



Techno-Economic Impact of Li-ion Battery Lifetime Modeling on Energy Storage System Sizing

June 19-22, 2016 | du 19 au 22 juin 2016

Montréal, Québec, Canada

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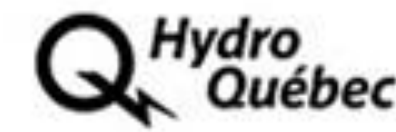
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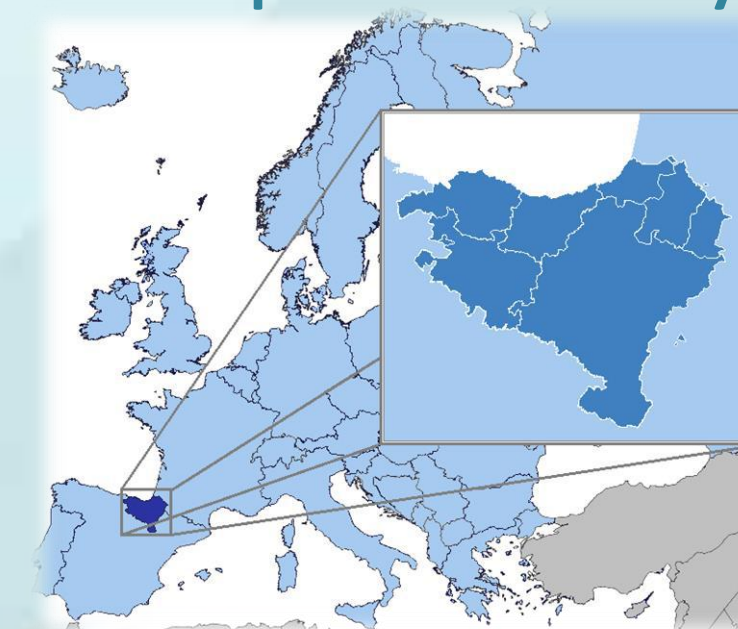


Technology

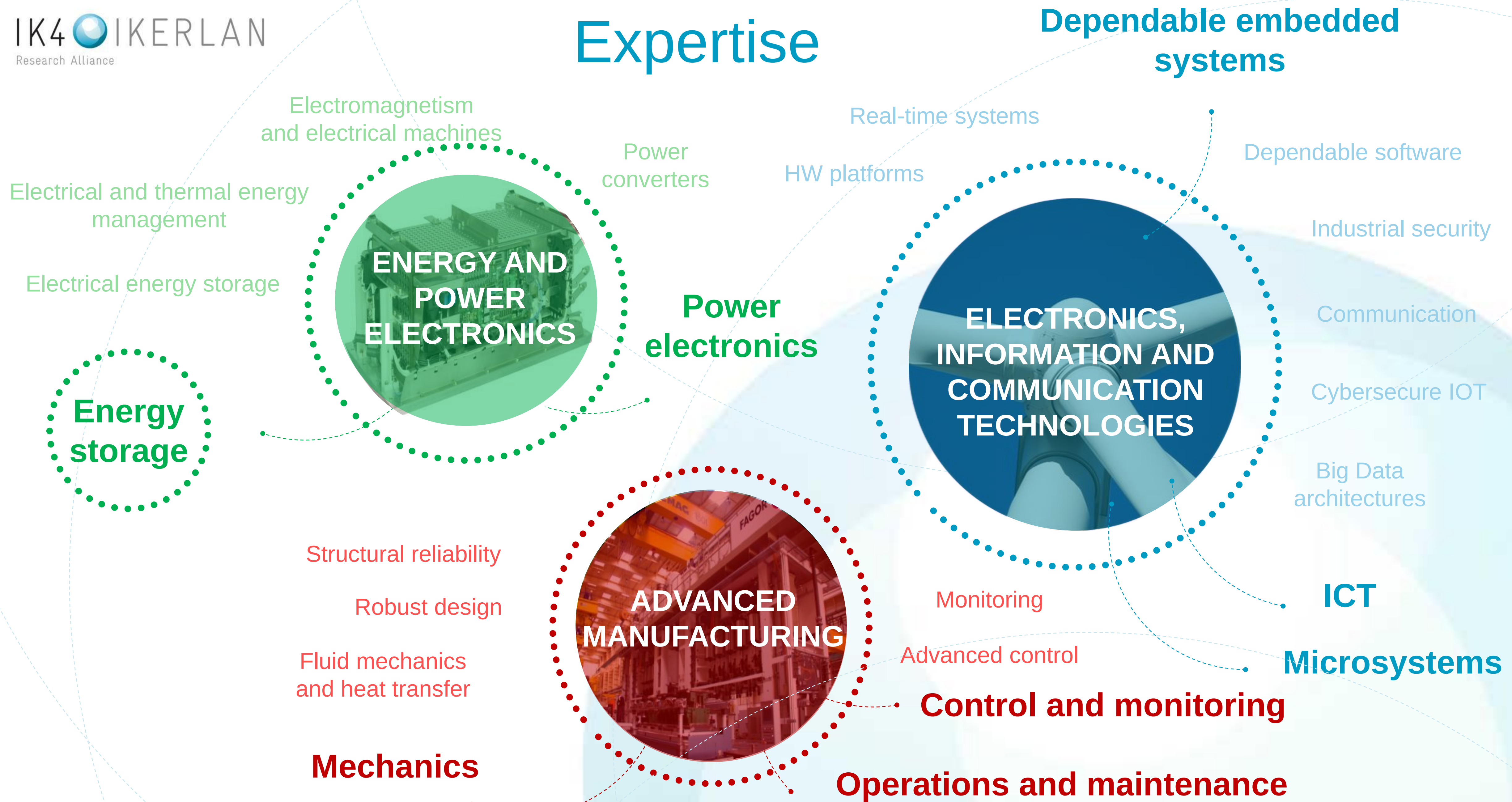


People

Basque Country



Expertise



1. Motivation**2. Scenario Overview****3. Ageing Models Considered****4. Optimization Problem Formulation****5. Results****6. Conclusions**

Increasing concerns on transportation

- Sustainable use of energy resources
- Reduce emissions
- Sustain current level of mobility



Technology evolution trend

Electrification of the transportation sector

Case Study: Tramway Application

Current typical tramways

Main drawbacks:

- ✗ Powered by overhead cables (Catenary)
- ✗ Peak power absorbed from grid
- ✗ Low efficiency in the braking energy recovery



Future tramways

Pursued solution:

- ✓ Catenary-less zones
- ✓ Reduced Peak power consumption
- ✓ Increased efficiency during braking.

SUPERCAPACITOR

- High power density
- Large number of cycles ($>10^5$)
- Limited energy

Li-ion BATTERY

- High energy density
- Limited power capability
- Limited number of cycles ($<10^4$)

Hybrid ESS

- ✓ Absorb peak power (regenerative braking)
 - Increased energy efficiency
- ✓ Inject peak power (acceleration)
 - Reduced peak power

- ✓ Energy supply during catenary-less zone
 - Increased autonomy
- ✓ Energy supply in emergency operation conditions

MAIN GOAL

Optimal operation



Optimal sizing

- ✓ Fulfill application constraints
- ✓ Low ESS degradation
- ✓ Minimum operating cost

How to ...

