Techno-Economic and System-Level Evaluation of PV-Integrated Energy Storage Systems for High Renewable Penetration Grids

AHMED G. ABO-KHALIL[1], ABDEL-RAHMAN AL QAWASMI[2,*]
[1]Sustainable and Renewable Energy Engineering Department,
College of Engineering,
University of Sharjah,
UAE

[2]Department of Electrical and Computer Engineering,
College of Engineering,
Dhofar University,
P.O. Box 1, Salalah 211,
SULTANATE OF OMAN

*Corresponding Author

Abstract: - Energy Storage Systems (ESS) are increasingly recognized as critical enablers of grid flexibility in power systems with high renewable energy penetration. This study presents a comprehensive techno-economic and system-level evaluation of a photovoltaic (PV)-integrated ESS operating under grid-connected and emergency modes. Unlike prior studies that focus primarily on conceptual or policy perspectives, this work integrates operational modeling, economic feasibility analysis, and national-level storage sizing considerations within a unified framework. At the project level, a 5 MW / 20 MWh commercial-scale ESS operating under time-of-use (TOU) pricing was evaluated. An arbitrage-only operation yielded an internal rate of return (IRR) of 7–9% and a payback period of approximately 10–11 years, indicating marginal yet feasible profitability under current tariff spreads. When multi-service revenue stacking—incorporating frequency regulation, reserve provision, and peak shaving—was applied, IRR improved to 11–14%, and the payback period decreased to 7–8 years. Sensitivity analysis confirmed that a 30% reduction in battery capital costs is the dominant factor affecting economic viability, with an IRR above 15%. Operationally, annual simulations of the PV–ESS system demonstrated a round-trip efficiency of approximately 87%, a 20% reduction in peak demand, and emergency autonomy exceeding the required 2-hour duration.

Key-Words: - Energy Storage System (ESS), Photovoltaic (PV) Integration, Grid-Connected Operation, Peak Shaving, Battery Energy Management, Renewable Energy Integration, Load Management.

Received: March 7, 2026. Revised: May 8, 2026. Accepted: June 11, 2026. Published: September 7, 2026.

1 Introduction

Energy storage technology is currently being commercialized in various ways, and technological development is also actively underway. Demonstration projects for already developed technologies are also actively being pursued. An energy storage system (ESS) is a system or device that stores generated energy and supplies it when needed. ESS is expected to be an effective means of establishing a stable and efficient energy supply and demand system, and has tremendous market potential. It has recently attracted attention as a new growth engine, [1]. Major advanced countries are already supporting technological development to expand ESS, while also promoting ESS demonstration projects funded by government budgets, providing subsidies, tax breaks, and mandating them. Companies are also actively interested in the ESS market, which is expected to yield tangible results. Domestically and internationally, peak electricity demand is growing faster than consumption, and seasonal and time-of-day demand is also expanding. With the rise of renewable energy sources with high output variability, the need for electricity storage is growing. A variety of electricity storage technologies are being developed, extending beyond conventional pumped storage systems, and some are undergoing demonstrations and entering initial deployment, [2]. Recently, demonstration projects for various storage technologies have been launched in the international energy storage system market, producing tangible results. Advances in battery technology, including increased capacity and improved performance, have made it possible to meet these demands to a certain degree, making this field particularly noteworthy. In particular, the potential for energy storage systems utilizing lithium batteries, whose prices have recently fallen significantly, is anticipated, [3].

To promote the widespread adoption of energy storage systems, ensuring economic feasibility is crucial for consumers, who are the primary drivers of installation, investment, and operation. When deciding whether to invest in energy storage systems, it is crucial to estimate the benefits associated with the project's investment plan (cost) and determine whether the project is economically viable. When conducting an economic feasibility analysis, it is crucial to first determine from whose perspective the analysis will be conducted, [4]. Even if an energy storage system investment project is economically viable nationally, market adoption is impossible without economic viability from the consumer perspective. Therefore, ensuring economic feasibility from the consumer perspective is crucial for the widespread adoption of energy storage systems. If the operational benefits (energy cost savings) of an energy storage system are not sufficient to offset the investment costs, consumers will not actively consider adopting an energy storage system. If market adoption is hindered, the transition to mass production of energy storage systems will be delayed, making it difficult to anticipate a rapid decline in installation costs, [5]. In parallel, research on solar-thermal technologies has emphasized advanced heat-transfer fluids for parabolic trough collectors, [6]. At the policy level, a certain level of financial support and legal and institutional supplementation are necessary to support this initiative. To achieve this, a consumer-facing economic analysis and sensitivity analysis of changes in key factors affecting economic feasibility are prioritized. The economic feasibility of energy storage systems, a prerequisite for the active market penetration of demand-side managed energy storage systems, is assessed from the perspective of consumer benefits, based on the current time-of-use rate system. Even if the initial market is formed through government subsidies and pilot projects, market vitality ultimately depends on consumers' willingness to invest. It is deemed urgent to assess the appropriate price level in the current environment, [7]. While various storage technologies are being commercially developed, this study focuses on secondary battery-based energy storage systems, which are close to market penetration in terms of economic feasibility and technology, including the characteristics and price of the current time-of-use rate system. Consumer benefits are calculated using an optimal charge/discharge scheduling model for energy storage systems designed to minimize electricity costs. Annual investment costs are divided by the social discount rate to convert them to present value in the base year. Expected benefits are also estimated by year, divided by the social discount rate, and converted to present value in the base year.

Economic feasibility is verified by comparing the benefits converted to present value with the costs converted to present value using the same standard. Payback, net present value (NPV), internal rate of return (IRR), and cost/benefit (B/C) analysis are widely used methods for verifying economic feasibility. This study applies a structured techno-economic framework combining cost–benefit analysis, discounted cash flow modeling, and sensitivity analysis. Economic feasibility was evaluated by considering key parameters including initial capital cost, annual operation and maintenance expenses, time-of-use (TOU) rate structures, annual discharge hours, and applicable discount rates. Because energy storage projects operate over multi-year horizons, expected lifetime costs and benefits were assessed using net present value (NPV) and internal rate of return (IRR) metrics, [8].

Sensitivity analysis was conducted to evaluate the relative influence of installation cost reductions and tariff structure adjustments on project viability. Results indicate that capital expenditure remains the dominant determinant of profitability. A 20–30% reduction in installation cost significantly improves IRR and shortens payback periods, while enhanced revenue streams through extended peak-hour pricing or demand-side management (DSM)-based tariffs further strengthen economic returns. The findings confirm that both cost declines and optimized rate design are critical to accelerating ESS deployment.

This study presents a unified techno-economic and system-level framework for evaluating photovoltaic (PV)-integrated energy storage systems (ESS) under high renewable energy penetration, with specific application to the UAE power system. Unlike conventional studies that treat economic analysis, operational modeling, or grid-level planning as separate problems, this work integrates these dimensions into a single coherent methodology that links project-scale performance with national-scale system requirements. The novelty of this research lies in three key aspects. First, the study combines detailed operational simulation of a PV–ESS system, including state-of-charge management, peak shaving, emergency supply capability, and round-trip efficiency, with a comprehensive techno-economic assessment based on time-of-use pricing and multi-service revenue stacking. Second, the work extends beyond typical project-level evaluations by quantifying the role of ESS in addressing large-scale grid challenges associated with high solar penetration, particularly the Duck Curve phenomenon, through explicit modeling of midday curtailment, evening ramping requirements, and reserve capacity contributions. Third, the study provides a UAE-specific system-level sizing methodology that estimates the required ESS capacity (on the order of 15 GW and 45–50 GWh) to ensure supply–demand balance, reduce renewable curtailment, and enhance grid stability under projected 2030 conditions. By bridging operational, economic, and system planning perspectives within a unified framework, this work offers a more comprehensive and practically relevant contribution compared to prior studies, including the authors' earlier publications, which addressed these aspects individually rather than in an integrated manner.

2 Energy Storage System Concept

Modern society is facing security challenges in power supply and demand, driven by rapid economic growth, rising incomes, and improved standards of living, leading to rapidly increasing power consumption. Furthermore, regulations on greenhouse gas emissions, which contribute to and exacerbate global warming, have highlighted carbon emissions as a key issue. Consequently, the installation of renewable energy sources such as solar and wind power is expanding, driven by the government's renewable portfolio standard (RPS) mandate, to establish trading systems and alternative solutions. The spread of renewable energy has partially resolved the problem of rapidly increasing power consumption and greenhouse gas emissions, [9]. However, due to the characteristics of renewable energy, such as the phenomenon of power generation being concentrated at certain times and the significant fluctuation of output due to external environments, many difficulties are encountered in planning and operating them, resulting in system instability. To solve the problem of imbalance in power supply and demand, ESS is receiving a lot of attention. In conjunction with various government policies such as assigning Renewable Energy Certificate (REC) weighting when installing ESS in renewable energy power plants such as solar and wind power, mandating ESS installation in public buildings, and using emergency power sources, the number of ESS projects has rapidly increased over the past 3-4 years. Various renewable energy markets utilizing ESS are being revitalized, and the ESS market is expected to bloom and lead to corporate profitability. Figure 1 (Appendix) illustrates the concept of ESS, [10].

Table 1 (Appendix) summarizes the main purposes, functions, and expected benefits of ESS across generation, load, renewable support, and power quality categories.

ESS stores generated power and supplies it when it's most needed, increasing energy efficiency. It enables storage across the power generation, transmission, and distribution stages, as well as at the consumer level. Consequently, by efficiently utilizing power through ESS, the power supply system has shifted from a focus on supply facilities to a focus on demand management. ESS has transformed the unidirectional power flow into a two-way flow, enabling active consumer participation in the market. As the scope of ESS utilization has diversified, it has been categorized into sub-segments within the power generation, transmission, and distribution sectors, based on customer and application, [11]. Figure 2 (Appendix) illustrates the application areas of ESS. In the power generation sector, ESS is subdivided into load leveling for existing large-scale power plants and integrated renewable energy generation. In the transmission and distribution sector, ESS is used for reserve capacity, grid load balancing, and frequency regulation to provide spare capacity to respond to peak demand and fluctuations in power generation. At the consumer end, market requirements vary, with applications such as energy storage for peak demand response, renewable energy generation storage, and seamless power output response during power outages. ESS can be used for various purposes, such as long-term and short-term storage of electricity, and can be categorized into power generation resources, load resources, renewable energy support, and power quality depending on their function. As a power generation resource, ESS can be used for power supply, power reserves, frequency regulation services (governor-free control; GFC, automatic generation control; AGC), and system marginal pricing (SMP). As a load resource, it can be used for transmission congestion reduction, demand management capacity bidding, time-of-use (TOU) demand response, and uninterruptible power supply (UPS), [12].

Energy storage systems (ESS) utilize various forms of energy, such as chemical, kinetic, and potential energy, to store energy for ultimate conversion into electricity. The scope of energy storage technology varies depending on storage capacity and options for short- and long-term operation cycles. Large-scale storage devices have capacities ranging from tens to hundreds of megawatts (MW) and can store energy for several hours per day. Conversely, small-scale distribution storage devices, located at transmission and distribution points and directly connected to power consumers, have capacities in the kilowatt range and can store energy for minutes, [13]. ESS offers diverse applications, ranging from improving power quality to energy management. These applications include demand management (DM) applications for power supply, such as load management; grid operation auxiliary service applications that improve power quality and efficiency; renewable energy applications required for integrating renewable energy systems; and distributed energy storage applications. To manage peak loads in the power system, demand management applications store idle power during light loads and utilize stored power during overloads, enabling load management. Integrating energy storage systems with the grid can create utility benefits such as increased system capacity, securing transmission reserves, and power arbitrage. In other words, energy storage technology enhances the balance between power supply and demand, price competitiveness, and energy efficiency. By securing reserves, it enables an effective response to peak power and large-scale power outages, [14].

System operation support services maintain power system frequency by adjusting power supply in response to fluctuations in supply and demand of less than a few minutes, ensuring reliability and power quality. These services include frequency regulation, reserve power, and voltage regulation. It is expected that most energy storage systems will play a key role in providing system operation support services in the future. An imbalance in power supply and demand can lead to frequency fluctuations, disrupting power quality, and these frequency fluctuations can be felt throughout the power system, [15]. Therefore, to prevent frequency degradation, there are two types of operation: governor-free operation, which automatically adjusts generator output in response to frequency fluctuations, and automatic generation control (AGC) operation, which remotely adjusts generator output from an EMS installed in the central power control center. To address imbalances in power supply and demand, the operation service provides operational power reserves (standby reserves) that can be utilized within 10 minutes and non-operational reserves (alternative reserves) that can be utilized within 120 minutes. The system operation support service secures reserves to balance power supply and demand and provides a rapid response to system contingencies, such as power facility failures or generator outages. Voltage regulation is closely related to the supply of reactive power and occurs locally. Long-distance transmission is impossible, and maintenance of the grid reference voltage is required at the point of reactive power consumption, [16].

