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Battery Energy Storage System Sizing, Lifetime and Techno-Economic Evaluation for Primary Frequency Control: A Data-driven Case Study for Turkey

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Abstract

The share of renewable energy sources (RES) in power systems has been increasing in recent years. Future power systems will have lower inertia and difficult controllability, especially due to intermittent and variable renewable energy that is not dispatchable easily due to its fluctuating nature. Thus, it is necessary to increase the grid's flexibility to ensure system stability. For this need, new technologies such as battery energy storage systems (BESS) are widely discussed. It is thought to be very useful to create a fast and accurate response in frequency control services with BESSs, especially in low inertia grid conditions. The sizing, charge-discharge control, and lifetime of a BESS providing frequency control service depend heavily on the changes that may occur in the power systems. So, it is a very complex issue to decide during the investment phase. In this study, the optimum sizing, lifetime, and techno-economic evaluations of BESS providing primary frequency control (PFC) service have been made by grid's frequency data-driven. For this purpose, firstly; the BESS design providing PFC is created for Turkey's electricity system. Secondly, with the developed algorithm, the number of charge-discharge cycles of the BESS is calculated and the lifetime and capacity fading of the BESS are determined according to the frequency deviation. Finally, economic evaluations have been made for BESS considering the investment- operating costs and PFC market prices.

1. INTRODUCTION

In recent years, most of the global electricity needs are met from RES and the renewable generation capacity is constantly increasing. Since the beginning of 2020, the total capacity of RESs globally has exceeded 2.7 TW. Hydro energy has the highest capacity with 1.2 TW, followed respectively by wind energy (732 GW), solar energy (709 GW), and bioenergy (127 GW) in Figure 1[1]. However, the biggest increase in capacity in recent years is seen from wind and solar energy. It is estimated that the total wind and solar capacity will double by 2025, and with this growth may surpass the installed capacity of natural gas and coal. However, this increase in capacity creates new problems and needs in terms of ensuring the supply security of the grid. Supply of energy from intermittent and variable sources such as wind and solar causes fluctuations in energy production [2], [3]. The power systems need to increase flexibility to tackle increasing contributions from variable renewable energy (VRE). In general, the control of imbalances that may occur in the power systems could be ensured by many compensatory measures. Flexibility alternatives for efficient VRE integration are allocated on the demand and supply side of the energy system, respectively: highly flexible conventional power plants, energy storage systems, curtailment of renewable surplus generation, demand-side management, grid expansion, virtual power plants [4].

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Although the estimation studies for imbalance projects caused by RESs have progressed at an acceptable level, they have not reached a sufficient point yet. In this process of change occurring in modern power systems, it will have a very important place for grid operators and consumers in the supply process of electricity storage system [5]–[7]. According to SHURA energy conversion center report for Turkey, the long-term electricity system planning purposes the contribution of Turkey, in 2023 the basic field goals and strategies, both short and long term, we need an integrated energy and climate change strategy determination. In the report, where wind and solar installations stand out as the least costly options, it is emphasized that policies to increase energy efficiency that provide versatile cost-effective benefits should be considered together with other policies that encourage renewable energy and protect the environment and follow a holistic approach. On the other hand, energy storage technologies that provide flexibility to the system for more renewable energy integration are recommended to be supported by market mechanisms [8].

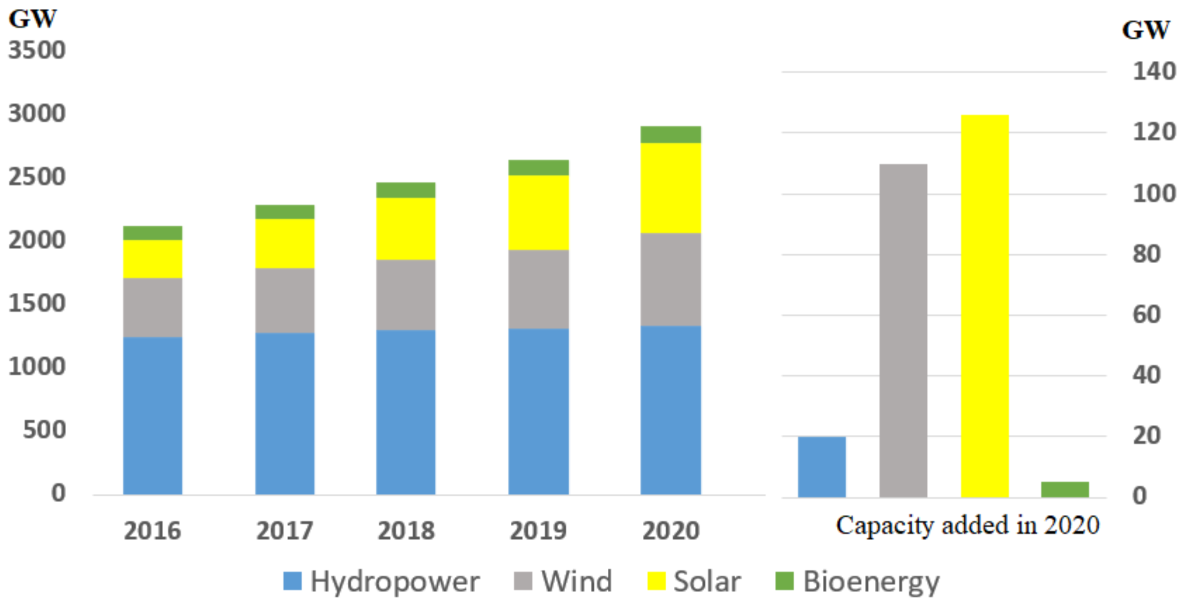

Figure 1. *Renewable power capacity growth over the world* [1].

Electricity storage (ES) can be used for many different services needs with many different technologies and application architectures. Generally, ESs could be generally classified according to their functions and methods of stored energy. Basically, we can define ESs in five groups according to the technology type: chemical, electrical, electro-chemical, electro-mechanical and thermal [9]. ES technologies mainly used today: pumped hydro storage (PHS), compressed air energy storage, flywheel, supercapacitor energy storage; electrochemical energy storage including lead-acid, nickel-cadmium, sodium-sulfur, lithium-ion (Li-ion), and flow battery energy storage. The main factors that separate ES technologies according to their intended use are energy-power density, lifetime, cost, efficiency, technology maturity, response time, self-discharge time, power rating, discharge time, and environmental impacts. PHS has the highest rate with a capacity of about 170 GW today and is mostly used in energy shifting service. Also, they have some difficulties such as site dependence, limited capacity, or response capabilities. However, Electrochemical energy storage can provide the capacity, positioning and fast response flexibility required to meet a much wider range of service options than many other storage technologies. Thermal, electro-chemical and electro-mechanical energy storage power capacity by main-use case and technology group are shown in Figure 2 [10], [11]. As shown in Figure 2, electro-chemical storage, that is batteries, are more widely used in frequency regulation services because they provide fast frequency response due to their short response times. Thus, the using of BESS in the frequency regulation market is rapidly increasing in next years.

