Economic Analysis of Centralized Energy Storage and Impact on NEM

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Abstract—Energy storage has a broad prospect in the future electricity market. Hornsdale Power Reserve (HPR), the largest battery energy storage system in Australia, was selected as the research case to evaluate the impact of energy storage systems on the National Electricity Market (NEM) operation and its economic benefits. The analysis of HPR includes its performance in the NEM and FCAS markets, its profitability, and its impact on the different markets, thus reflecting the feasibility and superiority of the energy storage system. The results show that energy storage is active in the FCAS market. By comparing the FCAS regulation performance of HPR and the conventional OCGT in South Australia and researching the response to sudden frequency changes, it is found that energy storage has accuracy, speed in regulating frequency, and maintaining system frequency stability. The economic analysis results show that the primary revenue of energy storage comes from the FCAS market. Taking HPR as an example, more than 70% of its electricity sales revenue comes from the FCAS market, especially the Contingency FCAS market. Comparing HPR with wind farms and PV farms of the same power size (100MW), its high IRR, short payback period, and relatively high NPV demonstrate the investment potential of energy storage systems. Optimizing HPR's energy storage configuration achieves the maximum benefit when its scale expands by 50% (150MW). There will still be huge profits when grown by 100% (200MW), proving energy storage systems' development potential. Using the economic sensitivity analysis of HPR to find ways to improve the energy storage system's economic benefits, it can be seen that increasing the participation rate of the FCAS market and improving the technical level of the battery are the effective methods.

1. INTRODUCTION

Although all kinds of energy storage technology will remain diversified, most technologies are still in the stage of technical improvement and technical verification. Yet, adequate security, long cycle life, low cost, and high energy efficiency have always been the development direction of energy storage technology in the future. In different energy storage applications, the challenges faced by various technologies vary and need to be continuously optimized and validated through demonstration applications. A variety of energy storage technologies will play their respective advantages in different application areas and gradually mature in the future.
TABLE I. DIFFERENT ENERGY STORAGE TECHNOLOGIES

| Type               | Rated Voltage (V) | Monomer Capacity | Response Time | Energy Density (Wh/L) | Efficiency (%) | Lifetime (year) |
|--------------------|-------------------|------------------|---------------|------------------------|----------------|-----------------|
| Pump Hydro         | N/A               | N/A              | min           | 0.2-2                  | 70-80          | >50             |
| Compressed Air     | N/A               | N/A              | min           | 2-6                    | 41-75          | 40-50           |
| Flywheel           | N/A               | 0.7-1.7 MW       | <s            | 20-80                  | 80-90          | 15-20           |
| Lead-acid Battery | 2                 | 1-4000 Ah        | <s            | 50-80                  | 75-95          | 3-15            |
| Lithium-ion Battery| 3.7               | 0.05-100 Ah      | <s            | 200-400                | 85-98          | 5-15            |
| Na-S Battery       | 2.1               | 4-30 Ah          | <s            | 150-300                | 70-85          | 10-15           |
| Liquid Flow Battery| 1.8               | N/A              | <s            | 65                     | 65-75          | 5-10            |
| Super-capacitor    | 2.5               | 0.1-1500 F       | <s            | 10-20                  | 85-98          | 4-12            |

In the next decade, the energy storage capacity of developing countries will increase by 40 times, and the capacity will rise from 2GW in 2016 to 80GW. The growth rate could reach 40% per year about the energy storage deployments in emerging markets. The largest energy storage market is China and India. To meet the needs of developing countries for low-carbon electricity, energy storage plays a key role. According to the IEA, by 2020, these countries will need to double their power generation, accounting for 80% of global energy production and consumption growth by 2035 [1]. As Philippe Le Houerou (CEO of IFC) said, expanding energy storage capacity will encourage countries to achieve the goal of using clean energy and renewable energy and solving one-fifth of the world's population's inability to use electricity [1].

The battery is another primary electricity storage in Australia. Up to 2018, over 4GW commercial battery is operating, constructing, planning and proposing in Australia [2]. In the future four emerging batteries are likely to be developed rapidly in the next 20 years which are: advanced lead-acid battery, lithium-ion battery, zinc bromide battery, and sodium nickel chloride molten salt battery [3].

Table 2 shows the cost and manufacturing and technology readiness levels for each kind of battery. Although some of these costs are high, some professors predict that the capital cost of lead-acid batteries and lithium batteries will drop by 53% by 2025, and the capital costs of the other two batteries will drop by 79% by 2025.

TABLE II. SUMMARY DATA FOR FOUR EMERGING BATTERIES

| Technology       | Min cost ($/kWh) | Average cost ($/kWh) | Max cost ($/kWh) | Technology Readiness Level | Manufacturing Readiness Level |
|------------------|------------------|----------------------|------------------|-----------------------------|------------------------------|
| Advanced Lead acid | 750              | 875                  | 1000             | 8                           | 7                            |
| Lithium          | 442              | 543                  | 562              | 9                           |                              |
| Zinc Bromide     | 1101             | 1188                 | 1276             | 9                           | 8                            |
| Molten salt      | 1500             | 1500                 | 1500             | 8                           | 7                            |

There are many benefits to battery installation. It has a significant effect on the national electricity market and customers.

