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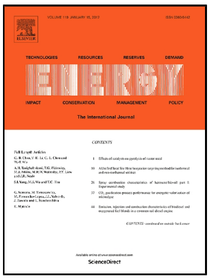

Economic Viability of Battery Energy Storage and Grid Strategy: A Special Case of China Electricity Market

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Highlights

- Presenting an arbitrage model to determine BES’s optimal scale and operation mode.
- Energy storage can realize positive profit in some districts of China.
- Analyzing the factors that may impact revenue of energy storage.
- The grid can reduce the shock of energy storage by optimizing price mechanism.

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Economic Viability of Battery Energy Storage and Grid Strategy: A Special Case of China Electricity Market

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ABSTRACT

Battery energy storage (BES) plays an important role in the integration of intermittent renewable power and distributed generation. The price arbitrage is a major source of energy storage income. In China, the electricity price is tightly regulated by the government. It's interesting to find out whether the BES is economic viability in such a special electricity market, and what's the optimal response of the grid (or regulator) when facing the arbitrage activities of BES. This research starts with a price arbitrage model to evaluate the feasibility of energy storage in China's electricity market, which can be used to determine the optimal investment scale and operation mode of energy storage. A quantitative assessment is also implemented to discuss the influence when factors change. Following this, an optimal pricing strategy for grid is established. The results reveal that the storage investment can realize positive profit in some districts where the price gap between peak/off-peak periods is high. Appropriate subsidies can be quantitatively described by sensitivity analysis. In terms of social welfare, the energy storage can be deployed on a large-scale at a low social cost under a suitable price mechanism.

Keywords: Battery energy storage; China's power market; Price arbitrage model; Pricing strategy

1. Introduction

China is currently in the process of industrialization and urbanization; hence requires large amount of energy. The sustainability of China's economic growth faces a series of environmental and energy problems. Jiang and Lin (2012) forecast that China's 2020 primary energy demand may reach 4519 to 5188 Mtce among various scenarios. By 2030, this number may reach 6000 Mtoe (8600 Mtce) according to the estimation of Brockway et al. (2015). It's obvious that the requirement of energy cannot be satisfied if it is still supplied by traditional energy in the future. The CO2 emission problem will be more serious. The economic growth in China needs to choose a low-carbon development road (Li et al., 2016). The main solution for these problems is the large-scale deployment of renewable energy sources (RES). However, the fast growing shares of intermittent RES may threaten the reliability of grid and the operation of conventional power systems. The electricity system must be seen afresh as a complex system amenable to analysis using techniques from complexity science (Bompard et al., 2015). The electrical energy storage (EES) is a key section to deal with these challenges.

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The advantages for the adoption of energy storage include (International Electrotechnical Commission, 2011): (i) promoting the penetration of renewable energy, and assisting the deployment of distribution generators (Ma et al., 2015; Notton, 2015; sedghi et al., 2016); (ii) enhancing the reliability of grid, and making more efficient use of the network (Eyer, 2009; Sioshansi et al., 2009; Saboori et al., 2015); (iii) using storage to decrease the gap between peak and off-peak periods, which can smooth the generation output (Barzin, et al., 2015; Upshaw et al., 2015);(iv) pricing arbitrage and balancing market (Bradbury et al., 2014; Salles et al., 2016).

In general, EES can be categorized into mechanical (pumped hydroelectric storage, compressed air energy storage and flywheels), electrochemical (rechargeable batteries and flow batteries), electrical (super capacitors etc.), thermal energy storage and chemical storage (hydrogen storage) (Luo et al., 2015).The most common commercialized storage systems are pumped hydro storage (PHS) and compressed air energy storage (CAES). They are known as bulk energy storage because of their high technical maturity and large energy capacity.

Although the battery energy storage technologies still have high costs, it's now mature for practical application and close to commercialization stage. The electrical arbitrage, which stores power purchased at low demand periods and sells or uses it on peak, is the major revenue components of BES. Previous studies prove the economic feasibility of electrical storage (Krishnan and Das, 2015). Carson and Novan (2013) presented a simple two-period model to examine the private and social benefits as well as the potential impact of arbitrage on emissions provided by bulk storage in the Texas electricity market. Bradbury et al. (2014) calculated the internal rate of return (IRR) of price arbitrage in the electrical market of United States, and found that in the conventional BES technologies, only ZEBRA can get positive returns in all the markets. Das et al. (2015) assessed the benefits and economics of compressed air energy storage (CAES) in the power grid. Kloess and Zach (2014) analyzed the economic performance of bulk electricity storage in the German and Austrian electricity market. Zafirakis et al. (2016) applied different energy trade strategies to evaluate the value of arbitrage in Europe market, and found the arbitrage value maximizes for the weekly back to back energy trade strategy. Salles et al. (2016) discussed the opportunities in energy arbitrage define the greatest scale for storage applications in the Mid-Atlantic region. Moreover, the arbitrage has the potential to be combined with surplus renewable energy (Andresen et al., 2014).

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Anuta et al. (2014) reviewed the grid scale electricity storage and figured out that the cost of ESS is higher than conventional solutions for covering peak electricity demand. However, in some markets with high electricity retail prices, ESS can be profitably operated by integrating with residential photovoltaic systems. Hoppmanna et al. (2014) investigated the economic viability of BES integrated with residential photovoltaic in Germany, and concluded that the net present value of battery investment is positive without policy support if the retail electrical price was 0.28 EUR/kWh and discount rate was 4%.

The return of BES is mainly affected by the cost of battery. Nykvist and Nilsson (2015) showed that industry-wide cost was estimated to decline by approximately 14% annually between 2007 and 2014. From the cost data collected by Zakeri and Syri (2015), the total capital cost of Li-ion battery was 546€/kWh on average, and 220€/kWh on average for Zn-Br. In April 2015, Tesla launched a commercial lithium battery system Powerwall where the price was only $350 /kWh (Tesla, 2015). Similarly, the price of EOS commercial zinc battery was only $160/kWh (EOS Aurora, 2015). Considering the high rate of BES's technology progress, it is necessary to evaluate the economic feasibility by using the latest cost data.

Electricity arbitrage is a market-oriented method to promote the development of energy storage. From the perspective of the grid, the existence of arbitrage enables the grid to shift peaking by adjusting power price. In some regions in China where there are large amount of imported electricity, the peak price is significantly higher than off-peak price, which creates space for arbitrage. However, few studies have focused on the economic viability of BES investment in China. Considering the characteristics of China's electricity market, this paper develops an optimization model to calculate the maximum possible revenue the BES could achieve through price arbitrage. The solution of the model provides the optimal size and operating mode under different load conditions.

To account for the uncertainties of input parameters, a comprehensive sensitivity analysis is conducted to investigate the factors which may affect the investment revenue, including lifetime, cost, discount rate, and price in peak/off-peak period. In addition, the mainstream commercial batteries are compared in this model.