How battery lifetime prediction affects optimal ESS sizing?



- Publications in literature rarely emphasize on the ageing model employed for ESS sizing.
- Lifetime is a key parameter for battery-based ESS cost calculation:
 - Large battery costs and limited lifetime.
 - ESS sizing and operation conditioned by ESS costs.
- Case study: Tramway application:
 - Hybrid-ESS optimization constrained by BT and SC ageing models.
 - BT: the most sensitive element. Large impact over total system costs.
 - Two different battery ageing models implemented for Hybrid-ESS optimization.

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4. Optimization Problem Formulation

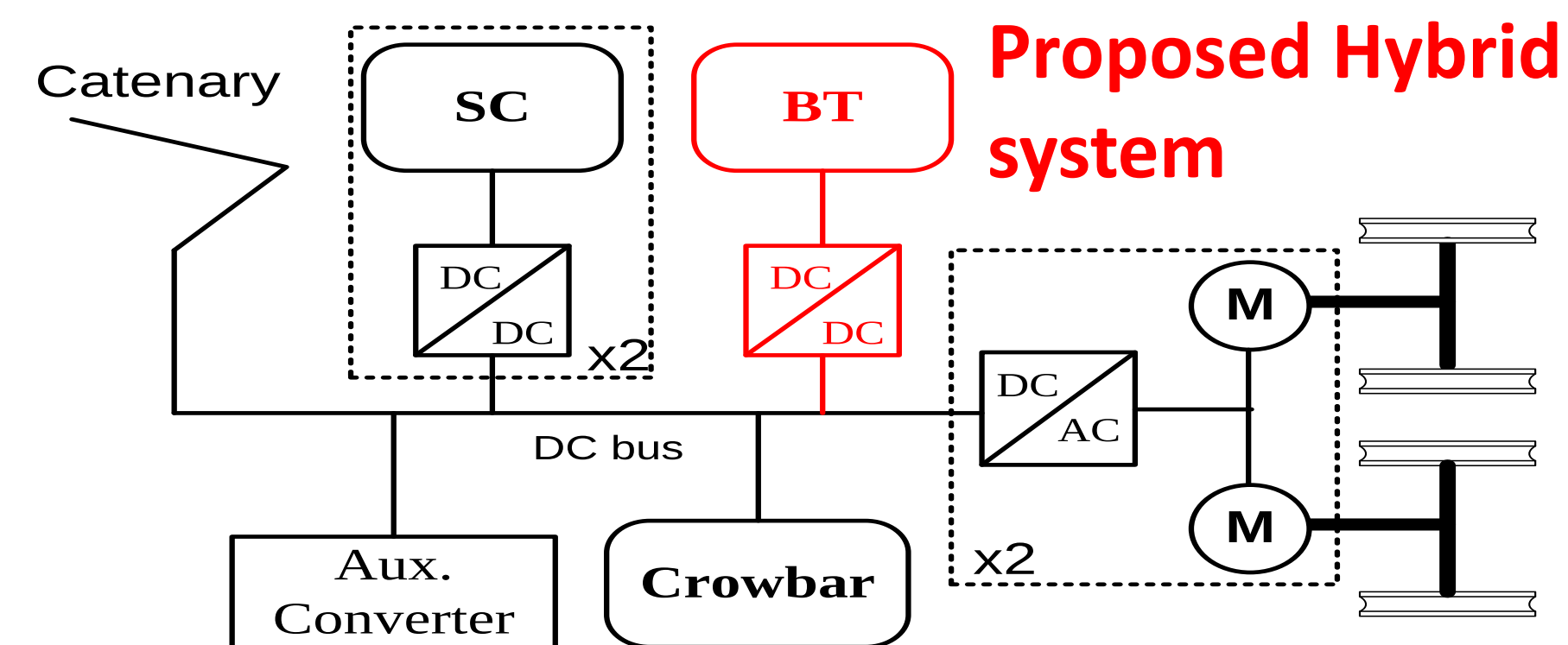
5. Results

6. Conclusions



Considered tramway

- Pedestrian section (city center)
- Catenary-less zone (500 m)
- Currently SC-based



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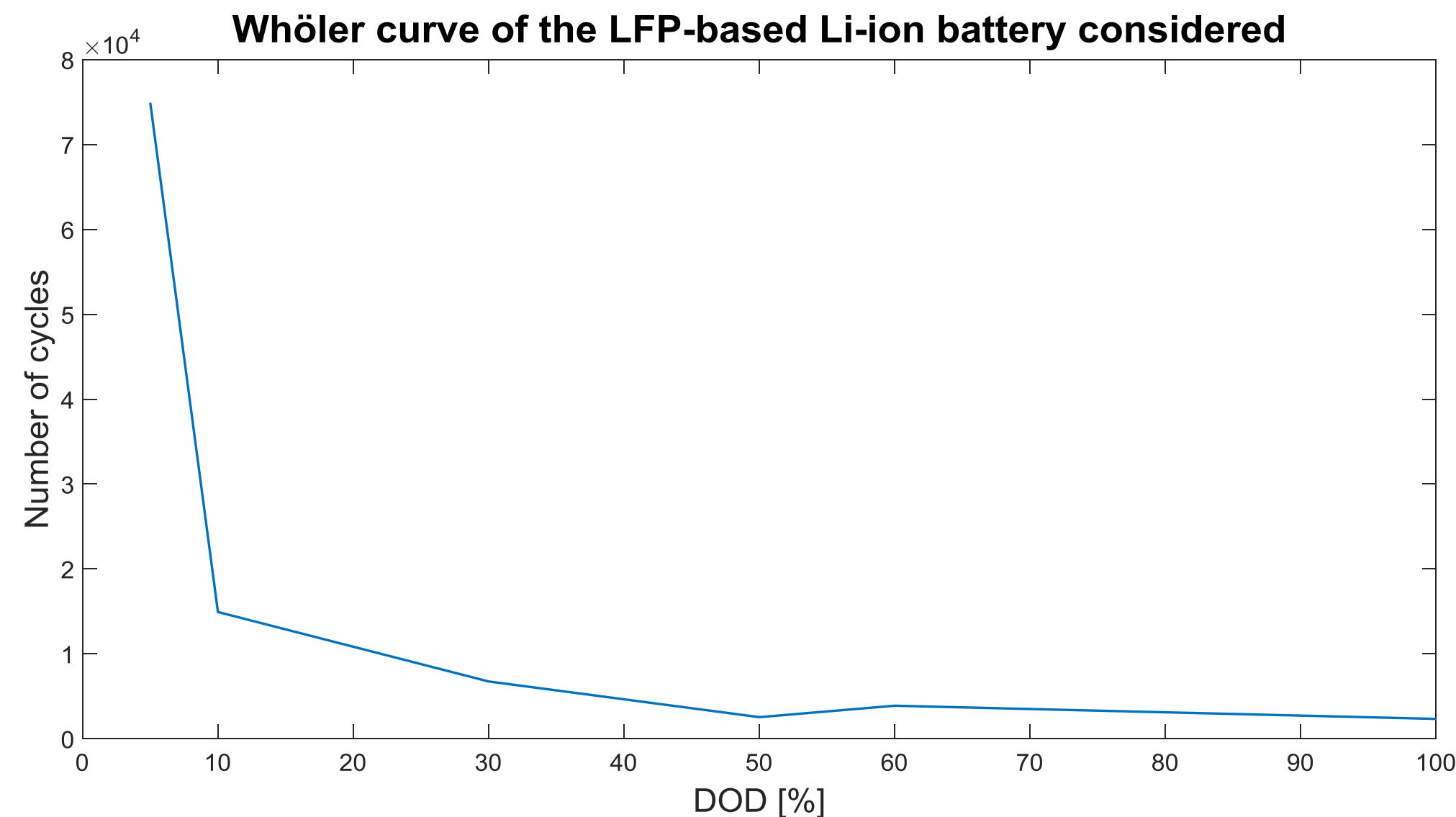
4. Optimization Problem Formulation