- It could meet peak demand and fluctuated demand for both the energy and FCAs markets when other generation resources are insufficient.
- Its speed rate is fast and can quickly replenish the power supply, enabling the grid to supply electricity to customers in time.
- Make renewable resources more competitive. In some cases, renewable resources such as wind energy could not be connected to the grid. If the battery is installed and integrated with a wind
farm, the electricity could be stored in the battery and sold properly.

- Require less time for its installation and could be put into practice in a short time compared with other generation resources [4].

With the depletion of fossil energy, renewable generation will occupy an increasing proportion of power generation systems. However, due to the intermittent characteristics of renewable generation, high penetration of renewable significantly challenges the operation and control for the whole electricity system [5]. For example, renewable generation cannot meet the dispatch output when there is a sudden weather change. Another problem is that renewable generation has to be cut due to low load demand at some minimum operation level. Fortunately, the rapid charging and discharging of the battery can solve this problem by charging at peak renewable output and low load demand and discharging when the weather suddenly changes. Moreover, battery storage power plants have no special requirements for the location of the plant [6]. It can be built with new energy plants to provide stable electricity to guarantee a promised output.

In general, each battery has advantages and disadvantages. At present, their technology is not mature enough, but customers and grids have various demands. Therefore, any battery cannot meet all the requirements of the energy market and users. In the short term, lithium batteries and advanced lead-acid batteries operational opportunities. The national electricity market should issue policies as soon as possible to develop battery technology and evaluate the implication of batteries on the energy market, targeted development of batteries that meet market demand, and improve its operational opportunities.

2. METHODOLOGY
This article analyzes energy storage's economic performance, taking Hornsdale Power Storage (HPR) in South Australia as a research case to analyze its energy profitability and its impact on FCAS. Then technical modeling and economic modeling are performed on HPR. Technical modeling includes energy storage configuration model and technical constraints, and financial modeling consists of a cost model and revenue model. Based on the model, the System Advisor Model (SAM) is used to conduct an economic analysis of HPR, and finally using the real data from NEM Open Source Information Service (NEMOSIS) to analyze the profitability of HPR in 2018. Through a detailed analysis of HPR, general conclusions can be drawn: the impact of energy storage on the national electricity market (NEM) and the operational opportunities of energy storage in the future.

3. HORNSDALE POWER RESERVE

3.1. Background
Hornsdale Power Reserve is closed to Hornsdale Wind Farm, Jamestown, north of Adelaide SA. Tesla supplied the technology for this largest lithium-ion battery energy storage system worldwide. At the same time, Neoen is the owner of this plant and be responsible for the operation.

This battery storage system has a 100MW charge capacity. 30MW is for bidding in the market and FCAS by Neoen, while the SA government arranges 70MW for system security and FCAS. The market capacity is used for energy arbitrage and Regulation and contingency FCAS. SA government reserved capacity is used for system security, Regulation, and contingency FCAS. Table 3 is clearly shown the objectives of the different capacity operation.

| Operation                        | Capacity | Service               |
|----------------------------------|----------|-----------------------|
| SA Government Reserved Capacity  | 70MW     | System Security       |
|                                  |          | Regulation FCAS       |
|                                  |          | Contingency FCAS      |

TABLE III. DIFFERENT SERVICES PROVIDED BETWEEN SA GOVERNMENT AND NEOEN
3.2. Operation Characteristic
Operational data from NEMOSIS has been analyzed, and the results are shown in Table 4. Results show that the battery does not have a minimum operation level, demonstrating the battery storage system's reliability. The large plant start number and zero unit-off days show that battery equipment is very reliable as renewables. The low capacity factor shows that it an only participant in a small section of the wholesale market.

**TABLE IV. OPERATIONAL CHARACTERISTICS FOR DIFFERENT TECHNOLOGY**

| Unit Type         | Min Operating Level (%) | Capacity Factor | Plant Start No. | Off days (%) |
|-------------------|-------------------------|-----------------|-----------------|--------------|
| Coal              | 40                      | 0.41            | 468             | 38           |
| CCGT              | 32                      | 0.57            | 28              | 10           |
| OCGT              | 0                       | 0.27            | 287             | 35           |
| Battery Storage   | 0                       | 0.04            | 9889            | 0            |
| Wind              | 0                       | 0.39            | 745             | 0            |
| Utility PV        | 0                       | 0.03            | 9889            | 0            |

3.3. System Security
The battery storage system can protect system security, and it can decrease the possibility of blackout events. Since the lack of coal-fired power stations, South Australia highly relies on gas power plants and power imported from other states (e.g., from Victoria by Haywood Interconnector). In this case, substantial flows on Haywood Interconnector will occur if there is a loss of multiple generations, leading to a trip [7]. To protect the power system from this risk, South Australia designed the System Integrity Protection Scheme (SIPS). There are three stages in SIPS, and the first stage requires the ability of fast response of the battery energy storage system [7]. Hornsdale Power Reserve is one of the participants in SIPS. As more and more battery storage systems are established in the states, it is believed to play a more significant role in electricity system security.

