Stacked-Value of Battery Storage: Effect of Battery Storage Penetration on Power Dispatch

by

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ABSTRACT

In this work, the stacked values of battery energy storage systems (BESSs) of various power and energy capacities are evaluated as they provide multiple services such as peak shaving, frequency regulation, and reserve support in an ‘Arizona-based test system’ - a simplified, representative model of Salt River Project’s (SRP) system developed using the resource stack information shared by SRP. This has been achieved by developing a mixed-integer linear programming (MILP) based optimization model that captures the operation of BESS in the Arizona-based test system. The model formulation does not include any BESS cost as the objective is to estimate the net savings in total system operation cost after a BESS is deployed in the system. The optimization model has been formulated in such a way that the savings due to the provision of a single service, either peak shaving or frequency regulation or spinning reserve support, by the BESS, can be determined independently. The model also allows calculation of combined savings due to all the services rendered by the BESS.

The results of this research suggest that the savings obtained with a BESS providing multiple services are significantly higher than the same capacity BESS delivering a single service in isolation. It is also observed that the marginal contribution of BESS reduces with increasing BESS energy capacity, a result consistent with the law of di-

minishing returns. Further, small changes in the simulation environment, such as factoring in generator forced outage rates or projection of future solar penetration, can lead to changes as high as 10% in the calculated stacked value.

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NOMENCLATURE

A_g	Production cost in \$ when the generator *g* is operating at the minimum generation capacity $P_{g,min}$
AS_i	Stacked annual savings for *i* th year in \$
a_g	Numerical coefficient of the quadratic term of total heat rate curve of unit *g*
B_g	Production cost in \$ when the generator *g* is operating at the maximum generation capacity $P_{g,max}$
b_g	Numerical coefficient of the linear term of total heat rate curve of unit *g*
C_g	Production cost in \$ when the generator *g* is generating $limit1_g$
Cf_g	Fuel cost of generator *g* in \$/MMBTU
$Co\&m_g$	O&M cost of generator *g* in \$/MWh
Cs_g	Start-up cost of generator *g* in \$
c_g	Constant term of the total heat rate curve of unit *g*
D_t	System demand during hour *t* in MW
DT_g	Minimum downtime for generator *g* in hours
$del1_{g,t}$	Power produced in block-1 of the piece-wise linear production cost function of unit *g* in period *t*
$del2_{g,t}$	Power produced in block-2 of the piece-wise linear production cost function of unit *g* in period *t*
E^b_{max}	Maximum energy that can be stored in the BESS in MWh
E^b_{min}	Minimum energy that can be stored in the BESS in MWh
E^b_t	Energy in the BESS at hour *t* in MWh
$Gen\_cost_{g,t}$	Generation cost of generator *g* in \$ during the hour *t*

IR	Inflation rate in %
$limit1_g$	Average of $P_{g,min}$ and $P_{g,max}$ in MW
Net_D_t	Net system demand during hour *t* in MW
P_{ct}^b	Charging power of the BESS at hour *t* in MW
P_{dt}^b	Discharging power of the BESS at hour *t* in MW
$P_{g,max}$	Maximum generation capacity of generator *g* in MW
$P_{g,min}$	Minimum generation capacity of generator *g* in MW
$P_{g,t}$	Generation in MW from generator *g* during the hour *t*
P_i	Normalized probability of *i* th system state
$P_{maxlevel}^b$	Maximum charging/discharging power limit of the BESS in MW
$P_{minlevel}^b$	Minimum charging/discharging power limit of the BESS in MW
R	System reserve requirement in MW
$R_{b,t}$	Available power reserve from the BESS during hour *t* in MW
R_g^+	Maximum hourly ramp-up rate of generator *g* in MW/hour
R_g^-	Minimum hourly ramp down rate of generator *g* in MW/hour
R_g^{SU}	Start-up ramp rate of generator *g* in MW/hour
R_g^{SD}	Shut-down ramp rate of generator *g* in MW/hour
$R_{gen,t}$	Total spinning reserve available from generators during hour *t* in MW
r	Discount rate in %
$rate1_g$	Slope of block-1 of the piece-wise linear production cost function of unit *g*

$rate2_g$	Slope of block-2 of the piece-wise linear production cost function of unit *g*
S_t	Solar generation during hour *t* in MW
$(TC)_i$	Production cost for *i* th system state in base case scenario
$(TCB)_i$	Production cost for *i* th system state with BESS in the test system
$U_{g,t}$	Unit commitment decision for unit *g* during hour *t*
UT_g	Minimum uptime for generator *g* in hours
$V_{g,t}$	Start-up decision of generator *g* during hour *t*
$W_{g,t}$	Shutdown decision of generator *g* during hour *t*
Z_{ct}	Binary variable giving the status of BESS charging during hour *t* (1=charging, 0=not charging)
Z_{dt}	Binary variable giving the status of BESS discharging during hour *t* (1=discharging, 0=not discharging)
Δt	Simulation time step
η_c	Charging efficiency of the BESS
η_d	Discharging efficiency of the BESS

1 INTRODUCTION

1.1 Importance of battery energy storage system (BESS) and its application

In recent years, the United States (U.S.) has witnessed notable renewable energy (RE) deployment. This is especially true for intermittent renewable sources such as wind and solar. In 2016, wind electricity capacity grew 8.2 GW and solar electricity capacity increased by 11.4 GW accounting for 40.6% and 56.7%, respectively, of the newly installed renewable electricity capacity [1]. As of December 2016, wind electricity and solar electricity represent 7% and 2.9% of the U.S. cumulative installed electricity capacity, respectively [1]. The rapid growth in renewable deployment can be attributed to recent legislative mandates and technological progress, and the trend is expected to continue in the near future. Increased integration of fluctuating renewable sources will stress the aging U.S. electricity infrastructure presenting unique challenges to the security and reliability of the U.S. electrical grid [2]. Conversely, it may also act as a catalyst to the efforts aiming to modernize the electrical grid, including the increased deployment of the battery energy storage system (BESS).

Large-scale integration of variable renewable resources to the U.S. power grid has always been challenging for system operators, planners and grid engineers [2]. With the implementation of renewable portfolio standards (RPS) – a regulation that requires increased production of electricity from renewable sources such as wind and solar etc., the challenges to maintain supply-demand balance will be aggravated [3]. BESS can help balance supply and demand when renewables are not generating or can prevent wind/solar from spilling during times of over generation.

Furthermore, BESS provides a multitude of primary and ancillary services such as peak shaving, reserve support, frequency regulation, transmission/distribution expansion deferral, transmission congestion management, black start capability and power quality improvement etc. generating value streams either as monetary benefits or as avoided costs/losses [4]-[11].

Peak shaving involves storing power in BESS during off-peak hours and delivering it back to the system during on-peak hours. By using BESS for peak shaving, utilities reduce the system operation cost by reducing the need for expensive peaking units [5].

Upon the occurrence of a generation or transmission outage, a BESS can respond instantly until the backup generators are brought online. Provision of reserve support from BESS eliminates the need for blocking spare capacity of online generator units resulting in savings in system operation cost [6].

In the electric power system, variable power generation from renewables and other sources, load fluctuations, etc., cause the system frequency to change continuously. Use of BESS for frequency regulation is appropriate considering its fast response and efficient operation [7].

Transmission congestion occurs when the flow of power in the transmission line is restricted due to the physical limitations of the transmission infrastructure. Factors contributing to transmission congestion are demand growth, increased deployment of renewables and distributed energy resources (DERs), fuel availability and electricity price differences, etc. Transmission and distribution system upgrades are necessary when line congestion happens. BESS can be placed appropriately near the congested infrastructure to reduce the transmission congestion deferring investments in transmission infrastructure. In the distribution system, flattening peak load using a BESS allows utilities to delay distribution system investments [8]-[9].

Black start capability is the ability to restart a conventional energy system, e.g. fossil fuel power plant when power from the external power sources is unavailable. This is another important grid function for which the prospect of utilizing BESS is being explored.

A BESS can be placed in a distribution system for improving power quality and for protecting downstream sensitive loads against power quality problems such as voltage sag, swell and short supply interruptions etc. [10].

In summary, large-scale BESS when used properly enables the electrical grid to operate efficiently, improves electric power quality, and ensures enhanced grid security and reliability. Consequently, BESS's have gained increasing popularity and have attracted wider public interest over the last few years.

1.2 Battery energy storage (BES) deployment status at a glance

Battery energy storage (BES) is one of the most rapidly growing energy storage technologies. The global operational installed BES capacity is around 1.6 GW and the operational installed BES capacity in the U.S. is around 0.6 GW [12]. Figure 1.1 and Figure 1.2 depict global and U.S. installed BES capacity, respectively, operational during the 1996-2018 time frame [12].

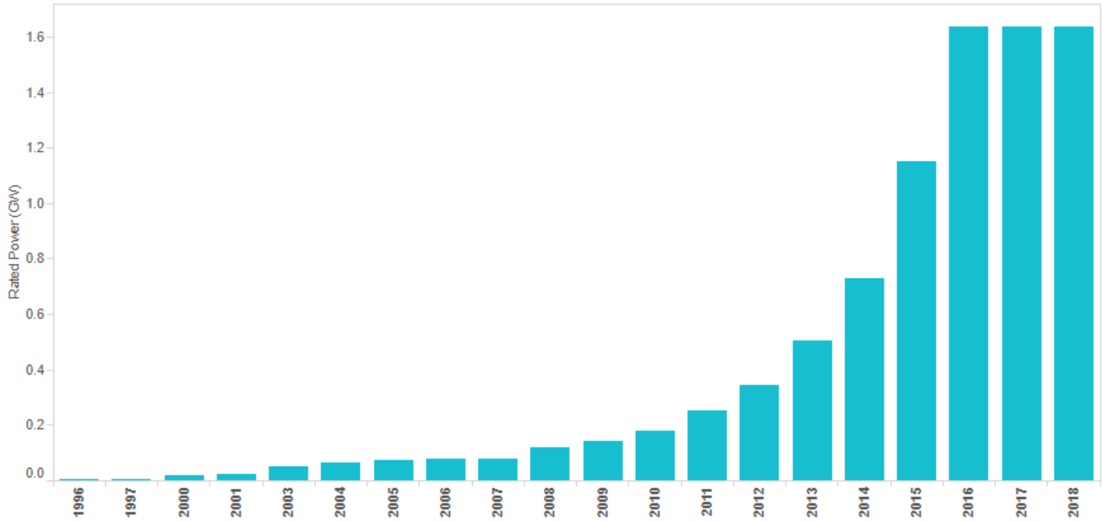

Figure 1.1 Global battery energy storage capacity, 1996-2018 [12].

Li-ion BES technology constitutes the largest share (59%) of the global operational installed capacity as of mid-2017 [13]. Also, there are other important, prevalent BES technologies such as lead-acid, high-temperature batteries, and flow batteries, etc., to name a few.

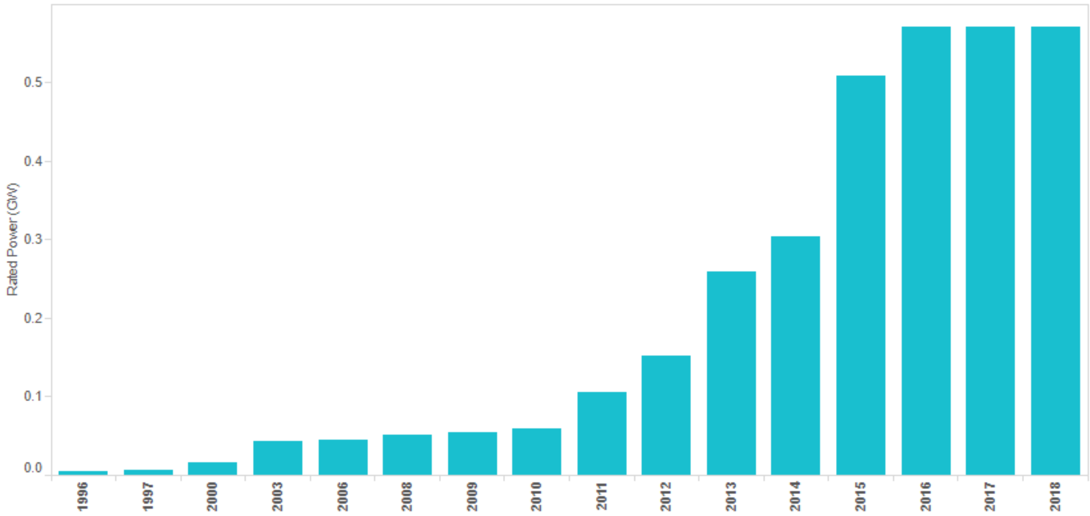

Figure 1.2 U.S. battery energy storage capacity, 1996-2018 [12].

As per [12], the global installed BES power capacity is poised to scale up with the future BES projects adding 1.2 GW power capacity within the next few years. Upcoming project installations in the U.S. alone will contribute to more than half (51.2%) of this additional BES power capacity [12].

1.3 Objective

Recent advancements in battery chemistry research, the economy of scale and fierce market competition between major BES manufacturers have resulted in an appreciable cost reduction of the BES technology over the last few years. For example, a recent study by Bloomberg New Energy Finance (BNEF) shows that the average selling price of lithium-ion batteries in 2017 was $209/ kWh – a drop of 79% since 2010 [14]. Again, a steeply falling BES balance of system costs and lesser engineering, procurement and construction expenses are some important factors promoting project financing and investments in the electrochemical energy storage sector. Also, recent policy decisions by federal and state regulatory bodies are making the U.S. wholesale energy market accessible to BES technologies [15]-[16]. All these have led to an increased deployment of BES in the U.S. electrical grid. Utilities, regulators and other power-sector stakeholders have begun establishing the value that large-scale BES deployment can bring to the U.S. electricity industry. Using a BESS in a power grid for a single service may yield a small net economic value; however, much more value can be generated from a BESS when it is used to provide multiple services, which are technically and operationally compatible. Hence, to establish the true value of a BESS, the so-called stacked value of providing multiple services must be evaluated [17].

In recent years, the economic benefits of large-scale BES in power systems have been studied extensively. In [18], the authors proposed a unit commitment (UC) formulation for a power system with thermal units and a generalized energy storage system (ESS). The ESS performed peak shaving and reduced the system operation cost. In [19], the authors investigated the value of deploying BES for peak shaving and reserve support. That BES model took into account the charging and discharging efficiency, charging and discharging power limit, and energy capacity limit etc. In [20], the authors assessed the economic benefit of employing ESS for peak shaving and frequency regulation in a small isolated power system in Spain. A similar study was conducted in [21], in which the authors examined the impact of installing a BESS for the daily operation of the insular power grid in Crete, Greece.

The goal of the research presented in this document is to build on what others have done in this area and perform an economic analysis of a BESS providing multiple services in an Arizona-based test system modeled using the yearly (sanitized) operational data shared by Salt River Project (SRP). The primary objective is to estimate the stacked savings in total system operation cost under the following operational scenarios:

i. BESS for peak-shaving: To estimate the savings in production cost with the use of BESS for peak-shaving in the Arizona-based test system.

ii. BESS for reserve support: To calculate the stacked savings when sufficient storage capacity exists to provide reserve support (frequency regulation and spinning reserve support).

iii. BESS with solar generation: To evaluate the net economic benefits of the use of BESS in the Arizona-based test system with significant solar generation.

iv. BESS assuming generator forced outage rate (FOR): To determine the stacked savings in generation costs when forced outage rates (FORs) of the generation units in the resource stack are considered.

The evaluation of the stacked value of the BESS has been achieved by developing a mixed-integer linear programming (MILP) based optimization model that captures the operation of BESS in the Arizona-based test system. The model formulation does not include any BESS system costs as the objective is to estimate the net savings in total system operation cost after the BESS is deployed in the test system. The decision of not including BESS system costs was a joint one made with the sponsor of this research.

The optimization model has been formulated in such a way that the savings due to the provision of a single service, either peak shaving or frequency regulation or reserve support, by the BESS can be determined independently. The model also allows calculation of combined savings due to all the services rendered by the BESS.

1.4 Summary of chapters

Chapter 2 contains a brief literature survey on various electric system services provided by a BESS.

Chapter 3 presents the Arizona-based test system and some assumptions made to model a BESS. Furthermore, the development of a MILP-based optimization model used to evaluate the stacked value of BES in the Arizona-based test system is discussed in great detail in this chapter.

In chapter 4, the results from numerous simulations for various system scenarios are discussed.

Finally, the conclusions to this research and directions for future work are presented in chapter 5 and chapter 6, respectively.

2 LITERATURE REVIEW

The literature review presented in this chapter discusses various applications of BES in electric power systems [22]. Benefits from some of these applications are difficult to quantify due to the complexity of simulations needed and also due to the difficulty of accurately assigning probabilities to many power systems events.

2.1 Peak shaving

Peak shaving involves storing power in BESS during off-peak hours when the marginal costs of electricity generation are low and delivering it back to the system during on-peak hours when the energy prices are high. By using BES for peak shaving, utilities reduce the system operation cost by reducing generation from expensive peaking units. Also, with the use of BES, investments for the installation of generation capacity to supply the peaks of system demand can be avoided in the long term. Figure 2.1 depicts the process of peak shaving [23]. As can be seen in the figure, the BESS is charged during early morning off-peak hours by increasing generation from cheaper baseload plants. The stored energy is then discharged back to the network during on-peak hours to avoid costlier peaking generation.

In recent years, efforts have been made to establish the economic value of peak shaving service offered by various energy storage technologies. In [18], the authors used UC formulations to estimate the savings in system operating cost as a generalized ESS rendered peak shaving service in a single bus power system with several thermal units. With the ESS delivering peak shaving service, the dispatch from the costlier thermal units decreased and as a result, the system operation cost was reduced. Similar results were obtained in [9] where the authors established the economic value of a pumped hydro storage (PHS) providing peak shaving service in the Arizona transmission system modeled using a dc optimal power flow (DC OPF) model. In [24], the authors presented an economic analysis of ESSs providing peak shaving service in a small isolated power system in the Canary Islands, Spain. An optimization model was developed to capture the weekly economic operation of ESSs in the isolated power system of the Canary Islands. The obtained results showed that the provision of peak shaving service by ESSs could be an economic alternative to costlier peaking units in the isolated power system.

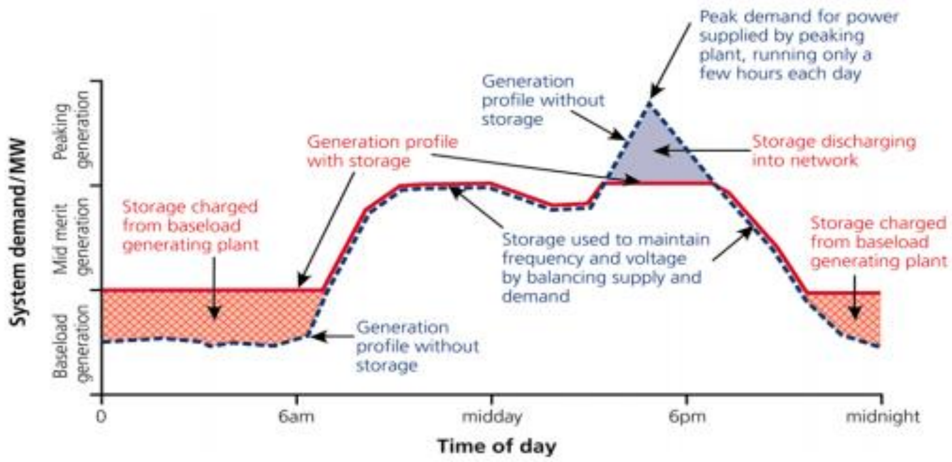

Figure 2.1 Peak shaving with energy storage [23].

2.2 Frequency regulation

In the power grid, the system frequency changes continuously due to generation and demand mismatch. In order to keep it within the pre-set limits, frequency regulation is performed by ramping (up or down) generation assets. For a thermal unit providing this service, rapid and frequent ramping affects efficiency. This may lead to the consumption of additional fuel (typically 0.5%-1.5%) as a result of the efficiency loss [25]. Use of BESS for frequency regulation service is desirable considering its fast response and efficient operation. Using batteries this way can contribute significantly to the stacked value since this service often has a very high value among the power market ancillary services. This is why, recently, there have been some attempts to estimate the monetary benefits of BESS when providing frequency regulation service. In [20], the authors assessed the economic benefit of employing ESSs for frequency regulation service in a small isolated power system in Spain. Substantial savings were obtained as ESSs in the system provided frequency regulation service. Also, the provision of regulation service by ESSs eliminated the need for scheduling spare generation capacity of the on-line units in the isolated power system. In [26], the author performed an economic analysis of a Li-ion BESS rendering frequency regulation service in a renewable resource-rich power system. In that work, a stochastic UC based formulation was used to capture the benefits coming from a BESS delivering regulation service in a wind-resource-rich power system. With its energy-shifting and fast-ramping capabilities, battery storage showed great potential to render the frequency regulation service in a renewable resource-rich power system while yielding substantial savings on the system operation cost.