ESS is an effective tool for establishing a stable and efficient energy supply and demand system, and its enormous market potential is expected to attract attention as a new growth engine. Major advanced countries are supporting technology development and promoting demonstration projects funded by government budgets to expand the ESS market. They are also promoting widespread adoption through subsidies, tax breaks, and mandates. The global ESS market is still in its infancy, with demonstration and pilot projects underway. These demonstration projects are confirming technological reliability and gradually producing tangible results, [17].

Table 2 (Appendix) presents the industry trends of the key ESS components, namely the battery, the power conditioning system (PCS), and the system integrator (SI).

3 The Role of ESS

ESS plays a variety of roles in the power grid. Broadly speaking, it serves three purposes. First, it provides power stability (i.e., frequency regulation). Changes in voltage or frequency within the power system can cause problems with power equipment. For example, if a power system operating at 120 Hz experiences a voltage fluctuation that drops it to 60 Hz, the power equipment in use may not function. ESS provides power system stability through frequency and voltage regulation. Second, it provides grid support. Power is produced and designed based on peak demand. Using ESS can help distribute peak demand. By distributing total demand through ESS, the burden on the power system is reduced. Without ESS, power systems would have to be designed based on temporary peak demand periods, which would increase costs as power demand increases, [18]. The widespread adoption of electric vehicles is particularly likely to lead to a surge in power demand in the early evening. This would require the installation of a power grid based on final demand, which could increase costs. Third, it serves as an emergency power source. It can be used for emergency purposes during times when the power supply is unavailable. While temporary power outages are rare in UAE, temporary power outages at data centers, telecommunications companies, etc., can have catastrophic consequences, making the installation of emergency backup power sources essential. Until now, thermal power generation has accounted for a large portion of overall power generation, so ESS has primarily served as a backup power source. However, as the share of renewable energy increases, the roles of the first and second sectors are expected to gradually expand. Because renewable energy cannot control its power generation, its design capacity is likely to be higher than that of existing thermal power plants, [19].

The functional application areas of ESS are summarized in Table 3 (Appendix).

3.1 Power Stability Grid – Peak-Speed Generation

Electric power generation is broadly divided into base-load and peak-load generation. Base-load generation, as its name suggests, serves as the foundation for power generation. Peak-load generation is power production that increases in response to rising demand. Specifically, it refers to rapid generation during periods of temporary surges in demand. Base-load generation primarily uses energy sources with low unit power costs, while peak-load generation relies on sources capable of rapid power generation over a short period, rather than focusing on unit costs. LNG or pumped storage power generation has been the primary energy source for peak-load generation due to its ability to quickly respond to rising power demand. Figure 3 illustrates the distinction between base-load and peak-load generation over a daily demand cycle.

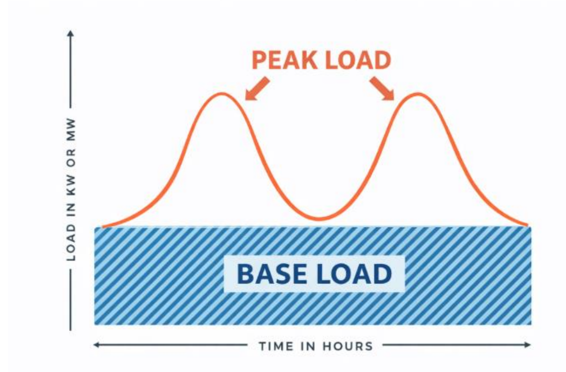

Fig. 3: Base load and peak load.
Source: Created by the authors.

Pumped storage power generation is ideal for peak-load generation, storing water during periods of high energy production and releasing it when needed, [20].

However, due to the need to consider regional characteristics, natural gas has been the primary choice in most regions. Natural gas not only has the advantage of lower carbon emissions than conventional thermal power generation but also offers the shortest operating times among power sources.

The continued increase in natural gas consumption was expected because rising production of renewable energy sources has led to greater power instability, and its role in compensating for this has been highlighted. Considering economic feasibility and carbon emissions, natural gas power generation was considered the most realistic option, [21]. Table 4 (Appendix) compares the start-up time, ramp rate, and generation cost characteristics of the main power generation types.

3.2 Advantages of ESS as a Peak Power Generation System

Natural gas has primarily been used for city gas and power generation. Developed countries are aiming for a gradual reduction in gas consumption. First, the sharp rise in natural gas prices following the Russian War highlighted the risks of external dependence on key resources. As the issue of external dependence on key resources became more prominent, countries sought to reduce consumption to reduce dependence, [22]. In response, active investment in offshore plants and renewable energy sources emerged in various regions. Second, despite offering various advantages, the unit price of lithium-ion battery-based BESS, once a cost barrier, has fallen with the widespread adoption of electric vehicles. Third, ESS can reduce grid loads, thereby reducing grid investment costs. Fourth, environmental concerns, such as extreme temperatures, have reached a point where they cannot be ignored, [23]. Figure 4 (Appendix) illustrates how ESS discharge during peak hours mitigates the system peak load.

3.3 Power Grid Support – Easing the Burden of Transmission and Distribution

ESS reduces the peak output of the transmission and distribution network by using stored energy during temporary power loads. For this purpose, the US has the NWAs system, and Europe has the VPL system. Furthermore, the farther away a power plant is from another power plant, the more high-voltage transmission lines are needed. Producing and storing power closer to demand can save on investment costs, [24]. Figure 5 (Appendix) illustrates the role of ESS in supporting the power grid by relieving the transmission and distribution burden. Table 5 lists the transmission and distribution loss rates in major countries.

Table 5. Transmission and Distribution Loss Rates in Major Countries.

Country	Loss Rate
Canada (19 years)	3.4% per year
Japan (17 years)	4.7% per year
United States (19 years)	5.1% per year
Italy (19 years)	5.6% per year
China (19 years)	5.9% per year
Germany (17 years)	6.8% per year
France (19 years)	7.7% per year
United Kingdom (19 years)	8.0% per year

Source: [24]

3.4 Mathematical Modeling and Optimization Framework

To provide a more rigorous analytical basis for the proposed photovoltaic (PV)-integrated energy storage system (ESS), this section presents a mathematical formulation that captures the interaction between load demand, renewable generation, and storage operation. The formulation is developed to support both operational analysis and techno-economic evaluation under grid-connected conditions.

The net load of the system represents the residual demand that must be supplied by dispatchable resources after accounting for PV generation and ESS operation. It is defined as

$$P_{net}(t) = P_{load}(t) - P_{PV}(t) - P_{ESS}(t) \quad (1)$$

where $P_{load}(t)$ is the system demand, $P_{PV}(t)$ is the photovoltaic generation, and $P_{ESS}(t)$ represents the ESS power, which is positive during discharge and negative during charging. This formulation enables explicit modeling of the role of ESS in reducing peak demand and mitigating renewable variability.

The dynamic behavior of the ESS is governed by the state-of-charge (SoC), which evolves over time according to the charging and discharging processes. The SoC is expressed as:

$$SOC(t+1) = SOC(t) + \eta_c P_{ch}(t)\Delta t - \frac{P_{dis}(t)\Delta t}{\eta_d} \quad (2)$$

where η_c and η_d denote the charging and discharging efficiencies, respectively, $P_{ch}(t)$ is the charging power, $P_{dis}(t)$ is the discharging power, and Δt is the time step. The operation of the ESS is constrained within predefined limits to ensure safe and reliable performance, such that

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (3)$$

and

$$0 \le P_{ch}(t) \le P_{ch}^{max}, \; 0 \le P_{dis}(t) \le P_{dis}^{max} \quad (4)$$

These constraints ensure that the ESS operates within its physical capacity and power rating limits.

To evaluate the economic performance of the system, the ESS operation can be formulated as an optimization problem that maximizes the net economic benefit over a given time horizon. The objective function is defined as

$$\max \sum_t [\lambda(t)P_{dis}(t) - \lambda(t)P_{ch}(t)] - C_{cap} - C_{O\&M} \quad (5)$$

where λ(t) represents the time-dependent electricity price, C_{cap} is the capital cost of the ESS, and $C_{O\&M}$ denotes the operational and maintenance costs. This formulation captures the economic value of energy arbitrage and multi-service operation within a unified framework.

From a system-level perspective, the ramp rate is a critical indicator of grid stability, particularly under high renewable penetration. The ramp rate of the net load is expressed as:

$$R(t) = \frac{P_{net}(t+\Delta t) - P_{net}}{\Delta t} \quad (6)$$

This metric quantifies the rate at which the system must respond to changes in net demand. By appropriately scheduling ESS charging and discharging, the ramp rate can be reduced, thereby alleviating stress on conventional generation units.

The required energy capacity of the ESS can be analytically related to its role in absorbing excess renewable generation and supporting peak demand periods. This can be expressed as:

$$E_{ESS} = \int_{t1}^{t2} P_{excess}(t)dt + \int_{t3}^{t4} P_{ramp}(t)dt \quad (7)$$

where the first term represents the energy required to absorb surplus generation during low-demand periods, and the second term corresponds to the energy needed to support demand during high ramp intervals. This formulation provides a direct link between operational requirements and storage sizing.

Finally, the round-trip efficiency of the ESS, which is a key performance indicator, is defined as:

$$\eta = \frac{E_{discharged}}{E_{charged}} \quad (8)$$

This relationship reflects the overall energy losses in the system and is essential for evaluating both technical and economic performance.

4 ESS Classification and Characteristics

Fossil fuels, currently used as a power generation fuel, are highly concentrated energy sources and are easy to store and transport. On the other hand, renewable energy sources, excluding biomass and hydropower, cannot be stored or transported to consumption sites without first being converted to electricity. Considering that electricity is the most versatile and highest-grade energy source in our daily lives, efforts to store renewable energy as electricity for use when needed may be natural, [25]. While electricity can be easily transported to remote locations via transmission lines and distributed to consumers via distribution lines, it faces the constraint that production and consumption must always be in sync. To address this, numerous monitoring and control systems are being installed and operated, and ESS is emerging as an alternative. An ESS is a device that charges energy for electricity production, converts it into electricity when discharge is deemed effective, and supplies electricity to the power grid. Such ESS can participate in the electricity market in various ways depending on the energy storage and discharge method, [26]. Here, the term "ESS" refers to all forms of energy storage devices that exchange external energy with electricity. ESS must exchange energy with the outside world through electrical energy (power), and the equipment required for this exchange is the Energy Conversion System (PCS), which accounts for more than 25% of the total energy storage system cost. Electricity is stored directly or indirectly through various methods, such as mechanical methods, such as pumped storage or compressed air, and chemical methods, such as batteries. The main characteristics are as follows, [27].

4.1 Pumped Storage Power Generation

This ESS uses water pumped from a lower reservoir to an upper reservoir to generate electricity when demand is high. When electricity demand is high, water drops from the upper reservoir to the lower reservoir, turning turbines to generate electricity. Power generation and pumping are accomplished by a single machine capable of pump-turbine conversion or by separate pumps and turbines. The conversion from generation to pumping occurs within minutes and can be repeated anywhere from once or twice a day to more than 40 times a day, depending on the installation location and intended use. The amount of energy that can be stored is proportional to the elevation difference between the upper and lower reservoirs and the water volume, [28]. Coordinated operation of floating PV plants with hydropower has also been investigated as an approach for integrating solar generation with reservoir-based power systems, [29]. There are 300 pumped storage systems in operation worldwide, and they are generally classified as 24-hour or multi-day operations. Because pumped storage systems have a relatively low energy density, they require large reservoir capacities and high water-level differences. Typically, a pumped storage power plant has a lifespan of 30 to 50 years, an efficiency of 65 to 75%, an investment cost of 500 to 1,500 Euros/kW, 10 to 20 Euros/kWh, and a fast response time (less than 1 minute), making it suitable for frequency control and as a reserve resource. On the other hand, a pumped storage power plant requires large upper and lower reservoirs, so it has topographical constraints and takes a long time to build (typically 10 years), [30]. It is a facility that converts surplus energy into electricity at the point of use and supplies electricity to the power grid. Such ESS can participate in the electricity market in various ways depending on the form of energy storage and discharge. Here, the ESS includes all forms of energy storage devices where external energy exchange is done in the form of electricity. ESS must exchange energy with the outside world through electrical energy (power). The equipment required for this exchange, known as the Power Conversion System (PCS), accounts for more than 25% of the total energy storage system cost. Electricity can be stored directly or indirectly through various methods, including mechanical methods like pumped-storage power generation or compressed air, and chemical methods like batteries. The key features of ESS are as follows, [31].

4.2 Compressed Air Storage

This ESS compresses air using electricity generated during off-peak or low-price periods and stores it in an air storage device. A special type of clutch is required to enable the turbine-generator to operate in both directions, i.e., for charging and discharging. Air storage can be achieved using aquifers, caves, or artificial spaces, with aquifer storage currently considered the most cost-effective. When charging, the generator acts as a motor, supplying the energy needed to compress air and send the compressed air to the storage device. When discharging, the compressed air is combusted with fuel, rotating a turbine to generate electricity. This device is currently operating in two locations worldwide (290 MW in Germany and 110 MW in the United States). Its energy density is 12 kWh/m3, its estimated efficiency is 70%, and its expected lifespan is approximately 40 years. The investment cost, depending on the underground air storage conditions, is approximately \$400-\$800/kW. Furthermore, its very low self-discharge rate is considered to enable long-term energy storage compared to pumped storage, making it suitable for applications requiring large-capacity power and energy storage in the power system, [32].