5. Results

6. Conclusions

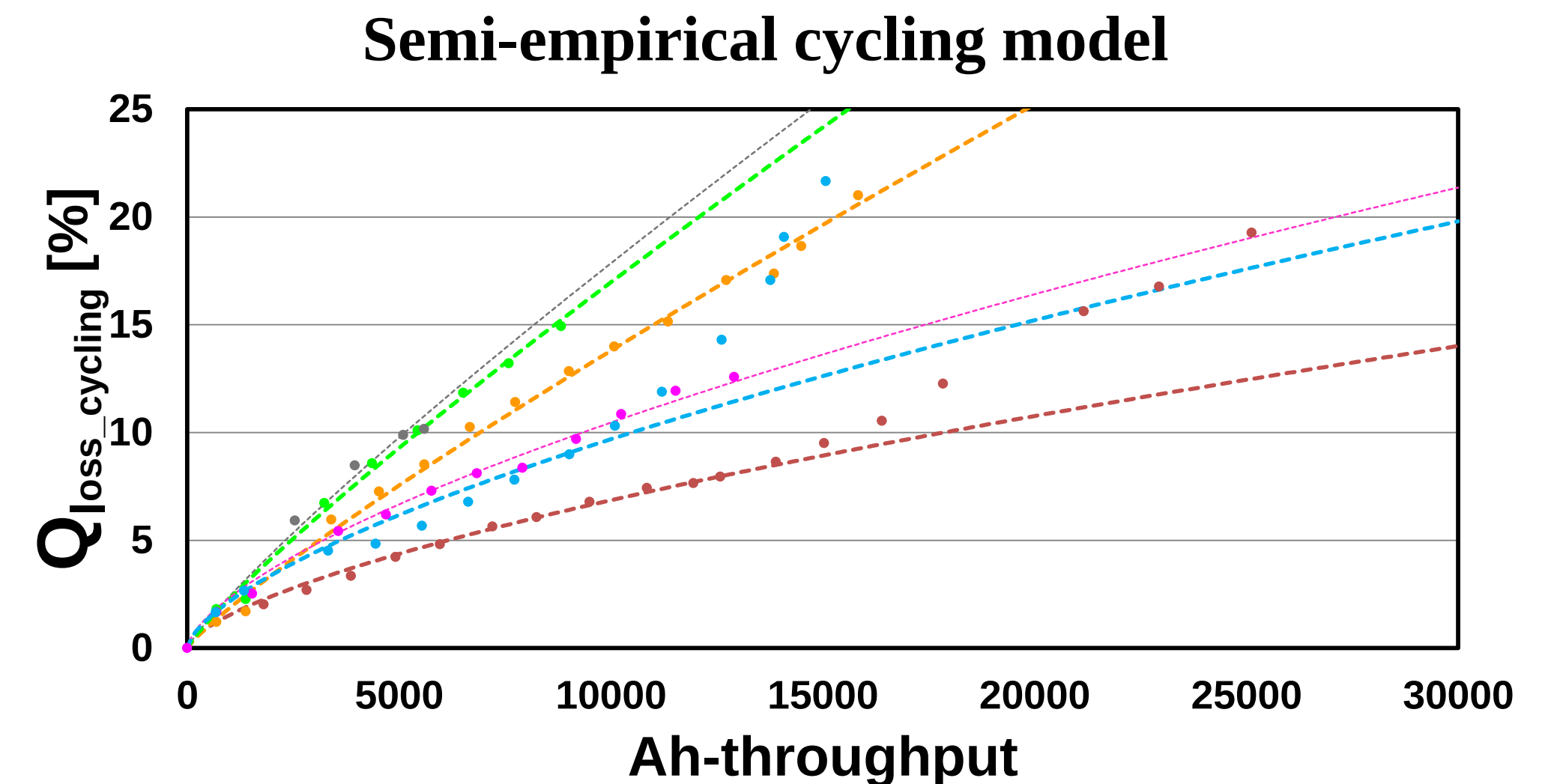
Two main battery ageing models were implemented (2.3 Ah LFP-based cell)

Whöler curve based ageing model



- Very used in literature publications for sizing purposes.
- Requires lower experimental effort.
- Only accounts for effect of DOD over cycling.
- No calendar life effect.

Semi-Empirical ageing model



- Comprehensive cycling + calendar ageing model.
- Requires larger experimental effort.
- Factors considered: DOD, SOC, Temp, Ah, time.
- Thoroughly validated : $RMSE \leq 1.8 \%$

