Degradation and Operation-Aware Framework for the Optimal Siting, Sizing and Technology Selection of Battery Storage*

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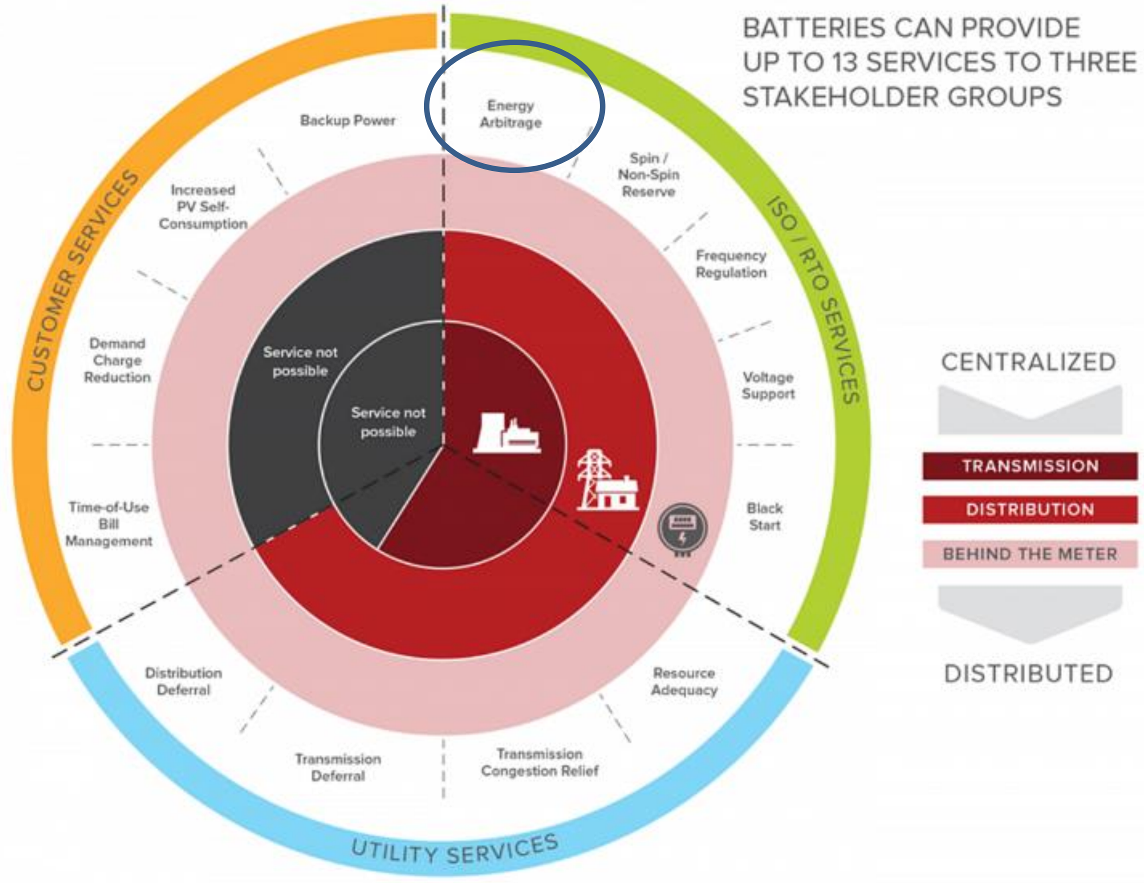
What this talk is about

- Interdisciplinary problem: combination of power systems, battery technology and maths
- I am a power system engineer, not a technologist: Energy System Storage (ESS) is a black box with certain characteristics
- Aim: use ESS to reduce the cost of operation
- Novelty: take into account degradation, i.e. capacity fade, due to Depth of Discharge (DoD) and average State of Charge (SoC), and variable End of Life (EoL)
- Investment problem :
  - Optimal choice of site, size and technology of ESS wrt optimal power system operation (minimal cost)
  - End of Life (EoL) is now not a fixed value but a variable depending on operation: a trade-off between CAPEX and OPEX
- Non-linear, non-convex optimisation problem so no standard solver can guarantee globally optimal solution
- Solution: Mixed Integer Convex Programming (MICP) reformulation