4.3 Battery. Lead-acid battery

Among batteries, it is the most mature and inexpensive technology. It uses lead for the cathode, lead dioxide (PbO_2) for the anode, and sulfuric acid for the electrolyte. The price is \$300~600/kWh, and the efficiency is 70~90%, but it has the disadvantages of deteriorating performance at low and high temperatures, a relatively short lifespan, and low power and energy density. B. Nickel-based battery, commonly called a Ni-Cd battery, uses cadmium hydroxide for the cathode, nickel cadmium for the anode, and potassium for the electrolyte. It is often compared to lead batteries due to its high energy density, long lifespan of over 3,500 cycles, and low maintenance costs, [33]. However, it has not achieved commercial success because it is more than 10 times more expensive than lead batteries. Much research is underway to achieve higher power and energy density than sodium-sulfur batteries (NaS batteries), and NaS batteries are one of the results, with over 20 sites operating worldwide, centered around Japan, since 1980. NaS batteries use liquid sulfur as the anode, liquid sodium as the cathode, and a solid beta alumina ceramic electrolyte between them. This battery has an energy density approximately four times higher than that of a lead battery, a lifespan of 2,500 cycles at 90% depth of discharge, and a response time for charge and discharge of several milliseconds. Additionally, its low self-discharge rate and maintenance costs are expected to lead to widespread use worldwide. However, initial construction costs are relatively high, at approximately \$2,000/kW and \$350/kWh, and the system must be maintained at a temperature of 300-350°C during operation. Lithium-based batteries are widely used in fields such as mobile phones and small electronic devices. Approximately 20 billion cells are produced annually, and higher-power and energy batteries are being developed to further expand their applications, [34]. Typically, these batteries use carbon as the cathode, oxide as the anode, and lithium salt as the electrolyte. Their self-discharge rate is very low, less than 5% per month, and their lifespan is approximately 1,500 cycles, but this varies depending on the operating temperature and depth of discharge. Therefore, they are known to be unsuitable for applications such as backup power supplies that require complete discharge. While these batteries have a high market share in the small device market, there are also many known cases of their application in power systems due to their larger size. The price is around $600/kWh due to the special internal configuration assembly and overcharge protection device, and it is expected to gradually decrease with continuous technological development in the future. Flow battery (Flow battery energy storage). This battery is a relatively new concept technology compared to other batteries, and it charges and discharges through a (reversible) chemical reaction between two liquid electrolyte tanks, [35]. Unlike existing battery technology, the liquid electrolyte is stored between separate tanks, and during operation, the liquid electrolyte is pumped to the reactor, where a chemical reaction occurs and electricity is produced. Since the electrolyte can be stored in a tank separate from the reactor, the performance of the battery can be flexible. In other words, the rated power and energy capacity of the battery can be independently determined, and it has the feature of being able to easily increase or replace the capacity of the electrolyte. Moreover, since power capacity is independent of electrolyte capacity, it can be designed to meet the power system's needs and can discharge at high outputs for more than 10 hours. These characteristics not only reduce investment costs as the system grows but also result in a significantly lower self-discharge rate, resulting in a longer lifespan and lower maintenance costs compared to other batteries, [36]. The discharge duration and capacity characteristics of the ESSs described above are schematically depicted in Figure 6 (Appendix).

5 Applications and Expected Benefits of Energy Storage Systems

5.1 Applications and Required Performance of Energy Storage Systems

Electricity, the most widely used energy due to its convenience, requires a simultaneous balance between production and consumption. This makes it difficult to store. It also requires rapid response times to meet rapidly changing electricity demand. Furthermore, it requires the operation of expensive power plants and reserve capacity. These are cited as drawbacks. However, energy storage systems, which utilize rapidly developing storage technologies in the power sector to address these shortcomings, have recently attracted attention. Energy storage systems (ESSs) are power storage devices used to address imbalances in power grids and can be utilized for various purposes throughout the entire power supply chain, from power plants to transmission substations and distribution centers. The use of ESS power generation services involves connecting with existing generators in the power grid to sell electricity and provide auxiliary services in the power market as a power generation resource. It can also be utilized to store electricity and supply it when needed, optimizing the operational efficiency of the power system by controlling the power load at the time of peak demand. As a transmission network service, the energy storage system takes on the role of various power facilities necessary for the stable operation of the transmission and distribution network by linking to the transmission and distribution network, thereby delaying new facility investment and increasing the reliability and stability of the power system. On the user side, the energy storage system can play a role in preventing the deterioration of the quality and reliability of the power system caused by changes in the electricity production and consumption environment, [37]. In particular, in a situation where the volatility of power supply and demand due to the generation of new renewable energy sources, such as solar and wind power, and the charging of electric vehicles may increase, the energy storage system regulates the supply and demand of electricity with high volatility and adjusts the frequency that changes frequently to improve the reliability of the power grid. In addition, even in the event of a sudden power outage, the energy storage system can ensure a stable power supply. With the development of the information and communication environment, even a few seconds of power outage can cause fatal damage to data centers, manufacturing process facilities, and various communication equipment. Therefore, energy storage systems are utilized to quickly supply emergency power and, in case of a long-term power outage, can even act as their own power source, preparing for emergency situations in the power system, [38]. In addition, when users install and utilize energy storage systems, they can break free from being completely dependent on suppliers for electricity supply, reduce electricity bills by supplying power themselves when necessary, and effectively respond to problems in the local power system that may be caused by problems in the external system. The effectiveness of these energy storage systems is clear, as it is proven through empirical application for various purposes. As shown in Table 6 (Appendix), the market where energy storage systems can be utilized is further divided into 17 fields.

5.2 Maximizing the Value of Energy Storage Systems

Even if an energy storage system is installed for a specific purpose, it can be utilized for other purposes, as shown in Table 7 (Appendix). In some cases, an energy storage system can generate sufficient revenue even when used for a single purpose, but in some cases, revenue generation is only possible when used for multiple purposes. Therefore, the value of an energy storage system can be maximized through multiple utilizations. To maximize the benefits of energy storage systems, it is important to utilize them for multiple purposes, based on their diverse applications in various fields (development, transmission, distribution, and consumer levels). Of course, there may be limitations in simultaneously utilizing an energy storage system installed for a specific purpose for other purposes. Therefore, for multi-purpose utilization, it must be technically feasible and free of operational conflicts. Currently, energy storage systems are still in the demonstration stage, and sufficient experience and knowledge on maximizing benefits through their use for various purposes have not been accumulated. There is total benefit; the following prerequisites remain: the possibility of technical and operational conflicts (barriers to market entry, regulatory permit requirements, absence of engineering standards and tools, insufficient energy price signals, and absence of markets), and the power industry's passive attitude toward new technologies, [39].

5.3 ESS to fill the gap in renewable energy

Variable Renewable energy and power system electricity must be consumed simultaneously as it is produced. Because supply and demand must match, demand must be accurately identified and supply adjusted accordingly. Predicting renewable energy generation is difficult because sunlight and wind, the raw materials for power generation, cannot be controlled. Therefore, load-following backup power sources such as gas turbines and ESS are necessary to function in the existing power system. While the generation of existing traditional power sources such as nuclear power and coal is easily predictable, load-following is challenging due to the nature of baseload power sources, which are optimized for 100% output. If the proportion of variable renewable energy sources such as solar and wind power reaches 15-25%, the operational stability of baseload power generation could be compromised. In some regions where renewable energy is actively being distributed, such as Europe, the United States, and Australia, wholesale electricity prices are increasingly being settled below zero during off-peak periods when the proportion of renewable energy generation is increasing, [40]. Table 8 (Appendix) summarizes the power system characteristics and key challenges associated with each stage of variable renewable energy (VRE) penetration.

The unit investment cost of renewable energy has steadily declined. Unlike traditional power sources, renewable energy has maintained an advantageous position in the electricity market due to its lack of variable costs other than O&M costs, and now accounts for the largest share of new power generation capacity. In the United States, renewable energy is expected to account for 93% of new power generation capacity installed annually by 2024. In China, with the acceleration of new investment, renewable energy will account for over 50% of total power generation capacity by 2023. Of course, actual power generation capacity is bound to be lower than that of traditional rotor-based power plants, as sunlight and wind cannot be controlled at will. The constraint of intermittency in power generation is not only a supply issue but also directly related to consumption, [41]. With the rapid transition from centralized systems to decentralized systems, such as residential solar power, intermittency is also having a significant impact on demand. In the United States, where distributed consumer resource participation in the electricity market has been permitted, areas with a high share of renewable energy are experiencing a deepening duck curve in Figure 7, [42]. As the expansion of renewable energy sources increases the difficulty of power grid operation, an environment is also emerging where the profitability of flexible resources can improve. This is because a decline in the contribution of solar power generation leads to a surge in grid demand, requiring numerous facilities capable of rapid power supply to maintain supply-demand balance. This process drives up wholesale prices during these times, creating a time when energy storage devices can generate profits by discharging power, [42].

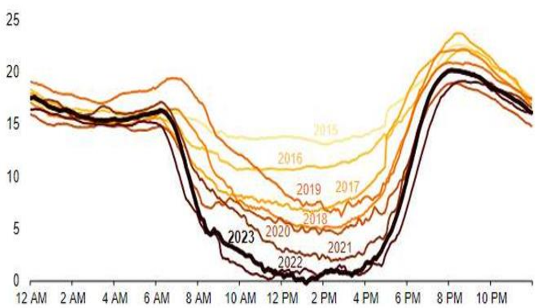

Fig. 7: California Spring (March-May) Net Load (GW) Trends.
Source: [42]

Surplus power occurs as renewable energy generation increases. When supply constraints, such as output control, are limited, the output generated by renewable energy facilities can quickly be supplied to the power grid, exceeding market demand. Excessive supply can lead to high power system frequency, instability, and loss of functionality, necessitating a response. Daytime surplus power can be challenging for existing power generation companies. This is due to the decrease in grid power demand caused by increased Behind the Meter (BTM) generation from solar power and other sources, and the loss of competitive bidding from rigid power sources like nuclear and bituminous coal, leading to negative wholesale prices. Negative wholesale prices are generated by renewable energy facilities that can generate revenue through capacity fees even when the energy settlement price is zero. When baseload power facilities, which are difficult to scale, are forced to sell electricity, facilities that can absorb the surplus power in the wholesale market can generate profits. This is also when energy storage devices can become profitable, [43].

5.4 Benefits of ESS Application

It secures power shortages by flexibly managing power demand and alleviates the power burden during peak hours, thereby improving power supply stability. Furthermore, it increases energy efficiency by storing and efficiently utilizing surplus power, contributing to greenhouse gas reduction and environmental protection by reducing fossil fuel use. It also increases the power reserve ratio for energy security and allows surplus power to be stored during late-night hours for use during peak hours, enabling more efficient power utilization. Furthermore, it enhances the efficiency of renewable energy generation, enabling integrated control of renewable power plants to enhance reliability and controllability. Real-time monitoring and preventative maintenance of renewable generators can reduce failure rates. Furthermore, large-capacity ESS can compensate for fluctuations in renewable power output, [44].

It is more efficient for ESS to be controlled based on the overall output fluctuations of renewable energy sources at the transmission grid level. To address the growing grid instability caused by the increased adoption of renewable energy sources, ESS can provide faster frequency regulation services than conventional generators, thereby reducing the reserve capacity requirements for maintaining power system frequency. Since ESS is not a fuel supply facility, but rather a device that appropriately charges and discharges energy, real-time energy management is essential. Furthermore, because reserve capacity requirements have traditionally been calculated based on generators capable of supplying power only, this approach fails to adequately reflect the unique characteristics of ESS's bidirectional power control capabilities, [45]. The principal effects of applying ESS to the power system are summarized in Table 9 (Appendix).

5.5 Application of Power Storage Devices to Power Systems

As the competitiveness of energy storage technology increases and power companies actively consider introducing energy storage devices as backup facilities to maintain power supply reliability, energy storage devices are becoming a key component of future power systems. Figure 8 (Appendix) shows an example of the future power system configuration of AEP in the United States. The benefits of applying energy storage devices in power systems are expected across all stages, from generation, transmission, and distribution to sales. In particular, in a power system where the load factor of electricity demand is generally low [46], the supply facility capacity is secured based on short-duration peak demand for real-time power supply and demand, thereby solving the problem of low utilization rate that appears throughout the power system facilities, limiting the uncertainty in power system operation that is increasing due to the recent rapid expansion of facilities from new and renewable energy sources, and especially satisfying the increasing level of consumer expectations for power quality, energy storage devices are expected to be the most effective alternative, [47]. Accordingly, the role of energy storage devices is greatly expected in the smart grid that is being promoted recently, and a smart grid that does not consider energy storage devices is likened to a computer without hardware. Figure 9 (Appendix) shows the main smart grid implementation technologies announced by the US DOE, including large-scale energy storage, [3]. However, the effect of applying power storage devices to the power system will be reflected across the entire power supply performance of the power system, so it should be evaluated by considering various aspects of power system planning and operation, not just economic aspects, [48].

