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Integrating Battery Storage with Renewables: A Techno-economic Analysis

(On-grid and off-grid solutions)

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List of Abbreviations

AC	Alternate Current
BESS	Battery Energy Storage System
BMS	Battery Management System
C	C-Rate
CF	Capacity Factor
DC	Direct Current
DERs	Distributed Energy Resources
DOD	Depth of Discharge
EMS	Energy Management System
FO&M	Fixed Operations & Maintenance Cost
Hz	Hertz
IGCEP	Integrated Generation Capacity Expansion Plan
KE	K-Electric
kW	kilowatt
kWh	kilowatt-hour
LCOE	Levelized Cost of Energy
Lithium Ion	Li-ion
MoE	Ministry of Energy
MW	megawatt
NEP	National Electricity Plan
NEPRA	National Electric Power Regulatory Authority
NTDC	National Transmission & Despatch Company
Pmax	Max Power
PCS	Power Conversion System
RE	Renewable Energy
REs	Renewable Energy Sources (Wind and Solar)
ROE	Return on Equity
ROEDC	Return on Equity During Construction
SOC	State of Charge
SOH	State of Health
UNE	Universal National Electrification
VO&M	Variable Operations & Maintenance

Glossary

Base demand:

Base demand represents the consistent and continuous demand of electricity over an extended period such as a day, a month or a year. Base demand is linked with the essential services that occur continuously such as streetlights, refrigeration and some industries.

CTBCM:

CTBCM stands for Competitive Trading Bilateral Contracts Market. It is a market mechanism that facilitates the trading of electricity through bilateral contracts between buyers and sellers in a competitive environment. CTBCM allows market participants, such as generators, retailers, and large consumers, to negotiate and enter into contracts for the purchase and sale of electricity at mutually agreed prices and terms.

IGCEP:

Indicative Generation Capacity Expansion Plan refers to the power generation planning which involves strategy for producing electricity to meet the demand of consumers. IGCEP includes determination of optimum mix of power generation sources that can meet the electricity demand based on least cost. In Pakistan, the System Operator (National Transmission & Despatch Company) is mandated to prepare the IGCEP every year with a ten-year rolling horizon.

Peak charge avoidance:

Refers to the strategies employed to reduce electricity bills by shifting energy consumption to off-peak hours or using alternative energy sources and storage systems to minimize reliance on grid.

Peak demand:

Peak demand refers to the instance when electricity demand is maximum. It represents the highest level of electricity consumption that occurs during the periods of high activity such as turning on an air conditioner during heat wave, during a hot summer day.

Spinning reserve:

Refers to the portion of power generation capacity that is online and synchronized with the grid but not supplied to consumers. The generators providing spinning reserve are kept in standby mode and are ready to increase their output in the event of sudden load fluctuations. Spinning reserves play an important role in grid stability by providing response to unforeseen fluctuations in supply or demand.

RE curtailments:

Refers deliberate reduction or limitation of electricity generation from renewable energy sources such as wind or solar power plants due to over generation of electricity from renewable energy sources relative to demand or capacity of the grid. It usually occurs when the electricity demand is lower but electricity production from renewable energy sources is maximum. In Pakistan, another major reason behind RE curtailments is obsolete transmission infrastructure.

Take or Pay Fuel contracts:

In these types of agreements, a fixed amount of fuel (e.g., RLNG) is secured for the contract duration, and the supplier guarantees its availability at defined intervals. Consequently, a power plant is obligated to consume the contracted amount of fuel or incur charges for it, for instance, if a power plant shuts down due to low demand and does not require fuel.

Energy density:

Associated with batteries, energy density refers to the amount of energy in kilo watt-hours (kWh) that can be stored in battery per unit mass (kilograms). It indicates how much energy can be stored in the battery for every kilogram of battery's weight.

State of Charge (SOC):

Associated with batteries, SOC refers to the level of energy that is stored in a battery relative to its maximum capacity. SOC is expressed in percentage and is an essential parameter to avoid over charging and over discharging of a battery.

