Design of Hybrid Energy storage systems – Optimal sizing and control

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Design of Hybrid Energy storage systems – Optimal sizing and control

Problem statement

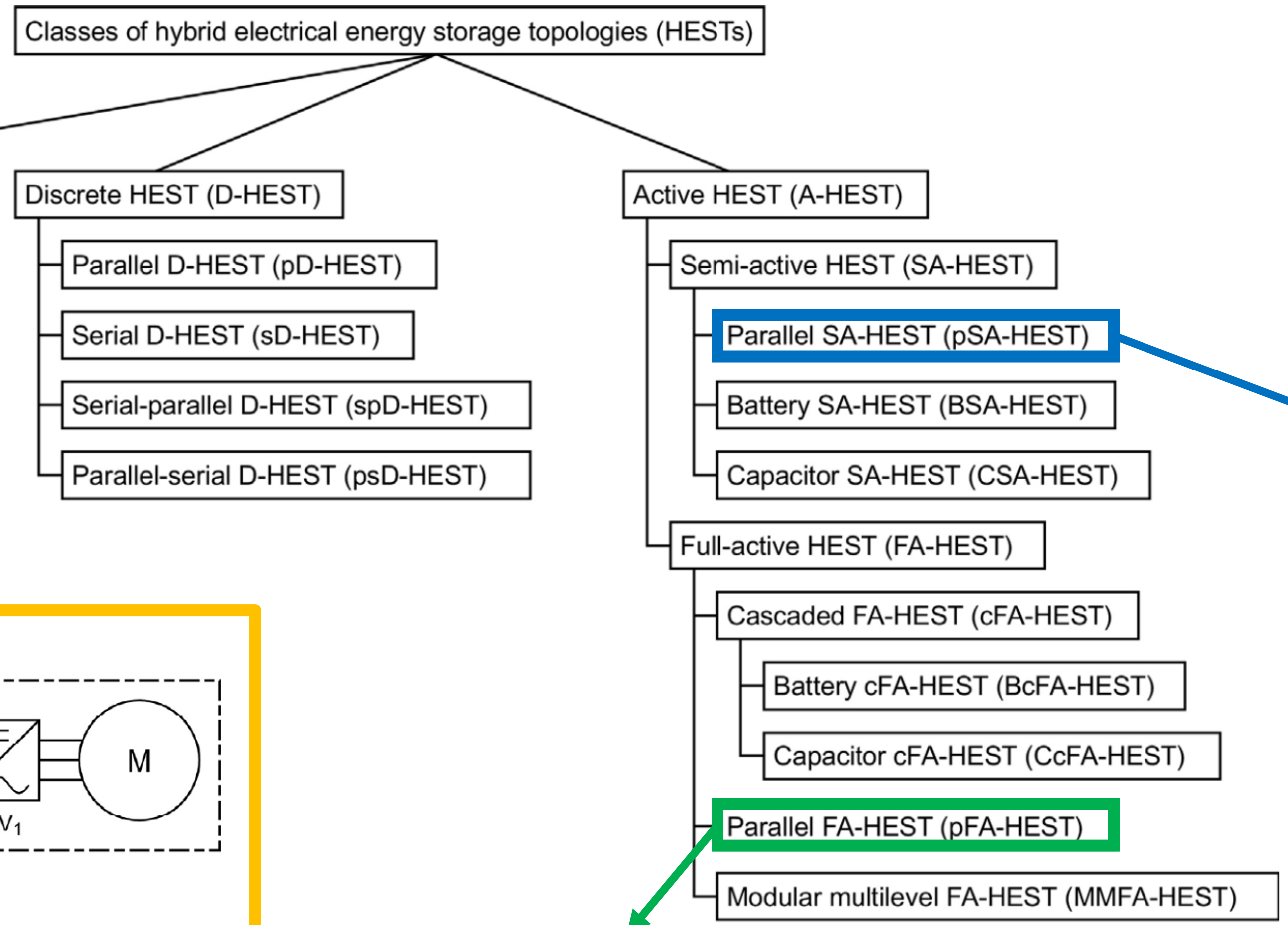
- **Hybrid Energy Storage System (HESS)**
  - Satisfies both high specific energy and high specific power requirements
  - Thus reduce over-sizing of energy storage systems such as batteries.
- **Optimal system design of the Hybrid Battery system**
  - Lowest possible system size of both HP** & HE** Batteries
  - Optimal powersplit control between HP & HE batteries
- **To compare different battery topologies**
  - Cost of topology with lowest system cost

Solution

- **Combine optimal sizing of different components of the battery with powersplit control**
- **Perform Codesign optimization**

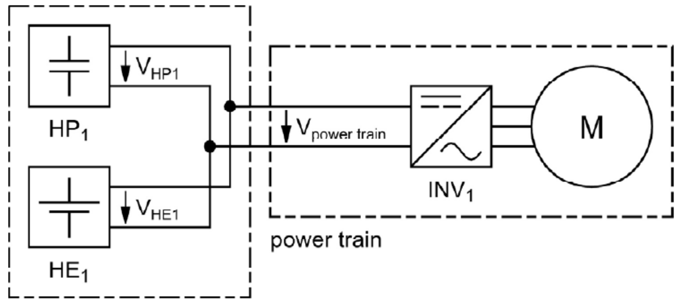
** HP – High Power cells, HE - High energy cells