1. Motivation

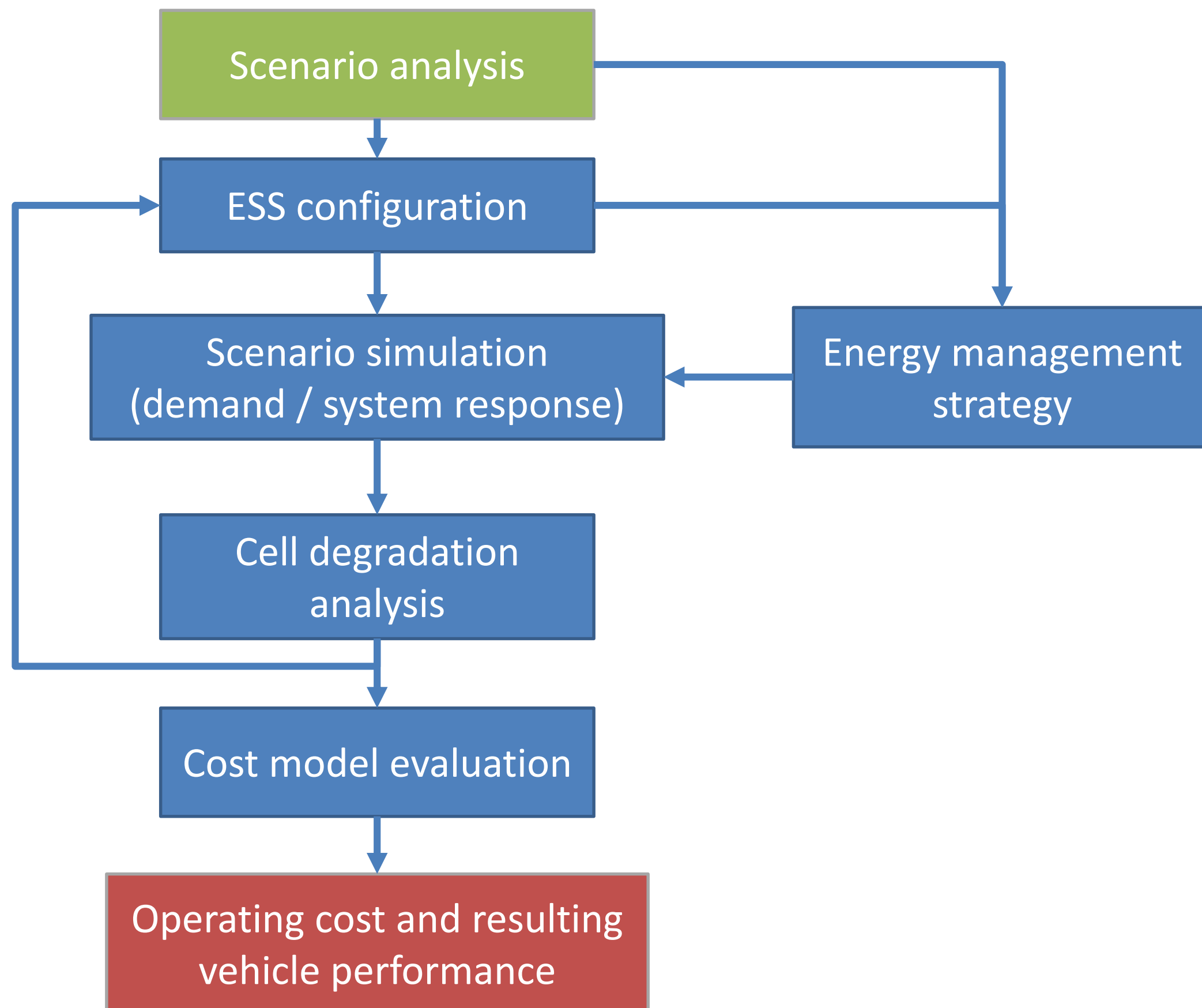
2. Scenario Overview

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Objective Function:

$$\min_{X \in \Omega} C_{Op_TC}(X) = [BT_{TC}(X), SC_{TC}(X), Cat_{TC}(X), CB_{ic}(X)]$$

ESS costs

Energy from
catenary

Lost energy in
crowbar

- Objective functions are **competitive and conflictive**
- There is no global optimal solution
- Optimized via Genetic Algorithms (GA)
- Population “evolves” towards a set of optimal solutions

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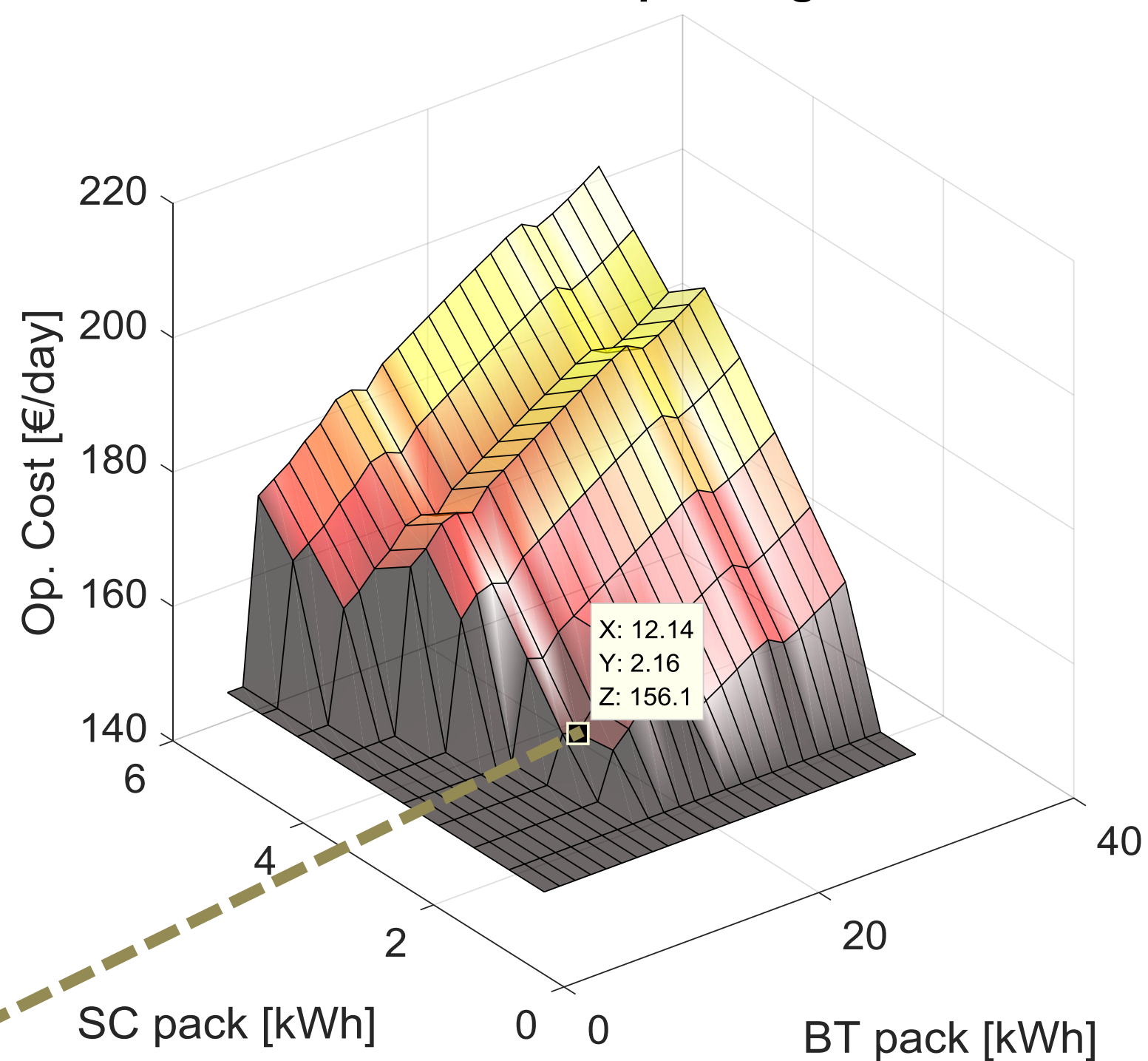
5. Results

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Results comparison:

Whöler curve based BT ageing model

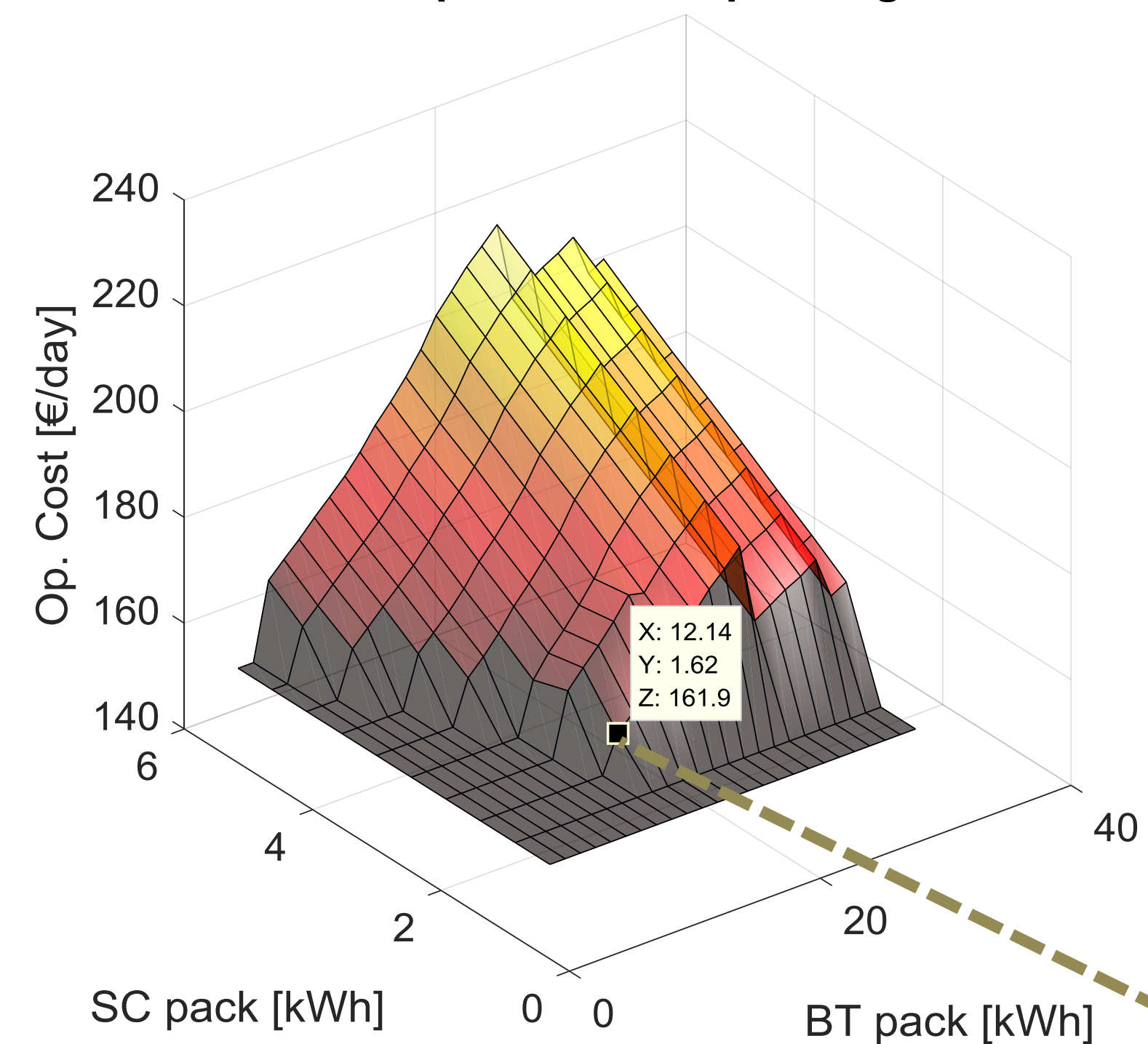
Whöler Total operating cost



X: 12.14
Y: 2.16
Z: 156.1

Semi-Empirical BT ageing model

