SINTEF

DESIGN ALGORITHM FOR HYBRID ENERGY STORAGE SYSTEMS BASED ON MODULAR MULTI-LEVEL TOPOLOGY

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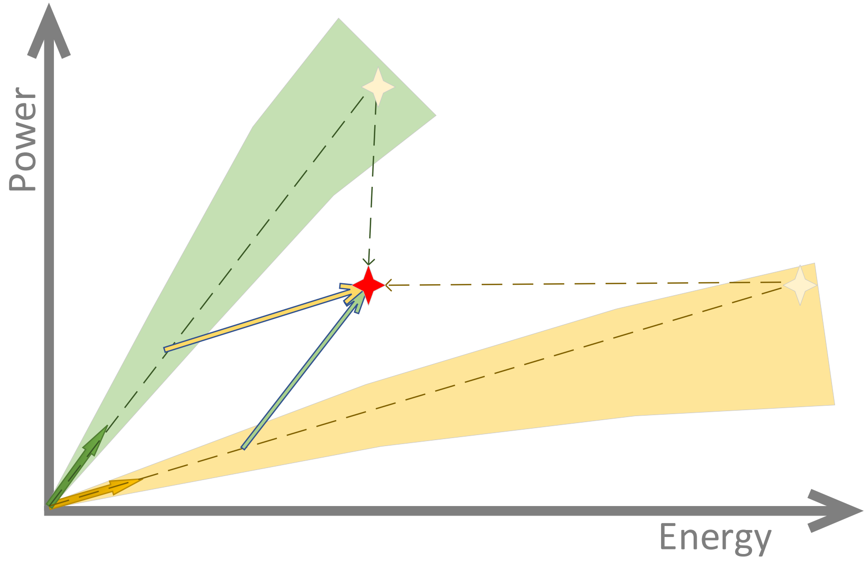
Background (1)

- Battery technology with well defined trends

  High Energy (HE) vs. High Power (HP)

- Applications with Energy-Power requirements in between of what could be obtained with HE and HP battery systems end up with oversized HE or HP battery solutions.
- Hybrid Energy Storage System (HESS) brings a solution combining HE and HP technologies avoiding oversized solutions.

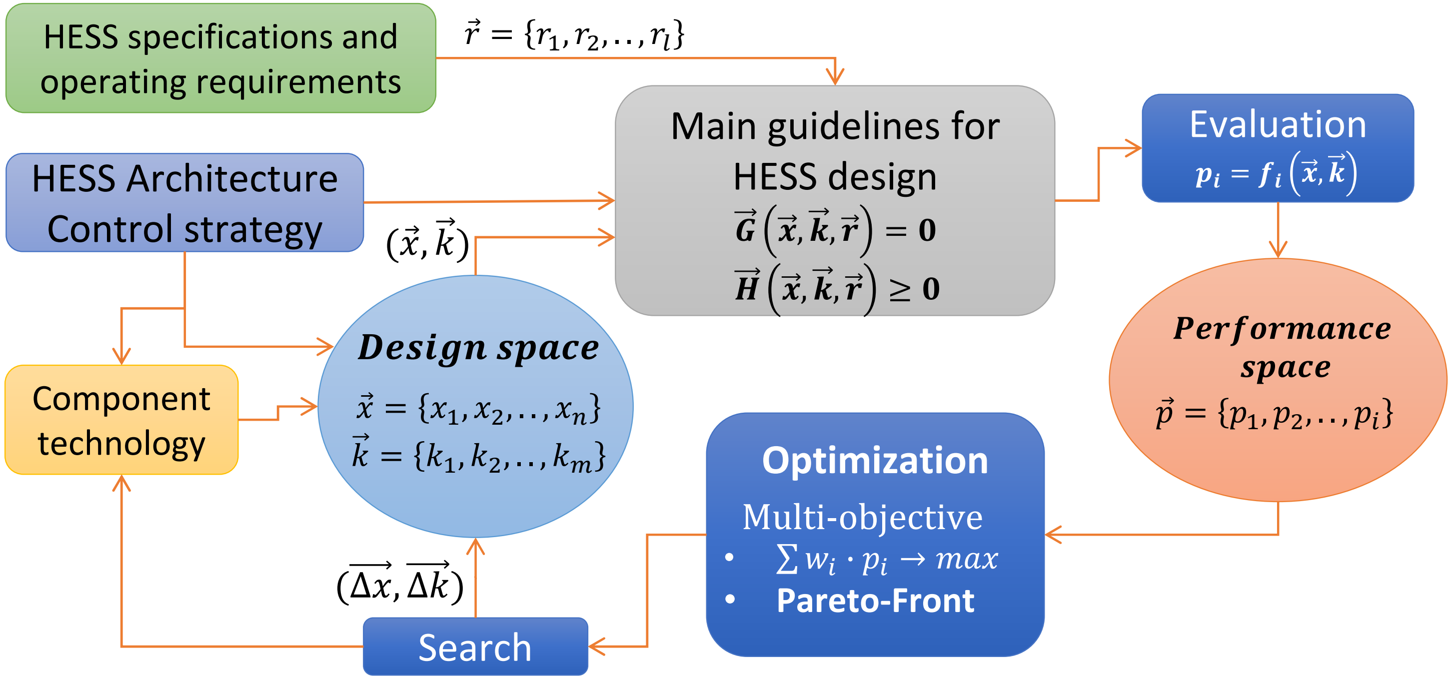


Background (2)

- Battery system design is a complex process involving different design choices and device technology alternatives, with the optimal design linked to the core cell technology.
- Standard battery system topology with well defined design trends.
- HESS requires adaptation of new topologies with additional degrees of freedom in the battery system design.
- There is a need for analysing the interdependency between the different design choices in new HESS topologies as the optimal design could be far away from the optimal design of the standard battery systems.

HESS design methodology

- For a given couple of core units (HE and HP cells), the design algorithm explores the design space to bring up a set of design alternatives which represent the best trade-off between the different performance indices while fulfil HESS specification and requirements.



HESS specifications and operating requirements

$\vec{r} = \{r_1, r_2, .., r_l\}$

HESS Architecture Control strategy

Main guidelines for HESS design

$\vec{G}\left(\vec{x}, \vec{k}, \vec{r}\right) = 0$

$\vec{H}\left(\vec{x}, \vec{k}, \vec{r}\right) \geq 0$

Evaluation

$p_i = f_i\left(\vec{x}, \vec{k}\right)$

$(\vec{x}, \vec{k})$

Component technology

Design space

$\vec{x} = \{x_1, x_2, .., x_n\}$

$\vec{k} = \{k_1, k_2, .., k_m\}$

Performance space

$\vec{p} = \{p_1, p_2, .., p_i\}$

Optimization

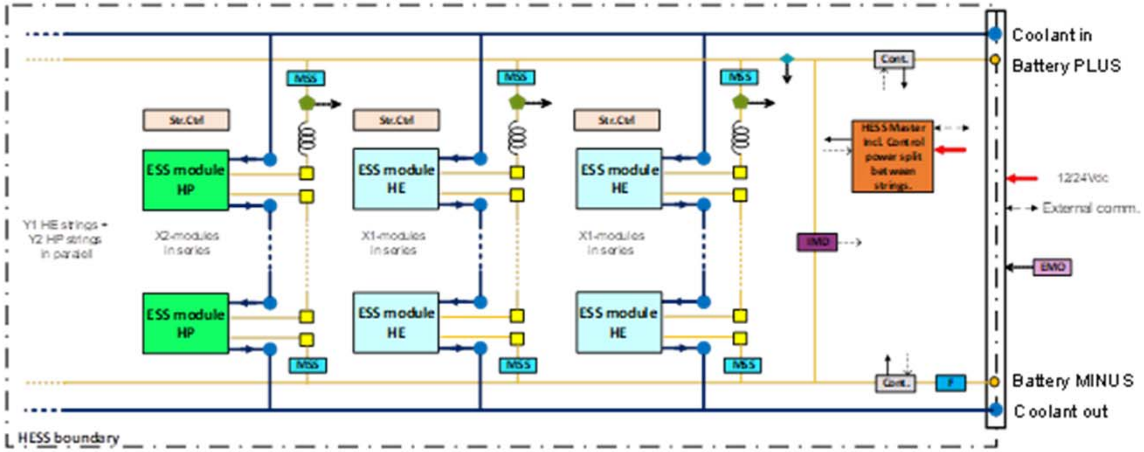
Multi-objective

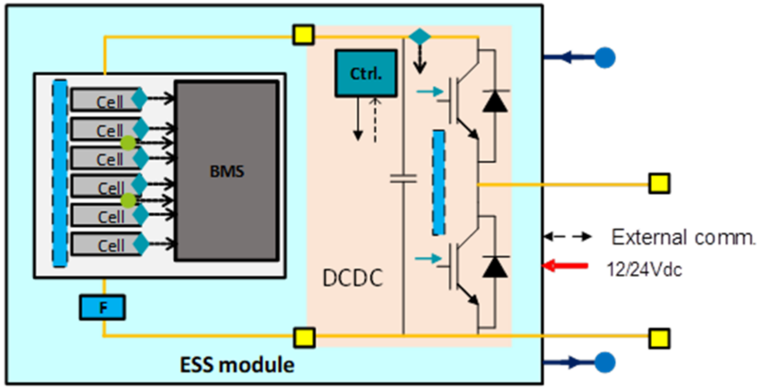
- $\sum w_i \cdot p_i \rightarrow max$
- **Pareto-Front**