Functions of Energy Storage

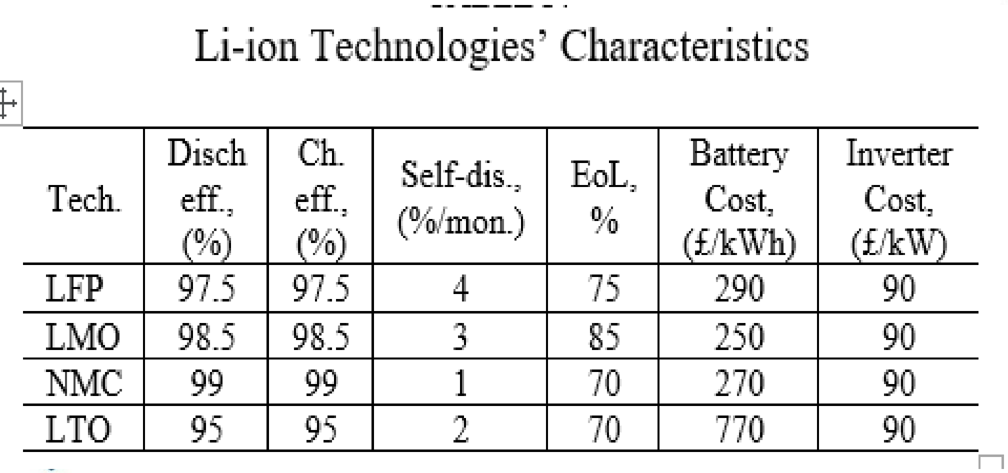
- Here: energy arbitrage
- Charge when the price is low, discharge when the price is high
- Roughly half of the possible revenue stream



Credit: Rocky Mountain Institute, 2015

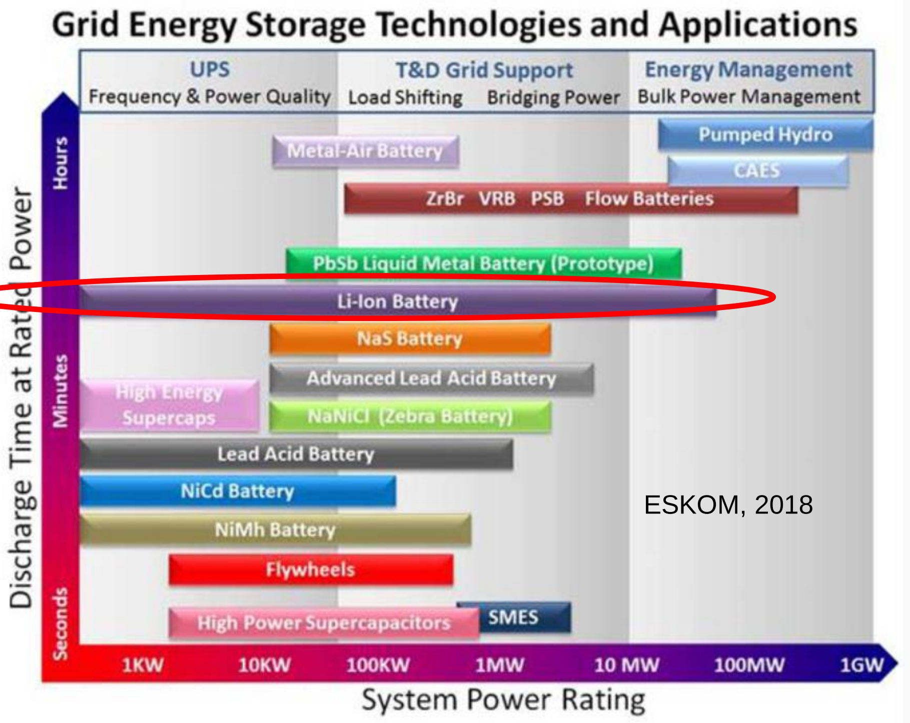
Technologies considered

- Li-Ion:
  - $LiFePO_4$ (LFP),
  - $LiMn_2O_4$ (LMO),
  - $LiNiMnCoO_2$ (NMC),
  - $Li_4Ti_5O_{12}$ (LTO).