2.3 Spinning reserve support

Spinning reserves are power plants that are kept operational to respond instantaneously upon the occurrence of generation or transmission outages. Alternatively, some spare capacities of online generators are blocked as per the system spinning reserve requirement. These lead to increased system operation cost which can be avoided with the use of BESS for reserve support. BESS is appropriate for providing this service as BESS can respond quickly by charging or discharging energy in seconds or less and can react faster and more accurately than thermal power plants [27]. Also, as depicted in Figure 2.2 Flexibility for reserve support, 100 MW BESS (left) vs 100 MW gas turbine (right) [27]., a BESS having the same capacity as a fossil fuel power plant has greater operational flexibility for reserve support. Both negative (charging power) and positive (discharging power) capacity of BESS can be used for ramping down/up reserves with a faster ramp rate than fossil fuel power plants while the thermal power plant offers lesser flexible range. Also, for the thermal power plant to operate as a spinning reserve, a minimum generation level needs to be maintained while BESS has no such requirement [27]. For example, in Figure 2.2, for the gas turbine to provide 25 MW down reserve, it needs to operate (at a minimum) at 75 MW of generation while BES storage has no such requirement.

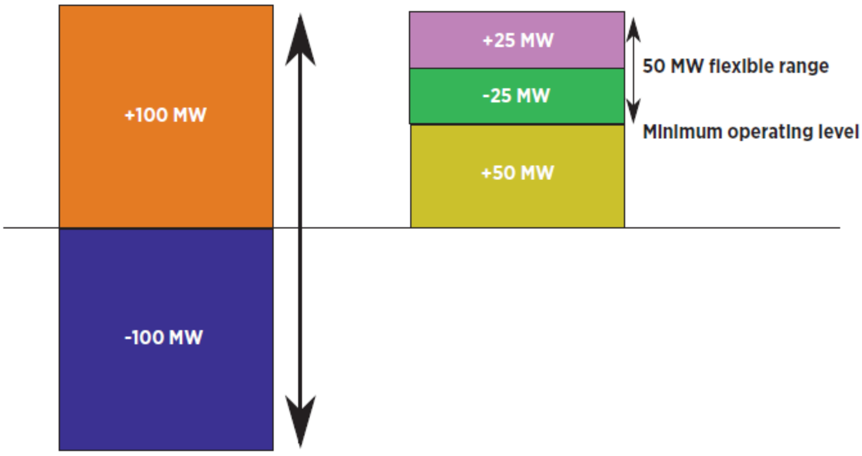

Figure 2.2 Flexibility for reserve support, 100 MW BESS (left) vs 100 MW gas turbine (right) [27].

In recent years, economic benefits of energy storage systems delivering spinning reserve support service have been studied widely. In [19], the authors investigated the value of BESS for providing spinning reserve support service in an IEEE RTS 24-bus test system using a security-constrained unit commitment (SCUC) formulation. The results showed that the BESSs relieved the thermal units from providing spinning reserve during peak load periods which led to substantial savings on the system operation cost. Also, in this work, the authors performed a sensitivity analysis of savings with different levels of BESS penetration. It was observed that the savings were sensitive to the level of BESS penetration and the marginal contribution of BESS reduced with the increase of BESS energy capacity. In [26], an attempt was made to estimate the savings in system operation cost as a BESS in a wind resource-rich power system delivered spinning reserve support. It was observed that the operation cost of the wind resource-rich power system reduced as the BESS in the system provided spinning reserve support service.

2.4 Facilitating renewable integration

Over the last lustrum, the U.S. has witnessed substantial renewable deployment [1]. With the growth of RPS, the trend is likely to continue. The challenges to maintain the supply-demand balance will be aggravated by the increasing penetration of renewable resources into the U.S. electrical grid. BES can help balance supply and demand when renewables are not generating or can prevent wind/solar from spilling during times of over generation. For example, most wind generation occurs at night when the energy demand is low. BES can be used to store this low-cost energy for use during high demand periods.

Another challenge due to the increased renewable generation is the need for faster ramping reserves to operate in response to the steep changes in renewable output, as observed most noticeably in the California Independent System Operator (CAISO) netload curve, i.e., the duck curve, as depicted in Figure 2.3 [28].

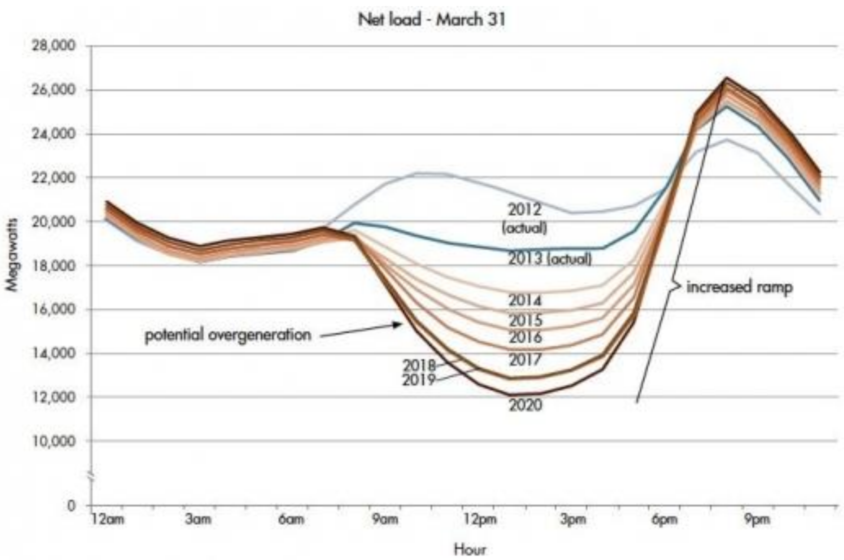

Figure 2.3 Duck curve for CAISO system with high renewable penetration for a spring day [28].

As can be observed in the figure, with increasing renewable penetration from the study year 2012 to 2020, the ramping requirement is going to be steeper. Because of its fast ramp rate capability, BES can be used to overcome the challenges due to steeper ramp rates.

Photovoltaic (PV) generation in a distribution system poses some unique challenges such as rapidly varying output, degradation of power quality, back-feeding of power and generation-demand mismatch etc. BES can be deployed near PV power plants to manage these challenges [29].

In recent years, there have been studies to assess the ability of ESS to facilitate large-scale renewable integration. In [30], a stochastic SCUC formulation was used to establish the value of a PHS enhancing renewable dispatchability in a renewable resource-rich power system. With the PHS in the system, the wind dispatchability was improved and the system operation cost was reduced. In [31], the authors studied a BESS in a power system with substantial wind generation. The results showed that the BESS reduced dispatch from expensive units to reduce system operation cost. It also reduced wind curtailment to effectively increase generation from wind, thereby, reducing the system operation cost.

2.5 Transmission & Distribution (T&D) expansion deferral

Transmission and distribution system upgrades are necessary when line congestion restricts power flow through the existing circuit. Placing a bulk BESS at the receiving end of the circuit could reduce transmission line loading and hence, could defer investments in transmission infrastructure. In the U.S., the Charleston NaS BESS installed by American Electric Power (AEP) is a transportable storage system rendering T&D upgrade deferral service [32]. Also, in the distribution system, flattening peak load using a BESS allows utilities to delay distribution system investments [11].

2.6 Transmission congestion management

Transmission congestion occurs when the flow of power in the transmission line is restricted due to the physical limitations of the transmission infrastructure. Other factors contributing to transmission congestion are demand growth, increased deployment of renewables and distributed energy resources (DERs), and electricity price differences, etc. During transmission congestion, some loads cannot receive the lowest-priced energy and in that scenario, the demands are met by ordering more expensive electricity [33]. As a result, the locational marginal price (LMP) at those locations are higher.

BESS can be controlled to avoid these congestion-related charges. This can be done by placing a BESS appropriately near the congested infrastructure, enabling the delivery of energy from off-peak to on-peak hours to reduce peak transmission capacity requirements [11].

2.7 Black-start capability

Black start refers to the restoration of the power functions of a generator unit without relying on the power from external power sources. A BESS can be used for this important grid function. Recently, a utility in southern California has successfully showcased the ability of a BESS to perform black starting [34]. The economic value of this service in the event of a power system disruption is difficult to establish.

2.8 Power system islanding

In the event of large-scale system disruption, the entire power network may be separated into several islands with out-of-balance generation and demand levels. A BESS can be used in such islands to maintain the balance between generation and load while keeping the operation of the islanded system intact and avoiding shedding of critical loads. The economic value of this type of service is difficult to determine.

2.9 Power quality improvement

A BESS can be placed in a distribution system for improving power quality and for protecting downstream sensitive loads against power quality problems such as voltage sag, swell and short supply interruptions, etc.

3 DEVELOPMENT OF OPTIMIZATION MODEL FOR ESTABLISHING THE STACKED VALUE OF BESS

In this chapter, the Arizona-based test system and some assumptions made to model the BESS are discussed. Then, a MILP-based optimization model, developed to evaluate the stacked value of BES in this Arizona-based test system, is presented.

3.1 Arizona-based test system

To design a simplified system model that represents SRP's system, resource stack information created by SRP has been obtained. The resource stack information includes a sanitized list of generator units typical of SRP's fleet with various other characteristics such as installed capacity, ramp rate, minimum and maximum generation level, start-up cost, variable operation and maintenance (O&M) cost, heat rate curve coefficients and fuel cost etc. Using such information, a representative model of SRP's system, namely the 'Arizona-based test system' has been designed as a single bus system with a BESS and 52 generator units of different generation types: nuclear, hydro, coal, combined cycle (CC), duct burner, steam, and combustion turbine (CT). Table 3.1 lists various resource stack parameters used for the development of the Arizona-based test system.

Table 3.1 Resource stack parameters used for the development of the Arizona-based test system.

Resource Stack Parameter	Unit of the Parameter
Installed capacity	MW
Number of generator units in each generation type	(none)
Minimum generation capacity	MW
Start-up cost	$
Variable O&M cost	$/MWh
Heat rate curve coefficients	(none)
Fuel cost	$/MMBtu
Ramp rate	MW/Min
Minimum uptime	Hour
Minimum downtime	Hour
Summer, winter daily average system demand	MW
Frequency regulation requirement	MW, MWh
Spinning reserve requirement	MW

Figure 3.1 shows the system configuration of the Arizona-based test system. Here, $P_1,\ P_2\ \ldots,\ P_{52}$ are power generations in MW from generator units of various generation types, P_{gen} is the total power generation in MW, D is the system demand in MW and $+/-P_{BESS}$ is the discharging/charging power, respectively, of BESS in MW.

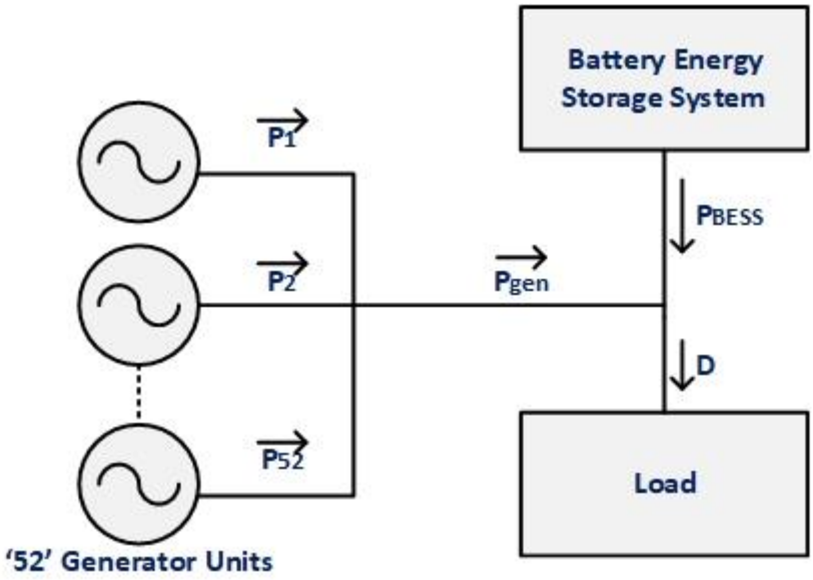

Figure 3.1 Arizona-based test system configuration.

SRP has also provided hourly solar generation data sets for both a typical summer and winter day for simulating the test system with significant solar generation. Here, zero cost is assumed for solar power generation. Using the hourly load and solar generation data, the hourly load and netload curves have been obtained for both a typical summer and winter day as depicted in Figure 3.2 and Figure 3.3, respectively.

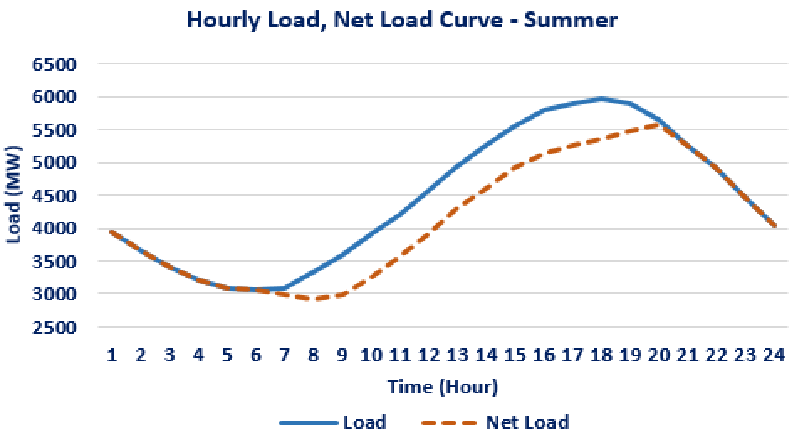

Figure 3.2 Hourly load, netload curve for a typical summer day.

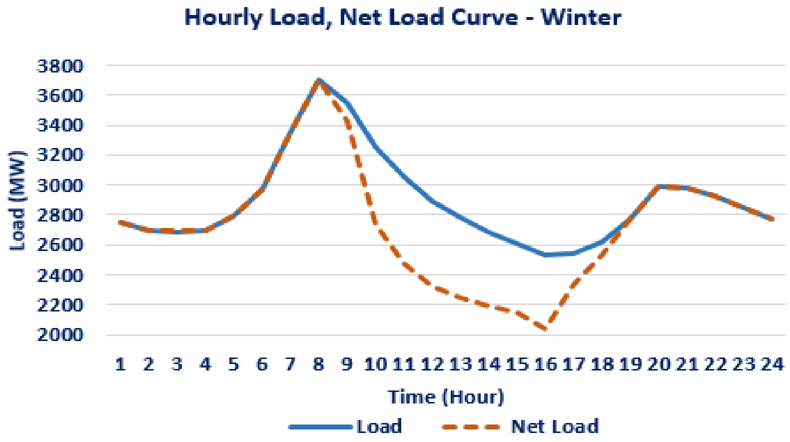

Figure 3.3 Hourly load, netload curve for a typical winter day.

The Arizona-based test system is to be operated with a total reserve requirement of 175 MW: 25 MW for frequency regulation and the remaining 150 MW for spinning reserves [35]. The energy requirement for the frequency regulation service is 5 MWh. A reduced generator efficiency of 1% is assumed when 2-on-1 combined cycle (CC) units in the test system provide frequency regulation service [35]. This leads to adding a 1% penalty to the daily operation cost of the 2-on-1 CC units participating in frequency regulation to account for the additional fuel consumed due to the efficiency loss [25].

To estimate the value of BESS during forced outages of generator units, the generator forced outage rate (FOR) information has been acquired from SRP. For fossil (except duct burner units) and hydro units, 10 outages per year with 2 days per outage are assumed, which translates to a FOR of 5.5%. For nuclear and duct burner units, zero FOR is assumed. However, for a CC unit experiencing an outage, its corresponding duct burner unit is lost as well [35].

3.2 Assumptions for BESS modeling

Here are some assumed storage parameters for modeling the BESS in the Arizona-based test system.

- BESS will be modeled so that it can provide any combination of peak shaving, frequency regulation and spinning reserve support in the Arizona-based test system.
- For the BESS in the test system, the battery technology is presumed to be Li-ion though another appropriate battery technology can be selected, depending on its suitability to provide the desired power/energy services.
- We assume the availability of a battery management system so that the BESS operation can be controlled at a cell/stack/container level. This enables the BESS to deliver multiple services simultaneously.
- The battery charging and discharging efficiencies are assumed to be 0.95 and 0.92, respectively, which are typical for a BES of Li-ion technology [19].
- The maximum charging/discharging power limit is equal to the power rating of the BESS. The minimum charging/discharging power limit is equal to 0.01 MW. We have set this minimum limit for the BESS model simulation to create a unique BESS idle state, as opposed to pseudo-idle states modeled as BESS charging/discharging states with zero power flow.
- The BES cycle life changes with the minimum state of charge (SoC) of the battery.

The minimum SoC corresponds to the minimum energy capacity that should always be maintained in the BES. Selecting a higher minimum SoC will increase the life expectancy of the BES but will lead to the availability of less stored energy for use. For this work, after referring to [26], a minimum SoC of 20% is selected. Also, from [36], the minimum SoC of 20% corresponds to the BES life of 20 years at optimum operating conditions (25º C or 77º F temperature), which is a reasonable number for the life of the BES and agrees well with our assumptions. We assume here that the batteries are stored in a temperature controlled environment, but no attempt has been made to model the power demand created by this environment and factor that into the modeling.

- For the assumed minimum SoC, it was observed during the performance of this work that, for the given daily system load patterns (both summer and winter), the savings due to the BESS usage are maximum if a day starts with the minimum energy (= minimum SoC × installed energy capacity) in the BESS. Hence, for this study, it is assumed that the BESS stored energy is equal to 20% of its energy capacity (i.e., minimum SoC) at the starting of each day.
- For this work, we assume that the BESS is operational with a zero forced outage rate (FOR).
- The annual savings due to the BESS usage are calculated assuming six summer months and six winter months.

- A discount rate of 11.47% and an inflation rate of 2% is assumed for calculating the net present value (NPV) of stacked benefits over the useful BESS life of 20 years [37].

3.3 Formulation of the optimization model

3.3.1 Mixed-integer linear programming (MILP) based unit-commitment (UC) formulation

Initially, to find the daily operating cost of the Arizona-based test system without the BESS, a unit commitment (UC) based formulation is used [38]. An optimal UC model with quadratic cost curves and a large number of integer variables has high computational complexity because of the nonlinearity of the cost curves. Hence, piece-wise linear approximations of the quadratic cost curves are used, which makes the UC problem mixed-integer linear programming (MILP) type that is less computationally complex and faster to solve. Furthermore, MILP based formulation guarantees convergence to an optimal solution in a finite number of steps [39].

The quadratic cost curves of the generator units, shared by SRP, are observed to be almost linear. Hence, in this work, the piece-wise linear approximations of the cost curves are modeled to have two segments. Though more piece-wise blocks could be used to approximate the cost functions, it would lead to additional computations without significantly improving the accuracy of the results. Figure 3.4 shows the piece-wise linear approximation of the quadratic cost curve.

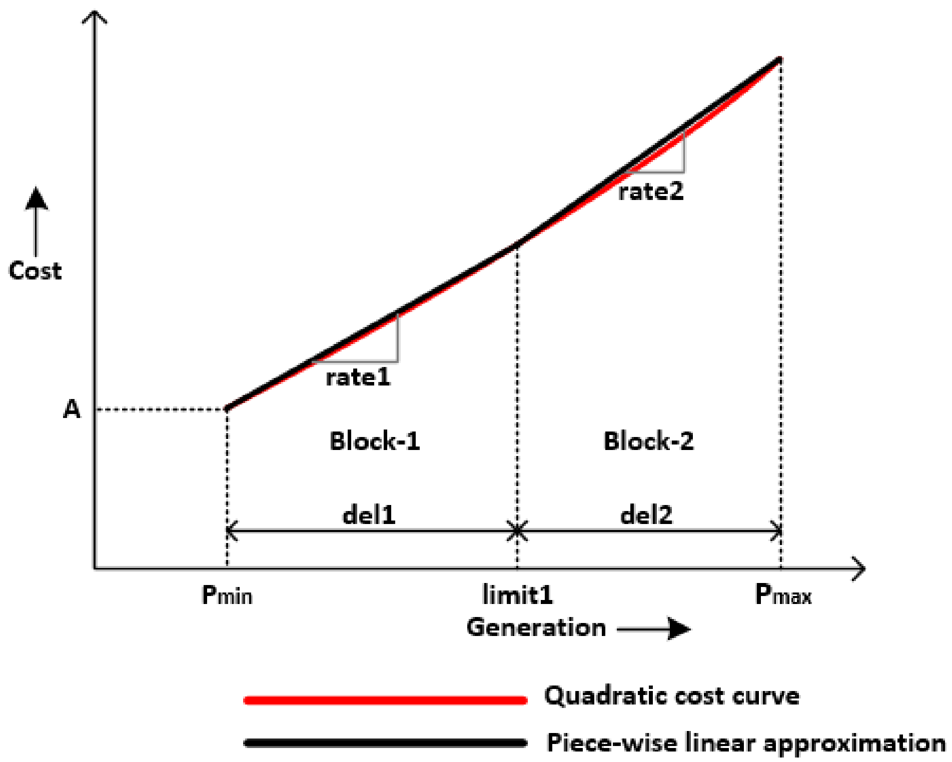

Figure 3.4 Piece-wise linear operation cost.