$(\overrightarrow{\Delta x}, \overrightarrow{\Delta k})$

Search

Modular Multilevel Hybrid Energy Storage System Topology





N_Y strings (parallel) with N_X ESS modules in series

N_{X1}*N_{Y1} HE modules && N_{X2}*N_{Y2} HP modules

- Modular design allowing redundant functionality within the strings.

ESS Module composed by two parts:

- **Battery Module:** energy storage based on battery cell array .
- **DC-DC converter**: Power flow control.

The sharing of power between HE and HP strings can be controlled by a master controller since power flow in each module can be controlled.

HESS design algorithm

Main inputs

- **The power profile** composed by N_{ts} power time series with expected annual repetition.
- High-Energy and High-Power **Core Cells.**
- HESS General specifications: **Nominal DC Voltage, desired lifetime.**

Main Outputs:

Set of HESS possible designs defined by the HE and HP sub-battery systems.

Performance Indices:

- Investment Cost
- Volume, Mass, efficiency
- Installed Energy and power capacity

HESS design algorithm

- Three main sub-algorithms:

1. Power Split:

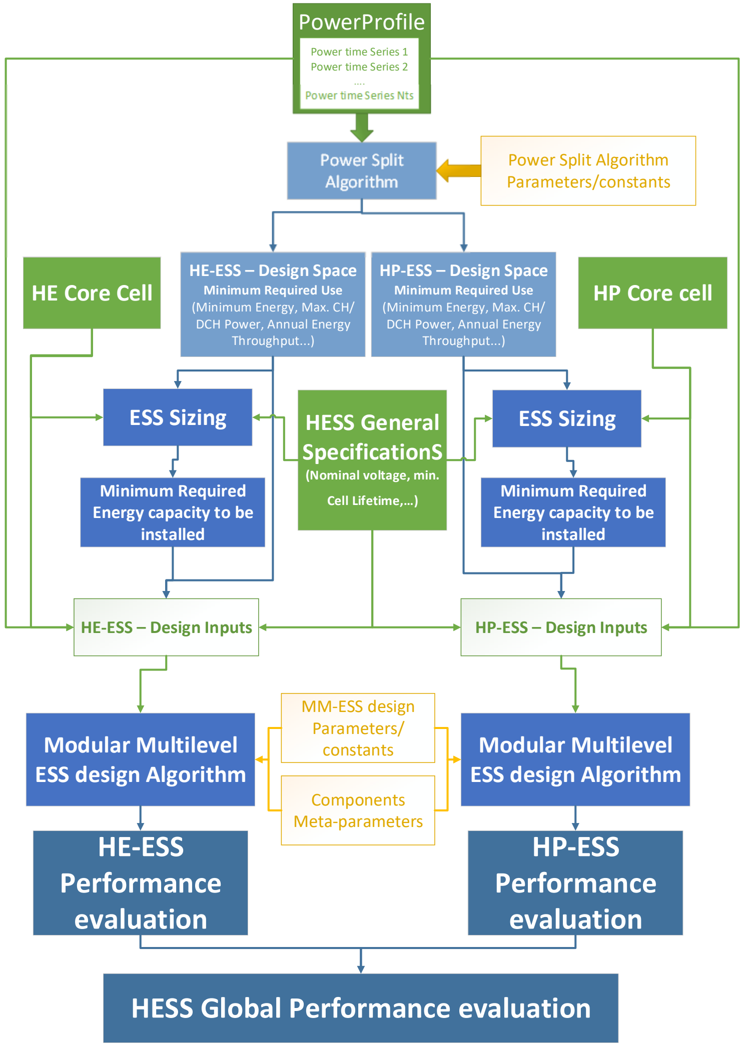
   HE vs HP power sharing

2. HE&HP ESS Sizing:

   Installed capacity vs lifetime

3. HE&HP MM-ESS design:

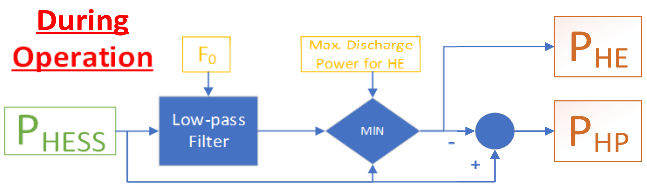
   ESS module, number of modules, number of strings… vs. performance indices

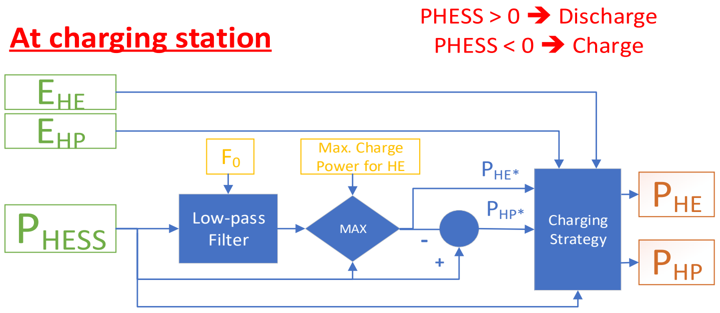


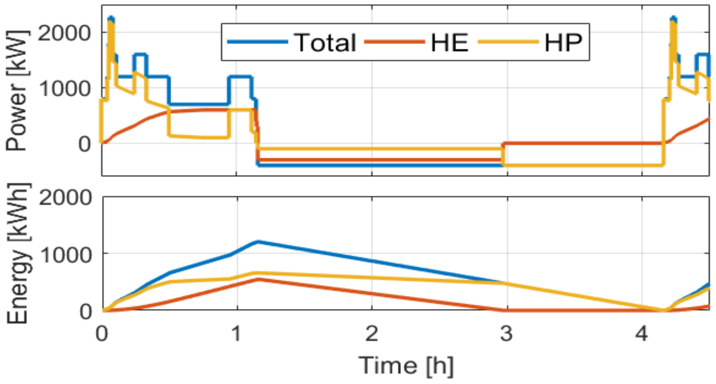
Power Split Algorithm (1)

- Algorithm based on low pass filtering of the load power demand.
- Easy implementation in a real power management system but it does not guarantee that the true optimal power split is found.
- Power Split Parameters
  - The low pass filter cut-off frequency (F_0)
  - The maximum discharge power of HE battery ($P_{HE.DCHmx}$)
  - The maximum charge power of HE battery ($P_{HE.CHmx}$).