Li-ion Technologies' Characteristics

Tech.	Disch eff., (%)	Ch. eff., (%)	Self-dis., (%/mon.)	EoL, %	Battery Cost, (£/kWh)	Inverter Cost, (£/kW)
LFP	97.5	97.5	4	75	290	90
LMO	98.5	98.5	3	85	250	90
NMC	99	99	1	70	270	90
LTO	95	95	2	70	770	90



ESKOM, 2018

Degradation model

- Integral decrease of energy capacity due to idling and cycling due to
  - Time
  - Cell temperature
  - Charging/discharging current (C-rate)
  - Average state of charge (SoC)
  - Depth of Discharge (DoD)
- Idling degradation: time, SoC, temperature
- Cycling degradation: number of cells, cell temperature, cycle depth, average SoC, C-rate

TABLE I

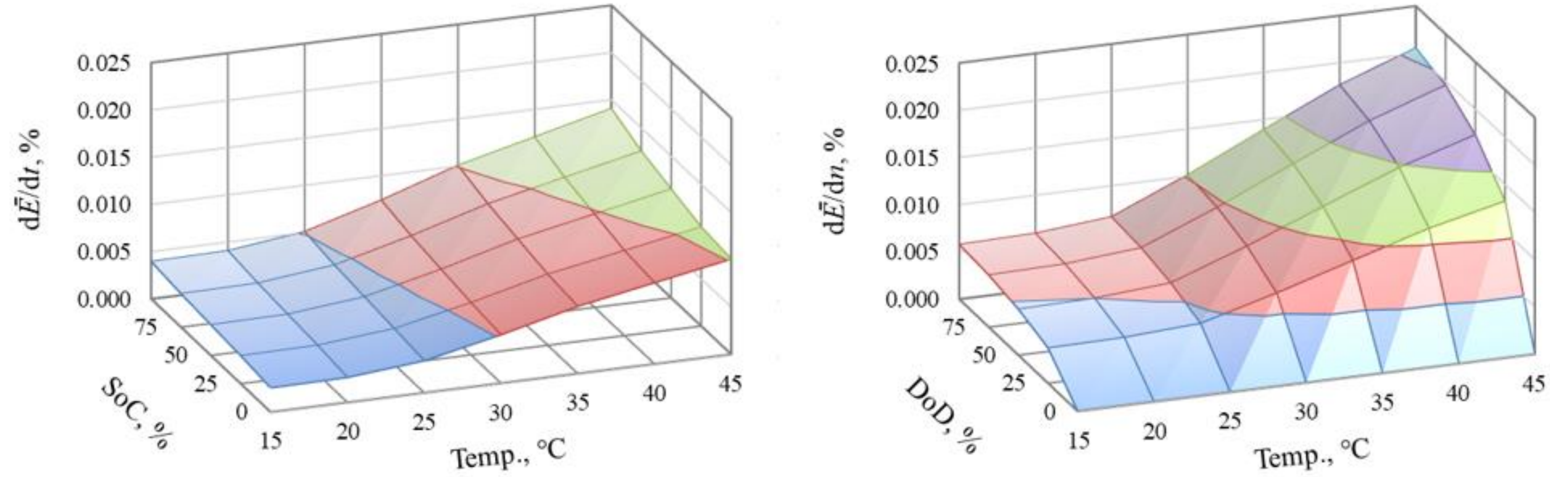
Idling Degradation Data

j	Technology	A_j^{Idl}	B_j^{Idl}	C_j^{Idl}
1	LFP	6.02E-06	1.35E-05	1.85E-05
2	LMO	6.81E-05	4.02E-05	1.63E-05
3	NMC	8.07E-06	3.41E-06	2.83E-05
4	LTO	3.03E-06	2.81E-05	5.02E-06

