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

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Article

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Abstract

Increasing electric vehicles (EV) penetration leads to significant challenges in EV battery disposal. Reusing retired batteries in distributed energy systems (DES) offers resource-circular solutions. We propose an optimisation framework to model the emerging supply chains and design strategies for reusing the retired EV batteries in DES. Coupling a supply chain profit-allocation model with a DES design optimisation model, the framework maximises the whole chain profit and enables fair profit distribution between three interactive sectors, i.e., EV, DES, dismantling and recycle (D&R) sectors. Our research highlights the system implications of retired batteries on DES design and new modelling insights into incentive policy effectiveness. Our case study suggests significant potential value chain profits (2.65 million US$) achieved by deploying 10.7 MWh of retired batteries in the DES application with optimal retired battery price of 138 US$/kWh. The revenue support on D&R sector is suggested as a promising incentive scheme than tariff support.

Introduction

The electric vehicles (EVs) offer a promising low-carbon solution to decarbonise transport sector[1]. However, the increasing production of EVs (above 5 million at 2020 in China) leads to significant challenges in EV battery disposal[2]. Typically, an EV lithium-ion (Li-ion) battery pack needs to be replaced when its capacity reduces to 80% of its rated capacity due to the safety and performance considerations[3]. The expensive disposal process and low recycling rate (less than 2%) cause environmental concerns e.g., active metals resource depletion[4,5]. Reuse of retired EV batteries for stationary applications e.g., in distributed energy systems (DES), has been suggested as a promising way to catalyse a resource-circular battery industry and create new supply chains for energy storage [6,7]. Such emerging supply chain not only leads to cost benefits for the entire industry, but also offers potential to reduce batteries' environmental impacts by extending life cycle of batteries, or avoidance of new battery production to meet demands for stationary energy sector[8,9].

To promote the reuse of retired EV batteries in stationary applications, global automobile industry leaders have launched initiative projects e.g., BMW in Germany, Nissan in US, Renault in the UK, and BJEV in China[10-12]. This topic has also attracted increasing research attention since 2010[13-15]. Previous studies have explored the retired batteries utilisation in the residential sector (with solar PV panels)[16,17], in commercial EV charging station[18], and industrial applications[19]. The published techno-economic modelling demonstrated the preliminary viability of reusing retired batteries in stationary energy applications[17,20-22].

Despite research efforts placed on evaluation of using retired batteries in stationary applications, several knowledge gaps exist. Modelling of the retired batteries under a generalised DES context beyond "renewable + storage" systems remains largely unexplored; the impacts of utilising retired batteries instead of new batteries on DES technical design has not yet been well understood; few studies are oriented from a whole supply chain perspective, the system implications of retired batteries' price, potential market volume and technology deployment policies deserve a further investigation.

To address knowledge gaps, we propose an integrative framework to model the emerging supply chains and design strategies for reusing the retired EV batteries in DES. By coupling game theory approach[23-25] and DES design optimisation[26-28], the interaction of supply chain nodes, including government agencies, EV and battery manufacturing sectors, DES sectors, and dismantling and recycling (D&R) sectors are modelled. Developing a case study on retired EV battery applications in China, we demonstrate the new insights such modelling framework can generate to inform decision-making on economic and technique aspects of utilising EV retired batteries in DES applications.

Model Framework

We propose a framework integrating a supply chain profit-allocation model with a DES design optimisation model as illustrated in Fig. 1(a). The supply chain profit-allocation model considers the cascade utilisation of retired batteries from the EV sector in the stationary applications for energy storage of the DES sector, and final disposal by the D&R sector. The whole supply chain profits are maximised while considering a fair profit-allocation among sectors, which is achieved by the Nash equilibrium type formulation[29,30] as structured in Fig. 1(b). Here, the fairness is defined as an equilibrium where all sectors involved in the supply chain achieve an acceptable or 'fair' allocation of total supply chain profit. Fig. 1(c) illustrates a DES where the design optimisation model derives the cost-optimal solutions for DES energy network design, system configuration design, and dispatch strategy[31-33] equipped with new or retired batteries for 20-year project lifetime. Beyond the typical "renewable + storage" system, we investigate system implications of utilising either new or retired batteries on the generalized DES design. This has been achieved by developing the DES optimisation model that covers renewable and non-renewable energy sources, energy network and exchange, and supply-demand co-design fulfilling the electricity, cooling and heating demands of a district with multiple buildings.

Eq. (1) defines the profit of each sector (π_{EV}, π_{DES} and $\pi_{\mathrm{D\&R}}$) in line with Fig. 1(b). The profit of EV sector is determined by the capacity of the retired batteries (CAP^{RB}) sold to the DES sector and the value difference between the retired battery sales price ($price^{\mathrm{RB}}$) and corresponding costs for collection & reassembling (C_{EV}). The profit of DES is defined as the energy system cost savings from implementing retired batteries ($C_{\mathrm{DES}}^{\mathrm{RB}}$) instead of new batteries ($C_{\mathrm{DES}}^{\mathrm{NB}}$), and these two costs are optimised by the DES design optimisation model (DES model details in **Method** Section). As for D&R sector, its profit is determined by the capacity of retired batteries (CAP^{RB}) discarded by the DES sector at the end-of-life, multiplied by per unit economic benefit ($\mathrm{benefit}^{\mathrm{D\&R}}$) of final processing and valuable material recovery.

$$\pi_{\mathrm{EV}} = CAP^{\mathrm{RB}} \times (price^{\mathrm{RB}} - \mathrm{C}_{\mathrm{EV}}) \tag{1a}$$

$$\pi_{\mathrm{DES}} = C_{\mathrm{DES}}^{\mathrm{NB}} - C_{\mathrm{DES}}^{\mathrm{RB}} \tag{1b}$$

$$\pi_{\mathrm{D\&R}} = CAP^{\mathrm{RB}} \times \mathrm{benefit}^{\mathrm{D\&R}} \tag{1c}$$

Based on these profits definitions, the ***capacity*** of retired batteries (CAP^{RB}) and sales ***price*** ($price^{RB}$) are two key decision variables that interlink all three sectors. The ***capacity*** of retired batteries sold by EV sector is equal to the capacity installed in DES and the capacity of batteries eventually discarded to the D&R sector at the end-of-life. Hence, the ***capacity*** (CAP^{RB}) represents the potential market volume for the entire supply chain. The sales ***price*** of retired batteries ($price^{RB}$) for EV sector is the same as the capital cost of retired batteries installation for the DES sector. The integrative model optimises these key decision variables with the defined parameters including C_{EV}, $benefit^{D\&R}$ and techno-economic parameters for the DES design model (specified in **Method** section).