3.4. Energy Arbitrage
The energy storage can offer a series of services that include the load shift, energy dispatch management, adjusting the frequency [8], etc. For the company, the economic availability is being placed increasing attention. In this part, one of the revenues of the Hornsdale Power Reserve will be focused on, which is the market arbitrages. Moreover, to ensure the truth and accuracy of market arbitrages’ incomes, the actual data modeling and analysis will be used in this part. The market arbitrages mean the battery of Hornsdale Power Reserve can charge the battery at a relatively low price while discharging the battery at a relatively high price. The storage units can use the price spreads in South Australia's energy market's electricity market price to make a profit [9]. The implement of market arbitrages is now receiving tremendous attention from the research community, particularly in the battery storage associated with intermittent renewable generation. Since the actual electricity price in the energy market is considerable volatile [10], the price spread can also be increased, which results in more considerable profit [11]. However, there are still difficulties when market arbitrage is carried out. For example, although the market arbitrage and revenue can be analyzed in the past, it is hard to forecast electricity prices for next year [12].
The real data of NEMOSIS can be used better to analyze the market arbitrage of HPR in NEM. The figure below shows the HPR behavior on a typical day (5 Oct 2018) and the hourly power purchase agreement price.

![HPR Behavior VS SA Hourly PPA Price](image)

**Figure 1.** HPR Behavior VS SA Hourly PPA Price

3.5. Frequency Control Ancillary Services (FCAS)

Frequency Control Ancillary Services (FCAS) includes regulation FCAS and contingency FCAS. AEMO controls Regulation FCAS, and the generators which provide Regulation FCAS should maintain the frequency between 49.85Hz and 50.15Hz [13]. Contingency FCAS is locally controlled. Measures to correct the frequency in contingency events include generator governor response, load shedding, rapid generation, and rapid unit unloading [14]. Since the battery storage system can take charge and discharge, it can rapidly raise and decrease the frequency. The FCAS market is divided into eight different markets, shown in the table below [13].

| TABLE V. EIGHT FCAS MARKETS |
|----------------------------|
| Contingency FCAS           |
| Fast Raise (6 second Raise)|
| Fast Lower (6 second Lower)|
| Slower Raise (60 second Raise)|
| Slower Lower (60 second Lower)|
| Delayed Raise (5 min Raise)|
| Delayed Lower (5 min Lower)|
| Regulation FCAS           |
| Regulation Raise          |
| Regulation Lower          |

When there is a contingency event, such as a sudden drop in generation due to a generator set accident or a sudden reduction in large-scale loads such as factories, the electricity system's frequency will suddenly change. The grid can purchase electric energy in the Contingency FCAS market to...
stabilize the frequency. Different markets can be selected according to the scale of the crisis of the contingency event. The Contingency FCAS services are provided within the time required by their markets, respectively, such as the immediate raise service will be delivered within 6 seconds of a contingency event. When there is a small deviation in frequency, Regulation FCAS can provide frequency correction services by increasing the power into the system or reducing the system power. Hornsdale Power Reserve registered and participated in all of the 8 FCAS markets. The revenue will be analyzed in the following section.

3.5.1. Regulation FCAS

The increase of renewable penetration can also result in instability in the power system. It is because renewable generators, unlike thermal generators, can only provide low (e.g., some wind turbine) or even not provide (e.g., PV plants) inertial response [15]. Inertial is an essential part of Frequency Control Ancillary Services (FCAS) to decrease frequency deviation, so there will be insufficient inertial control with the continuous growth of renewable penetration. However, battery storage technology can address this problem due to its rapid charging and discharging characteristics. Hornsdale Power Reserve Energy Storage System even demonstrates better performance following AEMO's central Automatic Generation Control (AGC) set-point and quickly respond to contingency events than traditional thermal generator [16].

3.5.2. AGC in NEM

The process of FCAS regulation in the NEM is presented as a flow chart in Figure 2. Critical steps of regulation control in FCAS markets are as follows.

- Step 1: Collecting both frequency and time errors every 40 seconds.
- Step 2: Combining two kinds of errors into regulation components.
- Step 3: Adjust and publish the set-point every 4 seconds based on the five-minute basepoint and regulation components.

![AGC in the NEM](source form AEMO)

3.5.3. Comparison of the FCAS regulation performance
NEMOSIS collects regulation components and basepoint data to the Hornsdale Power Reserve and a conventional FCAS unit (OCGT). As previously mentioned, the set-point and the actual output of those two units are depicted in Figure 3 and Figure 4. The conventional thermal plant has relatively worse performance, while the battery storage system has precise and rapid frequency respond in Regulation FCAS. The time lag of HPR battery units is exceptionally tiny, while it is significant with the OCGT plant.

![Figure 3. Conventional Thermal Plant Frequency Respond](image3)

![Figure 4. Hornsdale Power Reserve Frequency Respond](image4)

### 3.5.4 Impact on Regulation FCAS price

Hornsdale Power Reserve has a fast and accurate frequency response and has a considerable impact on the regulation FCAS price. There is a minimum 35MW FCAS regulation requirement in South
Australia since 2015[17]. However, FCAS's price is too high in South Australia because of the lack of local suppliers (coal-fired plants) and importing from other states [18]. Figure 5 simulates the total Regulation FCAS payment in South Australia. The yellow part represents HPR enters the market. Results show that, compared with the previous year, the operation of the Hornsdale Power Reserve Energy Storage System reduces the regulation FCAS cost by around $40 million in South Australia since December 2017.