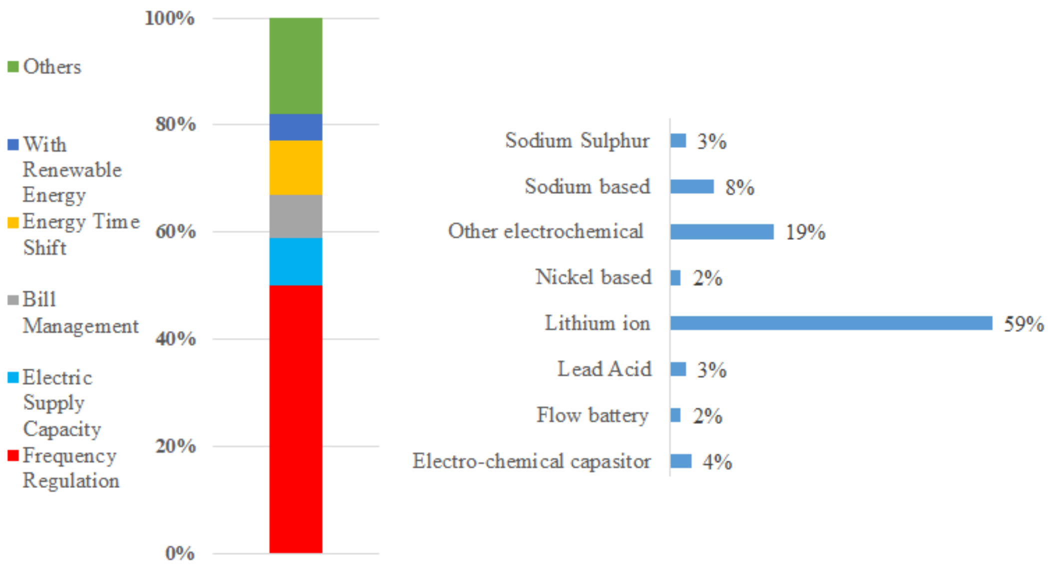

Figure 2. *The main usage services of electrochemical energy storage*

Power systems need reserve power capacity to operate stably and securely, and this capacity requirement varies according to the size of the grid and the dispatch speed. The determination and management of the reserve capacity is usually done by the transmission system operators (TSOs) according to the grid code. TSO is also responsible for maintaining system stability. The reserve capacity in a power system is mainly used for two main functions. First one; It is used to provide frequency control in supply and demand unbalance. With the change of frequency, the generation units must be in continuous operation and control their load to maintain the balance between supply and demand. Later, it is used in emergency situations to maintain system stability in sudden situations such as power loss or line openings that may occur in the grid. For emergencies, each TSO may have a different response time and application according to the grid code. However, in emergency situations, frequency control is generally managed in three sub-systems as primary, secondary, and tertiary. The PFC reserve is to stop the sudden frequency change at the beginning of the transient. Secondary frequency control (SFC) reserve should bring the frequency back to nominal level and void the primary reserves. Finally, it is the replacement for the previous one for the Tertiary frequency control (TFC) reserve. So, to simplify with a single sentence; The main role of the primary reserve is to stop the frequency drop during a transient state; Secondary control should bring the frequency back to the nominal level and release the primary reserves and the tertiary reserves can be seen as a substitute for the previous one. It aims to prevent frequency drops that may occur with PFC in milliseconds before reaching the lowest frequency limit of the grid. As a priority, it is to be able to provide frequency stability within the range of grid frequency limits. BESSs are one of the most important alternatives to provide fast frequency control response. The European Network of Transmission System Operators for Electricity (ENTSO-E) and Turkey must be operated in the range of 49.8 to 50.2 Hz frequency for the grid. In ± 200 mHz variation step changes, the reserves are required to react within the time specified. Primary reserve units should be provided with primary reserve support in any change in the frequency. There is no frequency dead band in primary reserves obtained from existing conventional sources. Similarly, in case of PFC from BESS, charge and discharge control is provided according to frequency deviation. It is necessary to measure the BESS correctly to provide charge-discharge control of BESSs according to the frequency change and to provide the required reserve capacity of BESSs.

It is important for both system operators and investors to correctly find an optimum size of utility-scale batteries intended for the grid services and to estimate the lifetime. System operators want to know the availability of each facility for short- and long-term planning. Likewise, every case should be taken into consideration both technically and economically for investors and the right decision should be made before the investment. The forecasting of state of charge (SoC), depth of discharge (DoD), and cycle number of batteries under operating conditions would be very useful before implementation, especially when considering frequency control services. Therefore, there are many studies conducted investigating the sizing and lifetime of BESS for power systems and investors. With a pilot application project in Thailand, the general arrangement of BESSs according to battery types has been explained to give a general idea [10]. Similarly, the comparative analysis of fast frequency response with BESS in Germany, Great Britain, and Sweden is presented to show technical regulatory frameworks[12]. In [13], a sensitivity analysis of frequency control reserve of BESS with different operational conditions in Germany is made within this project hybrid BESS with five different battery technologies. To support solar power with BESS for PFC in the Colombian power system., the BESS sizing strategy is proposed by optimizing energy capacity and operation set point of SoC [14]. In [15], the economic evaluation of solar power using hydrogen storage and battery solar power is studied for Poland. A hybrid form of BESS and solar installed in a football stadium is demonstrated as techno-economic aspects considering of Norwegian economic and regulatory framework [16]. A life prediction model is developed based on test results to use extrapolate lifetime for grid-connected Li-ion BESS. This study showed that the life model can be used to optimize the overall life-cycle benefit of integrating BESS on the grid [17]. With a different approach, the capacity degradation of BESSs is made by a statistical capacity aging model [18]. The life Cycle Estimation of BESS using PFC is made on basis of grid frequency analysis. It used time series analysis for frequency samples and estimated the number of charging/discharging cycles using the rain-flow procedure [19]. In [20], the capacity aging of providing PFC using a 1MW/1MWh BESS in Eastern Denmark is calculated according to the number of charge-discharge cycles. In [21], it is found the optimal economical size of BESS to minimize life cycle cost using different battery technologies and parameters. The comparative economic analysis between hydrogen storage and battery storage with a grid-connected photovoltaic system is studied. This study considers the rule-based operation strategy and scenarios based on pessimism and optimism [22] . It is investigated the economic benefits of the primary frequency control with BESS. It used to determine the sizing of BESS using a methodology of both basic and hysteresis frequency control based on small and large dead bands on the Powerfactory model. According to simulation results, the optimum energy capacity of BESS is obtained [23]. Similarly, to improve frequency response in TSO the optimal sizing of a utility-scale energy storage system is made by using grid model on Powerfactory [24]. Economic availability of BESS considering sizing and aging is tested by a model developed on distribution grids to stack ancillary services. As a results, this methodology could be benefit for the flexibility, safety, reliability and quality of the grid [25].