The interactions among energy storage investment, grid and emissions are also important issues

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that need to be considered. Kloess and Zach (2014) examined storage revenues by simulating optimal price arbitrage in Austrian and German power market. They found that revenues from load-leveling operation have decreased considerably, indicating a strong impact of spot market prices on revenues of storage investment. Lamont (2013) revealed that storage substantially reduces the peak prices. Zafirakis et al. (2016) also demonstrated that as European markets became more efficient, the revenue of energy storage arbitrage was reduced. Liu et al. (2017) proposed a new type of energy storage - cloud energy storage - which could provide energy storage services at a substantially lower cost in the level of grid-scale storage service. Hittinger and Azevedo (2015) estimated the effect of bulk storage on net emissions and demonstrated that electricity arbitrage will increase the system emissions using current storage technologies (mainly PHS). Oliveira et al. (2015) assessed the environmental performance of different electricity storage technologies. Kanakasabapathy (2013) considered the consumer and producer surplus of the individual market, and concluded that energy storage would increase the overall social welfare of the market. To evaluate the external influence of the storage, this paper analyzes the influence of the power grid when large-scale storages are deployed. The result shows that within the current price mode, the power grid will take a huge cost if large capacity of energy storage is invested. This also shows that China's current electricity pricing mode is not sustainable. Aiming at this problem, this paper further extends the arbitrage model to establish an optimal pricing model for the grid.

The rest of the paper is organized as follows. Section 2 explains the analysis framework of this study, as well as a description of the background and methodology underlying our model. Section 3 presents the results of the economic analysis and the grid pricing strategy, including optimal profitability, external evaluation, sensitivity analysis, comparison of different batteries, and the social costs and benefits under large-scale deployment of energy storage. This is followed by a discussion in Section 4. Conclusions as well as recommendations for future analysis are drawn in Section 5.

This study focuses on BES applied in distributed network. The traditional bulk energy storage technologies, such as PHS and CAES are excluded from this study. Besides, the usage pattern is assumed to be fixed, so the demand side management and smart grid are not considered.

2. Material and methods

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This section introduces the background and methodology of our study, including the profile of China's electricity market, the layout of the energy storage system, the latest cost of batteries, the arbitrage model for the private investor and the pricing model for grid.

2.1 Profile of China's electricity market

In 2011, China's total net generating capacity reached 4.47 trillion kilowatt-hour (kWh), surpassing the 4.1 trillion kWh of United States; hence became the largest electricity consumption country in the world. Meanwhile, the distribution of power resources is imbalanced, which means the electricity load center is away from the supply side. In 2014, the annual cross-transmission of electricity in China was 274.1 billion kWh; with Interprovincial transmission amounting to 842 billion kWh, which is 15.3% of the total electricity consumption (China Electricity Council, 2015). To this end, huge resources were invested in transmission lines each year.

The transmission and distribution (T&D) of electricity are deemed as a natural monopoly industry. In China, the T&D network and electricity retail are monopolized by two giant institutions: State Grid Corporation of China and China Southern Power Grid. Meanwhile, the sale process of electricity is also monopolized by these two giants. The resource endowment, geography, and economic development level among different regions are discrepant. The government regulates the retail price according to the T&D cost and the development level of each district. The regulator implements the identical retail price for the general industrial and commercial department. In some electricity importing districts of China, the peak price is significantly higher than off-peak price. Table 1 lists the electricity price in different districts (China Southern Power Grid, 2015; State Grid Corporation of China, 2015). The time is divided into three periods: Peak, Flat and Valley. The huge price difference in these districts create opportunity for the price arbitrage, and the fixed price mode provide stable profit forecasts

2.2 Layout of energy storage system

The layout of the energy storage system is shown in Fig. 1. It includes battery system, inverter, alternating current (AC) circuit and controller (Hoppmann et al. 2014). The input and output of the battery is direct current (DC), so an inverter is use for DC - AC conversion.

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Fig. 1. Layout of energy storage system

2.3 Electricity arbitrage model

Wide spectrums of studies address the economic assessment of energy storage. Lamont (2013) develops a theoretical framework to evaluate the marginal values of the components of a storage system. One theoretical approach is applied to an example system to illustrate the changes in marginal values when energy storage penetrates into the system. The model calculates the optimal operating pattern of each hour for a single year. Solving this problem requires 17,520 (i.e., 2*8,760) inequality constraints. To simplify the calculations, the large number of inequality constraints was converted to a much smaller set of equivalent equality constraints by decomposing the model into several full charging/discharging cycles. Bradbury et al. (2014) used linear optimization to find the ESS power and energy capacities that can maximize the internal rate of return (IRR) of price arbitrage in seven real-time markets in the United States for different ESS technologies. In the study by Hoppmann et al. (2014), the NPV was calculated to find the optimal storage and photovoltaic system size.

It can be simplified when carrying out the optimization problem in China's electricity market. The main reason is that under the regulation of the government, the pricing mode is repeated every day. That is, the price is identical at the same period of every day. Therefore, in the process of optimization, it is not necessary to carry out the price data for the whole year, but only consider the price of the day. Integrating the existing arbitrage model with the characteristics of China's electricity market, this paper establishes the following model:

2.3.1 Optimization model

The model for maximizing the arbitrage revenue is defined by Eq.(1), where NPV is the net present value of storage investment. The NPV which is determined by the earnings before interest depreciation and amortization (EBIDA), the total capital cost (TCC), the residual value (Res) and the discount rate (R), is presented by Eq.(2). Since the residual value is difficult to determine, the residual value is set to be 0 in this paper.

$$\max\ NPV \qquad (1)$$

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$$NPV = \left[\sum_{i=1}^{lifetime} EBIDA \Big/ (1+R)^{i} \right] - TCC + Res \Big/ (1+R)^{lifetime} \qquad (2)$$

TCC can be calculated by the cost of storage battery (C_{Stor}) and inverter (C_{Inver}) by using Eq.(3).

$$TCC = C_{Stor} + C_{Inver} \qquad (3)$$

EBIDA is presented by Eq.(4). It equals the annual cost reduction and the storage capacity. The cost reduction per day is equal to the cost variation before and after the application of storage system (Eq.(5)). The original cost and optimal cost are shown in Eq.(6) and Eq.(7), in which the electricity consumption is denoted by c_i,the price of electricity purchased from grid g_i is denoted by p_i.

$$EBIDA = 365 \times \mathrm{Cos}t\_red_{day} \Big/ Storage\ Capacity \qquad (4)$$

$$cost\_red_{day} = cost_{ori} - cost_{opt} \qquad (5)$$

$$cost_{ori} = \sum_{i=1}^{24} c_i \times p_i \qquad (6)$$

$$cost_{opt} = \sum_{i=1}^{24} g_i \times p_i \qquad (7)$$

The stored quantity of electricity is given by Eq.(8). It equals the sum of net input into the storage system x_i and the initial storage quantity s_0. The sum of net input power in one day is zero (Eq.(9)). The electricity purchased from grid is determined by the consumption and the net input, as presented by Eq.(10). If $x_i < 0$, the system discharges power. If $x_i \geq 0$, the system is in charge process. The energy loss in conversion process is reflected by the battery's efficiency η_{bat} and the inverter's efficiency η_{inv}.

$$s_t = s_{t-1} + x_{t-1} = s_0 + \sum_{i=1}^{t-1} x_i \qquad (8)$$

$$\sum_{i=1}^{24} x_i = 0 \qquad (9)$$

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$$g_i = \begin{cases} c_i - x_i/\eta_{inv} \times \eta_{bat} & x_i < 0 \\ c_i - x_i/\eta_{inv} & x_i \geq 0 \end{cases} \quad (10)$$