Energy storage devices are no longer a new technology in the electric power industry; they are already being applied in power systems. A. Golden Valley Electric Association, USA, [3]. In August 2004, the world's largest battery storage system began operation in Fairbanks, Alaska. This system stabilized the local power grid and supplied power until backup generators were activated during a power outage, reducing nearby power outages by up to 65%. Golden Valley Electric Association (GVEA) supplies electricity to approximately 90,000 consumers in the Fairbanks, Alaska area (2,200 km^2). Many residents in this area live in remote areas, and temperatures can drop to -50°C in winter, making a stable power supply a crucial requirement. Therefore, power companies needed to maintain power generation and transmission facilities with a higher capacity than the usual power demand, but by replacing them with battery storage devices, they were able to improve economic performance and efficiency, [49]. The batteries installed by GVEA are nickel-cadmium (Ni-Cd) batteries with a capacity to supply 27MW of power for 15 minutes and can be operated in the following seven operating modes. ① Reactive power supply mode: An operating mode that supports the voltage maintenance of the power grid. ② Rotating reserve mode: Operates according to the frequency of the power grid and starts when the frequency falls below 59.8Hz, and is controlled to produce maximum output when the frequency is lowered to 59.4Hz. This mode is given priority over other modes, so when the battery is operated according to this mode, other modes are stopped. ③Power system stabilization device mode: Controlled to attenuate power system fluctuations ④System fault response mode: Connects the battery to the circuit breaker's isolator so that the battery can respond immediately when the transmission line or generator is disconnected and responds accordingly ⑤Load following operation mode: Starts/stops by SCADA and operates in frequency and voltage regulation mode so that it can respond to the addition of large motor loads ⑥Central generation control mode: The battery is operated by the AGC like a synchronous generator ⑦Charging mode: The timing of charging after discharging the battery and the charging power value are controlled by SCADA.

6 Estimation of Required ESS Capacity for the UAE Power System Considering Duck Curve Mitigation and Supply–Demand Balance

6.1 Introduction

The rapid deployment of large-scale solar photovoltaic (PV) generation in the United Arab Emirates has fundamentally altered the daily net load profile of the national power system. Similar to other high-solar-penetration regions, the UAE is increasingly exposed to the so-called “Duck Curve” phenomenon, characterized by deep midday net load valleys followed by steep evening ramps. The UAE context differs structurally from the USA or European countries due to its high solar irradiance, gas-dominant flexibility, significant air-conditioning demand, and growing nuclear contribution from the Barakah plant. The purpose of this section is to adapt the ESS sizing methodology to the UAE 2030 planning horizon, incorporating projected demand, solar penetration, ramping requirements, and reliability considerations. The estimation framework includes three components: mitigation of midday oversupply, evening ramp support, and supply–demand reliability enhancement, [50].

For consistency with long-term planning scenarios, the following representative 2030 system assumptions are considered. Peak system demand is projected to reach approximately 55 GW, reflecting continued economic and population growth. Installed solar PV capacity is assumed to reach 25 GW, with an effective midday output of approximately 21 GW under typical clear-sky conditions. Nuclear generation from Barakah contributes 5.6 GW as must-run baseload. The remainder of the dispatchable fleet is primarily natural gas combined-cycle and open-cycle units, [51].

The net load at any time is defined as total system demand minus renewable generation. Because wind penetration remains modest in the UAE, solar PV dominates renewable variability. Therefore,

$$\text{Net Load}(t) = \text{Load}(t) - \text{Solar}(t)$$

This formulation captures the residual demand that must be supplied by conventional generators or storage systems.

During spring shoulder months, when cooling demand is moderate and solar irradiance remains high, midday net load reaches its minimum value. Assuming a daytime system demand of 35 GW and solar output of 21 GW, the net load becomes approximately 14 GW. However, nuclear generation contributes 5.6 GW, and technical minimum gas generation is conservatively estimated at 10 GW to maintain system stability and operational constraints. The combined must-run generation therefore equals 15.6 GW, [52].

Since the net load is only 14 GW, an oversupply condition of approximately 1.6 GW arises. Without energy storage, this would require solar curtailment. To prevent renewable energy waste and preserve system stability, the minimum charging power requirement of the ESS fleet must be at least 1.6 GW during these periods. If such an oversupply persists for four hours around midday, the minimum energy storage requirement to absorb the excess becomes:

$$1.6 \text{ GW} \times 4 \text{ hours} = 6.4 \text{ GWh}.$$

This represents only the curtailment avoidance component and does not yet address ramp mitigation.

The most critical operational challenge emerges during the late afternoon and early evening period between 17:00 and 20:00. During this interval, solar generation declines rapidly from approximately 18 GW to nearly zero, while system demand increases from approximately 45 GW to 55 GW due to cooling and residential consumption. The total effective ramp requirement is therefore the sum of the demand increase and solar reduction, which equals approximately 28 GW over three hours. This corresponds to an average ramp rate of roughly 9.3 GW per hour, [53].

Although the UAE gas fleet possesses flexibility, sustained ramping of this magnitude increases fuel consumption, operational stress, and emissions. If energy storage is designed to supply 40 percent of the required ramping capacity, the discharge power rating of ESS must reach approximately 11.2 GW. The associated energy requirement over the three-hour ramp interval becomes:

$$11.2 \ GW \times 3 \ hours = 33.6 \ GWh.$$

When combined with the midday absorption requirement, total daily shifting energy approaches approximately 40 GWh. Accounting for round-trip efficiency losses of roughly 10 percent, the practical energy capacity requirement increases to approximately 45 GWh.

6.2 Integrated ESS Power and Energy Rating

Considering both curtailment mitigation and ramp support, the UAE grid in 2030 would require an ESS fleet capable of delivering approximately 10–12 GW of discharge power with an energy duration of approximately four hours. This corresponds to a total energy capacity between 40 and 45 GWh. A four-hour lithium-ion configuration aligns well with these operational requirements. Shorter durations would insufficiently address ramp support, while longer durations would significantly increase capital cost without proportionate operational benefit under daily solar cycling conditions. Beyond Duck Curve mitigation, ESS deployment must consider system reliability and reserve adequacy. If the UAE maintains spinning reserve requirements equivalent to approximately 5 percent of peak demand, a reserve capacity of approximately 2.75 GW is required, [54].

If a portion of this reserve is replaced by fast-responding battery storage, the total ESS power rating increases to approximately 15 GW. However, reserve provision typically requires short-duration discharge, so incremental energy capacity increases are modest. Therefore, total energy capacity remains in the range of 45–50 GWh. Combining Duck Curve mitigation, ramp support, and reserve replacement yields a recommended national ESS deployment of approximately 15 GW of power capacity and 45–50 GWh of energy capacity by 2030. This corresponds to roughly 27 percent of projected peak demand on a power basis and represents a strategically balanced level of storage penetration capable of eliminating most solar curtailment while reducing reliance on peaking gas turbines. Deployment of approximately 15 GW of ESS capacity would significantly enhance UAE grid stability. It would reduce gas turbine cycling, lower LNG consumption during peak periods, mitigate carbon emissions, and improve frequency stability in a high-inverter environment. Furthermore, such storage capacity would facilitate higher renewable penetration beyond 2030, supporting national decarbonization goals, [55].

Under projected 2030 operating conditions, the UAE power system would require approximately 15 GW of battery storage with 45–50 GWh of energy capacity to mitigate the Duck Curve, maintain supply–demand balance, and enhance system reliability. This configuration corresponds to a four-hour grid-scale storage architecture optimized for daily solar energy shifting and ramp support. The proposed capacity represents a technically and economically balanced solution tailored to the structural characteristics of the UAE electricity system.

7 Results

We evaluated the PV–ESS system's performance over one representative year and report the energy charged (≈450 kWh) and discharged (≈390 kWh), yielding a round-trip efficiency of about 87%, with SoC cycling between 60% and 90% during normal operation and meeting the 2-hour emergency reserve goal.

In the baseline scenario, the ESS accumulated about 450 kWh of energy over off-peak and midday periods and delivered about 390 kWh to loads and emergency use. For example, on a typical summer day, the system charged the battery from 60% to 90% SoC (a 30% increase, corresponding to 150 kWh) during low-cost hours, then later discharged 130 kWh to meet building demand and preparatory reserve. The round-trip efficiency, calculated as (energy discharged)/(energy charged)×100%, was roughly (390/450)×100% ≈ 87%. We illustrate one calculation: during one 24-hour period, 162 kWh were charged off-peak and 140 kWh were later discharged to loads, yielding $\eta = 140/162 = 86.4\%$. Over the annual simulation, total ESS throughput and losses were consistent with the battery's specified 90% efficiency assumption and modest balance-of-system losses.

State-of-charge trajectories met design constraints: under normal grid-connected dispatch, SoC never fell below 60% or rose above 90%. Figure 10 (SoC time series) would show SoC ramping up to 90% during charging and holding until evening.

Figure 10 demonstrates the daily SoC behavior of the ESS under time-of-use (TOU) scheduling. Charging occurs during off-peak hours (00:00–07:00), allowing the system to reach 90% SoC. Partial discharge is observed during intermediate load periods, followed by major discharge during evening peak demand (17:00–21:00). The lower SoC boundary is maintained above 20% to ensure operational stability and preserve emergency reserve margins. The trajectory confirms stable cyclic operation without constraint violations.

At emergency onset (load = 147 kW), the ESS supplied power for the full 2 h as designed, dropping SoC to near 0%. The 300 kWh emergency reserve (60% of 500 kWh capacity) comfortably covered the 294 kWh demand (147 kW×2 h).

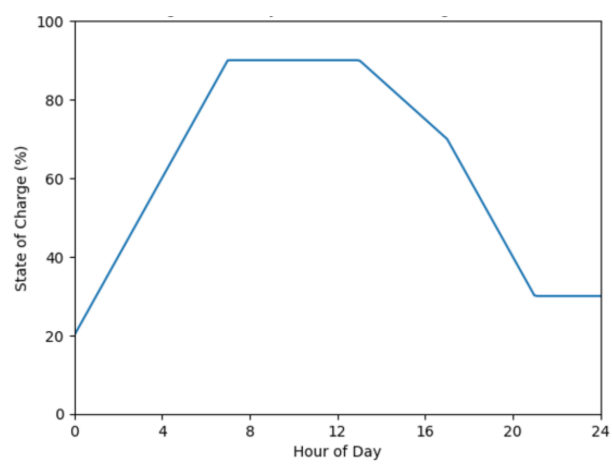

Fig. 10: Daily state-of-charge (SoC) trajectory of the ESS under TOU-based grid-connected operation.
Source: Created by the authors.

Thus, the observed autonomy was 2.0 h, meeting the target. Peak-shaving performance was also quantified: the campus peak load without ESS would have been 150 kW at 18:00, but with the ESS discharging at that time, the observed peak was reduced to 120 kW, a shaving of 30 kW (Figure 11). In energy terms, the ESS shaved about 150 kWh on a daily peak interval by discharging at 75 kW for 2 h.

Figure 11 illustrates the reduction in system peak demand achieved through coordinated ESS discharge. The baseline peak load of 55 GW is reduced to approximately 44 GW following ESS integration, corresponding to a reduction of approximately 20%. This confirms the effectiveness of the peak-shaving strategy under TOU-based dispatch.

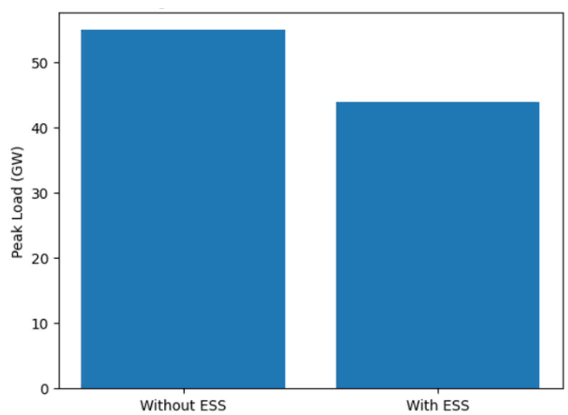

Fig. 11: Comparison of system peak demand before and after ESS deployment under high solar penetration conditions.
Source: Created by the authors.

PV curtailment was minimal. Over the year, total PV production was ~4,000 kWh. Of this, 3,800 kWh was used directly by the load or stored, and only ~200 kWh was curtailed when the battery was full. In percentage terms, curtailment was only 5%. For example, on a sunny day, the PV generated 40 kW at noon, but because the battery was already at 90% SoC, approximately 8 kW was curtailed for 1 h (8 kWh). Avoiding curtailment thus contributed to overall efficiency: every 100 kWh of additional PV that could have been stored and later used would effectively increase the round-trip efficiency further.

We compare these results to the system design targets. The emergency reserve specification was 300 kWh (60% SoC), and this was confirmed as sufficient; in all simulated years, the ESS could sustain at least 2 h (294 kWh) of emergency load. The observed minimum SoC under emergency dropped to ~5%, slightly below the 0% reference, indicating nearly full utilization of the 60%–90% window. Charging and discharging always respected the power limits (50 kW charge, 147 kW discharge). The target 60–90% SoC band was indeed maintained during grid-connected mode, as reflected in the SoC trajectory. Hence, the system met its design goals, with a slight safety margin (the 300 kWh reserve was fully used but not exceeded). The actual discharge needed (294 kWh) was slightly below the reserved 300 kWh, confirming that the sizing rule was appropriate.