3.5.5. Revenue for Regulation FCAS Markets
Figure 6 below shows the active degree of HPR in two Regulation FCAS markets (Regulation Lower and Regulation Raise) on a typical day (19 Mar 2018). It also shows the two Regulation FCAS markets' price changes on the same day, whose data is from NEMOSIS. The participation of HPR in the regulation Raise market is larger than that of a Regulation Lower market.
3.5.6 Contingency FCAS
To explain the frequency response of the battery storage system for contingency FCAS, the case of Queensland and South Australia system separation on 25 Aug 2018 is considered. On that day, a lightning strike on a transmission tower results in the interconnector trip between QLD and NSW, which leads to that frequency in other states immediately decrease [19]. Then a trip of the interconnector between SA and VIC results in the frequency of islanding SA suddenly increases [19]. As shown in Figure 7, Hornsdale Power Reserve maintained its rapid and accurate frequency response during this contingency event in about 20 seconds. This event leads to the load shedding both in NSW and VIC but zero load shedding in SA, possibly because of the role that battery storage system play. It demonstrates that the battery storage system can largely contribute to the contingency events in FCAS.

![Figure 6. HPR Regulation FCAS Behavior VS Half-hourly PPA Price](image-url)
3.5.7. Revenue for Contingency FCAS Markets

Figure 8 below shows the participation of HPR in contingency FCAS markets and the change of the market price on a typical day (19 Mar 2018). As an essential provider in contingency FCAS markets, HPR frequently provides energy in fast, lower, and delayed markets.

4. ENERGY STORAGE ECONOMY ANALYSIS

4.1. Cost Model

4.1.1. System Cost

The system cost contains battery cost and inverter cost, which is shown as follows:

\[ C_{\text{system}} = P_{\text{inv}}C_{\text{inv}} + Q_{\text{batt}}C_{\text{batt}} \] (1)
where $C_{\text{system}}$ is the system cost (S), $P_{\text{inv}}$ is the inverter rated power (kW), $Q$ is the energy storage rated power capability (kWh), $C_{\text{inv}}$ is the cost of an inverter (S/kW) and $C_{\text{Batt}}$ is the cost of energy storage (S/kWh).

### 4.1.2. Operation and Maintenance Cost

The operation and maintenance cost includes the cost associated with operating and maintaining to protect the equipment, ensure it usually works, and reach the expected life. The equation is shown as follows:

$$C_{\text{O&M}} = c_{\text{O&M}} P$$

where $C_{\text{O&M}}$ is the cost of operation and maintenance on a year (S/year), $c_{\text{O&M}}$ is the cost of operation and maintenance per unit (S/kW-year), $P$ is the rated power of the energy storage (kW).

### 4.1.3. Installation Cost

The installation cost includes the installation labor cost, installer margin and overhead cost, and the permitting cost, which are shown as follows:

$$C_{\text{ins}} = P C_{\text{labor}} + P C_{\text{im&o}} + P C_{\text{perm}}$$

where $C_{\text{ins}}$ is the cost of installation (S), $C_{\text{labor}}$, $C_{\text{im&o}}$, $C_{\text{perm}}$ are the cost of labor (S/kW), the cost of margin and overhead (S/kW), and the cost of permitting (S/kW), respectively.

### 4.1.4. Other Cost

The cost of building energy storage must consider the cost of land acquisition, the cost of connection, and development approval of transmission line extension costs. The equation is shown as follows:

$$C_{\text{other}} = C_{\text{la}} + C_{\text{CDA}} + C_{T}$$

where $C_{\text{other}}$ is the cost of other aspects (S), $C_{\text{la}}$ is the cost of land acquisition (S), $C_{\text{CDA}}$ is the cost of connection and development approval (S), $C_{T}$ is the cost of the transmission line extension (S).

### 4.1.5. Overall Cost

The operation and maintenance cost over the full life cycle should be calculated to present value initially because of the discount rate and inflation rate. After taking all the different types of cost listed before into account, the cost model can be described as follows:

$$C_{\text{overall}} = C_{\text{system}} + C_{\text{ins}} + C_{\text{other}} + \sum_{t_0=1}^{N_0} C_{\text{O&M}} \left( \frac{1 + r}{1 + d} \right)^{t_0}$$

where $C_{\text{overall}}$ is the cost of the energy storage in the full life cycle (S), $N_0$ is the lifetime of the energy storage (year), $t_0$ is the used time (year), $r$ is the inflation rate (%), $d$ is the discount rate (%).

