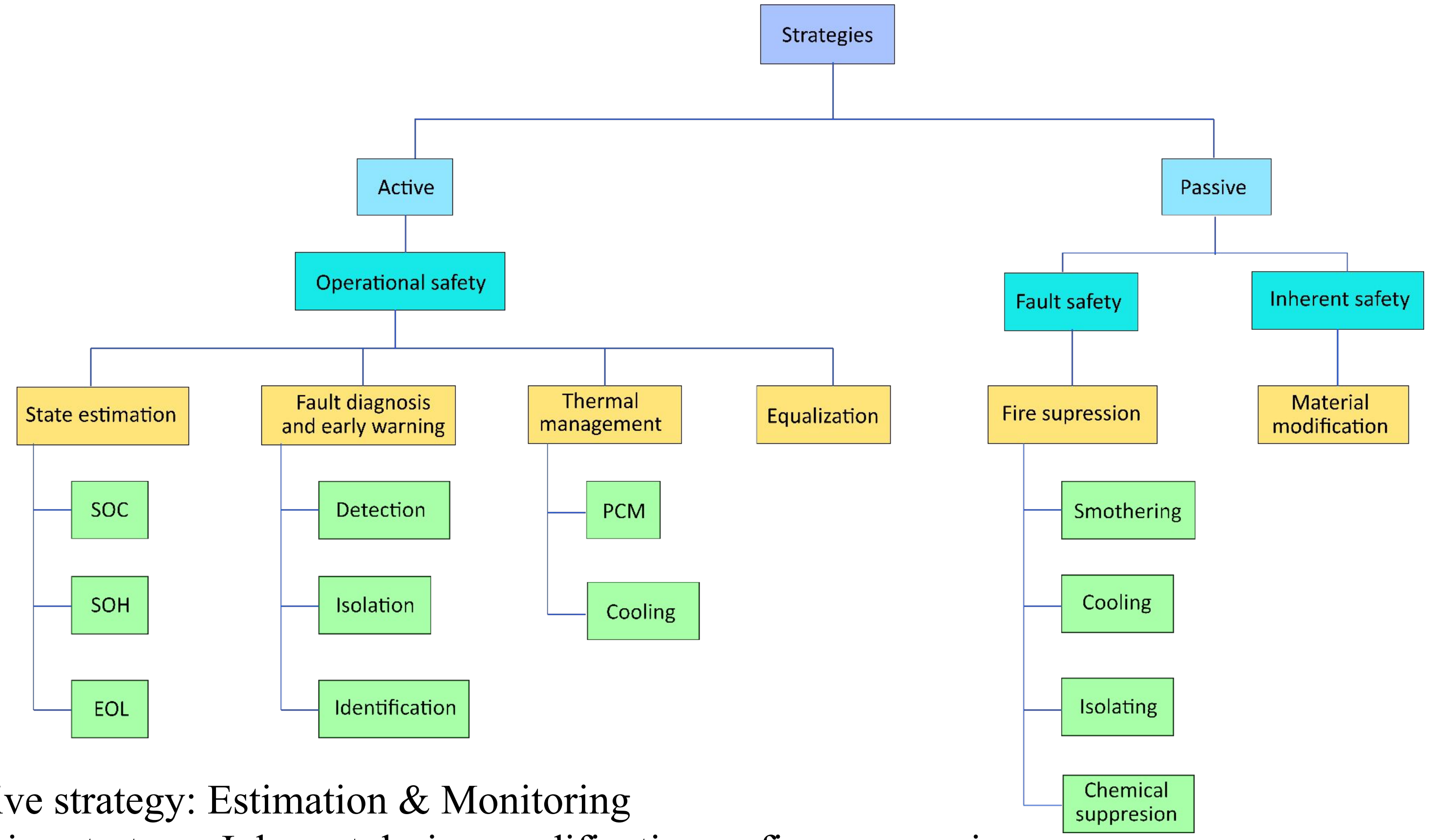
EV Fire Progression

An electric Nissan Shuike on charge at a DC unit ignited, destroying four other vehicles.

