Electric energy storage systems in a market-based economy: Comparison of emerging and traditional technologies

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A B S T R A C T

Unlike markets for storable commodities, electricity markets depend on the real-time balance of supply and demand. Although much of the present-day grid operate effectively without storage technologies, cost-effective ways of storing electrical energy can make the grid more efficient and reliable. This work addresses an economic comparison between emerging and traditional Electric Energy Storage (EES) technologies in a competitive electricity market. In order to achieve this goal, an appropriate Self-Scheduling (SS) approach must first be developed for each of them to determine their maximum potential of expected profit among multi-markets such as energy and ancillary service markets. Then, these technologies are economically analyzed using Internal Rate of Return (IRR) index. Finally, the amounts of needed financial supports are determined for choosing the emerging technologies when an investor would like to invest on EES technologies. Among available EES technologies, we consider NaS battery (Natrium Sulfur battery) and pumped-storage plants as emerging and traditional technologies, respectively.

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1. Introduction

Electric Energy Storage (EES) is the capability of storing electricity or energy to produce electricity and releasing it for use during other periods when its utilization is more beneficial [1]. Representative of these technologies include redox flow batteries [2,3], Natrium Sulfur (NaS) batteries [4], flywheels [5], lead acid batteries, Superconducting Magnetic Energy Storage (SMES), Compressed Air Energy Storage (CAES) [6] and pumped-storage. An EES plant can participate in the electricity markets in a number of ways depending on its energy storage and delivery characteristics [7]. Initial economic studies of EES plants focused on applications for peak shaving and as a capacity resource [8]. In recent years, attention has been increased on evaluating the economics of the EES systems as backup for intermittent renewable resources. Some examples include wind and CAES [9], wind and hydro or batteries [10,11] and solar photovoltaic coupled with batteries [12,13].

In a vertical electricity system, power generating companies with a large portfolio of generators may still use their EES plants to coordinate with their thermal plants, but in a competitive electricity market, an individual EES owner can purchase energy and sell it either on Day-Ahead (DA) market or spot market or through bilateral contracts. An individual EES plant can participate in the multi-markets, such as energy and ancillary service markets. This paper is focused on an economic comparison between emerging and traditional EES technologies. In order to achieve this goal, an appropriate Self-Scheduling (SS) approach must first be developed for each of them to determine their maximum potential of expected profit among multi-markets. Then, these technologies are economically analyzed using Internal Rate of Return (IRR) index. Finally, the amounts of needed financial supports are determined for choosing the emerging technologies when an investor would like to invest on EES technologies. Among available EES technologies, we consider NaS battery and pumped-storage plants as emerging and traditional technologies, respectively.

In this regard, rational SS approaches for owners of individual NaS battery and pumped-storage plants are developed in this paper to bid in DA energy and ancillary service markets. Then, the economic comparison between them in a same market is performed. The plants considered in this paper are price-taker, i.e., plants with no capability of altering the market-clearing prices (MCPs). The analysis will be performed considering energy, spinning reserve and regulation markets, simultaneously.

The rest of this paper is organized as follows. Section 2 provides the brief explanations of NaS battery and pumped-storage technologies.
Also, their technical and economic aspects are discussed in this section. Section 3 is devoted to the SS problem formulation of NaS battery and pumped-storage plants. Section 4 illustrates the numerical results of SS problem considering both EES technologies. Section 5 represents the economic comparison of NaS battery and pumped-storage plants in a same competitive electricity market. Section 6 is dedicated to conclusions of the paper.

2. EES technologies

2.1. NaS battery

- Principles and features
  Principles of the NaS battery system were first introduced by Ford Motor Company, USA, in 1966. Since then, active researches have been conducted in development and application of these batteries [14–16]. The NaS battery has fused sodium as the cathode-active material, and has fused sulfur and sodium polysulfide as the anode-active material. Moreover, beta alumina is used as a solid electrolyte, which conducts sodium ions selectively.

- Characteristics of operation control
  For the AC–DC converter device of the NaS battery system, a separately-excited inverter and self-excited inverter (current type and voltage type) have been used. Especially, the voltage type of the self-excited inverter can simultaneously adjust active and reactive powers at high speed, and charge and discharge of leading or lagging currents by reversing the firing angle. Thus, they can contribute to the system operation considerably [14–16].