In this study, technical and economic evaluation of a storage system providing PFC is performed using historical frequency data driven. BESS optimal sizing is determined based on the frequency control limits of Turkey's grid. According to the frequency data of the past two years; SoC, DoD and energy changes of BESS have been observed. According to the results obtained, the cycle number of BESS has been calculated with the developed algorithm, and according to these values, BESS aging and lifetime have been predicted. Finally, the economic evaluation of BESS according to investment and operating costs has been shown.

2.MATERIALS AND METHODS

2.1.OPTIMAL BESS SIZING FOR PFC ACCORDING TO TURKEY GRID CODE

To determine the optimum capacity of the BESS to be used in the PFC service, the PFC operating principles of the priority grid should be determined, and the energy and installed power capacity of the required BESS should be determined accordingly. In grid of Turkey, there is no battery facility in those who are engaged in business activities, legislation studies have been made for the use of battery systems in recent years. There are no grid requirements for battery systems and battery systems to participate in frequency control. However, for any plant the main technical requirements for PFC as stated by the TSO TEIAS are [26]:

- PFC must be activated within a “few” seconds of a frequency deviation. The measurement error and regulation sensitivity should be less than ±10 mhz.
- PFC must be fully activated at frequency deviations higher or equal to ±200 mHz, be achieved within 30 seconds and be maintained for at least 15 minutes.

As batteries both not have any primary supply sources and have a limited storage capacity, they need a continuous charging process. For they can be used in continuous services such as PFC, the required energy capacity must be determined for the initial state. To ensure PFC reserve by BESS, it need to enough energy capacity to meet alert and normal state of grid frequency. Accordingly, BESS must provide energy for alert states in frequency deviation more than ± 200 mHz during minimum 15 minutes. To do this, it must have energy capacity required for alert states during minimum 15 minutes according to Equation 1.

$$E_{\max} = 2\,x\,\frac{15_{\min}}{60}\,x\,P_{BESS}\quad [MWh] \tag{1}$$

According to Equation 1, a minimum of 0.5 MWh energy capacity is required to provide 1 MW PFC reserve for alert state in both directions. Similarly, BESS must support frequency deviations lower than ± 200 mHz in the normal state between 49.8 to 50.2 Hz. Thus, it can ensure frequency deviation and balance its energy state according to state according to frequency transitions. To make this, it is reserved 2 x 0.2 Hz x P_{BESS} = 0.4 MWh [27], [28]. In this direction, we could determine the optimum required total energy capacity to provide 1 MW of PFC is 0.9MWh as per unit value Turkey grid code.

2.2.THE LIFE CYCLE OF BESS AND CHARGE / DISCHARGE CYCLE COUNTING ALGORITHM

The lifetime of the BESS depends on the number of charge-discharge cycles that the battery can provide with decreasing the initial capacity of the battery. Depending on the frequency change of the grid and the possible operating conditions, the total number of cycles of the BESS must be estimated, because the BESS continuously discharge/charge in PFC. As each battery is used and recharged, it decreases the ability to use to its original capacity in time. Thus, the lifetime for a battery is the number of charge-discharge. And the lifetime depends on the types, materials of battery and how to use it.

The DoD shows the percentage of discharged energy relative to the battery's total capacity that it defines as the discharged energy capacity from a fully charged capacity divided by the nominal capacity. Generally, the more charge-discharge a battery is, the less its lifetime can be. At the same time, the faster and larger the DoD rate, the shorter the lifetime. In most cases, manufacturers of batteries determine and limit DoD of battery such as %60 or %80 according to the intended use. However, some manufacturers have rated their batteries with a 100% DoD that it could use the maximum capacity without excessively damaging the battery. Even if the DoD and SoC behavior of each electrochemical battery is different, the higher DoD and SoC affect the lifetime of the battery. The long-term use of BESS can be provided as a standard depending on the DoD and the operating range of the SoC. Figure 3 and Table 1 show basic examples of these features [29], [30].

Table 1. *Life cycle characteristic of a battery depending on DoD and the operation range of SoC*

DoD (%)	Operation range of battery SoC (%)	Cycles
100	0-100	4000
75	25-100	5651
50	50-100	7746
	25-75	11,556
30	50-80	20,317

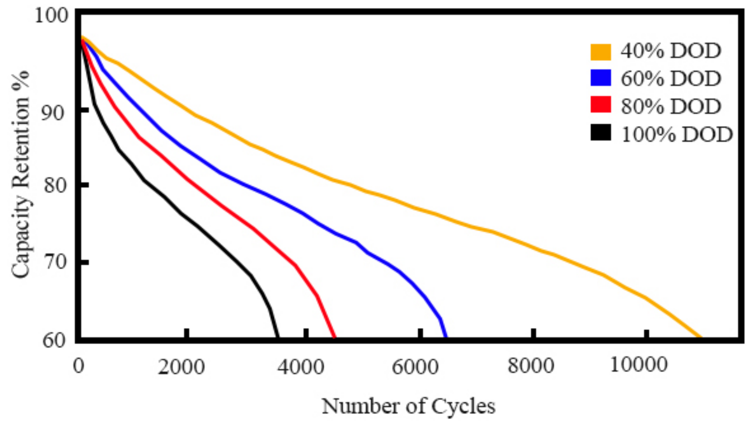

***Figure 3**. Capacity retention according to number of cycles*

The battery life is affected by the number of charge-discharge cycles. Thus, estimating battery life is important for maximizing return on investment for grid-scale battery energy storage applications. In this paper, to approximate the number of battery full charge / discharge cycles, a fast battery cycle counting method is used for grid-connected BESS that exposed to micro cycles. This method calculates the variable power BESS irregular charge-discharge cycles due to the actual grid frequency variation. As shown in Diagram 1[31], the fast cycle counting method is used to find approximate the number of complete cycles of a battery using historical BESS PFC data. The method is explained as follows:

- The algorithm loops through historical PFC data over a specified period.
- In the first step, the values of the PFC are obtained for every second.
- According to the algorithm used in this article, if it is greater than zero, the battery is charging; If it is less than zero, the battery is discharged; or if it equals zero, the battery is resting.
- In the second step, the sum of all charge indexes creates the battery Charge data set, and the sum of all discharge indexes creates the battery Discharge data set.
- In the third step, when each one equals 100%, the battery charge and discharge cycle is increased by 0.5 independently which is a parameter to indicate the charge and discharge of the battery. When it is added to the counter twice so one of it is for charging and the other one is for discharging in the algorithm, the battery completes one cycle.
- The algorithm is iterated over the history of the PFC data considered and obtains the Total Cycle data.

