Smart Battery and Hybrid Energy Storage Systems for Electric Vehicles and Drones: Advanced Energy Management Strategies and Applications

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Ph.D. in Electrical Engineering from Ecole Centrale de Lille, 2016 (Section CNU: 63)

Agreement for research management (*Habilitation à Diriger des Recherches HdR)* from Université de Strasbourg ,2023

OUTLINE

01

INSA Group
- INSA Strasbourg
- ICUBE Laboratory
- ICUBE Platforms

02

Context and Scientific Stakes
- ESS: Challenges and Innovations
- Role of the BMS
- Advanced BMS with AI
- Research Activities

03

AI for Batteries
- Horizon ENERGETIC Project
- Why BMS Need Explainable AI
- Transparency Issue in Deep Learning
- Results

04

Hydrogen Hybrid Power Sources
- Long-Endurance Drone
- Advanced Energy Management Strategy

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

ICUBE

OUR GROUP

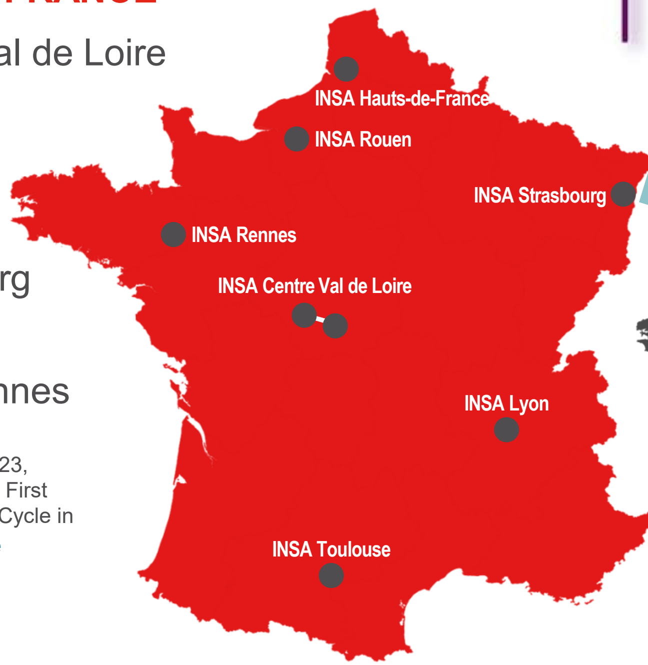
1875 2025

150 ANS

7 INSAS IN FRANCE

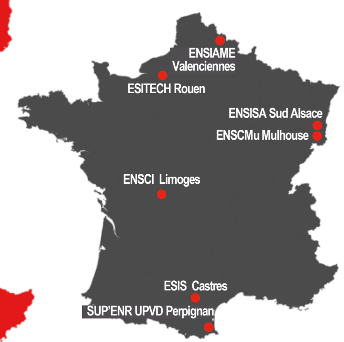
- Centre Val de Loire
- Lyon
- Rennes
- Rouen
- Strasbourg
- Toulouse
- Valenciennes

In September 2023,
Inauguration of the First
Engineering Training Cycle in
Martinique



PARTNER INSA SCHOOLS

ENSCI Limoges
- ISIS Castres
- ENSCMu Mulhouse
- ENSISA Sud Alsace
- ESITECH Rouen
- SUP'ENR UPVD Perpignan



1 INTERNATIONAL

- INSA Euro-Méditerranée/UEMF
Fès (Morocco)

Closed in 2003

Identification of a new site for INSA Morocco in progress…..

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

iCUBE

OUR GROUP

In figures (excl. INSA partners) …

- **22 179** students, incl. **433** architects and **162** landscape architects
- **3 334** engineers, **57** architects et **23** landscape architects **qualify every year**
- **1 354** PhD Students, **292** thesis last year, **60** research laboratories
- **34,7 %** females students
- **30,4 %** students with state grants
- **+ 300** agreements with partner universities abroad
- **18%** international students welcomed in first year of curriculum
- **4,649** overseas students
- **369 M€** consolidated budget

STUDENT NUMBERS

2,015 STUDENTS, including

- **214** first-year students (post-high school)
- **1 577** engineering students, including **347** apprentices
- **433** architecture students including **387** students following the dual engineering and architecture course
- **75** in a master program
- **49** in a specialist master's in eco-consultancy in partnership with the Institut Éco-conseil, accredited by the Conference des grandes écoles
- GENDER EQUALITY **35% / 65%** :This figure is an average, with proportions of female students varying considerably between specialtie
- Students with state grants : **35%**

OUR GRADUATES

GRADUATES (2021)

340 engineer
57 architects

OUR COURSES

Architecture training

Seven specialist engineering courses

- Civil engineering
- Surveying engineering
- HVAC and energy engineering*
- Electrical engineering*
- Mechanical engineering*
- Mechatronics*
- Plastics engineering**

A specialist master's

Co-supervised and partnership master's courses

(*) also available as apprenticeship programmes in partnership with ITII

(**) also available as apprenticeship programmes in partnerhip with CIRFAP

OUR STAFF

- A permanent teaching staff of **117**, including
  - **83** lecturer/researchers
  - **34** other lecturers
- Over **300** part-time or non-tenured lecturers
- **122** permanent administrative and technical staff and about thirty contract staff

OUR BUDGET

- Revenue: **€21.9m** (incl. 76% from the State)
- Expenditure: **€21.0m** (incl. 78% staff costs)
- **60%** training, **20%** research, **11%** property, **9%** management

ICUBE LABORATORY

UMR 7357

The ICube laboratory

Under the supervision of 5 establishments

- Born January 1, 2013
- 692 members
- + 200 patents
- + 59 M€ budget

ICUBE, A MULTIDISCIPLINARY LABORATORY

A MAJOR DRIVING FORCE FOR RESEARCH IN STRASBOURG (> 632 PEOPLE)

ICube is since 01/01/2013:

- a research laboratory in the Engineering, Computing and Imaging sciences with biomedical engineering, environment and sustainable development as privileged sectors.

Computing Engineering

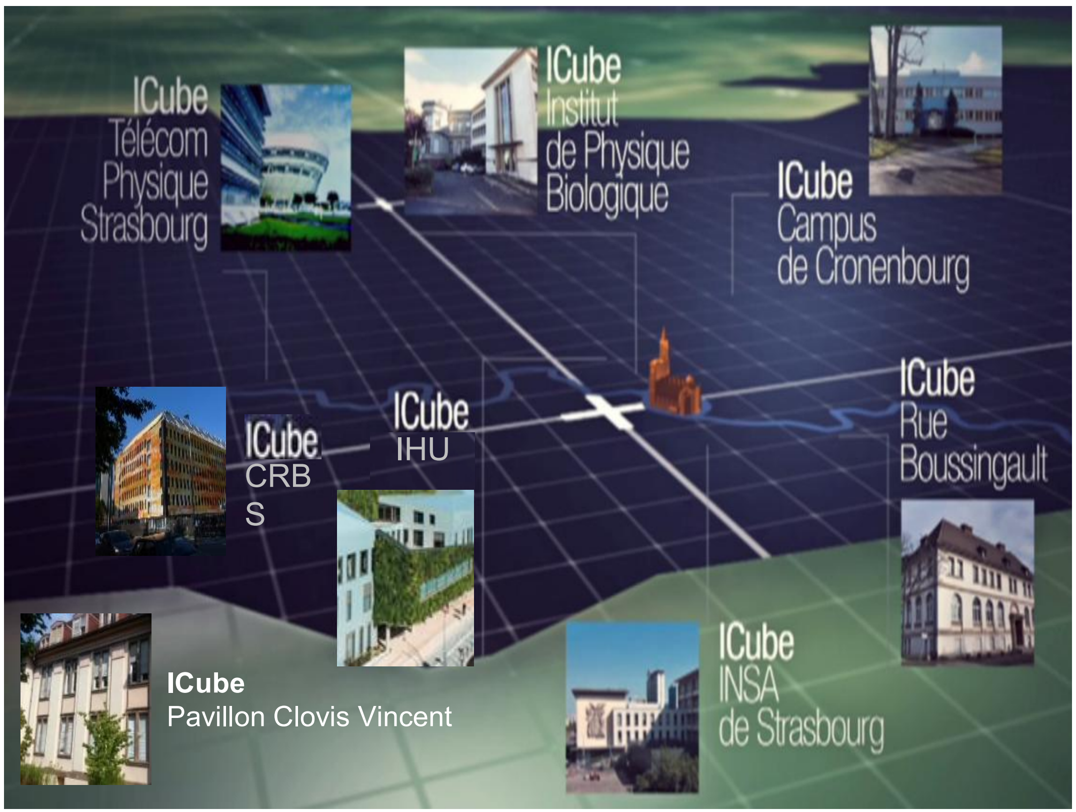
Imaging

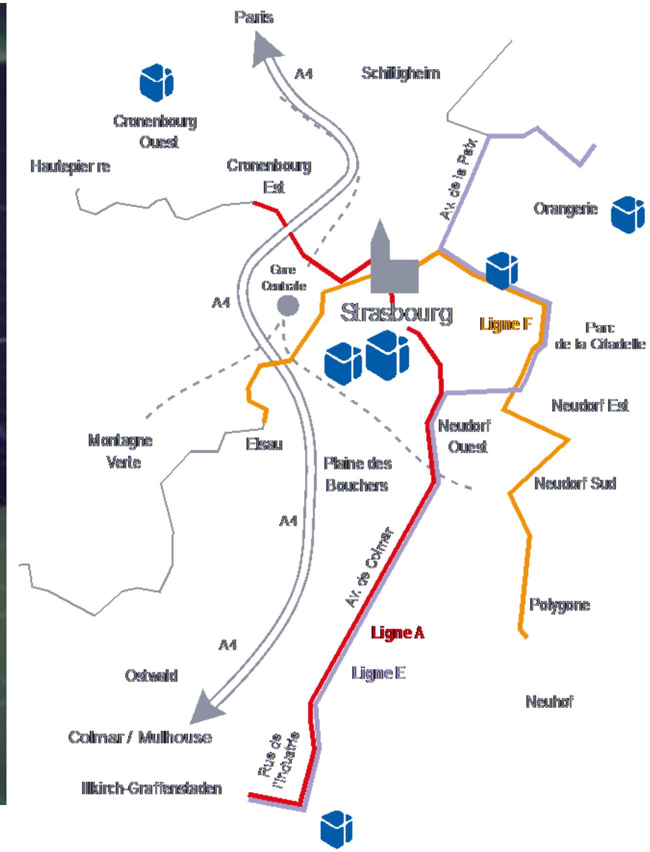
- a joint research unit (UMR7357) of university of Strasbourg, CNRS, ENGEES and INSA Strasbourg.

- with as privileged partners:

ICUBE, A MULTI-SITE LAB

8 SITES



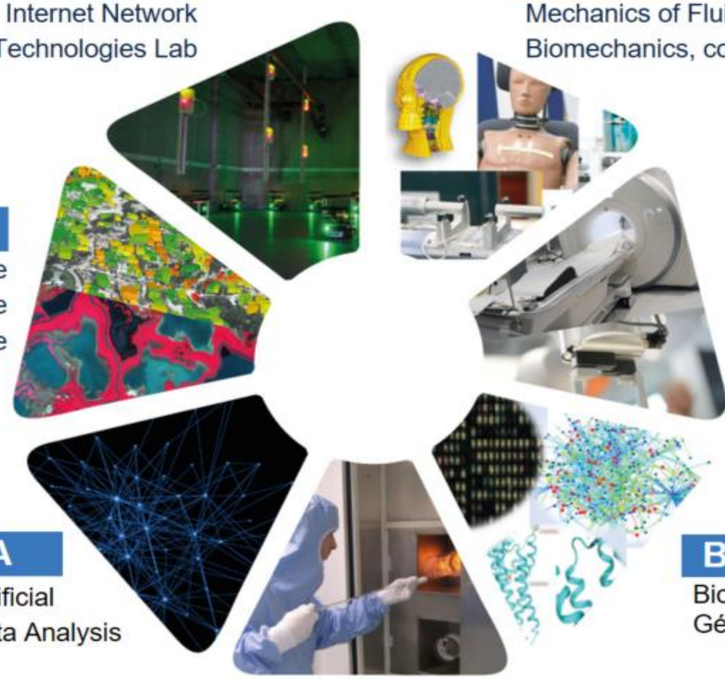


7 HARDWARE AND SOFTWARE PLATFORMS

Inetlab
Internet Network Technologies Lab

MechaniCS
Mechanics of Fluids and Materials, Biomechanics, conception and simulation

SERTIT
Regional Image processing and remote sensing service



IRIS
Innovative imaging of health platform

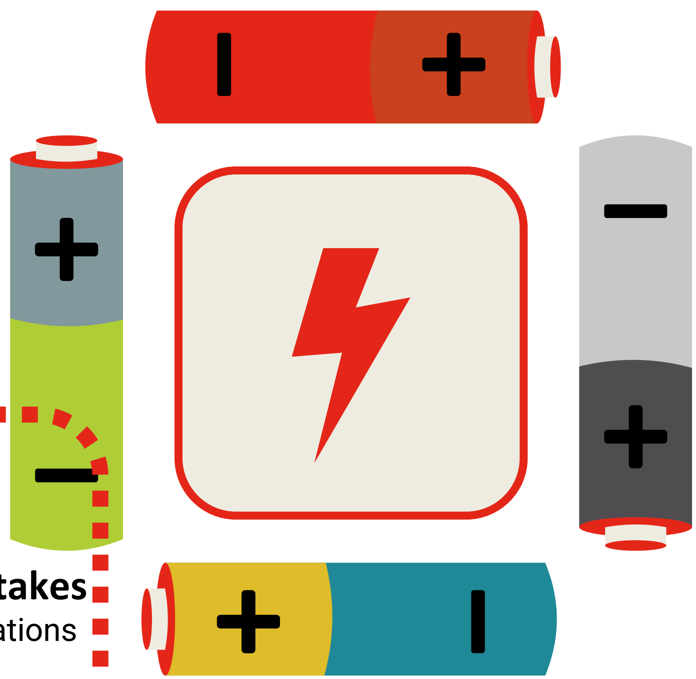
GAIA
Graphics, Artificial Intelligence and data Analysis

BiGEst-ICube
Bioinformatique et Génomique Est

C³Fab
Development and characterisation of materials for photovoltaics

ICube presentation 15.09.21 P 10

OUTLINE



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CONTEXT AND SCIENTIFIC STAKES

Energy Storage Systems: Challenges and Innovations

The Critical Role of Energy Storage

Integration

Storage systems enable seamless integration of intermittent renewable energy sources into existing power grids.

Electrification

They power electric vehicles and off-grid applications that reduce fossil fuel dependence.

Grid Stability

Energy storage provides critical balancing services during peak demand periods.

Key Statistics (2023):

- **14 million** new electric cars sold globally, **18%** of total car sales (1 in 5 cars sold).
- **40 million** EVs on roads globally, with **70%** being battery electric vehicles (BEVs).
- **35% YoY growth** (vs. 2022), **6x higher** than 2018 levels.
- **China:** Dominant market, ~60% of global EV sales.