### 4.2. Revenue Model

#### 4.2.1. Energy Arbitrage

Affected by the price of time-of-use electricity, a profit-making method for energy storage systems is to charge when the electricity price is low and discharge when the electricity price is high to earn a price difference[20].

$$R_{EA} = \sum_{t=1}^{T} T_s(t) [P_{\text{dis}}(t) \theta_{\text{dis}}(t) - P_{\text{cha}}(t) \theta_{\text{cha}}(t)] \Delta t$$
Where $R_{EA}$ is the energy arbitrage of energy storage on a day ($), $T$ is the electricity price which various in a different period ($/kWh), $P_{dis}, P_{cha}$ are the discharging power and charging power at $t$th period (kW). $\theta_{dis}(t), \theta_{cha}(t)$ are the discharging and charging state at $t$th period. $B_{EA}$ is the energy arbitrage of energy storage in the full life cycle ($), D is the running days in a year.

4.2.2 Frequency Control Ancillary Services Revenue
The profit-making process of the FCAS providers can be divided into two stages: the first stage is the Dispatch Interval (DI). The AEMO Dispatch Engine (NEMDE) determines the demand for various FCAS markets. According to the Trading Interval (TI) of different FCAS Providers, corresponding FCAS providers will receive remuneration based on the number of auxiliary services and the price of auxiliary services provided in the first stage. The FCAS Revenue of auxiliary service of the energy storage is shown in Equation (9):

$$R_{FCAS} = \sum_{t=1}^{T} T_{as} P_{as}(t) \Delta t$$

$$B_{FCAS} = \sum_{t=1}^{T_s} R_{FCAS} D \left( \frac{1 + r}{1 + d} \right)^{ts}$$

where $R_{FCAS}$ is the FCAS revenue of energy storage on a day ($), $T_{as}$ is the ancillary service price, which is also called the market-clearing price ($/kW), $P_{as}$ is the power provided by FCAS providers, which purchased by the FCAS markets to meet the requirement (kW), and $B_{FCAS}$ is the FCAS revenue of energy storage in the full life cycle ($).

4.2.3 Cost Saving Revenue [21]
Frequent energy storage charging and discharging can reduce the peak load, increase the transformer's life and update time, and achieve cost-saving.

$$B_{CS} = \mu_{tr} \left[ 1 - \left( \frac{1 + r}{1 + d} \right)^{n} \right] P$$

$$n = \frac{\log_{10}(1 + \alpha)}{\log_{10}(1 + \beta)}$$

Where $B_{CS}$ is the cost-saving revenue in the full life cycle ($), $\mu_{tr}$ is the coefficient of investment for electricity transformer upgrading ($/kW), $\alpha$ is the annual load growth rate (%), $\beta$ is the peak clipping rate.

4.2.4 Other Revenue
Other revenue includes revenue for the government. For example, in the first six months of 2018, the Hornsdale Power Reserve (HPR) invoiced 1.4 million euros (around $2 million) to the Australian government from the South Australia contract [22]. Define $R_{O}$ to present other revenue of energy storage on a year, define $B_{O}$ to present other revenue of energy storage in full life cycle, the equation is shown as follows:

$$B_{O} = \sum_{t=1}^{N_s} R_{O} \left( \frac{1 + r}{1 + d} \right)^{ts}$$

4.3 Energy Storage Configuration Model
4.3.1 Function
Combining the cost model and revenue model of Energy Storage, the function of the net profit of Energy Storage can be constructed from an economic perspective. The whole revenue contains the energy arbitrage, Frequency Control Ancillary Services (FCAS) revenue, cost-saving revenue, and other revenue. The net profit in the full life cycle is shown as follows:

$$N = B_0 + B_{CS} + B_{FCAS} + B_{EA} - C_{overall}$$  \hspace{1cm} (13)

Where $N$ is the net profit in the full life cycle of energy storage ($\$$).

### 4.3.2. Constraints

#### 4.3.2.1. Power Balance Equation

$$P_{grid}(t) = P_{load}(t) + P_{cha}(t)\theta_{cha}(t) - P_{dis}(t)\theta_{dis}(t)$$  \hspace{1cm} (14)

where $P_{grid}(t)$ is the power purchased from the grid at $t$th period (kW), $P_{load}(t)$ is the load at $t$th period (kW). This equation reflects the energy balance of energy Storage in a certain period. Firstly, the charging and discharging of energy storage cannot be carried out simultaneously. Therefore, when the load is larger than the battery capacity, additional energy needs to be purchased from the grid to meet the load demand\[23\]. When the load is less than the battery capacity, no extra power is required, and the battery itself can meet the load demand.

#### 4.3.2.2. Energy Storage Constraint

$$SOC_{min} \leq SOC(t) \leq SOC_{max}$$  \hspace{1cm} (15)

Where $SOC(t)$ is the state of charge in $t$th period of energy storage (%), $SOC_{min}$, $SOC_{max}$ are the minimum state of charge and the maximum state of charge, which is also called the upper and lower SOC limit. This constraint is the SOC limit of energy storage constraint.

$$\theta_{dis}(t) + \theta_{cha}(t) \leq 1$$  \hspace{1cm} (16)

$$0 \leq P_{dis}(t) \leq P_{dismax}\theta_{dis}(t)$$  \hspace{1cm} (17)

$$0 \leq P_{cha}(t) \leq P_{chamax}\theta_{cha}(t)$$  \hspace{1cm} (18)

where $P_{dismax}$ is the maximum discharge power of energy storage (kW), $P_{chamax}$ is the full charge power of energy storage (kW). The charge-discharge power in $t$th will not exceed the energy storage product's product maximum charge-discharge power. The charge-discharge state in $t$th, which is the energy constraint of energy storage.