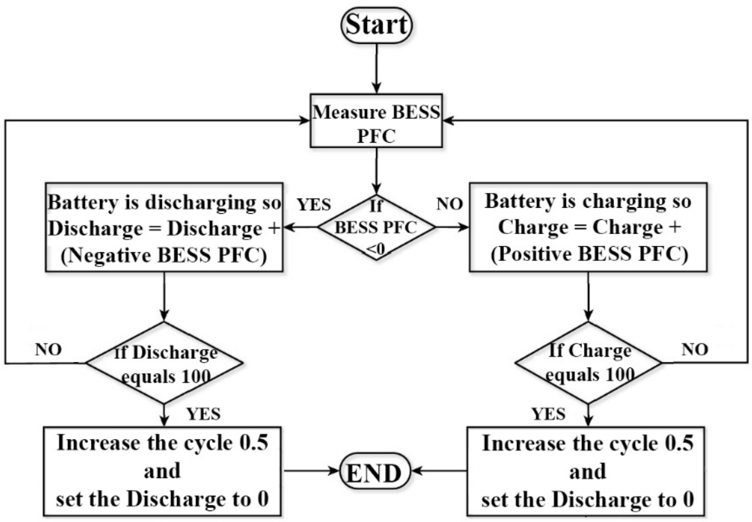

***Diagram 1.** Flow chart of fast battery cycle count estimation method used for a grid-connected battery energy storage system which exposed to micro cycles.*

2.3.ASSESSMENT OF BESS AGING

As with all electrochemical applications, aging is an inevitable process in batteries due to different side effects. The main factors that cause this aging are cycle number, fast charge, temperature and SoC. However, in general, we can define aging for BESS as calendaring aging and cycling aging. Calendaring aging: It is aging that occurs regardless of use, known as the shelf life of the battery. Cycling aging is the aging that occurs depending on the number of cycles and the depth of discharge each cycle. In other words, it is the decrease of energy capacity and efficiency of BESS [32], [33]. Calculation of the capacity loss of BESS depending on both factors can be estimated according to the SoC changes of BESS [34]. Basically, in the calculation of the capacity loss of a BESS should be made according to both factors. However, with the assumption that there will be a continuously charge / discharge change in frequency control services, calendaring aging can be neglected [35]. Based on the number of cycles of BESS, we can calculate the capacity loss according to Equation 2.

$$Cycle\_Aging = 0.021\ x\ e^{-0.0194\ x\ SOC\_average}\ x\ DOD_{MAX}{}^{0,7162}\ x\ N\_cycles^{0.5} \quad (2)$$

In this study, the monthly average of SoC and maximum DoD are calculated with the Charge / Discharge Cycle Counting Algorithm of BESS designed for PFC. By using this information, the capacity loss of BESS is determined monthly and yearly.

2.4.INVESTMENT-OPERATIONAL COST AND ECONOMIC EVALUATION

BESS generally consists of four main parts: battery system, power conversion, energy management and balance of system. The battery system includes the management system and battery cells. In this section, the cells are combined in groups to create the whole battery system. Management between cells and cell groups is provided by the battery management system. With the battery management system, all information is transferred to the BESS energy management system. The energy management system provides the control of charge and discharges management according to the grid service of BESS. The power conversion system is used for DC-AC conversion under charge-discharge conditions. Finally, balance of system can be defined as other necessary hardware, security and infrastructure parts that make up the BESS [36].

The cost calculation of BESS was determined according to the investment cost ($CAPEX_{BESS}$), annual processing and maintenance expense ($OPEX_{BESS}$) and the estimated lifetime (T_{years}). Basically, $CAPEX_{BESS}$ is calculated using unit prices of installed power rated (P_{BESS}) and energy capacity (E_{BESS}), other software, any engineering, procurement, and construction (EPC) costs. For the lithium-ion battery, these unit prices (UP) are decreasing every year. In the last decade, the total investment cost of 1 MWh capacity BESS has decreased by more than 80%. This value, which was 587 $ / kWh in 2017, was observed to be around 400 $ / kWh in 2020. It is expected that this decrease will continue in the coming years [37]–[40]. As can be seen in Figure 4, approximately 70% of the investment cost of BESS consists of balance of system and battery cost.

$$CAPEX_{BESS} = UP_{P\_BESS(MW)} + UP_{E\_BESS(MWh)} + COST_{EPC\_and\_SOFTWARE} \quad (3)$$

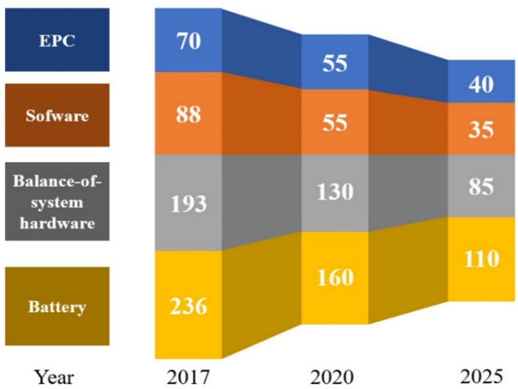

Figure 4. *Unit prices of BESS Capex*

BESSs provide two-way frequency control service up and down, and the PFC cost is calculated by the reserved power (MW) they provide. Pricing is made according to the hourly reserve power. However, in some countries, frequency reserves and pricing could be operated separately upward and downward. In Turkey, PFC reserve service and capacity pricing are made in two directions. Therefore, as BESS provides two-way control, the charging cost can be calculated cumulatively. In this study, the charging cost is neglected in the BESS income account for this reason. The income account of BESS is calculated according to Equation 4.

$$BESS\_Income = P\_BESS(MW)\ x\ Hourly\_PFC\_Price \quad (4)$$

One of the methods used in profitability analysis and economic evaluation of an investment is the Net Present Value (NPV) method. NPV shows the difference between investment income and expenses with their present value over a period. NPV is based on a discount rate that can be derived from the cost of capital required to make the investment. Discount rate reveals the risk level of the investment and the investor's attitude towards risk depending on the region where the investment is made. But basically, a positive NPV is expected from a project. Any investment with a negative NPV should be avoided [15], [41].