F_0 and $P_{HE.DCHmx}$ as free design parameters, then $P_{HE.CHmx}$ is estimated based on the energy used and available charging time



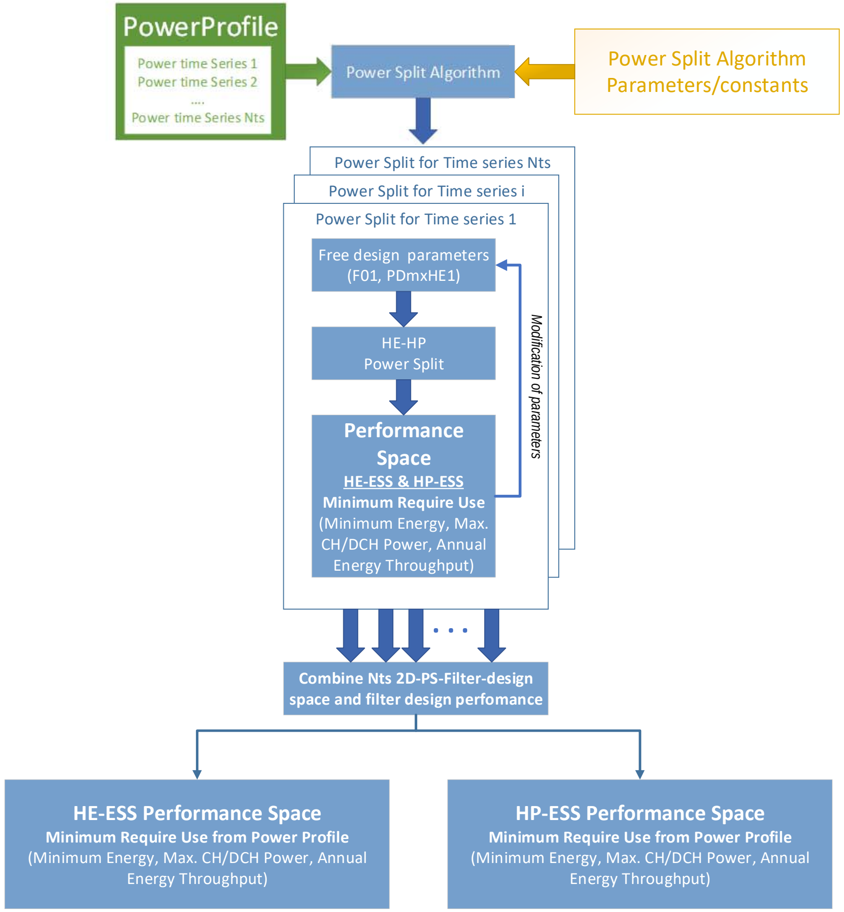




(F_0=50 µHz; $P_{HE.DCHmx}$= 600kW; $P_{HE.CHmx}$=300kW)

Power Split Algorithm (2)

- Different power split parameters per power time series.
- Multiple combinations of F_0 and $P_{HE.DCHmx}$ are explored, with a performance space defined by:
  - **The minimum usable energy of the battery sub-system**
  - **The required maximum continuous charge power**
  - **The required maximum continuous discharge power**
  - **The annual energy throughput (AET)**



PowerProfile

Power time Series 1
Power time Series 2
....
Power time Series Nts

Power Split Algorithm

Power Split Algorithm Parameters/constants

Power Split for Time series Nts

Power Split for Time series i

Power Split for Time series 1

Free design parameters (F01, PDmxHE1)

HE-HP Power Split

Performance Space
HE-ESS & HP-ESS
Minimum Require Use
(Minimum Energy, Max. CH/DCH Power, Annual Energy Throughput)

Modification of parameters

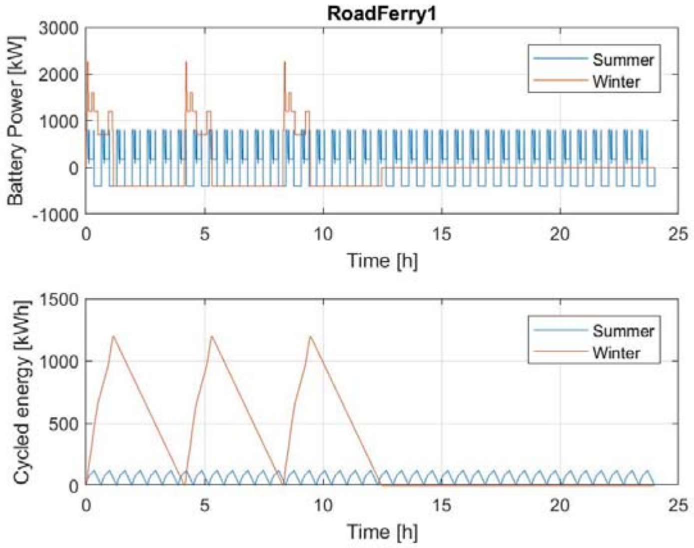
. . .

Combine Nts 2D-PS-Filter-design space and filter design perfomance

HE-ESS Performance Space
Minimum Require Use from Power Profile
(Minimum Energy, Max. CH/DCH Power, Annual Energy Throughput)

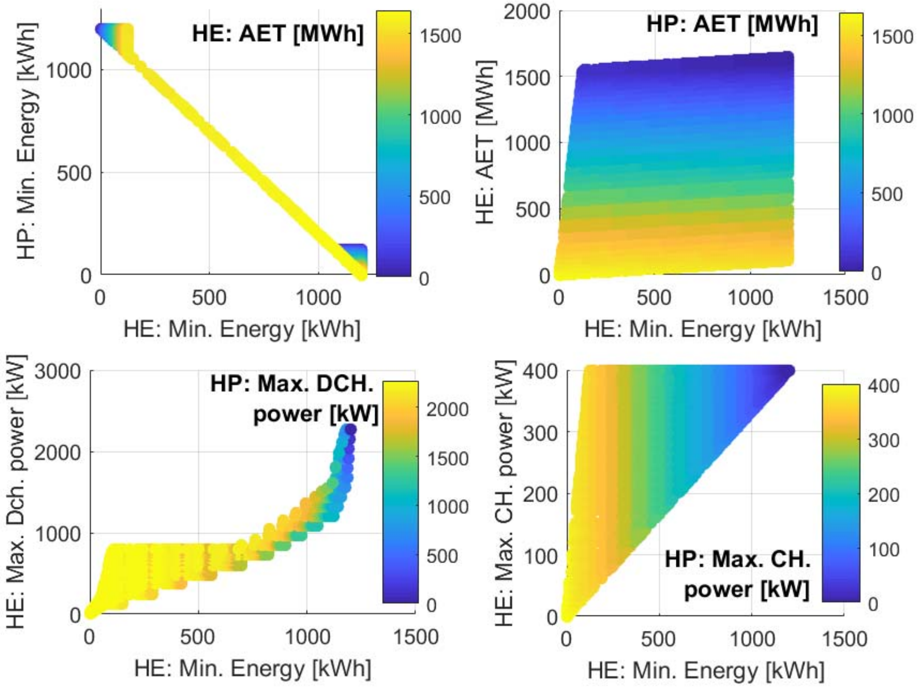
HP-ESS Performance Space
Minimum Require Use from Power Profile
(Minimum Energy, Max. CH/DCH Power, Annual Energy Throughput)

Power Split Algorithm (3)



Power Split Algorithm

Performance Space



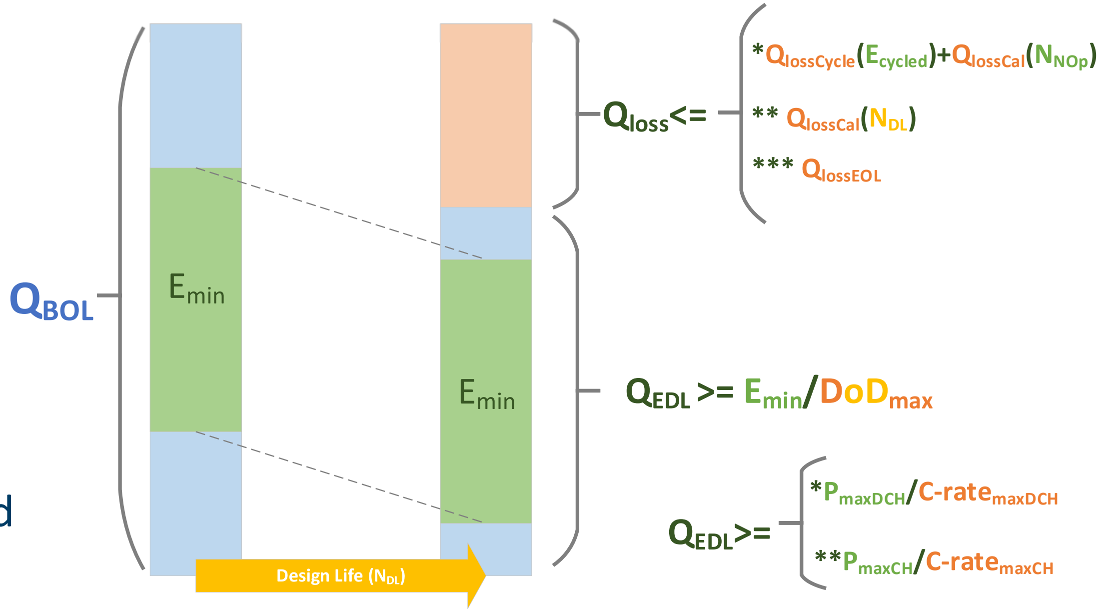
- Power profile composed by two power time series
- Design space defined by 20 different values of F0 (0, ∞), and 10 different values for $P_{HE.DCHmx}$

40.000 possible power split combinations

ESS Sizing (1)

- To estimate the minimum capacity to be installed considering:

1. Required maximum continuous charging/discharge power
2. SoC within the defined range
3. To avoid battery cells end of life before end of design life.
4. To account for calendar and cycling capacity degradation to ensure enough remaining capacity at end of design life.

