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Study on the economic benefits of retired electric vehicle batteries participating in the electricity markets

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ABSTRACT

The lithium-ion batteries of battery electric vehicles are generally replaced when their capacity decays below 80% of the rated capacity. In this way, a large number of retired electric vehicle batteries (REVB) will be produced in a short time and cause new environmental pollution if REVB are not treated properly. To address this problem, one of the major solutions is to realize the echelon utilization of REVB based on the requirements of different application scenarios. Therefore, this study investigates the economic benefits of REVB participating in different Danish electricity markets. The objective function maximizes the profit in the different markets with considering REVB life loss cost in the operational process. Rainflow counting method is employed to accurately estimate the REVB life loss cost, leading to a strong nonlinearity of the optimization problem. Afterward, simulated annealing based particle swarm optimization (SAPSO) method is used to solve the nonlinear problem and find the optimal operational strategies of the REVB. Finally, a case study with considering different situations is provided to analyze the economic benefits of applying REVB in different markets. The results reveal: 1) SAPSO method performs best in finding the optimal results compared with particle swarm optimization and simulated annealing methods, and 2) It is more likely and beneficial to invest in REVB to participate in the regulation market than the day-ahead market. This significance of the study can be summarized as: 1) Theoretically, apart from proposing a simple, cheap and eco-friendly green strategy, i.e., the echelon utilization of REVB in Danish electricity market, we advance the knowledge and call for attention about under which conditions that performing a green strategy can allow environmental-economic benefits simultaneously achievable. 2) The study provides new business opportunities for energy storage and new energy industries, and can help to realize sustainable development to improve people's life and environmental quality.

1. Introduction

The shortage of fossil resources and the aggravation of environmental pollution are related challenges in the field of transportation (Ahmed et al., 2016). In this case, battery electric vehicles (BEVs) become popular to replace the fossil-fueled vehicles (FFVs) worldwide to reduce fossil resources depletion and pollution emissions (Bicer and Dincer, 2017). Despite the BEVs as the promising alternatives to FFVs, the high price of batteries is one of the main obstacles to hinder the extensive use of BEVs (Zhang et al., 2020). Efforts are being made to address the issue of economical BEVs, e.g. exploring new battery materials with low cost and high energy density (Kim et al., 2018), and improving the additional value of BEVs via vehicle to gird technology (Lazzeroni et al., 2019). For BEVs, the lithium battery is generally replaced when its rated capacity is degraded to less than 80% to ensure their safety and performance requirements (Liao et al., 2017). Based on IDTechEx's latest report named Second-life Electric Vehicle Batteries 2020–2030, by 2030 there will be over 6 million battery packs retiring from BEVs per year (https://www.idtechex.com/, 2020). Battery manufacturers and local governments are under pressure to

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Nomenclature

A. Abbreviation

BEVs	Battery Electric Vehicles
FFVs	fossil-fueled vehicles
GSCM	Green Supply Chain Management
NRBV	Natural Resource Based View
PV	Photovoltaic
PSO	Particle Swarm Optimization
REVB	Retired Electric Vehicle Batteries
RBV	Resource Based View
SAPSO	Simulated Annealing based Particle Swarm Optimization
SA	Simulated Annealing
SSCM	Sustainable Supply Chain Management

B. Index

k	Year index
t	Time index
y	REVB lifetime
T	Total simulation time

C. Parameters

C^{loss}	REVB life loss cost (DKK)
$C^{loss,da}$	REVB life loss cost in the day-ahead market (DKK)
$C^{loss,reg}$	REVB life loss cost in the regulation market (DKK)
C^{inv}	The total investment cost of REVB (DKK)
C^{om}	The operation and maintenance cost of REVB (DKK)
C^{cap}	The capital cost of REVB (DKK)
DoD	Depth of discharge of REVB (%)
$\mathrm{DoD}^{\min}$	Minimum depth of discharge of REVB (%)
$\mathrm{DoD}^{\max}$	Maximum depth of discharge of REVB (%)
EP_t^{da}	Day-ahead electricity price (DKK/kWh)
EP_t^{dn}	Down regulation price (DKK/kW)
EP_t^{up}	Up regulation price (DKK/kW)
$E_{t+1}^{REVB,da}, E_t^{REVB,da}$	Energy stored in the REVB in the day-ahead market (kWh)
$E_{t+1}^{REVB,reg}, E_t^{REVB,reg}$	Energy stored in the REVB in the regulation market (kWh)
$E_0^{REVB,da}, E_T^{REVB,da}$	Energy stored in the REVB in the day-ahead market at the beginning and end of the day, respectively (kWh)
$E_0^{REVB,reg}, E_T^{REVB,reg}$	Energy stored in the REVB in the regulation market at the beginning and end of the day, respectively (kWh)
$E^{REVB,\max}$	Maximum energy level of REVB (kWh)
i	Interest rate (%)
LEL^{REVB}	Life expectancy loss of the REVB (%)
$N^{cyc}(\mathrm{DoD})$	Equivalent cycle numbers within each interval
$N^{ctf}(\mathrm{DoD})$	Total cycle numbers within each interval
$P^{ch,\max}, P^{dch,\max}$	Maximum charging and discharging power of the REVB, respectively (kW)
$R^{REVB,da}$	Profit obtained from the day-ahead market (DKK)
$R^{REVB,reg}$	Profit obtained from the regulation market (DKK)
Δt	Time interval (h)
δ	Allowable energy change during the simulation period (kWh)
η^{ch}, η^{dch}	Charging and discharging efficiency of the REVB, respectively (%)

D. Decision variables

$P_t^{ch,da}$	Charging power of REVB in the day-ahead market (kW)
$P_t^{dch,da}$	Discharging power of REVB in the day-ahead market (kW)
$P_t^{ch,dn}$	Charging power of REVB in the regulation market (kW)
$P_t^{dch,up}$	Discharging power of REVB in the regulation market (kW)

recycle and dispose of vast batteries retired from BEVs within a short time. Retired electric vehicles batteries (REVB) can be defined as the new battery that has reached its vehicle serve lifespan, which keeps 80% of its original capacity. Nowadays, many global automobile companies like Nissan, Renault, BMW and BYD all have launched many different projects and business initiatives on reusing REVBs. So investors have the access to get the REVBs from these companies. The REVB can be applied in a renewable energy based system since the requirements of batteries' performance are not so critical (Shokrzadeh and Bibeau, 2012). The advantages of using REVB include prolonging battery lifetime, saving resources and reducing environmental pollution. In addition, REVB can potentially achieve the cost reduction of both BEVs and renewable energy based system (Jiao and Evans, 2017). Fig. 1 presents the full life cycle of BEV batteries (Zhao, 2017). The battery capacity at the first stage is over 80% serving for BEVs. After the first stage, the BEV batteries can be reused for other purposes. The echelon utilization of BEV batteries can be regarded as one of the most promising strategies to achieve battery cost reduction via extending their service life (Xu et al., 2019a). Based on this, the study aims to address the research question "In what scenario does the application of REVB have economic benefits in the electricity markets?".

Researching on this topic is in line with the on-going and important proposition of green supply chain management (GSCM) and/or sustainable supply chain management (SSCM) (Srivastava, 2007; Ahi and Searcy, 2013). Specifically, this case study is about "the end-of-life management of the product after its useful life" in BEV industry, which is part of GSCM practices as defined by Srivastava (2007). The importance and benefits of GSCM and SSCM have been widely discussed (de Oliveira et al., 2018), which in general can produce the economic, social and environmental benefits, as shown in our REVB case as well. However, there are barriers and challenges of implementing GSCM and/or SSCM, such as lack of senior management support, lack of understanding, lack of government intervention, etc., among which expensive implementation is often described as the barrier especially considering gains are usually thought to be feasible but only in the long run (de Oliveira et al., 2018). Companies may have the external pressure from customers, government, and other stakeholders to adopt GSCM and/or SSCM (Hitchcock, 2012; Kuei et al., 2015), but gaining financial/economic benefits can be a critical self-motivator, which is also one of the important considerations by the government. As emphasized by Ref. (Hart and Dowell, 2011), self-motivation (cognition) is important for the managers to enact proactive environmental strategies. Essentially, the willingness and the ability to act on and profit from pollution prevention depend critically on managers' expectations that such opportunities exists (Hart and Dowell, 2011; King and Lenox, 2002). More recently, de Oliveira et al. call for more studies to investigate how to "reduce and/or overcome GSCM implementation barriers", such as a lack of managers' commitment and motivation (de Oliveira et al., 2018). Therefore, it is necessary not only to suggest GSCM practices (e.g.,