- NaS pulse limit
  The NaS battery can independently control the active and reactive power outputs through the AC–DC converter device. Such a system can instantaneously discharge the power from one to five times as much as the rated capacity, if the capacity of the AC–DC converter device is sufficient. However, NaS battery has an output limit based on the internal temperature, where the feasible discharging times are specified according to this limit which is called NaS pulse limit. Fig. 1 shows NaS pulse limit versus the different discharge duration. For instance, the NaS battery plant can discharge 7 h as much as the rated output, 3 h for 1.5, 1 h for 2.6 times and 15 min for 4 times of the rated power, respectively [6,14–16]. As it can be seen, increasing the NaS pulse factor will lead to more power losses.

2.2. Pumped-storage plant

A pumped-storage plant is an energy storage system with water being recycled between upper and lower reservoirs and has a 50 years life time, approximately. The largest issues for building these plants are the lack of suitable places and their environmental impacts [17]. In a vertically integrated power system, hydrothermal unit coordination is used to reduce the fuel cost by letting the pumped-storage plants serve the peak load and then pump the water back into the upper reservoir at light-load periods. Under a cost-based dispatch, it is not unusual for a pumped-storage plant to be always in either the selling or the purchasing mode, except for the changeover periods.
2.3. Technical and economic aspects

Tables 1 and 2 summarize the technical and economic aspects of NaS battery and pumped-storage plants [1,6].

3. Self-scheduling problem formulation

A self-scheduling problem is generally modeled in terms of an objective function (e.g., expected profit) to be maximized subject to some technical constraints. An individual EES plant owner is seeking to maximize his profit by optimally trading in DA energy and ancillary service markets.

References [18–23] are among the early works in which SS has been performed, based on the DA forecasted prices. Although, there are so many articles which have been developed in recent years dealing with SS of price-taker generators, the published papers on the SS of EES plants are rare. Ning Lu et al. [18] propose an approach for SS of an individual pumped-storage plant in energy and spinning reserve markets. In their approach, the constraint of water level in the upper reservoir has not been applied in the formulation of the objective function, but the aforementioned constraint is used as a corrective criterion. In their contribution, when the SS is terminated, the energy stored constraint in the upper reservoir is checked. If the constraint is violated, the result of the SS is valid until violation instance. Then, the SS problem should be reiterated for the remaining time. This is continued up to the end of the concerned time interval. Achieving to the global optima is not guaranteed by this method. In [19–21], the SS problem for a usual price-taker power plant has been investigated. In these works, only technical constraints of power plants were considered and other considerations such as fuel and/or emission constraints were not contemplated. In [22], the SS of pumped-storage plant in the energy, spinning reserve and regulation markets is investigated without considering energy stored constraint in the upper reservoir. In [23], a simple heuristic method for the SS problem of a hydro-electric plant and also a pumped-storage plant has been proposed. In this method, the SS problem is performed to maximize the potential of revenues in each hour. Although this method is very simple, it cannot achieve to the global optima.

In this paper, we develop rational approaches for SS problem of NaS battery and pumped-storage plants, based on their technical characteristics. In the SS problem formulation, various states of ancillary service markets and also the operating modes of EES plants must be considered which are described in the following sub-sections.

3.1. States of ancillary service markets

When an EES plant participates in the ancillary service markets for a specific hour, it receives hourly ancillary service price and also hourly spot price if EES plant is called to generate in ancillary service markets. In this paper, spinning reserve and regulation services are considered as ancillary services that EES plant can participate in their markets. Generally, if EES plant commits in the spinning reserve market, the following states may occur:

a. EES plant is called to generate: in this state, the plant receives both hourly spinning reserve and spot prices. The amount of the latter income depends on the amount of the extra generated energy as the spinning reserve power. The probability of being in this state is presented by $P_{del}$.  

![Fig. 2. Hourly forecasted energy market-clearing prices [27].](image)
b. EES plant is not called to generate: in this state, the plant receives according to hourly spinning reserve price. It is obvious that the probability of being in this state is equal to \(1 - P_{\text{del.}}\).