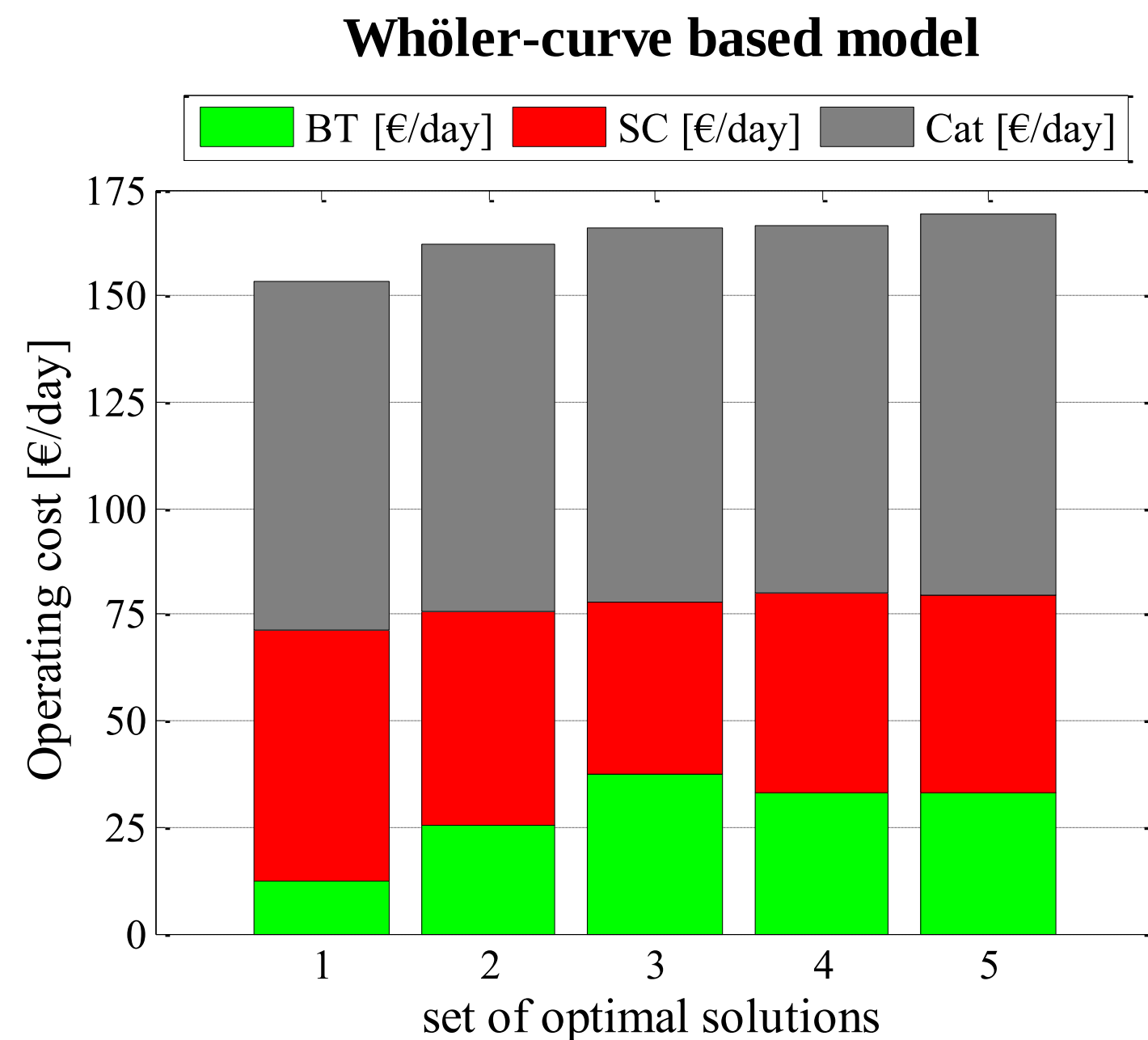
Semi-empirical Total operating cost



X: 12.14
Y: 1.62
Z: 161.9

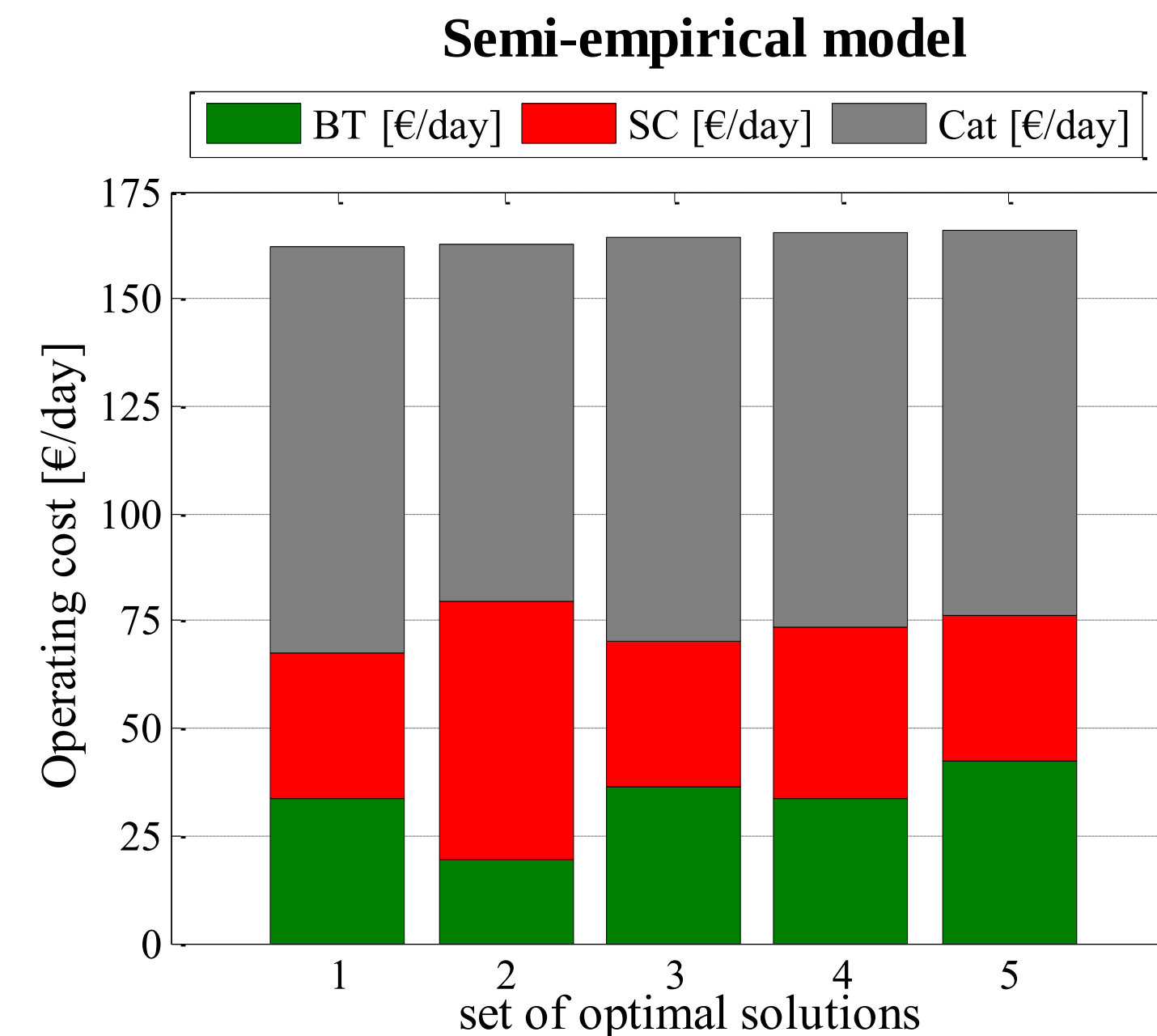
Results comparison:

Whöler curve based BT ageing model



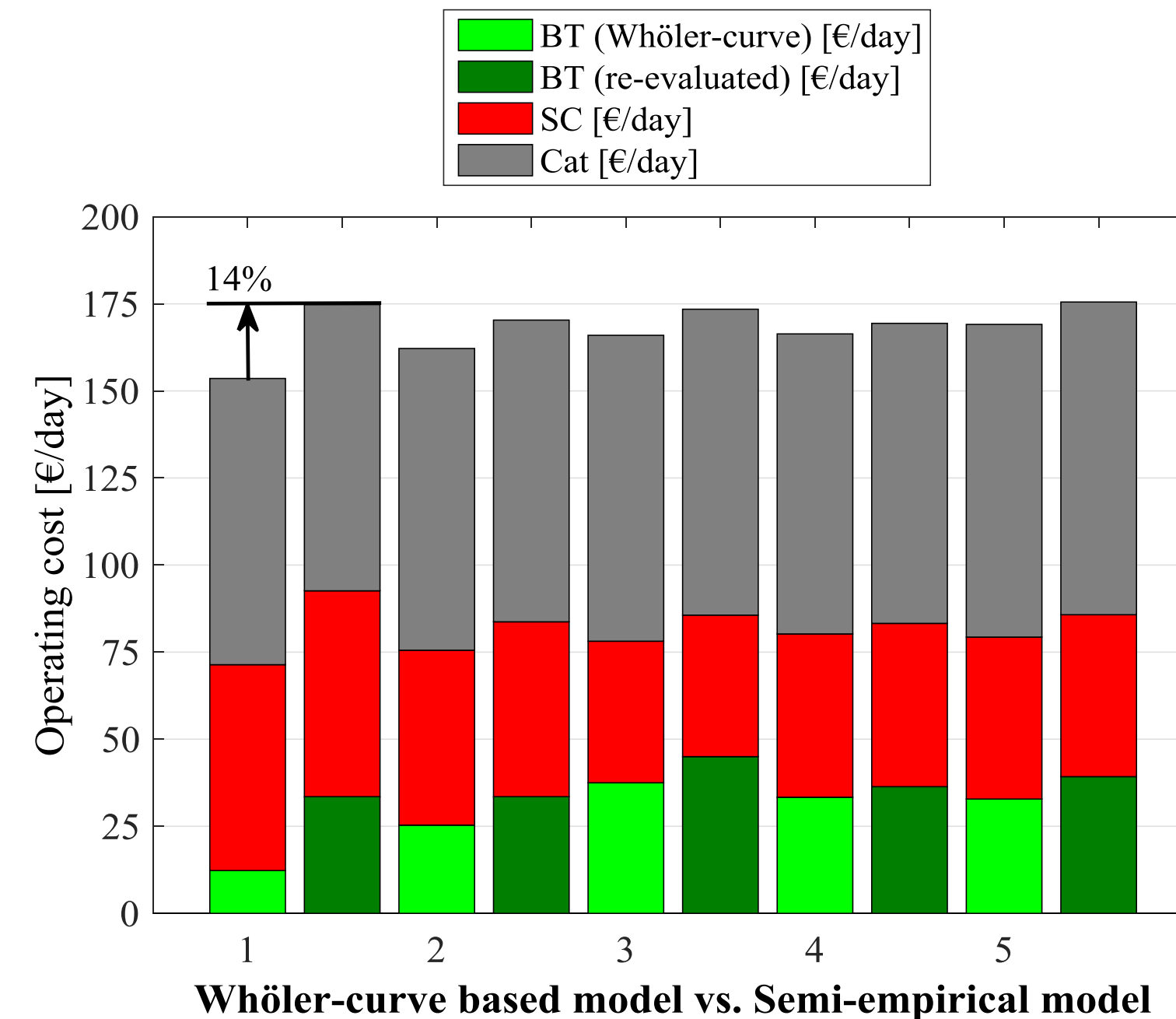
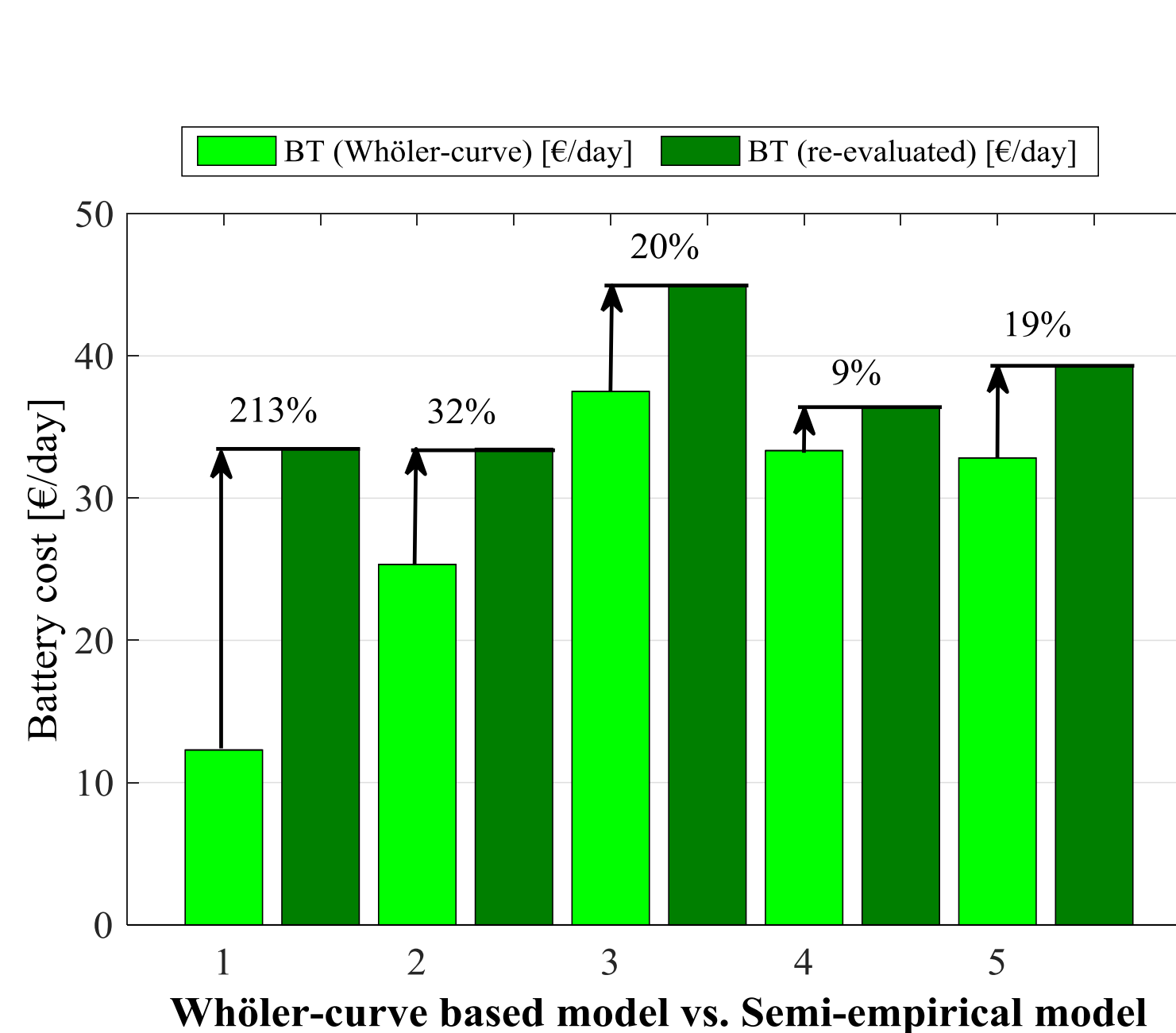
- Solution # 1 = Selected optimal solution
- Very low battery costs due to large battery lifetime est.
- Total costs = 156.1 €/day

Semi-Empirical BT ageing model



- Solution # 1 = Selected optimal solution
- Larger battery costs compared to Whöler curve sizing.
- Total costs significantly larger = 161.9 €/day

Results re-Evaluation:



- Results from Whöler curve based optimization re-evaluated with Semi-empirical ageing model.
- Battery costs due to overestimated battery lifetime underestimated
- Total costs increase by 14% vs the optimal costs expected.

- Real costs of Whöler curve based model opt.
= 174.81 €/day
- Real costs of Semi-Empirical model based opt.
= 161.9 €/day
- Savings = c.a. 47.000€ over 10 year lifetime

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How battery lifetime prediction affects optimal ESS sizing?



- Two main ageing models were compared for the sizing of a Hybrid-ESS .
- Battery ageing model accuracy significantly affects optimal sizing calculation.
- Tramway application: Using an accurate model supposed 8% savings on ESS costs in the scenario analyzed.
- Still to be evaluated the combined impact of accurate modeling of battery and supercapacitor lifetime.
- Results to be validated experimentally. Good battery ageing model accuracy.

