**Emerging supply chain of utilising electrical vehicle retired batteries in distributed energy systems**

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This Supplementary Information include (1) all the parameters adopted in the modelling framework, (2) the detailed validation procedure of the entire framework, (3) verification of the optimal results with previous research.

# SI 1 – Input parameters

The parameters in the modelling framework are defined in Table S1.

Table S1 A list of parameters applied in the modelling framework

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | Definitions | Value | Ref. |
| CEV | Cost of EV sector for reassembling the retired battery [$/kWh] | 27 | 1 |
| benefitVM | Benefit of D&R sector for recovering valuable material [$/kWh] | 13.5 | 1 |
|  | Unit capital cost of CHP [$/kW] | 1,000 | 2 |
|  | Unit capital cost of boiler [$/kW] | 60 | 2 |
|  | Unit capital cost of electric chiller [$/kW] | 120 | 2 |
|  | Unit capital cost of absorption chiller [$/kW] | 170 | 2 |
|  | Unit capital cost of heat pump [$/kW] | 140 | 2 |
|  | Unit capital cost of PV panel [$/kW] | 650 | 2 |
|  | Unit capital cost of heating and cooling network [$/m] | 200 | 3 |
|  | Unit capital cost of new battery storage [$/kWh] | 400 |  |
|  | Unit capital cost of cooling storage tank [$/kWh] | 35 | 3 |
|  | Capital cost of energy saving strategy *s’* by option *k’* at building *i* [$] | See Table S3 and S4 |  |
| *DXi,j* | Distance between buildings | See Table S2 |  |
| *η*CHP | Efficiency of CHP (ele) | 0.35 | 2 |
| H-to-P | Heat-to-power rate of CHP | 0.9 | 2 |
| *η*b | Efficiency of boiler | 0.85 | 4 |
| *η*ec | Efficiency of electric chiller | 4 | 4 |
| *η*ac | Efficiency of absorption chiller | 1.2 | 4 |
| *η*hp | Efficiency of heat pump | 2.5 | 4 |
| *η*pv | Efficiency of PV panel | 0.14 | 4 |
| *η*in-st | Efficiency of storage self-discharge for battery / cooling | 0.98 / 0.9 | 4 |
| *η*cha/disc | Efficiency of storage charge/discharge for battery / cooling | 0.93 / 0.9 | 5 |
|  | Unit cost of natural gas for CHP [$/kWh] | See Fig. 3 | 6 |
|  | Unit cost of natural gas for boiler [$/kWh] | See Fig. 3 | 6 |
|  | Maintenance cost of CHP [$/kWh] | 0.003 | 4 |
|  | Maintenance cost of boiler [$/kWh] | 0.0003 | 4 |
|  | Maintenance cost of electric chiller [$/kWh] | 0.001 | 4 |
|  | Maintenance cost of absorption chiller [$/kWh] | 0.001 | 4 |
|  | Maintenance cost of heat pump [$/kWh] | 0.001 | 4 |
|  | Maintenance cost of PV panel [$/kWh] | 0.003 | 4 |
|  | Maintenance cost of battery storage [$/kWh] | 0.003 | 4 |
|  | Maintenance cost of cooling storage [$/kWh] | 0.0003 | 4 |
|  | Unit price of grid electricity purchasing at hour *h* [$/kWh] | See Fig. 3 | 6 |
|  | Tariff for electricity sold back to grid at hour *h* [$/kWh] | See Fig. 3 | 6 |
|  | Heating demand in zone *i* at season *s* and hour *h* | See Fig. 3 | 6 |
|  | Cooling demand in zone *i* at season *s* and hour *h* | See Fig. 3 | 6 |
|  | Heating demand saved in building *i* by energy saving strategies *s’* via option *k’* | See Table S4 | 7 |
|  | Cooling demand saved in building *i* by energy saving strategies *s’* via option *k’* | See SI Table S4 | 7 |
| *Lo*c-pipe | Cooling network thermal loss rate | 6% | 8 |
| *Lo*h-pipe | Heating network thermal loss rate | 5% | 8 |
| *SRIs,h* | Solar Radiation index at season *s* and hour *h* | See Fig. 3 | 9 |

More details of the case study are presented here. Table S2 specifies the distances among buildings in line with Fig. 3d.