$$NPV = \sum_{t=0}^{N} \frac{NI}{(1+R)^t} \quad (5)$$

NI: Net income in period t (all income minus all expenses)

R: Discount Rate

N: Total number of periods in which income and expenses are evaluated

Another economic indicator is the internal rate of return (IRR). The IRR equates the NPV of an investment project to zero. It is the ratio that equates the NPV of incomes to the NPV of expenses. It is expected that the IRR value will be high in making an investment decision.

$$\sum_{t=0}^{T} \frac{NIS_T}{(1+IRR)^T} = 0 \quad (6)$$

NIS: Net income stream in period t (all income minus all expenses)

Finally, it is necessary to know the total income expected from an investment and the return of the investment. Return of investment (ROI) determines the profit-loss situation by considering the total profit and investment cost from the investment. In this way, the efficiency and sustainability of the investment are revealed.

$$ROI = \frac{(NII - CoI)}{CoI} \quad (7)$$

NII = Net Investment Income, CoI = Total Cost of Investment

3.RESULTS

In this study, the real measurement data of grid frequency of Turkey is used. The frequency data in one-second resolution for 2019 and 2020 years are shared as open source by the TSO of Turkey. The frequency data of two years are shown in Figure 5. For each year, there are over 31,5 million data points.

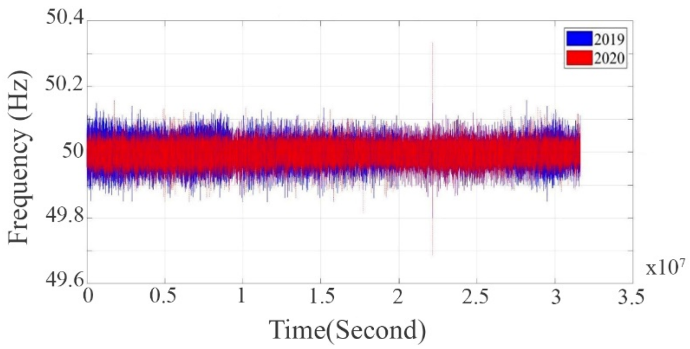

Figure 5. *The grid frequency data in one second resolution*

Based on the frequency data, to see how intense, the frequency is at which values, the frequency density graph is given in Figure 6.

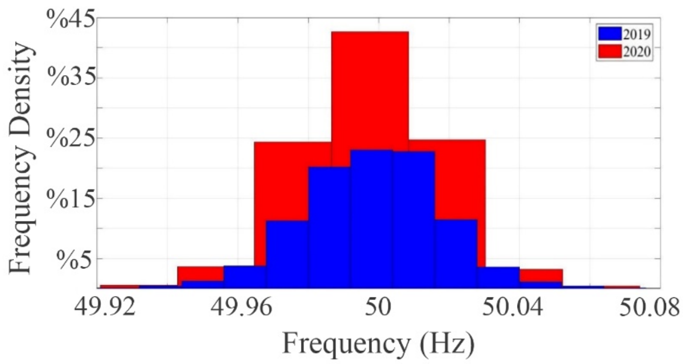

Figure 6. *Frequency density graph*

Using the frequency change values, the SoC parameter of the BESS is obtained with the help of the following equations.

$$Frequency\ \ Change\ (\Delta f) = f(t) - f(t+1) \tag{8}$$

$$Frequency\ \ Change\ \ Rate = \frac{\Delta f}{f_{nominal}} \tag{9}$$

$$Participation\ \ of\ BESS\ PFC = \frac{\Delta f}{f_{nominal}}\ x\ P_{BESS} \tag{10}$$

$$SoC_{end} = SoC_{Previous\ one}\ \ + \ \left(\frac{\Delta f}{f_{nominal}}\ x\ P_{BESS}\right) \tag{11}$$

As stated before, there is no dead band or any limit in PFC in Turkey. Also, there has not been any regulation related to using BESS in PFC of Turkey's Grid Code. However, dead band in frequency control services of BESS have been examined and applied in projects and regulation studies for different countries [42], [43]. Thus, in this study, the analyzes of BESS for Turkey have been examined separately according to three different dead bands: 0, ±10 mHz and ±20 mHz. Dead band is considered to be zero change in each frequency range. Based on this principle, the response characteristic of BESS for PFC are given in Figure 7 according to three different dead bands.

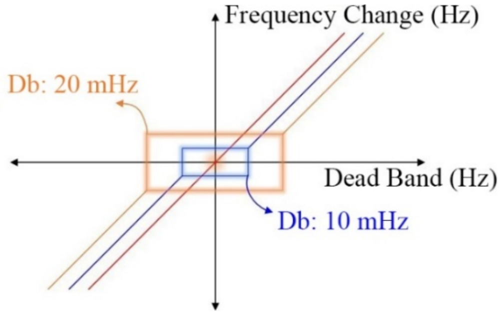

Figure 7. *The response characteristic of the BESS for PFC*

PFC participation of BESS is examined according to frequency change in seconds resolution according to grid frequency data. In Figure 8, The change of SoC of the BESS is given respectively according to the dead bands. As can be seen from here, as the dead band increases, the change in the SoC of the BESS decreases.