State of Health (SOH):

Associated with batteries, SOH refers to the overall condition of battery as compared to its original performance capability. It measures how well a battery can charge and discharge along with charge and storage duration. SOH is influenced by operating conditions.

Peaking plants:

Refers to thermal power plants that are operated to meet the short duration demand spikes (peak demand) in a system. These power plants are usually HSD/RFO based power plants having fast ramp rates but significantly higher operating costs.

Capacity factor:

Capacity factor is a term used in the context of power plants to describe the ratio of actual generation over a specified time interval to the maximum possible generation if the plant were operating at full capacity. It is calculated as the ratio of actual power output to the maximum power output.

Variable Operations & Maintenance (VO&M) cost:

Expressed in USD per Mega-Watthour, VO&M refers to the costs associated with ongoing operations and maintenance of a power plant or an energy storage system. The span of these costs varies and depends upon the nature of operations and the sort of maintenance that is required. Typically, VO&M costs include fuel costs, labor costs, lubricants costs and repairs & overhauling etc.

Fixed Operations & Maintenance (FO&M) costs:

Expressed in USD per kilo-watt-year, FO&M costs refers to the expenses associated with ongoing operations and maintenance of a power plant or an energy storage facility that remain constant irrespective of the output of a power plant or an energy storage facility.

Scope 2 emissions:

Represents indirect greenhouse gas (GHG) emissions resulting from purchased electricity generation by an organization. These GHG emissions occur outside of the organization’s direct control but are linked with the organization’s electricity consumption.

Scope 3 emissions:

Include all the indirect greenhouse gas (GHG) emissions that arise throughout an organization’s value chain, including activities such as procurement, transportation, waste disposal, and employee commuting. These emissions are not directly owned or controlled by the organization but are associated with its operations and activities.

Executive Summary

The electricity generation and consumption patterns vary significantly across sectors (industrial or commercial/ residential) and countries (developing or developed). While conducting the electricity generation planning exercises for the optimum electricity generation mix, the dynamics of that sector and country must be considered, including GDP growth rate, currency depreciation, inflation rate, industrial and residential demand projections, and projections of exogenous variables (Population, crude oil prices). These indicators significantly impact the electricity consumption in a country and are therefore crucial for crafting a well-thought-out and optimum electricity generation mix plan.

A critical examination of Pakistan's electricity consumption patterns reveals that electricity demand in Pakistan is highly variational, and while the peak demand has been increasing consistently over the past decade, the base demand has barely witnessed any significant increase. The negligence of this simple fact while drawing up electricity generation plans and policies has resulted in an installed generation capacity which is almost double the size of the utilized capacity. This concerning disparity, which has burdened ordinary consumers and business owners alike, must prompt reflection on the trajectory of decision-making and policy formulation in Pakistan. This current study is one such attempt of research-based reflection seeking to explore the potential of renewable energy technologies (REs) coupled with Battery Energy Storage Systems (BESS) in the context of variable demand patterns in Pakistan.

Energy storage technology using batteries has already demonstrated its commercial viability and estimates show that BESS market is expected to reach between 120 – 150 USD Billions by 2030 as per McKinsey's article on Battery energy systems[1].

The reason there has been so much inclination towards BESS installation is its compelling benefits. One of the key advantages of using BESS is that it offers improved frequency regulation as compared to traditional spinning reserves from thermal power plants and thereby also reduces RE curtailment. Likewise, BESS can provide peak charge avoidance to consumers via off-grid energy during on-grid peak consumption intervals. There are also instances where RE generation does not coincide with the electricity demand; the surplus power, in this case, can be stored in the BESS and used later when the demand is higher. Another significant benefit of integrating BESS with REs is promoting environmental sustainability by reducing dependence on fossil fuel power generation. The strategic integration of BESS with REs is a pivotal solution, offering peak support to avoid expensive Take or Pay fuel contracts and driving down consumer end tariffs.