TABLE II

Cycling Degradation Data

j	Technology	A_j^{Cyc}	B_j^{Cyc}
1	LFP	-4.72E-05	9.62E-05
2	LMO	-1.21E-04	4.01E-04
3	NMC	-4.05E-05	1.01E-04
4	LTO	-1.57E-05	4.40E-05



(a) Idling

(b) Cycling at C-rate ≤ 1

Fig. 1. Energy capacity fade rate characteristic of Li-ion NMC technology

$$\gamma^{\mathrm{Idl}}(SoC_{j,k}) = \mathrm{A}_j^{\mathrm{Idl}} \cdot SoC_{j,k}{}^2 + \mathrm{B}_j^{\mathrm{Idl}} \cdot SoC_{j,k} + \mathrm{C}_j^{\mathrm{Idl}} \qquad (1)$$

$$\gamma^{\mathrm{Cyc}}(DoD_{j,k,n}) = \mathrm{A}_j^{\mathrm{Cyc}} \cdot DoD_{j,k,n}{}^2 + \mathrm{B}_j^{\mathrm{Cyc}} \cdot DoD_{j,k,n} \qquad (2)$$

Optimisation problem

- Reduction of operation costs over a lifetime of ESS minus investment cost

Total generation cost

$$\min \sum_{s \in S} \pi_s \sum_{t \in T} \left[\sum_{i \in I} \left(\mathrm{A}_i^{\mathrm{G}} {P_{s,i,t}^{\mathrm{G}}}^2 - \mathrm{B}_i^{\mathrm{G}} P_{s,i,t}^{\mathrm{G}} \right) + \sum_{km \in Br} \left(F_{s,km,t}^2 \frac{\mathrm{R}_{km}}{\mathrm{V}_{km}^2} \mathrm{C}_{\mathrm{APL}} \right) \right] \Delta t + \sum_{k \in K} \sum_{j \in J} \frac{\bar{E}_{j,k}^{\mathrm{ES}} \mathrm{C}_j^{\mathrm{E}} + \bar{P}_{j,k}^{\mathrm{ES}} \mathrm{C}_j^{\mathrm{P}}}{365\, \mathrm{T}_j^{\mathrm{Lt}}}, \tag{3}$$

Transmission losses

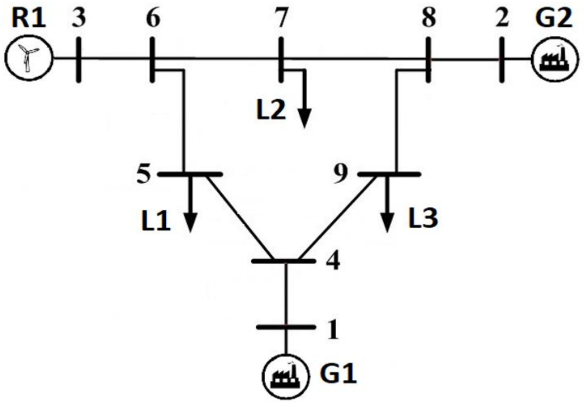
Investment cost

- Variables: output of generators, voltage angles, power flows, power output of ESS, rated capacity of each ESS, operational strategy of each ESS (SoS, DoD), capacity fade reserve
- Constraints: generation constraints, environmental constraints (wind availability), nodal power balances, thermal line limits, energy storage continuity constraint, ESS rating due to capacity fade, capacity fade reserve (less than EoL),