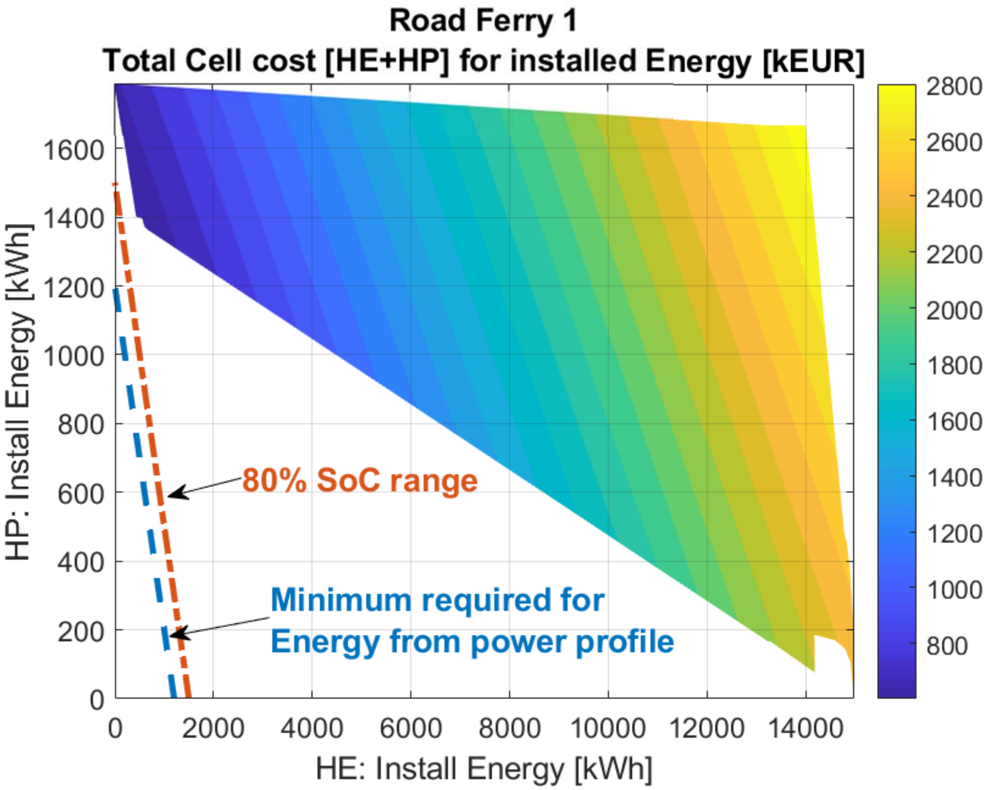


N_{DL}: Design Life time
N_{NOp}: Accumulative Non-operation time within N_{DL}
E_{cycled}: Total Energy Troughput during N_{DL}
$P_{maxCH/DCH}$: Maximum required charge/discharge power
$\text{C-rate}_{maxCH/DCH}$: Maximum allowed Charge/Dischage C-rate

🟩 Inputs from Load profiles
🟧 Parameters from selected Cell tech.
🟨 Design Requirements

ESS Sizing (2)

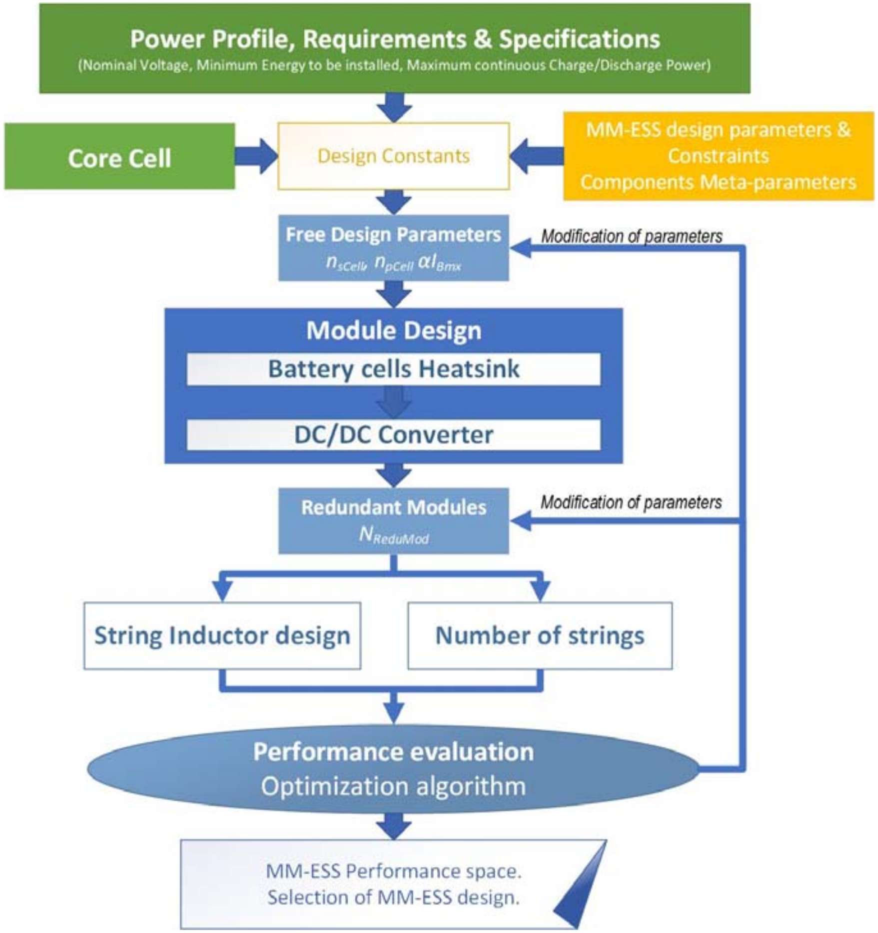
- ESS sizing depends on core cell properties.
- Algorithm based on a simple degradation model considering only effects on capacity fade by calendar and cycling aging.
- Calendar aging as a linear process and happening whenever the battery is not cycled
- Cycling degradation proportional to the energy throughput.



HE core cell: 155Ah-NMC @ REPT
HP core cell: 23Ah-LTO @Toshiba-SCiB

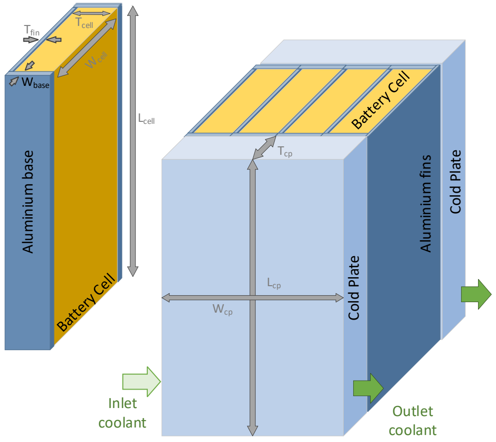
MM-ESS design (1)

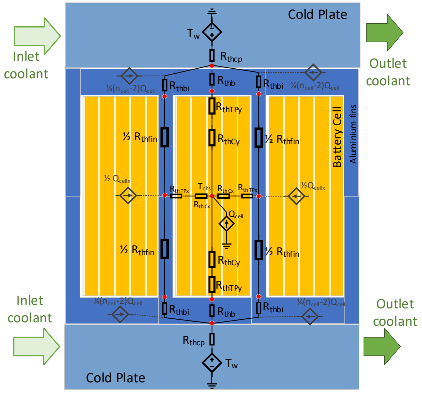
- Two battery sub-systems (HE & HP) needs to be defined for each power split combination.
- Main inputs:
  - **Nominal string Voltage**,
  - **Minimum Energy** to be installed,
  - Required Max. **Cont. Charge/Discharge Power** and
  - **Core Cell** properties.
- Main free design parameters:
  - Number of **series** and **parallel** cells per module
  - Maximum battery cell current utilization ratio
  - Number of modules per string (allowing redundant modules)