The landscape of BESS is rapidly evolving, witnessing remarkable technological advancements. In the exciting world of emerging technologies in BESS, the most notable technologies include Lithium-ion (Li-ion), Flow batteries (Iron or Vanadium), Sodium-Sulfur (NaS), and nickel-cadmium. While the BESS technologies are still evolving, this study focuses on Li-ion technology for maturity, low cost, and high efficiency. With a compelling energy density (150-250 Watt-hour per Kilogram), extended life span, and eco-friendliness, Li-ion emerges as the forefront choice for innovative energy storage solutions [2].

For on-grid RE-BESS systems, the study proposes a hybrid model (wind and solar combined) to deal with yearly variation of peak and base demand in the national grid. Under this combination, solar and wind technologies complement one another across diurnal and annual cycles while the surplus energy generated is stored by the batteries during periods of low demand. Similarly, for off-grid RE-BESS systems or independent projects of wheeling/CTBCM regime, the study explores the "firm capacity" scenario during which reliable and uninterrupted power supply can be provided for selected intervals. On a broader level, this study aims to answer two questions. First, Can Renewable energy sources coupled with Battery energy storage systems serve the purpose of meeting variational demand patterns of Pakistan?" Second, can these systems be utilized by on-grid and off-grid consumers at an affordable and competitive cost? Both the questions have been answered in the study after extensive data collection, simulation, and analysis.

The use cases presented within this study are designed to provide off-grid and on-grid solutions by leveraging daily and yearly generation patterns of REs coupled with the BESS. This innovative synergy ensures optimal energy utilization for a sustainable and resilient power ecosystem. The study provides a comprehensive examination of these use cases involving the integration of solar with BESS, wind with BESS, and the synergy of both REs with BESS. The outcomes include a detailed techno-economic analysis of the integrated hybrid solution (REs coupled with BESS), revealing its potential to introduce flexibility into the power system. The use case on the Firm capacity reveals that optimal combination of solar and batteries is well suited for the firm capacity while peak support can be best provided by combination of hybrid power plant (wind and solar) with the BESS.

Beyond enhancing the system's flexibility, the study underscores significant economic advantages in avoiding costly fossil fuel-based power generation. Ultimately, adopting REs coupled with BESS emerges not only as a strategic choice for flexibility but also as a catalyst for financial savings.

1. Introduction

The electricity demand in Pakistan has seen a dynamic trajectory over the recent years due to macro and micro economic factors, including population growth, economic development, and changing electricity consumption patterns. During peak intervals, the demand-supply gap often strains the power grid, leading to power outages, blackouts, and challenges in meeting the country's electricity needs. The peak demand trend as per the NEPRA's state of industry report [3] is shown in the figure below:

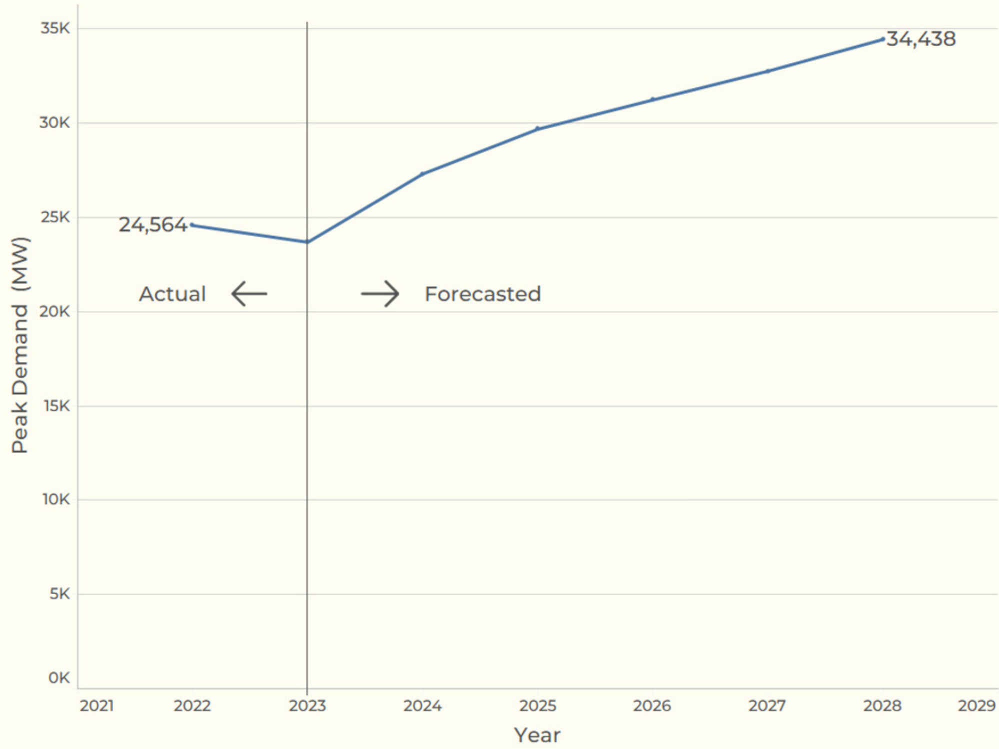


Figure 1 - Peak Demand Trend (Source: NEPRA State of Industries Report 2023)

The outlook of Pakistan's electricity demand profile exhibits two peaks during a typical day; one peak occurs during the day due to commercial and industrial loads, while the second peak occurs during the evening due to residential loads as shown in the figure 2 below [4]. The primary reasons behind these varying demand patterns include weather conditions, seasonal variations, spatial differences, and consumer behaviors. To ensure grid stability and reliability, efficiently meeting these fluctuations is imperative.

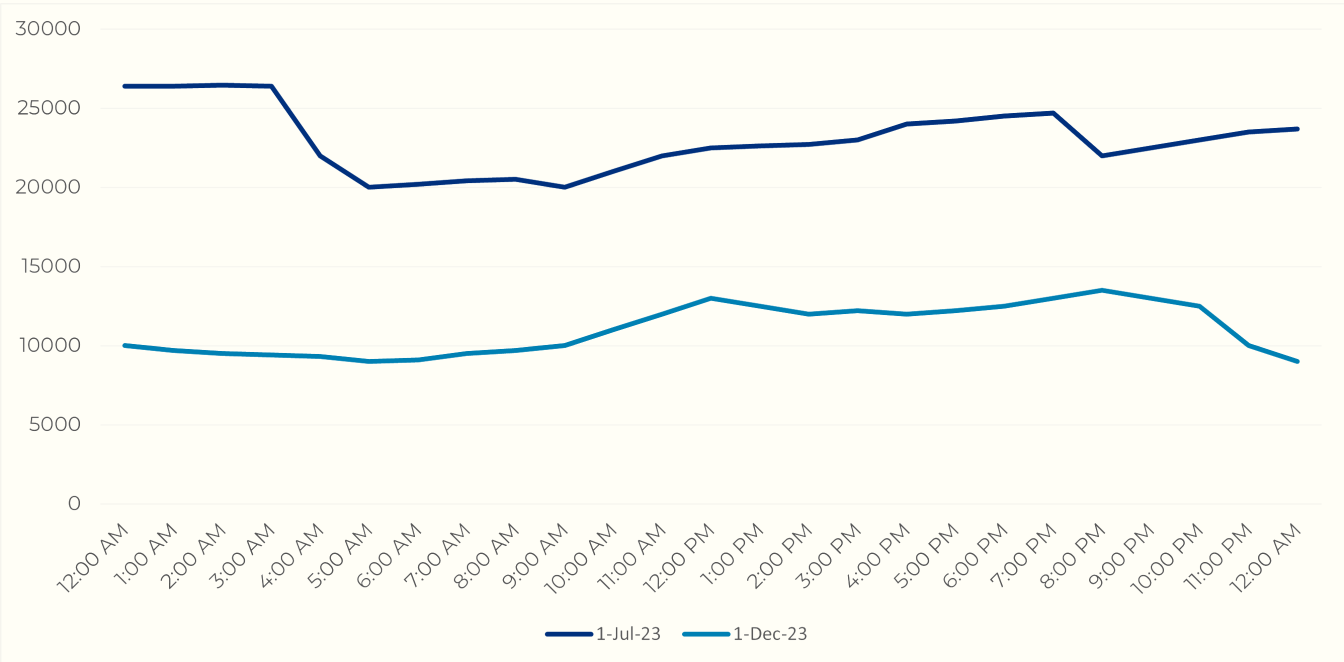


Figure 2 - Hourly Load Demand (Source: NTDC)

In Pakistan's Power sector planning, the key focus is on understanding and managing peak demand. Peak demand intervals are those where electricity demand is at its maximum, during the summer when the air conditioning load is at its maximum. The planning process involves forecasting peak demand to ensure sufficient electricity generation capacity to meet these high-demand periods, thereby averting shortages or blackouts.