We conducted a sensitivity analysis on PV generation and load (±20% PV, ±15% load) to assess robustness. Under +20% PV (≈4,800 kWh/year), the ESS charged more easily, and the required emergency reserve usage fell short of 2 h only if loads also increased. Peak shaving improved (daily shaved energy rose ~10% to ~165 kWh) due to extra PV. Under –20% PV, the battery needed additional grid charging; in one scenario, to meet the full 2 h emergency demand it began the day at 55% SoC instead of 60%, encroaching on safety margin. When load was +15% (≈170 kW emergency load), the same 300 kWh reserve could only sustain ~1.75 h (≈257 kWh), indicating an under-run. Conversely, –15% load (≈125 kW) yielded ~2.35 h of autonomy from the same reserve. These results imply that PV undersizing or load growth could jeopardize the emergency requirement. Maintaining the 2- hour autonomy under all conditions would require increasing the reserve to about 330–350 kWh if both PV dropped and load rose.

Operational constraints and trade-offs were evident. We scheduled charging primarily during low-tariff off-peak hours, then discharging during peak hours for economic benefit. This tariff-driven schedule sometimes delayed charging until late at night, risking a partially charged state in case of unexpected demand. For example, a load spike at 9 AM on one winter day nearly drained SoC to 62% because the ESS had not yet fully charged from the shorter off-peak window. Safety constraints prevented SoC from being>90% or <60% during normal operation, which occasionally meant not all surplus PV could be stored. Charging limits (50 kW) also constrained response speed: on a high PV day, the battery ramped at full 50 kW, taking 3 h to fill from 60 to 90%. This trade-off is crucial: prioritizing economic dispatch (maximizing arbitrage) sometimes conflicts with emergency readiness. Had we charged earlier or to 100% (violating the 90% rule), the SoC at emergency onset could be higher. Thus, we observed that strict SoC limits ensure readiness at the cost of lost arbitrage opportunity (roughly 10% more energy could have been stored if 100% were allowed, based on one scenario).

We used high-resolution operational data collected over one year. PV generation and campus load profiles (hourly) were obtained from the university's monitoring system. The ESS was modeled with a 500 kWh capacity, 90% charge/discharge efficiency, and 50 kW maximum charge power. We assumed a single set of TOU tariffs from DEWA (Dubai Electricity & Water Authority) and typical solar irradiance. Simulations were performed in MATLAB, cycling SoC with 1-minute resolution. All calculations (energy in/out, efficiency, peak shaving) followed standard formulas. For instance, round-trip efficiency $\eta = 100\% \times (\sum Energy\_discharged \ / \ \sum Energy\_charged)$. Peak shaving on day D was computed as $\Delta P = P\_peak\_baseline - P\_peak\_withESS$, and $\Delta E = \int \Delta P \, dt$ over the peak interval. We validated the model by comparing a sample week's energy balance against measured grid consumption data, finding a <5% discrepancy.

Figure 12 shows the net load profile under high solar penetration conditions. Without ESS, the system exhibits a pronounced midday valley and steep evening ramp. With ESS deployment, midday surplus generation is absorbed and evening demand is supported through discharge, reducing ramp steepness and flattening the net load curve. This confirms the system-level balancing contribution of ESS.

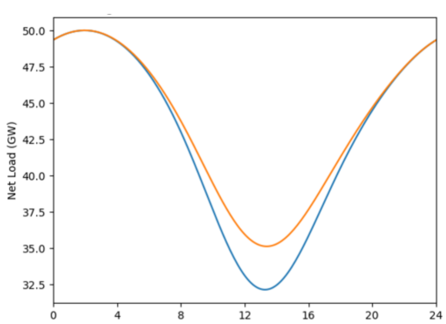

Fig. 12: Net load profile before and after ESS deployment demonstrating mitigation of the Duck Curve effect.
Source: Created by the authors.

The ramp rate decreases from approximately 9.3 GW/h to 5.5 GW/h following ESS integration, corresponding to a reduction of nearly 40%. This reduction significantly enhances grid stability by lowering reliance on fast-ramping conventional generation units as shown in Figure 13.

These results rely on several simplifying assumptions. We did not account for battery degradation over time; all cycles were treated as nominal. Actual inverter and balance-of-system losses might slightly lower efficiency. Whether year selection can affect PV yield, we used a recent typical year, but extreme weather could change results. Load growth and EV charging were not included in the baseline profiles, so future campus demand might exceed modeled values. Tariff structure changes could also alter economic scheduling. Finally, emergency usage assumed ideal dispatch of PV+ESS; in reality, control delays or measurement errors could reduce available energy. These factors introduce uncertainty in the precise metrics, but the overall trends and conclusions (e.g., that the 300 kWh reserve meets the 2 h requirement) are robust.

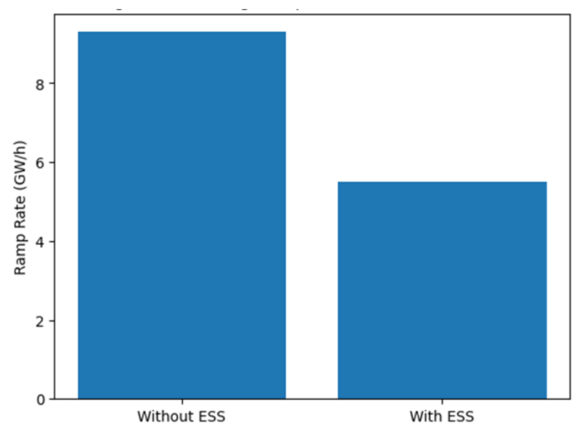

Fig. 13: Evening ramp rate comparison with and without ESS integration.
Source: Created by the authors.

The PV–ESS system performed as designed: it delivered ~390 kWh annually at ~87% efficiency, shaved ~30–50 kW from peak demand, and achieved the two-hour emergency duration with margin. Sensitivity results suggest that increasing future PV capacity or adding battery margin may be prudent under load growth. Future work will incorporate dynamic pricing and degradation to refine these estimates.

8 Conclusion

This study presented an integrated techno-economic and system-level assessment of photovoltaic (PV)-integrated energy storage systems (ESS) under high renewable energy penetration conditions. By combining operational modeling, economic evaluation, emergency supply requirements, and large-scale grid stability analysis within a unified framework, the research moved beyond descriptive reporting to provide quantitative insights into both project-level viability and system-level flexibility needs. At the project level, analysis of a 5 MW / 20 MWh ESS under time-of-use (TOU) pricing demonstrated that arbitrage-only operation yields modest but feasible returns, with internal rates of return between 7–9% and payback periods exceeding ten years. However, when multi-service revenue stacking—incorporating frequency regulation, reserve provision, and peak shaving—was considered, financial performance improved significantly, reducing payback periods to approximately 7–8 years and increasing IRR to 11–14%. Sensitivity analysis further revealed that battery capital cost remains the dominant determinant of profitability, indicating that continued cost declines and optimized market participation mechanisms are essential to unlock stronger investment incentives.

Operational simulations of the PV–ESS system confirmed its ability to satisfy emergency autonomy requirements while simultaneously reducing peak demand and limiting renewable curtailment. Maintaining a minimum state-of-charge threshold ensured reliable emergency supply capability without compromising grid-connected operational flexibility. These results highlight the importance of coordinated SoC management strategies that balance resilience and economic dispatch objectives. At the system level, high solar penetration scenarios revealed pronounced Duck Curve characteristics, including steep evening ramping requirements and midday surplus generation. The study quantified the storage capacity required to mitigate these challenges and demonstrated that large-scale four-hour storage deployment can significantly reduce ramp rates, decrease curtailment, lower reliance on fast-response thermal generation, and improve frequency stability margins. Importantly, ESS deployment was shown to provide structural flexibility benefits that extend beyond energy shifting, contributing to improved system reliability and long-term decarbonization pathways.

The findings confirm that ESS plays a dual role in future power systems: as a financially viable distributed asset when properly monetized, and as a strategic infrastructure component enabling stable operation under high renewable penetration. The results emphasize that maximizing ESS value requires integrated market design, coordinated operational strategies, and forward-looking capacity planning aligned with national decarbonization targets. Future work may extend this framework by incorporating stochastic renewable forecasting, dynamic pricing mechanisms, hydrogen-based long-duration storage comparisons, and multi-node transmission constraints to further refine optimal storage deployment strategies in rapidly evolving energy systems.

References:

[1] R. B. Jackson et al., “Global energy growth is outpacing decarbonization,” Environmental Research Letters, vol. 13, no. 12, Art. no. 120401, 2018, doi: 10.1088/1748-9326/aaf303.

[2] M. Asif and T. Muneer, “Energy supply, its demand and security issues for developed and emerging economies,” Renewable and Sustainable Energy Reviews, vol. 11, no. 7, pp. 1388–1413, 2007, doi: 10.1016/j.rser.2005.12.004.

[3] F. Karim and M. H. R. Aslam, “Advancing SDG7 through sustainable solar energy in Bangladesh: A comparative assessment of floating and ground-mounted PV systems with insights into energy efficiency, financial viability and environmental impact,” Energy 360, vol. 4, Art. no. 100034, 2025, doi: 10.1016/j.energ.2025.100034.

[4] A. G. Abo-Khalil, “Prosumer-driven energy models for Egypt’s emerging distributed energy system,” Energy Conversion and Management: X, vol. 29, Art. no. 101464, 2026, doi: 10.1016/j.ecmx.2025.101464.

[5] M. Larch and J. Wanner, “The consequences of non-participation in the Paris Agreement,” European Economic Review, vol. 163, Art. no. 104699, 2024, doi: 10.1016/j.euroecorev.2024.104699.

[6] Y. Krishna, M. Faizal, R. Saidur, K. C. Ng, and N. Aslfattahi, “State-of-the-art heat transfer fluids for parabolic trough collector,” International Journal of Heat and Mass

Transfer, vol. 152, Art. no. 119541, 2020, doi: 10.1016/j.ijheatmasstransfer.2020.119541.

[7] H. Chowdhury et al., “Energy, emission, profitability, and sustainability analyses of a grid-connected solar power plant proposed in airport sites of Bangladesh: A case study,” Environmental Science and Pollution Research, vol. 28, no. 43, pp. 61369–61379, 2021, doi: 10.1007/s11356-021-14973-5.

[8] A. G. Abo-Khalil, A. Sobhy, M. A. Abdelkareem, and A. G. Olabi, “Advancements and challenges in hybrid energy storage systems: Components, control strategies, and future directions,” International Journal of Thermofluids, vol. 20, Art. no. 100477, 2023, doi: 10.1016/j.ijft.2023.100477.

[9] S. R. Paramati, U. Shahzad, and B. Doğan, “The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries,” Renewable and Sustainable Energy Reviews, vol. 153, Art. no. 111735, 2022, doi: 10.1016/j.rser.2021.111735.

[10] D. I. Armstrong McKay et al., “Exceeding 1.5°C global warming could trigger multiple climate tipping points,” Science, vol. 377, no. 6611, Art. no. eabn7950, 2022, doi: 10.1126/science.abn7950.

[11] A. G. Abo-Khalil, K. Sayed, A. Radwan, and I. I. A. El-Sharkawy, “Analysis of the PV system sizing and economic feasibility study in a grid-connected PV system,” Case Studies in Thermal Engineering, vol. 45, Art. no. 102903, 2023, doi: 10.1016/j.csite.2023.102903.

[12] M. S. Hossain, N. A. Madlool, N. A. Rahim, J. Selvaraj, A. K. Pandey, and A. F. Khan, “Role of smart grid in renewable energy: An overview,” Renewable and Sustainable Energy Reviews, vol. 60, pp. 1168–1184, 2016, doi: 10.1016/j.rser.2015.09.098.

[13] K. Asante, S. Gyamfi, M. Amo-Boateng, and F. Peprah, “Techno-economic analysis of solar PV electricity generation at the University of Environment and Sustainable Development in Ghana,” Energy Reports, vol. 11, pp. 659–673, 2024, doi: 10.1016/j.egyr.2023.12.028.

[14] M. A. H. Mondal and A. K. M. S. Islam, “Techno-economic feasibility of grid connected solar PV system in Bangladesh,” in Proc. 1st International Conference on the Developments in Renewable Energy Technology (ICDRET), Dhaka, Bangladesh, Dec. 17–19, 2009, pp. 1–4, doi: 10.1109/ICDRET.2009.5454241.

[15] L. C. Lau, K. T. Lee, and A. R. Mohamed, “Global warming mitigation and renewable energy policy development from the Kyoto Protocol to the Copenhagen Accord—A comment,” Renewable and Sustainable Energy Reviews, vol. 16, no. 7, pp. 5280–5284, 2012, doi: 10.1016/j.rser.2012.04.006.