Hybrid Energy Storage Systems (HESS) - Topologies

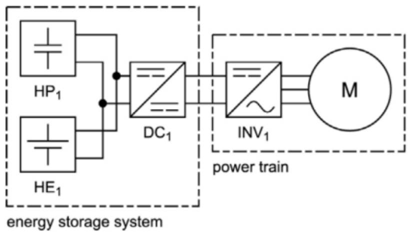


Legend

c: cascaded
p: parallel
s: serial
FA: Full-active
SA: Semi-active



→ No power electronics
→ No control over power distribution
→ Limited ESS operating voltage range



(a) pSA-HEST

-> 1 DC/DC converter
-> ESS connected in parallel

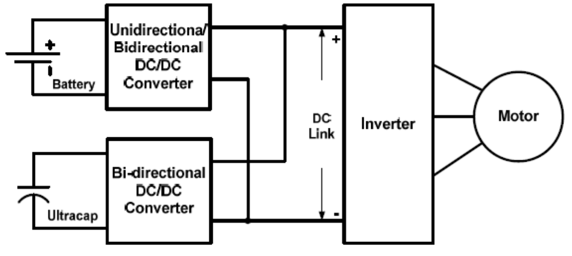


Figure 4. Multiple converter configuration.

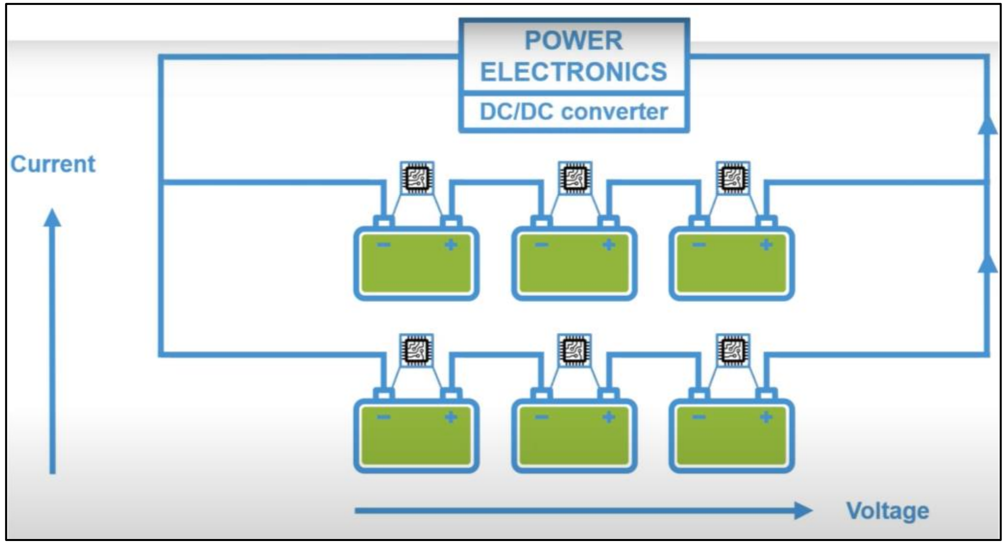
-> 2 DC/DC converter
-> Full control over power distribution
-> Flexible ESS operating voltage range

Discrete battery system

- **Conventional fixed battery systems,** → fixed interconnection between the cells
  - Requires a DC/DC converter to regulate the output voltage for the load.

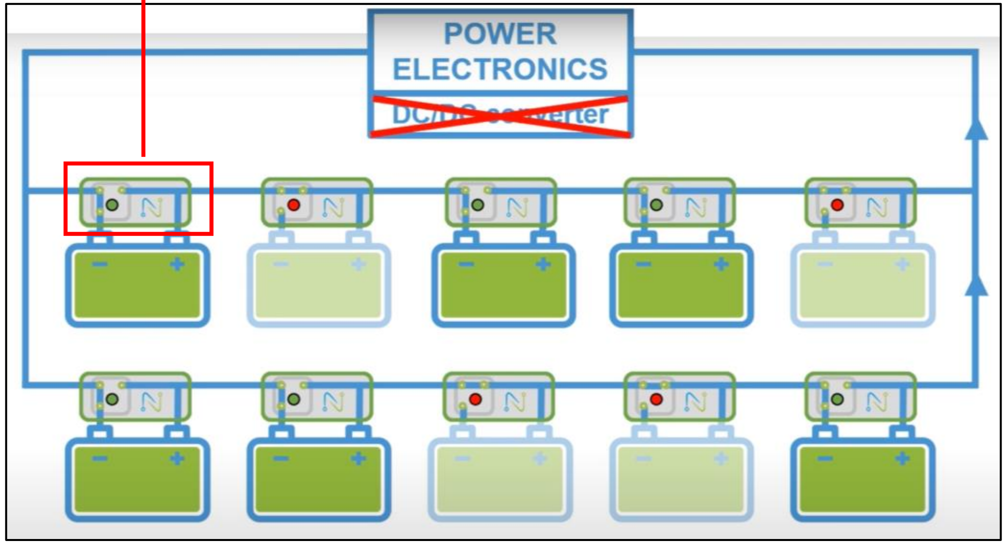
- **Discrete battery system** → battery interconnection pattern is changeable using switching elements. The switching elements allow to engage or bypass the cells
  - No need of DC/DC converter to adapt dynamically to the load.