Mixed Integer Convex Problem (MICP) formulation

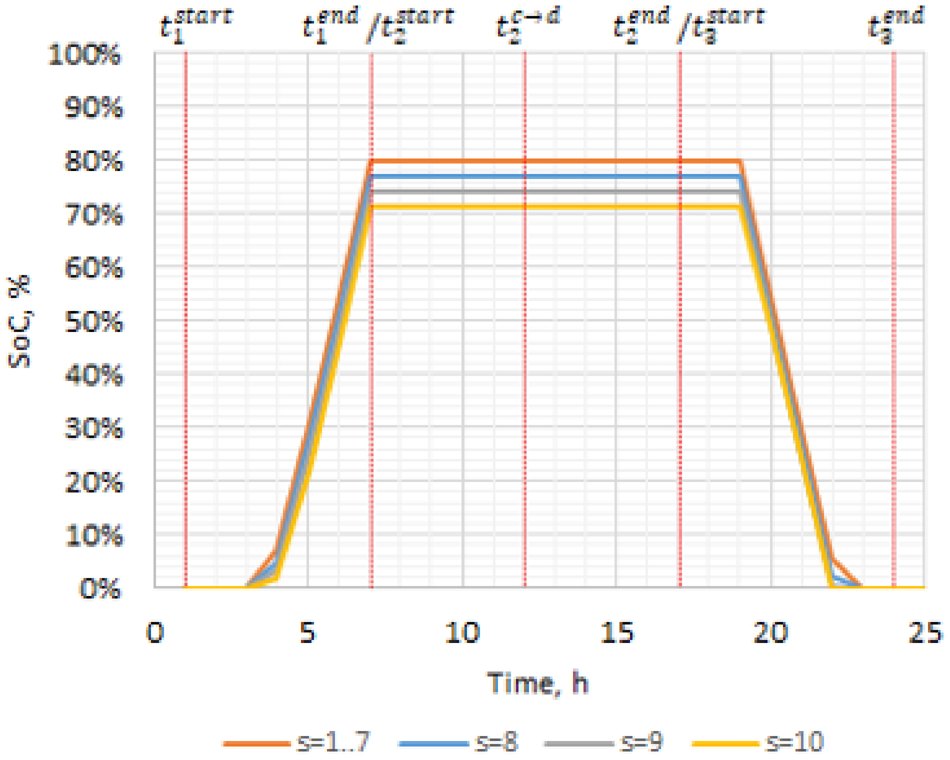
- The optimisation problem is non-linear and non-convex – standard numerical approaches fail
- Substitute continuous variables SoC and DoD which are the cause of non-convexity with integer variables
- Nonconvex continues problem becomes MICP which is convex for fixed SoC and DoD
- That would require a whole enumeration which is computationally prohibitive
- Apply Branch and Bound algorithm - partial enumeration procedure employing tests of feasibility and comparison to an incumbent solution to fathom candidate problems

Case Study



- Four Li-ion technologies: LFP, LMO, NMC, LTO
- 10 year demand and wind data from Customer-Led Network Revolution project
- We account for charge/discharge efficiencies, self-discharge rate, EoL criterion, the investment costs for battery capacity and inverter power rating.