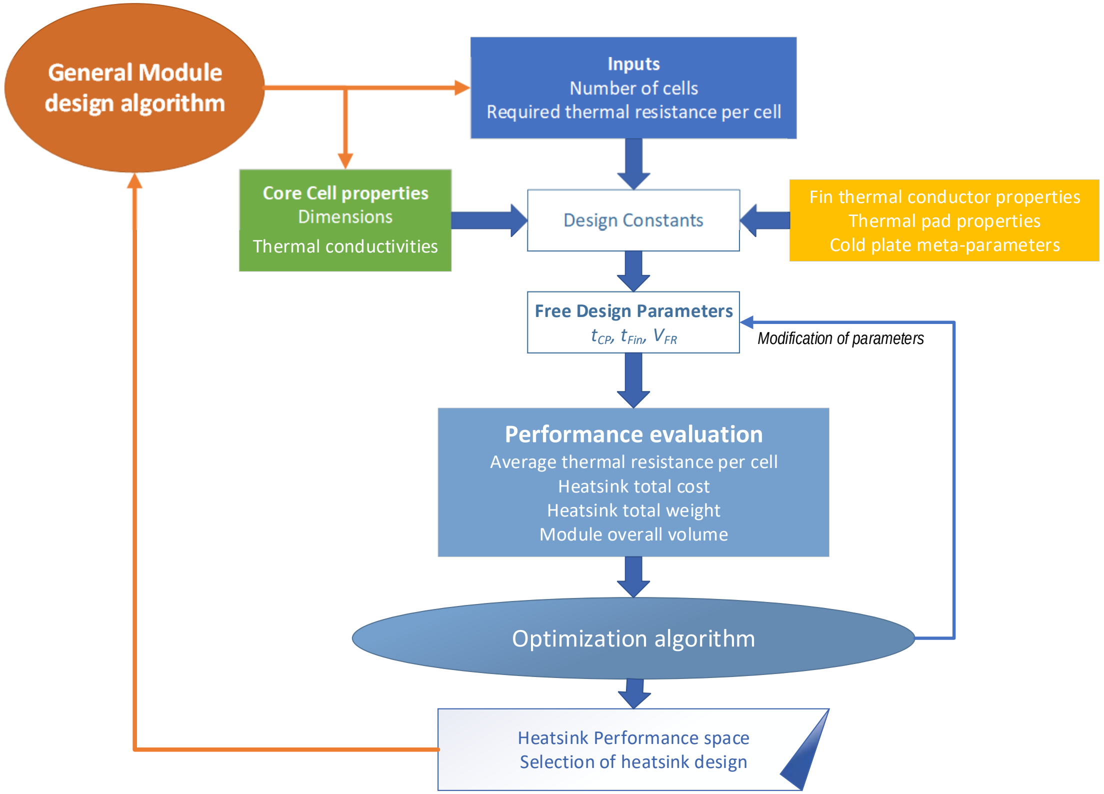
MM-ESS design (2)

Battery cell cooling system based on thermal conductive fins and cold plates





Heatsink design based on average thermal model.



General Module design algorithm

Inputs
Number of cells
Required thermal resistance per cell

Core Cell properties
Dimensions
Thermal conductivities

Design Constants

Fin thermal conductor properties
Thermal pad properties
Cold plate meta-parameters

Free Design Parameters
t_{CP}, t_{Fin}, V_{FR}

Modification of parameters

Performance evaluation
Average thermal resistance per cell
Heatsink total cost
Heatsink total weight
Module overall volume

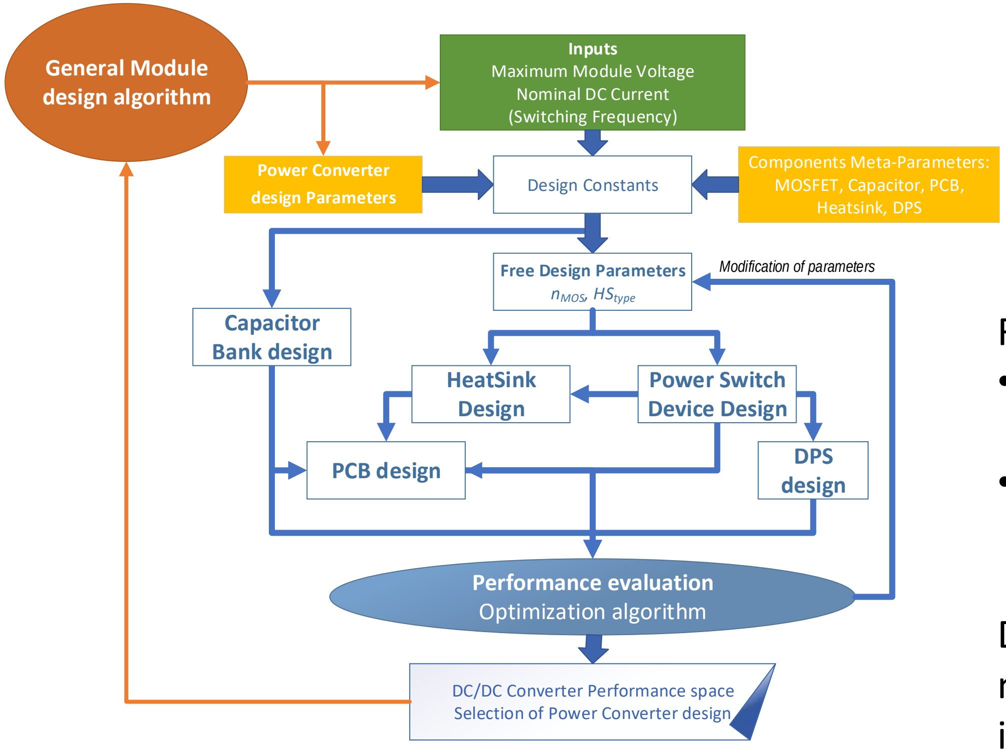
Optimization algorithm

Heatsink Performance space
Selection of heatsink design

Free design parameters:

- Fin material: Al vs. Cu
- Fin thickness
- Cold Plate thickness and Flow Rate

MM-ESS design (3)



General Module design algorithm

Inputs
Maximum Module Voltage
Nominal DC Current
(Switching Frequency)

Power Converter design Parameters

Design Constants

Components Meta-Parameters:
MOSFET, Capacitor, PCB,
Heatsink, DPS

Free Design Parameters
n_{MOS}, HS_{type}

Modification of parameters

Capacitor Bank design

HeatSink Design

Power Switch Device Design

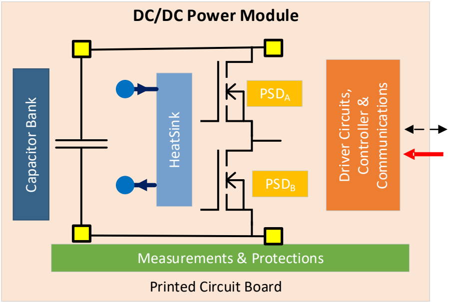
PCB design

DPS design

Performance evaluation
Optimization algorithm

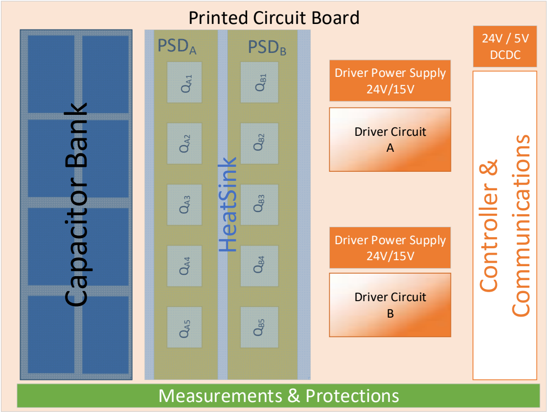
DC/DC Converter Performance space
Selection of Power Converter design

DC/DC Power module based on half-bridge topology



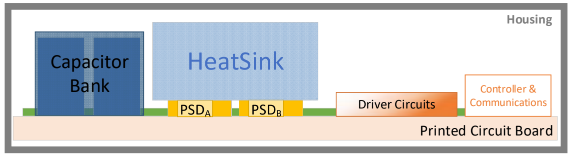
Design algorithm based on predefined layout