Fixed battery system



switching element

Discrete battery system



Discrete battery system

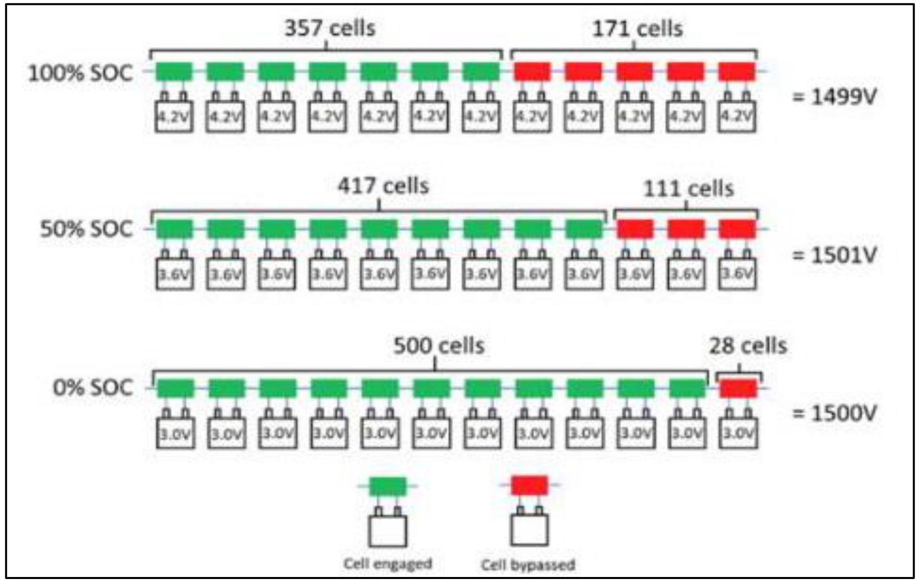
- No need of DC/DC converter
  - ➢ Customized terminal voltage by engaging/bypassing the cells

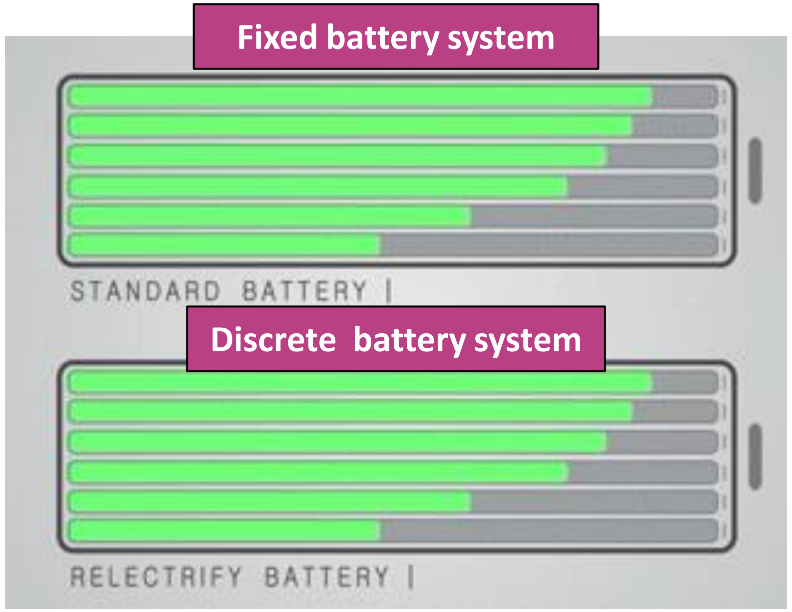
- Extended energy delivery
  - ➢ Schedule the operation of batteries for faster and enhanced energy conversion (e.g., putting cells to rest once they have reached the upper voltage limit)

- Charge and Temperature Balancing
  - ➢ Cell balancing is possible without any additional balancing circuitry

- Enhanced fault tolerance and safety
  - ➢ Quickly disconnect faulty cells while reconnecting the remaining normal ones

Engaging the cells to achieve a constant voltage



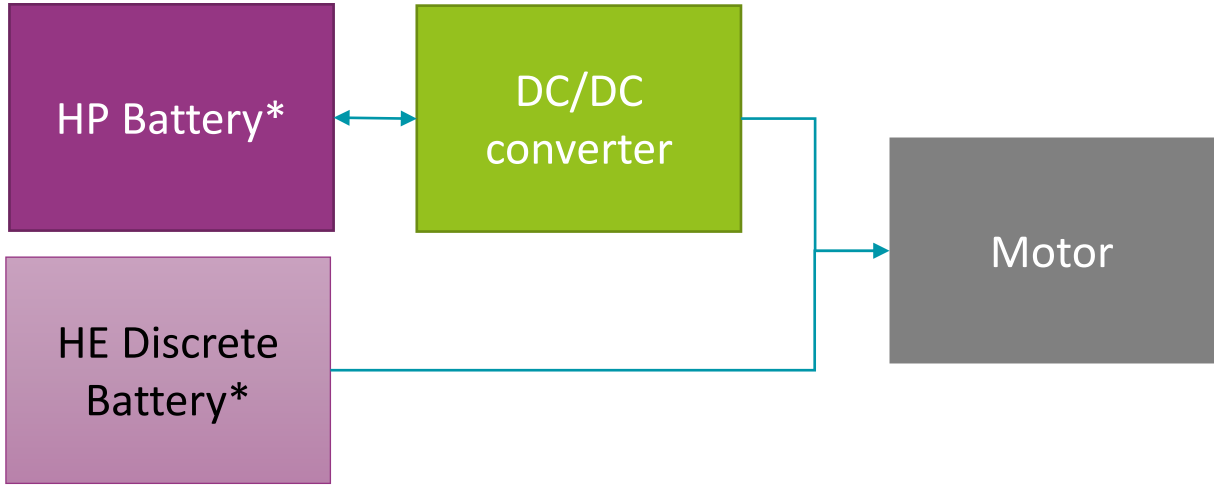


Selected Battery topologies

1) Baseline Monotype Battery system

- Typical battery system found in most electric marine applications
- DC/DC converter ensures constant input voltage to the motors