The input matrix can be defined by Eqs. (11)-(14). The net input in each hour is less than the power limitation (Eq.(15)), and the stored quantity in each hour is greater than 0 and less than the max storage capacity (Eq.(16)). In our case, investor can only purchase electricity from the grid. The power stored in the system can only be used by the investors themselves, and it cannot be sold in the wholesale electricity market, as presented by Eq.(17).

$$X = \begin{bmatrix} x_1 & x_2 & \cdots & x_{24} \end{bmatrix}_{1\times 24} \quad (11)$$

$$S = \begin{bmatrix} s_1 & s_2 & \cdots & s_{24} \end{bmatrix}_{1\times 24} \quad (12)$$

$$C = \begin{bmatrix} c_1 & c_2 & \cdots & c_{24} \end{bmatrix}_{1\times 24} \quad (13)$$

$$P = \begin{bmatrix} p_1 & p_2 & \cdots & p_{24} \end{bmatrix}_{1\times 24} \quad (14)$$

$$-1 \times power \leq X \leq power \quad (15)$$

$$0 \leq S \leq s_{\max} \quad (16)$$

$$C - X \geq 0 \quad (17)$$

The optimization problem is solved by the optimum toolbox of MATLAB. As is shown in Eq.(18), the decision variables include the capacity of storage, initial storage quantity and the net input into the storage system in each hour. The objective function is given by Eq.(19), which is structured by Eqs.(2) -(7). The inequality constraint, Eq.(20), is organized by Eq.(8), Eq.(10), and Eqs.(15)-(17). The equality constraint in Eq. (21)is build by Eq.(9).

$$Input = [s_{\max} \quad s_0 \quad x_1 \quad \cdots \quad x_{24}]^T_{26\times 1} \quad (18)$$

$$NPV = f(Input) \quad (19)$$

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$$A_{uneq} * Input \le B_{uneq} \qquad (20)$$

$$C_{eq} * Input = D_{eq} \qquad (21)$$

2.3.2 Specification of model parameters

The profitability of storage investment might be affected by the load mode. For this reason, 6 scenarios are simulated to compare the optimal storage size and investment revenue. The dynamic load curves are displayed in Fig. 2, with a normalized load data.

Fig. 2. Dynamic load curves under different scenarios

The parameter setting of the electricity storage system is given by Table 2. The parameters of battery system are referring to the correlation data of Tesla Powerwall. The degradation of lithium-ion batteries over time is taken into account. The depth of discharge (DOD) of the battery is decrease with the cycles increase (Dufo-López and Bernal-Agustín, 2015). We assume the average DOD of the storage is 80% during the lifetime, so the cost corresponding includes a 20% markup accordingly. In addition, cost and efficiency of the inverter are also considered therein. The conversion efficiency of inverter is set as 97%.

The cost of battery is a main factor affecting the applications of BES. It is generally considered that BES is still subject to higher costs and temporarily unable to carry out large-scale commercial applications. However, many studies of BES were presented few years ago, and the cost estimation from different literature vary widely (Walawalkar et al., 2007; Dunn et al., 2011; Larcher and Tarascon, 2015). These may make it hard to evaluate the economic feasibility of energy storage technology. In recent years, the cost of battery declined significantly. It's necessary to use the latest data when carrying out the economic evaluation of energy storage. Table 3 shows the technical parameters of some commercialized BES products (Shahan, 2015).

2.4 Pricing strategy for the grid

In practice, there has been a controversy about electricity arbitrage based on energy storage for the reason that energy will be lost in the charge/discharge cycle of storage, and power consumption will increased. Carson and Novan (2013) examined the social benefits of bulk storage in the Texas

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electricity market by analyzing the marginal emissions during peak/off-peak periods; they demonstrated that arbitrage will decrease the daily average emissions of NOX and increased daily average emissions of CO2 and SO2. Hittinger and Azevedo (2015) modeled the economic and emissions effects of bulk energy storage in American, and got similar conclusions. Though the energy storage may increase the emission, the social welfare will increase due to the marginal utility of electricity is different intertemporal. Kanakasabapathy (2013) graphically analyzed the changes in consumer and producer surplus of a market due to pumped storage energy trade, and concluded that energy storage will increase the overall social welfare of the market.

As is shown in Table 4, due to the fact that energy storage investors only consider the private cost, the energy storage may result in negative effects such as increase in total electricity consumption, and exacerbation of load fluctuation of the power grid. More importantly, in China, most of the social cost is undertaken by the grid under current price model. The power grid is likely to adjust price to deal with the expansion of the scale of energy storage, which may increase the uncertainty of storage investment. Lamont (2013) illustrated the changes in marginal values as storage penetrated the system and indicated that storage substantially reduced the peak prices. So it’s important to figure out whether there exists a way to guide the storage system playing its peaking functions and to reduce the negative impact through pricing optimization as far as possible. To solve this problem, on the basis of the electricity arbitrage model, this section further develops a power grid pricing model.

2.4.1 Two level optimization model

The price arbitrage will reduce the revenue of power grid. Obviously, the current pricing mode is not sustainable if the energy storage is developed rapidly. From the point of the power grid, how to optimize pricing is an important issue. Since China's electricity pricing is regulated by the government, any decision to change the pricing mode may be affected by the interests of the stakeholders. In order to reduce the resistance associated with the reform of the pricing mechanism, it has been hypothesized that: from the perspective of the grid, it is hoped that through the development of distributed energy storage, the peak load may decrease, while the grid's revenue remain unchanged. From the user's point of view, they will determine their optimal energy storage investment size and storage model based on the given price. This constitutes a two level optimization problem:

The objective of grid's pricing strategy is to minimize the peak load (Eq.(22)), where the incomes remain unchanged (Eq.(23)). In this equation, $Earn_{ori}$ represents the original revenue, which is the sum of the original electricity price multiplied by the power consumption (Eq.(24)). While $Earn_{opt}$ represents the revenue after deploying energy storage, which is the sum of the optimal electricity price multiplied by optimal purchases (Eq.(25)).

$$\min\ load_{\max}(P) \qquad (22)$$

$$S.T.\ Earn_{ori} = Earn_{opt} \qquad (23)$$

$$Earn_{ori} = \sum_{i=1}^{24} p_i^{ori} * c_i \qquad (24)$$

$$Earn_{opt} = \sum_{i=1}^{24} p_i^{opt} * g_i \qquad (25)$$

The consumer uses the arbitrage model to maximize the private benefits of energy storage investment as shown in Section 2.3.

2.4.2 Simplified model

Since the two-level optimization problem is difficult to solve by the conventional algorithm, the model is simplified into a single-stage optimization problem. The objective of the model is still to minimize the peak load (Eq. (26)), while the decision variables are composed of the energy storage capacity, initial energy storage volume, net energy input of the system and the electricity price of each hour (Eq.(27)). The grid gets constant returns (Eq.(28)). The NPV of storage investment is set to be larger than the target value (Eq.(29)).

$$min\ \ load_{\max}(Input2) \qquad (26)$$

$$Input2 = [S_{\max} \quad S_0 \quad x_1 \quad \cdots \quad x_{24} \quad p_1 \quad \cdots \quad p_{24}]_{50\times1}^{T} \qquad (27)$$

$$S.T.\ Earn_{ori} = Earn_{opt} \qquad (28)$$

$$NPV \geq NPV_{goal} \qquad (29)$$

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3. Results

As private decision, the goal of energy storage investment based on electricity arbitrage is to maximize the private benefits. However, the externality should not be neglected. Thus, the economic viability of energy storage investment is evaluated, and meanwhile, the yields of energy storage investment and its externality are analyzed. In order to analyze the effect of income level when changing the factors which are related to the investment yields, a sensitivity analysis is conducted in this section. Due to the fact that features of each commercial energy storage battery systems are different, their investment income and external influences will be different as well. Therefore, different battery systems are compared in this section.