DC/DC Converter Layout



Free Design Parameters:

- Number of parallel connected MOSFETS
- Heatsink type:
  Air-forced vs. water cooled



Design selection based on minimum cost with a constraint in volume/dimensions

HESS Design Example (1)

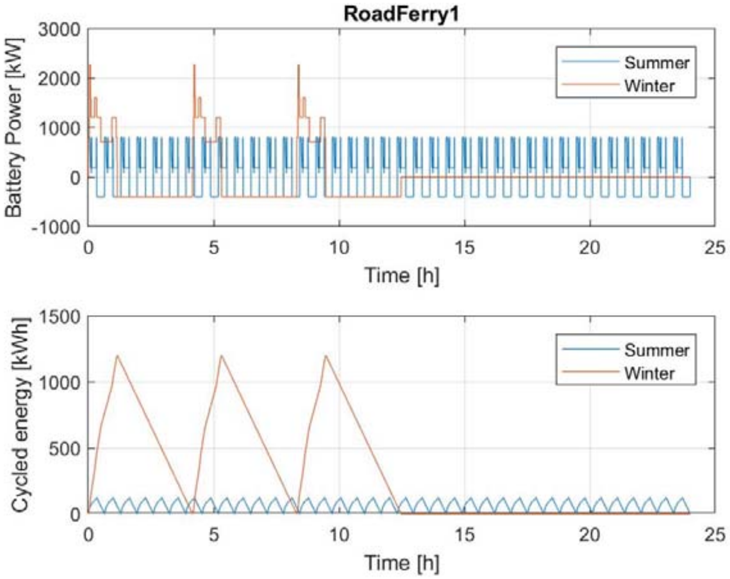
HESS Specs. and Requirements	
Voltage	1000 V
Design Life	10 years

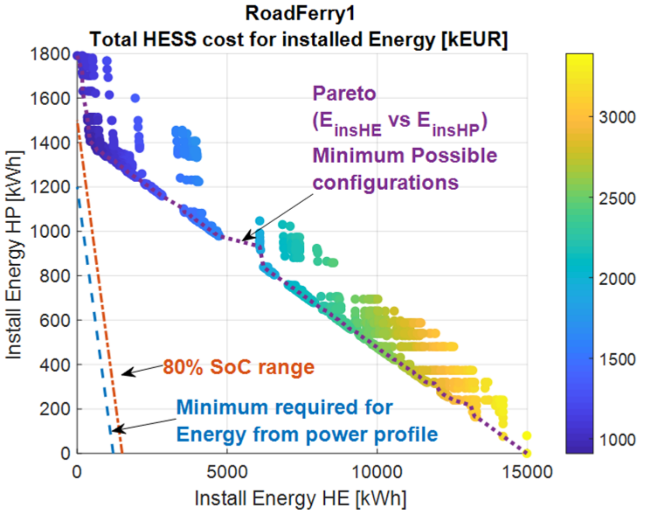
Battery Cells	High Energy	High Power
Chemistry	NMC @ REPT	LTO @Toshiba-SCiB
Capacity	155 Ah (565Wh)	23 Ah (53Wh)
Voltage [V]	3.65 {2.8, 4.3}	2.3 {1.5,2.7}
Cont. Discharge	310 A (2 C-rate)	92 A (4 C-rate)
Cont. Charge	186 A (1.2 C-rate)	92 A (4 C-rate)
Cost	159.5 EUR/kWh	0.25 EUR/Wh

Design constraints	
Maximum cell weight per module	75 kg
Max. p-p current ripple	15 % (per string)
Max. Cell temperature	35 °C
SoC range	80% (10% - 90%)
Switching freq.	3000 Hz
Max. string floating voltage for redundant modules	2 kV

Device Technologies	
Semiconductors	Power MOSFET @ Infineon
Capacitors	MKP snubber series B3262x @TDK
Inductors	SIDAC Iron-Core Smoothing Reactors @ Siemens
Heatsink	Air-forced: Extrusion & Stamped Al structure Water cooled: Al cold plate

HESS Design Example (2)
Performance trade-off

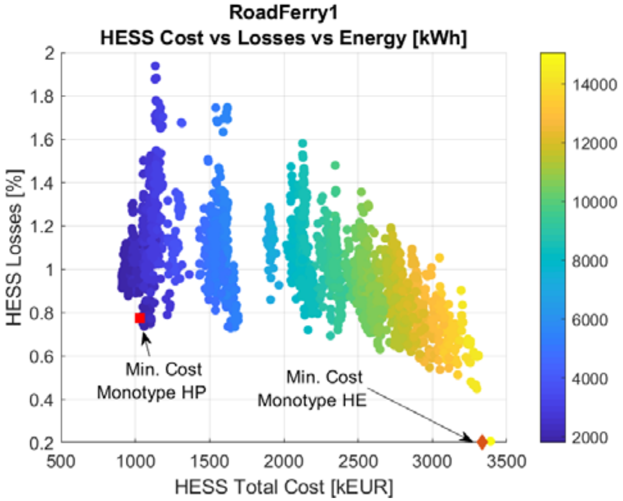




Pareto
(E_{insHE} vs E_{insHP})
Minimum Possible configurations

80% SoC range

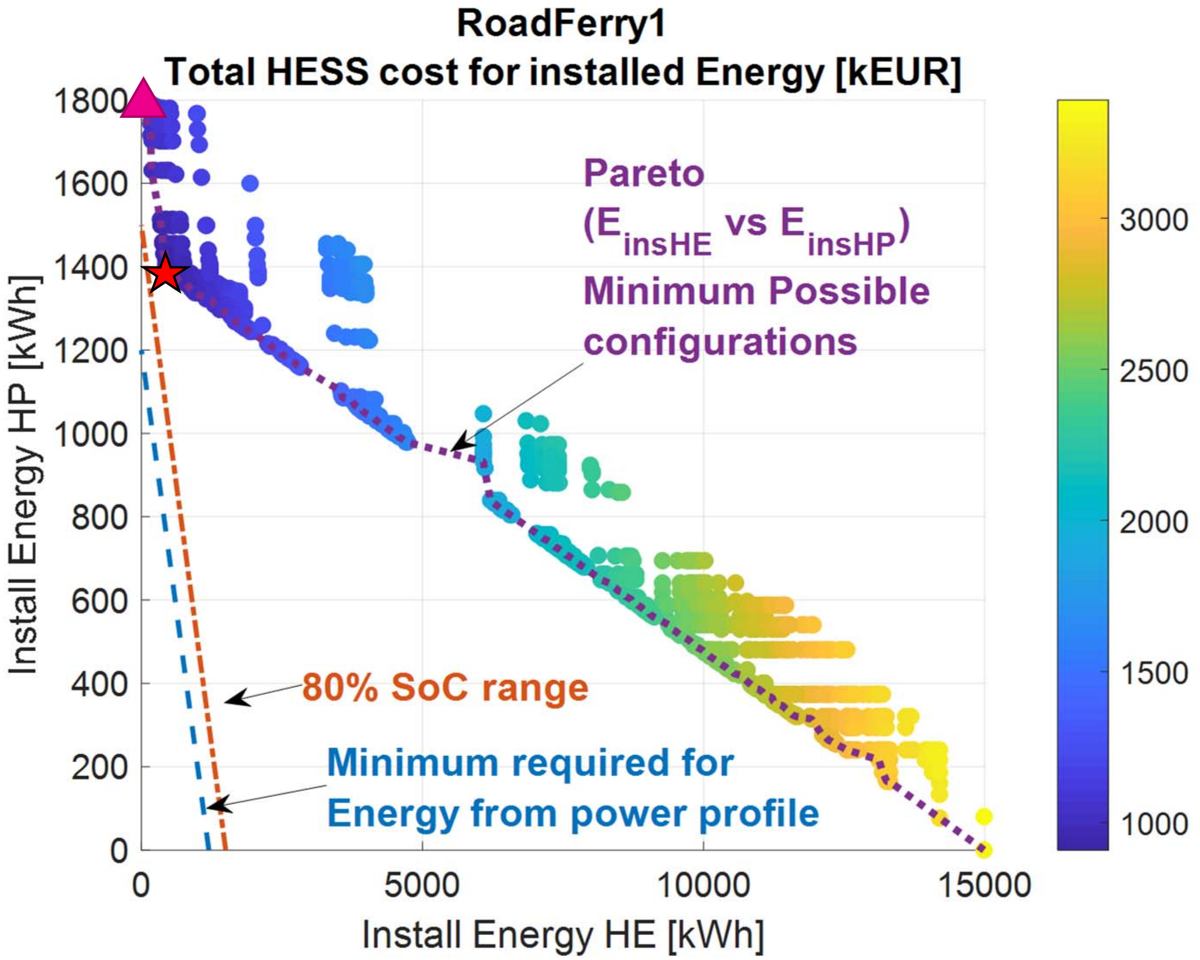
Minimum required for Energy from power profile