The flowchart in Fig 2 illustrates how the components in the modelling framework are interlinked and resolved. In general, the modelling framework simultaneously optimises (1) the cost-efficient energy system design with retired batteries and (2) the fair profit allocation scheme for the modelled supply chain, to determine the optimal market volume and selling price of reusing EV retired batteries, as well as the potential profit of the whole supply chain. All model formulations are detailed in **Method** section.

Case Study And Optimal Solutions

We apply the proposed framework to evaluate the system implications of reusing EV retired Lithium-ion batteries for a DES application in an urban district in Shanghai, China. Six commercial buildings in this district represent a 20-year DES application to fulfilling their cooling, heating, and electricity demands equipped with retired batteries. Fig. 3 shows the model parameterization in accordance with Fig. 2 including energy demands, energy tariffs, locations, etc. Fig. 3a-c demonstrate the typical annual energy demands, which reflect the variation in demand profiles in a typical year. Fig. 3d shows spatial distribution of six buildings, which impact the energy networks. The energy tariffs given in Fig. 3e affect both system design and dispatch strategies to achieve cost optimal system; solar radiation index in Fig. 3f impacts the renewable energy generation from rooftop PV panels. As defined by Eq. 1, the reassemble cost for the EV sector and per unit economic benefit for the D&R sector are two given parameters to determine the key decision variables i.e. the ***capacity*** of retired batteries and sales ***price.***. In this case, we assume the reassemble cost for the EV sector as 27 US$/kWh and the economic benefit for the D&R sector as 13.5 US$/kWh based on the recent market estimation[34,35]. The average capital cost of new batteries was assumed as 410 US$/kWh with a range of 250~670 US$/kWh[36]. The retired batteries are expected to have a lower capital cost than the new batteries; both retired and new batteries were assumed to have similar performance during the DES application, i.e., 93% charging/discharging efficiency and 2% self-discharge rate[3]. However, the retired batteries have shorter lifetime and replacements are required every 5-years during the DES application lifespan[16]. Note that these assumptions, particularly on cost values, are case specific and could be sensitive to future development of battery technologies and recycling technologies.

The model optimizes profit allocation strategy from the market regulation perspective to enable the emerging supply chain of retired EV battery. The optimal solution with the maximum supply chain profit under the fair profit allocation strategy is shown in Fig. 4. The whole supply chain can achieve an overall profit of **2.65 million US$** for this application, in which **D&R**, **EV**, and **DES** sectors account for **6%**, **45%**, and **49%**, respectively. The profit of the EV sector comes from the sales income of the retired batteries. The D&R sector's profit relies on the market volume (i.e., installed capacity) of retired batteries. As for the D&R sector, the larger capacity of retired batteries been adopted in the supply chain, the higher amount of valuable material can recycle for higher profits. The obtained optimal sales price of retired batteries is 138 US$/kWh. The market volume of retired batteries is projected as 10.7 MWh, which is equivalent to reusing the battery pack of approximately 515 hybrid electric passenger car (HEPC), 258 battery electric passenger car (BEPC) or 74 battery electric commercial vehicle (BECV). The optimization solution are derived based on the average energy density of retired batteries, i.e., 75wh/kg (with the range of 60~90wh/kg), average weights of battery pack for HEPC, i.e., 275kg (with range of 150~400kg), BEPC, i.e., 550kg (with range of300~800kg), and BECV, i.e., 1900kg (with range of 800~3000kg)[37].

DES design with retired EV batteries

The lower capital cost by using retired batteries not only directly affects the profit of DES but also leads to different DES designs as shown in Fig. 5(a), which contributes to the profit allocation of DES sector. Due to the lower price of retired batteries than new batteries, a significantly higher capacity of batteries is adopted within the system, i.e., 10.7 MWh of retired batteries compared to 1 MWh of new batteries. Hence, the peak/off-peak electricity tariff, as well as the feed-in tariff, are efficiently utilised to power the district to reduce the DES costs, and also gain more income by selling electricity back to the grid during the peak period. Consequently, the installed capacity of CHP reduces significantly in the retired batteries cases in comparison with new batteries case. The lower capacity of CHP installation further leads to a lower heating supply, which results in an 10% increased investment on energy-saving strategies (i.e., more advanced retrofit options been applied). Thus, the capacity differences of heating/cooling energy supply technologies are insignificant for the two cases under investigation.

The 10.7 MWh capacity of retired batteries not only impacts the design of DES significantly but also influences the operational strategy of DES. Fig. 5(b) illustrates the operational strategy of retired batteries. In the morning, to reduce the self-discharge and fully utilise the off-peak tariff, battery charging happens 2-3 hours before the peak periods (starting from 8 a.m.), and then the batteries discharge the stored electricity during the following 4-5 hours. In the afternoon, the batteries are charged for 2-3 hours with a normal tariff before the evening peak periods (starting from 6 p.m.), then the batteries discharge for DES utilisation over the peak periods.