Source: https://youtu.be/Bp1z8Q-3JMM,

0.32 Dark cloud of heavy metal particles
0.39 Whistling noise of venting gases
0.44 Lighter vapour cloud above vehicle
0.50 Small vapour cloud explosion, vapour cloud is consumed

An Overview of the Safety Strategies for LIBs



- Active strategy: Estimation & Monitoring
- Passive strategy: Inherent design modification or fire suppression

Source: Y. Qiu, F. Jiang, A review on passive and active strategies of enhancing the safety of lithium-ion batteries, International Journal of Heat and Mass Transfer 184 (2022) 122288

Gas Detection

Target gases are selected on the basis of -

Consistency
Found in high concentration for all chemistry and abuse conditions?

Early Presence
Found in first venting and detectable with few seconds?

Leakage Detection
Main component of cell leakage?

*Vent gas composition under abuse conditions-

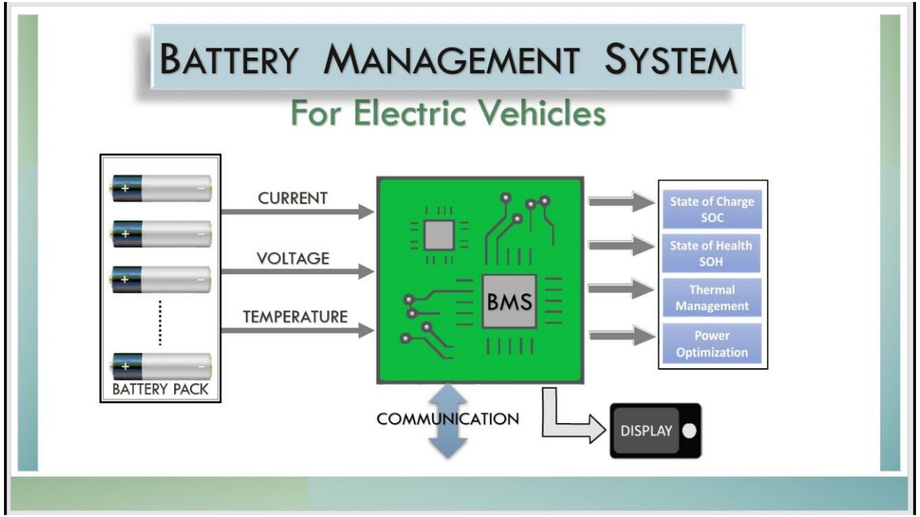
Conditions		CO_2	CO	H_2	VOCs
Overheating: SOC = 100%	NMC pouch	36.6%	28.4%	22.3%	12.4%
	LCO cylindrical	8%	10%	-	2.5%
Nail Penetration: charged to 4.3V	NMC pouch	>2%	>2%	Detected	High intensity
Overcharging: at the end of test	LFP cylindrical	47%	4.9%	23%	24%
Cell Leakage	NMC prismatic	32.3-58.4%	31.7-45.1%	-	4.7-9.1%
	LCO cylindrical	1.7%	-	-	44.6%

Experiments conducted in air, VOC: Volatile Organic Components (hydrocarbons like methane, ethane)

Source Cai, T., Valecha, P., Tran, V., Engle, B., Stefanopoulou, A., & Siegel, J. (2021). Detection of Li-ion battery failure and venting with Carbon Dioxide sensors. *ETransportation*, *7*, 100100.