From [39], the quadratic cost curve can be written as:

$$Gen\_cost_{g,t} = \left(a_g * U_{g,t} + b_g * P_{g,t} + c_g * P_{g,t}^2\right) * Cf_g + Co\&m_g * P_{g,t} \cong A_g + del1_{g,t} * rate1_g + del2_{g,t} * rate2_g \tag{3.1}$$

$$P_{g,t} \cong P_{g,min} * U_{g,t} + del1_{g,t} + del2_{g,t} \tag{3.2}$$

$$A_g = (a_g + b_g * P_{g,min} + c_g * P_{g,min}^2) * Cf_g + Co\&m_g * P_{g,min} \tag{3.3}$$

$$B_g = (a_g + b_g * P_{g,max} + c_g * P_{g,max}^2) * Cf_g + Co\&m_g * P_{g,max} \tag{3.4}$$

$$limit1_g = (P_{g,min} + P_{g,max})/2 \tag{3.5}$$

$$C_g = (a_g + b_g * limit1_g + c_g * limit1_g^2) * Cf_g + Co\&m_g * limit1_g \tag{3.6}$$

$$rate1_g = (C_g - A_g)/(limit1_g - P_{g,min}) \tag{3.7}$$

$$rate2_g = (B_g - C_g)/(P_{g,max} - limit1_g) \tag{3.8}$$

$$0 \le del1_{g,t} \le limit1_g - P_{g,min} \tag{3.9}$$

$$0 \le del2_{g,t} \le P_{g,max} - limit1_g \tag{3.10}$$

where,

- t is an integer index representing time intervals lasting one hour and varies from 1, 2, …, 24.
- g is an integer generator identity index and varies from 1, 2, …, 52.
- a_g, b_g and c_g are total heat rate curve coefficients of generator g.
- $del1_{g,t}$ is the power produced in block-1 (see Figure 3.4) of the piece-wise linear production cost function of unit g in period t.
- $del2_{g,t}$ is the power produced in block-2 (see Figure 3.4) of the piece-wise linear production cost function of unit g in period t.
- $rate1_g$ is the slope of block-1 of the piece-wise linear production cost function of unit g.
- $rate2_g$ is the slope of block-2 of the piece-wise linear production cost function of unit g.
- $P_{g,t}$ is the generation in MW from generator g during the hour t.
- Cf_g denotes the fuel cost of generator g in \$/MMBTU.
- $U_{g,t}$ is the unit commitment decision for unit g during hour t. For $U_{g,t} = 1$, the unit g is on during hour t and for $U_{g,t} = 0$, the unit g is off.

- $Co\&m_g$ is the O&M cost of generator *g* in \$/MWh.
- $P_{g,min}$ is the minimum generation capacity of generator *g* in MW.
- $P_{g,max}$ is the maximum generation capacity of generator *g* in MW.
- $limit1_g$ is the average of $P_{g,min}$ and $P_{g,max}$ in MW.
- A_g is the production cost in \$ when the generator *g* is operating at the minimum generation capacity, $P_{g,min}$.
- B_g is the production cost in \$ when the generator *g* is operating at the maximum generation capacity, $P_{g,max}$.
- C_g is the production cost in \$ when the generator *g* is generating $limit1_g$.
- $Gen\_cost_{g,t}$ is the generation cost of generator *g* in \$ during the hour *t*, which includes both fuel cost and O&M cost.

Then, the optimal UC formulation can be written as:

Minimize: Total operation cost given by (3.11),

$$\sum_{g,t}\left(Gen\_cost_{g,t}\right) + Cs_g * V_{g,t} \tag{3.11}$$

with the following constraints:

$$\textstyle\sum_g P_{g,t} = D_t \ \ \forall t \tag{3.12}$$

$$P_{g,min} * U_{g,t} \leq P_{g,t} \leq P_{g,max} * U_{g,t} \ \forall g, t \tag{3.13}$$

$$P_{g,t} - P_{g,t-1} \leq R_g^+ * U_{g,t-1} + R_g^{SU} * V_{g,t} \ \ \forall g, t \tag{3.14}$$

$$P_{g,t-1} - P_{g,t} \leq R_g^- * U_{g,t} + R_g^{SD} * W_{g,t} \ \ \forall g, t \tag{3.15}$$

$$D_t + R \leq \sum_g U_{g,t} * P_{g,max} \quad \forall t \tag{3.16}$$

$$U_{g,s} \geq U_{g,t} - U_{g,t-1} \quad \forall g,\ 24 \geq t \geq 2 \quad s \in \{t+1, \dots t + UT_g - 1\} \tag{3.17}$$

$$1 - U_{g,s} \geq U_{g,t-1} - U_{g,t} \ \forall g,\ 24 \geq t \geq 2\ , s \in \{t+1, . t + DT_g - 1\} \tag{3.18}$$

$$U_{g,t} = 1 \quad \forall t, g \geq 47 \tag{3.19}$$

$$U_{26,t} \leq U_{36,t} \tag{3.20}$$

$$U_{27,t} \leq U_{37,t} \tag{3.21}$$

$$U_{28,t} \leq U_{38,t} \tag{3.22}$$

$$U_{28,t} = U_{29,t} \tag{3.23}$$

$$U_{30,t} \leq U_{39,t} \tag{3.24}$$

$$U_{30,t} = U_{31,t} \tag{3.25}$$

$$U_{32,t} \leq U_{40,t} \tag{3.26}$$

$$U_{32,t} = U_{33,t} \tag{3.27}$$

$$U_{34,t} \leq U_{41,t} \tag{3.28}$$

$$U_{34,t} = U_{35,t} \tag{3.29}$$

$$U_{g,t}\ V_{g,t}, W_{g,t} \in [0,1] \tag{3.30}$$

where,

- Cs_g is the start-up cost of generator g in \$.

- $V_{g,t}$ is the start-up decision of generator *g* during hour *t*. For $V_{g,t} = 1$, the generator *g* is starting during hour *t* and for $V_{g,t} = 0$, the generator *g* is not starting.
- $W_{g,t}$ is the shutdown decision of generator *g* during hour *t*. For $W_{g,t}$= 1, the generator *g* is shutting down during hour *t*. For $W_{g,t}$= 0, it is not shutting down.
- R_g^+ is the maximum hourly ramp up rate of generator *g* in MW/hour.
- R_g^- is the minimum hourly ramp down rate of generator *g* in MW/hour.
- R_g^{SU} is the start-up ramp rate of generator *g* in MW/hour.
- R_g^{SD} is the shut-down ramp rate of generator *g* in MW/hour.
- D_t is the demand during hour *t* in MW.
- *R* is the system reserve requirement of 175 MW.
- UT_g is the minimum uptime for generator *g* in hours, and
- DT_g is the minimum downtime for generator *g* in hours.

Minimizing the objective function given by (3.11) minimizes the total cost of generation for a day, which includes several cost components such as the dispatch cost and the start-up cost of the generating units. In this work, the generator shut down cost is not considered. Equation (3.12) ensures that the total generation equals the total demand. The constraint given by (3.13) makes sure that the generators are operating within minimum and maximum generation level.

Constraints (3.14) and (3.15) define the ramp up and ramp down limits for generator units. The ramp up during any period should be less than or equal to hourly ramping limits for a spinning unit or should be less than or equal to the start-up ramp rate for a unit that is coming online. Similarly, the ramp down rate should be within hourly ramping limits for a spinning unit or should be less than or equal to the shutdown ramp rate for a unit that is going offline. Equation (3.16) ensures that the system reserve requirement of 175 MW is always being met using the spare capacity of online generator units. Constraints (3.17) and (3.18) are minimum uptime and minimum downtime constraints, respectively.

Equation (3.19) ensures that the coal and nuclear units are always operating as per the present operational practice of SRP. So, for coal and nuclear units (indexed 47 – 52), the unit commitment decision variables are set to 1. The constraints (3.20) to (3.29) define the operational relationship between the combined cycle (CC) units and duct burner units in the Arizona-based test system – a system model representing SRP's system.

In a CC power plant, the exhaust from the gas turbine generates steam for the steam turbine to operate. During peak hours, the duct burner unit corresponding to the gas turbine in the CC unit is fired for the purpose of making more steam for the steam turbine so that additional power can be generated from the CC unit. Hence, the operation of a duct burner unit is dependent on the generating CC plant and a duct burner cannot independently operate while the corresponding CC plant is non-operational. This operational dependency has been included in the optimal UC model by adding equations (3.20) to (3.29). For example, equation (3.20) ensures that the operation of the duct burner unit indexed 26 is dependent on the operation of the 1-on-1 CC unit indexed 36. When the 1-on-1 CC unit is not generating ($U_{36,t} = 0$), the duct burner unit cannot be operational, i.e. $U_{26,t} = 0$. But, when the 1-on-1 CC unit is operating ($U_{36,t} = 1$), the duct burner unit can either generate power or stay idle ($U_{26,t} = 0/1$) as decided appropriately by the unit commitment process.

The important outputs from the optimal UC model for the base case scenario (without the BESS) are unit commitment decisions, the dispatch from generator units and total cost of generation per day. Finally, a penalty of 1% is added to the daily operation cost of the 2-on-1 CC units as they provide frequency regulation service.

3.3.2 BESS for peak shaving

The equations needed to model the BESS in the optimal UC formulation to estimate savings in operation cost depend on what primary/ancillary services the BESS will be providing. When the BESS provides peak shaving service, the storage constraints to be added to the optimal UC model are:

$$E_{min}^{b} \leq E_{t}^{b} \leq E_{max}^{b} \ \forall t \tag{3.31}$$

$$0 \leq Z_{ct} + Z_{dt} \leq 1 \ \forall t \tag{3.32}$$

$$P_{minlevel}^{b} * Z_{ct} \leq P_{ct}^{b} \leq P_{maxlevel}^{b} * Z_{ct} \ \forall t \tag{3.33}$$

$$P_{minlevel}^{b} * Z_{dt} \leq P_{dt}^{b} \leq P_{maxlevel}^{b} * Z_{dt} \ \forall t \tag{3.34}$$

$$E_t^b = E_{t-1}^b + \left(P_{ct}^b * \eta_c - \frac{P_{dt}^b}{\eta_d} \right) * \Delta t \tag{3.35}$$

$$E_{Initial}^b = E_{24}^b \tag{3.36}$$

When batteries are providing peak shaving, the constraints (3.12) and (3.16) become, respectively:

$$\sum_g P_{g,t} + P_{dt}^b = D_t + P_{ct}^b \ \forall t \tag{3.37}$$

$$D_t + (P_{ct}^b - P_{dt}^b) + R \leq \sum_g U_{g,t} * P_{g,max} \ \forall t \tag{3.38}$$

where,

- E_t^b is the energy in the battery at hour *t* in MWh.
- P_{dt}^b is the discharging power of the BES at hour *t* in MW.
- P_{ct}^b is the charging power at hour *t* in MW.
- η_c is the charging efficiency of the BES, which is equal to 0.95.
- η_d is the discharging efficiency of the BES, which is equal to 0.92.
- $P_{minlevel}^b$ is the minimum charging/discharging power limit of the BES.
- $P_{maxlevel}^b$ is the maximum charging/discharging power limit of the BES.
- Z_{ct} is a binary variable giving the status of BES charging. For $Z_{ct} = 1$, the BES is charging; otherwise, it is not charging.
- Z_{dt} is a binary variable giving the status of BES discharging. For $Z_{dt} = 1$, the BES is discharging; otherwise, it is not discharging. (When both Z_{ct} and Z_{dt} are zero, the BES is idle, neither charging nor discharging.)

- E^b_{max} is the maximum energy that can be stored in the BES, and
- E^b_{min} is the minimum energy level to be maintained in the BES.
- Δt is the simulation time step, which is equal to 1 hour.

As mentioned previously, the results included in this report are generated assuming a BESS of power capacity of 200 MW and energy capacity of 800 MWh. The maximum and minimum charging/discharging power limits are 200 MW and 0.01 MW, respectively.

The battery energy limit constraint is given by (3.31). Equation (3.32) ensures that the battery cannot charge and discharge simultaneously. Battery charging and discharging limit constraints are given by (3.33) and (3.34). Equation (3.35) is the energy balance constraint. Constraint (3.36) ensures that the battery energy remains the same at the beginning and end of the 24-hour operating period. Equations (3.37) and (3.38) give 'supply equals demand' constraint and reserve requirement constraint with the BESS in the system.

The important outputs from the modified UC model considering storage are battery charging/discharging power at different hours, energy in the battery at different hours, commitment decisions, dispatch from generator units and daily total system operation cost assuming free storage. Now, subtracting the daily total system operation cost for this scenario from the daily total generation cost for the base case scenario without the

BES, the financial savings gained per day due to the use of BES for peak shaving can be calculated.

3.3.3 BESS for reserve support

The peak shaving formulation discussed previously can be used for implementing the scenario when BESS provides both peak shaving and frequency regulation services. For the provision of frequency regulation service, power and energy equivalent of head-room/footroom blocked in the BESS are 25 MW and 5 MWh, respectively, as suggested by SRP [35]. In that case, for a BESS of power capacity of 200 MW and energy capacity of 800 MWh, $P^b_{minlevel}$ and $P^b_{maxlevel}$ are limited to 0.01 MW and 175 MW, respectively. Also, E^b_{max} and E^b_{min} are equal to 795 MWh and 165 MWh. Although this leads to the availability of less storage capacity for peak shaving, significant savings are made when the 1% penalty on the daily operation cost of 2-on-1 CC units providing frequency regulation service is avoided. Again, the value of R is updated to 150 MW, as R is now the system spinning reserve requirement.

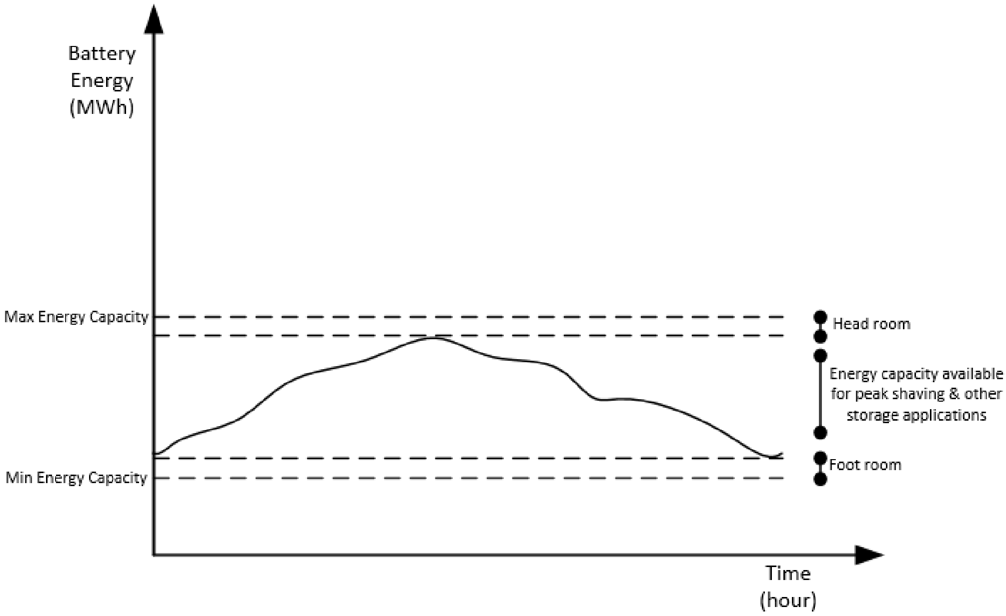

Figure 3.5 Energy equivalent of headroom/ footroom blocked in BESS.

For realizing the scenario when BESS provides peak shaving, frequency regulation, and spinning reserve services, (3.39) replaces (3.38) in the peak shaving model, while (3.40)-(3.43) are added to the model:

$$D_t + \left(P_{ct}^{b} - P_{dt}^{b}\right) + R \leq \sum_{g} U_{g,t} * P_{g,max} + R_{b,t} \ \forall t \qquad (3.39)$$

$$R_{gen,t} \leq \sum_{g} U_{g,t} * P_{g,max} - \sum_{g} P_{g,t} \ \forall t \qquad (3.40)$$

$$R_{b,t} \leq P_{maxlevel}^{b} - P_{dt}^{b} + P_{ct}^{b} \ \forall t \qquad (3.41)$$

$$R_{b,t} \leq (E_{t-1}^{b} - E_{min}^{b}) \frac{\eta_d}{\Delta t} - P_{dt}^{b} + P_{ct}^{b} \ \forall t \qquad (3.42)$$

$$0 \leq R_{b,t} \leq \mathrm{R} \ \forall t \qquad (3.43)$$

where,

- R is the spinning reserve requirement, which is equal to 150 MW.

- $R_{b,t}$ is the available reserve from the BES during hour *t* in MW.
- $R_{gen,t}$ is the total spinning reserve available from generators during hour *t* in MW.

The system spinning reserve requirement of 150 MW is met using the spare capacity of online generators and the available reserves from the BESS as ensured by (3.39). The amount of spinning reserves available from generator units is defined by (3.40). Equations (3.41), (3.42) and (3.43) define the amount of upward reserve that is available from the BESS depending on its operational status, including available power, and energy level. Comparing the daily total system operation cost for this scenario with the daily total generation cost for the base case scenario without storage, the stacked savings in a day due to the provision of multiple services such as peak shaving, frequency regulation, and reserve support by BESS can be estimated.

3.3.4 BESS with solar generation

A similar savings calculation can be performed for the test system with BESS and significant solar generation by replacing demand D_t in the equations discussed so far with net demand Net_D_t. Here, Net_D_t is defined below:

$$Net\_D_t = D_t - S_t \; \forall t \tag{3.44}$$

where,

- Net_D_t is the net demand during hour *t* in MW.
- D_t is the demand during hour *t* in MW and
- S_t is the solar generation during hour *t* in MW.

3.3.5 BESS stacked savings calculation assuming forced outage rate (FOR) of generator units

The UC based production simulations discussed previously do not consider random forced outages of generator units. Since generator units may experience unexpected outages, it is more appropriate to consider their unavailability in production simulation if results with better accuracy are to be obtained [40]. Generator forced outage rate (FOR) information can be used to account for the generator unavailability and under such scenario, it is interesting to estimate the stacked value that the BESS will provide as it renders services such as peak shaving, frequency regulation, and reserve support.

As per [41], FOR is the fraction of time during which a generator unit will not be available for generation on average. SRP has provided generator FOR information which allows us to construct the capacity outage probability table (COPT), which lists the generating system states and the probability associated with these states [42]. For the Arizona-based test system with 52 generating units, 41 units have a FOR of 5.5% and the remaining 11 units have a zero FOR. Then, the maximum number of possible generating system states is $2^{41} = 2.19 \times 10^{12}$. This is also the total number of enumerations needed in the complete COPT. Clearly including these many states in COPT is not practical. However, only assuming full capacity state, (when no generator units are experiencing an outage) and single generator contingency states, including the ones when a duct burner unit cannot operate due to the outage in corresponding CC unit, the total number of generating system states becomes 42 and, in that case, the COPT is constructed by normalizing the individual generating state probabilities with their sum resulting in a table with a reasonable number of entries and a practical estimate of generating state probabilities. This is justified as the probability of occurrence of more severe contingencies with two or more units experiencing outage is negligible. Table 3.2 gives the COPT constructed for the Arizona-based test system.

Table 3.2 COPT for the Arizona-based test system.

State	Type of Unit Experiencing Outage	Unit Experiencing Outage	Individual Probability	Individual Probability (Normalized)
1	-	No unit	0.098	0.29614
2 - 7	Peaker CTs	1 - 6	0.0057	0.01717
8 - 10	Steam	7 - 9	0.0057	0.01717
11 - 22	Aero CTs	10 - 21	0.0057	0.01717
23 - 26	Legacy Comb Cycle	22 - 25	0.0057	0.01717
27 - 28	1 on 1 Combined Cycle	36 - 37	0.0057	0.01717
29 - 32	2 on 1 Combined Cycle	38 - 41	0.0057	0.01717
33 - 37	Hydro	42 - 46	0.0057	0.01717
38 - 42	Coal	47 - 51	0.0057	0.01717

As mentioned previously, the individual probability values of system states in Table 3.2 are calculated using the generator FOR information shared by SRP. The individual probability for the full capacity state (no-contingency state) is calculated as follows:

(Individual probability for no contingency state) =

$$(1 - FOR)^{41} = (1 - 0.055)^{41} = 0.098 \tag{3.45}$$

Similarly, individual probability values for the single generator contingency states are obtained as follows:

(Individual probability for single generator contingency state) =

$$FOR * (1 - FOR)^{40} = 0.055 * (1 - 0.055)^{40} = 0.0057 \tag{3.46}$$

Using such individual probability values, the normalized probability is calculated for each system state in COPT:

(Normalized probability for a system state) =

(Individual probability of that state) / (Sum of all individual probabilities) (3.47)

Then, from [40], the daily total cost of operation for the base case scenario (without BESS) can be written as:

$$(\text{Daily total cost of operation})_{\text{base case}} = \sum_{i=1}^{42} P_i \times (TC)_i \tag{3.48}$$

where,

- P_i is the normalized probability of 'i' th state, and,
- $(TC)_i$ is the production cost for 'i' th state in base case scenario.