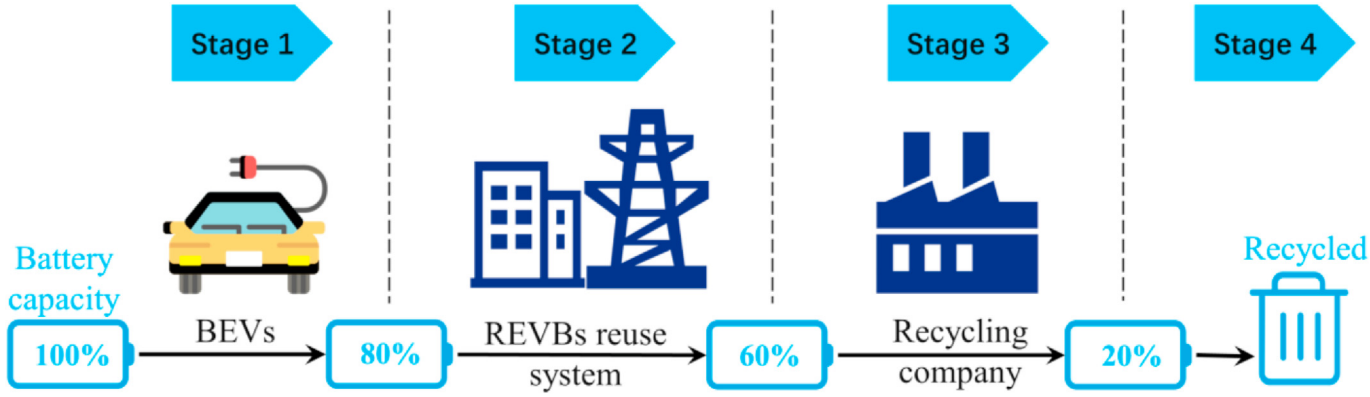

Fig. 1. Full life cycle of BEV batteries (Zhao, 2017).

the echelon utilization of REVB in electricity market in our study), but also to examine its feasibility, economic benefits, and the scenarios that allow such achievement.

By knowing these, we can ensure that both business and environmental sustainability can be simultaneously achieved, and this will greatly motivate both the firms and government join their efforts to adopt such practices. Especially, considering the constraints and challenges posed by the natural environment natural resources, natural resource based view (NRBV) (Hart, 1995) stresses that in order for the firms to achieve fully sustainable competitive advantages, the firms also need to have the internal resources and capabilities to avoid environmental damage and achieve environmental sustainability, apart from business sustainability focused in resource based view (RBV) (Barney, 1991). Based on this, we would say results of this study can also serves as the guidelines and the opportunities for the firms to develop sustainable competitive advantages. Moreover, based on a systematic review of GSCM research, Ref (de Oliveira et al., 2018). found a lack of studies on recycling, which as they emphasized, is "an important subject that significantly helps in mitigating environmental impacts". Furthermore, future green-based studies are encouraged to consider the contextual factors, such as the market dynamism (Mardani et al., 2020). which can be the contingencies that affect the environmental-economic performance relationship. Having said these, investigating the above raised question has both theoretical and practical implications.

As an option of energy storage, batteries have many applications in the power systems such as providing peak shaving (Liao et al., 2016), smoothing load profile (Purvins et al., 2013), and participating in electricity market (Xu et al., 2020a), depending on the applied systems. REVB can show the same effect comparing with new batteries in most cases, yet their investment cost is lower. Existing researches have investigated some application of REVB. The REVB are employed in an island power grid, and a method aiming to investigating the necessary capacity of REVB in an existing island system is introduced in (Matsuda and Tanaka, 2017). A REVB model considering the capacity fading of lithium batteries is proposed to design a standalone PV-hydrogen-REVB hybrid energy system (Huang et al., 2019). In addition, REVB are applied in on-gird systems as well. The application of REVB in an on-grid wind-photovoltaic (PV)-REVB system is analyzed in (Li et al., 2017). The research aims to minimize the electricity purchase and maximize the sale. The utilization of REVB to stabilize PV power is investigated and the result shows REVB can substantially reduce the impacts of fluctuating PV power (Kootstra et al., 2015). A comprehensive review of existing REVB projects is found in Gur et al. (2018), this study analyzes the economic benefits of using REVB to integrate renewable generations in Europe electricity grid. It is generally viewed that the application of REVB in the power grid is a bright idea, but plenty of key technical problems require to be solved, e.g. the accurate calculation of REVB degradation during secondary use.

With the development of electricity markets to promote the participation of battery energy storage systems, the owners of these systems need to develop bidding strategies to at least cover the operational cost. Battery degradation should be considered in the operational cost since the lifespan of electrochemical batteries is sensitive to the charge/discharge cycles (Vetter et al., 2005). A number of studies on batteries' economic benefits generally assume that they have a fixed lifespan (Kintner-Meyeret al., 2011). Batteries are assumed to be operated only one charge/discharge cycle each day based on the Electricity Storage Handbook from Sandia National Laboratories (Akhilet al., 2013). Moreover, the lithium-ion batteries are assumed to be replaced every five years (Zakeri and Syri, 2015). These assumptions are not valid in reality if batteries experience a high number of charging and discharging cycles per day since more frequent cycling increases the rate of degradation and decreases their lifespan. In order to extend the battery lifetime, the number of charge/discharge cycles per day has to be limited (Mohsenian-Rad, 2016). However, the limitation on cycle number can significantly reduce the operational flexibility and economic benefits. To fully discover the feasibility of batteries to participate in the electricity markets, the battery degradation cost considered as an operational cost, should be evaluated based on cycle numbers. In contrast to the new batteries, the capacity degradation of REVB cannot be ignored as REVB may experience a high cycle number in the operational process (Kim et al., 2013). Therefore, a rainflow counting method is adopted in this paper to count cycle numbers and quantify their cumulative impact during the simulation period (Wu et al., 2015), which aims to accurate estimate REVB degradation.

The rainflow counting method cannot be depicted by an analytical mathematical expression (Benasciutti and Tovo, 2005). Several efforts have been made to simplify the rainflow algorithm. In (Abdullaet al., 2018; Tran and Khambadkone, 1289), the cycle depth is simplified as the energy output of batteries within every control time interval. In (Koller et al., 2013), a cycle is calculated by the period between charge and discharge transitions. In (Xu et al., 2018), the actual electrochemical battery cycle aging mechanism is replaced by a proposed piecewise linear model. It aims to investigate the operational profits of new batteries in participating in ISO New England energy and reserve markets by considering the cycle aging cost. However, the simplification of these models leads to the concern of the result accuracy. The calculation accuracy of

battery operational cycles in the electricity markets determines the profits. Therefore, this study investigates the operational optimization problem of REVB participating in the electricity markets which aims to maximize the profits. The degradation cost of the REVB is accurately estimated using the rainflow algorithm. Besides, with considering the nonlinear characteristics of the optimization problem, the heuristic algorithms may be a suitable choice. There are many heuristic algorithms such as particle swarm optimization (PSO), simulated annealing (SA) and genetic algorithm (GA). Among these heuristic algorithms, GA and PSO are most widely used since they perform excellent in handling nonlinear problems and can effectively avoid falling into the local optimal solution (Luna-Rubio et al., 2012). However, the main problem with GA is that its complex optimization process, so it takes lots of time to find the optimal solution (Sankari and Chandrasekar, 2011). Therefore, it can be regarded that PSO is the first choice in complex optimization problems. A new maximum power point tracking technique was proposed in (Zeddini et al., 2016) based on PSO method, and the good performance of applying PSO was proved. Ref (Adedeji et al., 2020). combined PSO with adaptive neurofuzzy inference system to achieve very short-term forecast of wind turbine power output. The results indicated that the forecast accuracy improves by considering PSO method. Ref (Banerjee et al., 2016). used PSO method to address the hydro-wind-thermal scheduling problem and the results showed that PSO provides the best global optimum solution. SA algorithm based chaotic search and harmony search was proposed in (Zhang et al., 2018) to size different combinations of hybrid systems. The results showed that the SA algorithm based method performance better than the SA algorithm. It can be seen that the classical heuristic algorithms often make some improvements or combine with each other to achieve better optimization effects. In fact, both PSO and SA have advantages and disadvantages. Compared with SA, PSO has a faster convergence speed, but its global searching ability is weaker (Qi et al., 2018). SA can just make up for the shortcomings of PSO to improve its global searching ability (Javidrad et al., 2018). Therefore, this study selects the simulated annealing based particle swarm optimization (SAPSO) method which combines classic PSO and classic SA algorithm to accurately and quickly optimize the REVB operation in the electricity markets.

Based on the discussion above, the contributions of this study are listed as follows:

1. The economic benefits of REVB participating in different Danish electricity markets including regulation and day-ahead markets are firstly investigated.
2. The optimal operational strategies of REVB participating in electricity markets are proposed using SAPSO method.
3. A rainflow counting method is employed to count battery equivalent cycle times, and then REVB life loss cost is accurately calculated.
4. Based on the research findings, theoretical and practical implications of echelon utilization of REVB are discussed.

2. Problem formulations

The models and methods used in this study are generalized. Denmark aims to achieve 100 percent renewable energy use by 2050 (http://www.go100percent.o, 2020). The rapid development of renewable energy, especially wind power, has a significant impact on the electricity prices and volatility in the electricity market. Denmark is widely regarded as a role model for the developing wind energy, and has established a mature market mechanism. This makes Danish electricity market an ideal case study. Besides, the Danish electricity price fluctuate greatly and complex caused by the strong volatility and randomness of wind power. Therefore, this study selects two common Danish electricity markets, i.e. Danish day-ahead market and regulation market, to investigate the economic benefits of applying REVB in the two electricity markets. To the best of authors' knowledge, the application of REVB in the Danish electricity market has not been investigated in the previous studies. Additionally, it should be observed that the models and methods can be used in other electricity markets and other types of REVB. The models of REVB participating in different electricity markets are described below.