$$\mu = \begin{cases} \mu_c & P_{cha} \geq 0 \\ \frac{1}{\mu_d} & P_{dis} \geq 0 \end{cases}$$  \hspace{1cm} (19)

$$SOC(t + 1) = SOC(t) + \frac{P_{cha}(t)\mu_c\Delta t}{Q_{Batt}} - \frac{P_{cha}(t)\Delta t}{\mu_dQ_{Batt}}$$  \hspace{1cm} (20)

Where $\mu$ is the efficiency coefficient of energy storage. When energy storage is charging, $\mu_c$ represents the charging efficiency, when energy storage is discharging, $\mu_d$ represents the discharging efficiency. The next period SOC can be defined by the current period SOC with charging or discharging process, which is energy storage coupling constraint or regression constraint \[24\].

### 4.4. Financial Metrics

#### 4.4.1. Net Present Value

Net Present Value (NPV) is the value obtained by discounting the cash flow to the first year, according to the nominal discount rate. It is a measure of economic feasibility that includes both revenue and cost. If NPV is positive, the project's investment return is greater than the initial and continuous cash expenditure. That is, the project has economic benefits. If NPV is negative, the project has no financial benefit. NPV is used to analyze the investment feasibility and profitability of projects \[25\].

$$NPV = \sum_{i=0}^{T} \frac{C_i}{(1 + d)^n} = B_{overall} - C_{overall}$$  \hspace{1cm} (21)
where $C_i$ is the cash flow in year $i$ ($\), $T$ is the full life cycle time (year), $B_{overall}$ is the present value of total revenue ($\). The net profit objective function model mentioned in the previous section is a function to calculate NPV.

4.4.2. Payback Period
The payback period (PBP) is the time in the year when the total revenue and total cost are equal. PBP can deliver the project's tangible value at the fastest speed because its feasibility will be low if the project cannot obtain profits equal to the investment in the full life cycle [26].

$$T = \frac{C_{overall}}{R_{annual}}$$

where $T$ is the payback period for energy storage (year), $R_{annual}$ is the annual revenue ($\$).

4.4.3. Internal Return Rate
The internal return rate (IRR) is the discount rate when the net profit value is zero. IRR is an important indicator used to estimate the earnings potential. It is the maximum acceptable currency depreciation rate during the project life cycle, taking into account the time value of money (inflation depreciation). It is also the maximum annual acceptable interest rate for loan investment. IRR can be described in follows:

$$NPV = \sum_{i=0}^{T} \frac{C_i}{(1 + IRR)^n} = 0$$

5. SIMULATION & DISCUSSION
This section introduces the economic analysis of Energy Storage. Hornsdale Power Reserve, located in South Australia, is used as a case study. System Advisor Model (SAM 2020.2.29) is used to simulate its technical and economic performance. SAM is free software developed by the National Renewable Energy Laboratory (NREL) for detailed performance and financial analysis of various Renewable Energy technologies [27]. The information for battery modeling can be found in [28].

4.5. System Cost and Financial Parameters
Some financial parameters need to be defined to obtain a higher accurate economic model, which will affect the value of energy storage. In Table 6 below, the $C_{CPEX}$ includes the cost of the system, cost of installation, and cost of others. $C_{CPEX}$ and $C_{O&M}$ are from [29]. Other data of Hornsdale Power Reserve is from NEMOSIS include the recommended retail price (RRP) in NEM and FCAS, the charge, and discharge data.

| Parameters           | Values |
|----------------------|--------|
| $C_{CPEX}$ (million $) | 71     |
| $C_{O&M}$ ($/kW-year) | 66     |
| $\mu_{e}$ ($/kW)     | 20000  |
| $r$ (%)               | 1.97   |
| $d$ (%)               | 7      |

4.6. Financial Results
The results of the Hornsdale Power Reserve (HPR) economic and configuration model are shown in Table 7 as following, which are obtained by SAM simulation. Figure 9 below shows the cash flow and the IRR rate in the HPR life cycle. Figure 10 shows the annual energy production of HPR in the life cycle.
TABLE VII.  FINANCIAL INDEX RESULT OF HPR

| Name                          | Energy Storage Rated Power (kW) | Energy Storage Capacity (kWh) | Energy Storage Lifetime (year) | Payback Period (year) | NPV (million $) | IRR (%) |
|-------------------------------|---------------------------------|-------------------------------|-------------------------------|-----------------------|-----------------|---------|
| Hornsdale Power Reserve (HPR) | 100000                          | 129000                        | 15                            | 3.21                  | 114.90          | 30.65   |

Figure 9. Cash Flow and IRR in the Full Lifetime of HPR

Figure 10. Yearly Energy Production from HPR

4.7. Optimize the Energy Storage Configuration
The NPV and energy storage power changes of HPR throughout its full life cycle are shown in Figure 11 below to optimize the energy storage configuration. With the increase of energy storage power, NPV will peak when the energy storage power is 150MW. As storage increases to a specific value, the increase in revenue cannot offset the rise in costs. Meanwhile, it also proves that there is still a large space for energy storage development in the Australian electricity market.
4.8. Sensitivity Analysis

In this section, sensitivity analysis is carried out on several factors affecting the economic benefits of HPR, including price difference, capital cost, and operation & maintenance cost. It is especially important to analyze the profit conditions of HPR. By using the NPV index to analyze the profit conditions of HPR and the IRR to examine the investment conditions of HPR, precise results can be obtained in the following Figure 12 and 13. From the results, regardless of the profit conditions and the investment conditions, the electricity price difference factor will have a more significant impact than the capital cost factor.