EV Safety by BMS

- Prevents Thermal Runway
- Enhancing Battery Lifespan
- Avoid Overcharging and Overheating
- Proactive Safety Alerts

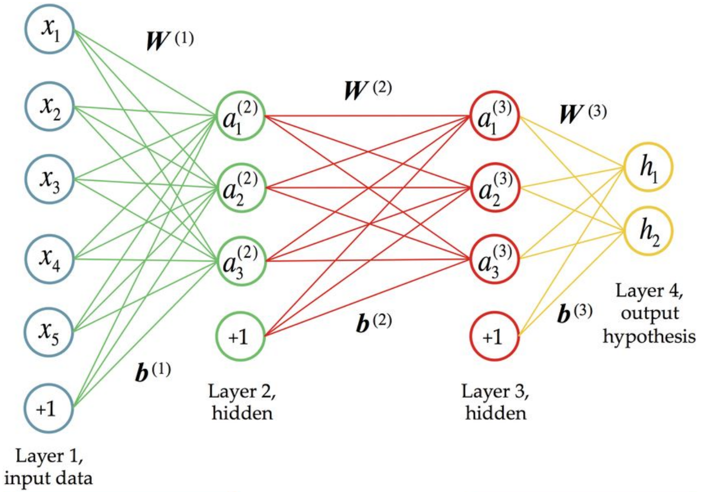


Thermal management and temperature prediction

- In extreme temperatures the safety and life of battery degrades
- Thus we must try to predict the temperature so that we can regulate it

Data driven vs Physical models

- Data driven models are preferred over physical models.
- Physical models offer slightly more accuracy but
- Struggle in real time prediction due to their complexity
- Data driven methods are easier to implement and use in a wide variety of cases
- Works best for aging batteries



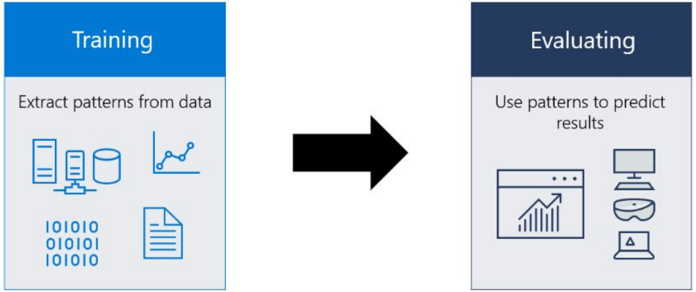
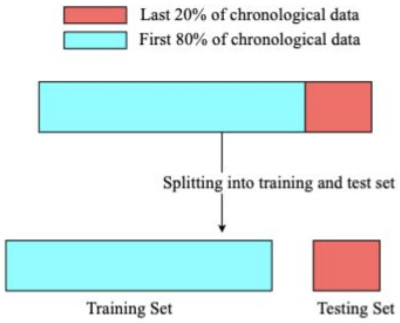
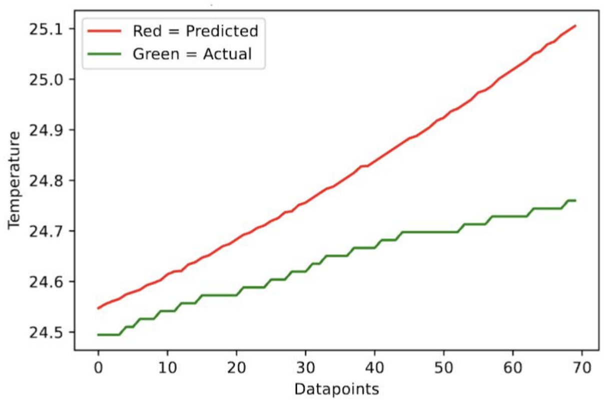


Figure Source: Sheehan, Sara & Song, Yun. (2016). Deep Learning for Population Genetic Inference. PLOS Computational Biology. 12. e1004845. 10.1371/journal.pcbi.1004845.