2.1. Participating in the day-ahead market

The day-ahead market is a physical market where prices and amounts are determined by the electricity supply and demand. Resulting prices and the overall amounts traded in the day-ahead market are made public. In the day-ahead market, REVB charge by purchasing electricity at a low price, and discharges to sale this stored electricity at a higher price to achieve temporal arbitrage (Mandal et al., 2010). The economic benefits of this arbitrage form depend on the price difference and the REVB life loss cost. When electricity price is stable, the expected arbitrage profits are small and REVB may not operate in order to extend their lifespan and reduce their life loss cost. Eq. (1) is the objective function which aims to maximize the profit with considering REVB life loss cost in the day-ahead market. In Eq. (1), the first term is the revenue obtained from the day-ahead market. And the second term is the REVB life loss cost caused by the charging and discharging behaviors of REVB, which is calculated by Eqs. 14–16. Eq. (14) calculates the life expectancy loss of REVB when participating electricity market. Eq. (15) is used to estimate the investment cost of REVB. Based on Eq. (14) and Eq. (15). The REVB life loss cost can be obtained as presented in Eq. (16). Eq. (2) is the constraint of the maximum and minimum charging power of REVB. Eq. (3) is the constraint of the maximum and minimum discharging power of REVB. Eq. (4) is a dynamic equation to reflect the energy change of REVB. The upper and lower available energy in the REVB at each hour is limited by Eq. (5). Compared to new batteries, the depth of discharge of REVB is smaller. Eq. (6) shows the stored energy in REVB can change slightly during the simulation period. REVB life loss cost is calculated using the rainflow counting method, and the detailed description of the method is given in the next section.

$$\max R^{REVB,da} = \sum_{t=1}^{T}\left[EP_t^{da}\left(P_t^{ch,da} - P_t^{dch,da}\right)\right] - C^{loss} \tag{1}$$

$$0 \le P_t^{ch,da} \le P^{ch,\max} \tag{2}$$

$$0 \le P_t^{dch,da} \le P^{dch,\max} \tag{3}$$

$$E_{t+1}^{REVB,da} = E_t^{REVB,da} + \eta^{ch} P_t^{ch,da} \Delta t - P_t^{dch,da} \Delta t \Big/ \eta^{dch} \tag{4}$$

$$E^{REVB,\max}\mathrm{DOD}^{\min} \le E_t^{REVB,da} \le E^{REVB,\max}\mathrm{DOD}^{\max} \tag{5}$$

$$-\delta < E_T^{REVB,da} - E_0^{REVB,da} < \delta \tag{6}$$

where C^{loss} is the REVB life loss cost. $\mathrm{DOD}^{\min}$ and $\mathrm{DOD}^{\max}$ are the minimum and maximum depth of charge of REVB, respectively. EP_t^{da} is the day-ahead electricity price. $E_t^{REVB,da}$ is the energy stored in the REVB in the day-ahead market. $E^{REVB,\max}$ is the maximum

energy level of REVB. $E_0^{REVB,da}$ and $E_T^{REVB,da}$ are the energy stored in the REVB in the day-ahead market at the beginning and end of the day, respectively. $P_t^{ch,da}$ and $P_t^{dch,da}$ are the charging and discharging power of REVB in the day-ahead market. $R^{REVB,da}$ is the profit obtained from the day-ahead market. $P^{ch,\max}$ and $P^{dch,\max}$ are the maximum charging and discharging power of REVB, respectively. Δt is the time interval. η^{ch} and η^{dch} are the charging and discharging efficiency of REVB. δ is the allowable energy change during the simulation period.

2.2. Participating in the regulation market

The regulation market is a real-time market covering operation within the hour. Its main function is to offer power regulation to deal with the imbalances related to day-ahead operation planned. REVB participate in down/up regulation market to get profits by charging/discharging electricity from/to the main grids (Li et al., 2018). In this market, it obtains revenue from both charging and discharging electricity. The objective function of Eq. (7) aims to maximize the profit considering the REVB life loss cost in the regulation market. The optimization models (Eqs. 8–12) of REVB participating in the regulation market are similar to the models in the day-ahead electricity market. Therefore, no detailed descriptions of Eqs. 8–12 are available here. Similarly, the life loss cost of REVB participating in regulation-ahead can also be calculated by Eqs. (14)–(16).

$$\max R^{REVB,reg} = \sum_{t=1}^{T}\left(EP_t^{dn}P_t^{ch,dn} + EP_t^{up}P_t^{dch,up}\right) - C^{loss,reg} \tag{7}$$

$$0 \le P_t^{ch,dn} \le P^{ch,\max} \tag{8}$$

$$0 \le P_t^{dch,up} \le P^{dch,\max} \tag{9}$$

$$E_{t+1}^{REVB,reg} = E_t^{REVB,reg} + \eta^{ch}P_t^{ch,dn}\Delta t - P_t^{dch,up}\Delta t \Big/ \eta^{dch} \tag{10}$$

$$E^{REVB,\max}\mathrm{DOD}^{\min} \le E_t^{REVB,reg} \le E^{REVB,\max}\mathrm{DOD}^{\max} \tag{11}$$

$$-\delta < E_T^{REVB,reg} - E_0^{REVB,reg} < \delta \tag{12}$$

where $C^{loss,reg}$ is the REVB life loss cost in the regulation market which can be calculated by Eq. (15). EP_t^{dn} is the down regulation price. EP_t^{up} is the up regulation price. $E_t^{REVB,reg}$ is the energy stored in the REVB in the regulation market. $E_0^{REVB,reg}$ and $E_T^{REVB,reg}$ are the energy stored in the REVB in the regulation market at the beginning and end of the day, respectively. $P_t^{ch,dn}$ and $P_t^{dch,up}$ are the charging power and discharging power in the regulation market, respectively. $R^{REVB,reg}$ is the profit obtained from the regulation market.

3. Methods

In the electricity markets, REVB investors can obtain benefits when the investment cost is lower than the revenue. For the REVB, its investment cost is determined by the number of cycles, i.e. the frequent charging and discharging behaviors of REVB will reduce its lifespan, and thus leading to a high investment cost. The accurate calculation of the number of cycles of REVB is crucial to explore its economic benefits. Rainflow counting method as one of the cycle counting methods can accurately calculate the life loss of REVBs caused by their charging and discharging behaviors. Besides, this method is relatively simple and easy to program. Therefore, it is applied in this study to accurately calculate the number of REVB cycles during the operational period. However, it complicates the optimization problem because it cannot be represented by mathematical analysis. SAPSO method can effectively adjust the ability of global search and local search. It makes the result not easy to fall into local optimum, and can get better optimization effect. Therefore, SAPSO method is selected since heuristic algorithms may be a good choice to address this problem. The detailed descriptions of the rainflow counting method and SAPSO method are given as follows.

3.1. Rainflow counting method

The rainflow counting method is widely employed in materials stress analysis to count cycles and quantify their cumulative effect. The method can also be applied to assess battery life (Muenzel et al., 2015). REVB life loss cost can be estimated below: Firstly, a REVB model with remaining life cycle is developed based on polynomial fitting. Then, the battery equivalent cycle times are counted via a rainflow counting method during the simulation period (Schaltz et al., 2009). Furthermore, the ratio of equivalent cycle numbers and remaining life cycle numbers is calculated. Finally, REVB life loss cost can be obtained. The detailed steps are given below:

1) REVB service life depends on cycle numbers and depth of REVB charge and discharge. A larger cycle number and a greater depth of charge can lead to shorter REVB service life. Compared to the small capacity of reused battery, large capacity of reused battery has more cycles and longer lifespan (Assunção et al., 2016). The Nissan Leaf has a large lithium-ion battery and this car accounts for a relatively large market share. Therefore, this paper selects the lithium-ion batteries retired from Nissan Lead as the research objects. Four order function is fitted to represent the relationship between number of cycles N^{cyc} and depth of discharge DoD based on (Assunção et al., 2016):

$$N^{cyc} = a_0(\mathrm{DoD})^4 + a_1(\mathrm{DoD})^3 + a_2(\mathrm{DoD})^2 + a_3\mathrm{DoD} + a_4 \tag{13}$$

where $a_0 \sim a_4$ are fitting coefficients which are −4464, 4167, 7991, −12120, and 4929, respectively. The curve of number of cycles and depth of discharge is given in Fig. 2.

2) In order to accurately calculate the REVB service life, the rainflow counting method is employed to count the equivalent number of REVB cycles. The basic steps of the method are given as follows:
   Step1: The change curve of REVB capacity should be defined.
   Step2: Based on the rainflow features, the equivalent full REVB cycles are counted.
   Step3: Every full cycle is removed individually.
   Step4: The valley and peak values of change curve are recorded to count half cycles.

Fig. 3 gives an example of the change curve of REVB capacity which contains two full cycles (BCD 20%, FGH 20%) and two half-cycles (ACDE 60%, EFGI 60%).