Trade-off between maximum profit and fairness

The above-mentioned optimal solution is considered as the ***baseline*** case, in which the D&R sector only shares 6% of the total profit, while other two sectors both account for over 40% of total profit. Here we assess the trade-off between fairness and profit maximisation across the value chain. Our model enables evaluating possible scenarios by configuring different profit distributions as shown in Fig. 6(a-c), where constraints are introduced to vary the profit-sharing ratio of a given sector (shown by x axis). The following insights have been generated:

(1) As shown in Fig. 6(a), the maximum of total profit for the D&R sector is achieved in the baseline case, where DES and EV sectors share over 45% of total profit with the remaining 6% profit allocated to the D&R sector. When the D&R sectors' profit is further reduced from 6% to 3%, the lost profits of the D&R sector are not captured by other sectors but result in the decline in total profit for the whole-supply chain. Considering the scenarios on the right-hand side of the baseline case, the profits of both DES and EV sectors decrease significantly to fulfill the constraints of increasing the ***share*** of D&R sector, which leads to the total profit drop. The underlying reason for these observations is that the theoretical maximum profit of the D&R sector is one order of magnitude smaller than that of other sectors based on the profit definitions in this study. Thus, in every scenario, the D&R sector always has reached or almost reached its maximum profit. Hence, to fulfill the constraint of increasing the ***share*** of D&R sector's profit, the total profit of the whole supply chain has to be reduced. Additionally, the price of retired batteries drops with the increase in D&R sector's profit share.

(2) A similar analysis of mandatory profit re-distribution is conducted for DES sector, which leads to different results compared to the D&R sector. Although an increase in the DES sector's profit also leads to a reduction of total profit, the decline is relatively minor compared to the results from the D&R sector. More interestingly, when the DES sector's profit is forced to decline to 40%, the total profit goes up slightly. As the D&R sector tends to reach its maximum profit level, the slight increase in total profit can be attributable to the rising EV sector profit.

(3) Fig. 6(c) suggests that the variation of EV sector's profit ***share*** does not significantly affect the total profit. This can be explained by the variation in EV sectoral profit being efficiently offset by the DES sectoral profit (the D&R sector's profit is still close to its maximum). Two interesting scenarios are marked by red circles in Fig. 6(b and c), which imply the less fair but profit-maximised solutions achieved when EV sector, DES sector and D&R sector account for 55%, 40%, 5% of total profit, respectively. In comparison with the profit-maximisation solution, the baseline case (i.e., EV, DES and D&R sectors account for 49%, 45%, and 6%, respectively) represents a fairer strategy for all supply chain players.

Overall, our results show that a "fairer" profit share scheme could be achieved with the drop of the total supply chain profit; and the trade-off exists between ***achieving a fairer market*** and ***maximised total profit with dominant players***. In the meantime, Fig. 6(a-c) suggest that the price of retired batteries goes up along with the increment of EV sectoral profit and the drop of DES sectoral profit, and vice versa; compared to two other sectors, the D&R sector tends to reach its maximum profit within a narrow range. These observations could inform decision-making on an effective scheme to incentivise this emerging supply chains.

Policy implications

Policy schemes are expected to promote the new technology penetration and regulate the markets[38]. Different technology deployment policies could be summarised and expressed as several key schemes[39], i.e., direct subsidy, revenue support, tax reduction, government loan, tariff support, green product purchasing, and certificate trading gain. Based on the observations in last section, here we present two scenarios to evaluate the effectiveness of revenue support policies for the low-profit D&R sector and the tariff support policies for the DES sector.

(1) Revenue support on D&R sector

The revenue support can enable the D&R sector to obtain extra income from recycling retired batteries, i.e., $benefit^{D\&R}$ goes up. As illustrated in Fig. 7(a), a higher profit share of D&R sector can be expected with the increase in revenue support. More importantly, a rising total profit and a fairer profit share among each player are also observed. When the revenue support reaches 40 $/kWh, the profit shares of the DES sector, EV sector and D&R sector are 45%, 35%, and 20%, respectively. Meanwhile, the price of retired batteries remains around 130 to 150 $/kWh. This scenario suggests that revenue support for the D&R sector contributes to the improvement of total profit and a fairer profit distribution.

(2) Tariff support on DES sector

It is interesting that the tariff support does not boost the total profit or fairness of profit share as expected. Tariff support for DES sector here is defined as a scheme that enables the DES to feed electricity back to national grid at a more competitive price during the peak periods. In fact, increasing the feed-in tariff price contributes to the promotion of ***batteries*** but not for ***retired batteries***. As shown in the third y axis in Fig 7(b), the installed capacity of new batteries increases significantly with the increase in feed-back tariff price. This leads to a higher capacity of new batteries and much lower energy cost of DES. However, based on the profit definition, if the DES energy cost including new batteries is low, the profit of implementing retired batteries declines instead. Hence, the total profit does not increase. Additionally, the price of retired batteries is not significantly affected by the tariff support, varying between 125 and 150 $/kWh.

Discussion

(1) Potential of the retired EV batteries as a resource-circular solution. Coupling game theory approach and DES design optimisation, we modelled the interaction of three sectors involved the emerging supply chain for retired EV battery re-use in urban DES. Our case study on a district with six commercial buildings in China demonstrates that a market volume of 10.7 MWh retired batteries can achieve significant supply chain profit (2.65 million US$). The projected optimal sales price for the retired batteries sales price is 138 US$/kWh, which agrees with the price range reported in previous research (see supplementary Table S5). However, the supply chain profit, market volume and price of the retired EV batteries in this study only represent the insights from a specific case study, which may vary with variation in system parameters e.g. costs of battery reassembling, types of stationary applications.

(2) Impacts on DES design. Our results suggest that retired EV batteries instead of new batteries can lead to significantly different design and operational strategy of DES. Due to the lower cost of retired batteries, the DES will install lower CHP capacity for onsite generation while install higher capacity of batteries and interact with the grid much more actively right before the peak period compared to the case of new batteries. A significant decline in energy cost of the DES can be expected by utilising the retired batteries, which could further be functional for peak shaving.

(3) Trade-off between maximum profit and fairness. By mandatory re-distribute the profit, we found a trade-off between a fairer market and maximised supply chain profit with dominant players. The proposed framework allows quantitative analysis on different profit allocation scenarios. Since the maximum profit of D&R sector (upper limit) is lower than other two upstream sectors, enforcing a "fairer" supply chain may lead to a reduced total profit across the supply chain. Such modelling evidence provides policy insights into key factors to regulate supply chains and enable retired battery adoption.