Example of SoC in bus 5

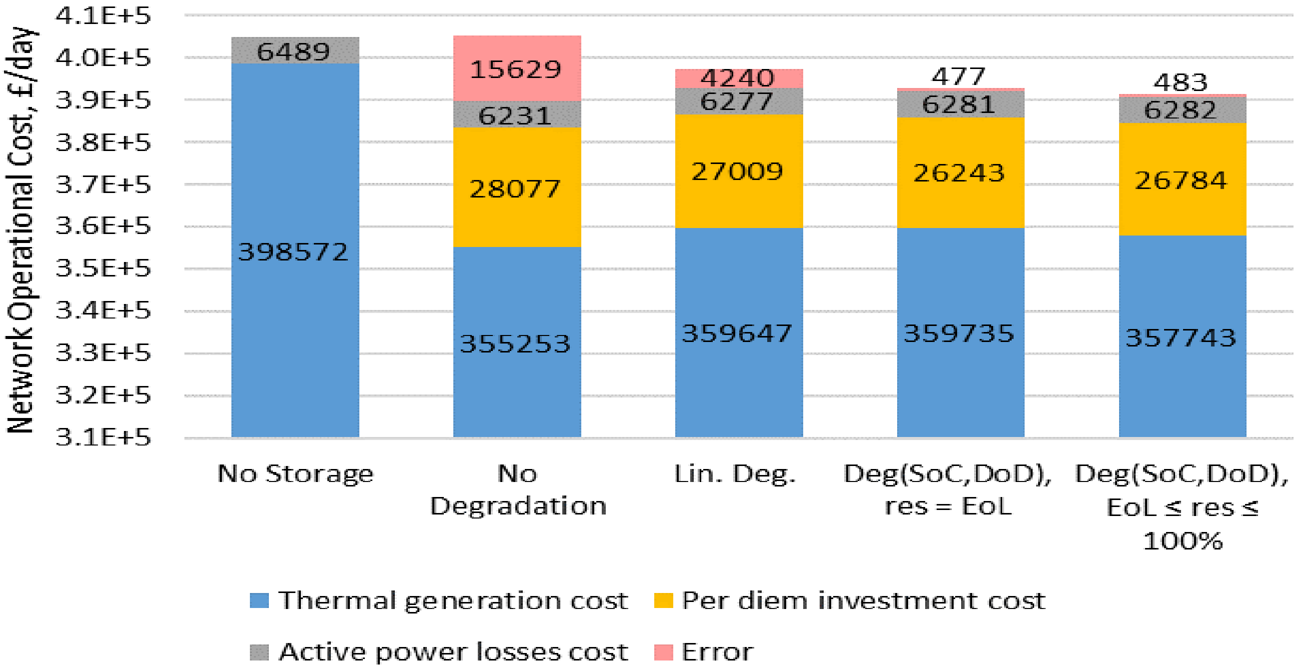


s - year

Comparison of 5 methodologies

1. No storage
2. Storage with no degradation
3. Degradation as a linear function of energy throughput and constant capacity fade = End of Life (EoL) criterion
4. Degradation considered as a function of DoD and SoC but capacity fade reserve = EoL criterion
5. Proposed approach - degradation considered as a function of DoD and SoC and capacity fade reserve is a variable in the optimisation problem

Comparison of results



- Error - accurate post-process degradation-aware simulation applied for the obtained solutions