2) Discrete hybrid battery system

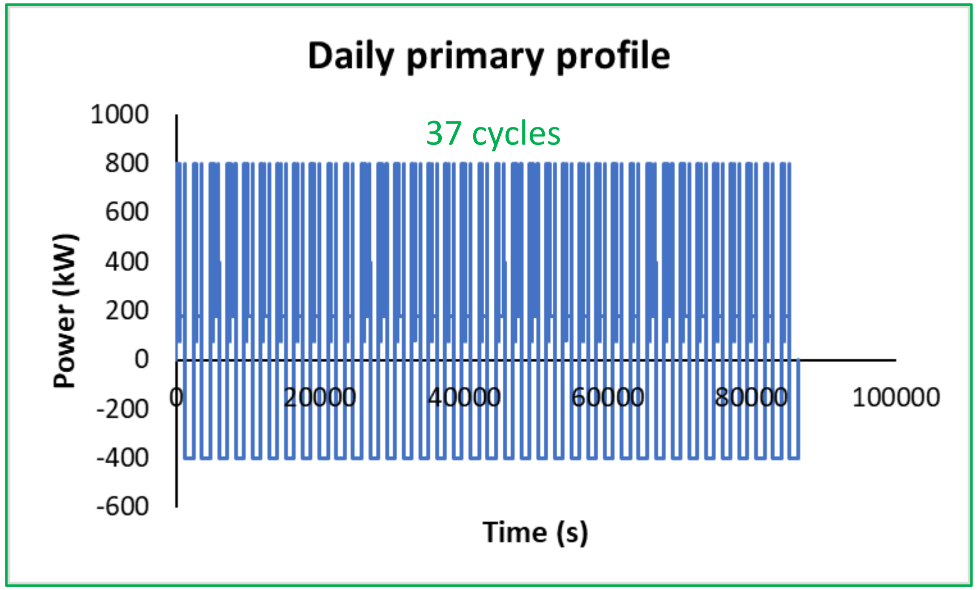


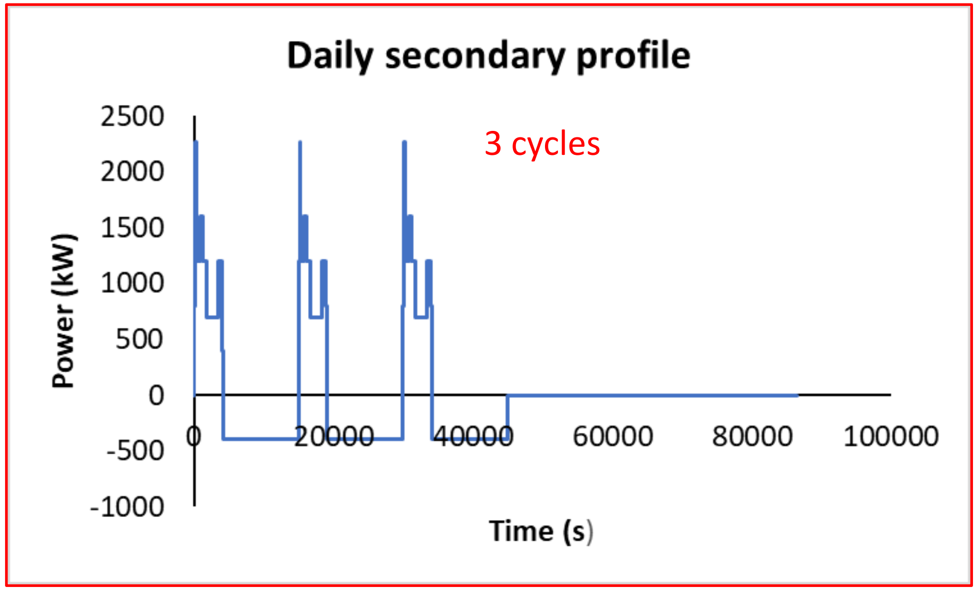
- Discrete hybrid battery system proposed as a cost efficient and better alternative to Baseline monotype battery pack.
- HE Battery is discrete battery. Switches present in each cell maintain the required input voltage to the Motor
- HP Battery is typical battery

* HP – High Power Battery, ** High energy (HE) Discrete battery

Application load cycle- Ro-Ro ferry 1

- Ro-Ro ferry 1 has a season dependent operational profile.
- Primary profile: A summer profile, 335 days per year making 37 cycles per day which requires 124 kWh energy
- Secondary profile: During winter, 30 days per year, making 3 cycles per day which requires 1200 kWh energy
- **Annual primary cycles ($N_{P-cycles}$):** 123950 cycles per 10 years
- **Annual secondary cycles ($N_{S-cycles}$):** 900 cycles per 10 years





Battery model – SoC and SoH

Battery State Of Charge (SoC) model

- Same for Baseline (NMC), HP (LTO) & HE (NMC) battery

$$SoC\ (t_{k+1}) = SoC\ (t_k) + \Delta\ SoC$$

$$\Delta\ \text{SoC} = \frac{P_{batt}}{Cap_{batt}} * 100$$

- We assume 100% efficiency of battery to simplify the system.
- Constraint :- Limit 10% < SoC <90%

Battery lifetime model – State Of Health (SoH)