3) In order to get the life loss cost of REVB during their operational period, the ratio of equivalent cycle numbers and remaining life cycle numbers at each time interval need to be calculated. The life expectancy loss expression (the ratio) is calculated by Eq. (14):

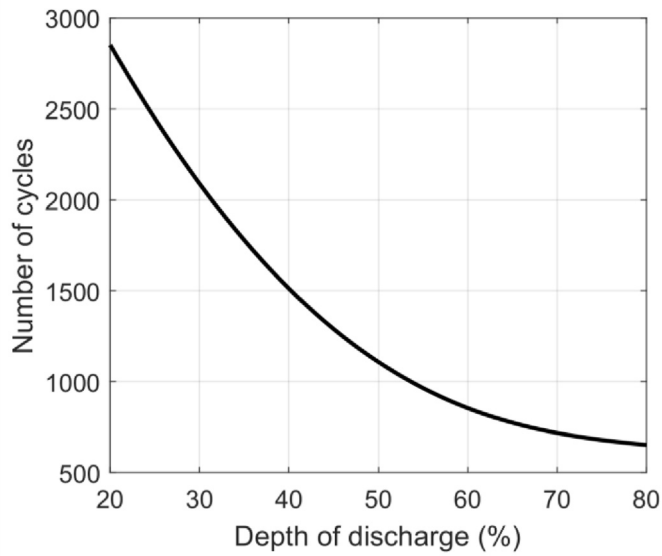

Fig. 2. The relation between number of cycles and depth of discharge.

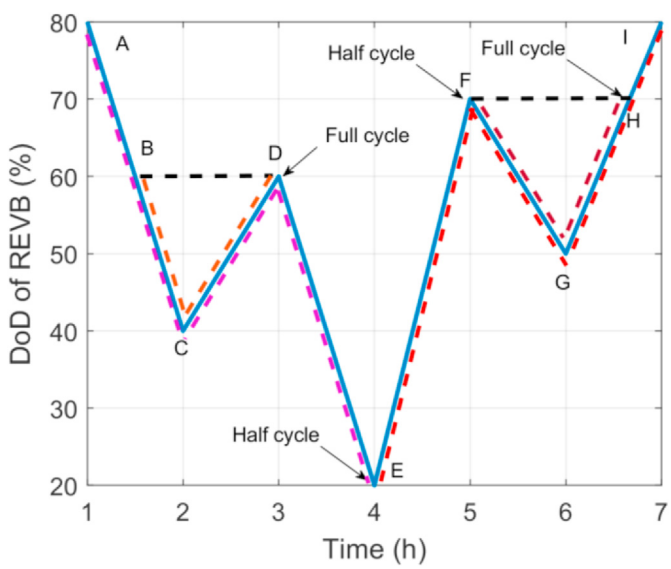

Fig. 3. Example of the rainflow counting method.

$$LEL^{REVB} = \sum_{\mathrm{DoD}=0.01}^{\mathrm{DoD}=1} \frac{N^{cyc}(\mathrm{DoD})}{N^{ctf}(\mathrm{DoD})} \tag{14}$$

where LEL^{REVB} is the life expectancy loss of the REVB. $N^{cyc}(\mathrm{DoD})$ is the equivalent cycle numbers within each interval. $N^{ctf}(\mathrm{DoD})$ is the total cycle numbers within each interval.

The investment cost of REVB contains capital cost and operation and maintenance cost which is calculated by Eq. (15):

$$C^{inv} = C^{cap} + \sum_{k=1}^{y} \frac{C^{om}}{(1+i)^k} \tag{15}$$

where C^{cap} is the capital cost of REVB. C^{om} is the operation and maintenance cost of REVB. i is the interest rate.

Then the REVB life loss cost can be evaluated based on Eq. (16):

$$C^{loss} = C^{inv} \cdot LEL^{REVB} \tag{16}$$

where C^{inv} is the total investment cost of REVB.

3.2. Simulated annealing based particle swarm optimization method

The SAPSO is a heuristic algorithm combining particle swarm optimization (PSO) method (Xu et al., 2019b, 2020b) and simulated annealing (SA) method (Javidrad and Nazari, 2017). PSO mainly relies on the information between particles to update their position and velocity in the optimization process. In this way, the particles are kept close to the optimal solution. The advantages of PSO are easy to precocity and fall into local optimum, late convergence speed and poor search accuracy. SA has a strong global search ability which is possible to accept the worse solution with a certain probability. Therefore, it can jump out of the trap of local optimal solution, converge to the region of the global optimal solution. The convergence rate of SA is very slow since it needs high annealing temperature. SAPSO can overcome the weak points of SA and PSO by learning from each other's strong points, which is the basic idea (Wang and Li, 2004).

The basic steps of SAPSO method are as follows:

(1) The related parameters, including population, iterations, particle dimensions, the particle swarm are initialized. Meanwhile, the fitness values based on the initial particle swarm are calculated.
(2) SA initialization contains initial temperature setting, initial solution S generation, evaluation function $C(S)$ calculation. $C(S)$ is regarded as the global optimal solution.
(3) The new solution S' is generated.
(4) The velocity and position of the particles are updated based on Eqs. (17) and (18). And the fitness value is evaluated.

$$v(t+1) = \omega v(t) + c_1 r_2 (p(t) - x(t)) + c_2 r_2 \left(p_g(t) - x(t)\right) \tag{17}$$

$$x(t+1) = x(t) + v(t+1) \tag{18}$$

(5) $C(S') = \min\{f(x_i)\}$ and $\Delta C = C(S') - C(S)$ are calculated, where $f(x_i)$ denotes the minimum fitness value. If $\Delta C < 0$ or $\exp(-\Delta C/T) > \mathrm{rand}(0,1)$, $C(S) = C(S'), S = S'$. The new solution S' is accepted and the velocity and position updating of the particles is updated based on S'. Otherwise, S' cannot be accepted. The velocity and position of the particles are updated based on S. In the end, the fitness value is evaluated.
(6) The global and local optimal solutions are updated based on the obtained fitness values.
(7) The stop criteria are checked. If it satisfied, the optimal value is found. Otherwise, the procedure goes to step (3).

Fig. 4 gives the research framework of this study, and it also includes the SAPSO optimization framework. Firstly, the real data of Danish electricity markets and REVB specifications is collected and processed. Then, the charging/discharging power of the REVB in different Danish electricity markets which are the optimization variables are optimized based on SAPSO method. Subsequently, the scenario analysis is conducted to investigate the economic benefits of REVB in different scenarios. Finally, based on the obtained results, a comprehensive discussion from perspective of the environment and society is provided to investigate the future development of REVB. Additionally, it

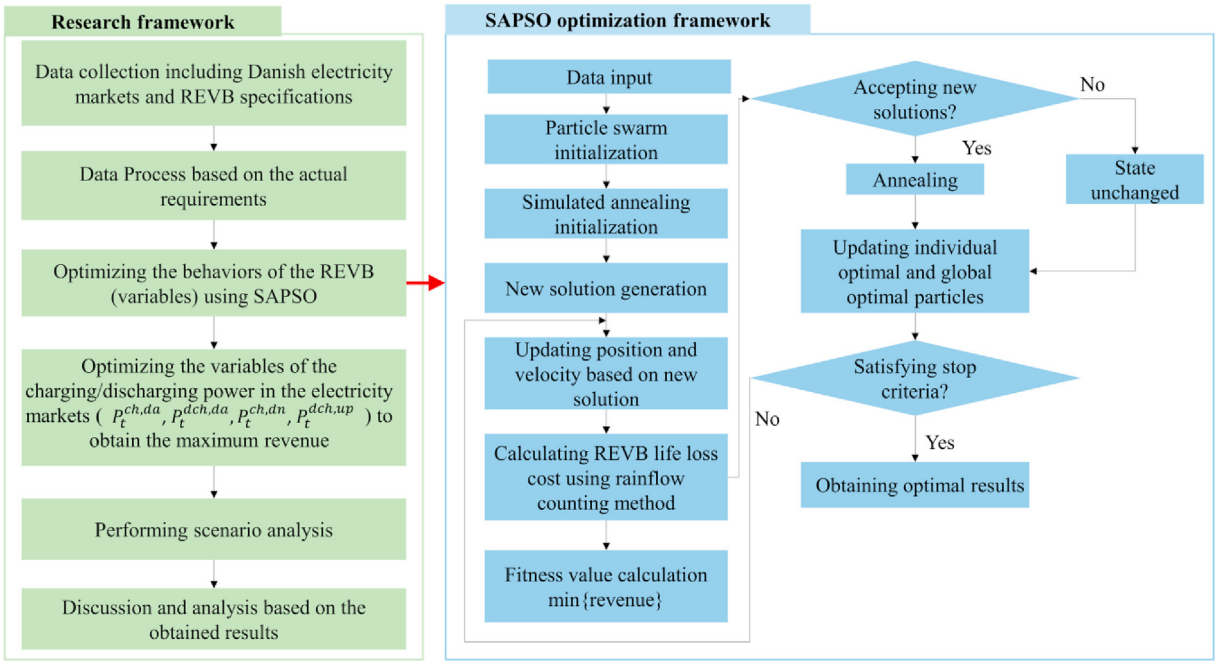

Fig. 4. Research framework including SAPSO optimization framework.

should be observed that the implementation of the SAPSO method is described in detail above.