In addition, if the EES plant participates in a DA regulation market, following states may occur:

a. Regulation-up: In this state, the amount of generated power must be increased. The plant receives all hourly energy, regulation and spot prices. The latest income depends on the amount of requested extra energy. \(P_{\text{r,up}}\) shows the probability of being in the regulation-up state.

b. Regulation-down: In this state, the amount of generated power is decreased. In regulation-down state, the plant receives according to hourly energy and regulation prices, but must repay for energy not generated according to hourly spot price. The probability of being in the regulation-down state is presented by \(P_{\text{r,down}}\).

c. No-regulation: In this state, the amount of generated power is not changed and the plant receives hourly energy and regulation prices. The probability of being in this state is equal to \((1 - P_{\text{r,up}} - P_{\text{r,down}})\).

It is rational that the SS results of an EES plant are changed considering different values for \(P_{\text{del.}}\), \(P_{\text{r,up}}\) and \(P_{\text{r,down}}\). So, these parameters must be considered in the objective function of the SS problem.

### 3.2. EES operating modes

EES plants can operate in three operating modes: selling, purchasing and off-line. The participation status of the EES plants in different markets versus its operating modes is shown in Table 3.

As it can be seen, an EES plant can participate in all of energy, spinning reserve and regulation markets when it operates in its selling mode. In its purchasing mode, EES plant purchases electricity but it can be committed for spinning reserve, because it can reduce its charging power and consequently reduces the overall system load. EES plants can only participate in the spinning reserve market when they are in their off-line mode.

### 3.3. SS problem formulation for the NaS battery plant

It should be noted that a horizon of one day is too short to consider the optimal utilization of the energy storage capability of the EES plants, while a horizon of one month is too long to forecast the prices [18]. Hence, the approach developed in this paper optimizes the EES plants on a weekly basis with hourly prices. The analysis will be performed considering energy, spinning reserve and regulation markets, simultaneously.

By assuming incomes, payments and O&M costs, the objective function of SS problem for a NaS battery plant over a week is represented by (1)–(17). All the symbols are introduced in the appendix.

Maximize:

\[
\begin{align*}
\sum_{d=1}^{D} \sum_{t=1}^{T} (P_d(t,d) - P_{p}(t,d)) \cdot \lambda_{e}(t,d) + \sum_{d=1}^{D} \sum_{t=1}^{T} P_{s}(t,d) \cdot \lambda_{sp}(t,d) \\
+ \sum_{d=1}^{D} \sum_{t=1}^{T} (P_{sp,s}(t,d) + P_{sp,p}(t,d)) \cdot \lambda_{sp}(t,d) + \sum_{d=1}^{D} \sum_{t=1}^{T} P_{r,up} \cdot \lambda_{r}(t,d) \\
- P_{r,down} \cdot P_{r}(t,d) \cdot \lambda_{spr}(t,d) + \sum_{d=1}^{D} \sum_{t=1}^{T} P_{p}(t,d) \cdot \lambda_{p}(t,d) \\
+ P_{sp,p}(t,d) \cdot \lambda_{spr}(t,d) - \sum_{d=1}^{D} \sum_{t=1}^{T} K_{1} + K_{2} \cdot (P_{s}(t,d) + P_{p}(t,d)) \\
+ (P_{1,up} - P_{r,down}) \cdot P_{r}(t,d) + P_{del} \cdot (P_{sp,s}(t,d) - P_{sp,p}(t,d))
\end{align*}
\]

s.t.