Global Energy Storage Landscape

320 GW
Installed Capacity
Worldwide in 2023

1,000 GW
2030 Projection
Bloomberg NEF forecast

20%
Annual Growth
Compound rate through 2030

$500B+
Total Investment
Expected by 2030

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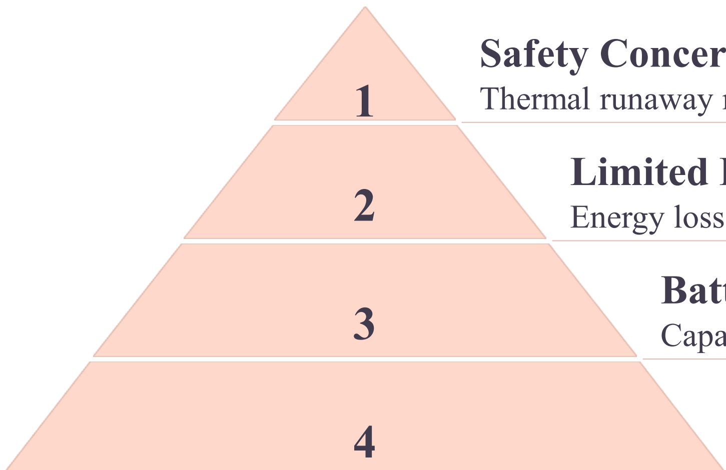
STRASBOURG

CONTEXT AND SCIENTIFIC STAKES

Energy Storage Systems: Challenges and Innovations

Current Challenges



Safety Concerns
Thermal runaway risks

Limited Efficiency
Energy loss during conversion

Battery Degradation
Capacity fade over time

Sustainability Issues
Resource-intensive production

These challenges create significant barriers to widespread adoption. They impact cost-effectiveness and reliability across applications.

CONTEXT AND SCIENTIFIC STAKES

Energy Storage Systems: Challenges and Innovations

Smart Battery Solutions

Real-time Monitoring

Advanced sensors track temperature, voltage, and degradation patterns continuously.

AI Diagnostics

Machine learning algorithms detect anomalies before they cause failures (**Generative AI and LLM**).

Predictive Maintenance

Systems forecast maintenance needs to prevent unexpected downtime.

Adaptive Management

Operating parameters adjust automatically to extend battery life.

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THE ROLE OF THE BATTERY MANAGEMENT SYSTEM (BMS)

The Battery Management System serves as the essential control layer in Large-Scale Battery Energy Storage Systems (BESS), ensuring safe operation, optimal performance, and extended lifecycle management.

Safety & Protection

Continuous monitoring of voltage, current, temperature, and pressure prevents critical safety events including overcharge, short-circuit, and thermal runaway through intelligent alarm handling and safe-shutdown strategies.

Lifecycle Management

Advanced estimation of key health indicators—State of Charge (SoC), State of Health (SoH), and State of Energy (SoE)—while tracking aging, cycling patterns, and degradation over time.

Operational Optimization

Intelligent cell balancing (active or passive), sophisticated thermal management, and seamless communication with inverter, EMS, and SCADA systems ensure peak performance.

Digital Interface

Reliable data acquisition and logging with local or cloud-based transfer capabilities provide partial traceability across the entire battery lifecycle for informed decision-making.

ADVANCED BMS WITH AI

Next-generation capabilities powered by artificial intelligence transform grid-scale Battery Energy Storage Systems, delivering predictive intelligence, optimization, and unprecedented transparency.

1

Predictive Intelligence

Machine learning enables accurate prediction of State of Health (SoH) and Remaining Useful Life (RUL), early anomaly and fault detection, plus fast, robust SoC estimation even under highly dynamic operating conditions.

2

Intelligent Energy Optimization

AI-driven dynamic charge and discharge dispatch, degradation-aware optimization strategies to extend battery lifespan, and sophisticated multi-asset coordination across hybrid systems including battery, hydrogen, supercapacitors, and renewables.

3

Explainable AI: Building Trust

Transparent, operator-readable explanations using feature importance and SHAP analysis justify why the BMS limits current, triggers alerts, or adjusts operation modes—critical for grid operators, insurers, and regulators.

4

Enhanced Traceability & Digital Passports

Automated, enriched data enables digital battery passport compliance with full lifecycle history including performance metrics, usage patterns, repairs, and environmental data—enabling circularity through second life, reuse, and recycling initiatives.

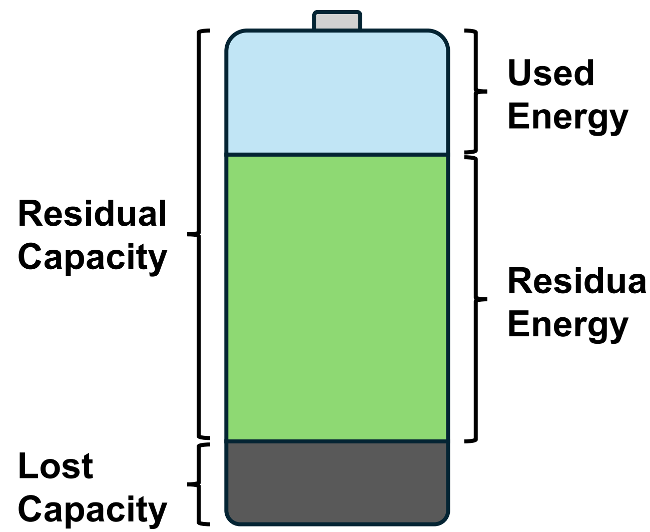
STATE INDICATORS FOR BMS

- **State of Charge (SOC):** Remaining usable energy
- **State of Health (SOH):** Decrease in total capacity
- **Internal Resistance (IR):** Increases over time due to aging, induces lower power performance

Aging mechanisms

Calendar aging (storage-related degradation)

Cycle aging (charge/discharge-related degradation)



Battery capacity diagram

- **SOC, SOH, and RUL (Remaining Useful Life) assessment**

→ optimized use and longer battery lifespan

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DATA-DRIVEN VS. PHYSICS-BASED BATTERY MODELS

Criterion	Data-driven Models	Multi-physics Models
Principle	Learn patterns from historical data	Use coupled electrochemical, electrical and thermal equations
Data Needs	High: large and diverse datasets	Low to moderate: need accurate physical parameters
Generalization	Limited to training distribution	Strong: based on physical laws, can extrapolate to new conditions
Explainability	Low: “black box”	High: each parameter has physical meaning
Computation	Low at inference, training can be heavy	High: solving coupled PDEs can be computationally intensive
Deployment	Easy to integrate in a BMS	Difficult for real-time deployment
Best Use	Fast prediction, fleet analytics, anomaly detection	Understanding degradation mechanisms, battery design, safety validation

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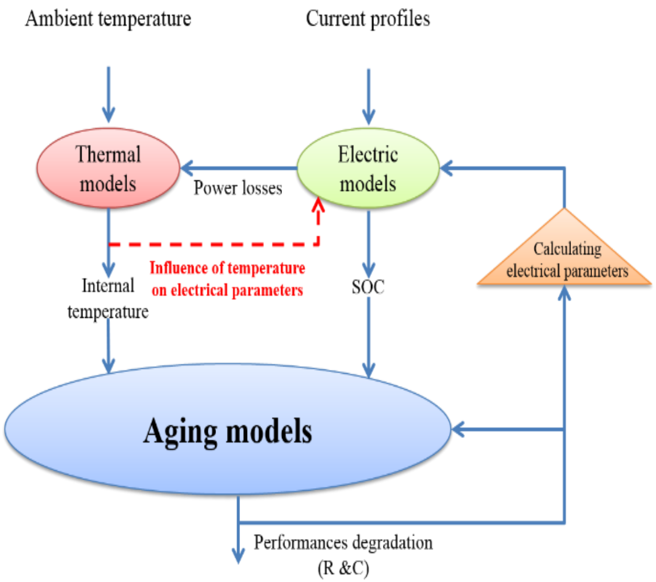
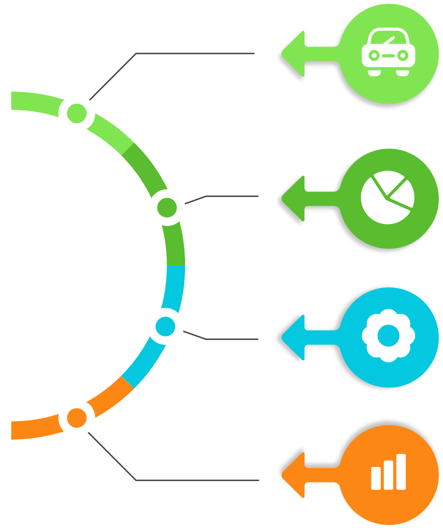
RESEARCH ACTIVITIES

Modeling and Data : Multi-physics and Data-driven Modeling

→ **Multi-physics Modeling with Cell Behavior Approach**





Technologies and Sizing

Technologies and sizing of energy storage systems are crucial factors in ensuring efficient and sustainable solutions

Source Hybridization

Source hybridization plays a key role in optimizing energy systems for enhanced performance and efficiency of EVs

Energy and Thermal Management

Effective energy and thermal management is crucial for maximizing the performance and longevity of energy systems

Lifetime and Total Cost of Ownership

Considering the lifetime and TCO is essential for evaluating the long-term sustainability and economic viability of energy systems

→ Component vision and technological mastery

↔

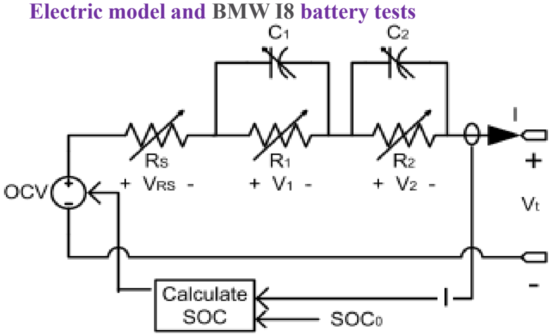
→ System Vision and Overall Performance Optimization

RESEARCH ACTIVITIES

Modeling and Data : Electric models (Thesis of Yasser GHOULAM - 2019-2023 & project VEHICLE)

→ **Dual Polarization Equivalent Circuit Battery Model with Two RC Branches**

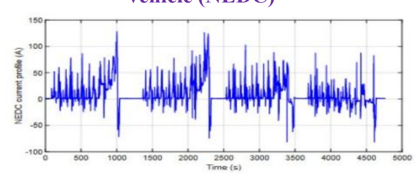
Electric model and BMW I8 battery tests



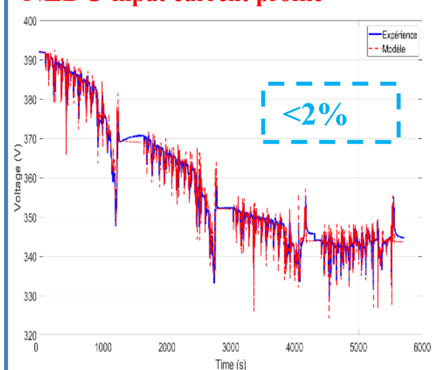
Dual polarization equivalent circuit model

Bath University -IAAPS (Pack bat 18Ah 400V)

Validation with drive cycle data of a hybrid vehicle (NEDC)

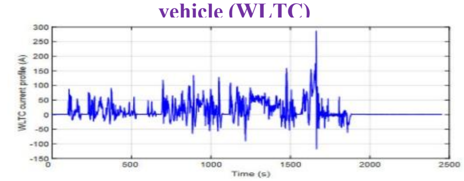


NEDC input current profile

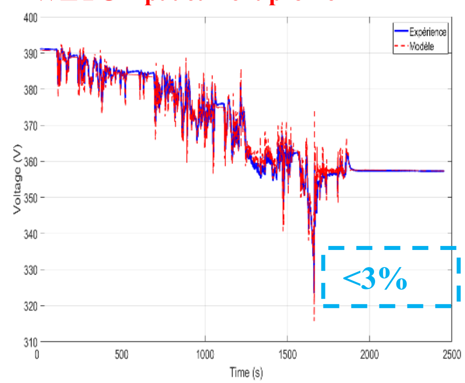


NEDC: Voltage curves (Expe _model)

Validation with drive cycle data of a hybrid vehicle (WLTC)



WLTC input current profile



WLTC: Voltage curves (expe _model)

1 PhD (40%)
1PRT

1 int. papers

3 int. conf.

project VEHICLE

HrT, IAAPS Bath. Univ

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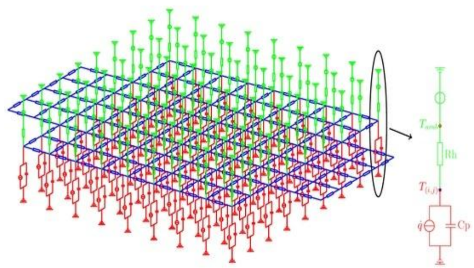
RESEARCH ACTIVITIES

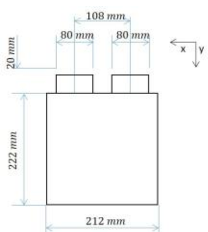
Modeling and Data : Thermal models (Rocio SUGRANES's Internship - 2017 & project VEHICLE)

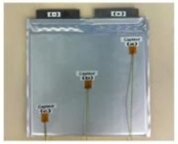
→ **Multi-node Thermal Model (The battery is divided into n×m nodes with two dimensions)**

Thermal model and NMC batteries tests



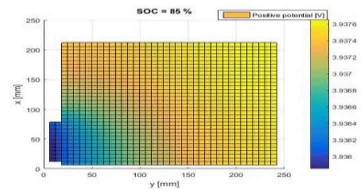
Multi-node thermal model of battery cell [Chenet al.2016]



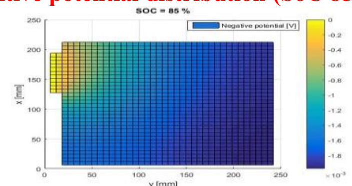


40 Ah NMC battery cell (Kokam) [-20 -60 °C]

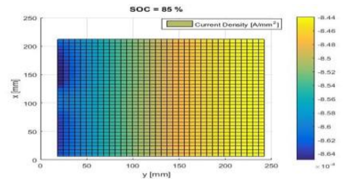
Validation with NMC batteries tests



Positive potential distribution (SoC 85%)

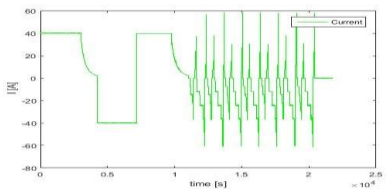


Negative potential distribution (SoC 85%)

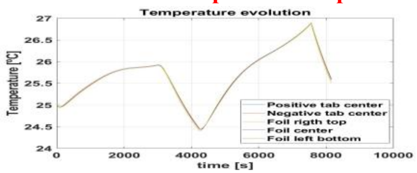


Current density distribution SoC 85%

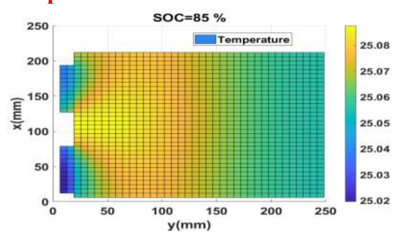
Validation with NMC batteries tests



CC-CV & Artemis input current profile



Temperature evolution



Temperature distribution (SoC 85%)

1 Master

1 int. papers

// int. conf.