Similarly, the daily total cost of operation when BESS provides services such as peak shaving and reserve support etc. can be written as:

$$(\text{Daily total cost of operation})_{\text{with BESS}} = \sum_{i=1}^{42} P_i \times (TCB)_i \tag{3.49}$$

where $(TCB)_i$ is the production cost for 'i' th state with BESS in the test system.

Subtracting (3.49) from (3.48), the daily savings made with the use of BESS in the Arizona-based test system, while considering forced outages of generator units, can be calculated.

3.4 Calculation of stacked savings over useful BESS life

After finding the daily summer and winter savings, net annual savings due to the use of a BESS can be calculated for different Arizona-based test-system scenarios. Again, these annual savings values along with the discount rate and inflation rate can be used to estimate the net present value (NPV) of stacked savings over the useful BESS life of 20 years. The following formulation is used to calculate the net present value of stacked savings over the useful life of a BESS while assuming a discount rate of 11.47% and an inflation rate of 2% [37]:

$$\text{(Stacked savings over useful BESS life)} = \sum_{i=1}^{20} \frac{AS_i \times (1+IR)^i}{(1+r)^i} \tag{3.50}$$

where,

- AS_i is the stacked annual savings for 'i' th year,
- IR is the inflation rate of 2% and
- r is the discount rate of 11.47%.

4 DISCUSSION OF SIMULATION RESULTS FROM THE ARIZONA-BASED TEST SYSTEM

The MILP-based formulation, discussed in the previous chapter, has been implemented using the AMPL-based Gurobi optimizer for savings calculation under the following four operational scenarios (A) BESS for peak shaving (B) BESS providing peak shaving, frequency regulation, and spinning reserve support service (C) Use of BESS in the test system with significant solar penetration (D) Use of BESS assuming forced outages of generator units. The obtained results from the simulation are presented here.

4.1 BESS for peak shaving

Figure 4.1 depicts the event of peak shaving on a typical summer day with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system. As can be observed in the figure, increased generation from generator units during off-peak hours implies the charging of the BESS and reduced generation during on-peak hours indicates the discharging of the BESS signifying the provision of peak shaving service. This is corroborated by Figure 4.2 which shows the charging/discharging power of the BESS during summer days. Figure 4.3 shows the stored energy in the BESS during different hours of the day. As can be seen, battery stored energy is within energy limits and a minimum SoC of 20% is always being maintained.

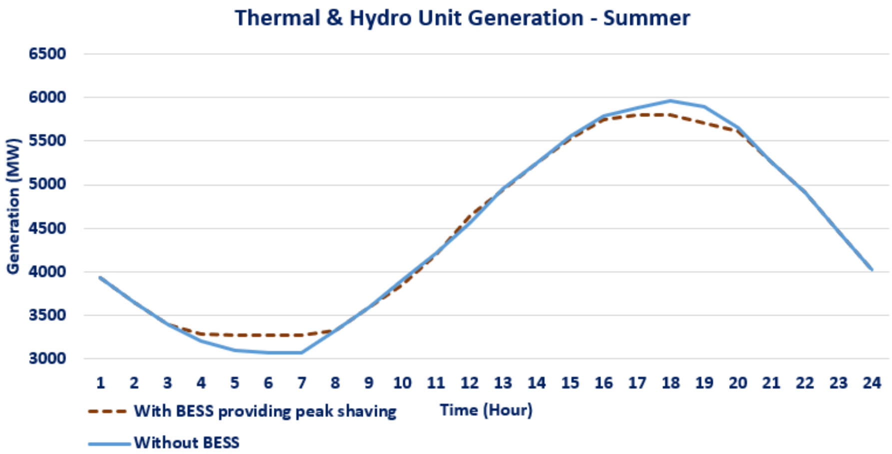

Figure 4.1 Peak shaving during summer days with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system.

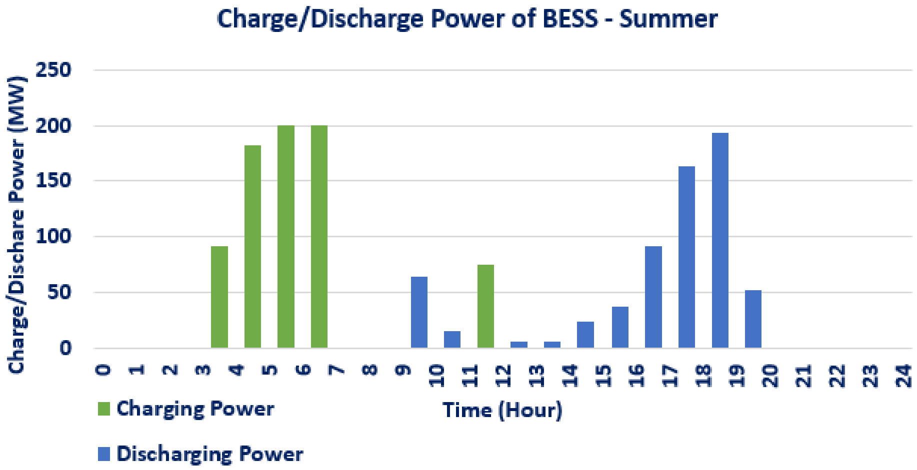

Figure 4.2 Charging/ discharging power of the 200 MW/800 MWh capacity BESS during summer days.

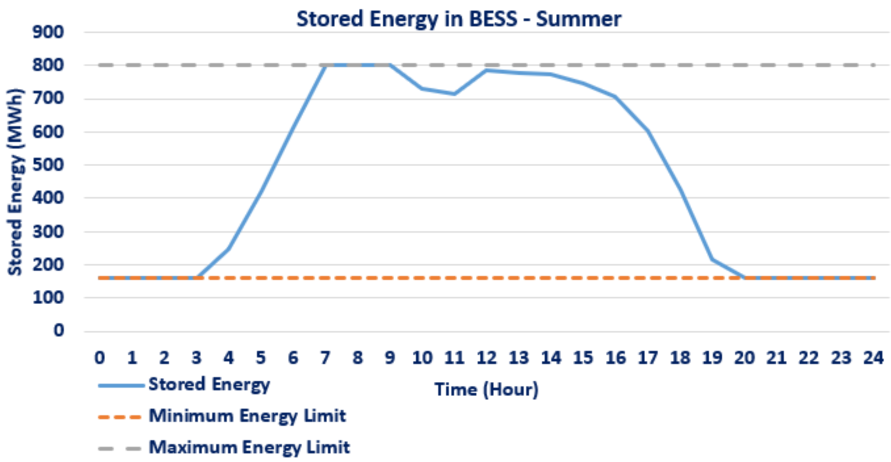

Figure 4.3 Stored energy in the 200 MW/800 MWh capacity BESS during summer days.

Similar results have been obtained with the same capacity BESS for winter days as shown in Figure 4.4, Figure 4.5 and Figure 4.6.

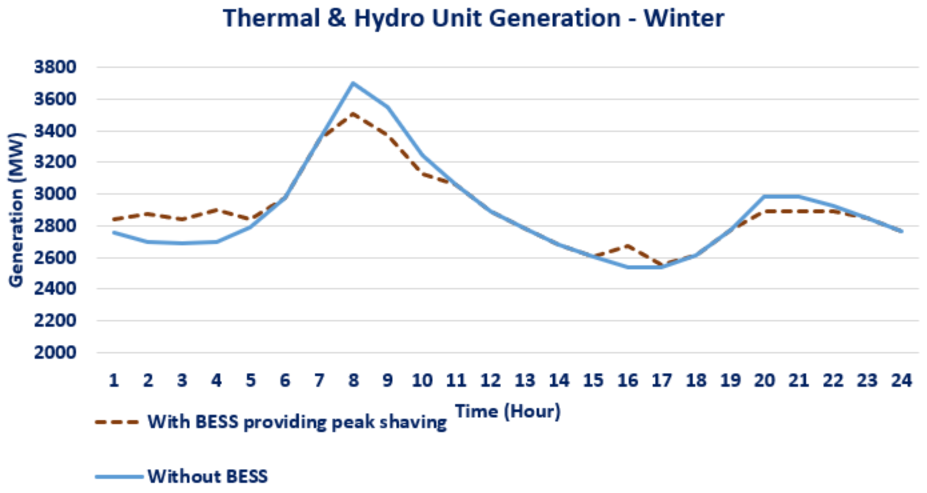

Figure 4.4 Peak shaving during winter days with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system.

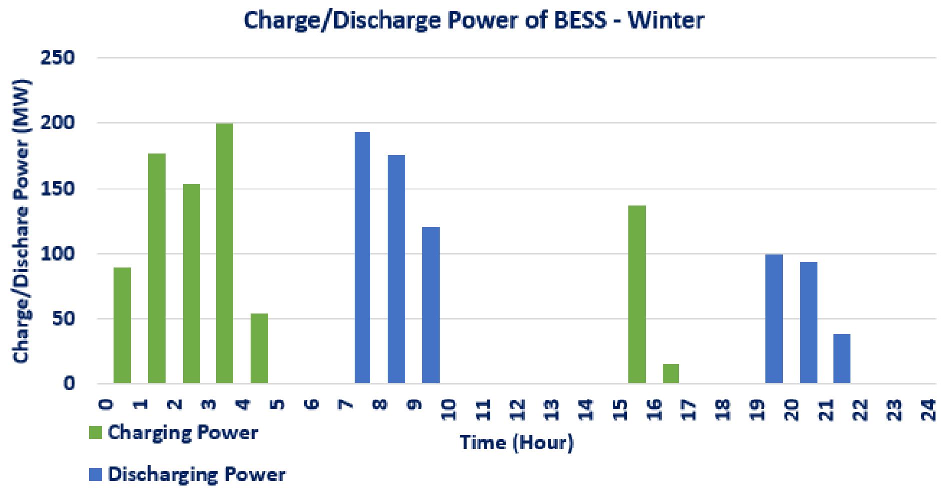

Figure 4.5 Charging/ discharging power of the 200 MW/800 MWh capacity BESS during winter days.

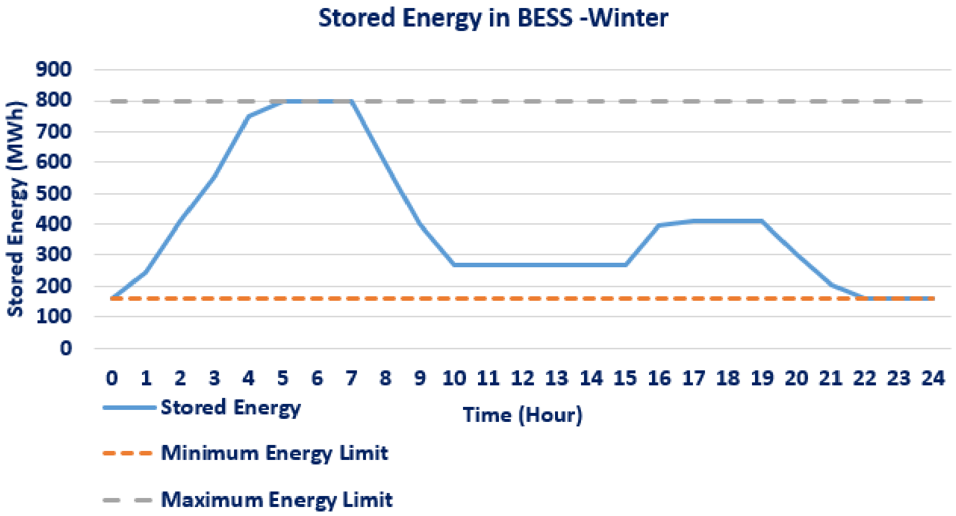

Figure 4.6 Stored energy in the 200 MW/800 MWh capacity BESS during winter days.

The total cost of generation for the base case scenario (without the BESS) on a typical summer day is found to be $2,158,844, while the total system operation cost with the 200 MW/800 MWh BESS in the test system providing peak shaving service is $2,147,463. Hence, a savings of $11,381 is made on a typical summer day when a BESS of power capacity of 200 MW and energy capacity of 800 MWh is used for peak shaving. Similarly, the savings made on a typical winter day due to the use of the same capacity battery storage for peak shaving is $6,241. Using these daily saving values, annual savings made with the use of BESS for peak shaving is calculated to be $3,172,177. Furthermore, the present worth of savings over the useful life of BESS is estimated to be $28,380,095.

Similar savings calculation has been performed for BESSs of other power and energy ratings. Table 4.1 lists the annual savings and BESS useful life savings for BESSs of various power and energy capacities.

Table 4.1 Annual savings and BESS useful life savings for BESSs of various power and energy capacities.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	0.54	4.83
50	100	0.84	7.55
50	150	0.97	8.63
50	200	1.08	9.62
50	250	1.16	10.33
100	100	0.85	7.56
100	200	1.51	13.48
100	300	1.67	14.97
100	400	1.86	16.68
100	500	2.02	18.08
150	150	1.34	11.95
150	300	1.81	16.16
150	450	2.17	19.40
150	600	2.47	22.06
150	750	2.71	24.21
200	200	1.59	14.21
200	400	2.21	19.74
200	600	2.81	25.13
200	800	3.17	28.38
200	1000	3.54	31.67

Finally, some observations have been made with respect to the effect of BESS energy capacity on daily savings for a BESS of power capacity of 200 MW. The daily savings saturating with the increase in BESS energy capacity is observed in Figure 4.7, though this saturation is more evident in Figure 4.8, where the marginal contribution of the 200 MW BESS is shown to reduce with increases in BESS energy capacity.

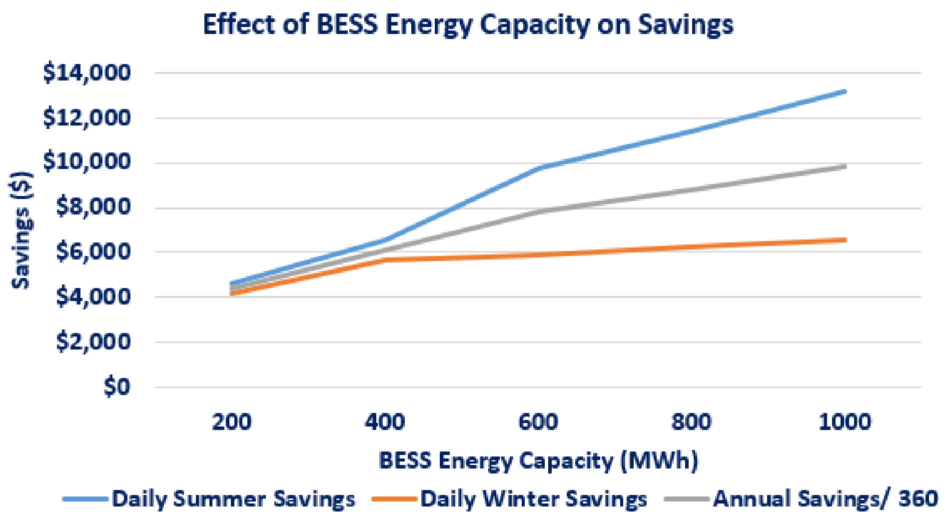

Figure 4.7 Daily savings with energy capacity for a 200 MW BESS.

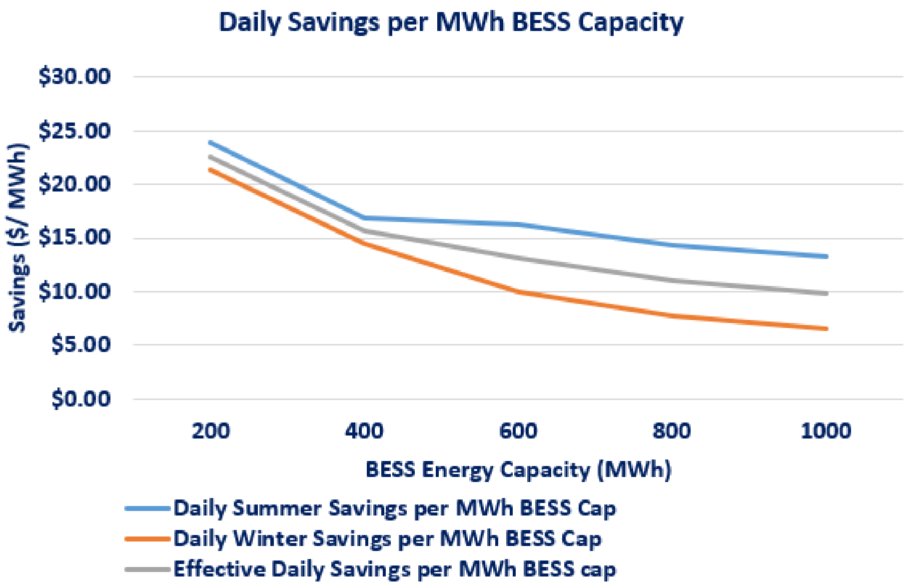

Figure 4.8 Daily savings per MWh of BESS energy capacity.

4.2 BESS providing peak shaving, frequency regulation, and spinning reserve support service

Here, we have estimated the stacked savings when BESS provides peak shaving along with the following reserve support services: (a) frequency regulation only (b) both frequency regulation and spinning reserve support.

Figure 4.9 shows the thermal and hydro unit generation on a typical summer day for the operational scenarios: (1) without the BESS (2) with the 200 MW/800 MWh capacity BESS providing peak shaving and frequency regulation, and (3) with the 200 MW/800 MWh capacity BESS providing peak shaving, frequency regulation, and spinning reserve support. As expected, peak generation is greater when the BESS provides all the three services compared to the scenario when the BESS provides peak shaving and frequency regulation. This is attributed to the blocking of some battery storage capacity for spinning reserve support service, which otherwise would be used for peak shaving. Similar plots are obtained for the thermal and hydro generations on a typical winter day as depicted in Figure 4.10.

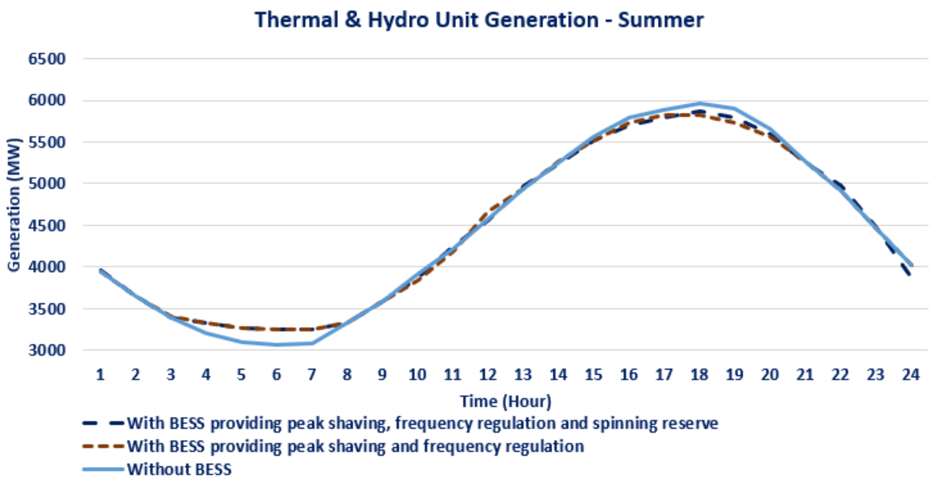

Figure 4.9 Thermal and hydro unit generations on a typical summer day for various operational scenarios.

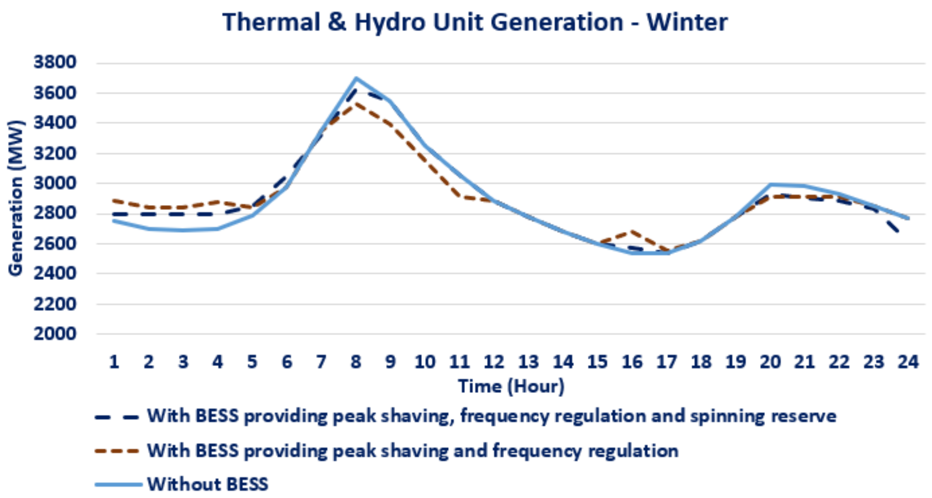

Figure 4.10 Thermal and hydro unit generations on a typical winter day for various operational scenarios.