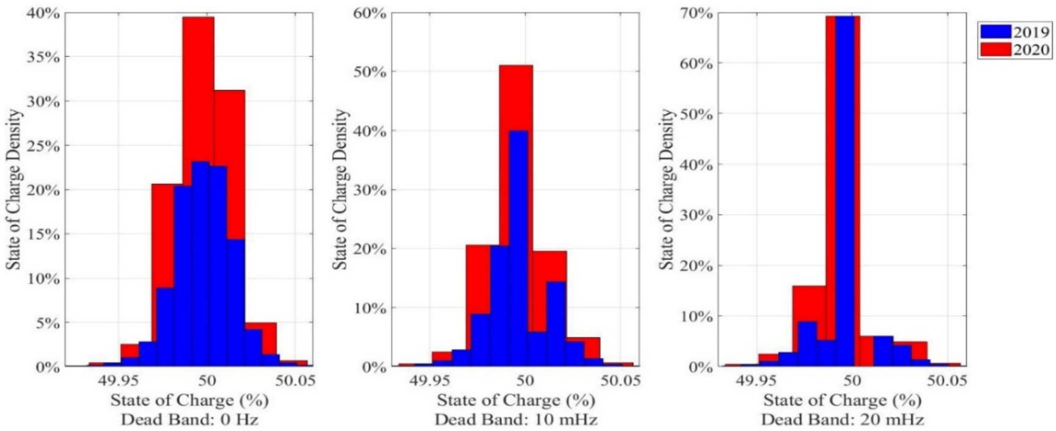

Figure 8. *Density of SoC according to dead bands.*

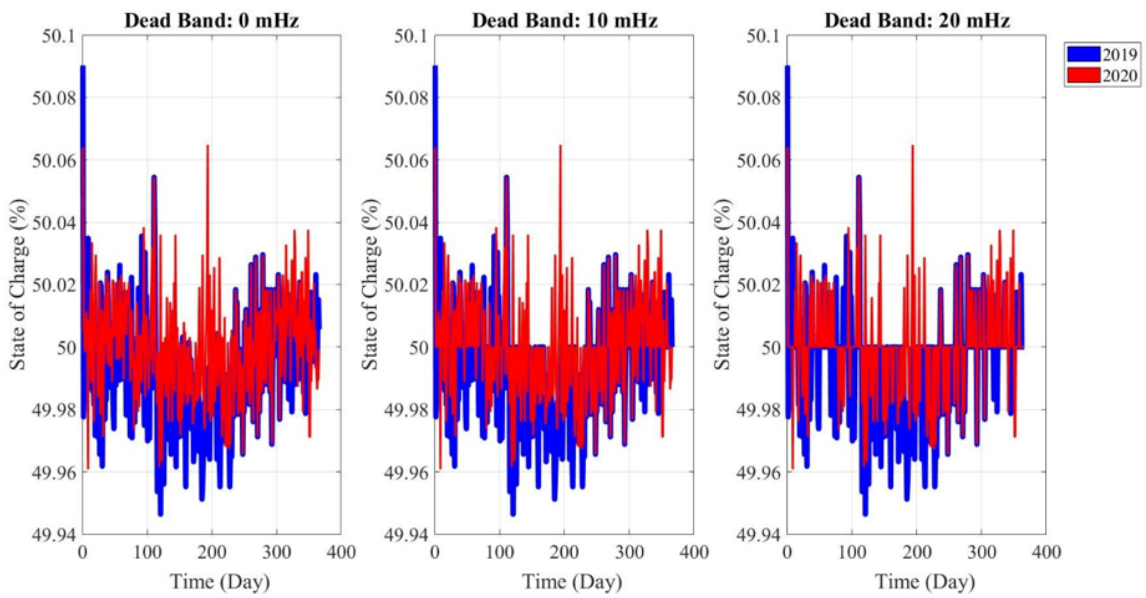

Figure 9. *Daily Maximum SoC*

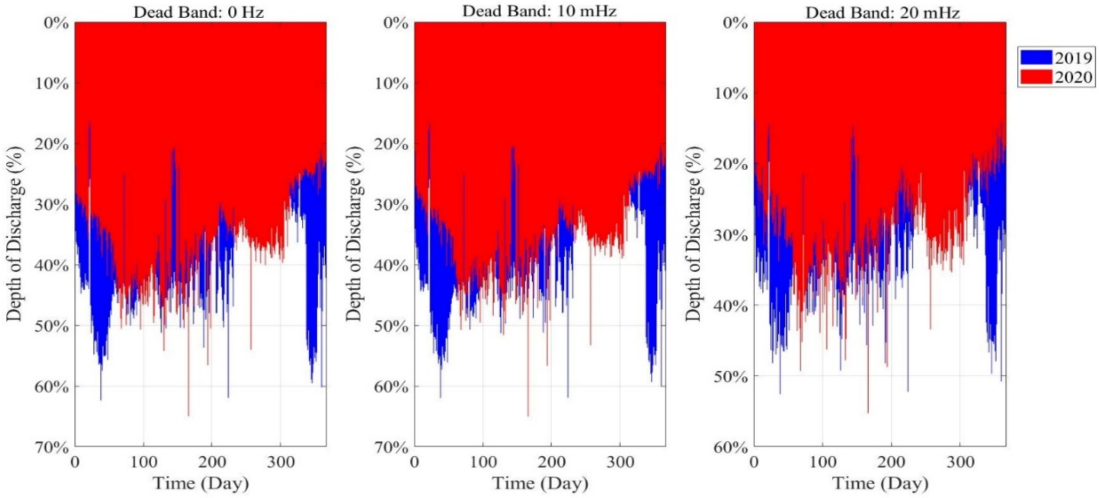

Figure 10. *DoDs According to dead bands.*

Based on the algorithm given in Diagram 1, the total number of cycles of the BESS on a monthly for a year is given according to dead band in Figure 11. At the same time, the total number of cycles for the whole year, as well as monthly, is given in Figure 12.