project VEHICLE

L2EP, ICube Univ.Str

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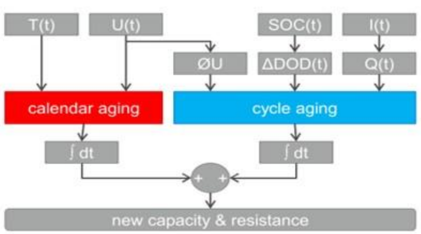
RESEARCH ACTIVITIES

Modeling and Data : Aging models (Franck BOUTOILLE's Internship - 2017& project VEHICLE)

→ Semi-empirical model of Li-ion battery aging (Calendar and cycling aging)

Aging model and NMC batteries tests

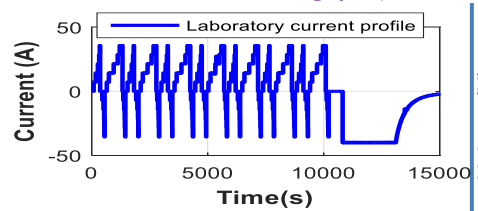


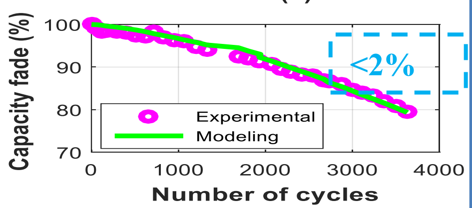
Semi-empirical model battery aging [Schmalstieg et al.2014b]

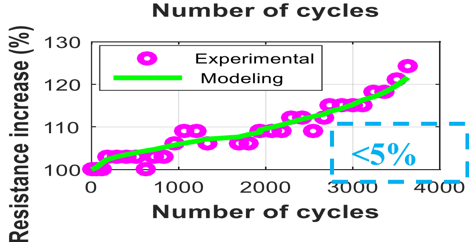
Kokam 40HP SLPB100216216H (NMC)

Kokam 40HE SLPB90216216 (NMC)

Validation with NMC batteries tests (Kokam 40HE + ARTEMIS driving cycle)

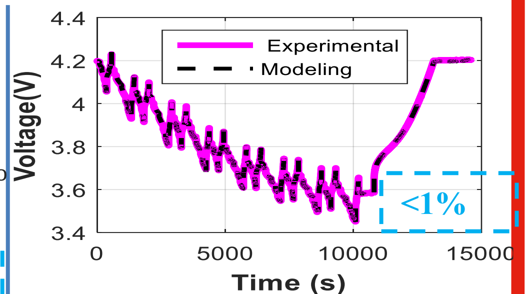




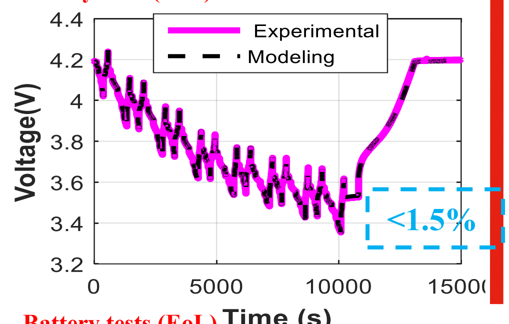


Identification (PSO / NM)

Validation with NMC batteries tests at BoL & EoL



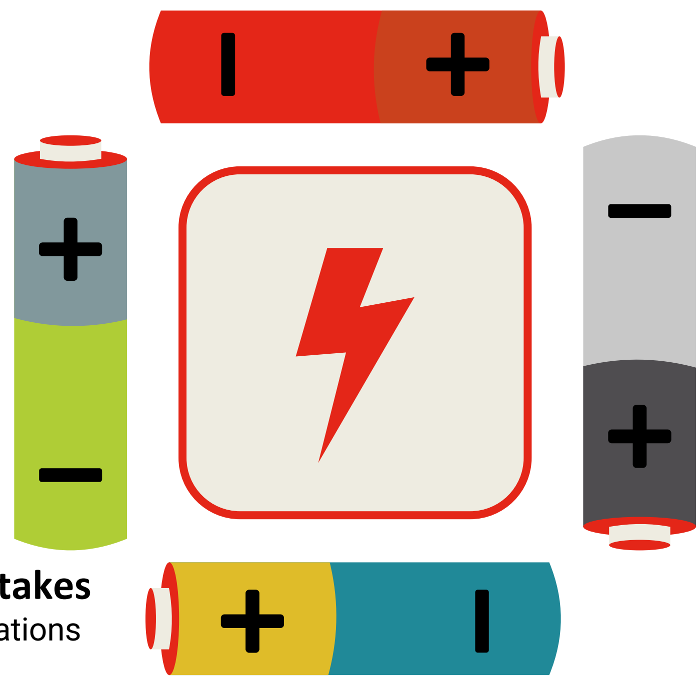
Battery tests (BoL)



Battery tests (EoL)

- 1 Master
- 2 int. papers
- // int. conf
- project VEHICLE
- L2EP, ICube Univ.Str

OUTLINE



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NEXT GENERATION BATTERY MANAGEMENT SYSTEM BASED ON DATA RICH DIGITAL TWIN

ENERGETIC

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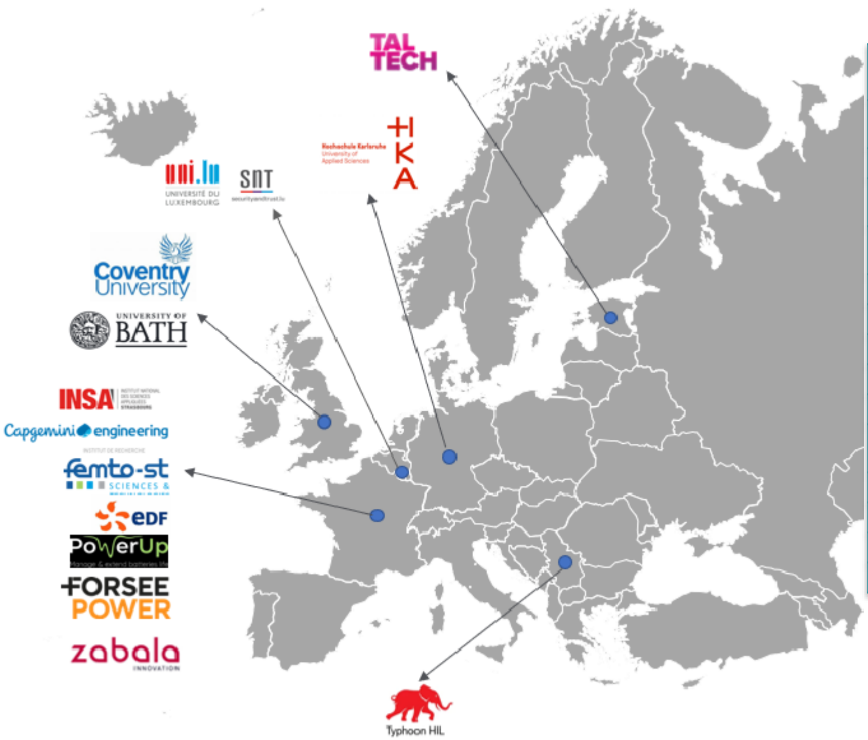
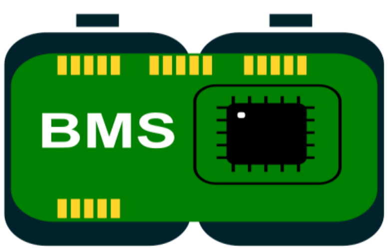
Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. N° CONTRACT 101103667.

ENERGETIC CONSORTIUM



Partners			
1	**INSA Strasbourg**	INSTITUT NATIONAL DES SCIENCES APPLIQUEES, STRASBOURG - COORDINATOR	**FR**
2	**CapGemini**	ALTRAN PROTOTYPES AUTOMOBILES - BENEFICIARY	**FR**
3	**UBFC**	COMMUNAUTE D' UNIVERSITES ET ETABLISSEMENTS UNIVERSITE BOURGOGNE - FRANCHE - COMTE - UBFC - BENEFICIARY	**FR**
3.1	**FEMTO-ST**	UNIVERSITE DE TECHNOLOGIE DE BELFORT - MONTBELIARD	**FR**
4	**SnT**	UNIVERSITE DU LUXEMBOURG - uni.lu - BENEFICIARY	**LU**
5	**EDF**	ELECTRICITE DE FRANCE - EDF - BENEFICIARY	**FR**
6	**ZABALA**	GBA ZABALA CONSEIL EN INNOVATION SA - BENEFICIARY	**FR**
7	**HKA**	HOCHSCHULE KARLSRUHE - BENEFICIARY	**DE**
8	**THIL**	TAJFUN HIL LIMITED LIABILITY COMPANY, NOVI SAD- BENEFICIARY	**RS**
9	**TalTech**	TALLINNA TEHNIKAÜLIKOOL - TALLINN UNIVERSITY OF TECHNOLOGY - BENEFICIARY	**EE**
10	**POWERUP**	POWERUP - BENEFICIARY	**FR**
11	**FORSEEPOWER**	FORSEE POWER - BENEFICIARY	**FR**
12	**BATH**	UNIVERSITY OF BATH - UBAH - ASSOCIATED PARTNER	**UK**
13	**CU**	COVENTRY UNIVESITY - ASSOCIATED PARTNER	**UK**



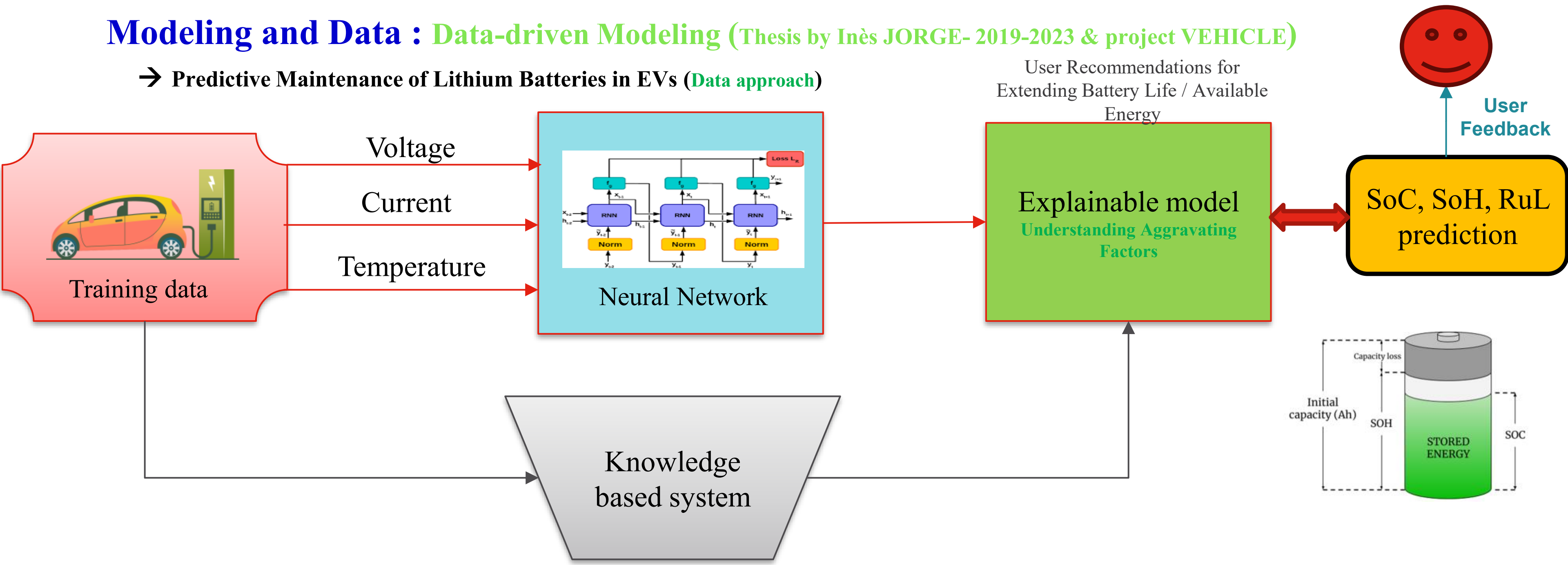
Call specifications	
Programme:	**Horizon Europe Framework Programme (HORIZON)**
Type of action:	**HORIZON - Research and Innovation Actions (RIA)**
Call:	**HORIZON-CL5-2022-D2-01-09**
Submission deadline	**6 September 2022**
Indicative Budget:	**€15 Million**

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

RESEARCH ACTIVITIES

Modeling and Data : Data-driven Modeling (Thesis by Inès JORGE- 2019-2023 & project VEHICLE)

→ **Predictive Maintenance of Lithium Batteries in EVs (Data approach)**



Prognostics and Health Management of Lithium Batteries

- Choice and design of deep learning models.
- Development of Recurrent Neural Network models for SoH and SoC prediction of batteries.
- Models based on battery usage data (Public data, industrial data, laboratory-specific data…)
- Explainability model to understand the aggravating factors impacting battery range and lifetime.
- Utilization of driving data as input in predictive models

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WHY BMS NEED EXPLAINABLE AI

Accelerating Deployment

Accelerating EV battery deployment through advanced fast-charging technologies, AI-driven BMS, and scalable gigafactory production. Enhancing sustainability via circular economy models, second-life applications, and robust EU supply chains.

Growing Complexity

Modern energy systems require integrated optimization across thermal, electrical, and operational domains to ensure safety, maximize performance, and extend service life under real-world constraints.

Traditional Limits

Conventional BMS approaches rely on deterministic rules and narrow modeling assumptions that cannot adapt to dynamic real-world conditions.

Explainable AI provides transparency for operators, enables systematic debugging, ensures safety compliance, and builds stakeholder trust through interpretable decision-making.

WHAT EXPLAINABLE AI MEANS FOR BMS

Transparency & Trust

XAI systems provide clear visibility into how AI models reach decisions, enabling operators to understand and validate autonomous control actions in real-time.

Safety & Compliance

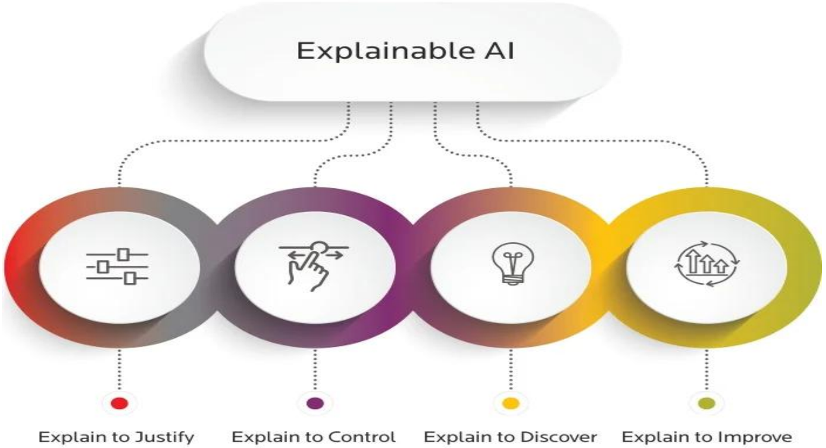
Regulatory bodies and insurers increasingly require auditable AI systems. XAI provides the documentation and transparency needed for certification and risk assessment.