- Same for Baseline (NMC), HP (LTO) & HE (NMC) battery
- SoH degraded after 10 years

$$SoH_{10\ years} = 100 - Cycle\ ageing_{\ 10\ years} - Calendar\ ageing_{10\ years}$$

$$Cycle\ ageing_{\ 10\ years} = \frac{1}{Cycle\ life}\left\{N_{P-cycles}\int |\Delta\ SoC|_{Primary\ cycle} + N_{S-cycles}\int |\Delta\ SoC|_{Secondary\ cycle}\right\}$$

$$Calendar\ ageing_{\ 10\ years} = \frac{Standby\ time_{batt}}{365} * 10 = 1\%\ \text{SoH per year of standby}$$

- Constraint :- End of life capacity = $SoH_{10\ years}$ >= 80%

Minimization function :- Topology cost

Topology cost for Baseline topology

$$Topology\ Cost_{Baseline} = Cost_{cells} + Cost_{DC/DC}$$

$$Cost_{cells} = N_{cells} * Cost\ per\ cell$$

$$N_{cells} = Ceil\left\lceil \frac{Cap_{batt}}{Cap_{cell}} \right\rceil$$

$$Cost_{DC/DC} = Cost\ per\ KW_{DC/DC} * \max(P_{load\ cycle})$$

Topology cost for Discrete Hybrid topology

$$Topology\ Cost_{Discrete-Hybrid} = Cost_{HP\ cells} + Cost_{HP\ DC/DC} + Cost_{HE\ cells} + Cost_{HE\ switches}$$

$$Cost_{HP/HE\ cells} = N_{HP/HE\ cells} * Cost\ per\ cell$$

$$N_{HP/HE\ cells} = Ceil\left\lceil \frac{Cap_{HP/HE\ batt}}{Cap_{HP/HE\ cell}} \right\rceil$$

$$Cost_{HP\ DC/DC} = Cost\ per\ KW_{HP\ DC/DC} * \max(P_{HP\ batt})$$

$$Cost_{HE\ switches} = Cost\ of\ 2\ switches\ per\ cell + Control\ circuit$$

Optimization approach – Codesign Optimization

Step 1 :- Define Optimization Parameters :- (Unknown)

a) Baseline battery topology – Capacity of battery

b) Discrete Hybrid battery topology - Capacity of HP battery, Capacity of HE battery, Powersplit at each sample time

Step 2 :- Model the system i.e Batteries and DC/DC converter as a function of optimization parameters