Battery Aging Problem Affects Temperature Prediction Accuracy



Test set fit

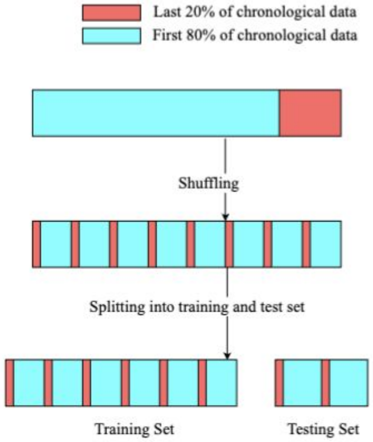


Model inputs

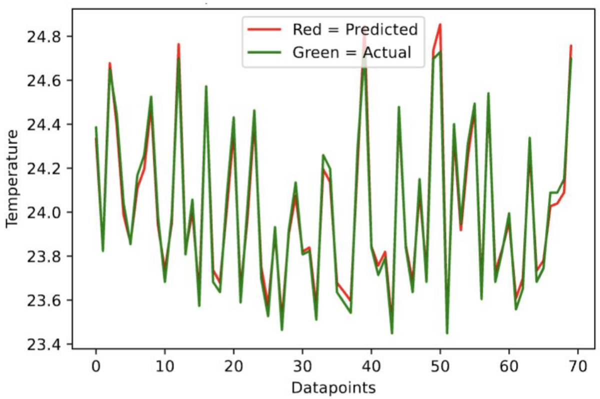
- Time
- Current
- Voltage

Model Output

- Temperature



Test set fit



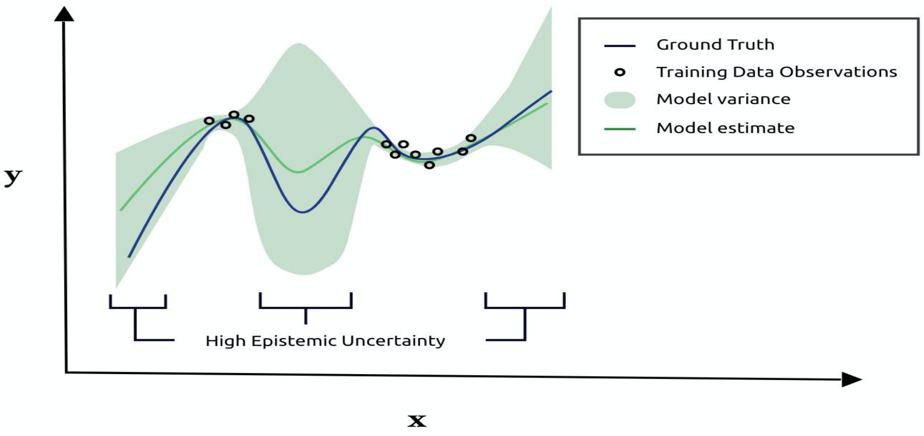
Source: P. Sachan and P. Bharadwaj, "Incorporating Uncertainty and Reliability for Battery Temperature Prediction using Machine Learning Methods," in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, doi: 10.1109/JESTIE.2023.3327052.

Dataset Description

  - Four 18650 Lithium-ion batteries were used.
  - Profiles were collected for different type of conditions.
- Each profile had the following data
  - Time
  - Voltage
  - Current
  - Temperature
  - Type of profile

Uncertainty Quantification

- Reliability in unseen data.
- Adaptability to unseen data.
- Worst case scenario awareness.
- Safety in alerting users.

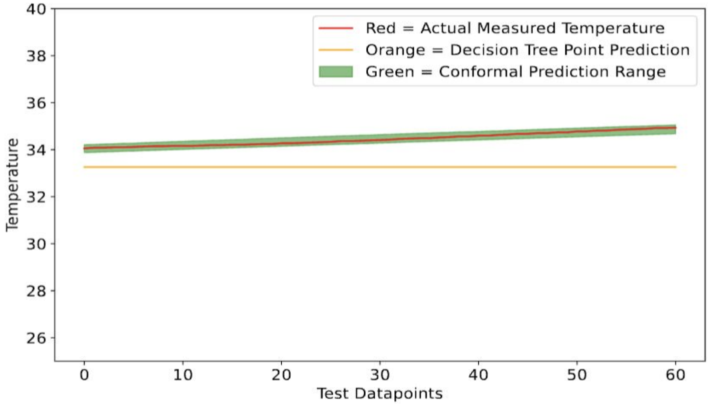


Source: https://everyhue.me/posts/why-uncertainty-matters/

Conformal Prediction Approach

Results

- Actual temperature value for the out-of-domain data were inside the predicted ranges 79% of the time
- For other 21% points the relative percentage error was 0.34%.
- The average width of prediction was 1.07 ℃.