\[
\begin{align*}
u_{s}(t,d) & \leq N_{\text{pulse}}(t,d) \leq 2.6 \cdot u_{s}(t,d) \\
0 & \leq P_{s}(t,d) \leq N_{\text{pulse}}(t,d) \cdot P_{\text{max}} \\
0 & \leq P_{p}(t,d) \leq u_{p}(t,d) \cdot P_{\text{max}} \\
0 & \leq P_{r}(t,d) \leq N_{\text{pulse}}(t,d) \cdot P_{\text{max}}/2 \\
0 & \leq P_{sp,s}(t,d) \leq N_{\text{pulse}}(t,d) \cdot P_{\text{max}}
\end{align*}
\]
For participation of the NaS battery plant in an hour-based DA market, it is essential that the plant be able to trade at least for 1 h, hence according to Fig. 1, the NaS pulse factor must be less than 2.6. This constraint is applied by (2). In (3)–(5), the lower and upper limits of selling, purchasing and regulation capacities are shown, respectively. In (5), the upper limit is considered as \( P_{\text{max}}/2 \), in order to respond to both regulations up and down requests. Also, the lower and upper limits of spinning reserve power in selling and purchasing modes are represented by (6) and (7), respectively. In order to ensure regulation-down service supplying, constraint (8) is considered. The summation of energy, regulation and spinning reserve in selling mode for a specific hour must be less than \( P_{\text{max}} \). This constraint is applied by (9). Equation (10) calculates the expected power to response in the energy, regulation and spinning reserve markets when NaS battery plant operates in its selling mode. In (11), the NaS pulse trend (Fig. 1) is modeled using a third order polynomial. Also, the power loss versus different NaS pulse factors is calculated by (12). To eliminate conflict between different modes in a specific hour, (13) is considered. Also, (14)–(17) are related to the amount of energy stored in the NaS battery plant. The amount of energy stored in each hour is calculated by (14). The lower and upper limits of energy stored amount are presented by (15), where \( E_{\text{min}}(t,d) \) is calculated by (17). The lower limit of energy stored in each hour must be adjusted so that the NaS battery plant can respond to the worst condition from the viewpoint of energy stored level. The worst condition may occur when both spinning reserve and regulation-up are required, simultaneously. In addition, in order to reserve enough energy stored for the subsequent week, (16) is applied. The parameter \( \tau \) adjusts the amount of energy that should

\[
0 \leq P_{\text{sp.p}}(t,d) \leq u_{\text{p}}(t,d) \cdot P_{\text{p}}(t,d) \tag{7}
\]

\[
P_s(t,d) \geq P_i(t,d) \tag{8}
\]

\[
P_s(t,d) + P_{\text{d}}(t,d) + P_{\text{sp.p}}(t,d) \leq N_{\text{pulse}}(t,d) \cdot P_{\text{max}} \tag{9}
\]

\[
P_{\text{exp}}(t,d) = P_s(t,d) + P_{\text{d}} \cdot P_{\text{sp.p}}(t,d) + (P_{\text{up}} - P_{\text{down}}) \cdot P_i(t,d) \tag{10}
\]

\[
d(t,d) = -3.4497 \cdot N_{\text{pulse}}^3(t,d) + 21.5962 \cdot N_{\text{pulse}}^2(t,d)
- 45.7961 \cdot N_{\text{pulse}}(t,d) + 34.7117 \tag{11}
\]

\[
P_{\text{loss}}(t,d) = \frac{7 - \left( N_{\text{pulse}}(t,d) \times d(t,d) \right)}{d(t,d)} \cdot u_s(t,d) \tag{12}
\]

\[
u_{\text{s}}(t,d) + u_{\text{p}}(t,d) \leq 1 \tag{13}
\]

\[
E(t,d) = E(t-1,d) - P_{\text{exp}} \cdot (t,d) - P_{\text{d}} \cdot \eta_{\text{p}} \cdot P_{\text{sp.p}}(t,d)
+ \eta_{\text{s}} \cdot P_{\text{p}}(t,d) - P_{\text{exp}} \cdot (t,d) \cdot P_{\text{loss}}(t,d) \tag{14}
\]

\[
E_{\text{min}}(t,d) \leq E(t,d) \leq E_{\text{max}}(t,d) \tag{15}
\]

\[
E_{\text{end}} = \tau \cdot E_0 \tag{16}
\]

\[
E_{\text{min}}(t,d) = (P_i(t+1,d) + P_{\text{sp.p}}(t+1,d)
+ P_{\text{sp.p}}(t+1,d) \cdot N_{\text{pulse}}(t+1,d) \tag{17}
\]

The first three terms of (1) represent the revenues of the NaS battery plant including the trading in energy, spinning reserve and regulation markets. In addition, the plant owner expects to receive income when EES plant is called to generate in one of the spinning reserve or regulation markets or in both of them. This expected income is presented by fourth and fifth terms in (1). O&M costs are considered by the latter term in (1) including fixed and variable costs.
be stored for the subsequent week. If lower prices for the next week are forecasted, the NaS battery plant owner will choose a low value for $\tau$. This parameter can be varied while energy stored constraints are satisfied. The profit maximization problem faced by the NaS battery plant is therefore an optimal operation scheduling problem that is formulated as a mixed-integer nonlinear programming (MINLP) problem. This problem can be solved by any commercial software. In this paper, it is solved using DICOPT under GAMS [24].