Grid pricing model is aimed at the question that how to adapt the grid to the large-scale development of energy storage system, and what's the corresponding impact on society. This section mainly consider the influence on social costs and benefits when the energy storage is extensively developed, including the influence from the increase of power consumption and corresponding costs, the balance of power grid load, etc.

3.1 Economic evaluation of energy storage investment

3.1.1 Benefits of grid's arbitrage model

Fig. 3 shows the net present value per unit investment under different load mode in various districts. As represented by formula(30), the net present value per unit investment (NPV_{unit}) is equal to the net present value of investment divided by investment spending. The profitability of investment can be directly compared in accordance with NPV_{unit} . As can be seen in the figure, under the same price mode (same district), the NPV per unit investment is similar for different scenarios.

$$NPV_{unit} = NPV/TCC \qquad (30)$$

The result in Fig. 3 confirms other current research. Bakkee et al. (2016) calculated the revenues of lithium-ion batteries in the German and UK markets, and found that the NPV could be positive under a interest rate of 4%. The payback period is 6.3 years in UK and 7.6 years in German. Wankmüller et al. (2017) presented that the break-even system cost of BES is 409 $/kWh under 7%

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interest rate.

Fig. 4 shows the dynamic simulation curve in 24 hours, which demonstrates the load of shopping mall in Jiangsu Province. Where "consumption" means the actual amount of consumption for customers, "purchase" means the amount of purchased electricity from grid, "price" means electricity price, "power flow" means the amount of electricity flow out the storage system, and "storage" means the charge capacity of energy storage system. If "power flow" is higher than zero, the system is in the process of discharge, else if the "power flow" is below zero, the system is charging.

Fig. 3. Optimal NPV per unit investment in different districts

Fig. 4. Dynamic simulation curves of the energy storage system in 24 hours

3.1.2 Externalities

During the operation of the energy storage system, the system charges in low electricity price periods, and discharges in high electricity price periods. The private investment only considers the maximization of private yields, and overlooks the external costs. Therefore, it is necessary to evaluate the externalities of the energy storage investment. As can be seen from the data in Table 4, in the power of arbitrage, the total electricity consumption increases, which is mainly cause by the power loss in charge/discharge process. In addition, the grid revenue reduces significantly. For the most significant one, the revenue of grid drop is decreased by 31.1%. Besides, because the private investment only considers profit maximization when making decisions, the energy will be stored when it is in flat period (as can be seen in Fig. 2, 13:00 to 16:00). Some purchasing electricity of peak period will transfer to flat period, causing a new peak which may be higher than the original load.

3.1.3 Sensitivity analysis

The investment income of the energy storage is affected by many factors, including discount rate, life of energy storage system, peak electricity prices, valley electricity prices, and the cost of energy storage system investment. The impact on investment income of those factors is analyzed in this section.

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Fig. 5 shows the change of NPV_{unit} under different lifetime. The NPV_{unit} can be used to evaluate the impact on investment benefit when the lifetime of the battery is change with the technology progress. As can be seen in the figure, under the 10-year warranty period of the Tesla, there are two districts can achieve positive net present value income. And if the15-year useful life of the battery is estimated, there are six districts that can achieve positive net present value income. Furthermore, if the lifetime can be extended to 20 years in the future, all districts can achieve positive net present value income.

Fig. 5. NPV per unit investment under different lifetime

Fig. 6 shows the NPV_{unit} under different battery costs. According to the figure, the changing of investment income can be measured when the battery costs reduction due to the development of technology.

Fig. 6. NPV per unit investment under different battery cost

As can be seen in Fig. 7, the changes of discount rate will infuence the income of the energy storage. Table 5 presents the average interest rate in China from 2005 to 2014 (calculated by the statistical data published by the World Bank). For commercial users, one third of the districts can achieve positive yields if the investment yields are calculated by the loan interest rate. For household users, more than half of the districts can achieve positive yields if the investment yields are calculated by deposit rate. If the electricity price in future is adjusted with the inflation, a positive yields can be achieved in most districts calculated by real interest rate.

Fig. 7. NPV per unit investment under different discount rate

The investment income of the energy storage will be significantly influenced by the peak-valley price. Fig. 8 show the impact on the energy storage investment income of the peak price in different change range.

Fig. 8. NPV per unit investment under different ratio of peak price variation

3.1.4 Comparison of various batteries

As shown in Table 3, the technical characteristics of current commercial batteries have

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significant difference. To make a comparison between different types of batteries, this paper inputs the relevant parameters into the model. The results are displayed in Fig. 9 and Fig. 10. From the net present value of unit investment for different types of batteries which is given by Fig. 9, the investment income of lithium-ion battery is not remarkable compared with Eos Aurora and Imergy whose NPV is higher. This is mainly due to the fact that Eos Aurora has lower unit cost, and reaches a lifetime of 15 years; Imergy has a lifetime up to 30 years, leading to a higher final return on investment.

But it's important to note that the charge and discharge efficiency of lithium-ion battery is higher; the power loss during the storage process is smaller than the other ones correspondingly. As is shown in Fig. 10, the incremental electricity consumption of lithium-ion battery is much lower than other brands of batteries, and the external cost is lower correspondingly.

Fig. 9. NPV per unit investment of different batteries

Fig. 10. Increment of electricity consumption of different batteries

3.2 The steady state under optimal pricing strategy

Since it's difficult to find the load characteristics in the open data, in our calculation, the data of a wider area are used to represent the load characteristics of each district. For instance, the load curves of Beijing, Tianjin and Hebei are uniform. Shanghai, Zhejiang, and Jiangsu use the load data of eastern China power grid (Fan and Xie, 2014).The load curves of Guangzhou and Shenzhen quote the load characteristic data of Guangdong power grid (Cai and Li, 2014). It is notable that this analytical method is also applicable to evaluate the single user.

The comprehensive influences are considered from the following dimensions:

No matter how the price is setting, the cost of energy storage will finally be reflect in the electricity price and paid by the customer. The "Expense Increment (EI)" represents the increase of total social electricity expenditures caused by using energy storage systems, which can be calculated by Eq.(31). The annual cost of energy storage investment C_a is represented by Eq.(33), which is deduced from Eq.(32). It should be noted that the application of energy storage may bring some positive externalities such as a lower grid investment and higher power plant efficiency. So the actual

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social cost may lower than the EI when allocating energy storage.

$$EI = C_a \Big/ \left[365 * \left(\sum_{i=1}^{24} p_i^{ori} * c_i \right) + C_a \right] \qquad (31)$$

$$\sum_{i=1}^{lifetime} \frac{C_a}{(1+R)^i} = TCC \qquad (32)$$

$$C_a = R * (1+R)^{lifetime-1} * TCC \Big/ \left[(1+R)^{lifetime} - 1 \right] \qquad (33)$$

Due to there exist energy loss in the charge/discharge process, the final power consumption will increase. The rate of “Power consumption increment (PI)” can be calculated by Eq.(34).

$$PI = \sum (g_i - c_i) \Big/ \sum c_i \qquad (34)$$

The load of grid may be more smoothly by the use of energy storage. We can compare the relative standard deviation (RSD) of load characteristic before and after applying the energy storage.