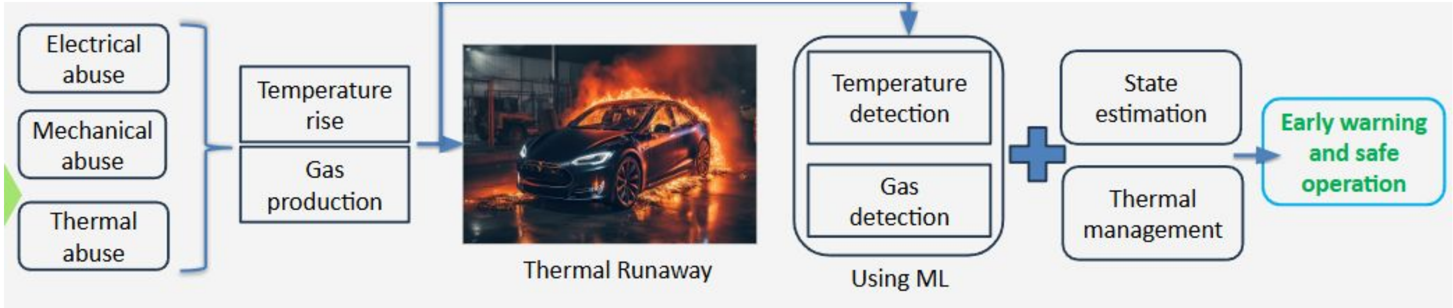
Benchmarking

Mean absolute error averaged across all Batteries (RW9-12): conformal prediction (CP), linear regression (LR), decision tree (DT) and random forest (RF).

Cycling Profile	CP	LR	DT	RF
Reference Charge	0.76	0.55	0.38	0.17
Reference Discharge	0.28	0.38	1.45	0.60
Pulsed Load (Rest)	0.06	0.12	0.31	0.09
Pulsed Load (Discharge)	0.03	0.04	0.40	0.15
Discharge (RW)	0.03	0.04	0.28	0.10
Charge (RW)	0.03	0.04	0.27	0.10
Pulsed Charge (Rest)	0.06	0.06	0.13	0.04
Pulsed Charge (Charge)	0.03	0.03	0.18	0.07
Low Current Discharge	0.72	0.28	0.27	0.33
Rest Post Low Current Discharge	0.37	0.21	0.14	0.14
Rest Post Reference Discharge	0.58	0.89	0.41	0.09
Rest Post Pulsed Load/Charge	0.26	0.25	0.24	0.10

Source: P. Sachan and P. Bharadwaj, "Incorporating Uncertainty and Reliability for Battery Temperature Prediction using Machine Learning Methods," in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, doi: 10.1109/JESTIE.2023.3327052.

Conclusion



- Energy storage devices like Lithium ion batteries : low tolerance for abuse.
- Solved with smart low-cost electronics: real-time health-monitoring + BDT.
- Battery digital twins correlate operation to abuse signature: extend life.
- Developed tool with real-time electro-thermal-aging diagnosis prevents fires.
- Save millions EV users by time-advanced warnings before a fire hazard.
- Offset high cost of compliance for AIS 156 and AIS 038 Rev 2.
- Support India’s transition to safer and more reliable electric vehicles.

Any Questions are welcome!

Research Impact

- P. Sachan and P. Bharadwaj, "Incorporating Uncertainty and Reliability for Battery Temperature Prediction Using Machine Learning Methods," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 5, no. 1, pp. 234-241, Jan. 2024, doi: 10.1109/JESTIE.2023.3327052.