3.4. SS problem formulation for pumped-storage plant

The principles of the SS problem for the pumped-storage plant are similar to the SS problem of the NaS battery plant. An objective function similar to (1) is used here for the SS problem of pumped-storage plant except that the O&M coefficients ($K_1, K_2$) are different. Also, the constraints (4), (7), (8), (10), (13), (15) and (16) are repeated in the SS problem of pumped-storage plant, but other constraints are different. The rest constraints of the SS problem of pumped-storage plant are represented by the following equations:

$$0 \leq P_s(t,d) \leq u_s(t,d) \cdot P_{\text{max}}$$ \hspace{1cm} (18)

$$0 \leq P_t(t,d) \leq u_s(t,d) \cdot P_{\text{max}} / 2$$ \hspace{1cm} (19)

$$0 \leq P_{sp,s}(t,d) \leq u_s(t,d) \cdot P_{\text{max}}$$ \hspace{1cm} (20)

![Fig. 5. The NaS battery and the pumped-storage plants biddings in the energy and the regulation markets in their selling modes.](image5)

![Fig. 6. The NaS battery and the pumped-storage plants biddings in the energy market in their purchasing modes.](image6)
\[ P_s(t, d) + P_t(t, d) + P_{sp,s}(t, d) \leq u_s(t, d) \cdot P_{\text{max}} \]  
(21)

\[ E(t, d) = E(t-1, d) - P_{\text{exp}}(t, d) - P_{\text{del}} \cdot \eta_p \cdot P_{sp,p}(t, d) \]  
+ \eta_p \cdot P_p(t, d) \]  
(22)

\[ E_{\text{min}}(t, d) = P_t(t+1, d) + P_{sp,s}(t+1, d) + P_{sp,p}(t+1, d) \]  
(23)

\[ u_s(t-1, d) + u_p(t, d) \leq 1 \]  
(24)

\[ u_p(t-1, d) + u_s(t, d) \leq 1 \]  
(25)

Equations (18)–(23) are basically similar to (3), (5), (6), (9), (14) and (17) in the SS problem of the NaS battery plant. In (24) and (25), changeover times of the pumped-storage plant are applied. The changeover time of a pumped-storage plant is typically between 15 to 30 min. For a DA market operated on an hourly basis, this constraint translates to a plant having a buffer of at least one hour at zero generation between selling and purchasing modes.

4. Numerical results

The numerical results which are presented in this section, consists of the SS problem for individual price-taker NaS battery and pumped-storage plants in a same DA market. The capacity of these EES plants is considered to be the same and equal to 100 MW. The time horizon comprises of 168 h. The probability of calling EES plant to generate in spinning reserve market \( P_{\text{del}} \) is assumed to be 3% which can be calculated by historical data [25]. Also, the probabilities of regulation-up and regulation-down states are considered as 40% and 35% respectively, which seems to be rational assumptions [26]. The base case forecasted prices for the energy, spinning reserve

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Fig. 7. The NaS battery plant bidding in the spinning reserve market in its selling mode.

Fig. 8. The Pumped-storage plant bidding in the spinning reserve market in its selling mode.
and regulation markets are shown in Figs. 2–4. These price data are adopted from electric energy market of Mainland, Spain [27] with a few adjustments. The relevant data of the NaS battery and pumped-storage plants are represented in Table 4 [6,28].

To forecast the hourly spot price, the following random-based method is used [29]. The duration between the hours 9 and 18 are considered as the peak period. Also, to present the spike price in the peak hours, the spikes are randomly generated using Frechet distribution [30].

\[
\lambda_{\text{spot}}(t,d) = \begin{cases} 
(1 + \gamma)\lambda_e(t,d) & 0 \leq \gamma \leq 0.25 \quad t \in [9,18] \\
(1 + \mu)\lambda_e(t,d) & -0.1 \leq \mu \leq 0.1 \quad \text{otherwise} 
\end{cases}
\] (26)

Here, the coefficient \( \gamma \) is assumed to be 1. The results are presented in Figs. 5–9. In addition, the stored energy fluctuation of NaS battery and pumped-storage plants during the concerned time horizon is shown in Fig. 10. As it can be seen in these figures, the NaS battery plant participates more than pumped-storage plant in the markets, due to its pulse factor characteristic. Because of the higher profit potential in the spinning reserve market, these plants participate in this market actively in compare with the energy and regulation markets. The expected weekly profits of NaS battery and pumped-storage plants are equal to $875,769 and $498,434, respectively.