“Storage vol. vs. Day Consumption (SC) ” is the ratio between the volume of storage and daily consumption, which can be used for measuring the relative scale of energy storage. The value can be calculated by Eq.(35).

$$SC = S_{\max} \Big/ \sum_{i=1}^{24} c_i \qquad (35)$$

The final state is defined as “steady state”. In the steady state, the max load can be minimized under the constraints. Table 6 presents the variation of each valuable under the steady state, and Fig. 11 provides an intuitive example which demonstrates the simulated result of shopping mall in Jiangsu province. The load fluctuation of the grid is decrease under the more flexible price strategy.

Fig. 11. The comparison before and after using optimal strategy

4. Discussion

The previous section shows the economic evaluation results of private energy storage investment and the equilibrium under optimal grid pricing strategy. These results will be discussed in this section.

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4.1 Discussion of energy storage investment

According to the cost analysis, the energy storage investment is able to achieve positive returns in some districts. The comparison results in different districts demonstrate that, the higher the price difference between peak and off-peak period is, the better the returns from energy storage system will be. Under the existing peak-valley price, some districts, especially those who have high price variance, such as Beijing and Jiangsu, can be attracted by the energy storage returns. But a stable expectation should be given to investors. A contract with a stable long-term peak-valley price deviation may be effective. In other districts like Guangzhou, Shenzhen, Zhejiang, Hebei, etc., the development of energy storage relies on some appropriate incentives, such as direct subsidies for equipment investment, preferential loan rates, higher peak-valley price variance, etc.

The peak-valley price variance of Shenzhen is higher than Zhejiang, but Zhejiang has a higher NPV. This can be attributed to availability of a better system brought by three peak period in Zhejiang. So it can improve the economic feasibility by using more complex peak-valley division way, and optimizing the setting of peak and valley period.

Under the same pricing policy, the net incomes of different types of load patterns have little difference. The main reason is that the energy storage system supplies power outside in peak period and stores power in valley period. So the income is mainly affected by the peak-valley price variance, and the division way of peak-valley period. The peak-valley price variance affects energy storage income per cycle, and the division way of peak-valley period determines the efficiency of the energy storage system.

According to the externality analysis, the power consumption will increase due to the energy loss in the charging/discharging process. The increment ratio falls within the range of 2.9% to 6.7% in different districts. Overall, the growth of power consumption is not obvious. Due to the arbitrage profit and cost come from the power grid; the income of grid may decline significantly (13.2% - 31.1%). Furthermore, the operation of energy storage is mainly related to price variance and time period; this may leads to a higher peak load (an increase of 54.7% - 127.7%).Therefore, in accordance with the current pricing mode, the grid will undertake huge cost. With regards to this consideration, the current pricing mechanism of the grid is not sustainable and must be adapted to the development of the energy storage.

The sensitivity analysis shows how the income level will change with the influence factors. The extension of the service life can improve the income level of the storage investment. In accordance with the expected lifetime of 15 years, the energy storage investment can achieve positive returns in most districts. In addition, reducing investment costs can also significantly improve the income level. Under the estimated commercialized cost of \$250/kWh, most districts can obtain positive returns. Besides, the discount rate and peak-valley price variance have a certain impact on returns. Analysis in this section can provide valuable information for making subsidy policies. The analysis can quantitatively calculate the impact on returns by using direct investment subsidies, prime rate, adjustment of peak-valley price, etc.

Comparing the NPV and externality of different batteries, it can be found that although the investment return of Tesla's lithium battery is not the highest, the increment of the power consumption during charge/discharge process is minimal, and the corresponding external costs are relatively low owing to its high charge and discharge efficiency.

4.2 Discussion on the optimal pricing strategy of grid

The peak load can be effectively reduced by applied the pricing strategy of grid. As can be seen from Table 6, in the final steady state, the maximum load of the grid is declined significantly in various districts. At the same time, the relative standard deviation of the load greatly reduced under the optimization state. This is very meaningful in practice. On the one hand, the maximum load of the grid needs to adapt the peak load, so the more balanced the load is, the less the investment of grid is needed. On the other hand, a more balanced load can improve the operating efficiency and stability, which will reduce the cost of power plant.

After optimization, the increment of power consumption led by the energy storage only account for a small proportion in total power consumption. As can be seen from Table 6, the increment rate ranges from 0.7% to 1.1%.Some researches figured out that the current energy storage technologies may increase the electricity consumption due to the energy loss in the charge/discharge process. But if the energy storage system can be applied in a reasonable way, the power plant will be maintained at the optimum operating conditions. These may reduce the consumption of fossil fuels. Therefore, the carbon emissions caused by energy storage should be evaluated by further research.

With reference to the cost of electricity, the whole society's expenditure increases, ranging from

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6.1% to 11.2%. It should be noted that, in the setting of the model, the income of the grid is assume to remain unchanged in the hypothesis of the model, the cost of this increased expenditure is burdened by the consumer. But in actual operation, cost of the increased part can be transferred to the grid or supplied by government subsidies.

Under the steady state, the amount of electricity consumption per day is among the proportion of 4.6%-7.4%. This date demonstrates that the growth space of the energy storage investment is huge in the future. In Jiangsu province, for example, the total power consumption is 495.66 billion kWh in 2013. If energy storage capacity reached 50% level of the steady state, the requirement (of energy storage) will be 37.344 million kWh.

5. Conclusions and policy implications

Energy storage technologies might be one of the most crucial parts of energy system in the future. Whether the energy storage system can be economically feasible is an important question for policy makers and investors. In this paper, one optimal arbitrage model is established to analyze the benefit from the price arbitrage based on the peak and off-peak power price gap in China. Through the evaluation of economic feasibility, it can be found that the investment of energy storage can achieve positive returns in some districts. This result reveals an inspiring fact that the energy storage investment is already profitable without subsidies under some districts, and the development of energy storage can be promoted by the power of the market even without subsidies.

Moreover, this paper evaluates the quantitative relationship between investment revenue and impact factors such as the lifetime, cost per unit capacity, discount rate and peak-valley price. The results reveal that the storage investment can get a positive NPV in most districts if the lifetime of battery can be increased to 15 years or the cost can be reduced to \$250/kWh (which is expected as the cost of Tesla energy for utilities). A higher peak/valley price variation and a lower discount interest rate also have significant positive influence for the NPV. Besides, the investment revenue may be affected by the division method of peak-valley periods. These findings will help predict the influence of the large-scale energy storage system deployment, as well as provide useful information for the policy formulation. Furthermore, external influence of energy storage is analyzed. The application of energy storage technology will increase electricity consumption, and make a larger cost for grid. Hence, the current pricing method is not sustainable. Finally, by comparing the mainstream commercial batteries, it can be concluded that though the NPV of lithium battery is relatively low due to the high device cost, the social cost of the lithium battery is smaller than other rivals if consider the externalities. This result provides a reference for the BES's technology selection at grid level that the policy should focus on the lithium battery.