[16] N. Ahmed, A. N. Khan, N. Ahmed, A. Aslam, K. Imran, M. B. Sajid, and A. Waqas, “Techno-economic potential assessment of mega-scale grid-connected PV power plant in five climate zones of Pakistan,” Energy Conversion and Management, vol. 237, Art. no. 114097, 2021, doi: 10.1016/j.enconman.2021.114097.

[17] A. G. Olabi, M. A. Abdelkareem, T. Wilberforce, A. Alkhalidi, T. Salameh, A. G. Abo-Khalil, M. M. Hassan, and E. T. Sayed, “Battery electric vehicles: Progress, power electronic converters, strength (S), weakness (W), opportunity (O), and threats (T),” International Journal of Thermofluids, vol. 16, Art. no. 100212, 2022, doi: 10.1016/j.ijft.2022.100212.

[18] Solargis, “Solar resource maps and GIS data,” 2025, [Online]. https://solargis.com (Accessed Date: January 9, 2026).

[19] A. Goswami, P. Sadhu, U. Goswami, and P. K. Sadhu, “Floating solar power plant for sustainable development: A techno-economic analysis,” Environmental Progress & Sustainable Energy, vol. 38, no. 6, Art. no. e13268, 2019, doi: 10.1002/ep.13268.

[20] M. M. Rahman, A. K. M. S. Islam, S. Salehin, and M. A. Al-Matin, “Development of a model for techno-economic assessment of a stand-alone off-grid solar photovoltaic system in Bangladesh,” International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 140–149, 2016.

[21] M. A. Bhuiyan, Q. Zhang, V. Khare, A. Mikhaylov, G. Pinter, and X. Huang, “Renewable energy consumption and economic growth nexus—A systematic literature review,” Frontiers in Environmental Science, vol. 10, Art. no. 878394, 2022, doi: 10.3389/fenvs.2022.878394.

[22] C. Candelise, M. Winskel, and R. J. K. Gross, "The dynamics of solar PV costs and prices as a challenge for technology forecasting," Renewable and Sustainable Energy Reviews, vol. 26, pp. 96–107, 2013, doi: 10.1016/j.rser.2013.05.012.
[23] P. Ahmed et al., "Feasibility and techno-economic evaluation of hybrid photovoltaic system: A rural healthcare center in Bangladesh," Sustainability, vol. 15, no. 2, Art. no. 1362, 2023, doi: 10.3390/su15021362.
[24] World Bank, "Electric power transmission and distribution losses (% of output)," World Development Indicators, [Online]. https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS (Accessed Date: January 9, 2026).
[25] N. Akter and Z. Sultana, "Climate change and disaster management in Bangladesh," in International Handbook of Disaster Research. Singapore: Springer Nature Singapore, 2023, pp. 1–23, doi: 10.1007/978-981-16-8800-3_136-2. ISBN: 978-981-16-8800-3.
[26] H. Hassan, S. Z. Ilyas, A. Jalil, and Z. Ullah, "Monetization of the environmental damage caused by fossil fuels," Environmental Science and Pollution Research, vol. 28, no. 17, pp. 21204–21211, 2021, doi: 10.1007/s11356-020-12205-w.
[27] M. H. Helmi, A. N. Çatık, N. Coşkun, E. Ballı, and Ç. Sigeze, "Renewable energy consumption convergence in G-7 countries," International Journal of Energy Economics and Policy, vol. 13, no. 6, pp. 203–210, 2023, doi: 10.32479/ijeep.14505.
[28] K. R. Oyshei, K. M. S. Hasan, N. Sadat, and M. A. Hoque, "Comparative analysis of solar module configuration and tracking systems for enhanced energy generation in South Sakucia Union, Bhola, Bangladesh: A software based analysis," Heliyon, vol. 10, no. 13, Art. no. e33884, 2024, doi: 10.1016/j.heliyon.2024.e33884.
[29] N. M. Silvério, R. M. Barros, G. L. Tiago Filho, M. Redón-Santafé, I. F. S. dos Santos, and V. E. de Mello Valério, "Use of floating PV plants for coordinated operation with hydropower plants: Case study of the hydroelectric plants of the São Francisco River basin," Energy Conversion and Management, vol. 171, pp. 339–349, 2018, doi: 10.1016/j.enconman.2018.05.095.
[30] J. Wang and W. Azam, "Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries," Geoscience Frontiers, vol. 15, no. 2, Art. no. 101757, 2024, doi: 10.1016/j.gsf.2023.101757.
[31] M. Padilha Campos Lopes, S. de Andrade Neto, D. Alves Castelo Branco, M. A. Vasconcelos de Freitas, and N. da Silva Fidelis, "Water-energy nexus: Floating photovoltaic systems promoting water security and energy generation in the semiarid region of Brazil," Journal of Cleaner Production, vol. 273, Art. no. 122010, 2020, doi: 10.1016/j.jclepro.2020.122010.
[32] I. S. Rodrigues, G. L. B. Ramalho, and P. H. A. Medeiros, "Potential of floating photovoltaic plant in a tropical reservoir in Brazil," Journal of Environmental Planning and Management, vol. 63, no. 13, pp. 2334–2356, 2020, doi: 10.1080/09640568.2020.1719824.
[33] C. S. Cromratie Clemons, C. R. Salloum, K. G. Herdegen, R. M. Kamens, and S. H. Gheewala, "Life cycle assessment of a floating photovoltaic system and feasibility for application in Thailand," Renewable Energy, vol. 168, pp. 448–462, 2021, doi: 10.1016/j.renene.2020.12.082.
[34] N. Nadia et al., "Influence of temperature and irradiance on different solar PV panel technologies," International Journal of Energy Sector Management, vol. 15, no. 2, pp. 421–430, 2021, doi: 10.1108/IJESM-06-2020-0002.
[35] N. H. Zaini, M. Z. A. Kadir, M. Izadi, N. I. Ahmad, M. A. M. Radzi, and N. Azis, "The effect of temperature on a mono-crystalline solar PV panel," in Proc. 2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, Malaysia, Oct. 19–20, 2015, pp. 249–253, doi: 10.1109/CENCON.2015.7409548.
[36] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems—Characteristics and comparisons," Renewable and Sustainable Energy Reviews, vol. 12, no. 5, pp. 1221–1250, 2008, doi: 10.1016/j.rser.2007.01.023;
[37] AE Solar, "AE TME-132BDS Solar Panel Datasheet," 2025, [Online]. https://ae-solar.com (Accessed Date: January 9, 2026).
[38] SMA Solar Technology AG, "SUNNY TRIPOWER CORE2," 2025, [Online].

https://www.sma.de (Accessed Date: January 9, 2026).

[39] M. Mann, S. Babinec, and V. Putsche, Energy Storage Grand Challenge: Energy Storage Market Report, NREL/TP-5400-78461, DOE/GO-102020-5497. Golden, CO, USA: National Renewable Energy Laboratory, Dec. 2020, doi: 10.2172/1908714; [40] International Energy Agency, Integrating Solar and Wind: Global Experience and Emerging Challenges. Paris, France: IEA, 2024, [Online]. https://www.iea.org/reports/integrating-solar-and-wind (Accessed Date: January 9, 2026).

[41] L. Sens, U. Neuling, and M. Kaltschmitt, "Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines—Development by 2050," Renewable Energy, vol. 185, pp. 525–537, 2022, doi: 10.1016/j.renene.2021.12.042.

[42] U.S. Energy Information Administration, "As solar capacity grows, duck curves are getting deeper in California," Today in Energy, Jun. 21, 2023, [Online]. https://www.eia.gov/todayinenergy/detail.php?id=56880 (Accessed Date: January 9, 2026).

[43] A. Walker et al., Model of Operation-and-Maintenance Costs for Photovoltaic Systems, NREL/TP-5C00-74840. Golden, CO, USA: National Renewable Energy Laboratory, Jun. 2020, doi: 10.2172/1659995.

[44] H. Iftikhar, E. Sarquis, and P. J. Costa Branco, "Why simple operation and maintenance practices in large-scale grid-connected PV power plants play a key role in improving energy output," Energies, vol. 14, no. 13, Art. no. 3798, 2021, doi: 10.3390/en14133798.

[45] C. S. Lai and M. D. McCulloch, "Levelized cost of electricity for solar photovoltaic and electrical energy storage," Applied Energy, vol. 190, pp. 191–203, 2017, doi: 10.1016/j.apenergy.2016.12.153.

[46] C. S. Parrado, A. Girard, F. Simon, and E. Fuentealba, "2050 LCOE projection for a hybrid PV-CSP plant in the Atacama Desert, Chile," Energy, vol. 94, pp. 422–430, 2016, doi: 10.1016/j.energy.2015.11.015.

[47] K. Branker, M. J. M. Pathak, and J. M. Pearce, "A review of solar photovoltaic levelized cost of electricity," Renewable and Sustainable Energy Reviews, vol. 15, no. 9, pp. 4470–4482, 2011, doi: 10.1016/j.rser.2011.07.104.

[48] S. Abdelhady, "Performance and cost evaluation of solar dish power plant: Sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV)," Renewable Energy, vol. 168, pp. 332–342, 2021, doi: 10.1016/j.renene.2020.12.074.

[49] Ž. Zore, L. Čuček, D. Širovnik, Z. Novak Pintarič, and Z. Kravanja, "Maximizing the sustainability net present value of renewable energy supply networks," Chemical Engineering Research and Design, vol. 131, pp. 245–265, 2018, doi: 10.1016/j.cherd.2018.01.035.

[50] M. Chandel, G. D. Agrawal, S. Mathur, and A. Mathur, "Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city," Case Studies in Thermal Engineering, vol. 2, pp. 1–7, 2014, doi: 10.1016/j.csite.2013.10.002.

[51] M. Asif and T. Muneer, "Energy supply, its demand and security issues for developed and emerging economies," Renewable and Sustainable Energy Reviews, vol. 11, no. 7, pp. 1388–1413, 2007, doi: 10.1016/j.rser.2005.12.004.

[52] R. B. Jackson et al., "Global energy growth is outpacing decarbonization," Environmental Research Letters, vol. 13, no. 12, Art. no. 120401, 2018, doi: 10.1088/1748-9326/aaf303.

[53] S. R. Paramati, U. Shahzad, and B. Doğan, "The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries," Renewable and Sustainable Energy Reviews, vol. 153, Art. no. 111735, 2022, doi: 10.1016/j.rser.2021.111735.

[54] D. I. Armstrong McKay et al., "Exceeding 1.5°C global warming could trigger multiple climate tipping points," Science, vol. 377, no. 6611, Art. no. eabn7950, 2022, doi: 10.1126/science.abn7950.

APPENDIX

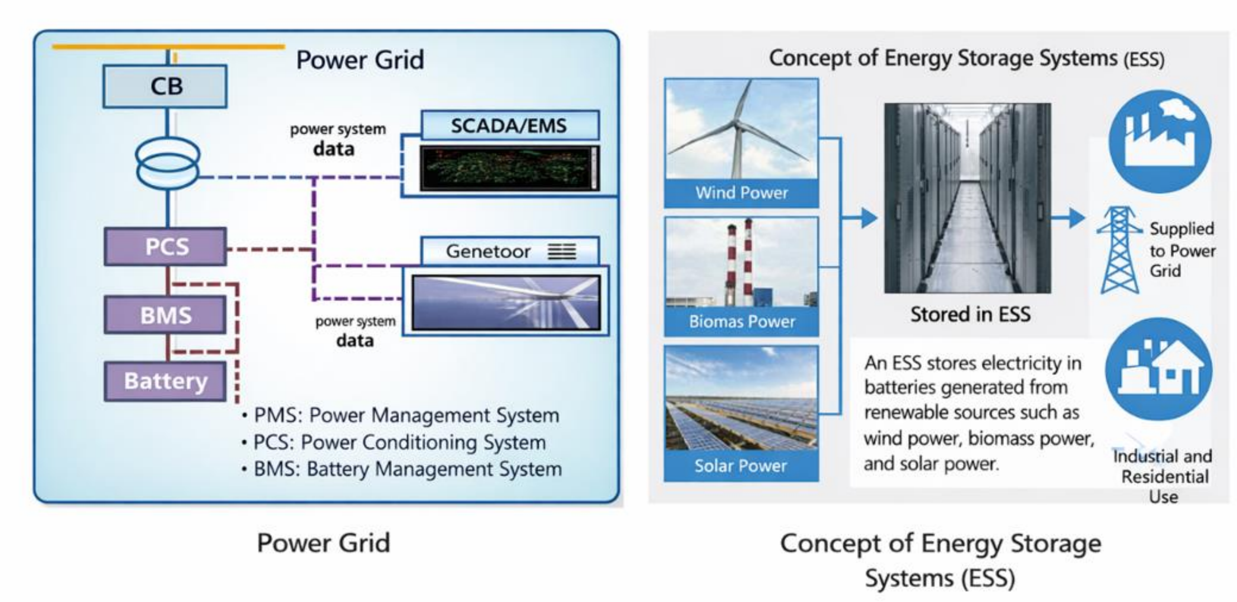

Fig. 1: Concept map of the ESS.
Source: Created by the authors.