Figure 4.11 and Figure 4.12 show charging/discharging power measured at the terminals of the battery on a typical summer and winter day, respectively, when the 200 MW/800 MWh capacity BESS provides peak shaving and frequency regulation services. Figure 4.13 and Figure 4.14 depict charging/discharging power when the BESS in the test system provides all the three services. As expected, the maximum charging and discharging power is limited to 175 MW as the remaining 25 MW of BESS capacity is reserved for the frequency regulation service.

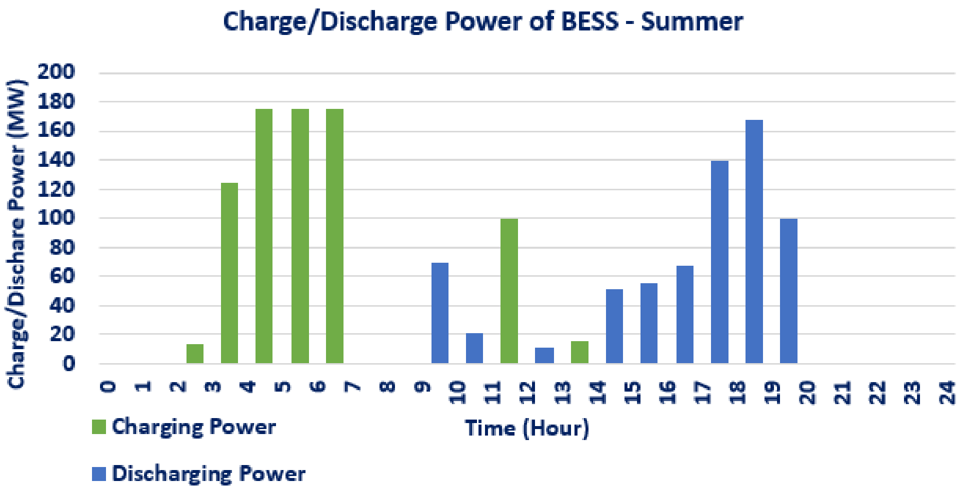

Figure 4.11 Charging and discharging power when the 200 MW/800 MWh capacity BESS provides peak shaving and frequency regulation on a typical summer day.

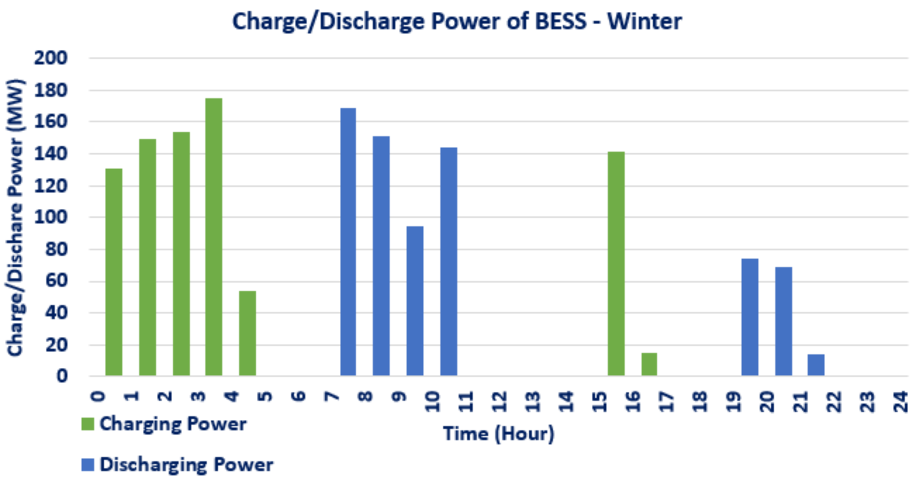

Figure 4.12 Charging and discharging power when the 200 MW/800 MWh capacity BESS provides peak shaving and frequency regulation on a typical winter day.

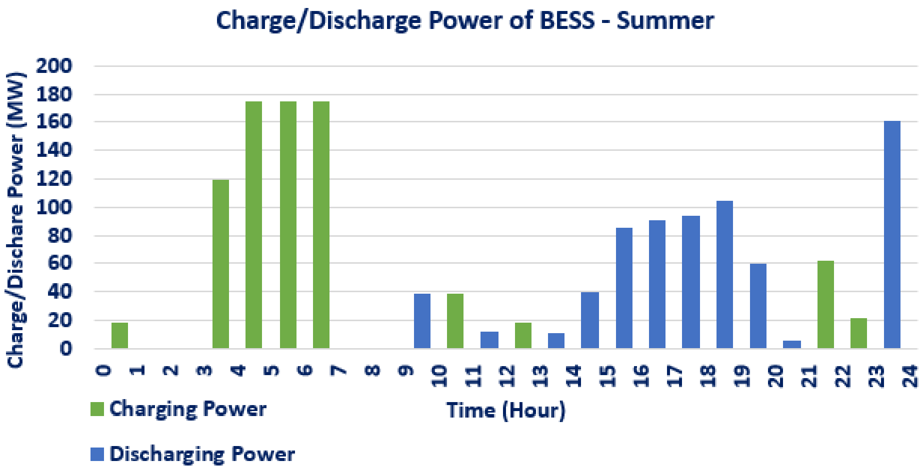

Figure 4.13 Charging and discharging power when the 200 MW/800 MWh capacity BESS provides peak shaving, frequency regulation, and spinning reserve support on a typical summer day.

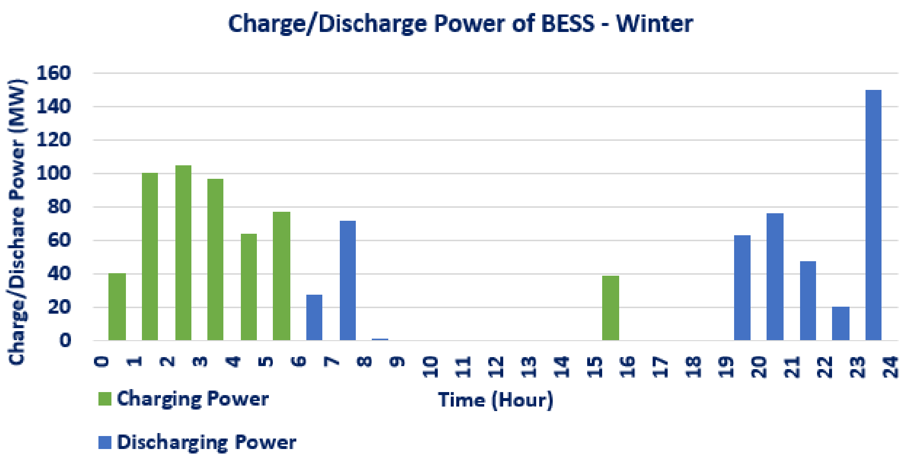

Figure 4.14 Charging and discharging power when the 200 MW/800 MWh capacity BESS provides all three services on a typical winter day.

Figure 4.15 to Figure 4.18 depict stored energy in the 200 MW/800 MWh capacity BESS during different hours of a day for various operational scenarios.

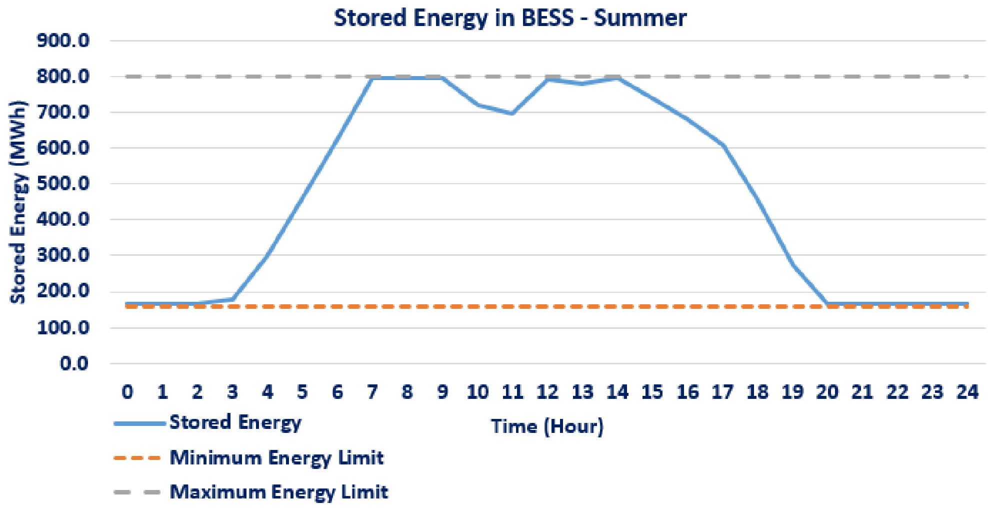

Figure 4.15 Stored energy during summer days when the 200 MW/800 MWh capacity BESS provides peak shaving and frequency regulation.

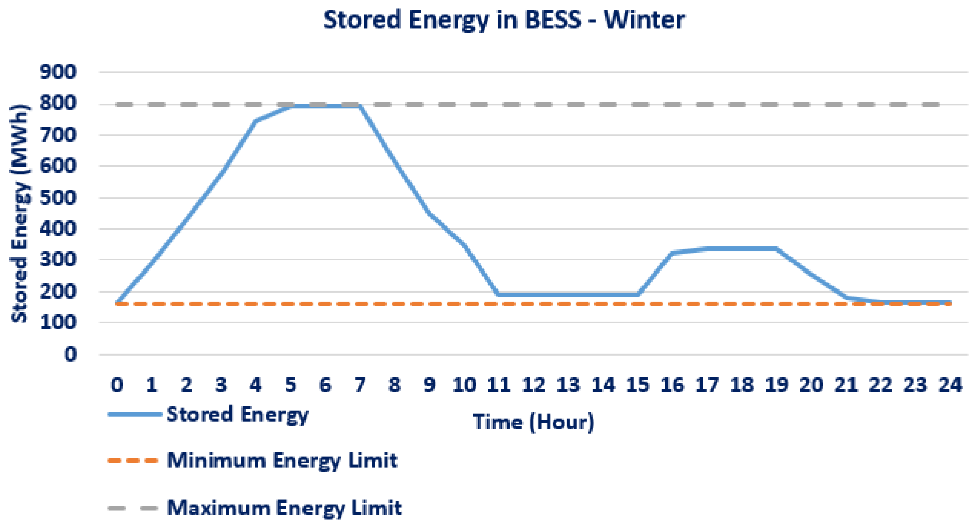

Figure 4.16 Stored energy during winter days when the 200 MW/800 MWh capacity BESS provides peak shaving and frequency regulation.

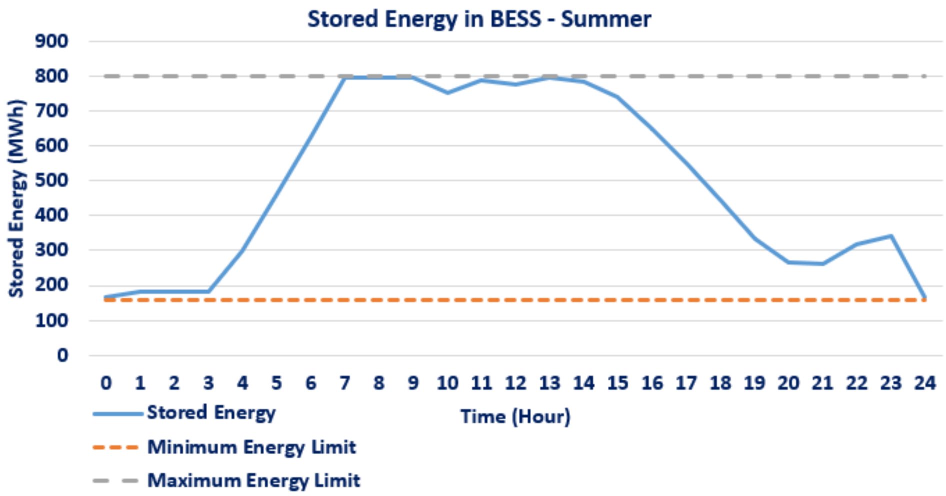

Figure 4.17 Stored energy during summer days when the 200 MW/800 MWh capacity BESS provides peak shaving, frequency regulation, and spinning reserve support.

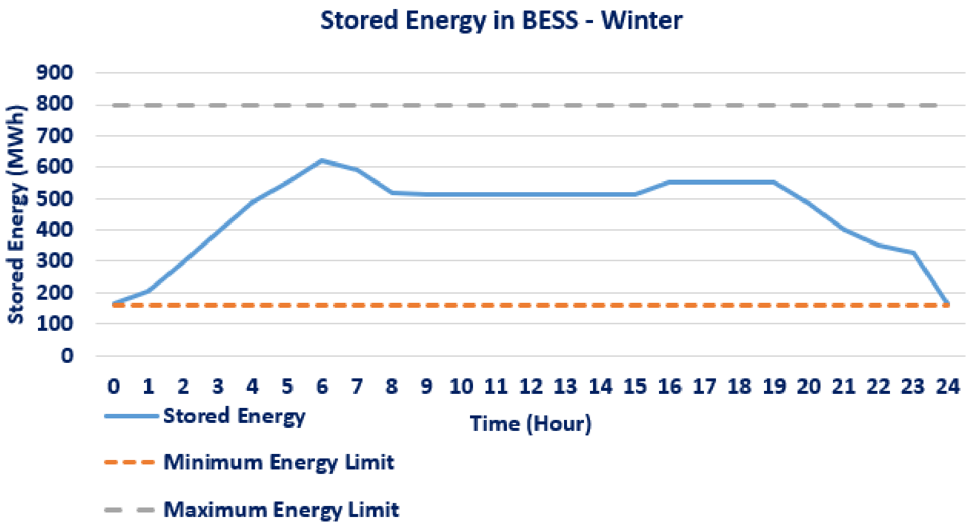

Figure 4.18 Stored energy during winter days when the 200 MW/800 MWh capacity BESS provides peak shaving, frequency regulation, and spinning reserve support.

When BESS provides only peak shaving and frequency regulation services, the system spinning reserve requirement is fulfilled by the generator units in the test system. However, for the scenario, when BESS also provides spinning reserve support service, cheaper power from generator units fulfill the system reserve requirement during off-peak hours while during the remaining hours, both the BESS and generator units contribute to the reserve requirement making the overall system operation economical. Figure 4.19 and Figure 4.20 depict the reserve availability from generator units and the 200 MW/800 MWh capacity BESS on a typical summer and winter day under such a scenario.

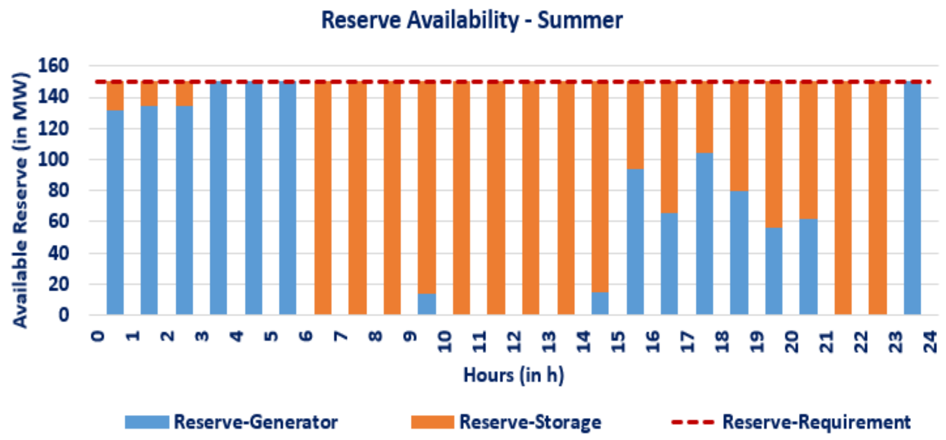

Figure 4.19 Reserve availability on a typical summer day when the 200 MW/800 MWh capacity BESS provides peak shaving, frequency regulation, and spinning reserve support services.

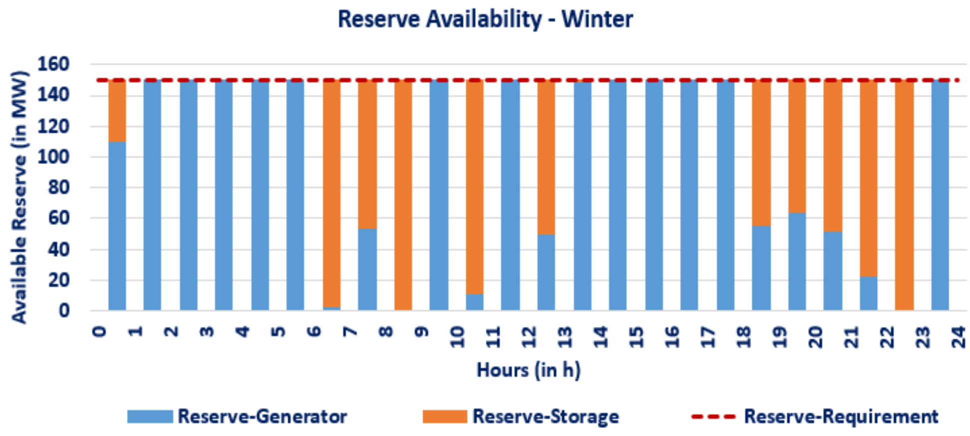

Figure 4.20 Reserve availability on a typical winter day when the 200 MW/800 MWh capacity BESS provides peak shaving, frequency regulation, and spinning reserve support services.

The total cost of generation on a typical summer day, when a BESS of power capacity of 200 MW and energy capacity of 800 MWh provides peak shaving and frequency regulation services, is found to be $2,136,865. Comparing this value with the base case operation cost, a daily summer savings of $21,979 is obtained. Again, with the 200 MW/800 MWh capacity BESS providing peak shaving, frequency regulation services and spinning reserve support service, the daily operating cost reduces to $2,131,848. In that case, the daily summer savings made is $26,996. Previously, with the same capacity BESS providing only peak shaving service, the daily summer saving was found to be $11,381. Now, with multiple services stacked, the value that the same capacity BESS can generate during summer days is increased significantly over that when only peak-shaving is provided. Also, similar results are obtained for the BESS in the test system during winter days. Table 4.2 and Table 4.3 show the stacked savings made in US $ with the 200 MW/800 MWh capacity BESS delivering several services on a typical summer and winter day.

Table 4.2 Stacked savings on a typical summer day.

Scenario	Operation cost ($)	Savings ($)
Without the BESS	$2,158,844	$0
With the BESS providing peak shaving	$2,147,463	$11,381
With the BESS providing peak shaving and freq. regulation	$2,136,865	$21,979
With the BESS providing peak shaving, freq. regulation, and reserve support	$2,131,848	$26,996

Table 4.3 Stacked savings on a typical winter day.

Scenario	Operation cost ($)	Savings ($)
Without the BESS	$1,161,352	$0
With the BESS providing peak shaving	$1,155,111	$6,241
With the BESS providing peak shaving and freq. regulation	$1,151,758	$9,594
With the BESS providing peak shaving, freq. regulation, and reserve support	$1,149,545	$11,807

Then, we calculate net annual savings and net present worth of stacked savings over the useful BESS life (using (3.50)) for the following two scenarios: (a) when BESS provides peak shaving and frequency regulation (b) when BESS provides peak shaving, frequency regulation, and spinning reserve support services. Table 4.4 and

Table 4.5 list the annual savings and BESS NPV of the useful life savings for BESSs of various power and energy capacities for both the scenarios.

Table 4.4 Annual savings and BESS useful life savings when BESS provides peak shaving and frequency regulation services.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	3.26	29.19
50	100	3.36	30.04
50	150	3.39	30.30
50	200	3.41	30.53
50	250	3.43	30.71
100	100	3.76	33.63
100	200	4.03	36.10
100	300	4.22	37.78
100	400	4.34	38.81
100	500	4.45	39.82
150	150	4.01	35.90
150	300	4.45	39.77
150	450	4.67	41.81
150	600	4.94	44.18
150	750	5.14	45.96
200	200	4.18	37.39
200	400	4.73	42.34
200	600	5.29	47.31
200	800	5.68	50.85
200	1000	5.98	53.49

Table 4.5 Annual savings and BESS useful life savings when BESS provides peak shaving, frequency regulation, and spinning reserve support.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	3.40	30.43
50	100	3.43	30.68
50	150	3.46	30.93
50	200	3.48	31.17
50	250	3.50	31.33
100	100	4.46	39.87
100	200	4.66	41.70
100	300	4.72	42.20
100	400	4.77	42.71
100	500	4.83	43.20
150	150	5.26	47.10
150	300	5.66	50.62
150	450	5.75	51.41
150	600	5.83	52.17
150	750	5.92	52.93
200	200	5.80	51.89
200	400	6.65	59.47
200	600	6.84	61.21
200	800	6.98	62.49
200	1000	7.10	63.50

Finally, Figure 4.21 to Figure 4.24 show the effect of scaling the size of the BESS (energy capacity) on daily savings for a BESS of power capacity of 200 MW. As observed earlier, the marginal contribution of the 200 MW BESS reduces with increasing BESS energy capacity.