(4) Policy implications. We develop a tool to understand how policies could promote the industry of utilising retired batteries in DES. The revenue support on D&R sector improves the total supply chain profit and leads to a fairer profit distribution, showing that the revenue support policy has the potential to support the D&R sector breaching its upper limit of profit. The profitability of the supply chain grows with D&R sectoral profits. Although tariff support is regarded as a practical policy to incentivise the market penetration of batteries in stationary applications, it is not effective for the retired batteries. This could be explained by the decrease in marginal cost-savings of retired batteries, as a consequence of tariff support which reduces the cost of using new batteries. These observations not only provide valuable insights but also importantly highlight how the proposed framework can inform policymaking on effective incentive scheme design.

Conclusion And Future Perspectives

The increasing number of electric vehicles (EV) leads to significant challenges in the disposal of EV retired batteries. Under a circular economy context, new supply chains are emerging to reuse the EV retired batteries for stationary DES applications, which enable the multiple sectors to benefit from cost-effective energy supply and battery reuse. To advance the understanding of system implications of retired batteries price, market volume and technology deployment strategies, we present an optimisation framework which integrates a supply chain profit-allocation model with a DES design optimisation model. The developed modelling framework not only optimises supply chain profit and allocation strategies but also captures the design and flexible operation of batteries in DES with hourly temporal resolution.

The case study in Shanghai shows a great potential of reusing the retired batteries in stationary application in urban areas. This has been demonstrated by a significant capacity (10.7 MWh retired batteries) and a supply chain profit of 2.65 million US$ in a 6-building urban district. Our case study also suggests that EV and DES sectors tend to dominate the supply chain profit share by 45% and 49%, respectively, whereas the D&R sector shows the trend reaching its maximum profit. Our modelling results demonstrate that the policy support on the D&R sector has the potential to increase both whole chain profit and profit share fairness. However, the effectiveness of technology deployment policy is worth modelling exploration – the policy incentive for new batteries may not be effective for the retired EV batteries.

Overall, our research presents a mathematical modelling tool to inform decision-making on the emerging supply chain of reusing retired batteries in DES applications. The proposed framework is extensible, which can be further expanded to explore multi-criteria decision-making considering environmental sustainability and economic viability, as well as simulate the interaction and competition between market players.

Methods

Due to technical limitations, the Methods section is only available as a download in the supplemental files section

Declarations

Data availability

The input and output data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

R.J., J.W. and M.G. designed the study. R.J. and J.W. collected the data and built the model. R.J. and M.G. analysed the results. R.J. drafted the paper. N.S. and M.G. edited the paper. M.G. provided the fund.

Declaration of Interests

The authors declare no competing interests.

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Figures

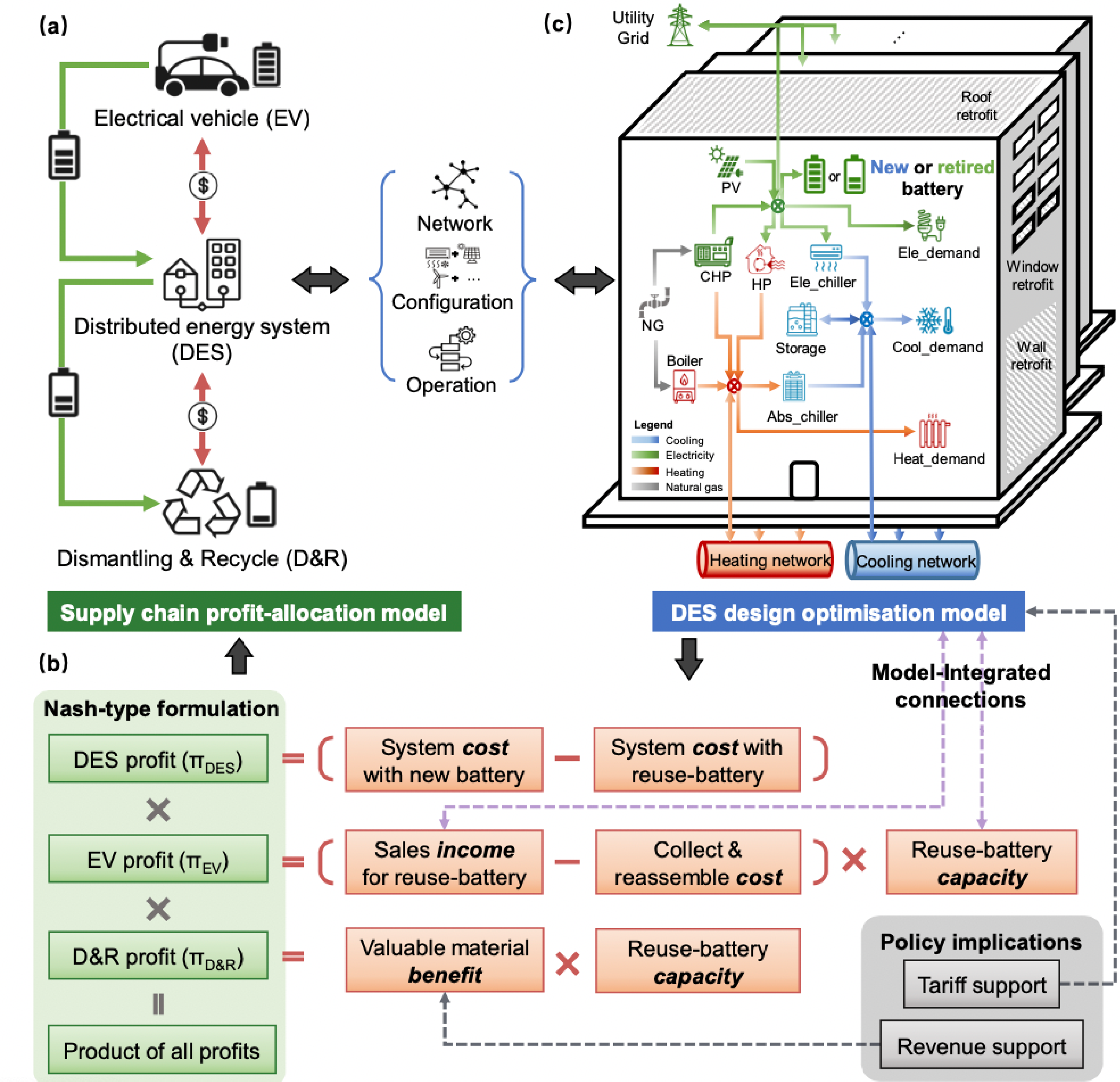


Figure 1

Schematic of the proposed modelling framework for reusing EV retired batteries in DES. (a) shows the integration of the supply chain profit-allocation model with the DES design optimisation model. (b) illustrates the Nash-type formulation structure of the proposed framework with definitions of the profit for each sector, two implementation of incentive policies, and the connections for model integration. (c) illustrates the DES that the design optimisation model can achieve a cost-efficient energy system design that fulfilling electricity, cooling, and heating demand simultaneously. Abbreviation in DES design optimisation model: solar photovoltaic (PV), combined heating and power (CHP), heat pump (HP), natural gas (NG), electrical chiller (ele_chiller), and absorption chiller (Abs_chiller).