Baseline – NMC; HP battery – LTO; HE battery - NMC

Step 3 :- Optimization formulation :-

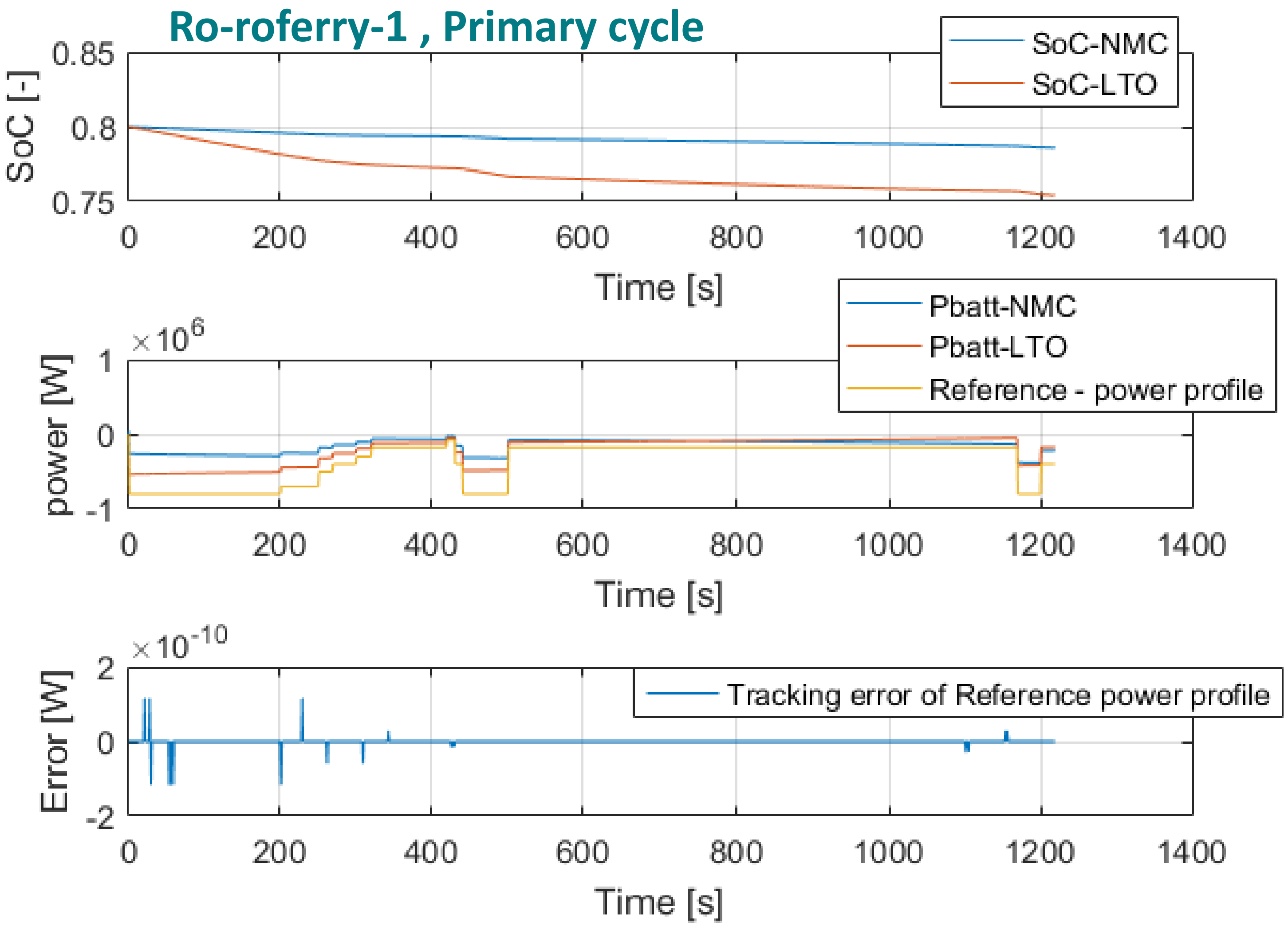
Constraints :-

1. SoC range – [10% , 90%]
2. End of life capacity >= 80%
3. Max. charging/ discharging power of each Battery
4. Satisfy the Required Power by the Load cycle

Step 4 :- Objective function :- Minimize Topology cost

- **Optimization constraints and Objective function is modelled as a function of optimization parameters.**
- **Optimization problem is solved using Direct Multiple shooting optimization technique.**