Pakistan possesses significant potential for wind and solar energy due to its geographical positioning. Yet, there is only a 6% share of REs in the country's power generation mix. Due to intermittency issues and variability associated with REs like wind and solar, REs have been critiqued, particularly in Pakistan. While REs are acknowledged for their cost-effectiveness in electricity generation, there is a prevalent perception that the inherent variability of REs makes them costly. There is also an argument that baseload generation is imperative for a power system, and peak demand intervals can only be best met with thermal power plants, so-called peaking plants. Despite concerns about the variability of REs in power systems, there needs to be more discussion on leveraging the combined potential of REs and BESS to meet the fluctuating electricity demand in Pakistan effectively. This hybrid proposition serves the purpose of meeting the variational nature of demand in Pakistan. It will also replace the costly fossil fuel power generation and avoid expensive take or pay fuel contracts. Since BESS can provide better frequency regulation due to fast demand response time, fast ramp rates, accurate frequency regulation due to controlled output, and can be easily scaled up or down, integrating them with REs will complement the RE generation by effectively managing the intermittencies associated with REs.

Various technologies for large-scale renewable energy storage currently exist, each with unique advantages, limitations, potential, and applications. Among the notable options are lithium-ion batteries, sodium-sulfur batteries, vanadium-redox flow batteries, metal-air batteries, pumped hydro storage, flywheels, and compressed air energy storage. These technologies are either actively employed or under consideration for grid-scale energy storage. Battery technologies used in energy storage devices can be categorized based on energy density, charge, and discharge efficiency (round trip efficiency), lifespan (cycles), and eco-friendliness. Energy density refers to the energy a system can store per unit volume or weight. For instance, lithium secondary batteries have an energy storage capacity ranging from 150 to 250 watt-hours per kilogram. They can hold 1.5 to 02 times more energy than sodium-sulfur (Na–S) batteries, 02 to 03 times more than redox flow batteries (vanadium or iron), and around 05 times more than lead storage batteries. A comparison among various BESS technologies is provided in the table 1 below:

Technologies	Lithium-Ion				Sodium Sulfur	Redox Flow
	NMC	NCA	LFP	LTO		
Characteristics						
Operating Life (Yrs.)	10	12	20	20	>20	>20
Cycles	4800	5000	12000	15000	20000	20000
Energy Density (kWh/m3)	200-250	250-300	95-200	50-80	150-350	30
Efficiency (%)	97	97	97	97	90	90
Capital cost ($/kWh)	170-210	250-300	150-190	400-900	300-600	240-390
Operating cost ($/kWh)	8	8	8	6	8	11
Maturity	Mature	Mature	Mature	No	No	No

Table – 1 Comparison Matrix-Storage technologies (Source: World Bank)

Therefore, Lithium-ion-based BESS is considered for this study due to its maturity, cost-effectiveness, and higher efficiency than other technologies. For its maturity, flexibility, and adaptability, Li-ion BESS has been actively deployed across the globe for large-scale energy storage. According to the International Energy Agency, China has emerged as the market leader in grid-scale battery storage additions, with yearly installations approaching approximately 5 Gigawatts. Next to China is the United States, which is also heavily investing in the grid-scale BESS, with annual installations reaching up to 4 GW [[5]. According to PV Magazine, Ark Energy secures approval for 275 MW and 2200 MWh Lithium-iron phosphate batteries that will be the world's largest 08-hour Lithium battery in the Australian state of New Wales [6].