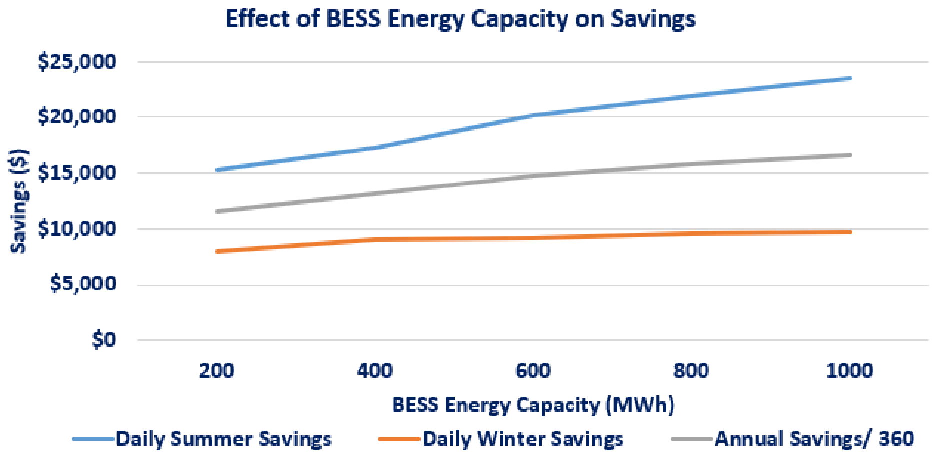

Figure 4.21 Daily savings with energy capacity for a 200 MW BESS when it provides peak shaving and frequency regulation.

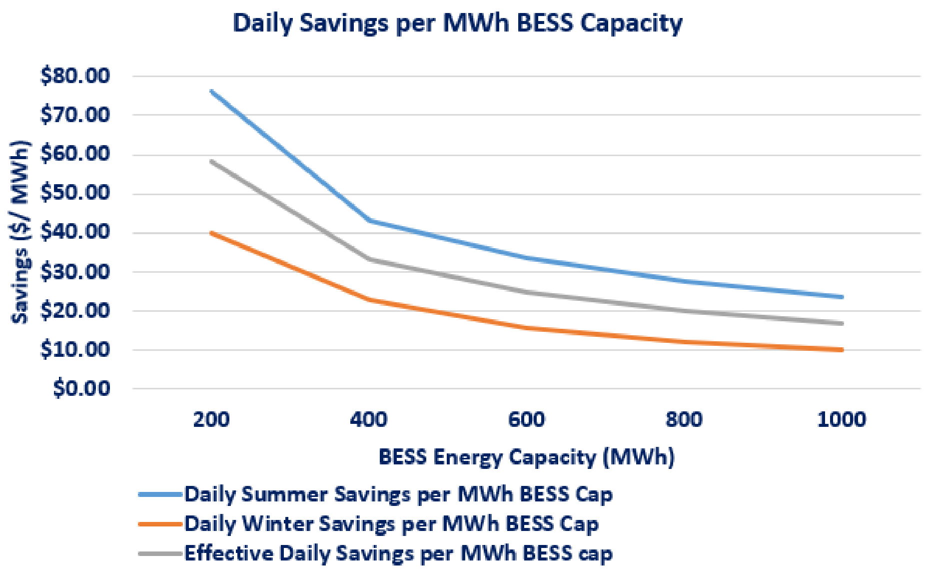

Figure 4.22 Daily savings per MWh of BESS energy capacity when it provides peak shaving and frequency regulation.

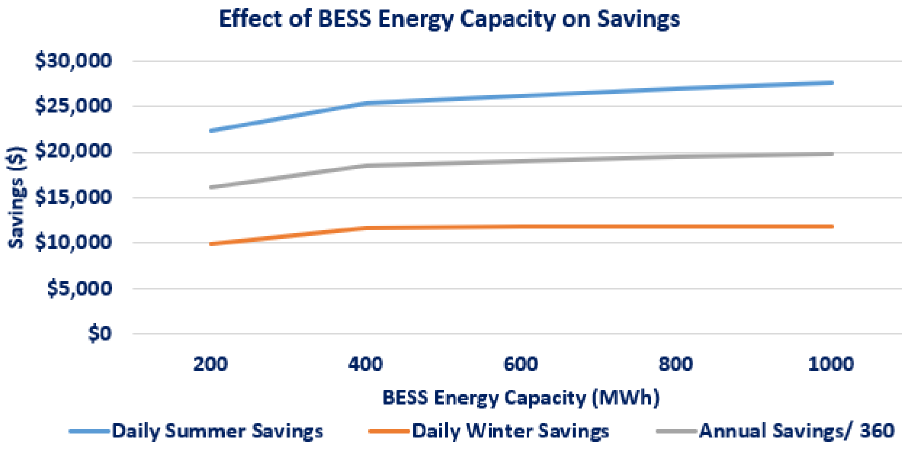

Figure 4.23 Daily savings with energy capacity for a 200 MW BESS when it provides peak shaving, frequency regulation, and spinning reserve support.

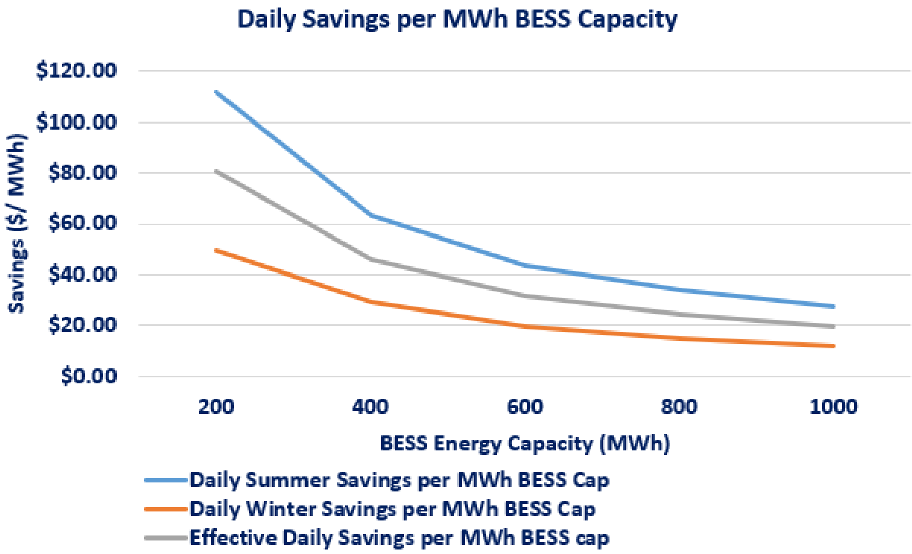

Figure 4.24 Daily savings per MWh of BESS energy capacity when it provides peak shaving, frequency regulation, and spinning reserve support.

4.3 BESS with significant solar generation

Here, we have presented results from the simulation of the Arizona-based test system with significant solar generation for the following usage scenarios of a 200 MW/800 MWh capacity BESS in the test system: (a) when the BESS provides only peak shaving service (b) the BESS providing peak shaving and frequency regulation services (c) when the BESS provides peak shaving, frequency regulation, and spinning reserve support.

Figure 4.25 and Figure 4.26 depict generation from thermal and hydro units in the test system during summer and winter days, respectively, for various operational scenarios of the BESS. As observed previously, BESS charges during off-peak hours and discharges during on-peak hours signifying the provision of peak shaving service.

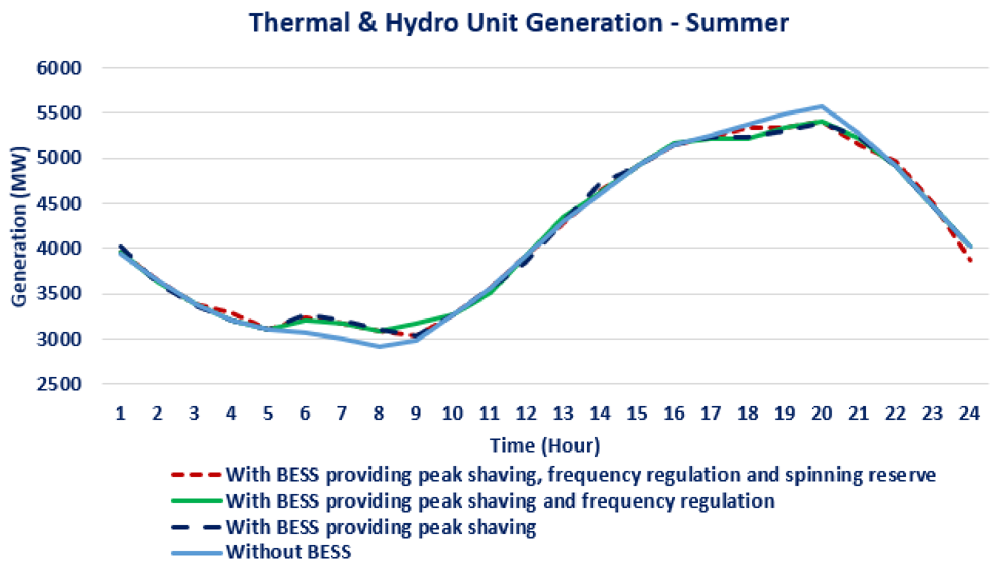

Figure 4.25 Thermal and hydro generations on a typical summer day for various usage scenarios of a 200 MW/800 MWh capacity BESS.

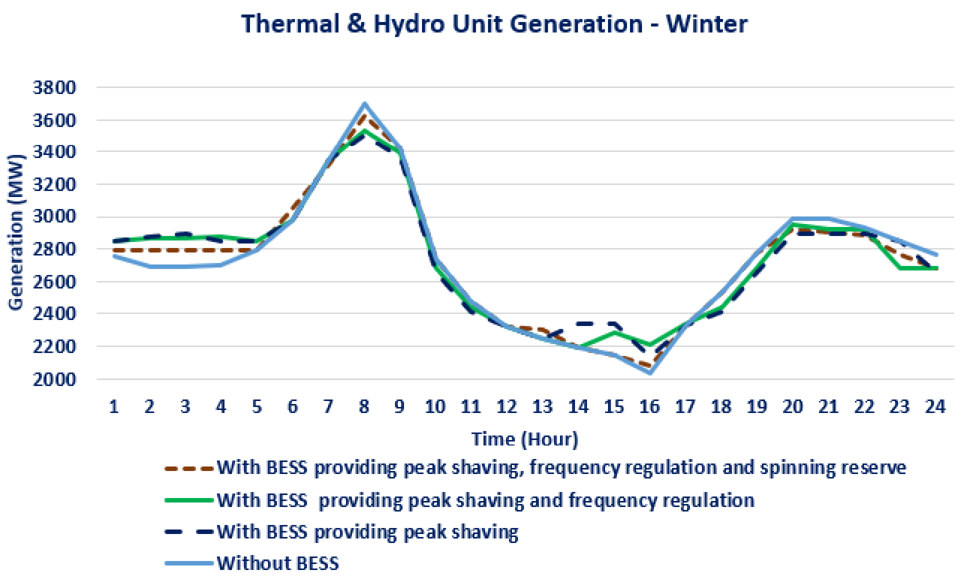

Figure 4.26 Thermal and hydro generations on a typical winter day for various usage scenarios of the 200 MW/800 MWh capacity BESS.

Figure 4.27 to Figure 4.32 show charging/discharging power of the 200 MW/800 MWh capacity BESS during different hours of summer and winter days for various BESS usage scenarios.

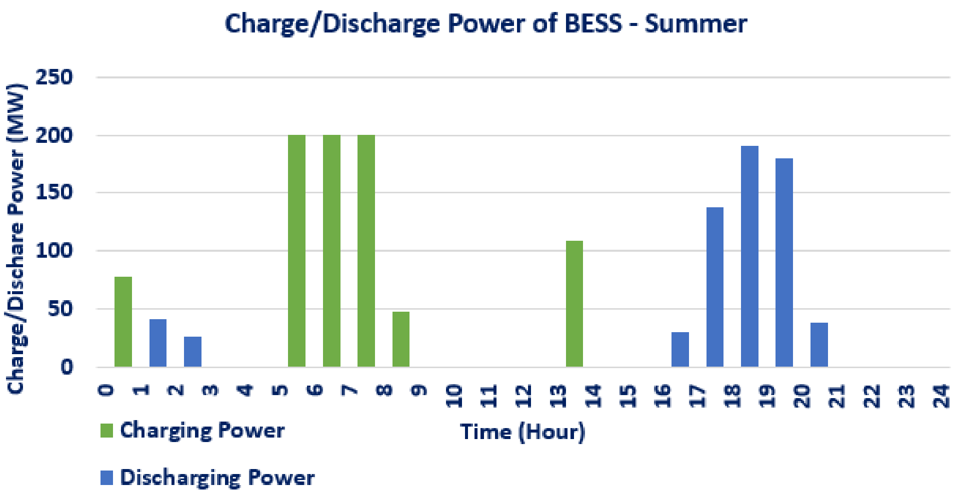

Figure 4.27 Charging/discharging power when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provide peak shaving on a typical summer day.

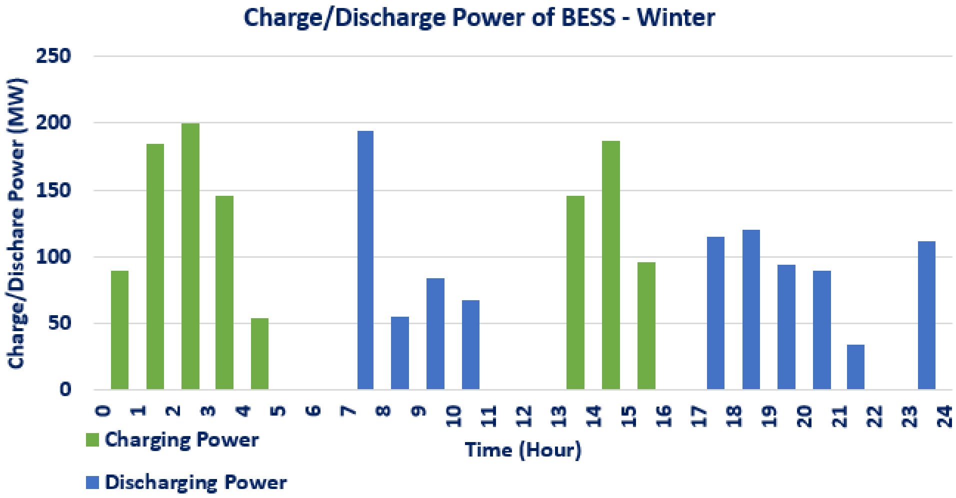

Figure 4.28 Charging/discharging power when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provide peak shaving on a typical winter day.

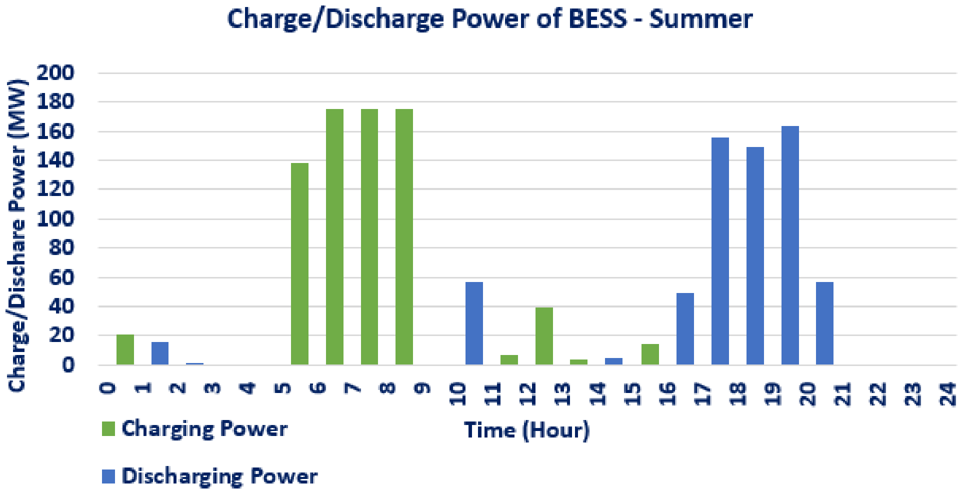

Figure 4.29 Charging/discharging power when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provide peak shaving and frequency regulation during summer days.

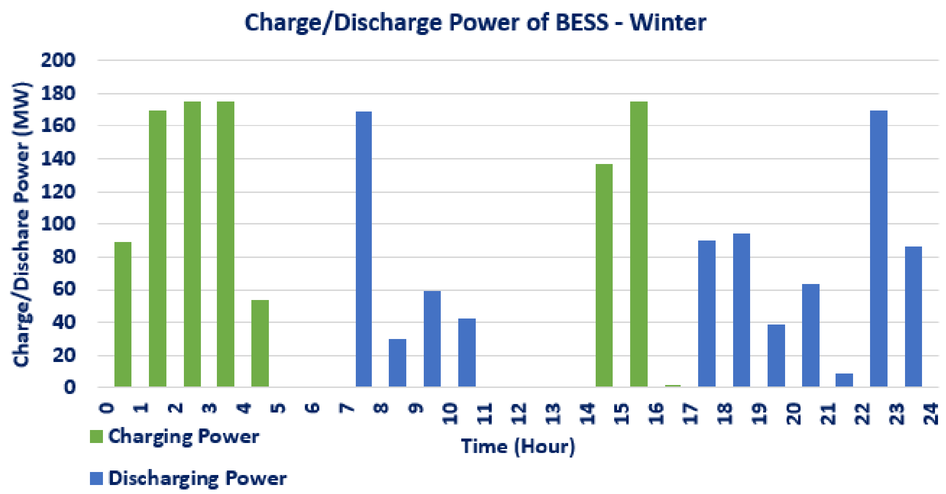

Figure 4.30 Charging/discharging power when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provide peak shaving and frequency regulation during winter days.

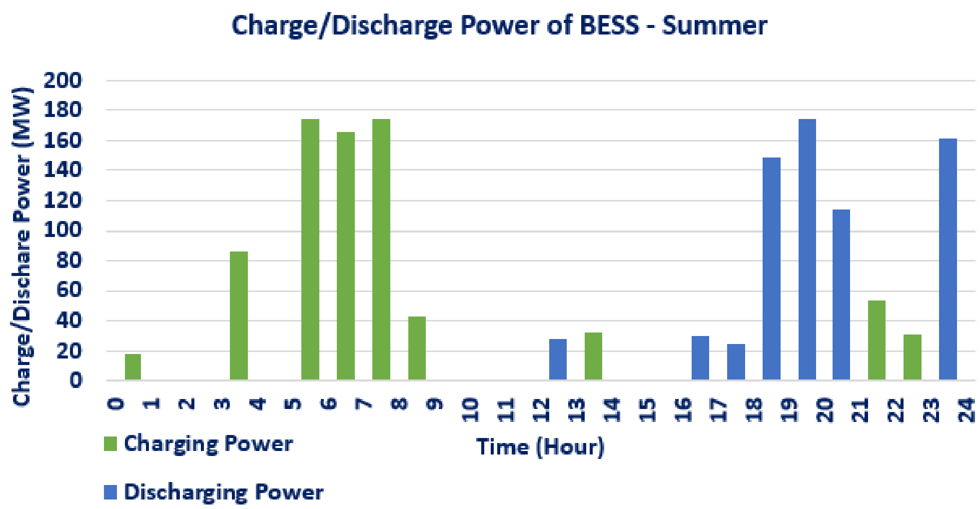

Figure 4.31 Charging/discharging power with the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) providing peak shaving, frequency regulation, and spinning reserve support on a typical summer day.