With the development of BES, the revenue of the power grid will reduce under current price mechanism. As an extension of the arbitrage model, this paper establishes an optimal pricing model from the point of view of the grid. The simulate results indicate that the grid could relieve the shock of energy storage by formulate a more elastic price model. Under the optimal price mechanism, the load of the grid will be more balanced, and the power plant will be able to run more stably and efficiently. The optimal investment scale under steady state is also estimated. The result reveals that there exists huge space for the deployment of BES.

The conclusions of this study have proposed a series of useful information for policy makers and stakeholders. The crucial points are as follows:

- According to the result of economic viability analysis, the cost of energy storage has already declined to the level of practical application under some certain conditions. With the sustained decline in cost, the BES may possess the potential to be large-scale deployed in the near future. The stakeholders such as power grid, power plant, distributed generators, consumer and market regulator, should change their strategy and behavior to adapt this new transformation.
- The BES owns externalities. On the one hand, energy storage may enhance social welfare. On the other hand, the final electricity consumption may increase due to the energy loss. These influences should be systematically considered when making the support policy.
- The grid enterprise may suffer shocks from energy storage; the current pricing mode is not sustainable. This implies that the current price mechanism of China's electricity market needs a further reform. This research proposes a pricing strategy for the grid, which can prompt the BES running at an effective way.

With the development of energy storage technology, significant changes may happen in the world's energy market. The power grid and power plant may operate more efficiently, and the ability to absorb the renewable energy may be enhanced. It can be expected that in the near future, these changes may profoundly impact the energy structure of the world, and even the way of human's live.

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Table 1.Electricity price in different districts

District	Peak		Flat		Valley	
	Period	Price[a] RMB/kWh	Period	Price RMB/kWh	Period	Price RMB/kWh
Beijing general industrials	8:00-11:00 18:00-21:00	1.4182	7:00-8:00 15:00-18:00 21:00-23:00	0.8925	23:00-7:00	0.3928
Beijing Commerce	8:00-11:00 18:00-21:00	1.4402	7:00-10:00 15:00-18:00 21:00-23:00	0.9145	23:00-7:00	0.4148
Shanghai	8:00-11:00 18:00-21:00	1.226	6:00-8:00 11:00-18:00 21:00-22:00	0.764	22:00-6:00	0.363
Tianjin	8:00-11:00 18:00-23:00	1.3689	11:00-18:00	0.9149	23:00-7:00	0.4829
Guangzhou etc.	14:00—17:00 19:00—22:00	1.0766	8:00-14:00 17:00-19:00 22:00-24:00	0.6525	0:00-8:00	0.3263
Shenzhen	14:00—17:00 19:00—22:00	0.9778	8:00-14:00 17:00-19:00 22:00-24:00	0.6930	0:00-8:00	0.3090
Zhejiang	8:00-11:00 13:00-19:00 21:00-22:00	1.1426	—	—	11:00-13:00 22:00-8:00	0.6196
Jiangsu	8:00-12:00 17:00-21:00	1.4585	12:00-17:00 21:00-24:00	0.8751	0:00-8:00	0.3917
Hebei	8:00-11:00 18:00-23:00	0.9562	7:00-8:00 11:00-18:00	0.4310	23:00-7:00	0.3653

[a] In some districts, the price is different in summer. Due to the summer price is only implement in a short time, and the price variance is small, so the model only consider the price which is implemented in most of the time. There exist cross subsidization when making the price, for example the price of resident is lower than other department. The paper use general industrials and commerce price mode in the research.

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Table 2. Parameter setting of electricity storage system

Discount rate	—	0.06
Unit cost of battery	RMB/kWh	350*6.25/0.8
Unit cost of inverter	RMB/kW	800
Maximum power/storage capacity	1/h	0.25
Battery efficiency	—	0.92
Inverter efficiency	—	0.97
Lifetime	year	10

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Table 3. The parameters of some commercialized BES products

Battery		Tesla Powerwall	Tesla for Utility (Estimate)	Eos Aurora 1000│4000	Imergy (Current)	Imergy (Projected)
Technology		Li-ion	Li-ion	Zinc hybrid cathode	Vanadium Flow	Vanadium Flow
Overall efficiency	%	92	92	75	70-75	70-75
Lifetime	Years	10	10	15	30	30
Life cycles	Cycles	5000	5000	5000	10000	10000
Unit cost	$/kWh	350	250	160	500	300

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Table 4.Externalities of energy storage system

District	Power Consumption Increment	Grid Revenue Reduction	Max Load Increment	Storage Vol vs. Day Consumption	NPV per Unit Investment
Beijing	2.9%	-16.4%	63.8%	12.3%	0.053
Shanghai	2.8%	-15.4%	57.1%	11.7%	-0.105
Tianjin	3.3%	-13.2%	59.7%	11.6%	-0.044
Guangzhou	3.8%	-20.1%	87.6%	15.6%	-0.212
Shenzhen	3.8%	-16.9%	87.5%	15.6%	-0.351
Zhejiang	4.6%	-14.4%	93.0%	16.0%	-0.317
Jiangsu	6.7%	-31.1%	127.7%	22.7%	0.226
Hebei	3.3%	-17.9%	54.7%	11.7%	-0.197

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Table 5.Average interest of China during 2005-2014

Deposit interest rate (%)	2.84
Lending interest rate (%)	5.98
Real interest rate (%)	1.60

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Table 6. The variation under optimal pricing mode

District	Expense Increment	Power Consumption Increment	Max Load Variation	Load RSD before Optimal	Load RSD after Optimal	Storage Vol vs. Day Consumption
Beijing	9.1%	1.1%	-8.9%	0.132	0.091	7.4%
Shanghai	6.6%	0.7%	-14.3%	0.117	0.000	4.6%
Tianjin	6.3%	0.9%	-12.1%	0.132	0.000	5.5%
Guangzhou	9.9%	1.0%	-16.3%	0.158	0.000	6.2%
Shenzhen	10.5%	1.0%	-16.3%	0.158	0.000	6.4%
Zhejiang	6.1%	0.7%	-14.3%	0.117	0.000	4.7%
Jiangsu	6.1%	0.7%	-14.2%	0.117	0.003	5.5%
Hebei	11.2%	1.0%	-10.4%	0.132	0.054	6.1%

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Nomenclature

c_i : Electricity consumption at time i (kWh)

C_{Inver} : Cost of inverter (RMB/kWh)

$Cost\_red_{day}$: Cost reduction per day (RMB/day)

C_{Stor} : Cost of storage battery (RMB/kWh)

$Earn_{opt}$: Revenue after deploying energy storage (RMB)

$Earn_{ori}$: Original revenue (RMB)

$EBIDA$: Earnings before interest depreciation and amortization (RMB)

g_i : Electricity purchased from grid at time i (kWh)

$load_{\max}$: Peak load (kW)

NPV : Net present value of storage investment (RMB)

NPV_{goal} : target net present value per unit investment (RMB/RMB)

NPV_{unit} : Net present value per unit investment (RMB/RMB)

p_i : Electricity price (RMB/kWh)

p_i^{opt} : Optimal price (RMB/kWh)

p_i^{ori} : Original price (RMB/kWh)