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Muchas gracias

Merci beaucoup

Thank you

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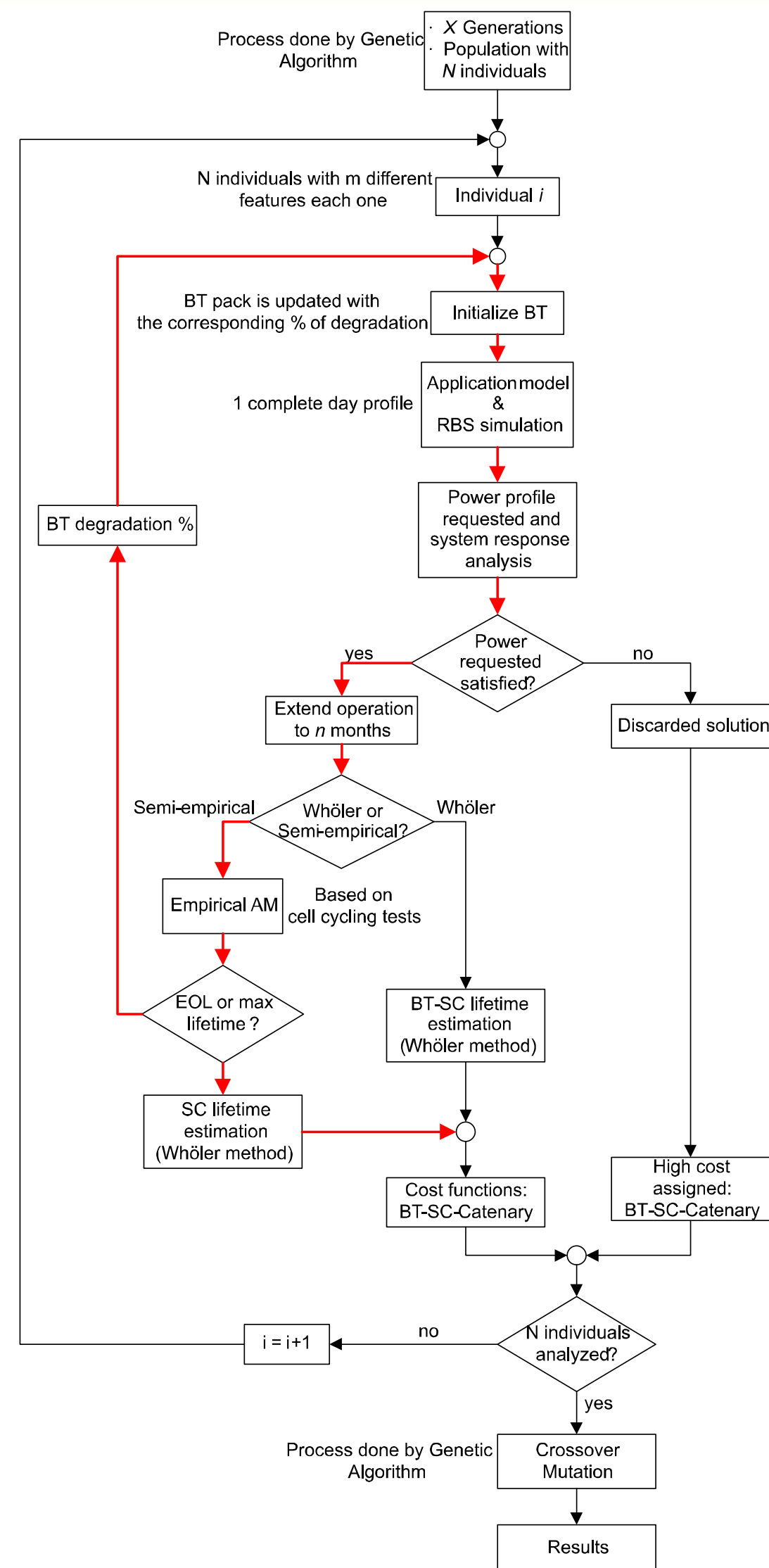
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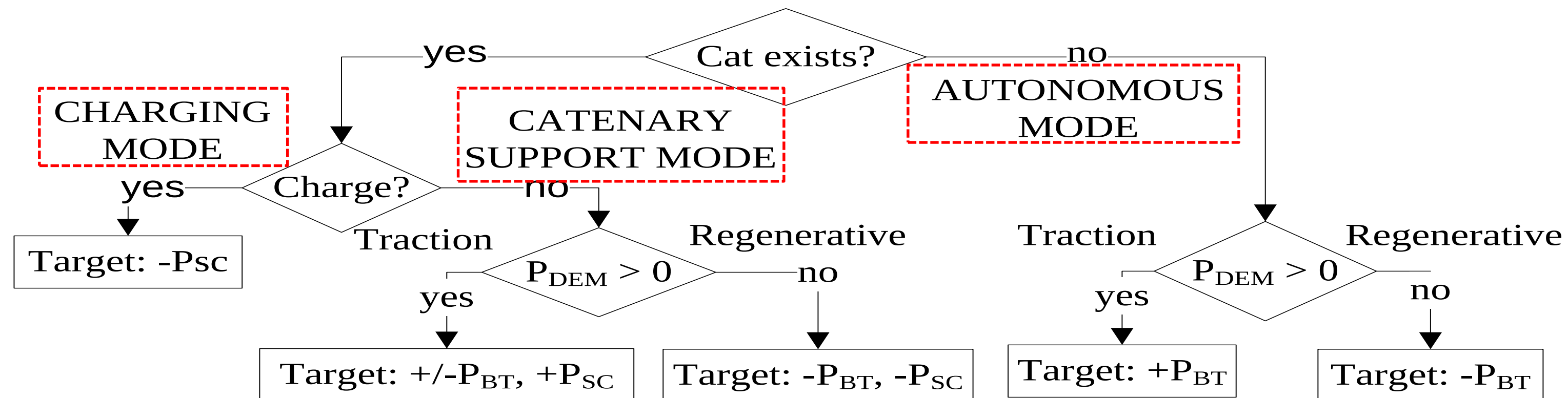
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P_{DEM} : power demanded P_{BT} : battery power P_{SC} : supercap. power



Power balance: $P_{DEM} = P_{BT} + P_{SC} + P_{CAT} + P_{CB} [kW]$

Energy charging mode

- o stopped at a station before entering into a catenary-less zone
- o **SC**: charged with a power control strategy
- o **BT**: is not charged

Catenary support mode

- ESS plays a double role:
- o **SC**: peak-power regulation (acceleration or regenerative braking)
 - o **BT**: energy supply assistance for traction and/or storing energy

Autonomous mode

- ESS must fulfill the energy and power needs during the travel:
- o **BT**: average energy demand
 - o **SC**: peak-power regulation

$$\min_{X \in \Omega} C_T(X) = [BT_{Tcost}(X), SC_{Tcost}(X), GRID_{Tcost}(X)]$$

$$BT_{Tcost} = (BT_{M_y} + BT_{Ca_y} + BT_{Re_y})/360$$

$$BT_{Ca_y} = (C_{kW_{PC}} \cdot P_{PC_{BT}} + C_{kWh_{BT}} \cdot Ca_{BT}) \cdot CRF$$

$$CRF = \frac{I \cdot (1 + I)^T}{(1 + I)^T + 1}$$

$$BT_{Re_y} = \sum_{k=1}^n (1 + I)^{-k \cdot Life_{BT}} \cdot C_{kWh_{BT}} \cdot Ca_{BT} \cdot CRF$$

$$GRID_{Tcost} = \sum_{i=1}^N (P_{CAT}(i) \cdot C_{kWh_g}/3600) [\text{€/day}]$$

$$LL_i = \frac{NE_i}{NE_i^{max}}$$

$$LL = \sum_i LL_i$$

$$Lifetime = \frac{1}{LL}$$

Whöler curve based ageing model

$$Q_{loss_{cal}} [\%] = \alpha_1 \cdot e^{\beta_1 \cdot T^{-1}} \cdot \alpha_2 \cdot e^{\beta_2 \cdot SOC} \cdot t^{0.5}$$

$$Q_{loss_{cyc}} [\%] (10\% \leq DOD \leq 50\%) \\ = (\gamma_1 \cdot DOD^2 + \gamma_2 \cdot DOD + \gamma_3) \cdot k \cdot Ah^{0.87}$$

$$Q_{loss_{cyc}} [\%] (10\% > DOD > 50\%) \\ = (\alpha_3 \cdot e^{\beta_3 \cdot DOD} \cdot \alpha_4 \cdot e^{\beta_4 \cdot DOD}) \cdot k \cdot Ah^{0.65}$$

$$Q_{loss} [\%] = Q_{loss_{cal}} + Q_{loss_{cyc}}$$

Semi-Empirical ageing model