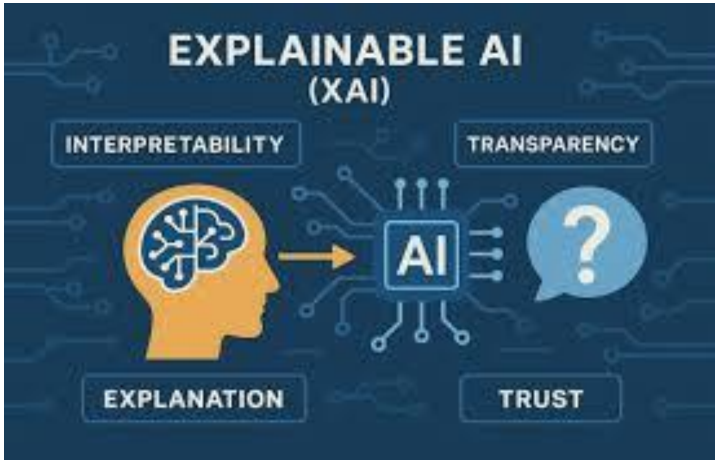
Debuggability

When systems behave unexpectedly, explainable models allow engineers to trace the root cause through interpretable feature contributions and decision pathways.

Risk Reduction

By making AI decisions interpretable, operators can identify potential issues before they escalate, improving overall system reliability and performance.





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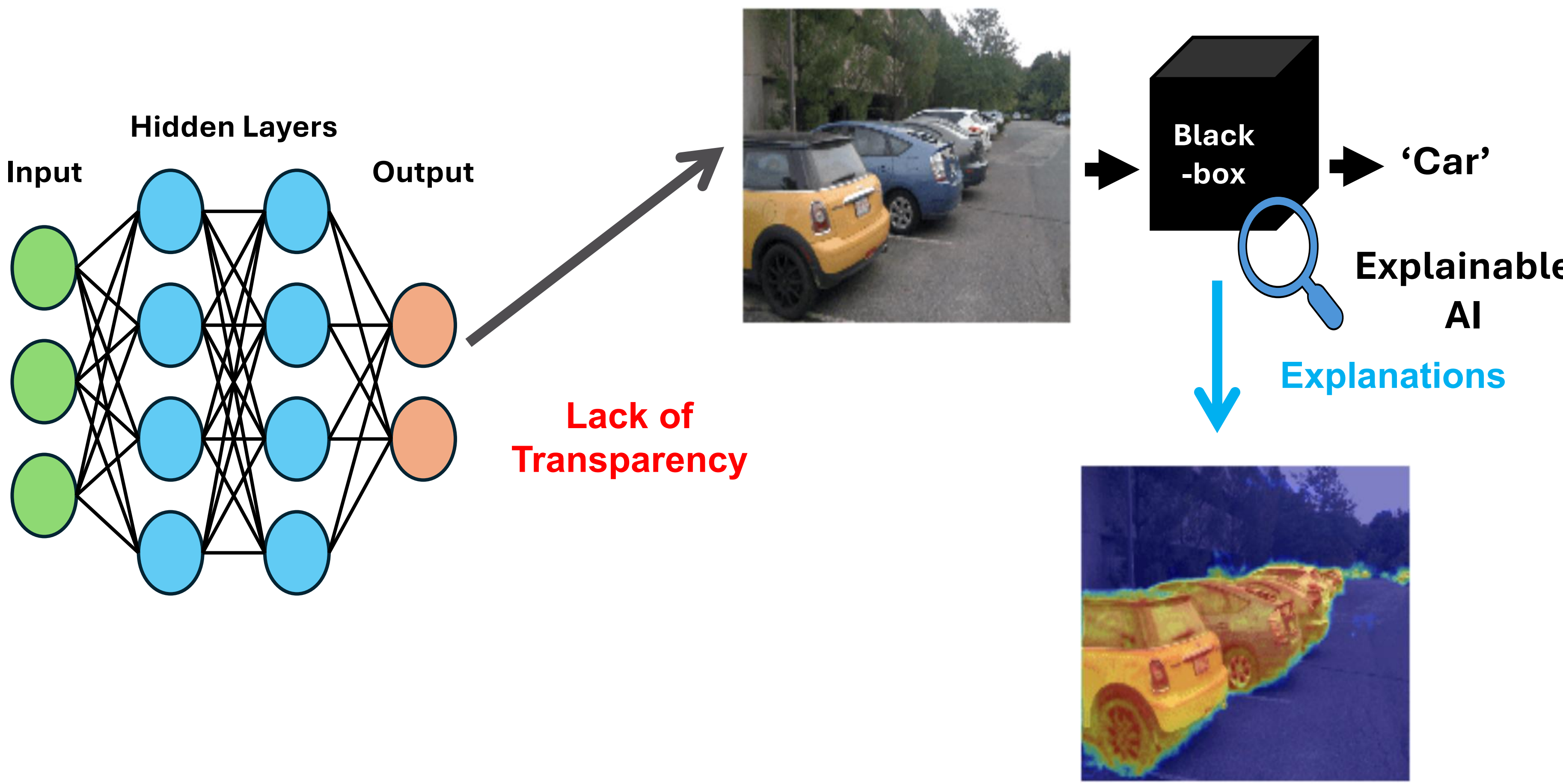
TRANSPARENCY ISSUE IN DEEP LEARNING MODELS



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DEFINITIONS OF EXPLAINABILITY AND INTERPRETABILITY

- **Explainability:** The ability to relate and make understandable the elements considered by an AI system in producing a result. **(CNIL)**

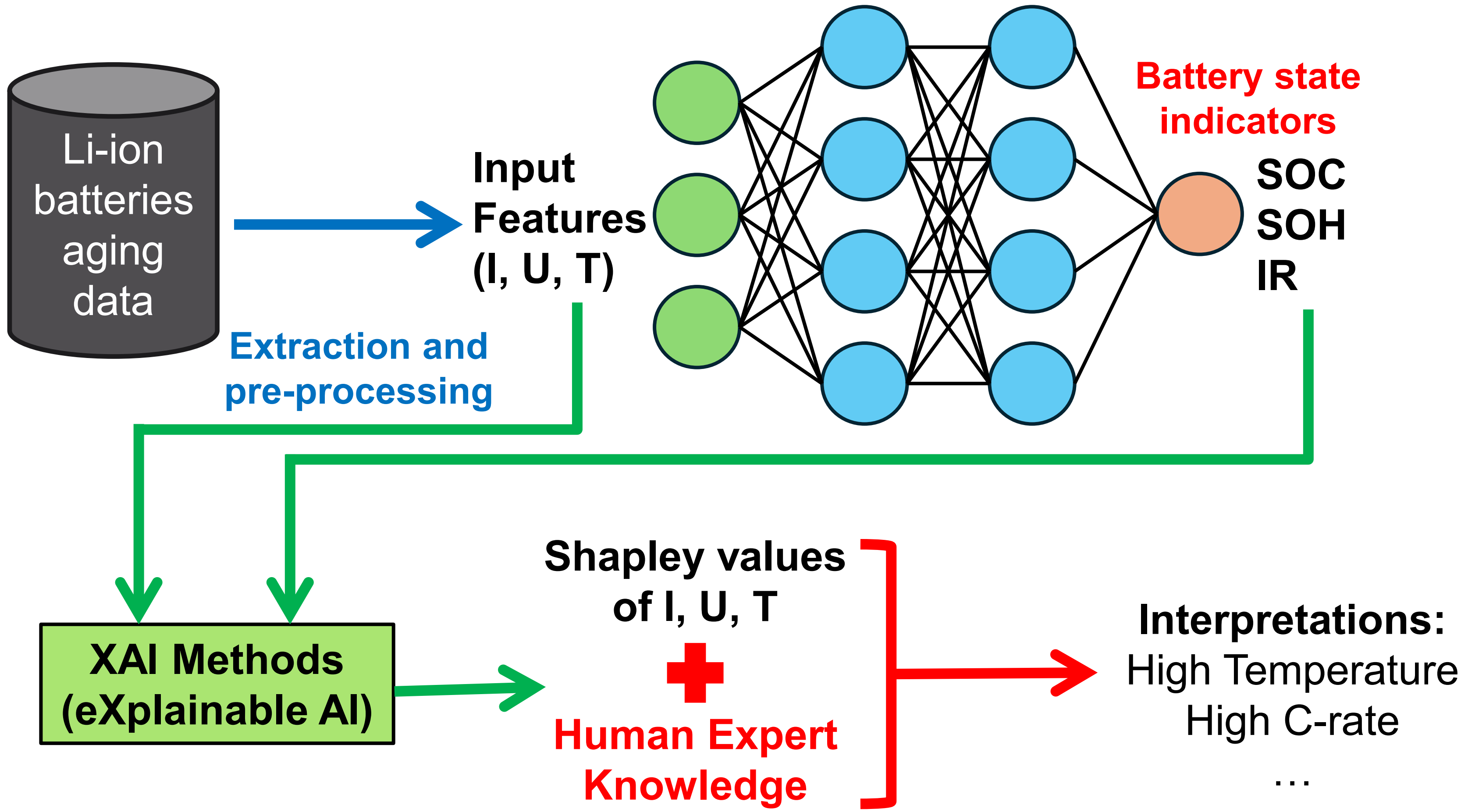
  Example: Input variables and their impact on the prediction of a score, and consequently on the decision.

- **Interpretability:** The ability to link physical phenomena accelerating battery aging to the explanations provided.

  Example: Impact of battery temperature, high charging current, etc.

CNIL: The National Commission for Information Technology and Freedoms (CNIL) is an independent French administrative authority.

DEFINITIONS OF EXPLAINABILITY AND INTERPRETABILITY



- Propose AI-based approaches to predict and explain battery aging in electric mobility
- Understand key factors affecting battery health starting from SOC to SOH to give practical user recommendations

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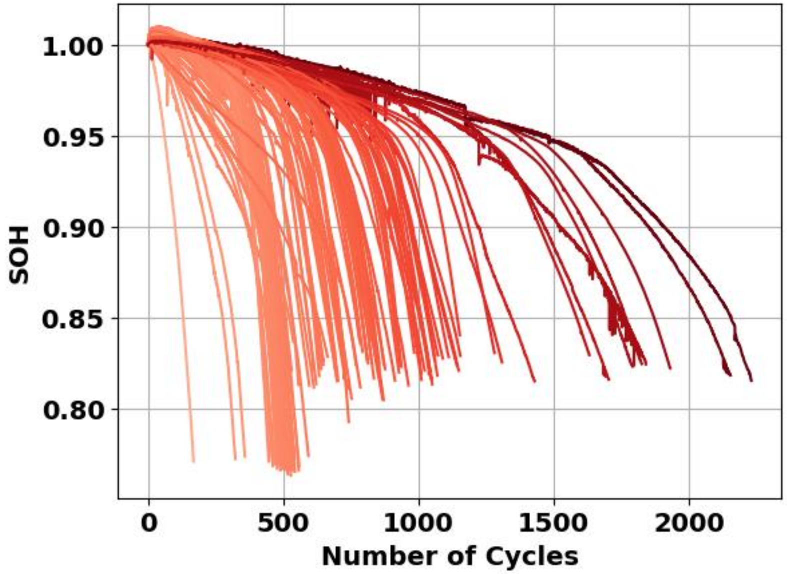
DATA OVERVIEW – MIT & TOYOTA RESEARCH INSTITUTE (TRI) DATASET (SEVERSON ET AL. 2019)

TOYOTA RESEARCH INSTITUTE

- Designed to study the effects of fast-charging protocols on battery lifespan
- **124 commercial LFP** (Lithium Iron Phosphate) 18650 cells, nominal capacity ~1.1 Ah
- Cells subjected to **72 different fast-charging protocols** at constant **30 °C**
- **Measurements**: Voltage, current, surface temperature and IR over each cycle

  → Capacity tracked until end-of-life (**EOL = 80%** of original capacity)



Articleshttps://doi.org/10.1038/s41560-019-0356-81Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. 2Department of Materials Science and Engineering, Stanford University, Stanford, CA, USA. 3Toyota Research Institute, Los Altos, CA, USA. 4Materials Science Division, Lawrence Berkeley National Lab, Berkeley, CA, USA. 5These authors contributed equally: K. A. Severson, P. M. Attia. *e-mail: wchueh@stanford.edu; braatz@mit.edu

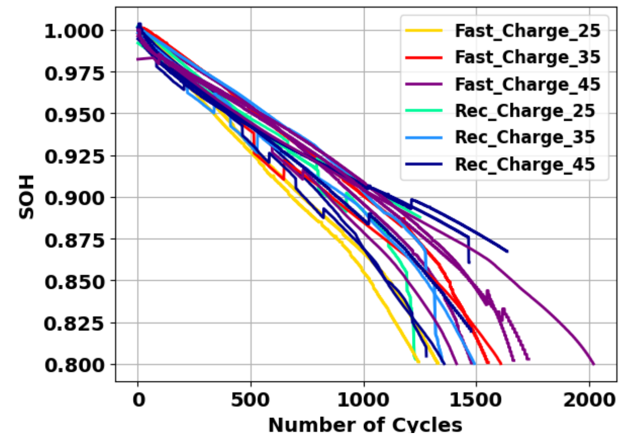
DATA OVERVIEW – INSA STRASBOURG DATASET

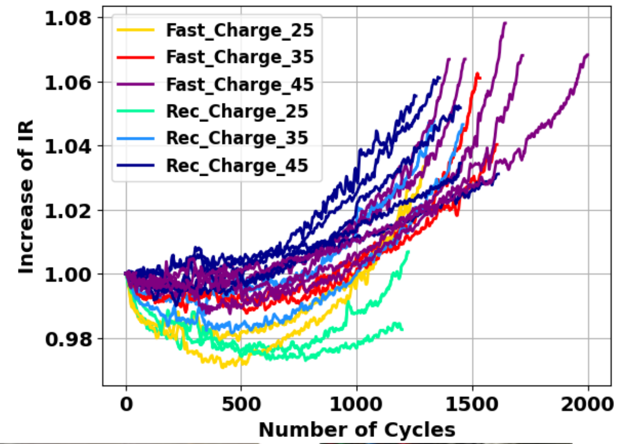
- Characterization cycles on LFP, sodium-ion

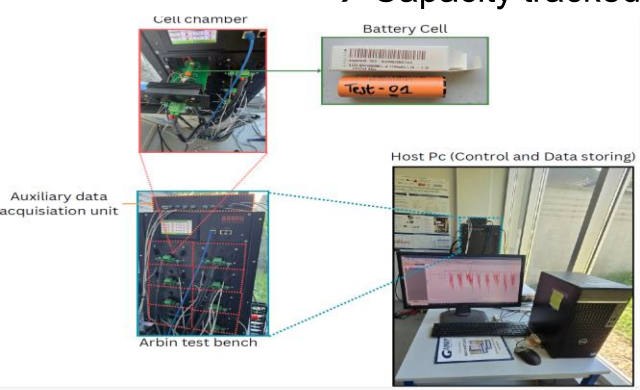
Battery Aging Experiment:

- 18 commercial LFP (same as MIT)
- Two charge types: **fast charge (4 A)** and **recommended charge (1.5 A)**
- Experiments at **three ambient temperatures**: 25 °C, 35 °C, 45 °C
- Each cycle includes **3 WLTP driving cycles** for realistic usage simulation
- **Measurements**: voltage, current, surface temperature over each cycle