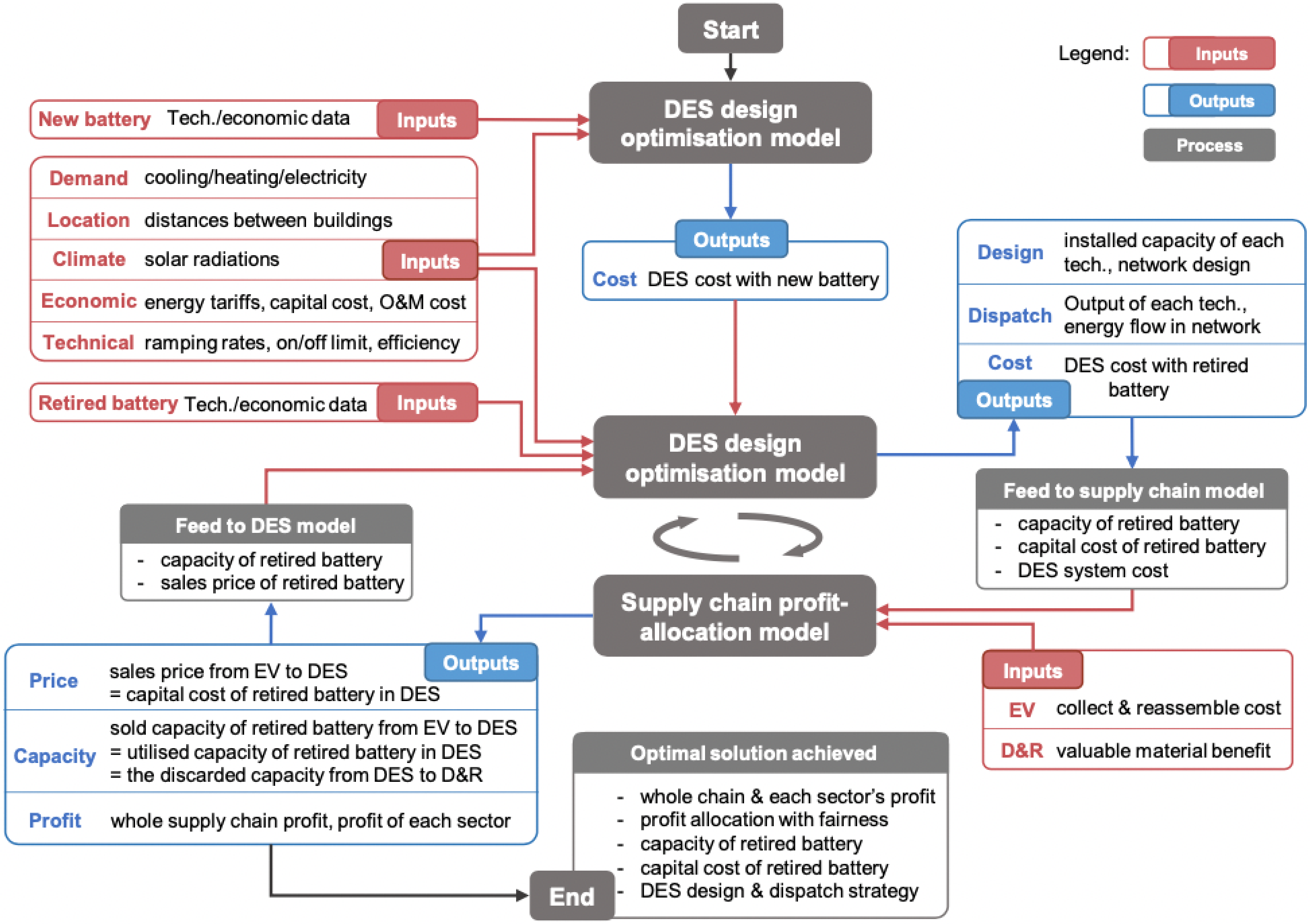


Figure 2

Interlink and workflow of the proposed modelling framework. The overall workflow starts with resolving the DES design optimisation model with the new battery; the optimal DES solution with the new battery is considered as a parameter as defined in Fig. 1(b). Then we optimise the DES design with retired battery, the obtained solutions for installed capacity and capital cost of the retired battery, as well as the DES system cost, are fed into the supply chain profit-allocation model to optimise the profit of the whole supply chain considering profit-allocation fairness. The updated solution on installed capacity and capital cost of the retired battery are fed back to the DES design optimisation model iteratively. Finally, the optimisation loop ends at the Nash equilibrium point with an optimal solution achieved.