4. Case study

To explore the economic benefits of REVB participating in the two different electricity markets, a simulation analysis is carried out in this section. Simulation results in different scenarios are presented and analyzed. The optimization period is 24 h for all simulations. All the simulations in are conducted in MATLAB 2019.

4.1. Data

This work investigates the operational problem of REVB participating in Danish electricity markets. Therefore, the specification of the selected REVB is given in Table 1 (Assunção et al., 2016). The selected REVB are from the Nissan Leaf vehicles since it accounts for a large market share, which is Lithium ion batteries. The depth of discharge of the REVB is between 20% and 80% which is the feature of the second use battery as shown in Fig. 1. The maximum cycle number of the REVB is 4929 and its relationship to depth of discharge is shown in Fig. 2. Notably, this study selects 10 identical REVB to carry out the simulations. Historical market price data derived from Danish electricity markets in 2017, including day-ahead, up regulation and down regulation electricity prices. The hourly day-ahead and up/down regulation prices over a year are given in Fig. 5, respectively. In order to reduce the computational burden, a typical day obtained by averaging the data of the whole year (Fig. 5) is selected to conduct the numerical experiments. The typical day including up/down regulation and day-ahead prices is given in Fig. 6. For the typical day, the day-ahead price is between up and down regulation prices. The maximum and minimum day-ahead prices occur at 17:00 and 2:00, respectively. It can be observed that the REVB can participate in the up and down regulation markets at any time on the typical day.

Table 1
Specification of the selected REVB.

Items	Parameters
Types	Nissan Leaf lithium-ion battery
Energy capacity	16.8 kWh
Charging/discharging power	5 kW
Charging/discharging efficiency	95%
DoD^{max}	80%
DoD^{min}	20%
Number of cycles	4929
lifetime	5 years
Investment cost	16312 DKK
Operation and maintenance cost	16.3 DKK
Discount rate	5%
Number of REVB	10

4.2. Results

SAPSO is selected to optimize the operational strategy of the REVB in the electricity markets. To validate the performance of SAPSO, other heuristic algorithms, including PSO and SA methods, are used to make a comparison. Under the situation of 10% of investment cost reduction and 50% of regulation price growth in the regulation market, the three methods aim to find the maximum profit and the number of the maximum iterations is set to be 200. The iteration curves of the three methods are given in Fig. 7. The start points of the three methods are the same to ensure that the three methods are conducted under the same scenario. Among the three methods, SA shows the worst convergence effect which cannot converge until 200 iterations. PSO starts to converge after 100 iterations, and it converges to its optimal result after 130 iterations. Notably, SAPSO performs best among the three methods with the highest profit and fastest convergence speed. Due to the good performance of the SAPSO, the paper adopts SAPSO to carry out the simulation analysis.

Based on the SAPSO, the economic benefits of the REVB in different scenarios, i.e., different percentages of regulation price growth and different percentages of investment cost reduction, are investigated and compared in different electricity markets. The

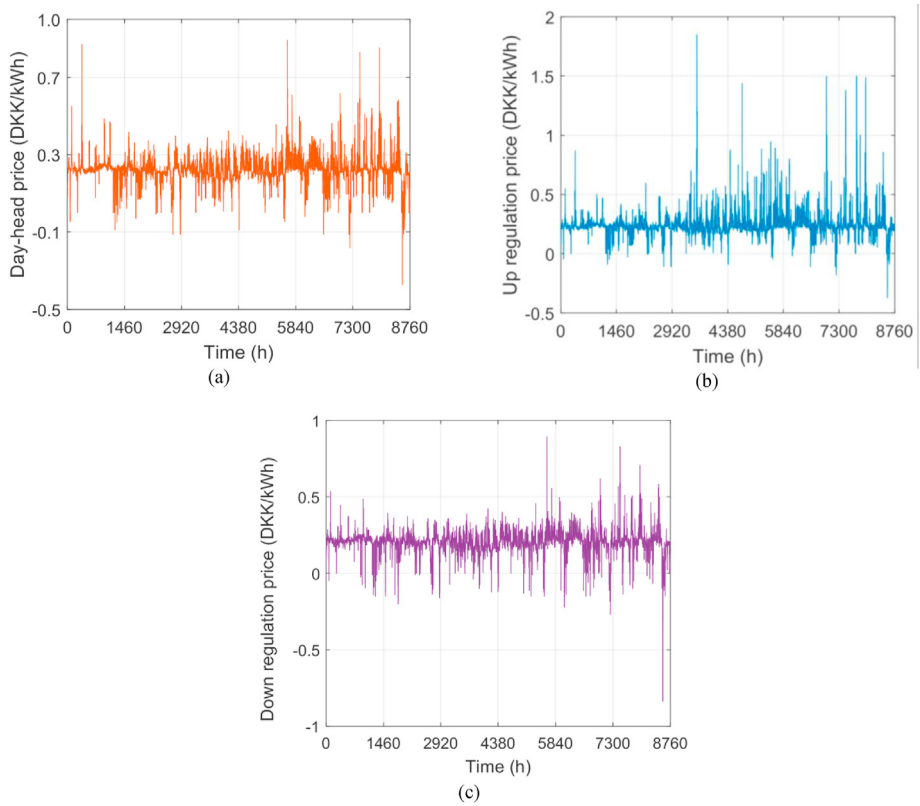

Fig. 5. Hourly Denmark electricity market prices: (a) Day-ahead price. (b) Up regulation price. (c) Down regulation price.

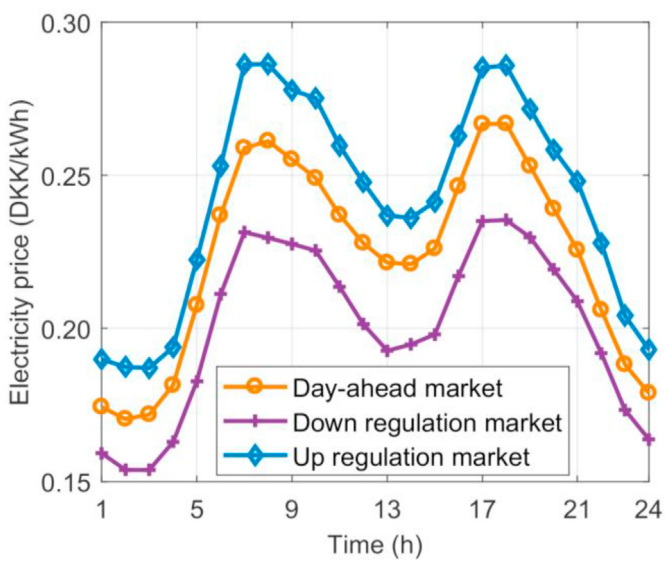

Fig. 6. A typical day for the day-ahead, up/down regulation markets.

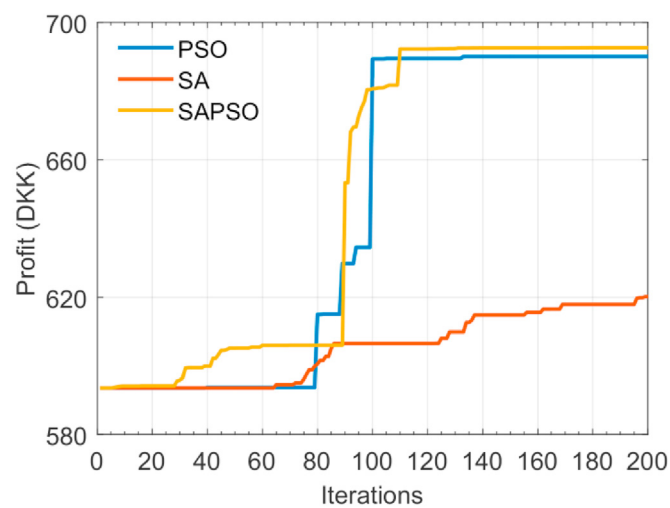

Fig. 7. Iteration curves of the three different methods.

results show that this study can provide new business opportunities for energy storage and new energy industries to obtain more profits, help to realize sustainable development to improve people's life and environmental quality and provides some observations to the policy makers on the echelon utilization of REVB. It should be noted that the profit mentioned below is the objective function which is equal to the profit obtained from the electricity markets minus the REVB life loss cost.

4.2.1. Participating in the regulation market

In the regulation market, REVB charge/discharge power to participate in the down/up regulation market. It can be observed that both behaviors of REVB can obtain profit. The economic benefits are mainly determined by the electricity price and REVB life loss cost. At present, due to the relatively low electricity price and high REVB investment cost, the behaviors of REVB can lead to a high REVB life loss cost which is much greater than the revenue obtained from the regulation electricity market, leading to no benefits in the regulation market. Therefore, it is not cost-effective to invest in REVB to participate in the regulation electricity market at present.