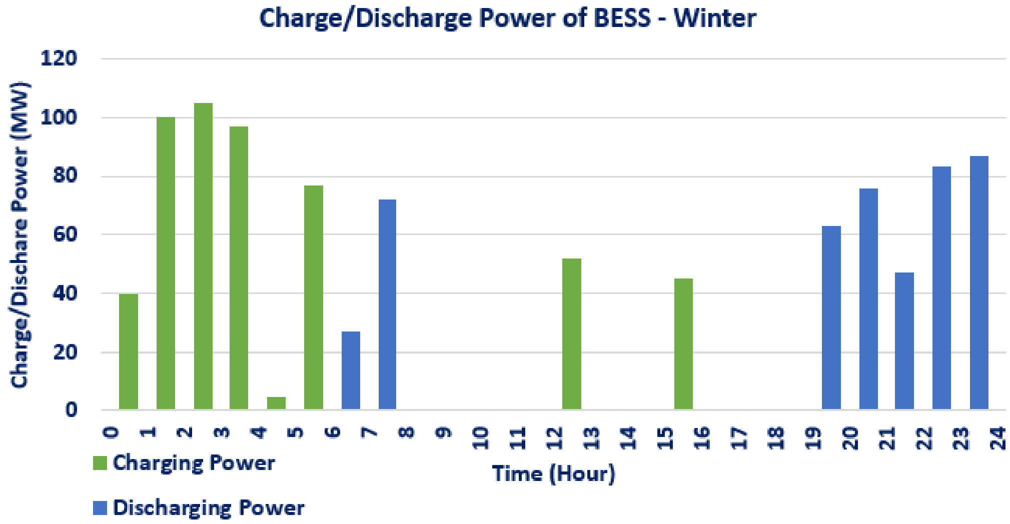

Figure 4.32 Charging/discharging power with the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) providing peak shaving, frequency regulation, and spinning reserve support on a typical winter day.

Figure 4.33 to Figure 4.38 depict the stored energy in the 200 MW/800 MWh capacity BESS during summer and winter days for various BESS usage scenarios. Comparing Figure 4.38 with Figure 4.36, it can be observed that the stored energy in the BESS does not attain the maximum value when the BESS provides peak shaving, frequency regulation and spinning reserve support service on a typical winter day. This can be attributed to both reduced system demand during winter days and to the blocking of battery power capacity for the spinning reserve support service leading to reduced discharging/charging power and hence, a diminished peak energy level of the BESS.

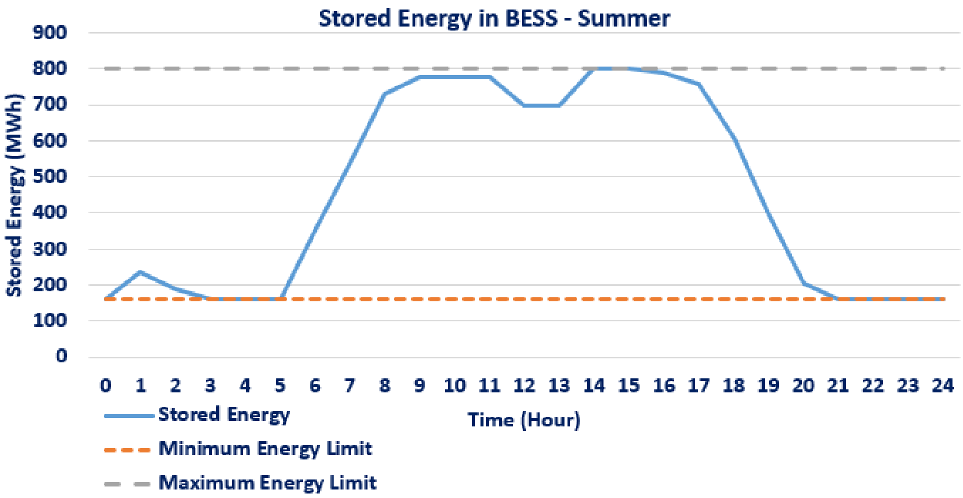

Figure 4.33 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving on a typical summer day.

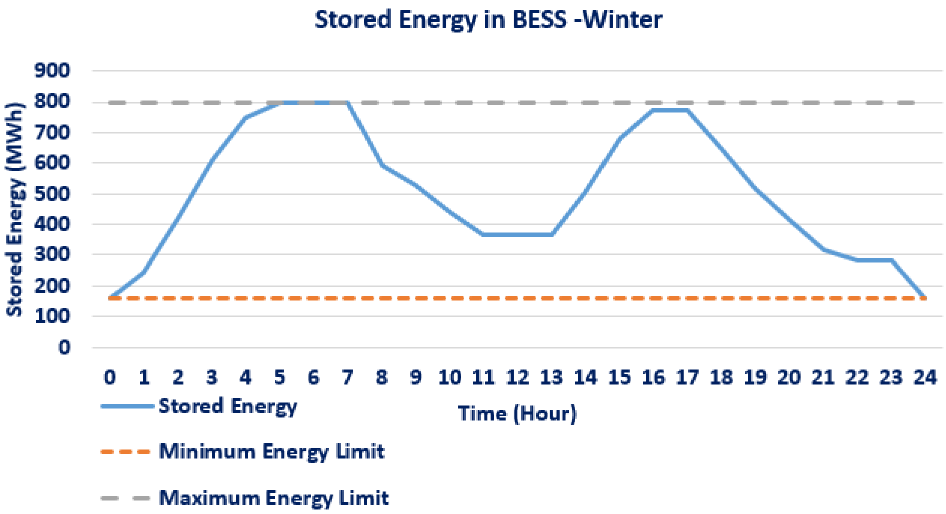

Figure 4.34 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving on a typical winter day.

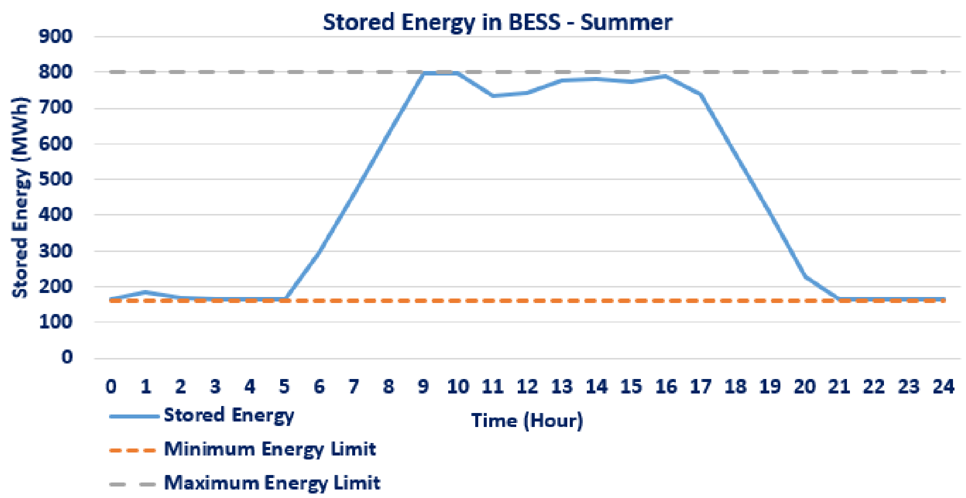

Figure 4.35 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving and frequency regulation on a typical summer day.

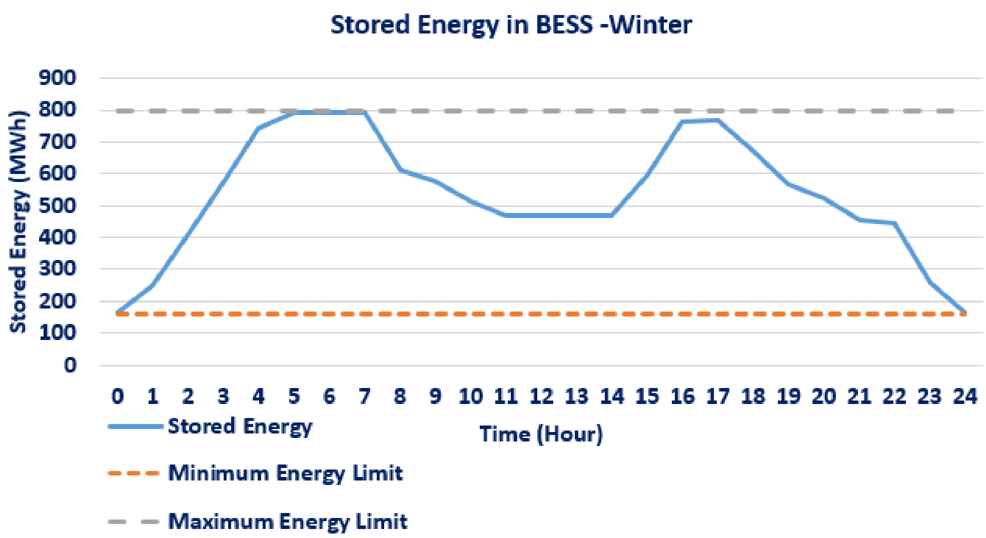

Figure 4.36 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving and frequency regulation on a typical winter day.

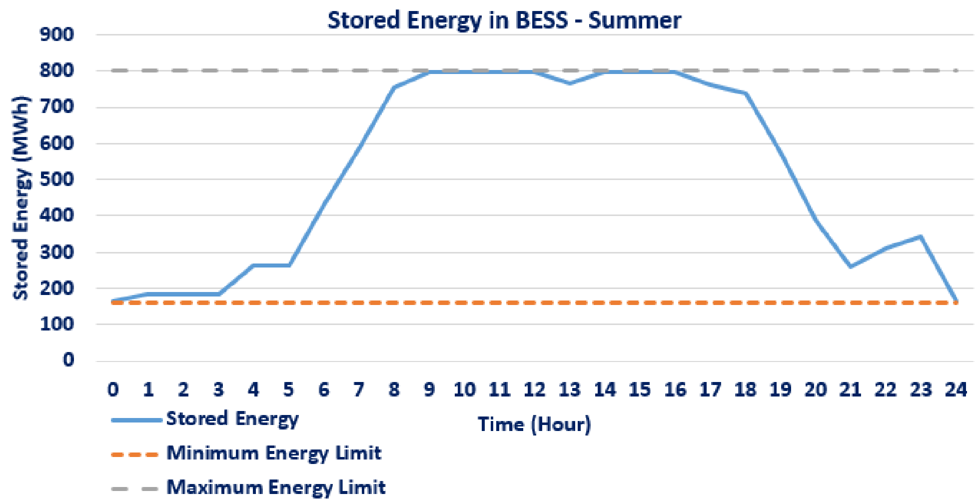

Figure 4.37 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving, frequency regulation and spinning reserve support on a typical summer day.

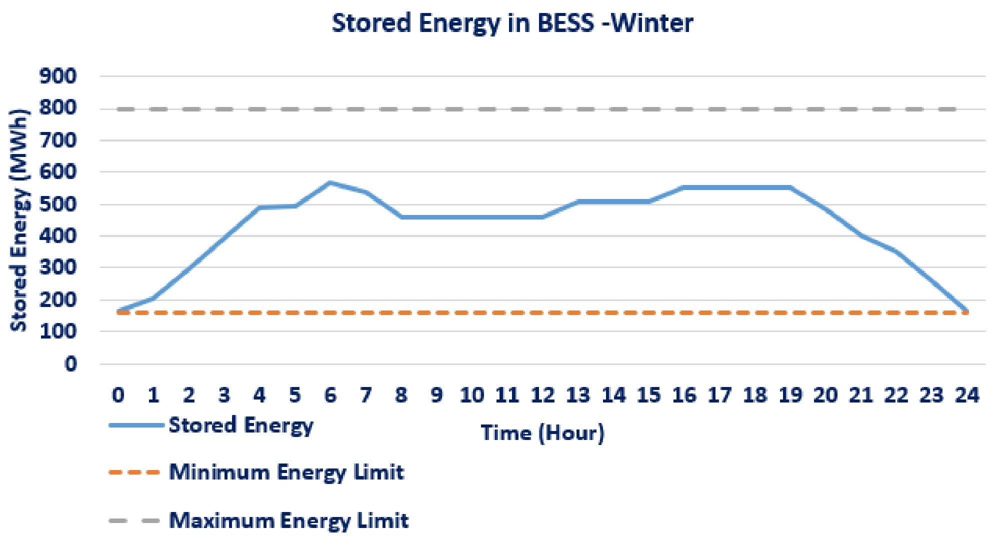

Figure 4.38 Stored energy in the 200 MW/800 MWh capacity BESS providing peak shaving, frequency regulation and spinning reserve support on a typical winter day.

For scenarios, when the 200 MW/800 MWh capacity BESS does not provide spinning reserve support, the system spinning reserve requirement is fulfilled by generation from thermal and hydro units in the test system. When the BESS provides spinning reserve support, both BESS and generator units contribute to the reserve requirement appropriately making the overall system operation more economical. Figure 4.39 and

Figure 4.40 show reserve availability from both generator units and the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) during summer and winter days, respectively. As can be seen, generator units fulfill reserve requirement during off-peak hours while during remaining hours both the BESS and generator units satisfy the spinning reserve requirement.

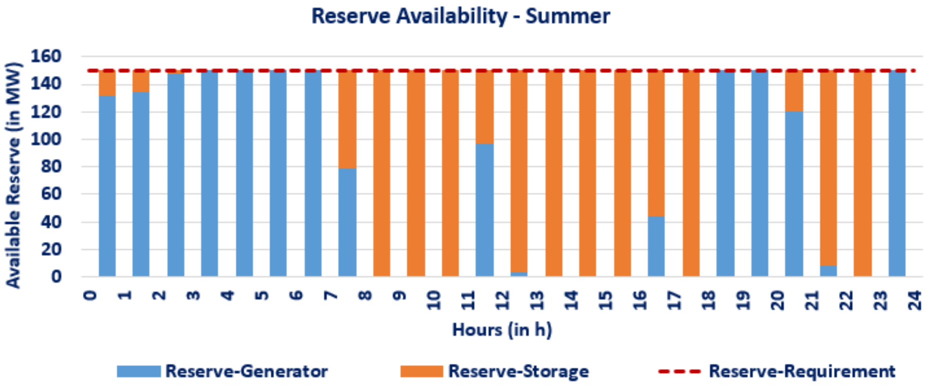

Figure 4.39 Reserve availability on a typical summer day when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provides peak shaving, frequency regulation, and spinning reserve support.

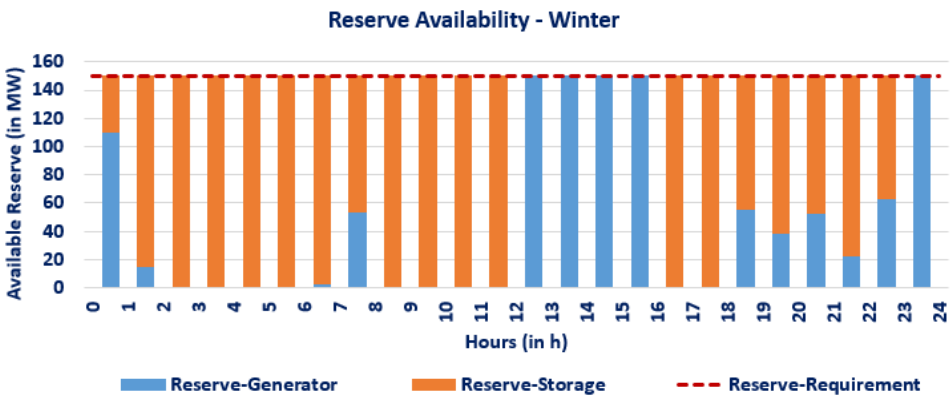

Figure 4.40 Reserve availability on a typical winter day when the 200 MW/800 MWh capacity BESS in the test system (with significant solar generation) provides peak shaving, frequency regulation, and spinning reserve support.

Table 4.6 and Table 4.7 show the savings made in US $ with the BESS of power capacity of 200 MW and energy capacity of 800 MWh delivering various primary/ancillary services in the Arizona-based test system (with significant solar generation) on a typical summer and winter day. With the BESS delivering only peak shaving service in the Arizona-based test system on a typical summer day, a daily savings of $9,785 is obtained due to a reduced system operation cost. But then, with the same capacity BESS providing additional frequency regulation service, the daily savings made on a summer day increases to $20,348. When the BESS delivers peak shaving, frequency regulation, and spinning reserve support services, the daily summer savings obtained escalates to $24,330. Hence, with the multiple services stacked, the value that the 200 MW/800 MWh capacity BESS can generate increases significantly. Also, similar observations are made for a winter day with the same capacity BESS providing various power system services in the Arizona-based test system (with significant solar generation). Table 4.8 through Table 4.10 list the annual savings and BESS NPV useful life savings for BESSs of various power and energy capacities for different BESS usage scenarios in the test system with significant solar penetration.

Table 4.6 Stacked savings on a typical summer day in the Arizona-based test system with significant solar generation.

Scenario	Operation cost ($)	Savings ($)
Without the BESS	$1,941,404	$0
With the BESS providing peak shaving	$1,931,619	$9,785
With the BESS providing peak shaving and freq. regulation	$1,921,056	$20,348
With the BESS providing peak shaving, freq. regulation, and reserve support	$1,917,074	$24,330

Table 4.7 Stacked savings on a typical winter day in the Arizona-based test system with significant solar generation.

Scenario	Operation cost ($)	Savings ($)
Without the BESS	$1,069,578	$0
With the BESS providing peak shaving	$1,061,644	$7,935
With the BESS providing peak shaving and freq. regulation	$1,059,872	$9,706
With the BESS providing peak shaving, freq. regulation, and reserve support	$1,056,808	$12,771

Table 4.8 Annual savings and BESS useful life savings when BESS in the test system (with significant solar penetration) provides peak shaving service.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	.75	6.69
50	100	1.08	9.69
50	150	1.19	10.61
50	200	1.26	11.29
50	250	1.34	11.96
100	100	1.16	10.42
100	200	1.63	14.58
100	300	1.88	16.79
100	400	2.04	18.25
100	500	2.21	19.74
150	150	1.52	13.61
150	300	1.94	17.32
150	450	2.24	20.06
150	600	2.63	23.53
150	750	2.85	25.54
200	200	1.69	15.08
200	400	2.35	21.07
200	600	2.88	25.75
200	800	3.19	28.54
200	1000	3.42	30.60

Table 4.9 Annual savings and BESS useful life savings when BESS in the test system (with significant solar penetration) provides peak shaving and frequency regulation.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	2.93	26.20
50	100	3.07	27.48
50	150	3.10	27.78
50	200	3.13	28.02
50	250	3.15	28.16
100	100	3.58	32.01
100	200	3.94	35.24
100	300	4.12	36.83
100	400	4.25	37.99
100	500	4.39	39.30
150	150	3.93	35.18
150	300	4.38	39.19
150	450	4.62	41.34
150	600	4.86	43.45
150	750	5.05	45.17
200	200	4.09	36.57
200	400	4.75	42.50
200	600	5.08	45.47
200	800	5.41	48.40
200	1000	5.70	50.97

Table 4.10 Annual savings and BESS useful life savings when BESS in the test system (with significant solar penetration) provides peak shaving, frequency regulation, and spinning reserve support.

Power Capacity (MW)	Energy Capacity (MWh)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
50	50	3.11	27.82
50	100	3.15	28.16
50	150	3.18	28.45
50	200	3.20	28.63
50	250	3.20	28.63
100	100	4.38	39.16
100	200	4.64	41.51
100	300	4.70	42.04
100	400	4.76	42.55
100	500	4.81	43.06
150	150	5.08	45.45
150	300	5.56	49.70
150	450	5.64	50.46
150	600	5.73	51.22
150	750	5.81	51.98
200	200	5.59	50.04
200	400	6.41	57.38
200	600	6.56	58.73
200	800	6.68	59.75
200	1000	6.79	60.76

Finally, Figure 4.41 through Figure 4.46 show the effect of BESS energy capacity on daily savings for a BESS of power capacity of 200 MW. As observed previously, the marginal contribution of BESS reduces with increasing BESS energy capacity.

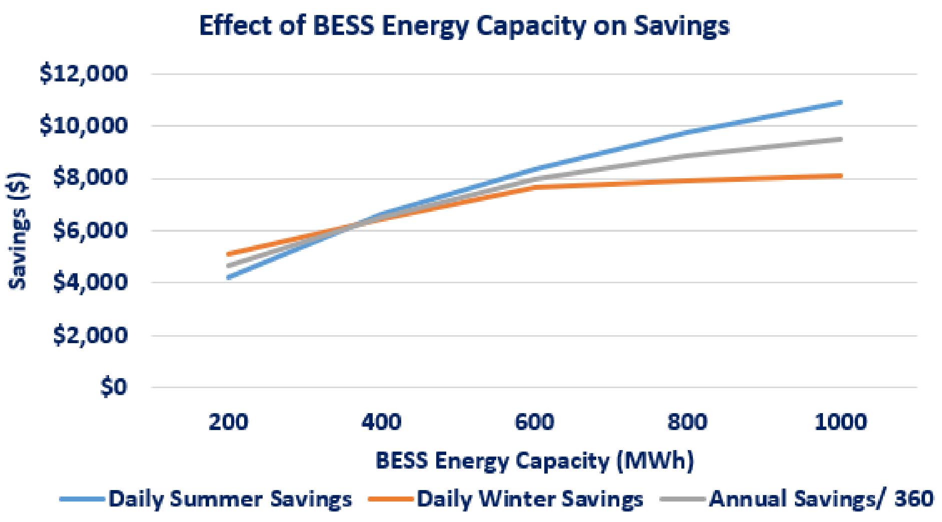

Figure 4.41 Daily savings with energy capacity for a 200 MW BESS when it provides peak shaving in the Arizona-based test system with significant solar generation.