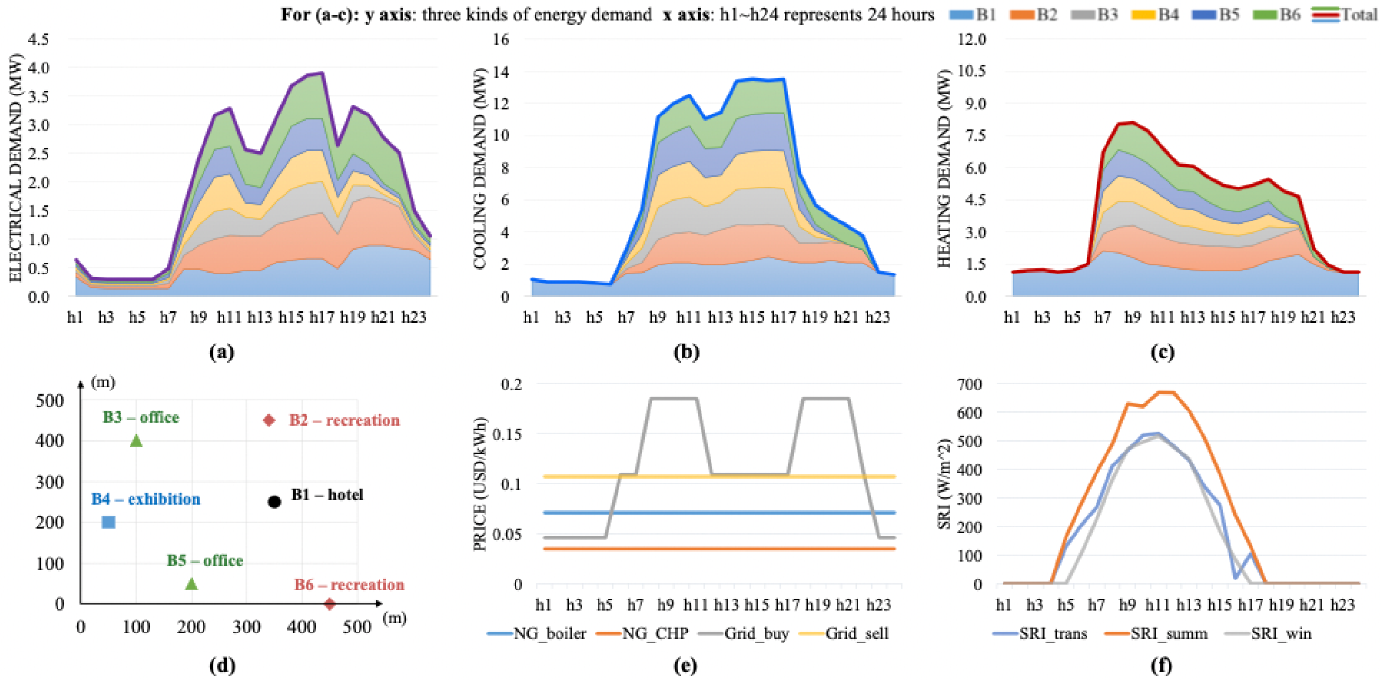


Figure 3

Model parameterization in the case study. (a)-(c) presents the hourly electricity, cooling, and heating energy demand of six buildings (B1~B6), respectively. (d) shows the locations of six buildings with distance measured by meters, which will affect the energy network design and energy exchange among buildings; (e) displays the real-time energy prices, including natural gas for boiler (NG_boiler), natural gas for CHP (NG_CHP), electricity purchased from the grid (Grid_buy), and electricity feed-back to grid (Grid_sell). Note that natural gas price for CHP is lower than that for boilers due to existing incentive policies. (f) shows the solar radiation index (SRI) for different seasons. Each year with the project-life is divided into three representative seasons of transition (trans), summer (summ), and winter (win). Detailed inputs are presented in Supplementary SI-1.

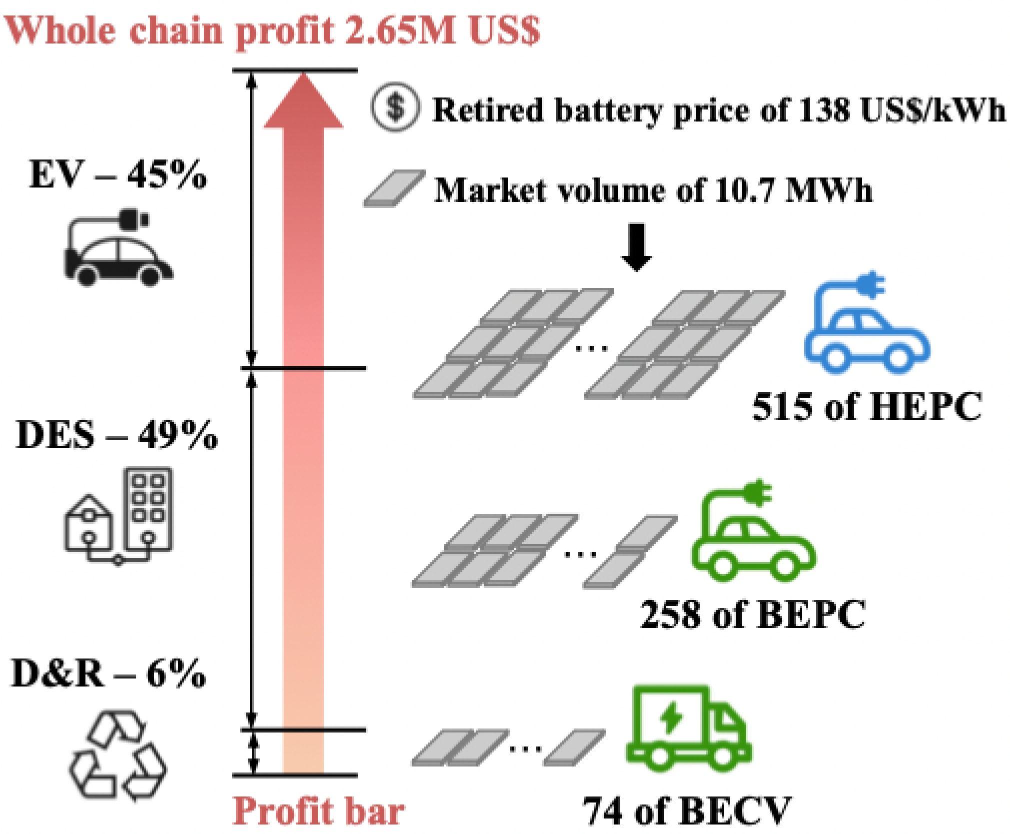


Figure 4

Optimised whole supply chain profit, profit allocation scheme, retired battery price, and market volume of retired battery been utilised in the case study.