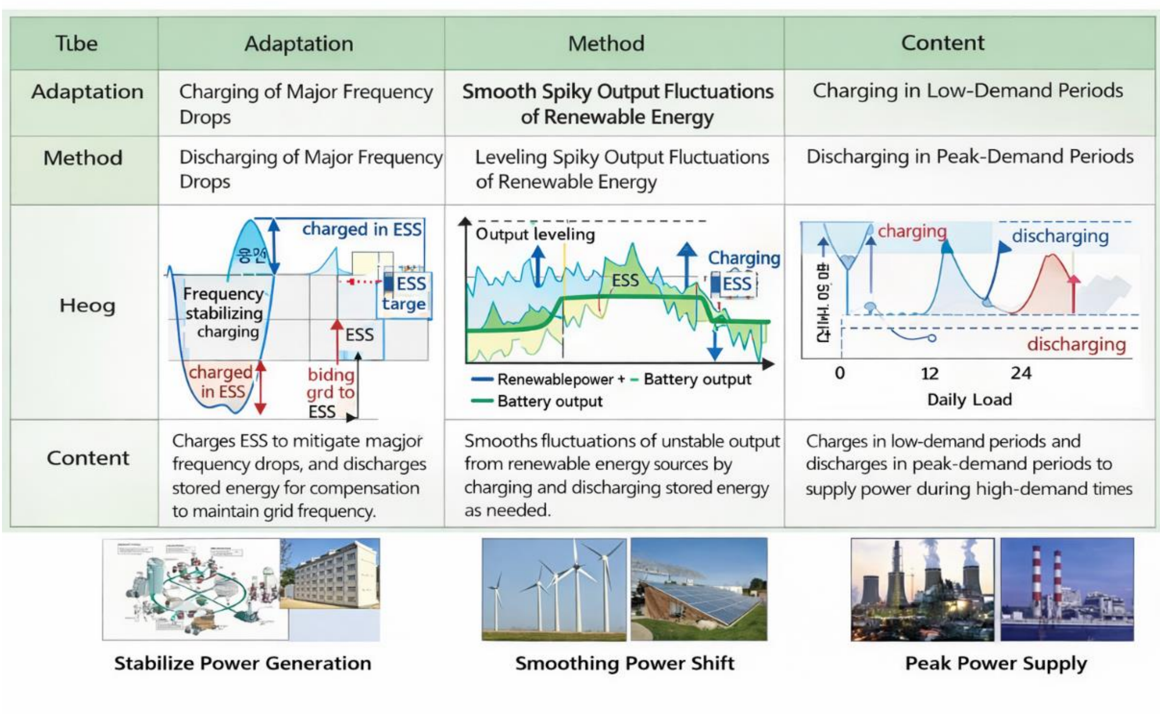

Fig. 2: Application fields of the ESS.
Source: Created by the authors.

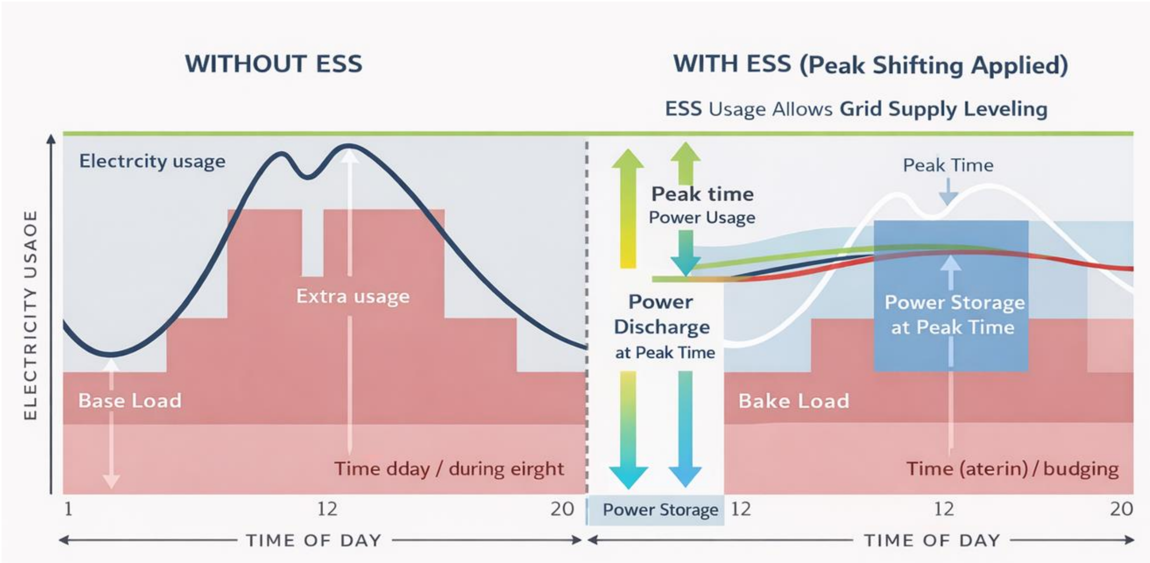

Fig. 4: Peak Load Mitigation by ESS.
Source: Created by the authors.

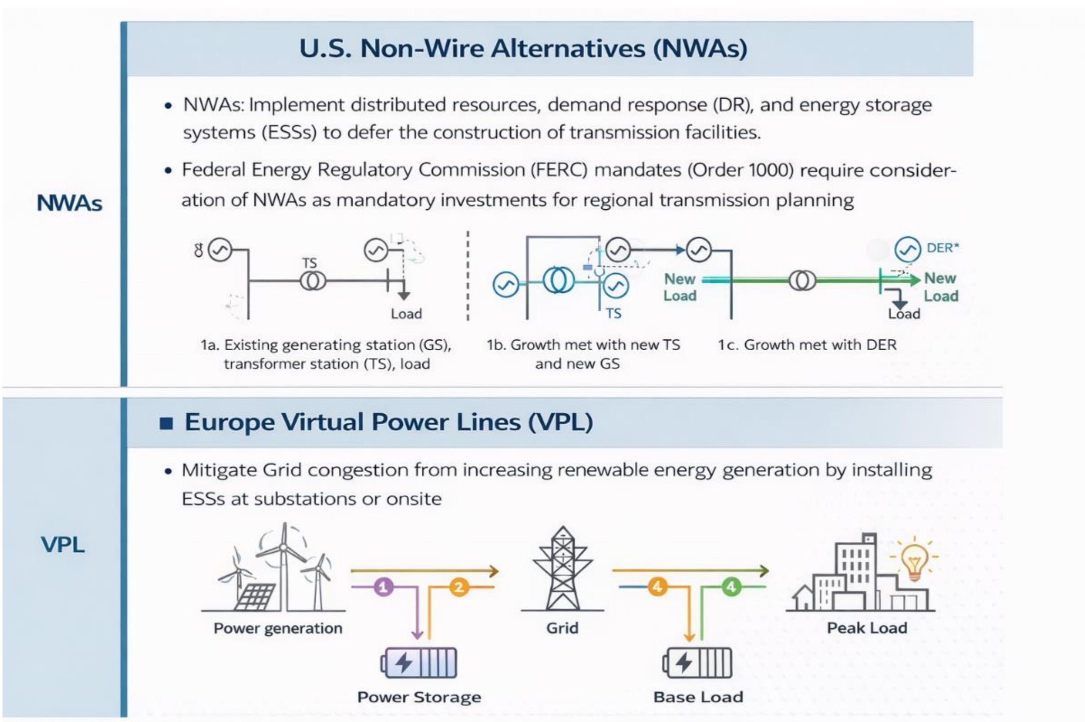

Fig. 5: ESS Supporting the Power Grid.
Source: Created by the authors.

Ahmed G. Abo-Khalil,
Abdel-Rahman Al Qawasmi

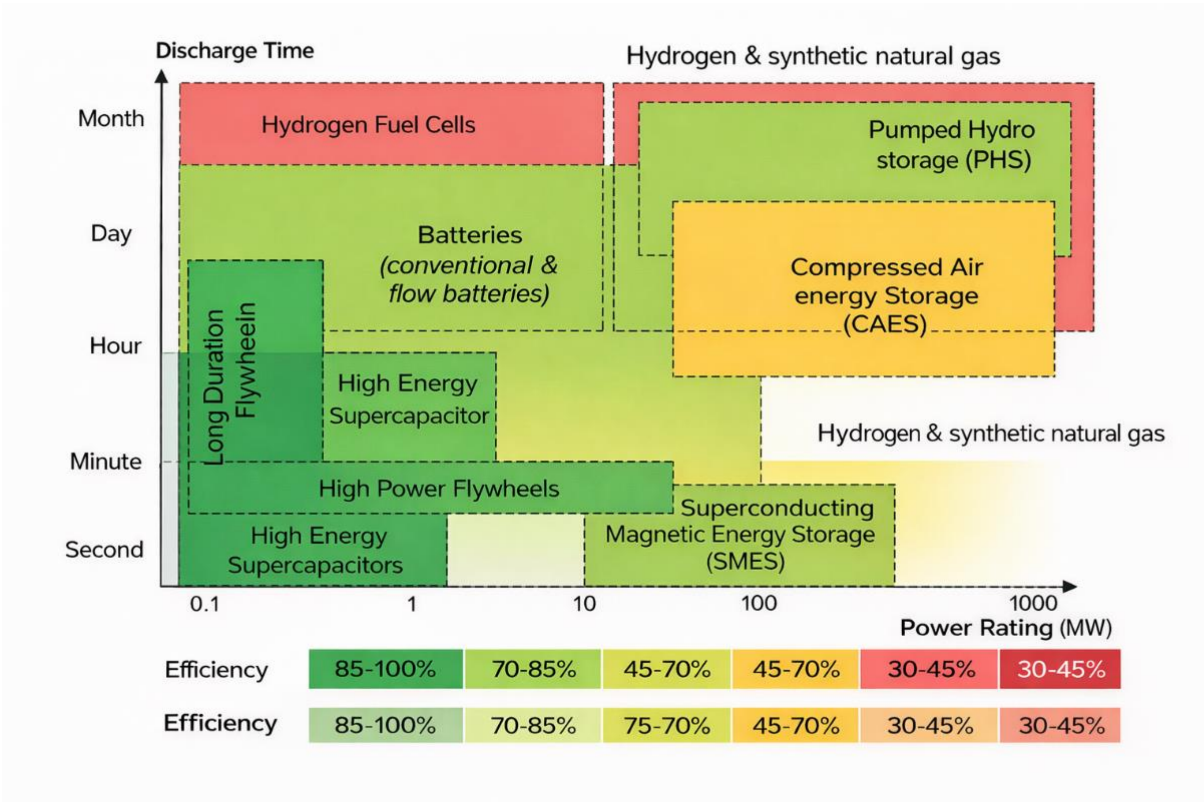

Fig. 6: Discharge Duration and Capacity Characteristics for Each ESS.
Source: [36]

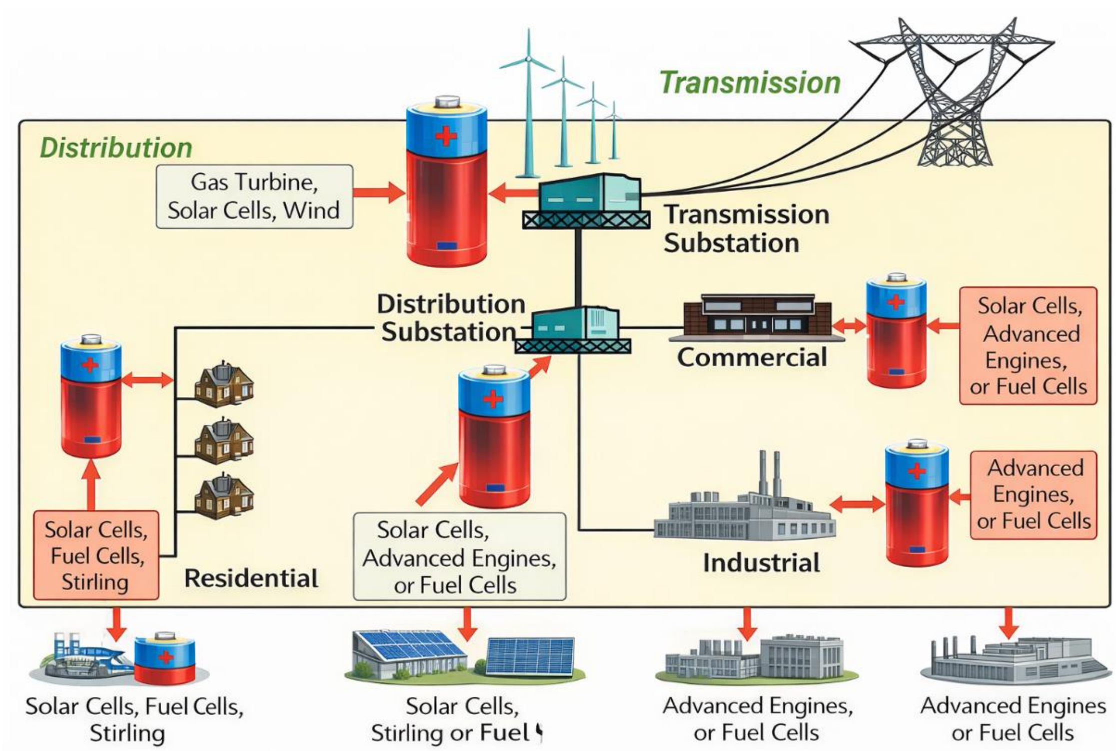

Fig. 8: Configuration of the Future Power System.
Source: Created by the authors.