5. Economic studies

After determining maximum expected profits of NaS battery and pumped-storage plants in a time horizon of one week, the economic merits of these plants during their life time are investigated. As it was described before, construction of the pumped-storage plants faces with the geographical and environmental constraints. Hence, although the pumped-storage plant possesses more economic merit, it is possible that investment on the
emerging EES technologies such as the NaS battery plants be preferred. In this regard, for encouraging investors on construction of emerging EES technologies, there should be enough financial supports by energy policy decision makers. Here, first the economic justification of NaS battery and pumped-storage plants in the same conditions are separately investigated by means of determining their Internal Rate of Returns (IRRs). Then, the amount of needed financial supports to invest on the NaS battery plant is determined. Other technical and economic aspects of these plants are represented in Table 5.

Based on the SS results in the previous section, the NaS battery often operates in high pulse factors. Therefore, the maximum value of the capital cost per kW is considered. Also, in this situation, the expected life time of the battery is more than when battery operates in the lower pulse factors [6]. Hence, the expected life time of the NaS battery are assumed to be 15 years. The utilization factor of pumped-storage plant is considered less than the NaS battery plant. This is due to its higher Forced Outage Ratio (FOR) and maintenance time. Here, we have assumed that the bids of both considered plants in the energy and ancillary service markets are accepted. To investigate the economic justification, the IRR for both plants is determined [31]. The Minimum Acceptable Rate of Return (MARR) is assumed to be 15%. We assumed that investment on a plant has economic justification if its IRR is more than the MARR. The results of economic studies for the NaS battery and the pumped-storage plant are represented in Table 6.

As it can be seen, both of the NaS battery and the pumped-storage plants are economically justificated. Although it is appeared that the economic merit of the pumped-storage plant is higher than the NaS battery plant, the validity of this issue must be investigated. To achieve this goal, the incremental IRR should be calculated based on the differences between their cash flows considering plants life time [31]. The incremental IRR is calculated 10.74%. Hence, in the same conditions, the pumped-storage plant possesses more economic merit in compare with the NaS battery plant. As it was described before, the financial supports are needed for encouraging the investors to select the NaS battery technology. Here, we consider two mechanisms of supports as following:

- Decreasing the tax rate
- Dedicated the gratuitous loan

By assuming the above financial supports, incremental IRR should be calculated again. The results of this economic study are represented in Fig. 11 considering different levels of supports.

In this figure, the incremental IRR versus different levels of decreasing the tax rate and dedicating the gratuitous loan is presented. Each of the trends in this figure shows the incremental IRRs versus the different levels of gratuitous loan in the specific tax rate. An investor prefers to invest on the NaS battery plant if the incremental IRR is higher than the MARR. According to Fig. 11, investment on the NaS battery plant will be preferred if 13.8% of the capital cost is provided by the energy policy decision maker, when the tax rate is assumed to be 5%. By decreasing the tax rate as a financial support, the amount of needed gratuitous loan decreases as well. For instance, the amount of needed gratuitous loan is approximately 13.0, 12.5, 12.0,

| Table 5 | Technical and economic aspects of the NaS battery and the pumped-storage plants. |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Characteristic   | NaS battery plant (100 MW) | Pumped-storage plant (100 MW) |
| Capital cost ($) | 225000000         | 60000000         |
| Expected life time (years) | 15               | 50               |
| Utilization factor (%) | 95               | 70               |
| Tax (%) | 5               | 5               |
| Salvage value (% of capital cost) | 15               | 15               |

| Table 6 | Economic studies concerned with the NaS battery and the pumped-storage plants. |
|------------------|------------------|------------------|------------------|------------------|
| EES               | NaS battery plant | Pumped-storage plant |
| Expected annual profit ($/year) | 43262989         | 18142998         |
| Depreciation loss ($/year) | 2250000         | 600000         |
| Net annual benefit ($/year) | 41212340        | 17265848        |
| Incremental IRR (%) | 16.77           | 28.74           |
| Economic merit status | Yes            | Yes            |

Fig. 11. Incremental IRR versus the different levels of financial supports.
11.4 and 10.8 percent of the capital cost when the tax rate is considered to be 4, 3, 2, and 0 percent, respectively.