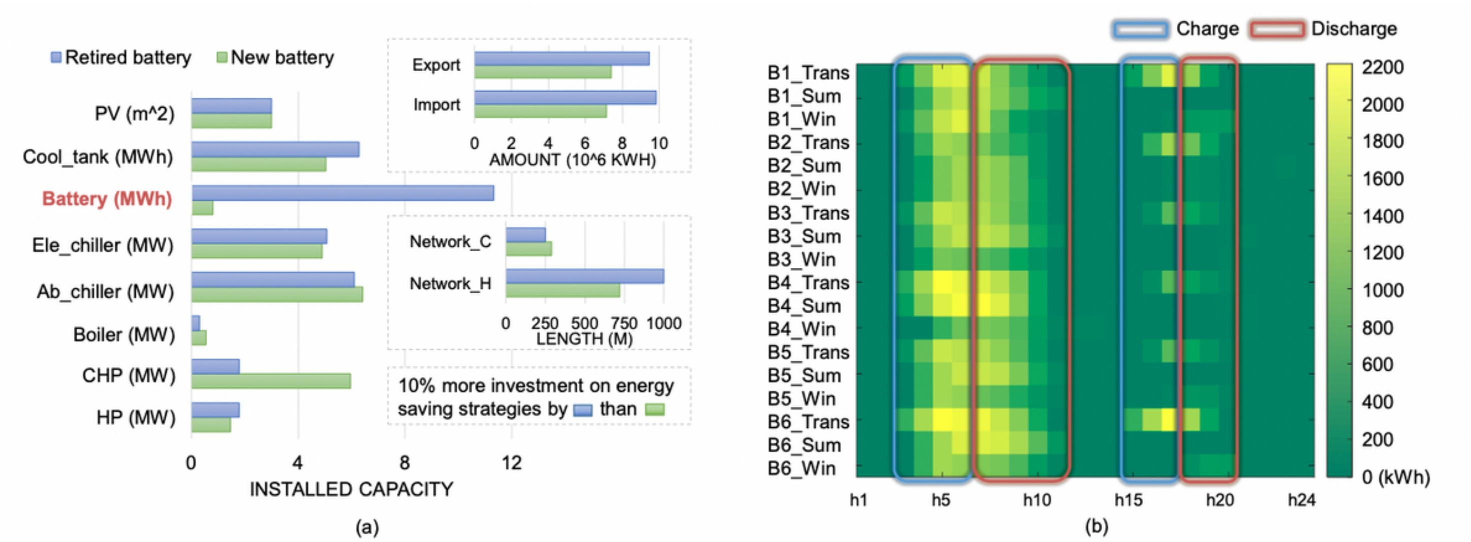


Figure 5

Comparison of system designs utilising either retired or new batteries (a), retired battery optimal dispatch strategy (b). (a) compares the system designs including the total installed capacities of combined heating and power (CHP), photovoltaic panels (PV), cooling storage tank (Cool_tank), electrical chiller (Ele_chiller), absorption chiller (Ab_chiller), heat pump (HP); cooling network length constructed (Network_C), heating network length constructed (Network_H); amount of electricity feed back to the utility grid (Export) and purchased from the utility grid (Import). (b) displays the batteries optimal state of charge, where primary y axis is each building (B1~B6) at each season of transition (Trans), summer (Sum), and winter (Win); secondary y axis is amount of electricity in storage; x axis represents 24 hours.