To explore the scenarios under which the REVB have economic benefits in the regulation market, Table 2 gives the simulation results when the investment cost is not changed. The regulation price growth refers to the increase of both up and down regulation electricity price. With the growth of the percentage of regulation price, the REVB life loss cost is almost unchanged while the profit increase significantly. Table 3 gives the simulation results when the regulation cost is not changed. Compared to the profit in Table 2, the profit in Table 3 is obviously less. This indicates that the impact of electricity price on profit is greater that the investment cost in the regulation market. As seen from the two tables, they show that the REVB owner can obtain the profits when 10% of investment cost reduction or 50% of regulation price growth achieves. In the future, with the growth of day-ahead electricity price and the decrease of REVB investment cost, it becomes profitable to invest in REVB to participate in the regulation market. In addition, the profit and REVB life loss cost under different percentage of investment cost reduction and regulation price growth are also investigated, as shown in Fig. 8 and Fig. 9. As shown in Fig. 9, the REVB life loss cost accounts for a large proportion, especially when the REVB investment cost is high. Therefore, the investment cost reduction of REVB can offer more possibilities to invest in REVB participating in the regulation market. As shown in Figs. 8 and 9, with the decrease of the investment cost of REVB and the increase of regulation price, it can be noted that the profit increases and the REVB life loss cost decreases significantly.

To present a detailed analysis of the REVB participating in the regulation market, the simulation results under the condition of 10% of investment cost reduction and 50% of regulation price growth are given in Table 4. The profit is 692.3 DKK that is equal to the revenue obtained from the regulation market (2264.3 DKK) minus the REVB life loss cost (1572.0 DKK). It can be noted that the REVB life loss cost accounts for over half of the revenue obtained from the regulation market. So, REVB investment cost is the major obstacle to hinder its application in the regulation market. The behaviors of the REVB participating in the regulation market during the typical day are shown in Fig. 10. The discharging/charging behaviors of the REVB are represented by negative/positive value. REVB participate in the up-regulation market from 8:00 to 10:00 and from 17:00 to 19:00 due to the high up-regulation price. As can be seen from Fig. 6, since the up-regulation price is higher than the down-regulation price during the typical day, the REVB prefer to participate in the up-regulation market in theory. But actually, the total power of REVB participating in the up and down regulation market is the same since the energy stored in the REVB at the beginning of the day is equal to that at the end of the day.

With the consideration of REVB life loss cost, it can not only improve REVB owner's profit, but also extend REVB lifetime. Fig. 11 gives the cycle counting process of the REVB in the regulation market. The first figure in Fig. 11 shows the DoD of the REVB during the typical day. The DoD of the REVB is limited between 20% and 80%. It reaches the upper limit at 2:00, 7:00, 16:00 and 22:00 and lower limit at 4:00, 10:00 and 19:00. The DoD of the REVB at the beginning of the day is approximately equal to that at the end of the day since it is assumed that the DoD allows a slight change after the typical day. The second figure in Fig. 11 corresponds to Step 2 in section 3.1 which can calculate the full cycles of the REVB. Notably, the operation of the REVB on a typical day includes three full cycles which are 0.5937, 0.5974 and 0.5966. Then the full cycles are removed (Step 3 in section 3.1). The third figure in Fig. 11 can be obtained which can count the half cycle of the REVB, it contains two half-cycles which are 0.3000 and 0.3236. Rainflow counting method leads to a high operational cost, since it reflects the investment cost of the REVB and calculate the operational cost more accurately.

4.2.2. Participating in the day-ahead market

In the day-ahead market, REVB purchase/sell electricity when the day-ahead electricity price is low/high to achieve temporal arbitrage. The economic benefits of this arbitrage form are mainly determined by the electricity price difference and the REVB life loss cost. Similar to the regulation market, it is not cost-effective to invest in REVB in the day-ahead electricity market at present. Therefore, the results under the condition of different percentages of day-ahead electricity price growth and percentages of investment cost reduction are analyzed. It shows that the REVB have no profit in the day-ahead electricity market in any condition. To explore the scenarios under which the REVB have economic benefits in the day-ahead market, the subsidies for the REVB are investigated. Notably, the subsidies for the REVB mean that REVB buy electricity from the day-ahead market has a lower price compared to the actual day-ahead electricity price. Fig. 12 and Fig. 13 show the profit and REVB life loss cost of REVB participating in the day-ahead market under different percentages of investment cost reduction and different percentages of purchased electricity price reduction. REVB can get profit under the condition of 70% of investment cost reduction and 70% of purchased electricity price reduction. This situation is difficult to occur. Therefore, compare with REVB participating in day-ahead market, REVB participating in regulation market is more likely and beneficial.

Table 5 gives the simulation results of REVB participating in the day-ahead market under the condition of 70% of investment cost reduction and 70% of purchased electricity price reduction. The profit of REVB participating in the day-ahead market is very low (18.8 DKK). Therefore, it is not recommended to invest in the REVB to participate in the day-ahead market. The behaviors of the REVB participating in the day-ahead market during the typical day are presented in Fig. 14. The discharging/charging behaviors of the REVB are represented by negative/positive value. From 5:00 to 10:00 and from 16:00 to 20:00, REVB discharge to sell electricity to the day-ahead market owing to the relatively high electricity price. In other hours, REVB charge by buying electricity from the market owing to the relatively low electricity price. Fig. 15 shows the cycle counting process of REVB participating in the day-ahead market. In Fig. 15, the first figure is the DoD of the REVB during the typical day. The DoD reaches the upper limit at 4:00 and 15:00, and lower limit at 10:00 and 20:00. The second figure corresponds to Step 2 in section 3.1, it counts the full cycles of the REVB during the typical day. It can be observed that the operation of REVB leads to only one full cycle. The third figure counts the half cycle of the REVB during the typical day, it contains three half-cycles which are 0.3, 0.6, and 0.25. Through the analysis of cycle counting process of REVB participating in the two electricity markets. The feasibility of the

Table 2
Simulation results when the investment cost is not changed.

Percentage of regulation price growth (%)	0	50	100	150	200	250	300	350
REVB life loss cost (DKK)	–	1747	1747	1747	1748	1748	1749	1749
Profit (DKK)	–	518	1275	2030	2788	3548	4308	5065

Table 3
Simulation results when the regulation price is not changed.

Percentage of investment cost reduction (%)	0	10	20	30	40	50	60	70
REVB life loss cost (DKK)	–	1574	1400	1226	1051	876	701	525
Profit (DKK)	–	60	118	294	470	645	820	995

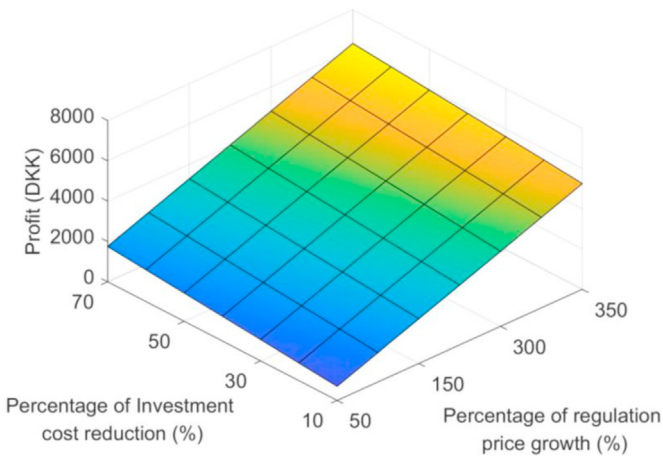

Fig. 8. Profit of REVB participating in the regulation market in various scenarios.

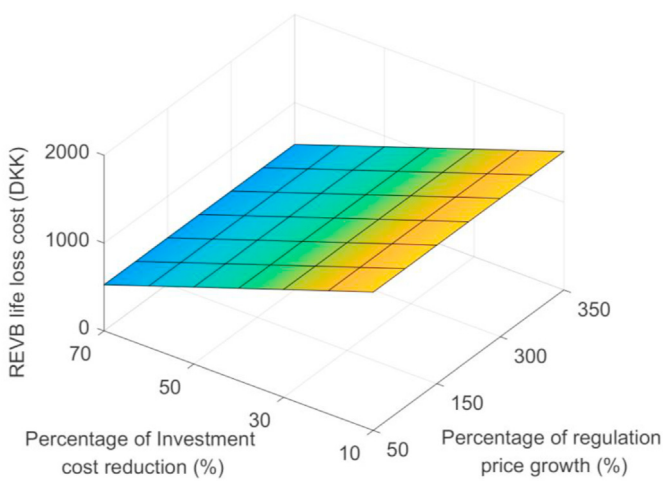

Fig. 9. Life loss cost of REVB participating in the regulation market in various scenarios

rainflow method is proved which can accurately estimate the REVB life loss cost.