6. Conclusions

In this paper, an economic comparison between emerging and traditional electric energy storage technologies was addressed. In order to calculate the maximum potential of expected profit in a specific time interval, a self-scheduling problem for both storage technologies was performed. Then, the economic merits of these plants were compared by their internal rate of returns. In this analysis, it has been shown that in the same conditions, traditional technologies such as pumped-storage plants possess more economic merit. Hence to select the emerging technologies, financial supports are needed. In a case study, the amount of needed financial supports was calculated.

In the present work, only direct storage of electricity was considered, however for more comprehensive study, considering indirect energy storage options such as conversion to hydrogen and then electricity generation in a fuel cell are necessary to be investigated, while considering the overall efficiency issues. This is an interesting topic which will be included in our future works.

Appendix. : List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>considered time interval in one day (typically 24)</td>
</tr>
<tr>
<td>$D$</td>
<td>considered time interval in one week (typically 7)</td>
</tr>
<tr>
<td>$\lambda(t,d)$</td>
<td>market-clearing price at hour $t$ on day $d$ ($/\text{MWh}$)</td>
</tr>
<tr>
<td>$P(t,d)$</td>
<td>amount of power bids at hour $t$ on day $d$ (MW)</td>
</tr>
<tr>
<td>$P_{\text{exp}}(t,d)$</td>
<td>the expected amount of generated power at hour $t$ on day $d$ (MW)</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>the capacity of EES plant (MW)</td>
</tr>
<tr>
<td>$u(t,d) \in [0 \text{ or } 1]$</td>
<td>indicates whether EES plant participates in the market or not at hour $t$ on day $d$</td>
</tr>
<tr>
<td>$N_{\text{pulse}}(t,d)$</td>
<td>NaS pulse factor of NaS battery at hour $t$ on day $d$</td>
</tr>
<tr>
<td>$d(t,d)$</td>
<td>discharge duration which is related to the NaS pulse factor at hour $t$ on day $d$ (hr)</td>
</tr>
<tr>
<td>$P_{\text{loss}}(t,d)$</td>
<td>power loss which is related to the NaS pulse factor at hour $t$ on day $d$ (MW)</td>
</tr>
<tr>
<td>$E(t,d)$</td>
<td>amount of energy stored in the EES at hour $t$ on day $d$ (MWh)</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>the lower limit of energy stored in EES (MWh)</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>the upper limit of energy stored in the EES (MWh)</td>
</tr>
<tr>
<td>$E_0$</td>
<td>amount of energy stored in the EES in the beginning of concerned time interval (MWh)</td>
</tr>
<tr>
<td>$E_{\text{end}}$</td>
<td>amount of energy stored in the EES in the end of concerned time interval (MWh)</td>
</tr>
<tr>
<td>$\eta_{\text{NaS}}$</td>
<td>NaS battery efficiency</td>
</tr>
<tr>
<td>$\eta_{\text{pumped}}$</td>
<td>pumped-storage plant efficiency</td>
</tr>
<tr>
<td>$P_{\text{del}}$</td>
<td>the probability of calling EES plant to generate in spinning reserve market</td>
</tr>
<tr>
<td>$P_{\text{rup}}$</td>
<td>the probability of regulation-up state</td>
</tr>
<tr>
<td>$P_{\text{tdown}}$</td>
<td>the probability of regulation-down state</td>
</tr>
<tr>
<td>$K_1$</td>
<td>the fixed term of O&amp;M cost</td>
</tr>
<tr>
<td>$K_2$</td>
<td>the coefficient of variable term in O&amp;M cost</td>
</tr>
<tr>
<td>$\tau$</td>
<td>adjusting constant for stored energy</td>
</tr>
</tbody>
</table>

Subscript

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$</td>
<td>selling mode</td>
</tr>
<tr>
<td>$p$</td>
<td>purchasing mode</td>
</tr>
<tr>
<td>$e$</td>
<td>energy</td>
</tr>
<tr>
<td>$r$</td>
<td>regulation</td>
</tr>
<tr>
<td>$sp$</td>
<td>spinning reserve</td>
</tr>
<tr>
<td>$sp,p$</td>
<td>spinning reserve in the purchasing mode</td>
</tr>
</tbody>
</table>