Optimization results :- Only Power-split optimization



Power-split optimization for Specific size

Capacity of NMC = 3481 kWh

Capacity of LTO = 1495 kwh

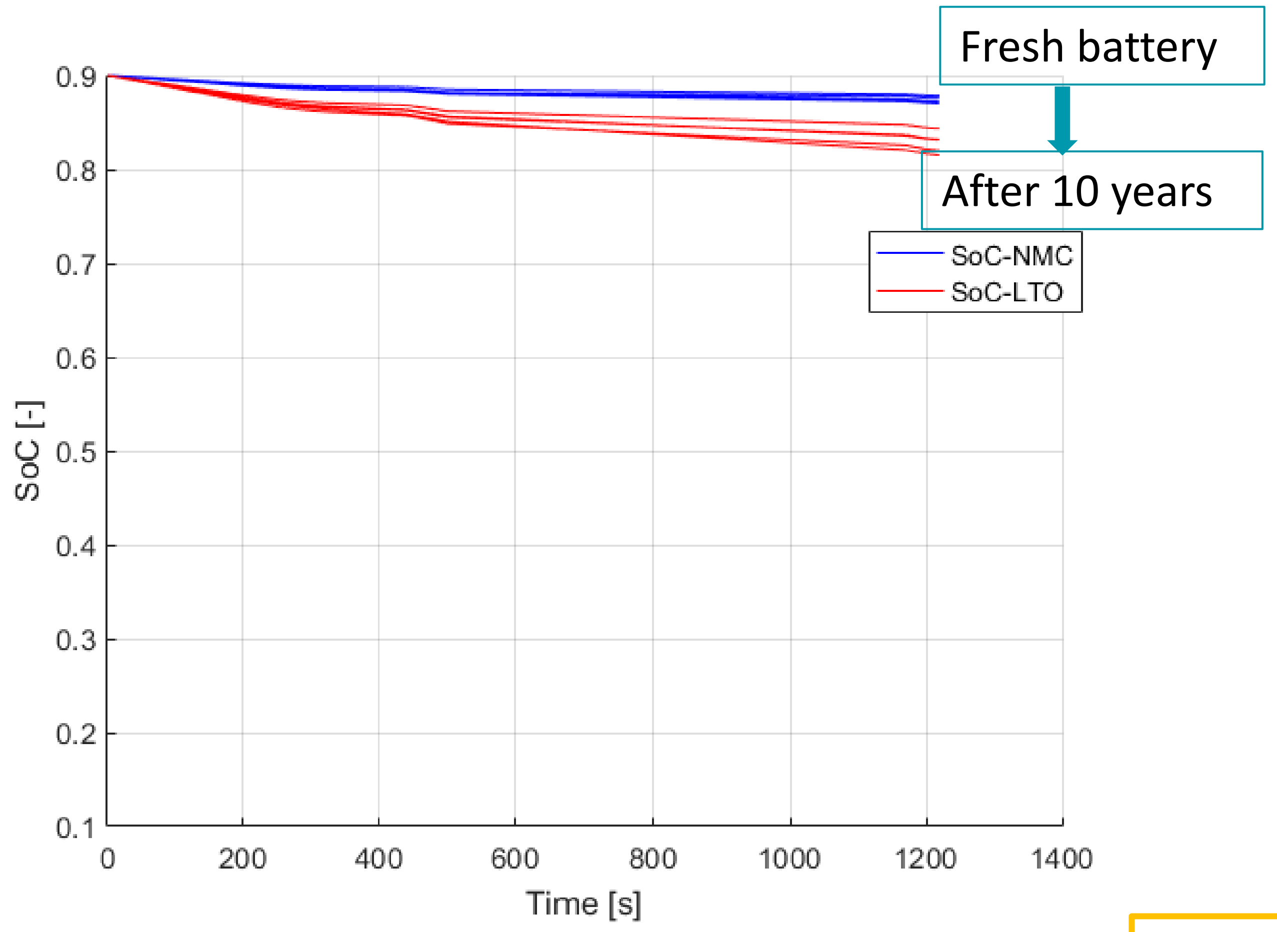
SoH degradation < 20% -NMC, LTO

SoH degradation = 1 cycle degradation * No. of primary cycles in 10 years

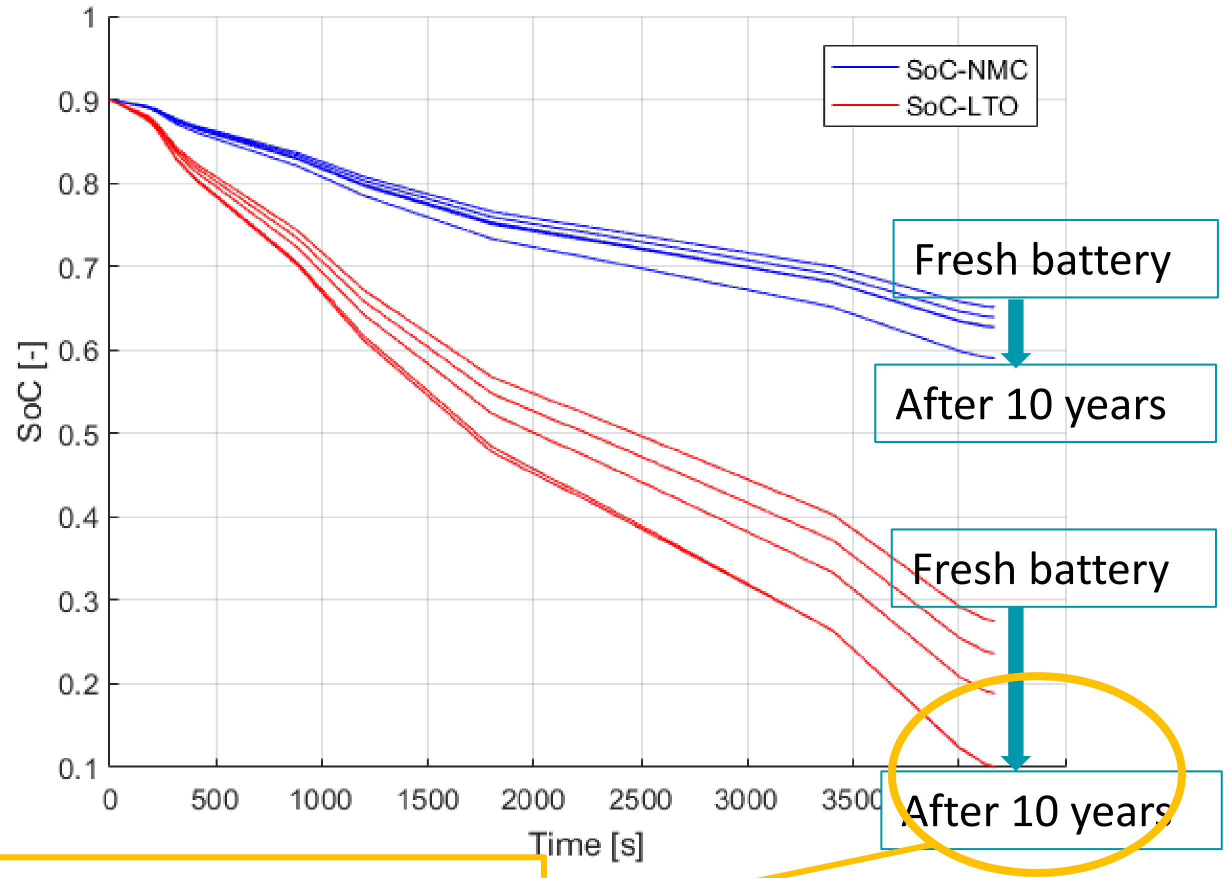
Optimization results :- Both Power split and Sizing optimization