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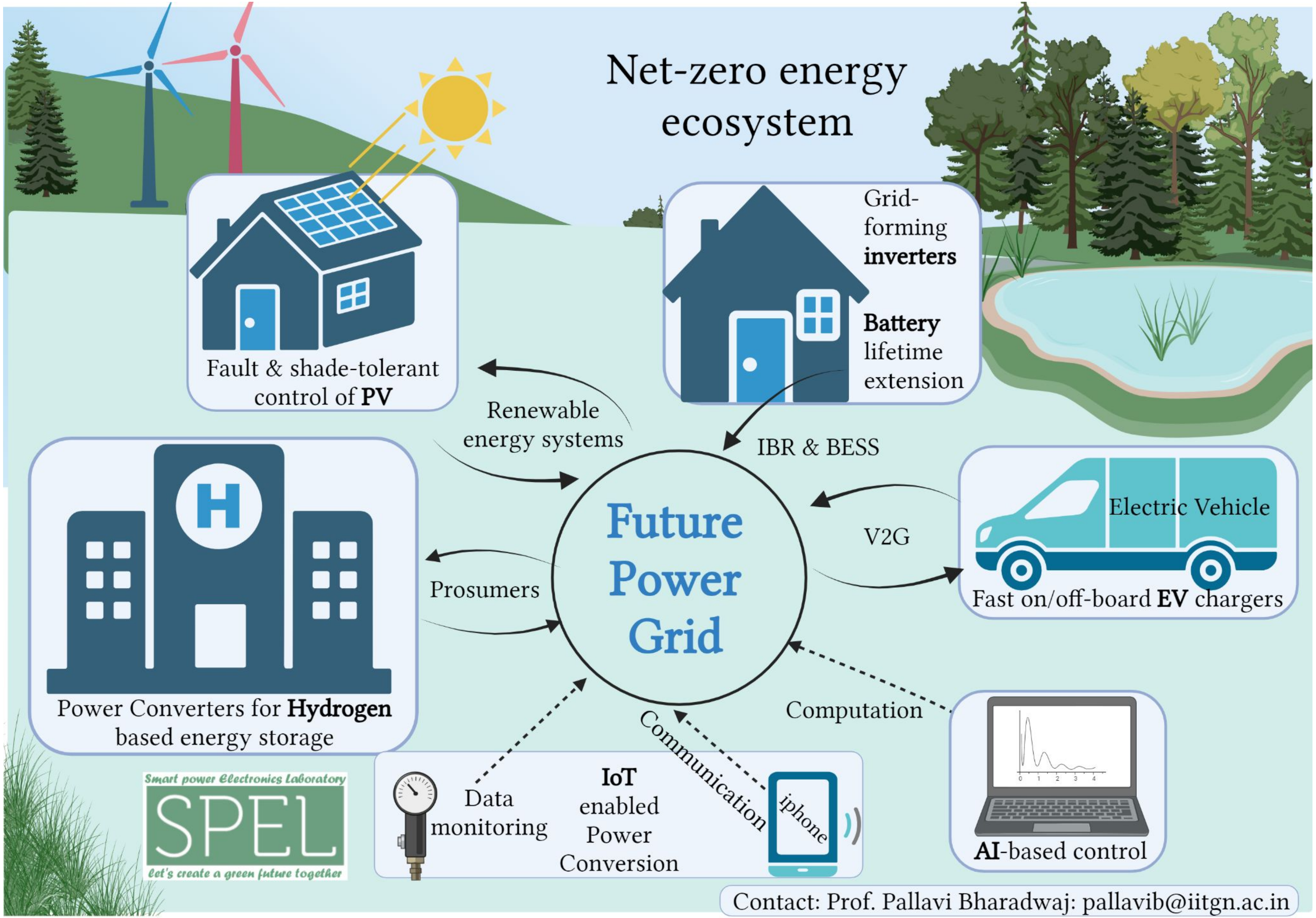
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Thank You!

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