R : Discount rate

Res : Residual value (RMB)

s_0 : Initial storage (kWh)

s_i : Storage volume of system at time i (kWh)

$s_{\max}$: Max storage capacity (kWh)

TCC : Total capital cost (RMB)

x_i : Net input into the storage system

η_{bat} : Efficiency of battery

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699 η_{inv} : Efficiency of inverter

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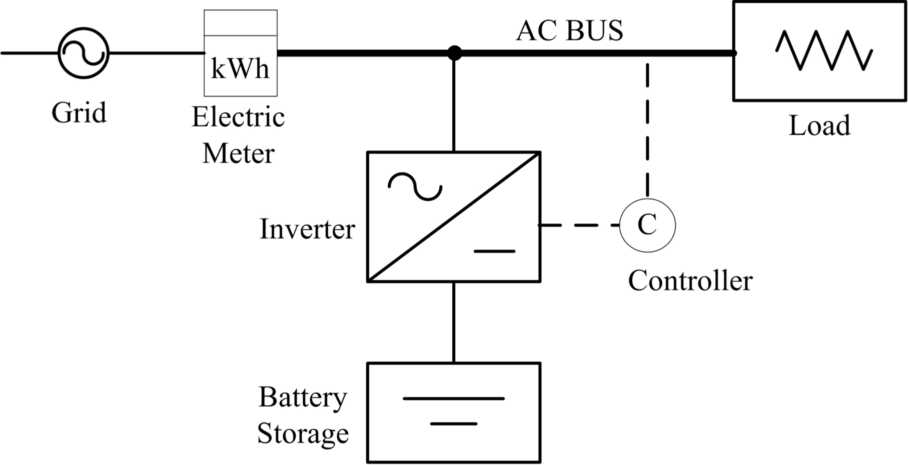
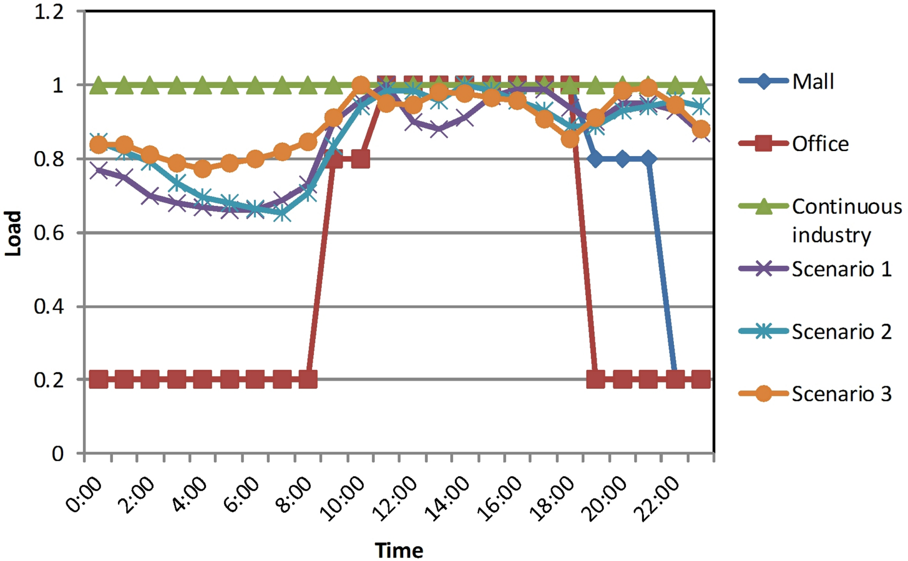

AC BUS
kWh
Grid
Electric
Meter
Load
Inverter
C
Controller
Battery
Storage


1.2
1
0.8
0.6
0.4
0.2
0
Load
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2:00
4:00
6:00
8:00
10:00
12:00
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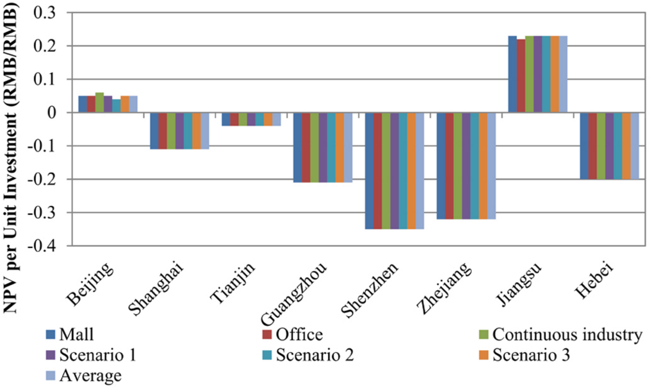
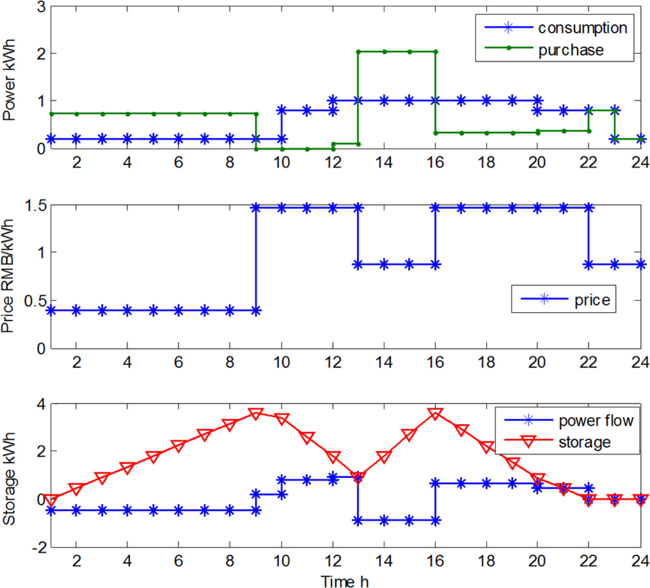
16:00
18:00
20:00
22:00
Time
Mall
Office
Continuous industry
Scenario 1
Scenario 2
Scenario 3


NPV per Unit Investment (RMB/RMB)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei
Mall
Office
Continuous industry
Scenario 1
Scenario 2
Scenario 3
Average