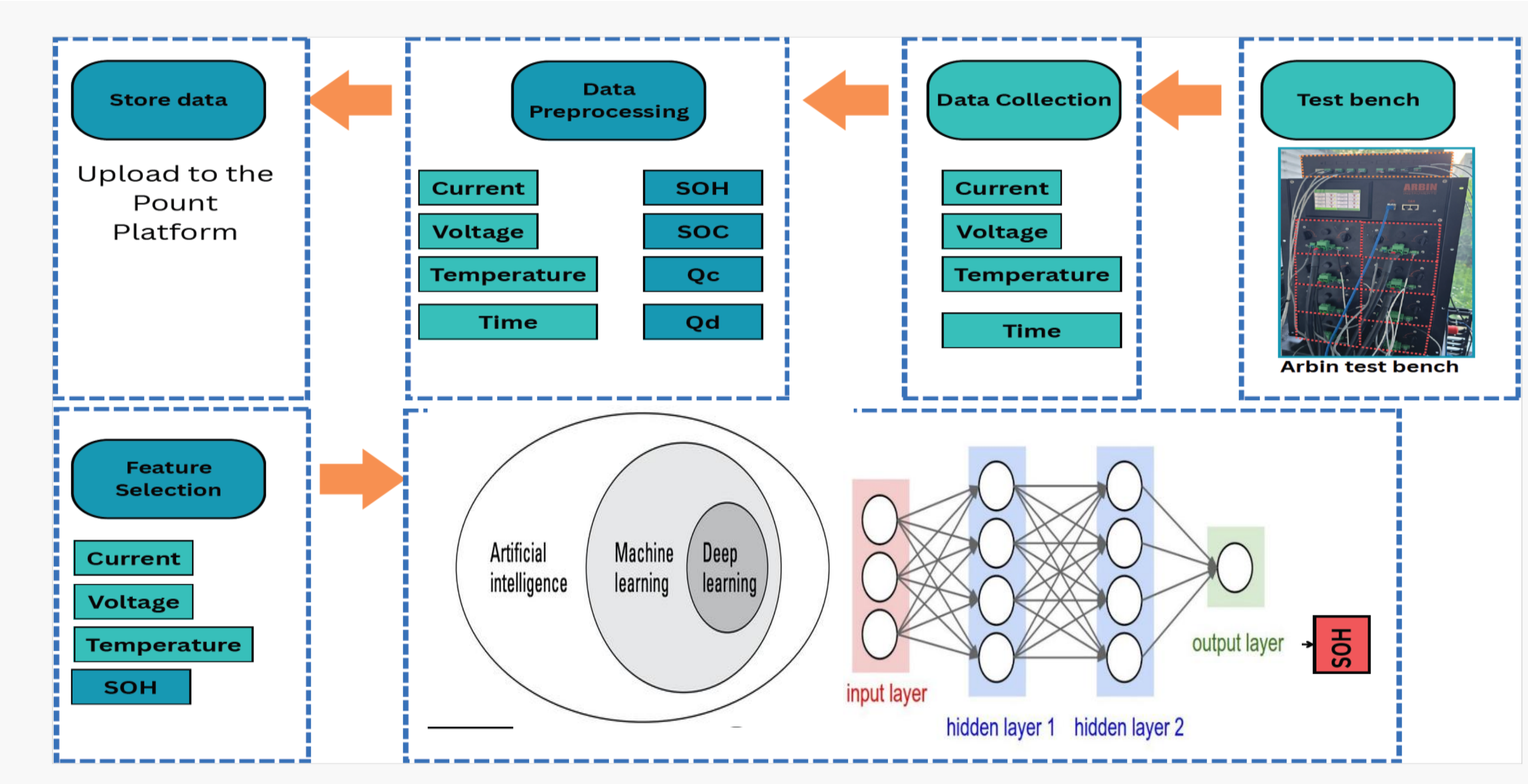
→ Capacity tracked until EOL (**SOH = 80%**)







DATA OVERVIEW – INSA STRASBOURG DATASET



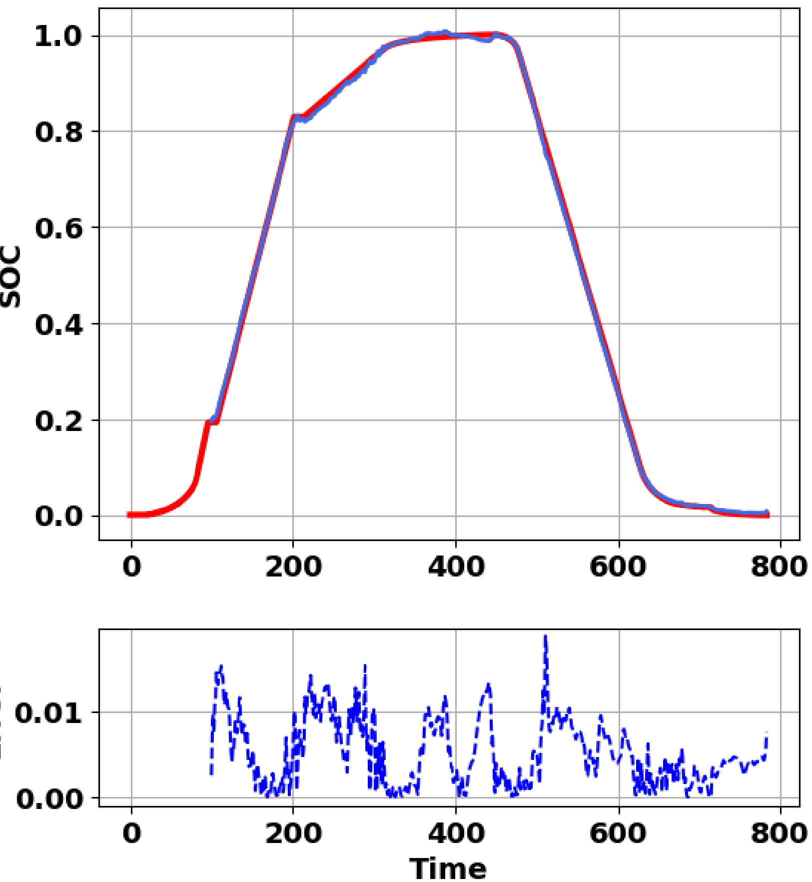
•**Objective:** To analyze the aging behavior of Lithium Iron Phosphate (LFP) batteries.

•**Batteries:** 18 Lithium Werks APR18650 cells

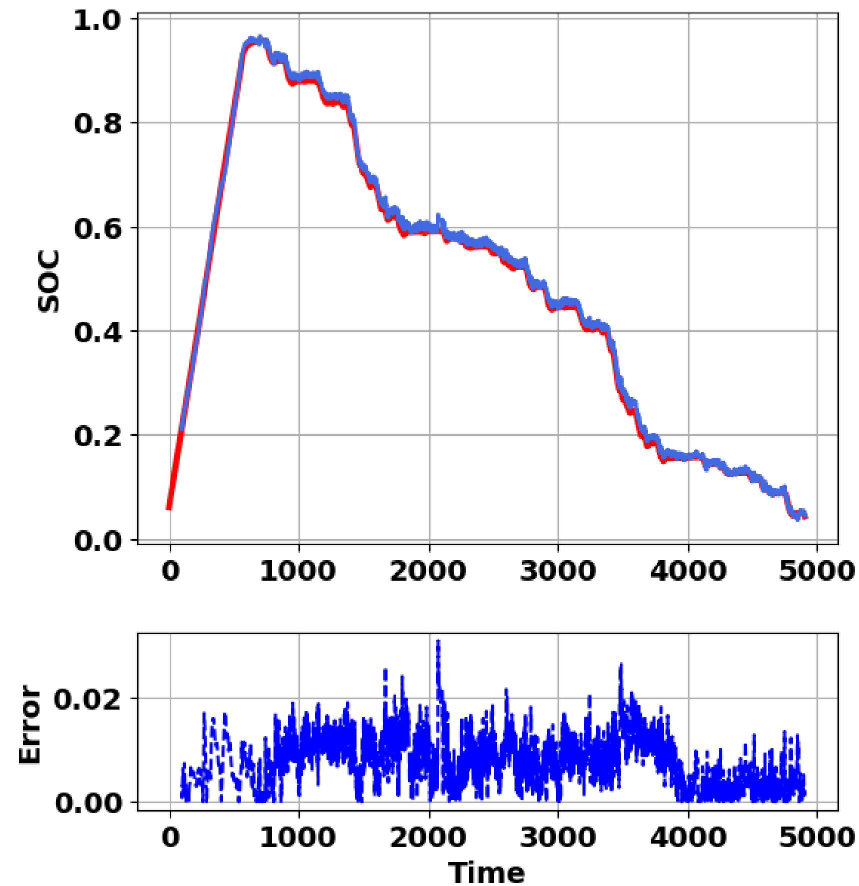
Tested Parameters:

- Temperature: 25°C, 35°C, and 45°C.
- Charging Current: 1.5A (standard) and 4A (fast-charging).
- Discharge : Standardized and pulsed profile
- Charge: CC-CV protocol

RESULTS



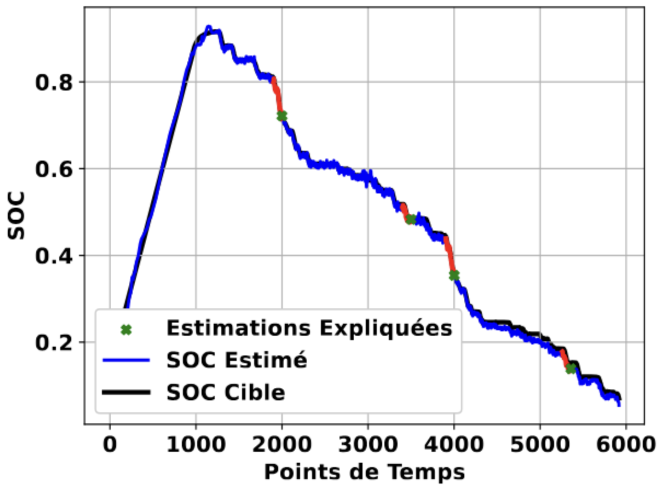
SOC estimation during a cycle from the MIT dataset



SOC estimation during a cycle from the INSA Strasbourg dataset

- **Optimization:** MAE loss, AdaMax, early stopping (20 epochs)
- **Data:** ~2.5M samples → 70% training, 15% validation, 15% test

UNDERSTANDING THE MODEL'S REASONING WITH SHAPLEY VALUES

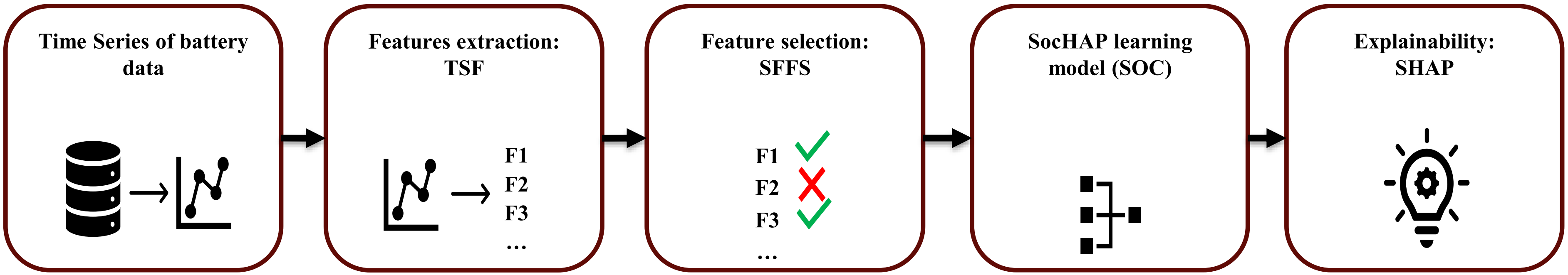


- Analyze how the model uses the input signals to estimate the SOC.
- Application of SHAP → computes Shapley values for each input

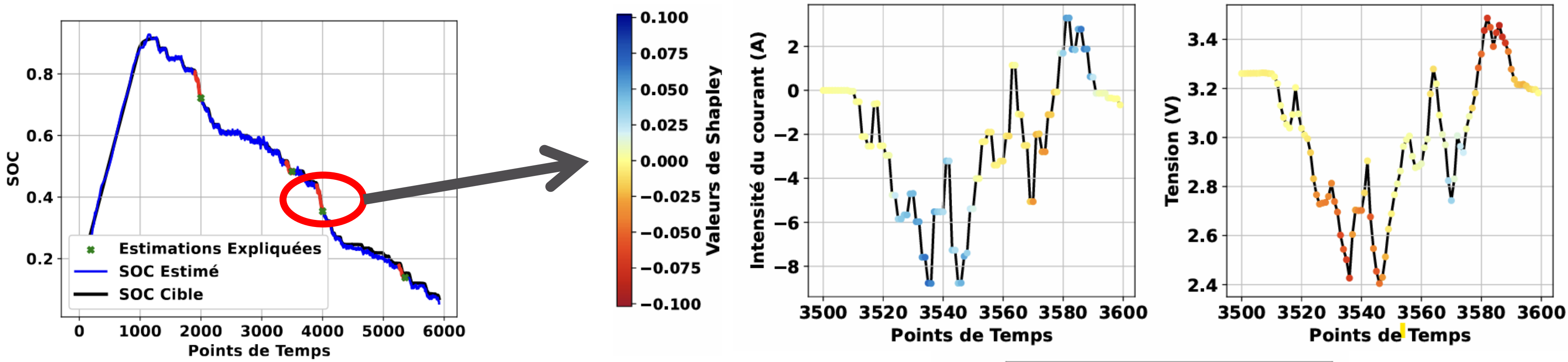
→ Visualization of the positive or negative contribution of each signal

Case studies: 4 SOC estimations taken from a real profile (INSA Strasbourg)

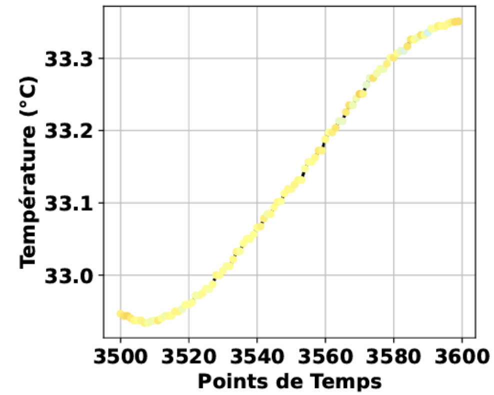
Scenarios: high power demand and rest phases, at both high and low SOC levels.