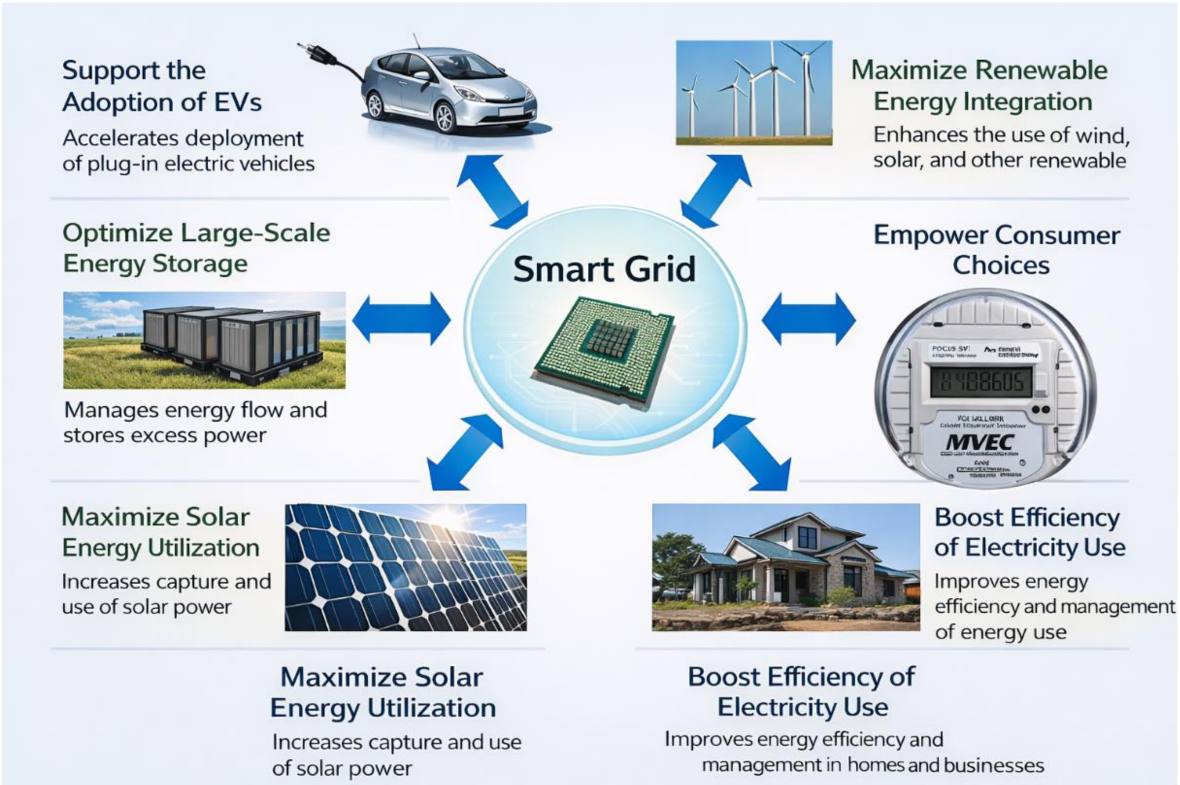

Fig. 9: Smart Grid Implementation Technology.

Source: Created by the authors.

Table 1. Several purposes, functions, and benefits of the ESS

Category	Function	Estimated Benefit (per 100 MW)	Description
Generation Resource	Capacity Resource	$1.74 million	Generates revenue by participating in the capacity market
	Energy Resource	$0.83 million	Generates revenue by participating in the energy market
	Frequency Regulation (GFC)	$3.28 million	Responds instantly to real-time frequency fluctuations
	Automatic Frequency Control (AGC)	$1.16 million	Charges/discharges to adjust power output
	SMP Arbitrage (Time-based trading)	$1.53 million	Generates revenue through time-based SMP price differences
	Transmission Congestion Relief	$1.71 million	Creates profit by charging and discharging during congestion
Load Resource	Demand Resource (Capacity)	$0.56 million	Operates as a demand response (negative load) to support the system
	Time-of-Use (TOU) Optimization	$0.74 million	Reduces electricity costs and increases revenue by responding to peak/off-peak pricing
	Emergency Demand Reduction	$0.56 million	Reduces power consumption during system emergencies
Renewable Support	Output Stabilization of Renewables	$1.89 million	Mitigates rapid output fluctuations of renewable energy
	Continuous Output Smoothing	$0.72 million	Maintains stable renewable energy output
Power Quality	Inertia Provision	$0.60 million	Supports grid stability considering low-inertia systems
	Voltage Stability Improvement	$0.21 million	Improves voltage stability by compensating for rapid load changes and reactive power

Source: Created by the authors.

Table 2. Industry trend of the ESS key components

Category	Battery	PCS (Power Conditioning System)	SI (System Integrator)
Business Nature	• Equipment industry • Requires large-scale investment	• Assembly industry • Requires small to medium-scale investment	• Equipment industry • Requires small to medium-scale investment
Manufacturer Characteristics	• Strong presence of companies from Korea, China, and Japan • U.S. and French companies relatively weak • Limited influence of SMEs	• Traditionally strong charger manufacturers are centered in the U.S., Switzerland, the Netherlands, and France	• (Large-scale) Utility companies, existing PCS manufacturers, and specialized SI firms mainly in Germany and China • (Small-scale) Presence of companies in Japan, Germany, China, Korea, and the U.S., including large corporations and SMEs
Market Environment	• Continuous large-scale facility investment required • Market dominated by large corporations • Difficult environment for SMEs	• Market dominated by large corporations to ensure high technical capability and quality assurance	• (Large-scale) ESS SI companies capable of EPC roles are required • (Small-scale) The market is dominated by large firms to ensure competitiveness in quality/price and after-sales service

Source: Created by the authors.

Table 3. Functional Application Areas of ESS

Category	Function	Application
Power System Stability Support	Reactive Power Supply (VAR Compensator)	Supplies reactive power to the grid to regulate voltage
	Improvement of Transmission Stability	Enhances voltage stability by compensating for sudden power/load changes, sag, resonance, and other transient phenomena
	Mitigation of Instantaneous Output Fluctuations of Renewable Energy	Mitigates sudden output variations of renewable energy sources
	Mitigation of Output Fluctuations in Grid-Connected Renewable Energy	Maintains stable output of renewable energy sources
	Frequency Regulation Service (FR)	Maintains power balance through immediate charging/discharging in response to frequency changes (G/F Control, AGC)
Power System / Market Support	Transmission Congestion Relief	Generates revenue through discharge during congestion when transmission expansion is delayed
	Demand Resource Bidding (DR Capacity)	Participates in capacity markets using demand reduction resources (electricity trading)
	Time-of-Use Demand Response (TOU-based DR)	Reduces electricity cost and contracted capacity by responding to time-based pricing
	Energy Arbitrage (SMP Arbitrage)	Generates revenue by bidding based on time-varying SMP prices
	Capacity Provision	Generates revenue by participating in the capacity market
	Reserve Capacity	Generates revenue by participating in the reserve market
Backup Power Generation	Emergency Power Supply (UPS, Uninterruptible Power Supply)	Minimizes outage damage by operating as emergency power during power interruptions

Source: Created by the authors.

Table 4. Comparison of Characteristics by Power Generation Type.

Category	Combined Cycle Gas Turbine (CCGT)	Open Cycle Gas Turbine (OCGT)	Coal Power	Hydropower	Nuclear Power
Start-up Time (Hot Start)	50–60 min	< 20 min	1–6 hours	1–10 min	13–24 hours
Ramp Rate (Output Variation Rate)	5–10%	20–30%	1–5%	20–100%	1–5%
Time to Reach Maximum Output (0–100%)	1–2 hours	< 1 hour	2–6 hours	< 10 min	15–24 hours
Minimum Generation Requirement	25%	25%	30–40%	15–40%	30–50%
Generation Cost (KRW/kWh)	121.2–202.1	121.2–202.1	45.7–70.9	—	3.6

Source: Created by the authors.

Table 6. ESS Application Service Areas**.**

Application Area	Detailed Service Applications
Generation Services	• Electric Energy Time-shift (Arbitrage) • Supply Capacity
Power System Ancillary Services	• Frequency Regulation • Reserve • Voltage Support • Black Start • Other Related Uses
Transmission Services	• Transmission Upgrade Deferral • Transmission Congestion Relief
Distribution Services	• Distribution Upgrade Deferral • Voltage Support
Renewable Support Services	• Renewable Capacity Firming (Mitigation of Short-Term Output Fluctuations) • Renewable Grid Integration (Mitigation of Continuous Output Fluctuations; Maintaining Stable Renewable Output) • Power Quality
Customer-Side Energy Storage Services	• Power Reliability • Electric Energy Time-shift • Demand Charge Management

Source Created by the authors.

Table 7. ESS Application vs. Technology Suitability Matrix.

Application / Technology	**Pumped Hydro**	**CAES**	**Lead-acid**	**NaS**	**Li-ion**	**Flow Battery**	**SMES**	**Supercapacitor**	**Flywheel**	**Hydrogen**	**Thermal Storage**
Load Leveling (Arbitrage)	●	●	○	○	●	●	⊗	⊗	◐	○	○
Supply Capacity	●	●	○	○	●	●	⊗	⊗	◐	○	○
Frequency Regulation	○	○	○	○	●	○	●	●	●	◐	⊗
Reserve	●	●	○	○	●	○	●	●	●	◐	⊗
Voltage Support	○	○	○	○	●	○	●	●	●	⊗	⊗
Transmission Congestion Relief	●	●	○	○	●	●	⊗	⊗	◐	○	○
Transmission Upgrade Deferral	●	●	○	○	●	●	⊗	⊗	◐	○	○
TOU Rate Management	○	○	○	○	●	●	⊗	⊗	◐	○	○
Peak Shaving	○	○	○	○	●	●	⊗	⊗	◐	○	○
Power Reliability	⊗	⊗	●	●	●	●	●	●	●	○	⊗
Power Quality	⊗	⊗	◐	◐	●	○	●	●	●	⊗	⊗
Renewable Integration	○	○	○	○	●	●	○	○	○	●	◐
Renewable Firming	○	○	○	○	●	●	○	○	○	●	◐
Centralized Power Generation	●	●	⊗	⊗	○	○	⊗	⊗	⊗	●	●

● Excellent ○ Good ◐ Fair ◌ Poor ⊗ Incompatible

Source: [39]

Table 8. Characteristics and Challenges of Power Systems by Variable Renewable Energy (VRE) Share.

Stage	**VRE Share**	**Power System Characteristics**	**Key Challenges**
Stage 1	≤ 3%	VRE has almost no impact on the overall power system. VRE output affects only localized areas near connection points.	Consider additional requirements in the Grid Code. Review localized grid operation impacts.
Stage 2	3–15%	The impacts of VRE become noticeable. System operators recognize the operational impacts of VRE capacity and adapt operational patterns to accommodate it.	Strengthen grid connection rules and improve the Grid Code. Introducing forecasting systems. Develop grid planning considering VRE.
Stage 3	15–25%	Priority given to flexibility. High uncertainty and variability make flexible resources important. Expansion of short-term variability and more frequent power imbalances.	Expand output forecast systems. Increase flexible resources. Improve coordination between transmission and distribution operators.
Stage 4	25–50%	Grid stability becomes increasingly important. Periods occur when VRE supplies 100% of demand. VRE affects system stability, requiring wide-area grid reinforcement and improved flexibility.	Ensuring grid stability becomes the highest priority. Enhance system flexibility and VRE grid contribution.
Stage 5	–	VRE expansion leads to structural oversupply. Large-scale curtailment occurs when supply exceeds demand.	Electrification of end-use sectors. Address long-term supply-demand imbalance.
Stage 6	–	Seasonal imbalance between VRE supply and demand. Seasonal supply shortages occur. Renewable generation alone may not meet demand.	Power conversion and storage technologies (e.g., gas & hydrogen). Seasonal storage solutions.

Source: [40]

Table 9. Effects of Applying Energy Storage Systems (ESS) to the Power System

Power System Component	**Limiting Factors**	**Effects of ESS Application**
Fuel	Price Volatility	Risk Mitigation
Generation	Load Factor	Base Load Balancing
Transmission	Local Congestion	Congestion Relief
Transmission	Overall Utilization Decline	Improved Utilization Rate
Distribution	System Stability	System Stabilization
Retail (Sales)	Sensitive Loads	Improved Power Quality

Source: Created by the authors.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

A. G. A: Conceptualization, Methodology, Investigation, Writing – original draft. [Author 2]: Formal analysis, Visualization, Writing – review & editing.

A. K. A: Supervision, Validation, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This research was funded by the university of Sharjah research fund No. (23020406247).

Conflict of Interest

The authors declare no conflict of interest.