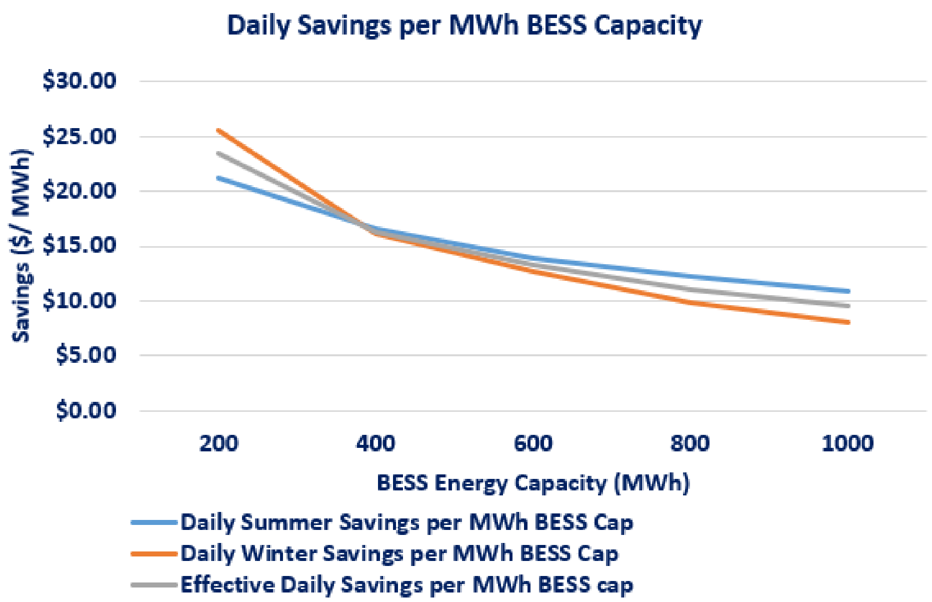

Figure 4.42 Daily savings per MWh of BESS energy capacity when it provides peak shaving in the Arizona-based test system with significant solar generation.

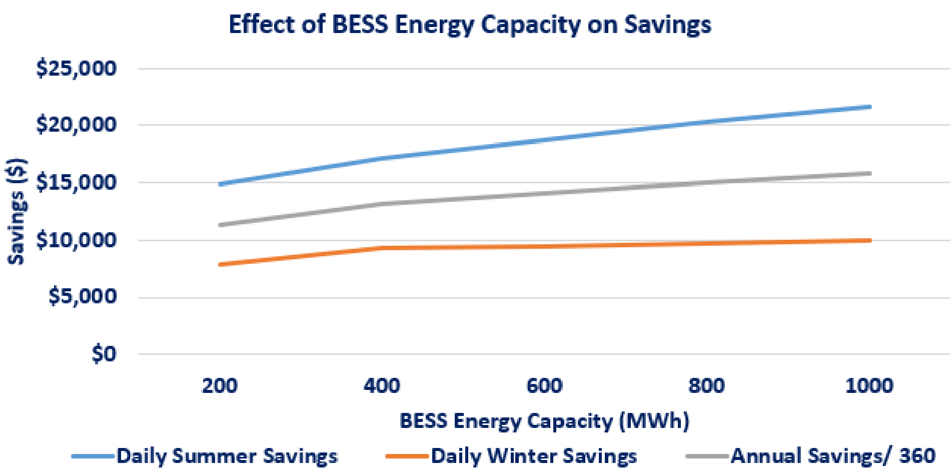

Figure 4.43 Daily savings with energy capacity for a 200 MW BESS when it provides peak shaving and frequency regulation in the Arizona-based test system with significant solar generation.

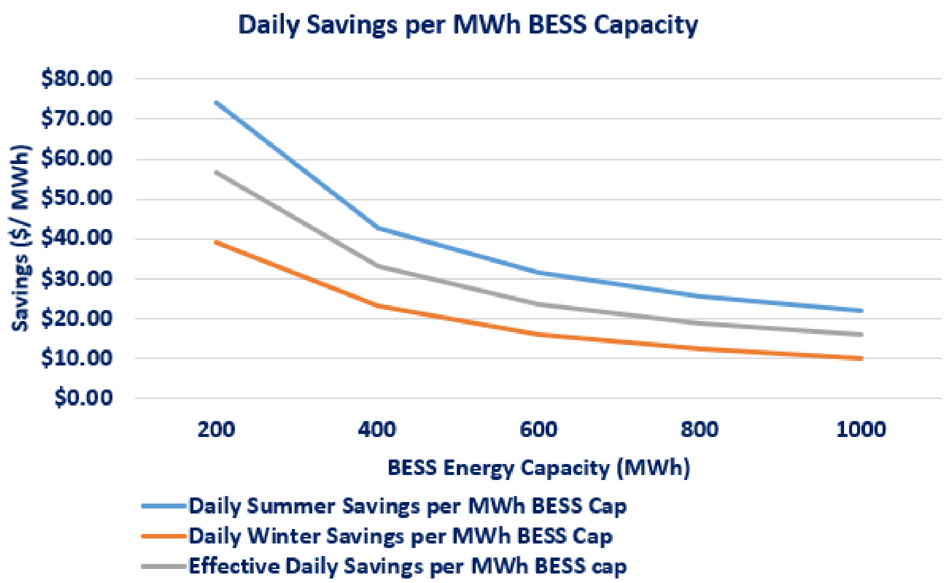

Figure 4.44 Daily savings per MWh of BESS energy capacity when it provides peak shaving and frequency regulation in the Arizona-based test system with significant solar generation.

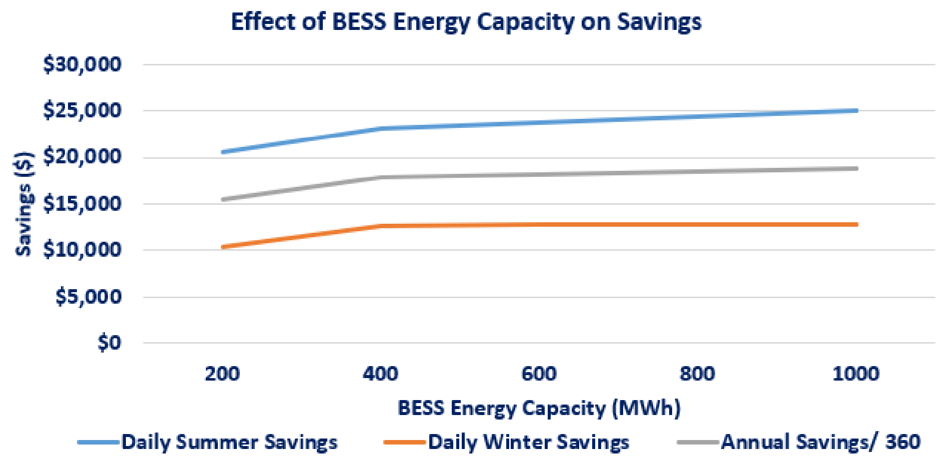

Figure 4.45 Daily savings with energy capacity for a 200 MW BESS when it provides peak shaving, frequency regulation and spinning reserve support in Arizona-based test system with significant solar generation.

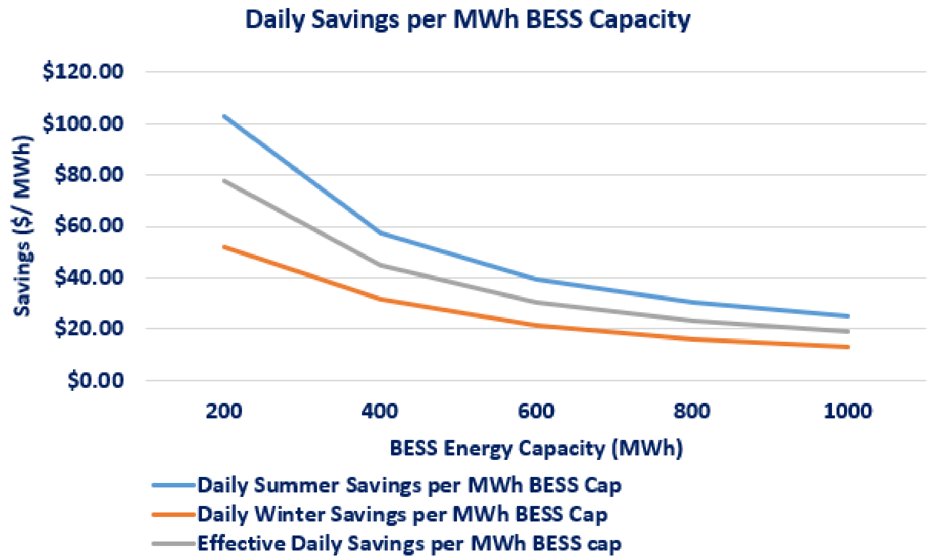

Figure 4.46 Daily savings per MWh of BESS energy capacity when it provides peak shaving, frequency regulation and spinning reserve support in the Arizona-based test system with significant solar generation.

4.4 Stacked savings calculation assuming forced outage rate (FOR) of generator units

Here, we have estimated the additional savings from BESS usage for peak shaving, frequency regulation and spinning reserve support services when the occasional unavailability of generator units in the Arizona-based test system is accounted for by considering generator FOR information (FOR assumptions are discussed in Chapter 3 section 3.1) in the optimization formulation under the following two test system cases: (a) without solar generation (b) with significant solar generation. A BESS of power capacity of 200 MW and energy capacity of 800 MWh is assumed for this task and the results obtained are presented below.

Table 4.11 and Table 4.12 are COPTs for the Arizona-based test system under 'without BESS and without solar generation' scenario during summer and winter days. These tables list the probabilities of units in the test system experiencing outages and the system operation costs during those outage scenarios. For example, during summer days in the Arizona-based test system without BESS and solar generation, the probability of generator unit indexed 5 of the Peaker CT type experiencing outage is 0.01717 and the system operation cost under such outage scenario is $2,158,844 as mentioned in Table 4.11. Then, using equation (3.48), effective operation costs during summer and winter days under 'without BESS and without solar generation' scenario are found to be $2,173,310 and $1,164,848, respectively.

Similarly, Table 4.13 and Table 4.14 are COPTs for the Arizona-based test system under 'with BESS and without solar generation' scenario during summer and winter days. Using equation (3.49), effective operation costs during summer and winter days for 'with BESS and without solar generation' scenario are found to be $2,143,280 and $1,152,455, respectively. Comparing effective operation costs for both the above scenarios, effective daily summer and winter savings obtained are $30,030 and $12,393, respectively.

Table 4.11 COPT for the Arizona-based test system during summer days for 'without BESS and without solar generation' scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$2,158,844
Peaker CTs	1-6	0.01717	$2,158,844
Steam	7-9	0.01717	$2,158,844
Aero CTs	10-21	0.01717	$2,161,680
Legacy Comb Cycle	22-25	0.01717	$2,163,848
1 on 1 Combined Cycle	36-37	0.01717	$2,192,540
2 on 1 Combined Cycle	38-41	0.01717	$2,230,415
Hydro	42-46	0.01717	$2,188,078
Coal	47-51	0.01717	$2,216,596
Effective Operation Cost ($)			$2,173,310

Table 4.12 COPT for the Arizona-based test system during winter days for 'without BESS and without solar generation' scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,161,352
Peaker CTs	1-6	0.01717	$1,161,352
Steam	7-9	0.01717	$1,161,352
Aero CTs	10-21	0.01717	$1,161,352
Legacy Comb Cycle	22-25	0.01717	$1,161,352
1 on 1 Combined Cycle	36-37	0.01717	$1,163,191
2 on 1 Combined Cycle	38-41	0.01717	$1,161,352
Hydro	42-46	0.01717	$1,186,405
Coal	47-51	0.01717	$1,176,291
Effective Operation Cost ($)			$1,164,848

Table 4.13 COPT for the Arizona-based test system during summer days for 'with BESS and without solar generation' scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$2,131,848
Peaker CTs	1-6	0.01717	$2,131,848
Steam	7-9	0.01717	$2,131,848
Aero CTs	10-21	0.01717	$2,132,794
Legacy Comb Cycle	22-25	0.01717	$2,131,848
1 on 1 Combined Cycle	36-37	0.01717	$2,154,882
2 on 1 Combined Cycle	38-41	0.01717	$2,193,547
Hydro	42-46	0.01717	$2,159,391
Coal	47-51	0.01717	$2,176,641
Effective Operation Cost ($)			$2,143,280

Table 4.14 COPT for the Arizona-based test system during winter days for ‘with BESS and without solar generation’ scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,149,545
Peaker CTs	1-6	0.01717	$1,149,545
Steam	7-9	0.01717	$1,149,545
Aero CTs	10-21	0.01717	$1,149,545
Legacy Comb Cycle	22-25	0.01717	$1,149,545
1 on 1 Combined Cycle	36-37	0.01717	$1,151,638
2 on 1 Combined Cycle	38-41	0.01717	$1,149,545
Hydro	42-46	0.01717	$1,172,810
Coal	47-51	0.01717	$1,159,344
Effective Operation Cost ($)			$1,152,455

Table 4.15 and Table 4.16 are COPTs for the Arizona-based test system under ‘without BESS and with solar generation’ scenario during summer and winter days. Effective operation costs during summer and winter days for ‘without BESS and with solar generation’ scenario are found to be $1,950,557 and $1,073,049, respectively. Similarly, Table 4.17 and Table 4.18 are COPTs for the Arizona-based test system under ‘with BESS and with solar generation’ scenario during summer and winter days. Effective operation costs during summer and winter days for ‘with BESS and with solar generation’ scenario are found to be $1,925,338 and $1,059,789, respectively. For the Arizona-based test system scenario with significant solar generation, effective daily summer and winter savings obtained are $25,219 and $13,260 respectively.

Table 4.15 COPT for the Arizona-based test system during summer days for ‘without BESS and with solar generation’ scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,941,404
Peaker CTs	1-6	0.01717	$1,941,404
Steam	7-9	0.01717	$1,941,404
Aero CTs	10-21	0.01717	$1,941,855
Legacy Comb Cycle	22-25	0.01717	$1,941,404
1 on 1 Combined Cycle	36-37	0.01717	$1,961,002
2 on 1 Combined Cycle	38-41	0.01717	$1,984,594
Hydro	42-46	0.01717	$1,966,867
Coal	47-51	0.01717	$1,979,105
Effective Operation Cost ($)			$1,950,557

Table 4.16 COPT for the Arizona-based test system during winter days for ‘without BESS and with solar generation’ scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,069,578
Peaker CTs	1-6	0.01717	$1,069,578
Steam	7-9	0.01717	$1,069,578
Aero CTs	10-21	0.01717	$1,069,578
Legacy Comb Cycle	22-25	0.01717	$1,069,578
1 on 1 Combined Cycle	36-37	0.01717	$1,073,600
2 on 1 Combined Cycle	38-41	0.01717	$1,069,578
Hydro	42-46	0.01717	$1,092,865
Coal	47-51	0.01717	$1,085,116
Effective Operation Cost ($)			$1,073,049

Table 4.17 COPT for the Arizona-based test system during summer days for 'with BESS and with solar generation' scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,917,074
Peaker CTs	1-6	0.01717	$1,917,074
Steam	7-9	0.01717	$1,917,074
Aero CTs	10-21	0.01717	$1,917,074
Legacy Comb Cycle	22-25	0.01717	$1,917,074
1 on 1 Combined Cycle	36-37	0.01717	$1,933,509
2 on 1 Combined Cycle	38-41	0.01717	$1,953,551
Hydro	42-46	0.01717	$1,942,856
Coal	47-51	0.01717	$1,951,806
Effective Operation Cost ($)			$1,925,338

Table 4.18 COPT for the Arizona-based test system during winter days for 'with BESS and with solar generation' scenario.

Unit Experiencing Outage		Normalized Individual Probability	Operation Cost ($)
No unit		0.29614	$1,056,808
Peaker CTs	1-6	0.01717	$1,056,808
Steam	7-9	0.01717	$1,056,808
Aero CTs	10-21	0.01717	$1,056,808
Legacy Comb Cycle	22-25	0.01717	$1,056,808
1 on 1 Combined Cycle	36-37	0.01717	$1,057,349
2 on 1 Combined Cycle	38-41	0.01717	$1,056,808
Hydro	42-46	0.01717	$1,080,568
Coal	47-51	0.01717	$1,067,562
Effective Operation Cost ($)			$1,059,789

After finding the effective daily summer and winter savings, annual and BESS useful life savings can be calculated for both 'without solar generation' and 'with significant solar generation' scenarios. Table 4.19 show the annual and BESS useful life savings obtained for 'without solar generation' and 'with significant solar generation' scenarios when considering the generator FOR in the optimization formulation.

Table 4.19 Effective annual and BESS useful life savings for 'without solar generation' and 'with significant solar generation' scenarios considering generator FOR.

Scenarios	Summer day savings ($)	Winter day savings ($)	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
Without solar generation	$30,030	$12,393	7.63	68.32
With significant solar generation	$25,219	$13,260	6.92	61.96

Table 4.20 lists the stacked annual and BESS useful life savings for the 'without solar generation' and the 'with significant solar generation' scenarios with BESS in the test system providing peak shaving, frequency regulation and spinning reserve support services for the following two cases (a) without considering FOR of generator units (b) assuming FOR of generator units. As can be observed, by considering the FOR of generator units, we add additional value of around $ 6 million to the BESS useful life savings for the 'without solar generation' scenario while the value added under 'with significant solar generation' scenario is about $ 2 million.

Table 4.20 Comparison of stacked savings between 'without FOR' and 'with FOR' cases.

Scenarios		Annual Savings (Million $)	BESS Useful Life Savings (Million $)
Without solar generation	Without FOR	6.98	62.49
	With FOR	7.63	68.32
With significant solar generation	Without FOR	6.67	59.75
	With FOR	6.92	61.96

5 CONCLUSION

The objective of this work was to investigate the economic effect of a BESS on power system operation as the BESS provided the following services: peak shaving, frequency regulation, and spinning reserve support. This was performed on a simplified representative system model of SRP's system – the so-called Arizona-based test system. A MILP based optimization model was used to determine the savings as the BESS in the test system rendered several primary/secondary services mentioned above. Table 5.1 summarizes the net present value of the savings obtained with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system (without solar generation) for various power system scenarios. Table 5.2 shows the net present value of the stacked savings obtained with the use of the same capacity BESS in the Arizona-based test system with significant solar generation.

The obtained results suggested that a BESS operated to provide a package of services has significantly more value than the same capacity BESS delivering a single service in isolation. It was also observed that the marginal contribution of BESS reduces with increasing BESS energy capacity.

Table 5.1 Savings with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system without solar generation.

Power System Scenarios	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
Without BESS	0	0
With BESS providing peak shaving	3.17	28.38
With BESS providing peak shaving and freq. regulation	5.68	50.85
With BESS providing peak shaving, freq. regulation and spinning reserve support	6.98	62.49
With BESS providing peak shaving, freq. regulation and spinning reserve support (generator FOR assumed)	7.63	68.32

Table 5.2 Savings with the use of a 200 MW/800 MWh capacity BESS in the Arizona-based test system with solar generation.

Power System Scenarios	Annual Savings (Million $)	BESS Useful Life Savings (Million $)
Without BESS	0	0
With BESS providing peak shaving	3.19	28.54
With BESS providing peak shaving and freq. regulation	5.41	48.40
With BESS providing peak shaving, freq. regulation and spinning reserve support	6.68	59.75
With BESS providing peak shaving, freq. regulation and spinning reserve support (generator FOR assumed)	6.92	61.96

6 FUTURE WORK

This work clearly illustrated that the net present value of a BESS can vary considerably based on the number of services it is providing. Hence, it is important to identify multiple value streams/services that are technically and operationally compatible with appropriate commercial prioritization and temporal alignment [43].

In this study, the economic value of a BESS providing various electric system services was established on a simple single bus power system. A subsequent study with a multi-bus power system can be carried out which will have more practical relevance.

Also, what remains to be determined next is where to deploy the BESS in the power grid to maximize the net value. This work done with a comparatively simpler dispatch model does not address that. However, the approach/methodology adopted in this work will be somewhat similar for the study trying to identify the optimal placement location of BESS in a power grid.

In [26], the economic analysis of a Li-ion BESS rendering frequency regulation service in a renewable resource-rich power system showed that a BESS, delivering regulation service with its energy-shifting and fast-ramping capabilities, yielded substantial savings on the system operation cost. A finer-grained time domain approach that can accurately capture the frequency regulation benefits of a BESS we believe is warranted.

Finally, a more sophisticated battery charger model may put a finer point on the value calculated here. Batteries charge at different rates based on their present SoC and this nonlinear charging capability could be included if a finer-time-step model were to be implemented.

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