Figure 11. Net Present Value in Various Energy Storage Size of HPR

Figure 12. Tornado Chart for Profit Sensitivity Analysis
4.9. Revenue Composition

According to the real data of NEMOSIS, the revenue composition of HPR in 2018 can be found, and the results are shown in the figures below. From the results, the primary revenue of HPR is the FCAS revenue. The main gain of FCAS revenue is the revenue of contingency FCAS markets, which accounts for 63.86% of total electricity sale revenue.

Figure 13. Tornado Chart for Investment Sensitivity Analysis

Figure 14. NEM and FCAS Market Profit of Hornsdale Power Reserve in 2018

Figure 15. NEM and FCAS Market Profit Percentage of Hornsdale Power Reserve in 2018
4.10 Economic Result Comparison

This section compares the three financial indexes (NPV, IRR, and Payback Period) of HPR with the same size wind farm and PV farm (100MW) to show the economic characteristics of energy storage more intuitively. The results are shown in the following Table 8. From the horizontal comparison results, energy storage has the shortest payback period and the largest IRR. Meanwhile, its NPV is higher than the photovoltaic (PV) farm and lower than the wind farm. The main reason is that energy storage revenue mainly comes from electricity arbitrage and auxiliary services, greatly affected by the price difference in electricity. The profitability of wind farms and PV farms is mostly through electricity sales, which is less affected by the electricity price difference.

| Name               | Energy Storage | Wind Farm[30] | PV Farm[31] |
|--------------------|----------------|---------------|-------------|
| NPV (million $)    | 119.4          | 360           | 14.22       |
| IRR (%)            | 30.65          | 22            | 15.62       |
| Payback Period (year) | 3.21          | 6.7           | 6.59        |

5. CONCLUSION & OUTLOOK

Compared with other energy generation systems, the energy storage system has outstanding characteristics in maintaining the system's stability. The comparison between HPR and South Australian traditional OCGT in FCAS regulation performance shows that energy storage has an accurate and fast frequency response in Regulation FCAS, and it has a shorter lag time compared with OCGT. In the event of a lightning strike in QLD and NSW on 25 Aug 2018, the energy storage system's outstanding response reduced the enormous economic loss. The performance of HPR in the contingency FCAS can also explain the effect of the energy storage system on maintaining the system's frequency stability.

From the optimization results of energy storage configuration, there is still a massive development of South Australia's energy storage in the future. From the 100MW energy storage system to the 200MW energy storage system, the estimated NPV values are all positive and more than 100 million dollars, indicating that even if the energy storage scale doubles, the energy storage system still has the value of the investment. When the energy storage scale reaches 150MW, investors can get the maximum profit in the full cycle life. The centralized battery energy storage plants probably have high profitability, can withstand the highest currency depreciation and it has the highest annualized rate accepted by investors. The project has the shortest payback time and good returns. These can promote investors to invest in energy storage projects. The income of energy storage mainly comes from FCAS. As the penetration rate of renewable energy continues to increase, the huge contribution of battery storage systems to Regulation and Contingency FCAS can potentially improve system stability. While the government supports clean energy power generation projects, it will also support energy storage projects. Meanwhile, the battery energy storage system can provide competitive services like the guarantee of system security, Regulation, and contingency.

From the economic sensitivity analysis results, the main factor affecting the energy storage system is the electricity price difference, which is the electricity sales revenue in different markets. Then it is capital cost and O&M cost. There are two main methods to improve the economic benefits of energy storage systems. With the development of technology, the cost of batteries decreases, and the lifespan of batteries increases. The other is to increase the participation scale of energy storage in the FCAS markets, which are the primary revenue source.

Notably, energy storage performance is fast and precise due to its advantages of fast charging or discharging ability. Though the cost of battery storage units is precisely higher than the conventional, the increased profitability and increasingly lower battery price could help battery storage technology play a significant role in the future energy market. Some emerging battery storage will be developed further in a few years with a more mature industry and cost reduction. Their limitations will be
addressed in a few years as well. According to the battery installation trend year by year, the Australian energy market will publish more enhancing battery development policies to increase operational opportunity.

Note that the key components of the energy storage system should be strengthened to avoid damage because the downtime for maintenance increases expenditure and reduces revenue, which dramatically affects the financial parameters of energy storage (such as the payback period). Some critical parameters of the energy storage system can utilize artificial intelligence and big data technology to optimize automatic dispatch to maximize revenue and minimize downtime.