Power kWh
consumption
purchase
Price RMB/kWh
price
Storage kWh
power flow
storage
Time h
3
2
1
0
1.5
1
0.5
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4
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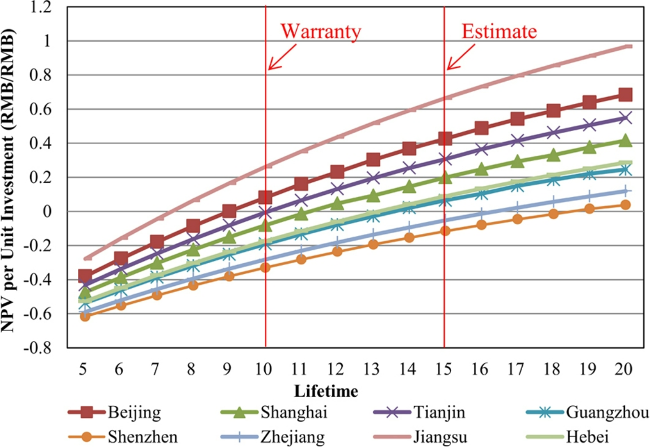
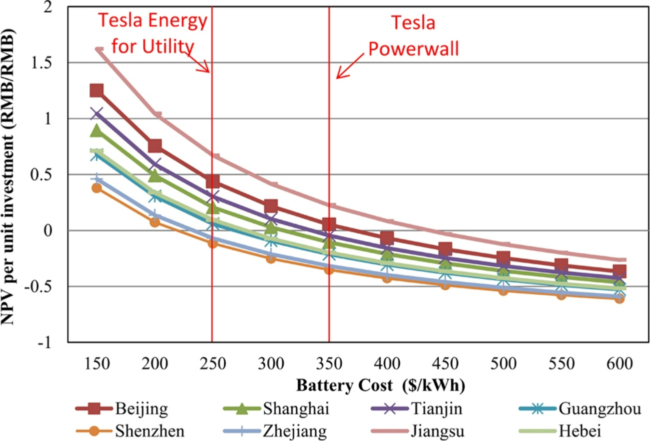
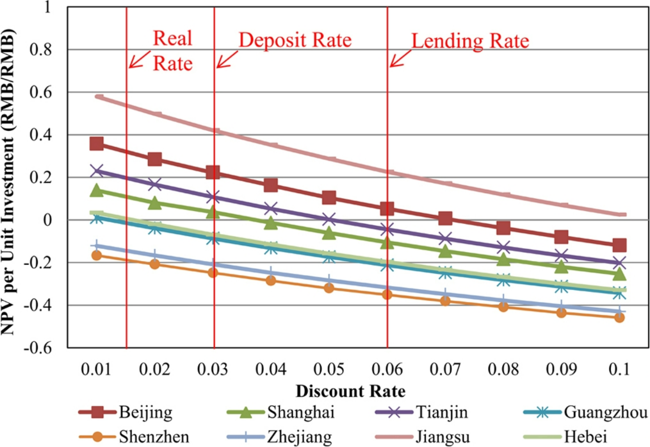
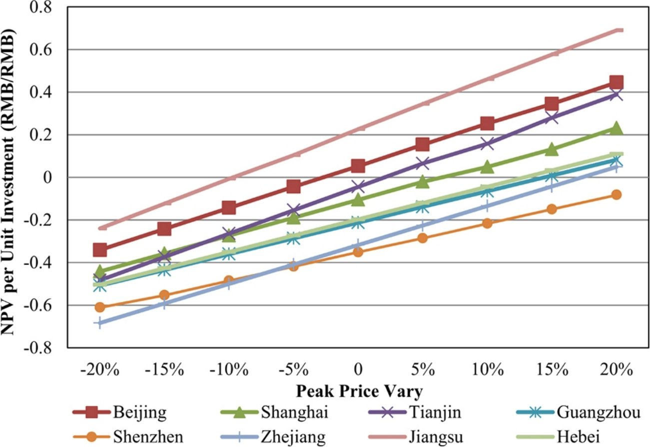
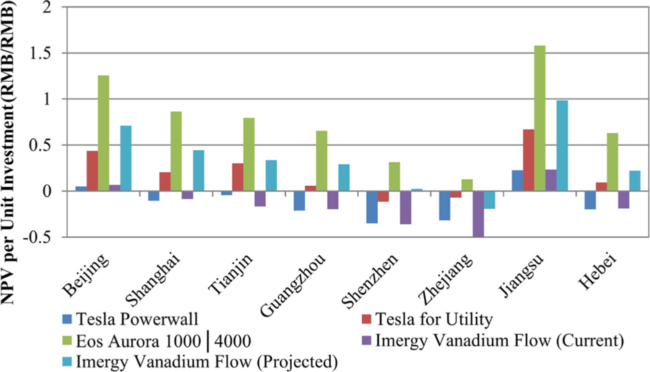
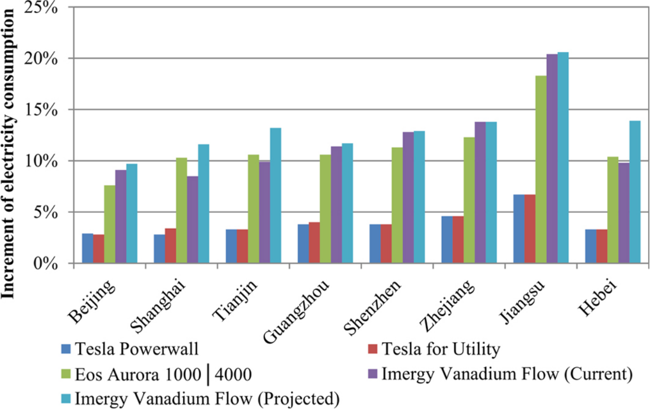

NPV per Unit Investment (RMB/RMB)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Warranty
Estimate
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Lifetime
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei

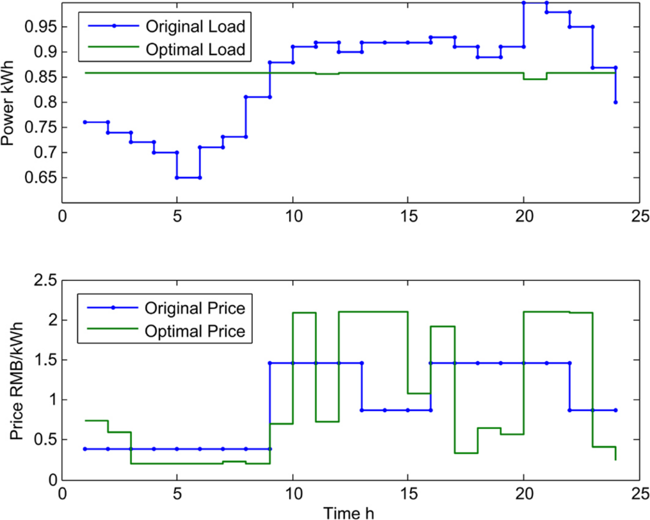

Tesla Energy for Utility
Tesla Powerwall
NPV per unit investment (RMB/RMB)
2
1.5
1
0.5
0
-0.5
-1
150
200
250
300
350
400
450
500
550
600
Battery Cost ($/kWh)
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei


Real Rate
Deposit Rate
Lending Rate
NPV per Unit Investment (RMB/RMB)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Discount Rate
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei


0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
NPV per Unit Investment (RMB/RMB)
-20%
-15%
-10%
-5%
0
5%
10%
15%
20%
Peak Price Vary
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei


2
1.5
1
0.5
0
-0.5
NPV per Unit Investment(RMB/RMB)
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei
Tesla Powerwall
Tesla for Utility
Eos Aurora 1000│4000
Imergy Vanadium Flow (Current)
Imergy Vanadium Flow (Projected)


Increment of electricity consumption
25%
20%
15%
10%
5%
0%
Beijing
Shanghai
Tianjin
Guangzhou
Shenzhen
Zhejiang
Jiangsu
Hebei
Tesla Powerwall
Tesla for Utility
Eos Aurora 1000 | 4000
Imergy Vanadium Flow (Current)
Imergy Vanadium Flow (Projected)


Original Load
Optimal Load
Power kWh
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0
5
10
15
20
25
Original Price
Optimal Price
Price RMB/kWh
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Time h