SHAPLEY VALUES ANALYSIS



- Voltage and current are the main determinants of SOC during peaks
- Temperature has a limited influence although it is physically correlated
- Combines voltage and current to remain independent of the initial SOC



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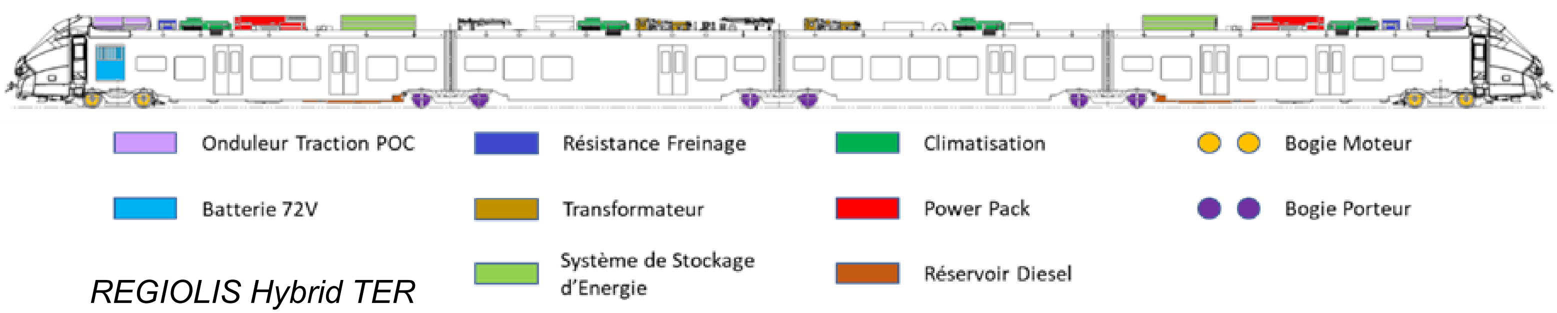
SOCHAP VALIDATION: REGIOLIS HYBRID TRAIN (CAF - CONSTRUCCIONES Y AUXILIAR DE FERROCARRILES, EX. ALSTOM-REICHSHOFFEN)

- Estimate SOC of energy storage systems (ESS) from real test data provided by CAF (4 round trips in April 2023)
- **4 traction modes:** Hybrid Thermal, Zero Emission, Hybrid Electric 1500 V and Electric 25 kV



REGIOLIS Hybrid TER Train Diagram

- Available data: Current, min/max voltage, min/max temperature, SOC
  → **Model input window adapted**
- **Sliding windows of 40 and 80 points to compare impact of historical context**

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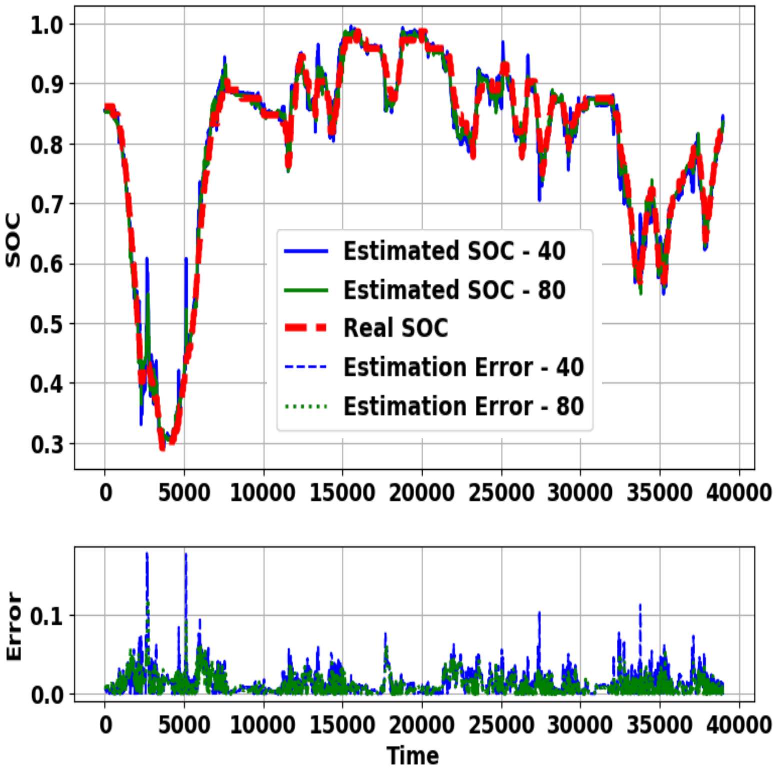
CASE STUDY RESULTS

Window Size	MAE	RMSE	SMAPE
40 points	0.0141	0.0239	1.99%
80 points	**0.0108**	**0.0188**	**1.53%**

- Min/max derived signals → reliable SOC estimates
- Shows potential of explainable data-driven models for onboard BMS integration



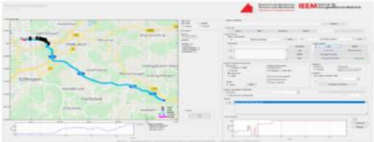
SOC Estimation – Hybrid TER Battery Pack (Rodez–Toulouse)

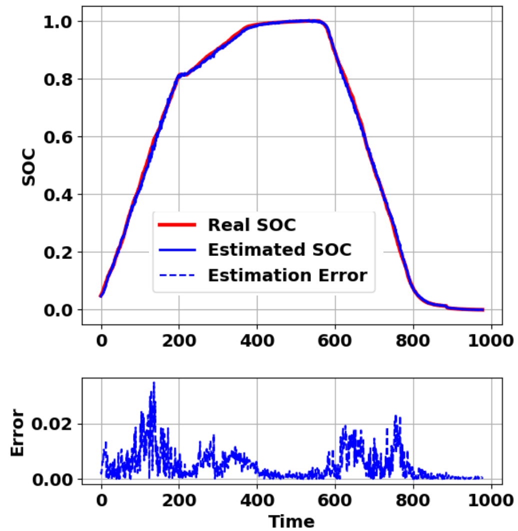
MULTI-TECHNOLOGY ADAPTATION: LI-ION AND SODIUM-ION

- **Tested technologies:**
  Li-ion (LFP) → MIT & INSA Strasbourg cycles
  Sodium-ion → characterization cycles performed at INSA Strasbourg

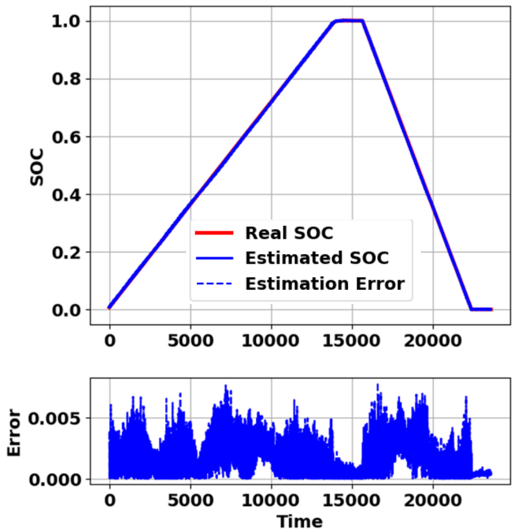
MAE	RMSE	SMAPE
0.0063	0.0153	3.60%

- **Able to accurately estimate SOC for chemistries with different electrochemical behaviors**
- **Limitation: specific retraining is still required for each new technology.**

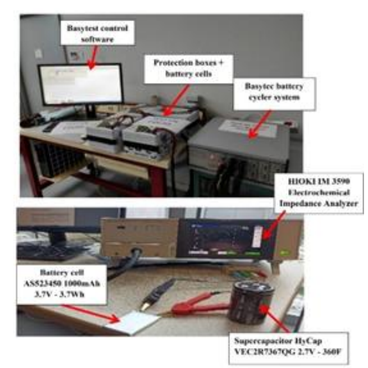




SOC Estimation – LFP Cell (MIT Dataset Cycle)



SOC Estimation of a Sodium-Ion Cell



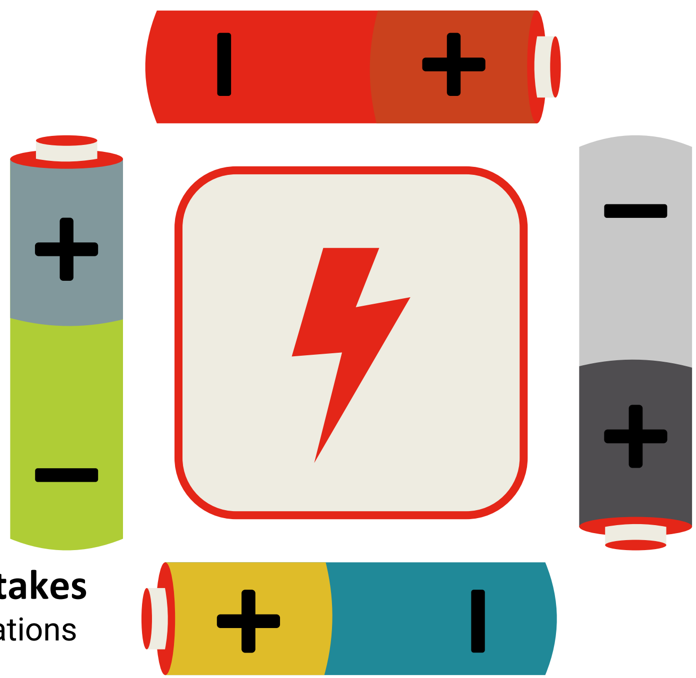
OUTLINE

01

INSA Group
- INSA Strasbourg
- ICUBE Laboratory
- ICUBE Platforms

02

Context and Scientific Stakes
- ESS: Challenges and Innovations
- Role of the BMS
- Advanced BMS with AI
- Research Activities



03

AI for Batteries
- Horizon ENERGETIC Project
- Why BMS Need Explainable AI
- Transparency Issue in Deep Learning
- Results

04

Hydrogen Hybrid Power Sources
- Long-Endurance Drone
- Advanced Energy Management Strategy

CONTEXT AND SCIENTIFIC STAKES

Energy Storage Systems: Challenges and Innovations

Hybrid Energy Storage Systems (HESS)

1

Load Distribution

Each storage technology handles its optimal load range, reducing stress.

2

Efficiency Boost

Combined systems achieve higher round-trip efficiency than single technologies.

3

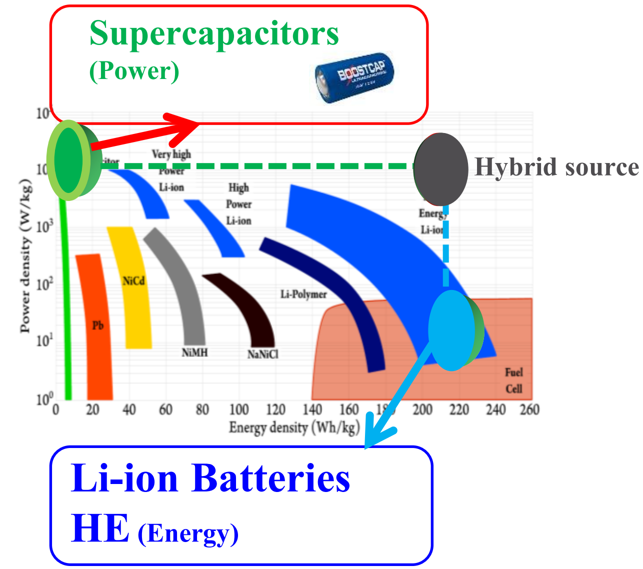
Extended Lifespan

Reduced cycling of batteries can extend system life by 10-30%.

4

Lower TCO

Total cost of ownership decreases despite higher upfront investment.



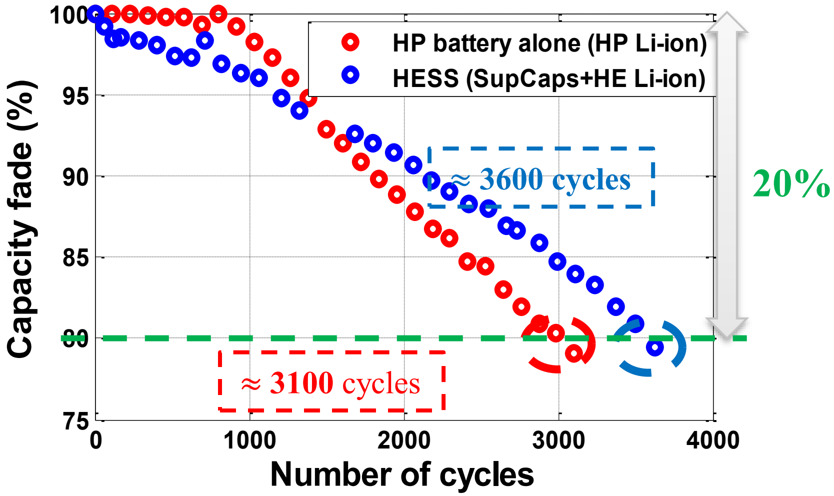
Ragone diagram

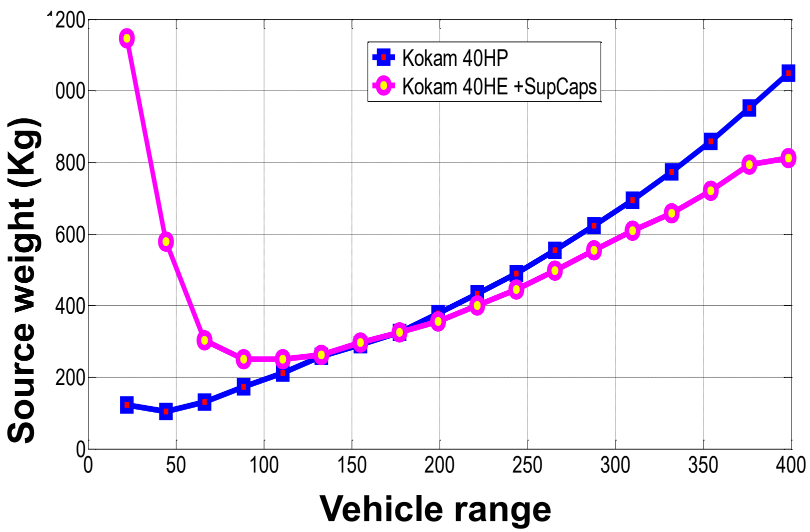
A. Shmaryahu et al., “Sizing Procedure for System Hybridization Based on Experimental Source Modeling for Electric Vehicles”, Energies, vol. 14, no. 17, p. 5275, Aug. 2021, doi: 10.3390/en14175275.