REFERENCES

[1] A. Eller and D. J. N. C. I. B. Gauntlett, CO, USA, "Energy storage trends and opportunities in emerging markets," 2017.

[2] S. E. Council, "Australian Energy Storage: Market Analysis," 2018.

[3] T. Brinsmead, P. Graham, J. Hayward, E. Ratnam, and L. J. C. Reedman, Australia, Report No. EP 155039, "Future energy storage trends: an assessment of the economic viability, potential uptake and impacts of electrical energy storage on the NEM 2015-2035," 2015.

[4] C. E. Council, "Charging Forward: Policy and Regulatory Reforms to Unlock the Potential of Energy Storage in Australia," 2017.

[5] J. Wang, A. Bruce, and I. MacGill, "Electric Energy Storage in the Australian National Electricity Market—Evaluation of Commercial Opportunities with Utility Scale PV," in Proc. Asia Pacific Solar Research Conference, Sydney, 2014, vol. 12, p. 2014.

[6] X. Luo, J. Wang, M. Dooner, and J. J. A. e. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," vol. 137, pp. 511-536, 2015.

[7] A. E. M. Operator, "Power System Frequency Risk Review-Draft Report," 2018c.

[8] J. Eyer and G. J. S. N. L. Corey, "Energy storage for the electricity grid: Benefits and market potential assessment guide," vol. 20, no. 10, p. 5, 2010.

[9] R. Sioshansi, P. Denholm, T. Jenkin, and J. J. E. e. Weiss, "Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects," vol. 31, no. 2, pp. 269-277, 2009.

[10] C.-K. Woo, I. Horowitz, J. Moore, and A. J. E. P. Pacheco, "The impact of wind generation on the electricity spot-market price level and variance: The Texas experience," vol. 39, no. 7, pp. 3939-3944, 2011.

[11] R. H. Byrne and C. A. J. S. N. L. Silva-Monroy, "Estimating the maximum potential revenue for grid connected electricity storage: Arbitrage and regulation," 2012.

[12] T. T. Kim and H. V. J. I. T. o. S. G. Poor, "Scheduling power consumption with price uncertainty," vol. 2, no. 3, pp. 519-527, 2011.

[13] A. E. M. J. A. E. M. O. M. Operator, Australia, "Guide to ancillary services in the national electricity market," 2015.

[14] J. Riesz, J. Gilmore, and I. J. T. E. J. MacGill, "Frequency control ancillary service market design: Insights from the Australian national electricity market," vol. 28, no. 3, pp. 86-99, 2015.

[15] M. Dreidy, H. Mokhlis, S. J. R. Mekhilef, and s. e. reviews, "Inertia response and frequency control techniques for renewable energy sources: A review," vol. 69, pp. 144-155, 2017.

[16] A. E. M. Operator, "Initial operation of the hornsby power reserve battery energy storage system," ed: Technical Report, Apr, 2018.

[17] A. E. M. Operator, "South Australian Historical Market Information Report," September 2017.

[18] T. Ackermann, G. Andersson, and L. Söder, "Electricity market regulations and their impact on distributed generation," in International conference on electric utility deregulation and restructuring and power technologies, 2000, pp. 608-613.

[19] A. E. M. J. A. I. Operator and T. R. Support Hub, Australia, "Final Report—Queensland and South Australia system separation on 25 Aug 2018," 2019.

[20] J. Dehler et al., "Self-consumption of electricity from renewable sources," 2015.
[21] L. Chen, T. Wu, and X. J. A. S. Xu, "Optimal configuration of different energy storage batteries for providing auxiliary service and economic revenue," vol. 8, no. 12, p. 2633, 2018.

[22] NEOEN, "Registration Document," 2018.

[23] Q. Wang, Y. Liu, W. Song, and K. J. A. o. E. E. Xuan, "Improved dynamic control method for energy storage units in PV dominated microgrids," vol. 68, no. 4, 2019.

[24] J. Li, Y. Xue, L. Tian, X. J. P. Yuan, and C. o. M. P. Systems, "Research on optimal configuration strategy of energy storage capacity in grid-connected microgrid," vol. 2, no. 1, p. 35, 2017.

[25] N. DiOrio, A. Dobos, and S. Janzou, "Economic analysis case studies of battery energy storage with SAM," National Renewable Energy Lab.(NREL), Golden, CO (United States)2015.

[26] W. Short, D. J. Packey, and T. Holt, "A manual for the economic evaluation of energy efficiency and renewable energy technologies," National Renewable Energy Lab., Golden, CO (United States)1995.

[27] N. J. Blair, A. P. Dobos, and P. Gilman, "Comparison of photovoltaic models in the system advisor model," National Renewable Energy Lab.(NREL), Golden, CO (United States)2013.

[28] S. SDI, "Smart Battery Systems for Energy Storage," 2016.

[29] Aurecon, "Aurecon Economic Impact Assessment " 2020.

[30] M. M. Rafique, S. Rehman, M. Alam, and L. M. J. E. Alhems, "Feasibility of a 100 MW installed capacity wind farm for different climatic conditions," vol. 11, no. 8, p. 2147, 2018.