Min. Cost Monotype HP

Min. Cost Monotype HE

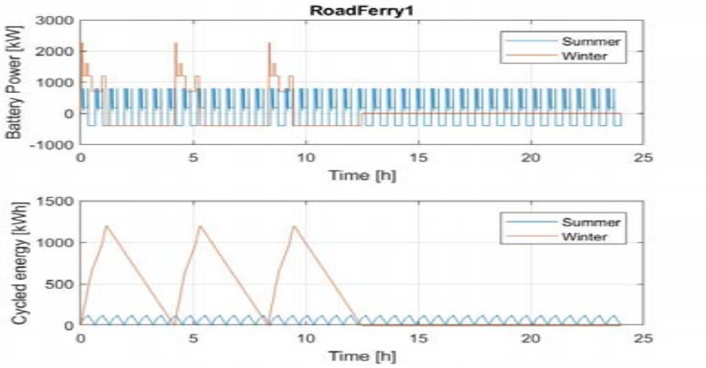
HESS Design Example (3)
Detailed solutions

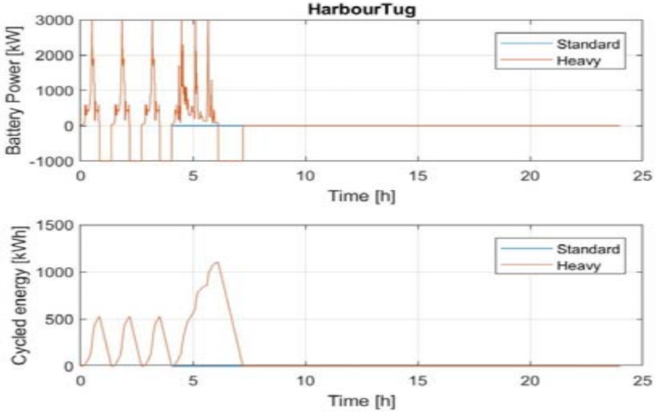


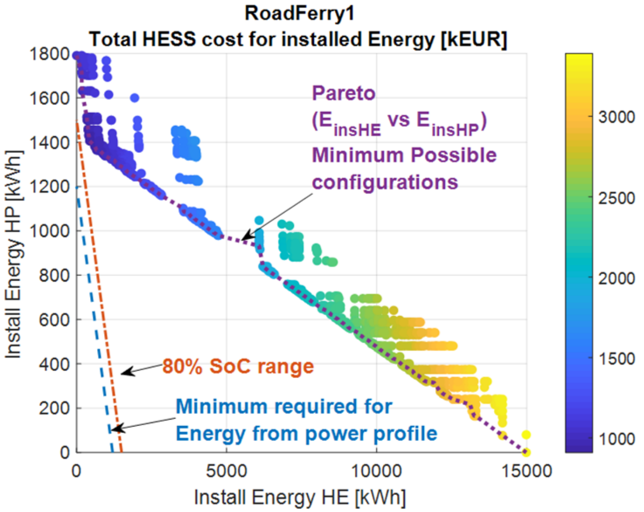
RoadFerry1
Total HESS cost for installed Energy [kEUR]

Design	★ Min Cost	▲ Monotype HP
Parallel Strings	HE: 2 HP: 13	16
Series Modules	HE: 14 HP: 15	16
Redundant modules	HE: 2 HP: 0	1
Installed capacity	1833 kWh HE: 428 kWh HP: 1405 kWh	1791 kWh
Max. CH/DCH power	2.58 / 2.7 MW HE: 186/310 kW HP: 2.4/2.4 MW	2.355 / 2.355 MW
Module Voltage	HE: 98.55V HP: 78.2 V	75.92 V
HESS Cost	909.22 kEUR (495 EUR/kWh) HE: 97.67 kEUR HP: 809.6 kEUR	1028 kEUR (574 EUR/kWh)

HESS Design Example (4)
Different power profiles






RoadFerry1

Total HESS cost for installed Energy [kEUR]

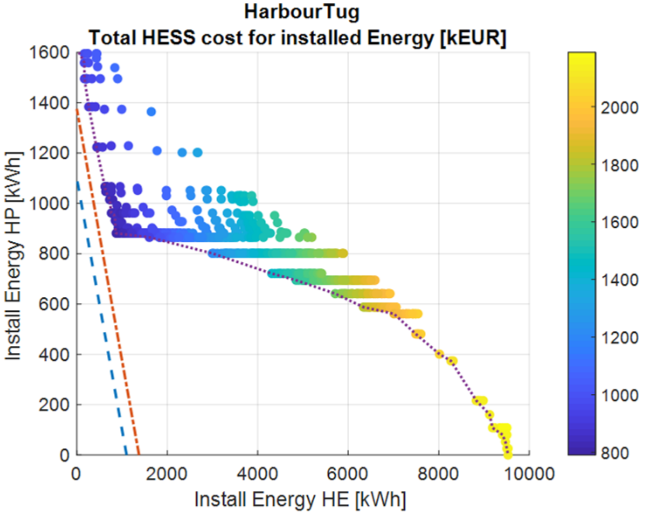
Pareto

(E_{insHE} vs E_{insHP})

Minimum Possible configurations

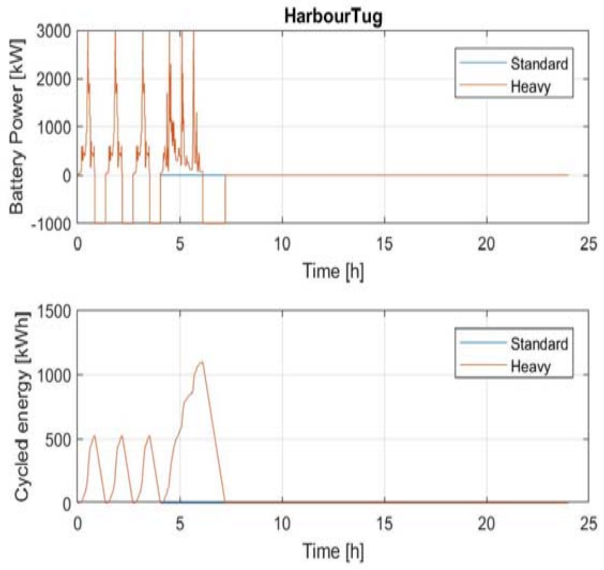
80% SoC range

Minimum required for Energy from power profile

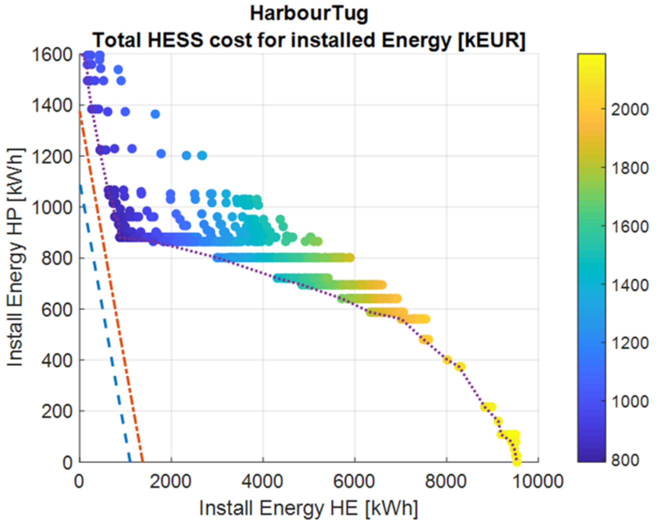

HarbourTug

Total HESS cost for installed Energy [kEUR]