SOME EXAMPLES OF RESEARCH ACTIVITIES FOR AUTOMOTIVE APPLICATIONS

Hybrid energy storage system (HESS)

Experimental results of cycling aging (ARTEMIS)





hybrid solution

The lifetime increase of the hybrid solution reached 10% for the same mission

150 km with ARTEMIS driving cycle + CC/CV battery charging protocol → 1 cycle (4h15)

RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

➢ *Project INTERREG ELCOD (2017-2020)* *www.elcod.eu*

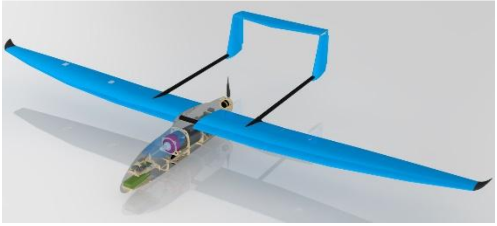
Development of a long-endurance drone with hydrogen fuel cell propulsion for air pollution measurement

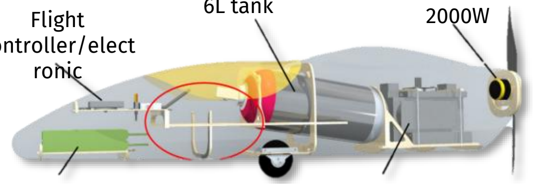
Equipement :

- Fuel Cell 1000W
- Tank de 6L (300bars max)
- BLDC motor 2000W
- MTOW 25Kg, wingspan 5m

Estimated performances :

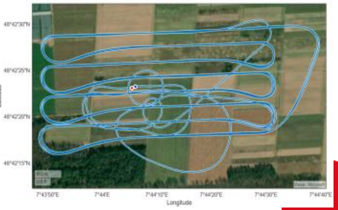
- Autonomy : 5-6h
- Two-way range : 250 km





SCAN ME

ELCOD : www.elcod.eu
https://youtu.be/AZTw9cO5zvM
INSA-Icube, ICPEES-CNRS,
Hochschule Offenburg-IUAS



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RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

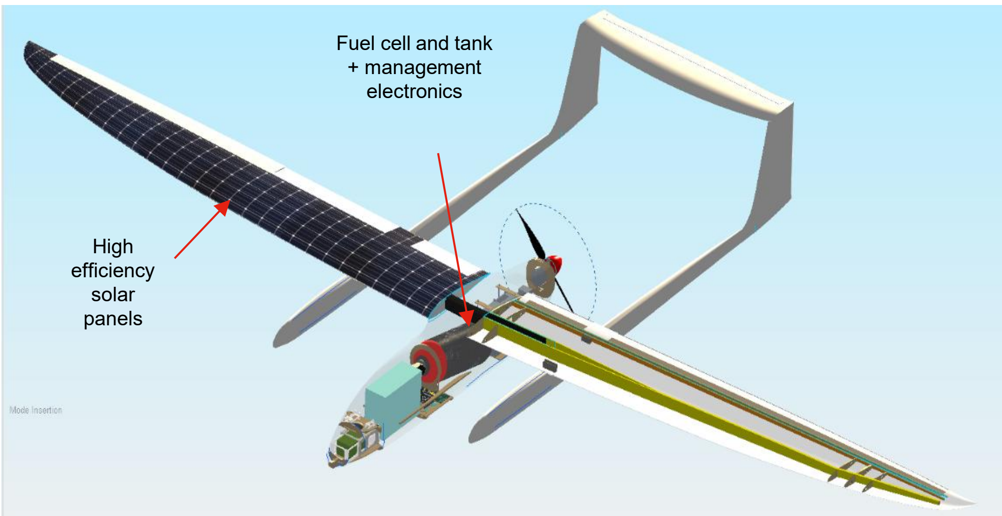
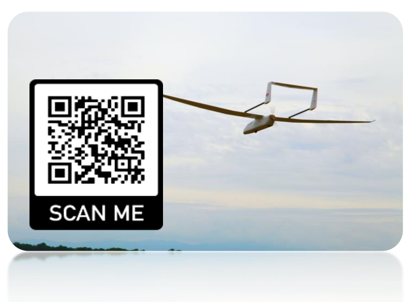


Photo of the Stork MkI prototype drone
INTERREG ELCOD (2017-2020)

Drone Stork MkII :

Same performances as Stork Mk.I

- Maximum mass 25kg, wingspan 5m
- Propulsion based on hydrogen fuel cell
- Payload : 5kg Max
- Autonomy: Range 450km, autonomy 5-6H
- Website : www.elcod.eu



Motivations:

- Decarbonization of the propulsion energy of autonomous drones or vehicles.
- Extending the range by optimizing the autonomy and intelligent consumption of energy.
- Extension of the life span of energy sources (fuel cells, super-capacitors, lithium-ion batteries)
- Working on bio-composite drone structures
- Use case with pollution and measurement applications etc..

RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

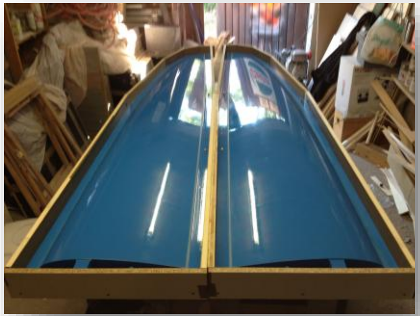
Context and motivations

Stork Mk.II drone design steps

Master

Finishing
Coating
Polishing

Finition des masters



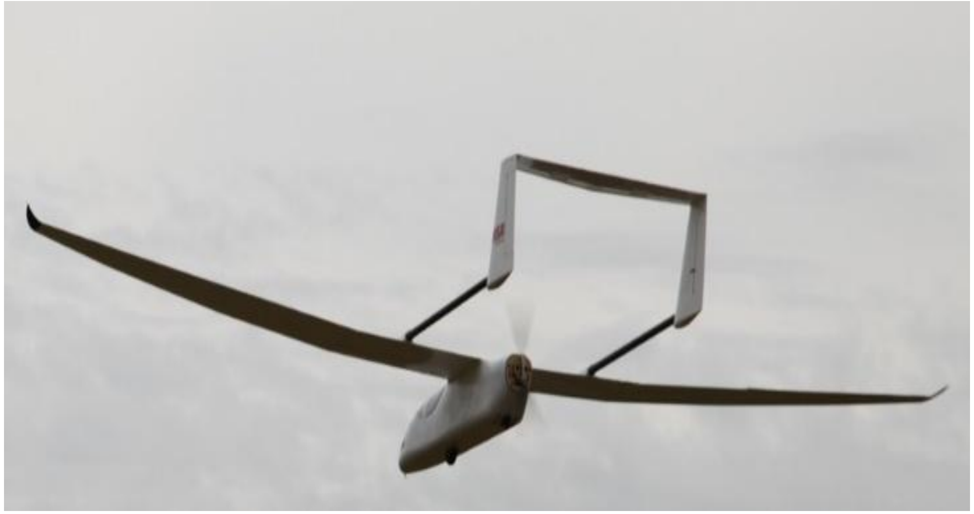
Conceptions steps
Stork Mk2

Moloding

Final composit wings

Research Activities

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

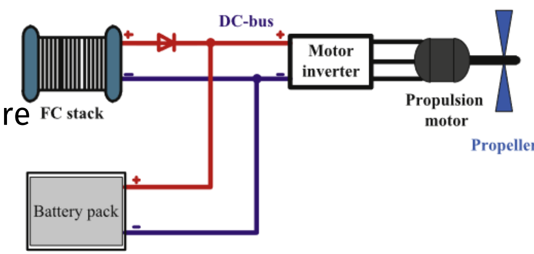


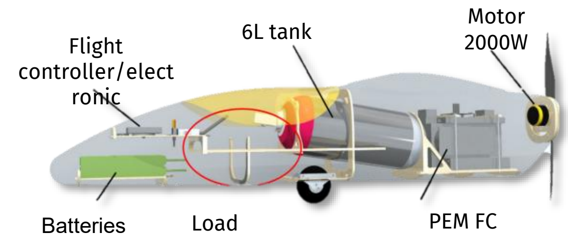
Use case with fire survey and fire pollution measurement

RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

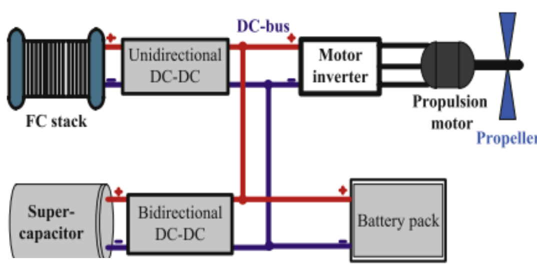
Conventional architecture





B Wang, D Zhao, W Li, Z Wang, Y Huang, Y You, and S Becker. Current technologies and challenges of applying fuel cell hybrid propulsion systems in unmanned aerial vehicles. Progress in Aerospace Sciences, 116:100620, 2020

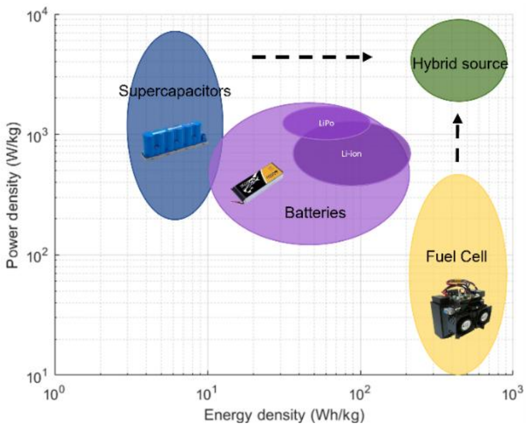
Semi active architecture under study



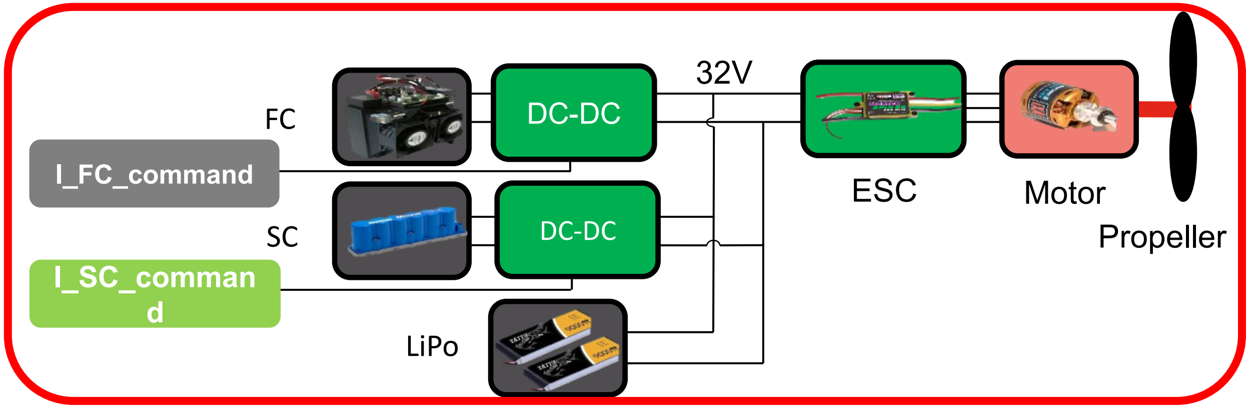
RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

Electric hybridization principle



Ragone diagram



Semi-active architecture

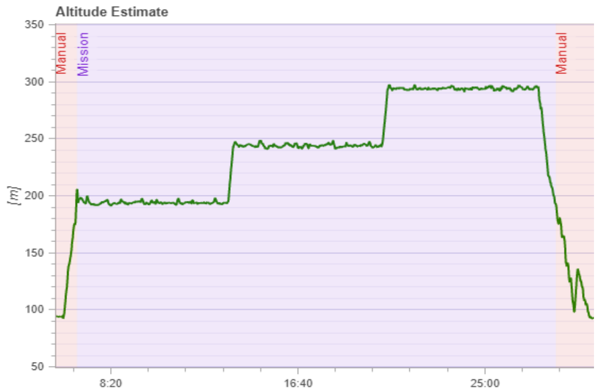
Take into account the advantages of each source by mixing them

Objectives : Develop Energy Management Strategy (EMS) algorithms to increase sources lifetime and flight autonomy by controlling the DC/DC converters

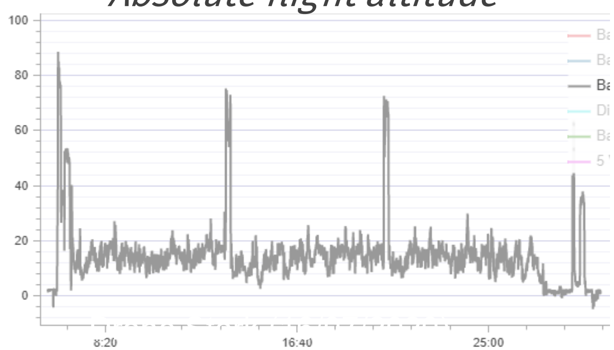
RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

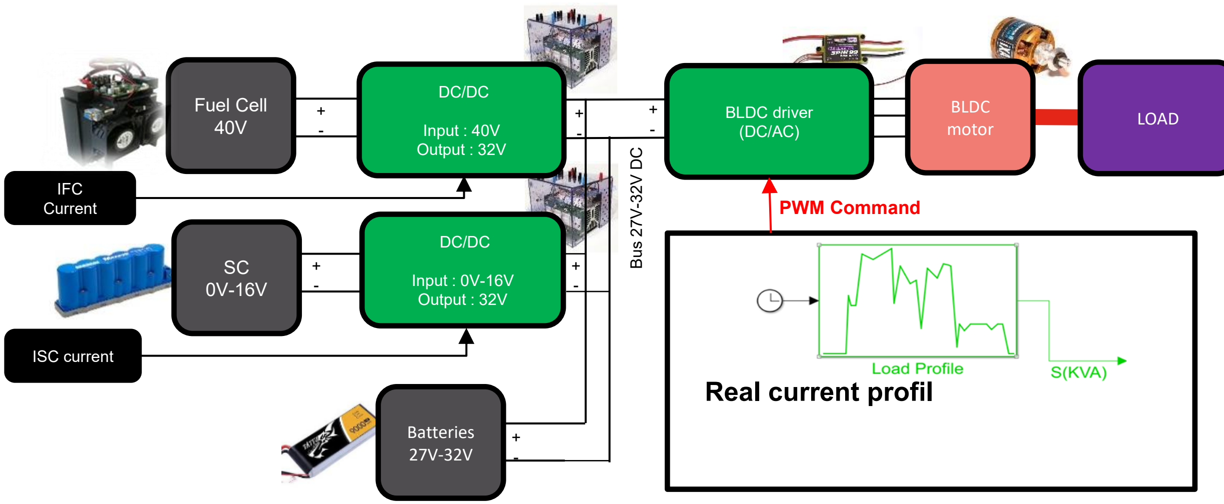
flight scenario to validate EMS algorithms on test bench and simulations



Absolute flight altitude



Consumed current



Test bench architecture

- **Real flight scenario for driving the test bench**
- **Development of a simulation model (Matlab Simulink) for the studies of hybridization strategies**

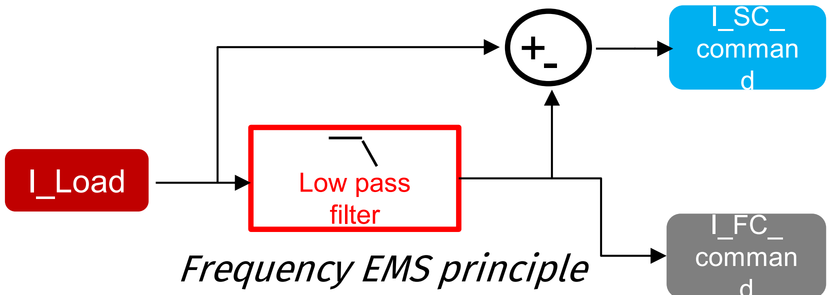
RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