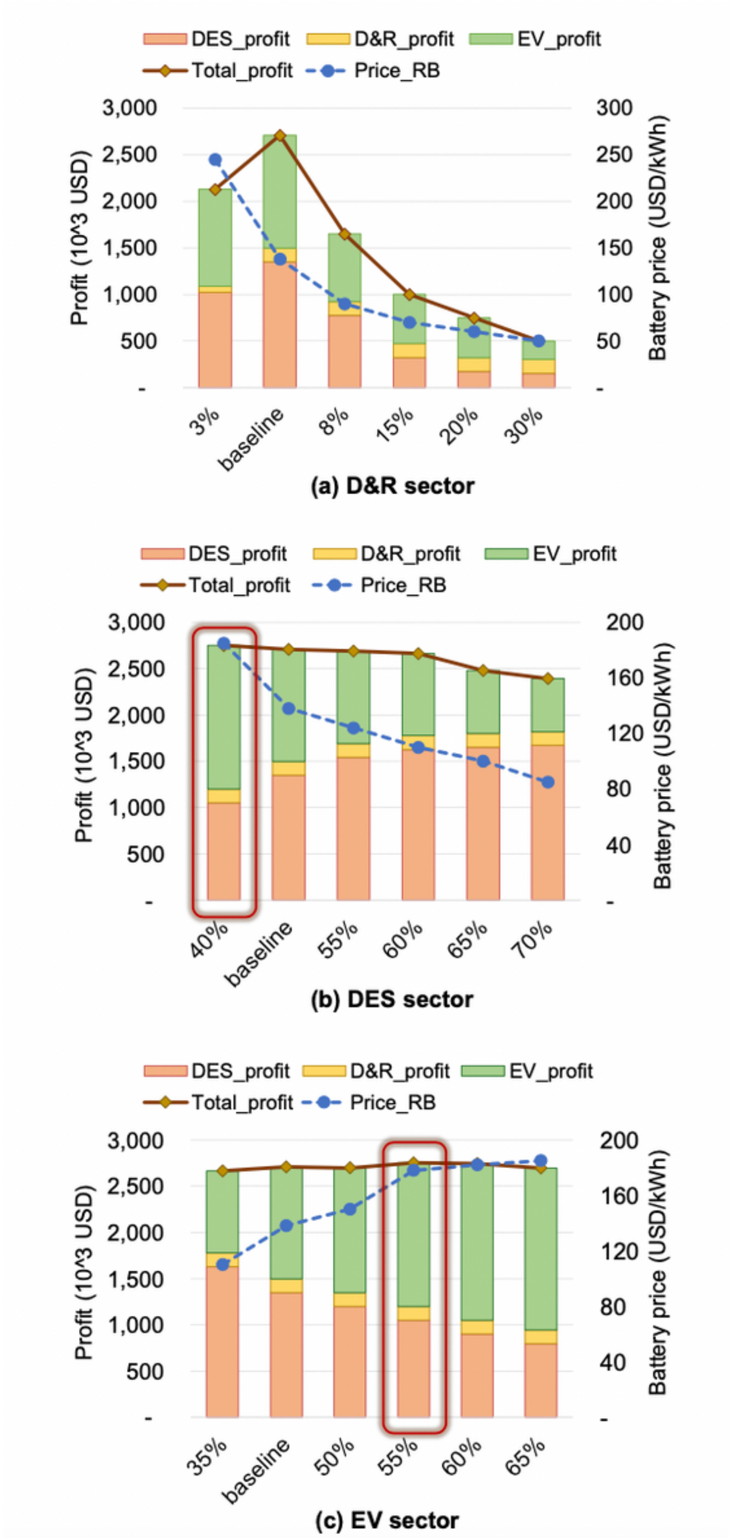
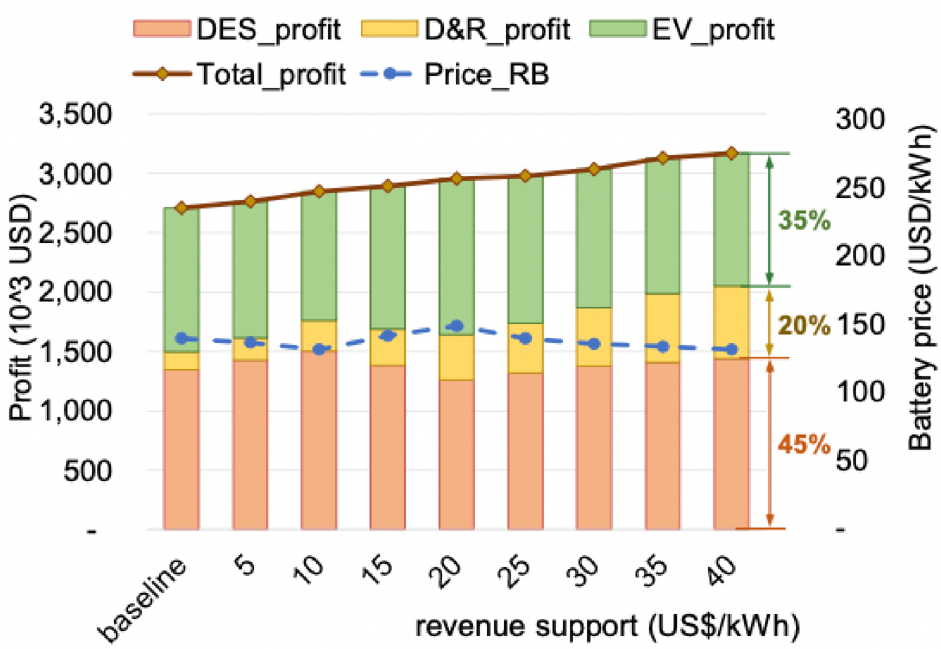
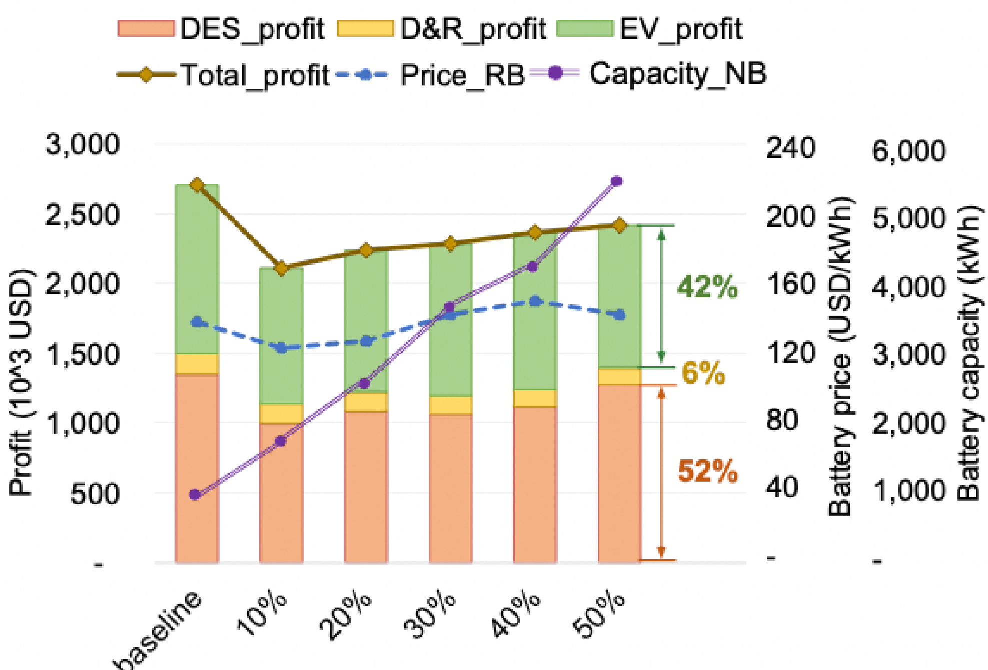


Figure 6

Profit variations with different mandatory profit share for different sectors. a-c, increase profit share mandatory for (a) D&R sector, (b) DES sector, (c) EV sector. x axis: different percentage of profit share mandatory assigned to D&R sector (a), to DES sector (b), and to EV sector (c), respectively. Primary y axis: values of profit. Secondary y axis: price of retired batteries (Price_RB) achieved in different mandatory profit share scenarios.



(a)



(b)

Figure 7

Profit share when revenue support on D&R sector and tariff support on DES sector. a-b, revenue support on D&R sector (a), Tariff support on DES sector (b). In (a), x axis: subsidy amount ($/kWh), primary y axis: profit archived of each sector, secondary y axis: retired battery price (Price_RB). In (b), x axis: different percentage of increase on feed-in tariff, primary y axis: profit archived of different sector, secondary y axis: price of retired battery (Price_RB), third y axis: installed capacity of new battery (Capacity_NB).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Methods.docx
- SupplementaryInformation.docx