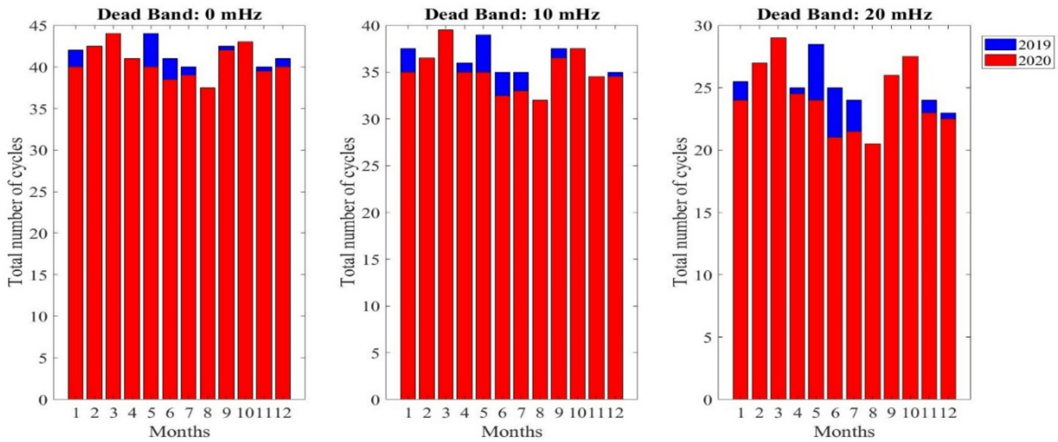

Figure 11. *Total number of cycles per month according to dead bands*

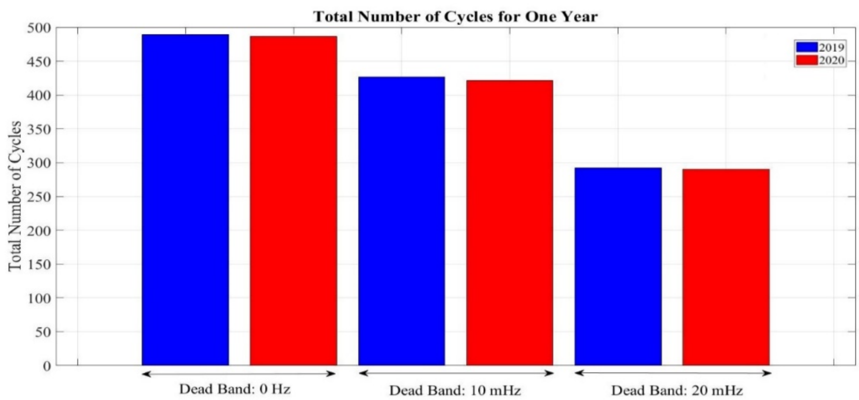

Figure 12. *Total number of cycles according to dead bands*

As seen in the examinations made according to the grid frequency data; when accepted that BESS has been taking part in the PFC continuously for two years; we observed that the SoC of BESS ranged from 49.9% to 50.1% and the SoC changed less with the dead-band expanded. Also, the number of cycles calculated with the algorithm used in the study varies according to the PFC dead band. The daily cycles calculated are 1.4 when there is no dead band, 1.2 when the dead band is ± 10 mHz, and less than 1.0 when the dead band is ± 20 mHz. In line with these results and the information in Table 1; if assumed that the change of the grid frequency will proceed similarly; the lifetime of the BESS to be established in Turkey could exceed 10,000 cycles in participation in PFC services. In other words, it could be used up to 15 years according to the total number of cycles per year, and if the dead band is applied, the lifetime could be further increased and guaranteed.

Capacity fading of BESS is calculated according to Equation 2. The capacity fading that will occur at the end of two years based on the monthly average SoC, max DoD, and cycle numbers is shown in Figure 13. Capacity fading rate according to operating conditions of BESS: 1.6% in 0 dead band, 1.45% in ± 10 10 mHz and 1.12% in ± 20 mHz. Dead bandwidth in PFC reduces the capacity fading of BESS. According to these results, the optimum energy capacity of BESS should be established approximately 15-25% more according to the dead band of PFC to ensure the usability of BESS for 15 years in PFC participation.

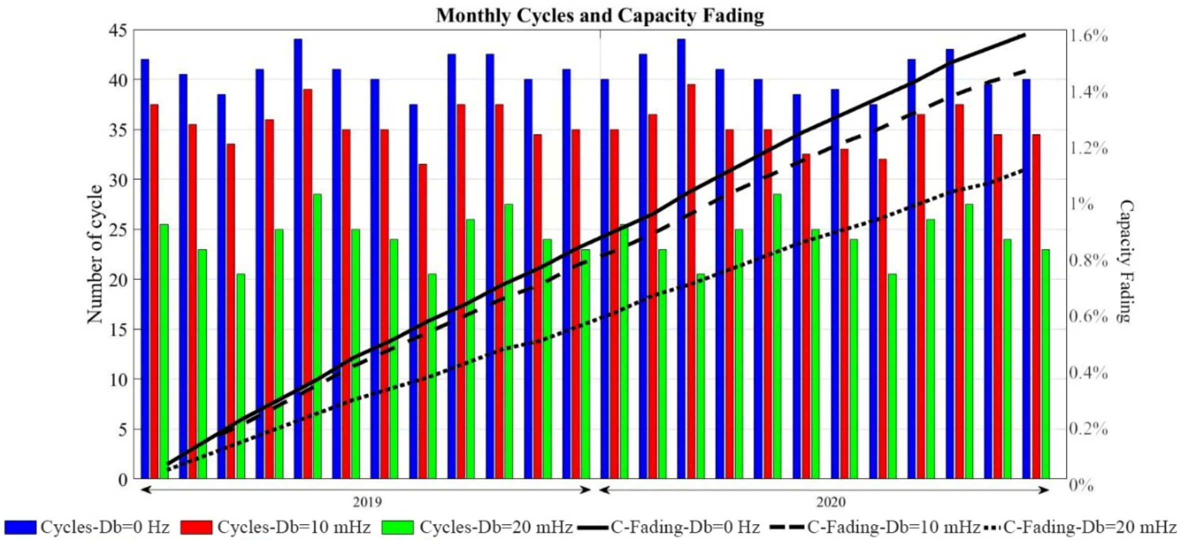

Figure 13. *Capacity fading of BESS*

After BESS sizing, lifetime, and capacity fading calculations; the economic evaluations have been made for BESS, which meet the primary frequency reserve requirements of the Turkish grid and have a service life of 15 years. Table 2 shows the scaled BESS capacity and financial basis values. To guarantee a life of 15 years, the energy capacity of BESS has been determined 20% more according to the calculated capacity fading. For the PFC income account of BESS, primary frequency capacity unit prices of the ancillary services market of Turkey are taken as a reference.

Table 2. *The scaled BESS capacity and financial basis values*

BESS Rated power	1 MW
BESS Energy Capacity	1.1 MWh
CAPEX	416000 USD
OPEX	For the first five years (%1*CAPEX) For later years (%2*CAPEX)
Lifetime	15 years
Discount Rate	%10

The primary frequency capacity market in Turkey is auctioned every day in blocks of four hours. For this reason, the actual prices for every four hours are published in Turkish Lira. The average PFC unit price are determined in USD, considering the unit prices for the years 2019-2020 and the monthly average exchange rate. Figure 14 shows the monthly average prices.