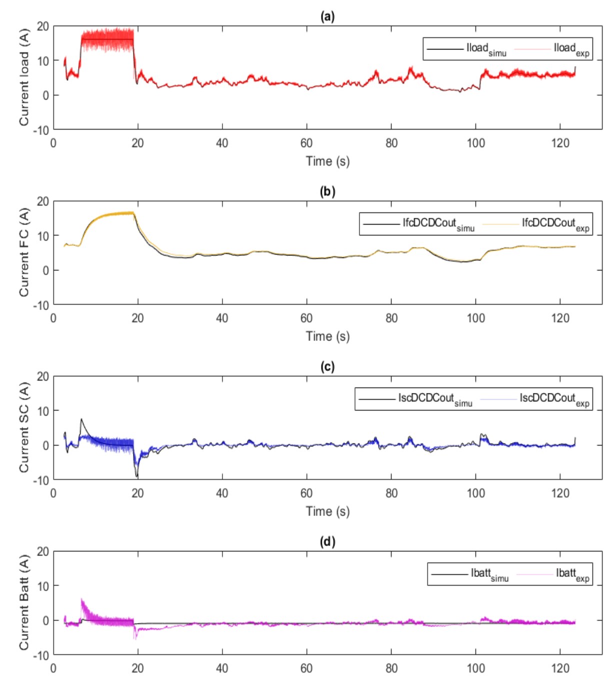
Fixed frequency EMS applied in simulation and on the test bench

Principles

- High frequencies sent to the SC
- Low frequencies sent to FC
- Auxiliary battery only to provide more than 500W if required



Frequency EMS principle
Experimental optimum frequency 0.2rad/s



Test bench results (Load current /3), Fc=0.2rad/s

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ICUBE

RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

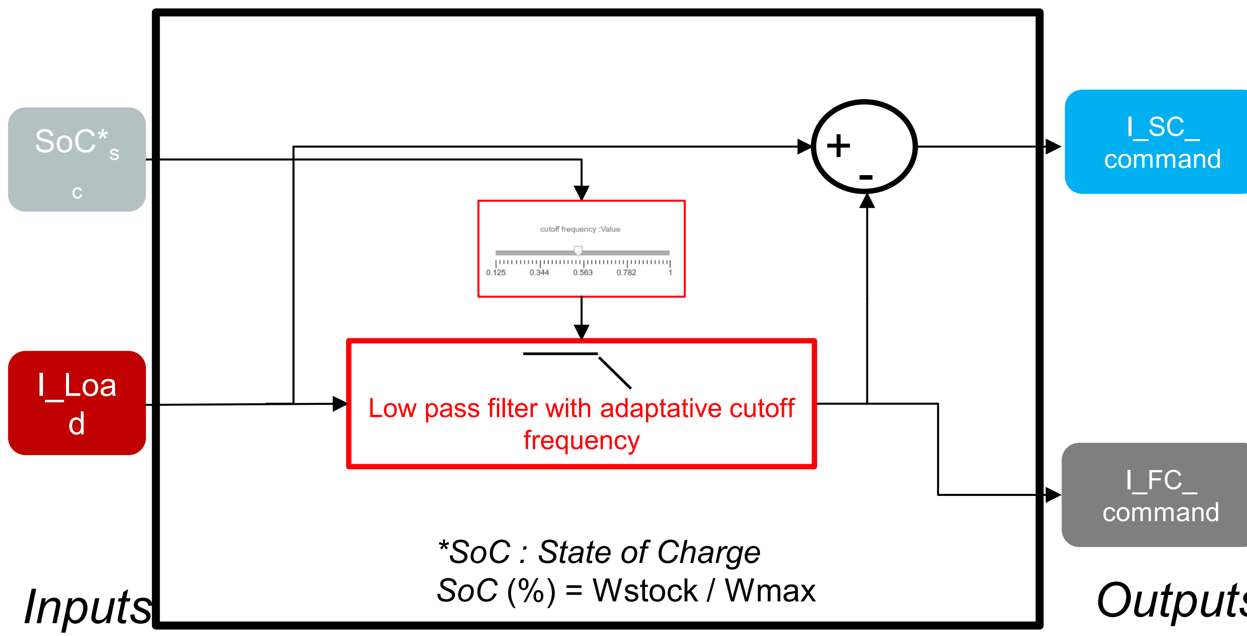
Innovative adaptive frequency Energy management strategy

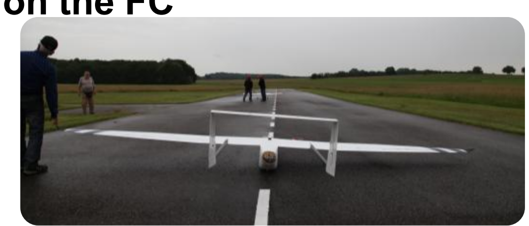
Idea

- **Vary the cutoff frequency according to the SoC (state of charge) of the SC.**

Advantages

- **No need to determine the ideal cut-off frequency**
- **Maximum use of SC charging and discharging amplitude (SOC)**
- **Limitation of current variations on the FC**





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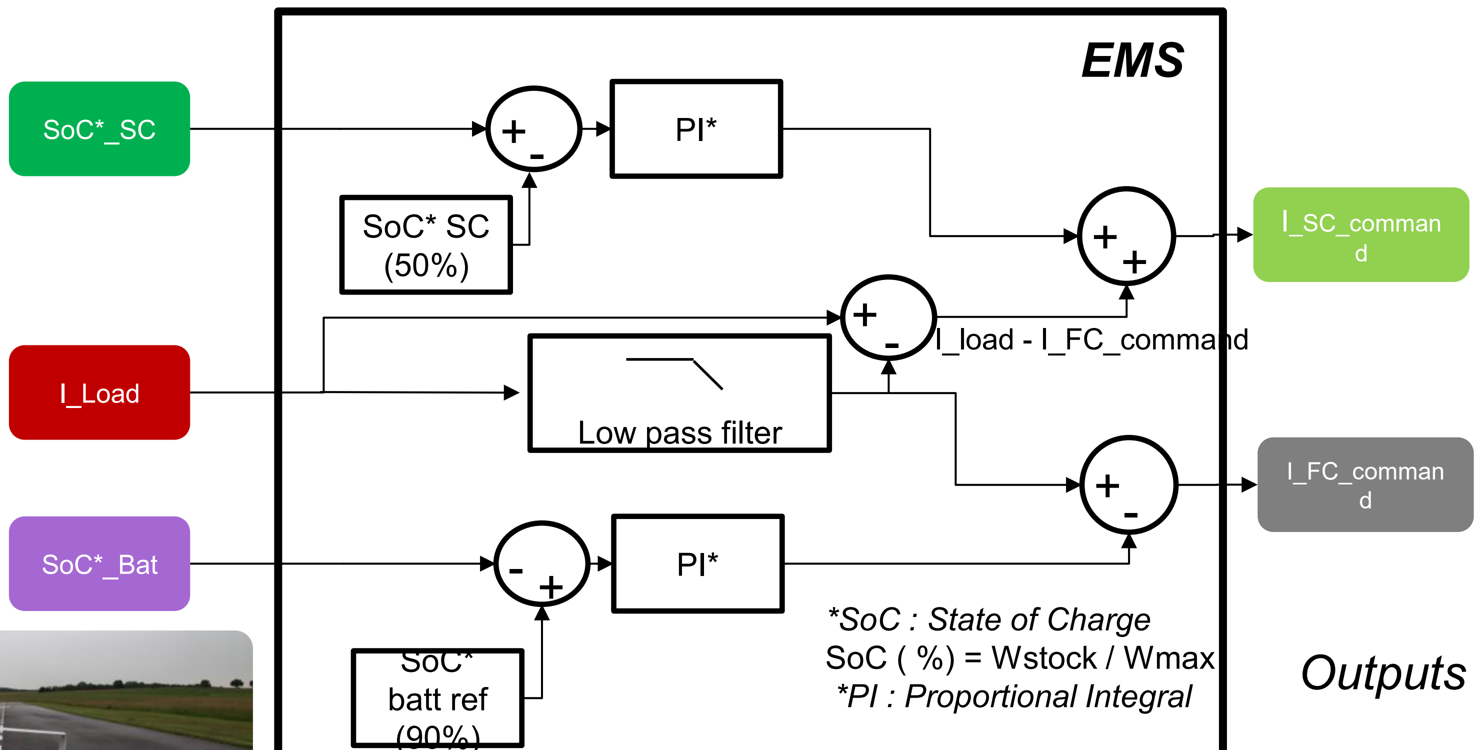
RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

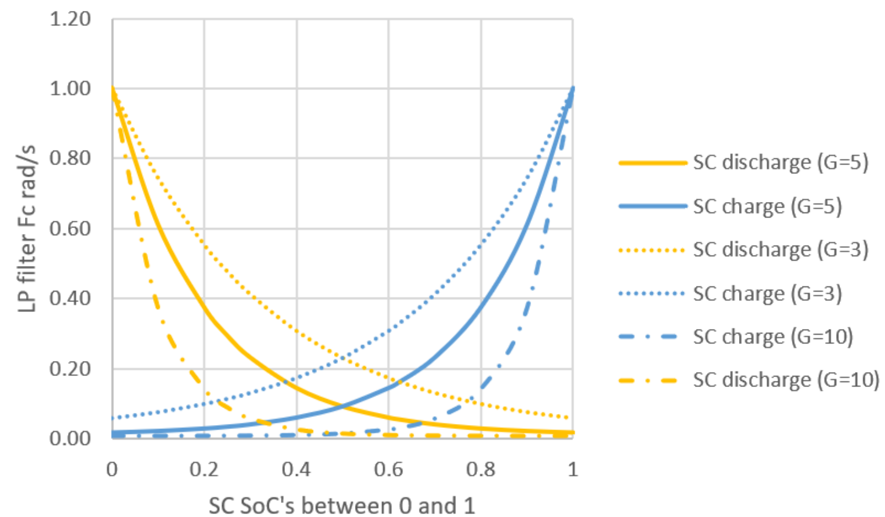
adaptive frequency strategy



RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

Innovative adaptive frequency strategy



Control behavior of the Low pass frequency filter vs the SuperCap SoC

Discharge of the SC :

$$\mathrm{fc}(SoC) = (F_{cHlim} - F_{cLlim}) \cdot e^{-G \cdot (SoC)} + F_{cLlim}$$

Charge of the SC :

$$\mathrm{fc}(SoC) = (F_{cHlim} - F_{cLlim}) \cdot e^{-G \cdot (1-SoC)} + F_{cLlim}$$

$$F_{cLlim} = 0.01\ rad/s$$
$$F_{cHlim} = 1\ rad/s$$
$$G = 3, 5, 10$$

The G parameter controls the dynamic range of the Super-Capacity..ie when discharging, the more the SC is charged, the more dynamic it is

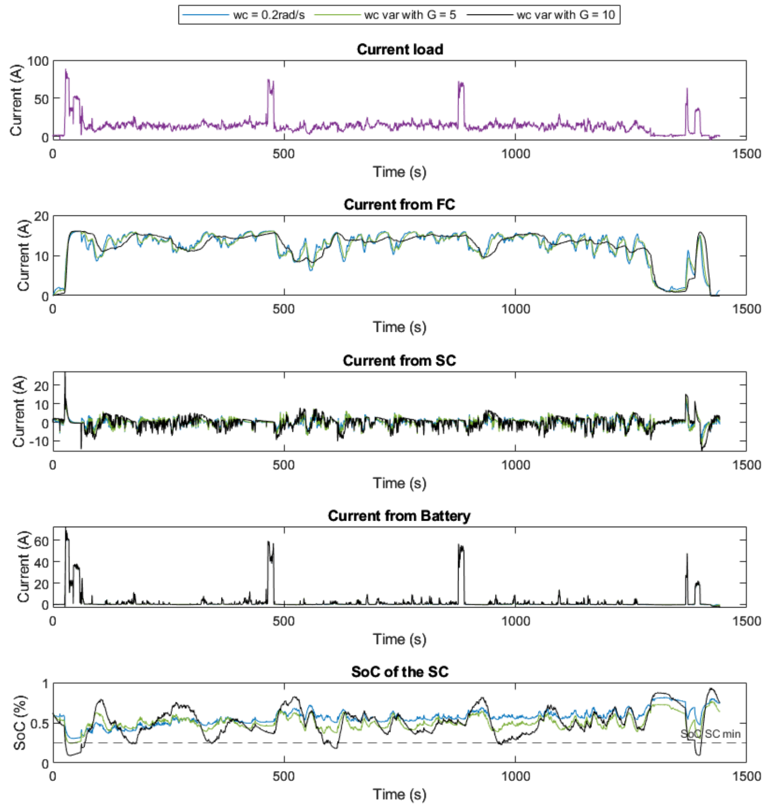
RESEARCH ACTIVITIES

Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

Simulation results for the adaptive frequency strategy

- Fixed frequency strategy with fc = 0.2 rad/s
- Adaptive frequency strategy with G = 5 and 10
- Low frequencies for FC
- High frequencies for SC
- Battery relay on power requirements during ascent phases
- Limit SC SoC discharge to 25%.

(lower values decrease of the efficiency of the DC/DC converter)



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RESEARCH ACTIVITIES

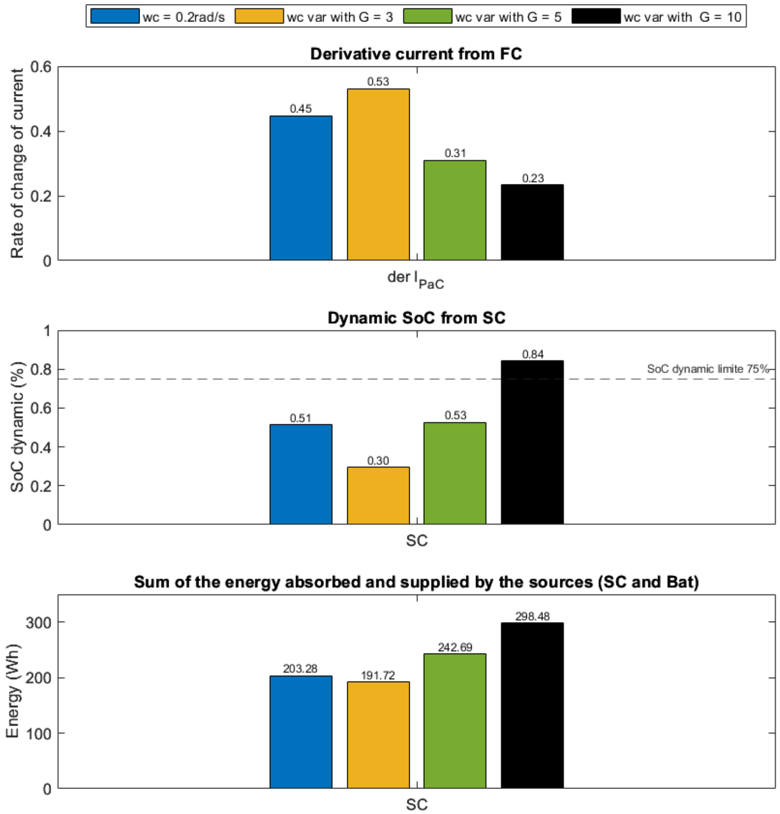
Designing a Long-Endurance Drone with Hydrogen Hybrid Power Sources

Simulation results comparisons

- Comparison between fixed and variable frequency

with G = 5

- 30% reduction in current variations required at the FC
- SoC dynamic remains equivalent on SC (approx. 50%)
- 15% increase in energy transiting the SC



SCIENCE

T. Pavot, R. Kiefer, T. Mesbahi and E. Laroche, "Adaptive Cut-Off Frequency EMS Tuning Methodology Applied on a Long Range UAV Powered by a Hybrid Fuel-Cell System," in *IEEE Transactions on Aerospace and Electronic Systems*, December, 2025 doi: 10.1109/TAES.2025.3638319.

THANK YOU FOR YOUR ATTENTION

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