5. Discussion and research implications

5.1. Research findings and theoretical contributions

This study investigates the feasibility of the echelon utilization of REVB in electricity markets and examines the scenarios under which economic benefits can be generated. Denmark is well-known for its mature electricity market mechanism, Danish electricity markets are therefore selected as the case study. The results indicate that applying REVB to the Danish electricity markets is not cost-effective in the current scenario, but will become economically beneficial in the scenarios when there is 10% of investment cost reduction or when electricity price in the regulation market grows by 50%. Notably, the two scenarios are realistic and can be achieved in the near future. To improve the battery performance and reduce battery investment cost, researchers have made great efforts. There is even an example where a BEV manufacturer ventured into its own battery manufacturing (Tesla Gigafactory) and has achieved a 35% reduction in battery cost (https://electrek.co/2017/, 2017). Many studies have also confirmed and demonstrated that the investment cost of batteries will be significantly reduced in the future (Schmidt et al., 2017, 2019). It is easy to understand that the investment cost reduction of new batteries will lead to the reduction of REVB investment cost. Ref (Hu et al., 2012). shows that Danish electricity price rose by over 160% from 2000 to 2010, so Danish electricity price may continue to rise in the future. Based on the above analysis, it can be concluded that the scenario of 10% reduction in REVB investment cost and 50% increment in electricity price is realistic.

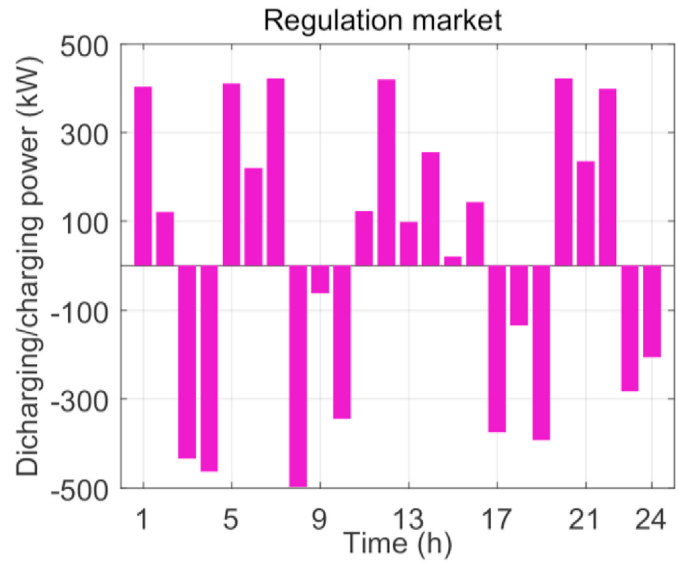

Fig. 10. The discharging/charging power of the REVB in the regulation market.

Apart from significant practical contributions to the society and business which will be discussed later, this study contributes to fill several research voids: more studies are required to investigate how the barriers of green business practices can be eliminated (de Oliveira et al., 2018); insufficient study of recycling practices that

Table 4
Simulation results for the selected scenario.

Item	Percentage of investment cost reduction	Percentage of regulation price growth	Revenue obtained from the regulation market	REVB life loss cost	Profit
Value	10%	50%	2264.3 DKK	1572.0 DKK	692.3 DKK

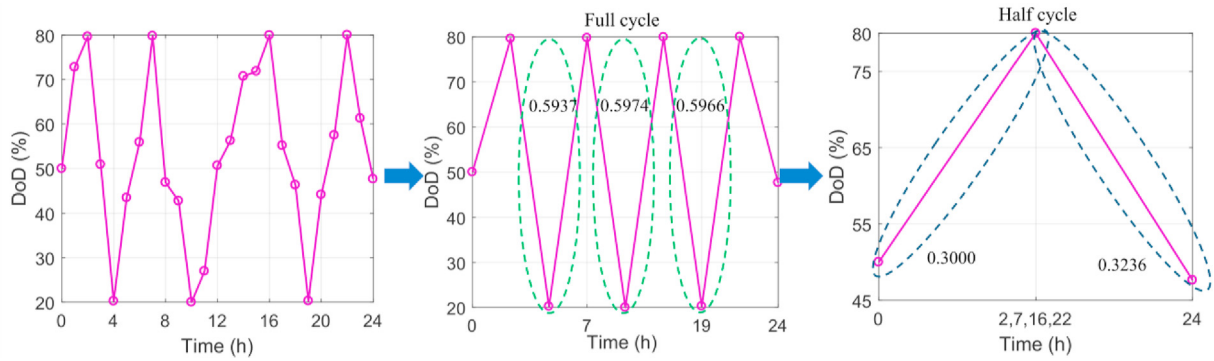

Fig. 11. The cycle counting process of REVB in the regulation market.

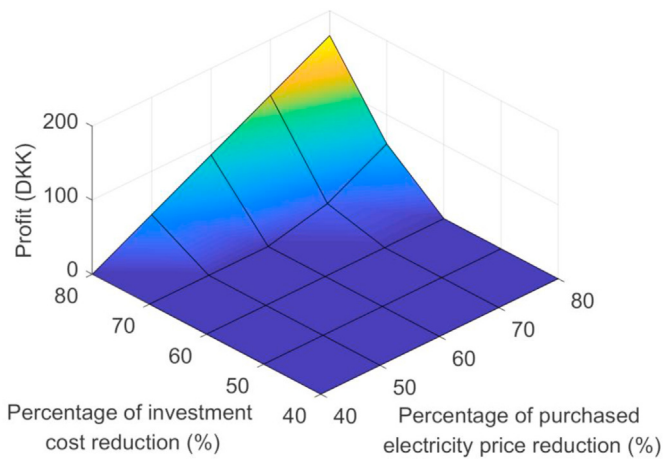

Fig. 12. Revenue of REVB participating in the day-ahead market in different scenarios.

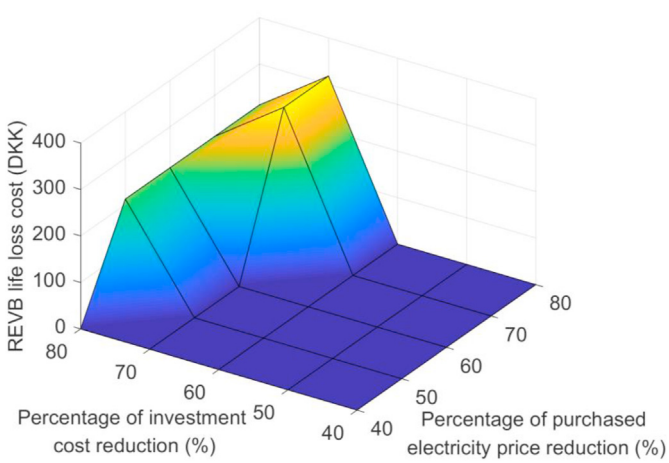

Fig. 13. Life loss cost of REVB participating in the day-ahead market in various scenarios.

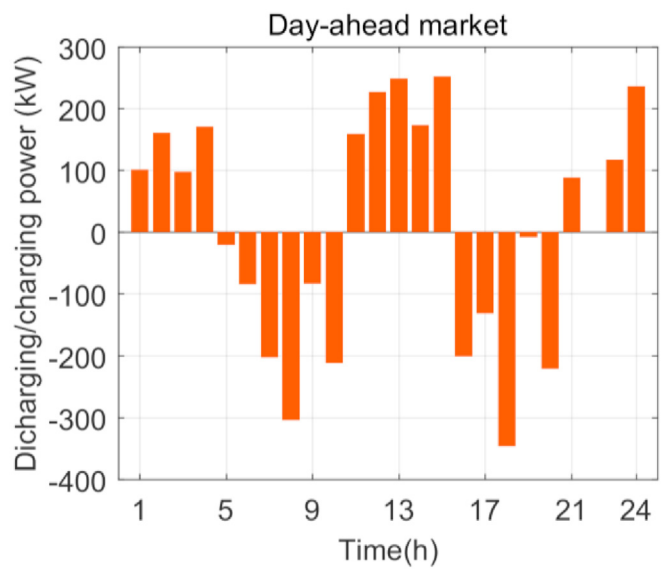

Fig. 14. The discharging/charging power of REVB participating in the day-ahead market.

are critical to environmental sustainability; and an overlook of contextual factors, such as market dynamism, which can be the contingencies determining environmental-economic performance relationship (Mardani et al., 2020). As we know a lack of managers' commitment/motivation and financial constraints are critical barriers of adopting green business operations, whereas the potential of gaining economic benefits will be a strong incentive for both enterprises and governments. However, there is a lack of understanding about under which conditions implementing GSCM practices (such as recycling and reuse) or NRBV strategies (i.e., pollution prevention, product stewardship, and sustainable development (Hart, 1995)) can make the business and environmental benefits simultaneously achievable. This study advances our knowledge in these regards. We not only propose a simple, cheap and eco-friendly strategy of the echelon utilization of REVB in

Table 5
Simulation results of REVB participating in the day-ahead market.