Table S2 Distances among buildings in the case study

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Building No. | b1 | b2 | b3 | b4 | b5 | b6 |
| b1 | - | 200 | 292 | 304 | 250 | 269 |
| b2 |  | - | 245 | 383 | 424 | 463 |
| b3 |  |  | - | 206 | 364 | 532 |
| b4 |  |  |  | - | 212 | 447 |
| b5 |  |  |  |  | - | 255 |
| b6 |  |  |  |  |  | - |

The building categories and roof/wall/window surface areas of six buildings in the case study are presented in Table S3.

Table S3 Basic information of buildings in the case study

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Building No. | Building Type | Roof surface area [m2] | Wall surface area [m2] | Window surface area [m2] |
| b1 | Hotel | 2,000 | 8,235 | 5,765 |
| b2 | Recreation | 5,000 | 5,294 | 3,706 |
| b3 | Office | 833 | 7,353 | 5,147 |
| b4 | Exhibition | 6,667 | 3,529 | 2,471 |
| b5 | Office | 833 | 7,353 | 5,147 |
| b6 | Recreation | 5,000 | 5,294 | 3,706 |

The unitary cost and saving effects of demand-side building energy saving strategies are listed in Table S4. Each building’s capital cost on demand-side energy saving strategies is defined as the product of selected strategies and corresponding surface area. In addition, the saving effects are measured as the saving rate of original building thermal demands, estimated by the methods presented in Ref. 7,10.

Table S4 Cost and saving effects of different energy strategies in the case study

|  |  |  |  |
| --- | --- | --- | --- |
| Energy saving strategies unitary cost | Basic | Improved | High standard |
| Wall upgrade cost [$/m2] | 9 | 17 | 30 |
| Window upgrade cost [$/m2] | 90 | 140 | 170 |
| Roof upgrade cost [$/m2] | 12 | 24 | 38 |
| Energy saving rate |  |  |  |
| Wall upgrade saving rate | 4% | 5% | 6% |
| Window upgrade saving rate | 4% | 5% | 6% |
| Roof upgrade saving rate | 2% | 3% | 4% |

# SI 2 – Model validation procedure

To keep the entire framework computational tractable and efficient, the non-linear problem of Eq. 2b is linearised by Eq. 23-26 as detailed in **Methods**. Fig. s1(a) illustrates the calculation procedure for *λq* θ*pq* appeared in Eq. 25a, where the number of discrete levels *q* is a user-defined parameter and special order variables (*λq*) are introduced to provide a linear equivalent.

However, a gap still exists between the non-linear term and the linear equivalent, which depends on the number of discrete levels *q*. Hence, the selection of *q* may affect the accuracy of the final results.

To validate the proposed model, the profit fluctuations with different linearisation pieces (*q*) of profit is shown in Fig. s1(b). When the discretisation level *q* is above 25, the results become stable – almost half of the total profit (49%) is allocated to the DES sector, the EV sector shares 45% of the total profit, and the remaining 6% is allocated to the D&R sector. Further details have been reported in the **Case study and optimal solutions** section accordingly.



Fig. s1 Using special order variable to discretise and calculate *θ*EV,*q* with *q* discrete levels (a), model validation with different number of *q* levels (b).

# SI 3– Verification with previous studies

Parameters and assumptions defined in the model may vary significantly, e.g., technical development and price drop of new batteries (assuming 410 US$/kWh in this case), cost of reassemble the retired batteries, economic benefit of the D&R sector, as well as types of stationary applications for various places. Thus, the optimal solutions derived from optimisation, e.g., profit of whole supply chain, market volume, and price of retired batteries are specific to the case study. We compared the sales price of retired batteries (i.e., 138 US$/kWh) obtained in our study with previous research in Table S5. It demonstrates that obtained retired battery price in this case is within a reasonable range.

Table S5 Sales prices od retired batteries in previous research

|  |  |  |  |
| --- | --- | --- | --- |
| No. | Prices | Applications | Ref. |
| 1 | 38~132 US$/kWh | various commercial and industrial applications | 11 |
| 2 | 127 €/kWh | to store surplus power from PV in a Spanish library | 12 |
| 3 | 147 US$/kWh | a PV-hydrogen hybrid energy system | 5 |
| 4 | 363 US$/kWh | a PV combined EV charging station in Beijing | 13 |
| 5 | 107 €/kWh | a residential PV-storage system for peak-shaving in Germany | 14 |

# Supplementary Reference

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