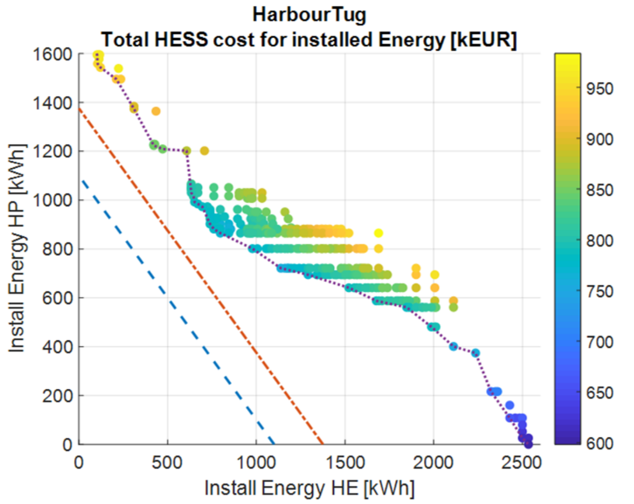
HESS Design Example (5)
Core cell solutions



NMC @ REPT
155 Ah
310/186 A
2/1.5 C-rate
159.5 (EUR/kWh)
1400 cycles



NMC @ Samsung
94 Ah
150/72 A
1.6/0.76 C-rate
150 (EUR/kWh)
4255 cycles



Conclusion

- The proposed HESS design algorithm allows to explore the design space and brings out the optimal solution for each battery sub-system.
- The algorithm is easily adapted to the power profile and core cell characteristics.
- The trade-off of multiple performance indices can be analysed from the algorithm outputs.
- The proposed methodology can be used for analysing the interdependency between the different design choices at early stage of design.

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Teknologi for et bedre samfunn

Evaluation approach

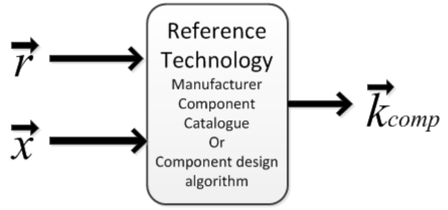
- To speed up the design evaluation, most of the components are modelled based on a meta-parametrised meta-modelling approach.

$$\boldsymbol{p_i} = \boldsymbol{f_i}\left(\vec{\boldsymbol{x}}, \vec{\boldsymbol{k}}\right)$$

$$\vec{k} = [\vec{k}_{Comp}, \vec{k}_{NonComp}]$$

Defined by the discrete components in the system (semiconductors, inductors, capacitors, cells…)

Defined by other design choices (system architecture, control strategy…)



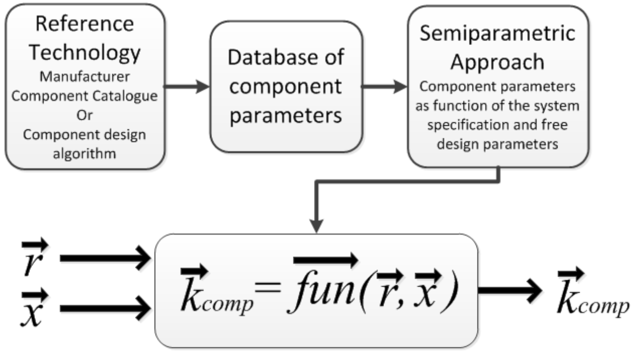
$\vec{r}$

$\vec{x}$

Reference Technology
Manufacturer Component Catalogue
Or
Component design algorithm

$\vec{k}_{comp}$

a) Standard component design constants estimation



Reference Technology
Manufacturer Component Catalogue
Or
Component design algorithm

Database of component parameters

Semiparametric Approach
Component parameters as function of the system specification and free design parameters

$\vec{r}$

$\vec{x}$

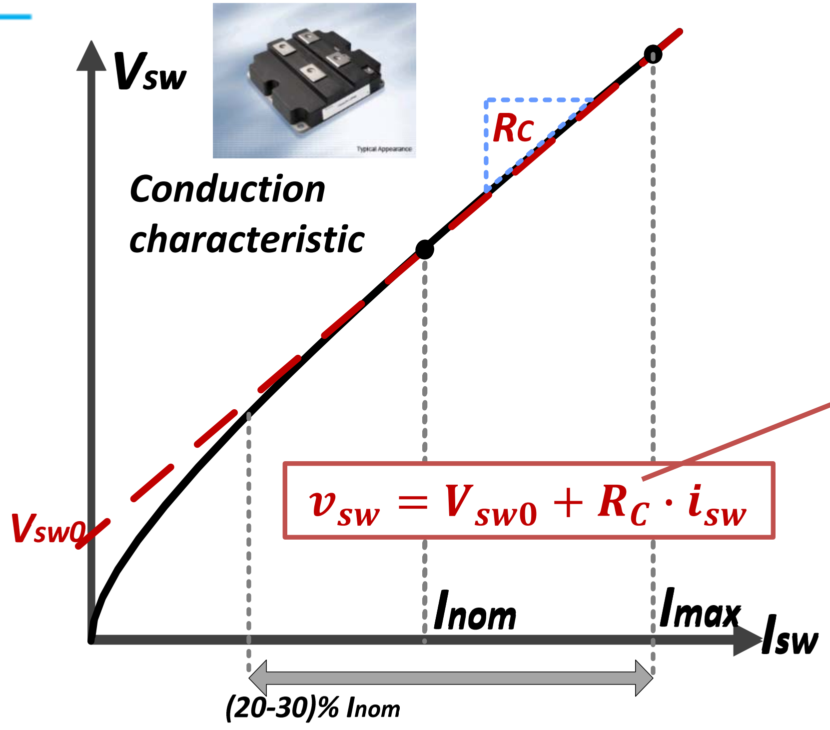
$\vec{k}_{comp} = \overrightarrow{fun}(\vec{r}, \vec{x})$

$\vec{k}_{comp}$

b) Proposed component design constants estimation

Evaluation approach - Example

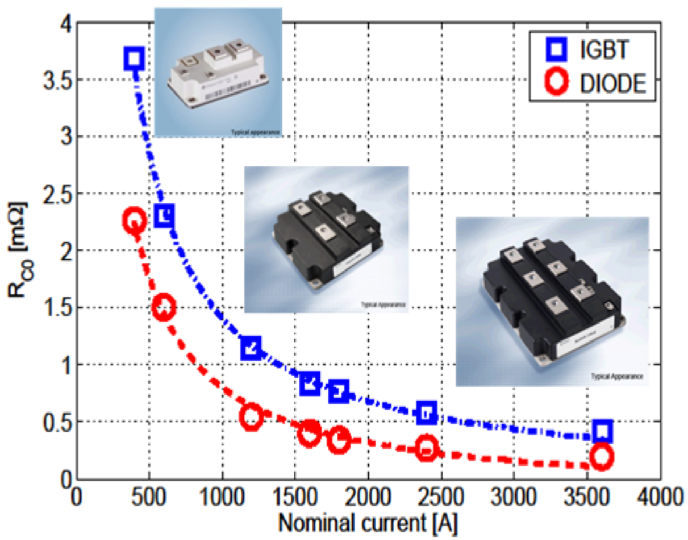
Meta-parametrised meta-modelling approach



$$v_{sw} = V_{sw0} + R_C \cdot i_{sw}$$

Meta-modelling

Infineon IGBT4 technology 1.7kV



$$R_C = fun(I_{nom}, V_{block})$$

Meta-parametrisation

HESS performance evaluation

- Required amount of cells:

$$n_{cellHE} = N_{Y1} \cdot N_{X1} \cdot n_{sHE} \cdot n_{pHE}$$

$$n_{cellHP} = N_{Y2} \cdot N_{X2} \cdot n_{sHP} \cdot n_{pHP}$$

- Total Volume

$$Vol_{HESS} \approx N_{Y1} \cdot (N_{X1} \cdot Vol_{HEMOD} + Vol_{LHE}) + \cdots$$
$$N_{Y2} \cdot (N_{X2} \cdot Vol_{HPMOD} + Vol_{LHP})$$

- Total Weight

$$W_{HESS} \approx N_{Y1} \cdot (N_{X1} \cdot W_{HEMOD} + W_{LHE}) + \cdots$$
$$N_{Y2} \cdot (N_{X2} \cdot W_{HPMOD} + W_{LHP})$$

- HESS Cost

$$Cost_{HESS} \approx N_{Y1} \cdot (N_{X1} \cdot Cost_{HEMOD} + Cost_{LHE}) + \cdots$$
$$N_{Y2} \cdot (N_{X2} \cdot Cost_{HPMOD} + Cost_{LHP}) + Cost_{Other}$$