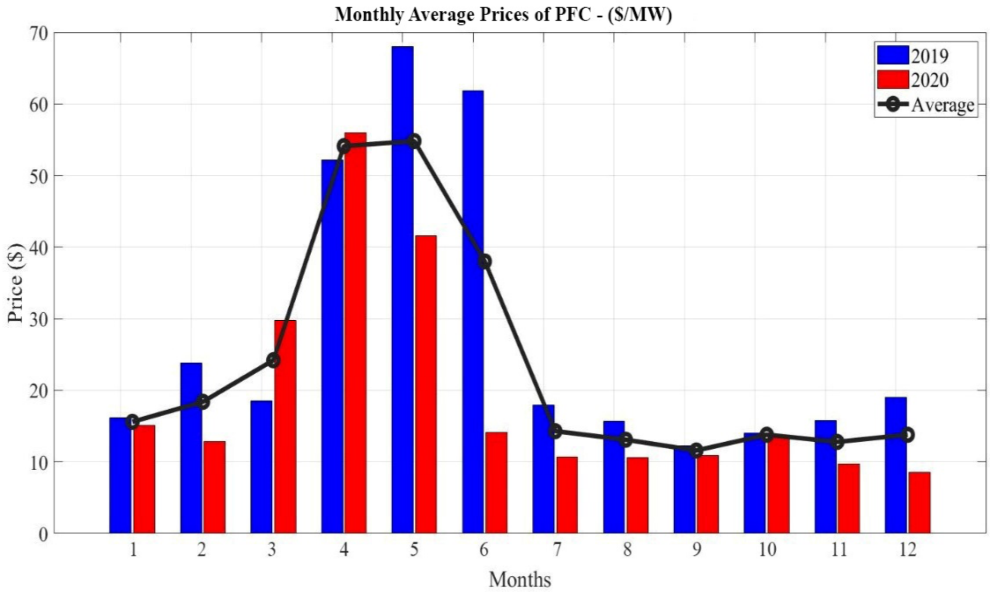

Figure 14. *Monthly average prices of PFC*

According to the monthly average prices, the monthly income of BESS has been calculated according to the PFC capacity, and the total annual income is foreseen. The economic evaluation of BESS has been made in three different scenarios. In the optimistic scenario, BESS provides the PFC service throughout the year. In the reasonable scenario, it participates in a maximum of five-block bidding periods each day. In the pessimistic scenario, it participates in a maximum four-block bidding period per day. For each scenario, the annual income is calculated according to the monthly average PFC prices, and the annual NPV is determined. The NPV and IRR values of the net income obtained at the end of 15 years are determined. The results of the economic evaluation are shown in Table 3.

Table 3. *The results of economic evaluation*

Scenarios	Optimistic	Reasonable	Pessimistic
Total Net Profit (NPV- $)	1.036.360,52	786.381,61	536.402,71
IRR (%)	32,8	25,5	17,9
ROI (%)	149	89	28,9

According to the results, it seems that BESS could derive a profit under the conditions of three scenarios. According to the grid frequency data, it is possible to participate in the PFC throughout the year, except for maintenance and failure conditions. Therefore, high profitability can be expected for optimistic conditions. However, when at least four and five blocks of tender participation are achieved per day, BESS can be positive in terms of investment depending on CAPEX.

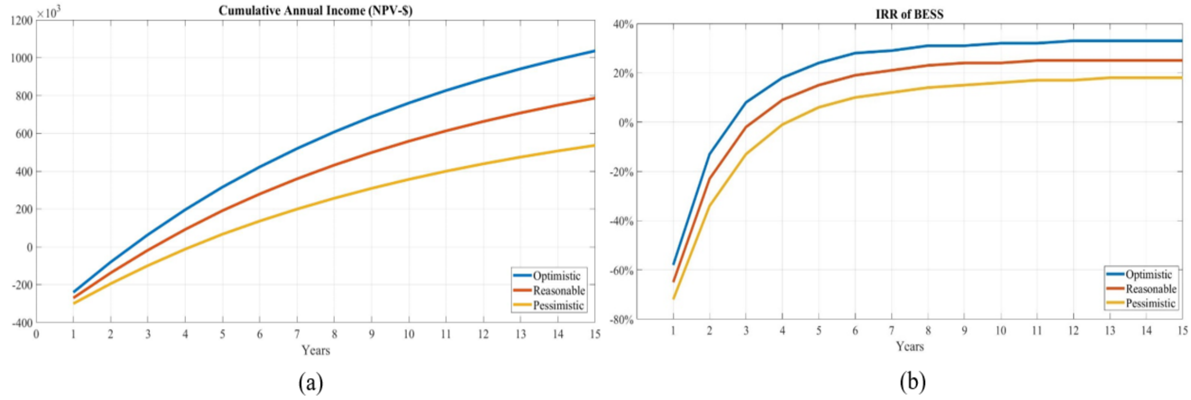

Figure 15. *(a) Cumulative annual income (b) IRR of BESS*

The annual cumulative income and IRR in all three scenarios are shown in Figure 15. Considering the 15-years lifetime; even in the pessimistic scenario, it is seen that positive earnings can be obtained after four years. The IRR is higher than the discount rate based on economic evaluations in all three scenarios, and it can be said that the investment can be profitable depending on the investor.

4.CONCLUSIONS

It is thought that the increase of RES, especially wind and solar, will create problems in terms of grid operations. To ensure frequency and voltage stability, grid flexibility must be increased. When viewed from this aspect, energy storage systems are one of the leading solutions. Especially with the developing technology in recent years, battery storage systems come to the fore as a grid-scale or distributed system. However, there are still potential concerns for system operators and investors regarding its implementation. In this study, the technical and economic evaluation of BESS, which provides PFC service, has been shown based on past frequency data. To sum up the following conclusions could be made:

- For frequency control services, the sizing and investment evaluation of BESS could be made according to past frequency data. In this way, the pre-evaluation can be provided for high investments.
- Before investment decisions, it is important to determine the lifetime and capacity fading of BESS according to the grid operating conditions. In this study, SoC and DoD changes of BESS according to the frequency deviations in seconds are examined; the lifetime and capacity fading of BESS has been successfully evaluated monthly and yearly. The calculated capacity fading can be used as a reference to the extra energy capacity that will be needed from the initial phase of the investment
- In terms of Turkey's grid and market conditions; the economic evaluation of BESS has been made. It can be said that a profit can be gained from the BESS investment according to the market participation scenarios foreseen in consideration of the past PFC average unit prices. However, with the foreseen BESS investment cost decreasing in the coming years, the predicted optimistic gains will not be difficult to realize.
- It has been shown that the dead band in PFC can affect the lifetime of BESS. According to the results, it will be beneficial to apply a dead band in frequency control of BESS in Turkey.

The methodology and motivations of this study will be a useful example for the power grids where BESS will be implemented newly. However, looking for future research; it would be beneficial to carry out similar studies according to different storage technologies such as flywheels, fuel cell, supercapacitor. Especially for Turkey, optimum battery reserve capacity should be studied for frequency reserve capacity of grid. Similarly, the use of renewable energy peak shaving and arbitrage usage for consumers can be examined according to the battery prices in the future.

Each new application like energy storage systems could be a new opportunity, but it will require to better commercialization status of these options to apply. As in many countries, storage systems can create new opportunities and new challenges in Turkey. BESS can be beneficial, and its prices may decrease in the coming years. But the investments of BESS will be difficult to implement in Turkey if battery supply is not possible economically. Similarly, new regulations and changes need to be made to implement energy storage systems in the existing electricity and market management. For this reason, it is of great importance to carry out preliminary studies for energy storage systems based on different technology, usable services, market, and operational regulation in Turkey.

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