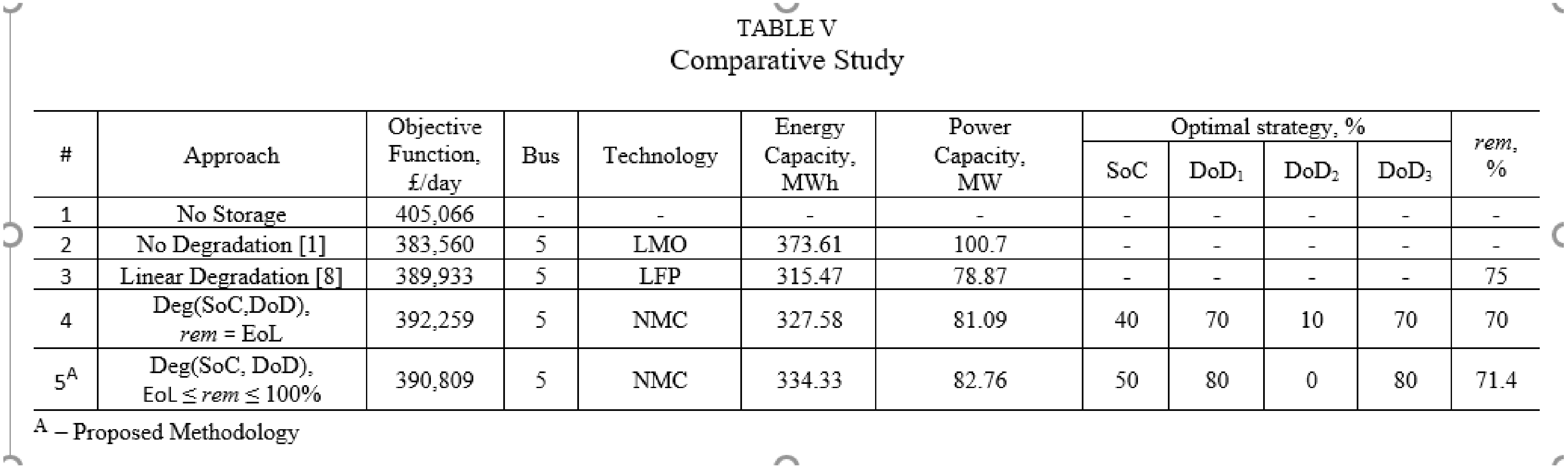


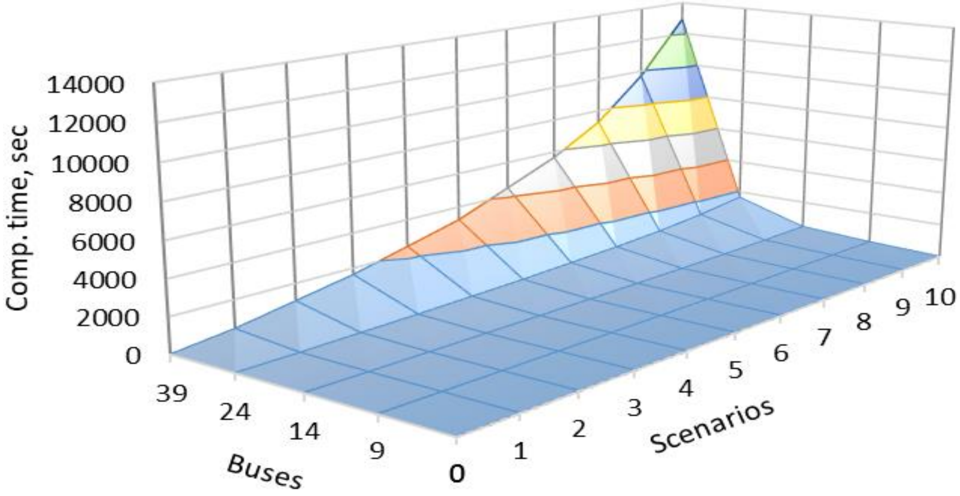
TABLE V
Comparative Study

#	Approach	Objective Function, £/day	Bus	Technology	Energy Capacity, MWh	Power Capacity, MW	Optimal strategy, %				*rem*, %
							SoC	DoD_1	DoD_2	DoD_3	
1	No Storage	405,066	-	-	-	-	-	-	-	-	-
2	No Degradation [1]	383,560	5	LMO	373.61	100.7	-	-	-	-	-
3	Linear Degradation [8]	389,933	5	LFP	315.47	78.87	-	-	-	-	75
4	Deg(SoC,DoD), *rem* = EoL	392,259	5	NMC	327.58	81.09	40	70	10	70	70
5^A	Deg(SoC, DoD), EoL $\leq$ *rem* $\leq$ 100%	390,809	5	NMC	334.33	82.76	50	80	0	80	71.4

^{A} – Proposed Methodology

The final capacity of the battery at the end of its service lifetime was 1.4% higher than the EoL threshold and

The profitability of the ESS throughout its lifetime was 11.7% higher then in the case when EoL criterion is imposed at the end of the service lifetime



Scalability

- The number of scenarios affects the convex part of the optimization problem
  - polynomial-time dependent on the number of variables - moderate growth along the number of scenarios axis.
- The number of considered buses affects the combinatorial part of the problem,
  - substantial effect on computational time - a rapid increase along the number of buses axis.

Conclusions

- An interesting problem illustrating the need for interdisciplinary research combining power systems, battery technology and maths
- A new battery degradation formulation for use in the optimal siting, sizing, and technology selection of Li-ion battery storage.
- The degradation model has been reformulated to embed it within the optimization problem.
- The resulting optimization problem became nonconvex so it has been reformulated to MICP problem by substituting continuous variables that cause nonconvexity with discrete ones.
- Solution using the Branch-and-Bound algorithm along with convex programming, which perform an efficient search and guarantee the globally optimal solution.

- The developed methodology has been compared to four other approaches to evaluate the effect of the proposed degradation model, particularly considering the degradation as a function of SoC and DoD.
- The proposed methodology performs more rigorous techno-economic assessment by taking into account degradation from both cycling and idling.
- There is a trade-off between idling and cycling degradation mechanisms, when the more profitable solution corresponds to battery operation ensuring slower degradation.
- Profitability of the ESS throughout its lifetime was 11.7% higher then in the case when EoL criterion is imposed at the end of the service lifetime