One of the primary reasons behind this significant attention to Li-ion batteries is the reduction of Li-ion battery pack prices that hit the record low price of $139 per kWh in 2023, according to Bloomberg NEF. Further technological advancements and improvements in the manufacturing process would also decrease the Li-ion battery pack prices to $113 per kWh in 2025 and $80 per kWh in 2030, as per BNEF [7].

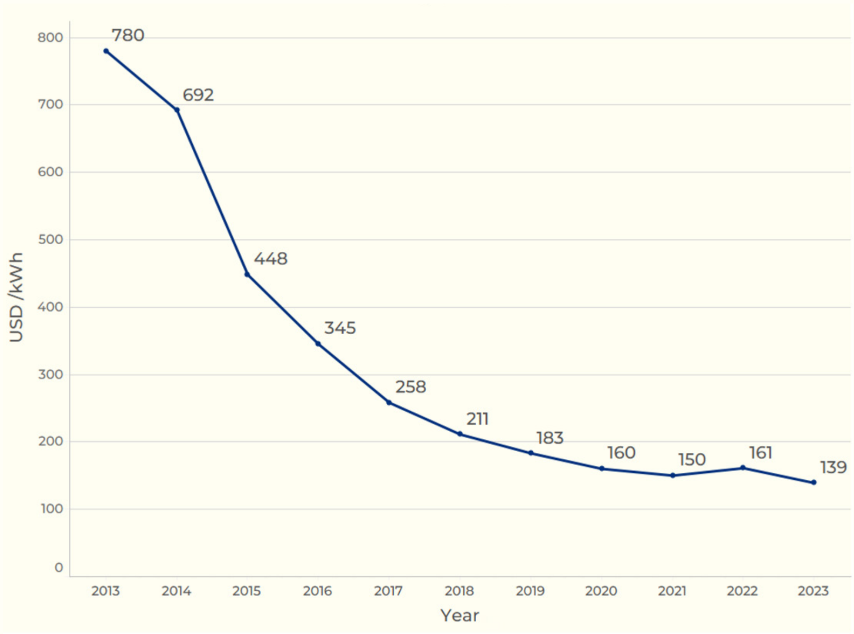


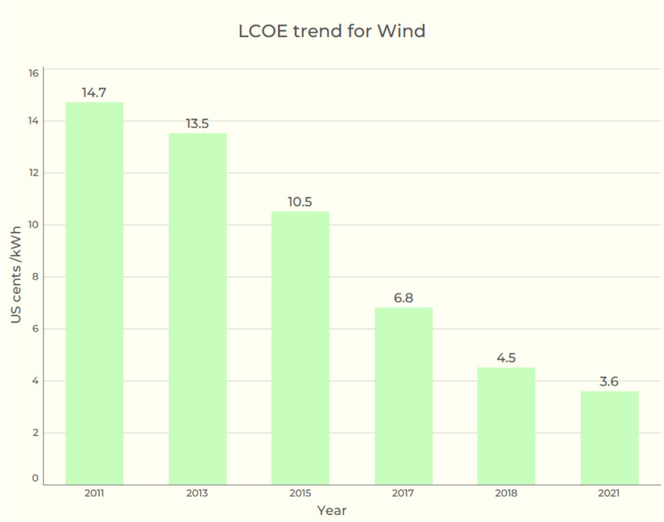
Figure 3 - Cost trend of the battery pack (Source: Bloomberg NEF 2023 Lithium-ion Battery Price Survey)

The techno-economic specifications highlighted above underscore the pivotal role of Li-ion Batteries, making them the cornerstone of this study. Hence, this study aims to investigate Li-ion batteries' economic and commercial feasibility through a comprehensive techno-economic analysis, focusing on specific use cases.