Item	Percentage of investment cost reduction	Percentage of purchased electricity price reduction	Revenue obtained from the regulation market	REVB life loss cost	Profit
Value	70%	70%	336.7 DKK	317.9 DKK	18.8 DKK

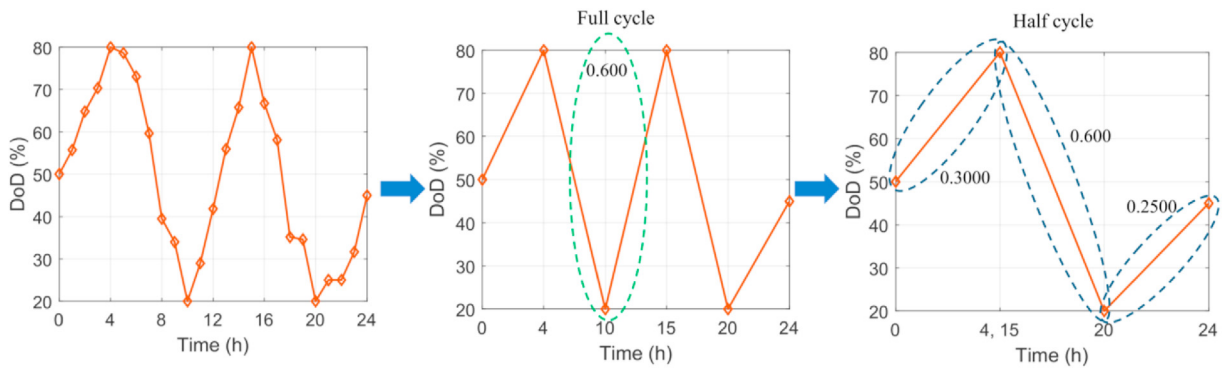

Fig. 15. The cycle counting process of REVB participating in the day-ahead market.

Danish electricity market, but also explore the scenarios under which such operation can generate the economic profits. As proposed by Ref. (Hart and Dowell, 2011), "the genesis of key resources that drive the link between environmental and financial performance" is one of the key areas for inquiry, for which we provide some insights using this specific case. Meanwhile, as they put "managers that search for opportunities to profit via pollution prevention have the potential to find such opportunities, but their prior expectations about whether such opportunities exist strongly affect their search" (Hart and Dowell, 2011). It is expected findings of this study can motivate multi-actors, such as government, enterprises, entrepreneurs, and investors, to perform and invest on such green practices, and some theoretical guidelines have also been provided.

5.2. Practical contributions (to industry, society and policy-makers)

Since REVB still have high energy value, its echelon utilization has both environmental protection and economic value. The echelon utilization of REVB can realize the comprehensive application of battery lifetime and maximize its use value and economic benefit. The investment cost of REVB is about 1000 CNY/kWh. If REVB cycle life is over 1000 times, the cost performance is better than that of lead-acid battery (http://www.elecfans.com/q, 2933). In fact, REVB cycle life is generally over 3000 times. Therefore, the echelon utilization of REVB has great competitiveness. Facing the huge development space of echelon utilization, energy storage and new energy industries can find the business opportunities. The results of this study prove the economic feasibility of applying REVB in the Danish electricity markets in the future scenarios. The energy storage industry can collect the REVB to participate in the electricity markets before recycling and dismantling. For the 10 REVB presented in this study, if the service life of REVB can reach two years, the scenario of 10% of investment cost reduction and the scenario of 50% of regulation price growth can obtain 43,800 DKK and 378,000 DKK under ideal conditions, respectively. This is a considerable income for the energy storage industry. Thereby, the development of battery technology can be promoted leading to the reduction of battery price. It can be concluded that investing in REVB in the electricity markets of the energy storage industry can form a virtuous cycle as it can help to reduce the battery price. For the new energy industry, such as wind power and solar power stations, REVB can be used to ease the fluctuation caused by the renewable energies. Notably, the power fluctuation of these stations has a negative impact on the safe and stable operation of the power grid. China has also issued related policies to limit the power fluctuations caused by the renewable energy power station. Compared to the new batteries, REVB are cheaper and its echelon utilization has the same concept of the renewable energy to achieve sustainable development. Therefore, we would say echelon utilization of REVB can a promising market of the future, BEV manufacturers, battery companies, or start-ups who manage to adopt the echelon utilization of REVB and take preemption will be able to enjoy a cost advantage over competitors, differentiating themselves, and graining reputation and social legitimacy. These elements not only can bring immediate profit but also lead to long-term competitive advantages from (natural) RBV (Hart, 1995; Barney, 1991).

The echelon utilization of REVB is beneficial to the societies. BEV owners can get a part of the effective battery cost compensation if the REVB can be utilized effectively. Thus, the cost of buying a BEV is reduced. To some extent, it reduces people's cost of life and improves their quality of life. In general, BEVs are considered to be more environment-friendly than the FFVs, but the disposal of REVB has become an increasingly serious environmental problem (Hu et al., 2017). The batteries contain large quantities of metals, rare earth elements, and toxic materials. These contents have adverse impacts on the environment and pose potential risk to human health (Richa et al., 2014). To address the environmental problems caused by the REVB and achieve sustainable development, one way is to improve battery technology, and thus lowering these contents and extending lifespan of BEV batteries. The other way is to make full use of the BEV batteries. In fact, the capacity of REVB still retain 70–80% of their original storage capacity. Although REVB cannot meet the demanding application of driving vehicles, they can still be given a "second life" for other purposes (Huang et al., 2018). Therefore, the echelon utilization of REVB can improve people's living environment as it is in line with the concept of sustainable development.

Policy schemes are expected to promote the penetration of new technologies and regulate the markets (Gaines, 2019). The results of this study indicate that the economic benefits of applying the REVB in the electricity markets in the future scenarios. The realizability of the scenarios is also proved in the previous subsection. But there are still some obstacles for the echelon utilization of REVB including immature industrialization technology and imperfect recycling system. For the immature industrialization technology, it is urgent to reformulate unified international discriminant standards of REVB, improve the detection technology of REVB and the evaluation technology of REVB residual value for echelon utilization. The imperfect recycling system is mainly caused by the lack of REVB recycling enterprises, few participants and imperfect recycling channels. Therefore, it is necessary to strengthen the coordination and cooperation between different enterprises including new energy vehicle enterprises, power battery enterprises and battery recycling enterprises, and effectively integrate resources. To

overcome these obstacles, the local government should intervene and formulates some policies on the unified international discriminant standards of REVB and coordination and cooperation between different enterprises to help the echelon utilization of REVB. These observations can offer valuable insights and illustrate how the results of this study can inform policy makers on effective inventive scheme design.

5.3. Methodological contributions

Heuristic algorithms have excellent performances for solving nonlinear problems. But in the complex nonlinear problems, the classical heuristic algorithms, e.g., PSO, GA and SA, are difficult to achieve a good effect. Therefore, the researchers often make some improvements or combine different heuristic algorithms to achieve better optimization effects. PSO is widely used in the previous literature, but it has the disadvantage of weak global searching ability. SA can just address the disadvantage. Therefore, SAPSO method which combines PSO and SA methods is selected in this study to accurately and quickly optimize the REVB operation in the electricity markets. Meanwhile, the rainflow counting method is used to estimate REVB life loss cost during the operation. Compared with other methods used to calculate battery life loss, the rainflow counting method is more accurate and more in line with the actual situation. To validate the performance of SAPSO, three method, i.e., SAPSO, SA and PSO, are compared and analyzed. The results show that SAPSO performs best among the three methods with the highest profit and fastest convergence speed. Therefore, for the operation optimization of REVB in the electricity markets, SAPSO can be a good choice to address the nonlinear optimization problem.

5.4. Future research

This study selects Danish electricity markets as the case study to investigate the economic benefits of applying REVB. In fact, the models and methods used in this study are generalized. First of all, more studies are encouraged to investigate not only green strategies/practices and incentive mechanisms, but also the conditions under which the triple bottom lines (economic, societal and environmental) can be reached simultaneously. This is important because it will motive multi-stakeholders to make a joint effort and proactively adopt green practices/strategies. Moreover, the application of REVB in other electricity markets shall be investigated and other types of REVB can be considered to conduct a more comprehensive analysis. Additionally, other applications of REVB can also be investigated, e.g., REVB can be integrated into the renewable energy generation systems to ease the power fluctuations and the home energy management system as energy storage devices to reduce household electricity bills.

6. Conclusion

This study investigates the economic benefits of applying REVB in the day-ahead market, regulation market. The objective function maximizes the profit of REVB participating in the different Danish electricity markets with considering REVB life loss cost. The REVB life loss cost which is related to the investment cost and operational strategies is calculated using the rainflow counting method. Compared to PSO and SA, SAPSO performs best in finding the optimal results. Therefore, SAPSO is selected to optimize the operational strategies of the REVB participating in different electricity markets. Both in the regulation and day-ahead market, REVB cannot obtain profit at present due to the relatively low electricity price and high investment cost of the REVB. In the regulation market, investing in REVB is feasible and advantageous when the REVB investment cost can achieve a 10% reduction or the regulation price can achieve 50% growth. In the day-ahead market, REVB can get profit when both the REVB investment cost and purchased electricity price can achieve a 70% reduction simultaneously. But this situation is difficult to occur. Therefore, it can be concluded that REVB participating in regulation market is more likely and beneficial. This study can offer REVB investors some useful and helpful suggestions on whether they can invest in REVB participating in electricity markets.

CRediT authorship contribution statement

Xiao Xu: Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing. **Weihao Hu:** Supervision, Funding acquisition, Validation, Software. **Wen Liu:** Validation, Visualization, Supervision, Data curation. **Daojuan Wang:** Theory, Methodology, Supervision. **Qi Huang:** Methodology, Supervision. **Zhe Chen:** Resources, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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