RoRoferry-1 – Optimal powersplit at different years of use

Primary load profile – Summer

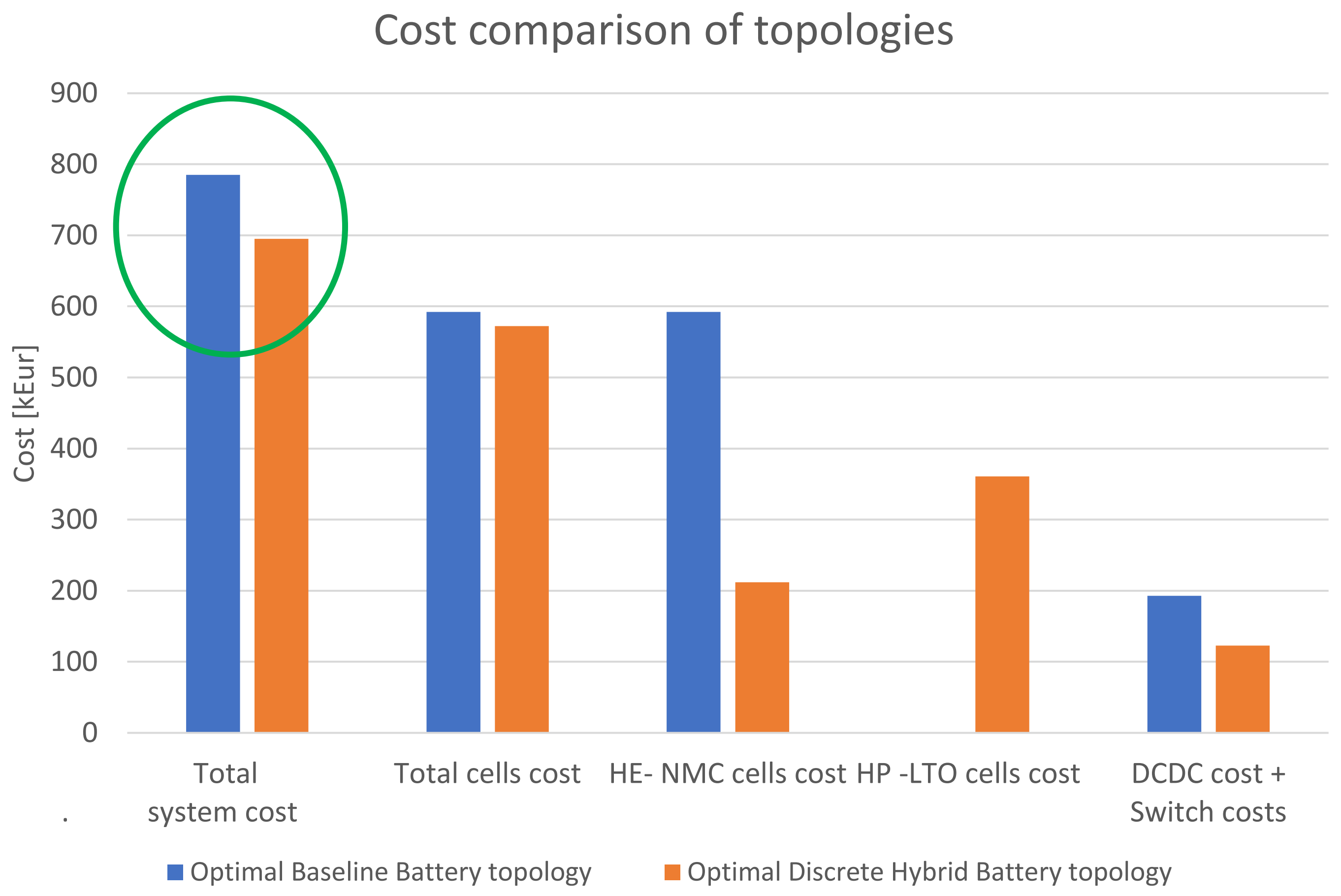


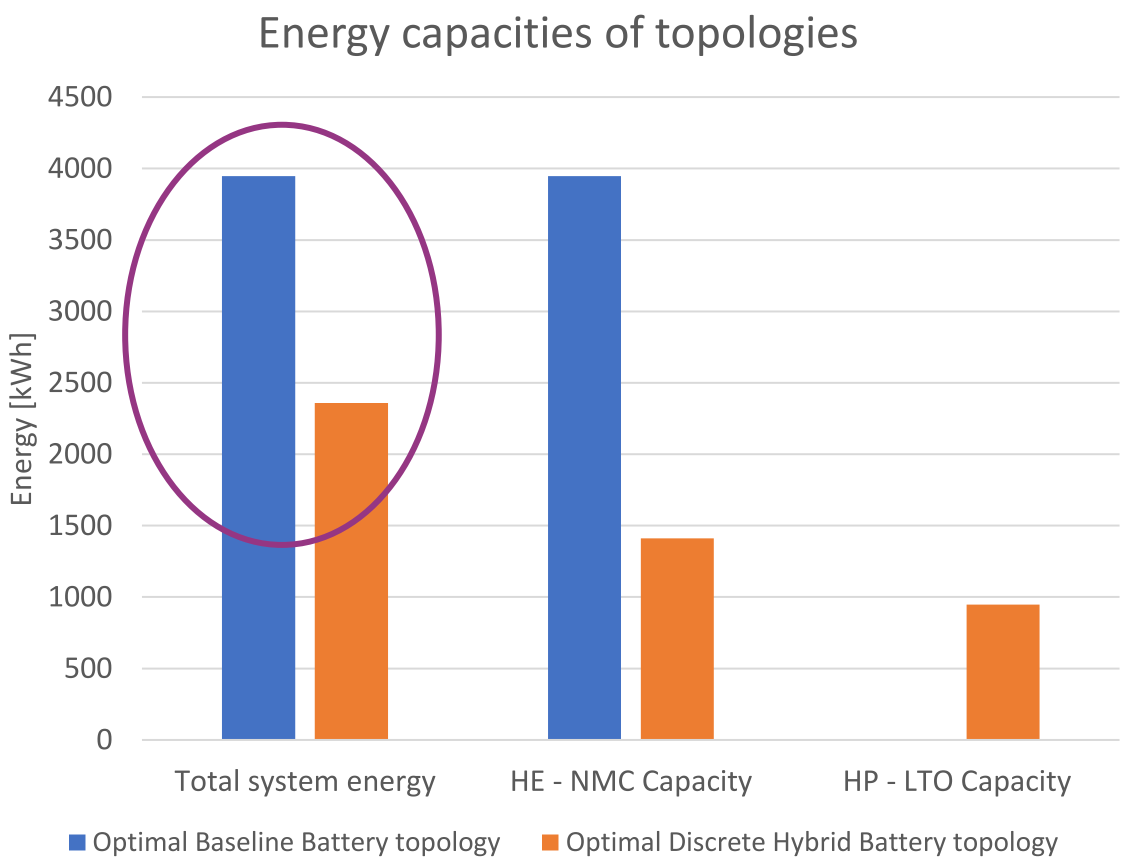
Secondary load profile - Winter



LTO battery Reaches the minimum SoC at the End of Life

Results of the optimization – RoRoferry-1





- 12.8 % Total system Cost reduction for Discrete Hyrbid topology
- 67 % Total energy reduction for Discrete Hyrbid topology

Conclusion

- Δ Different battery topologies (Hybrid) can be compared to find the cost-effective topology for a specific application
- Δ Optimal design for Hybrid Energy storage system is performed
- Δ Provides the optimal total cost of the system ensuring all the constraints
- Δ Ensures the powersplit control is optimal for the system specification
- Δ Discrete hybrid battery topology is cost-effective compared to Baseline topology for RoRoferry-1

Thank you