While applications of the BESS include frequency regulation, peak shaving, spinning, non-spinning and supplemental reserves, voltage support, and black start, this study underscores two compelling use cases: firm capacity and peak support. The firm capacity use case examines the practicality of utilizing this hybrid solution (BESS integrated with REs) to ensure a consistent and uninterrupted power supply at specified intervals. The firm capacity provided is essential for overcoming the inherent variability of REs. It is pivotal in maintaining grid stability, meeting energy demand, and ensuring a reliable and consistent power supply. Since it has been argued that large-scale integration of REs can pose severe problems to grid stability, integrating the BESS with REs can alleviate this problem by providing the firm capacity. By adequately scheduling the charging and discharging of BESS integrated with REs, they can ensure firm power during peak hours or specified intervals. Certain REs like wind and solar tend to have periods of higher generation during the off-peak hours that align with the valleys of net demand; for instance, wind generation can be maximum in the evening. Therefore, charging the BESS during the valleys of net demand and discharging them during peak hours can enhance the overall load factor and avoid the need for costly thermal peaking plants.

The electricity demand outlook of Pakistan indicates that demand in Pakistan is variational; the variations between the peak demand and base demand align with the generation of REs, which makes REs a cheaper source of meeting this variational demand. The adaptability of REs coupled with the BESS allows better management of the variational nature of demand by storing surplus power during off-peak hours and utilizing the stored power during peak demand intervals. This hybrid proposition would offer a flexible and sustainable approach that complements Pakistan's evolving energy needs in the coming years.

Regarding economic feasibility, the REs has seen a significant cost decline in Pakistan, with wind tariffs decreasing by 73% from 2011 to 2020 and solar tariffs falling by 78% from 2014 to 2020, the LCOE of wind and solar is given below as per NEPRA's tariff determinations [8].



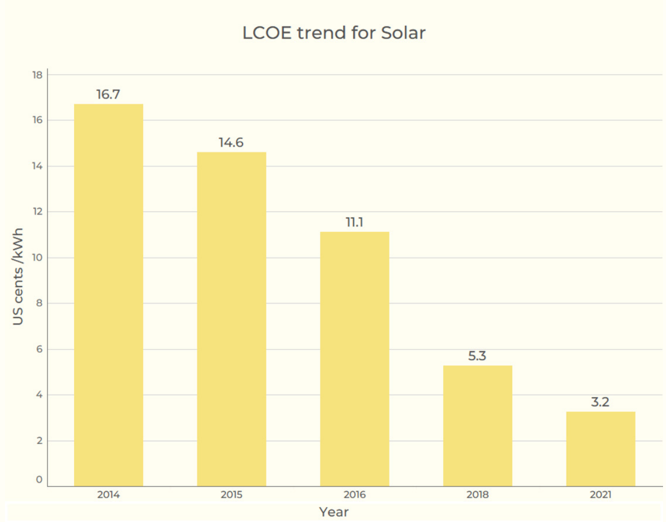


Figure 4 - Levelized Tariff for Wind & Solar Power plants (Source: NEPRA)

*Awarded to Moro Power Company Ltd., ** Awarded to Siachen Energy Limited

Hence, the topographic conditions, economic feasibility of REs, and their generation trends show that REs coupled with the BESS can address Pakistan's variations in electricity demand. This study's main objective is to demonstrate the techno-commercial viability of the hybrid proposition involving the coupling of REs with BESS.

This demonstration is accomplished through a comprehensive techno-economic analysis based on two critical use cases: firm capacity and peak support.

2. Overview of BESS

The BESS comprises four essential elements: a battery system, an inverter or power conversion system (PCS), a battery management system (BMS), and an energy management system (EMS).

- The battery system consists of multiple cells organized into modules, forming the battery pack. These cells convert chemical energy into electricity.
- The BMS ensures the safety of the battery system by monitoring cell conditions, including state-of-charge (SOC) and state-of-health (SOH). Battery Thermal Management System (B-TMS) safeguards against potential risks such as fires by controlling the temperature of cells in terms of temperature gradients in battery packs.
- The EMS monitors and controls power flow within the storage system, overseeing the operation of the BMS, PCS, and other components. It analyzes energy-related data to optimize the system's resources. The system monitoring and control is done by integration with overall supervisory control and data acquisition (SCADA).
- The inverter or PCS transforms direct current (DC) from the batteries into alternating current (AC) and vice versa. Equipped with bi-directional inverters, BESS systems facilitate both charging and discharging.

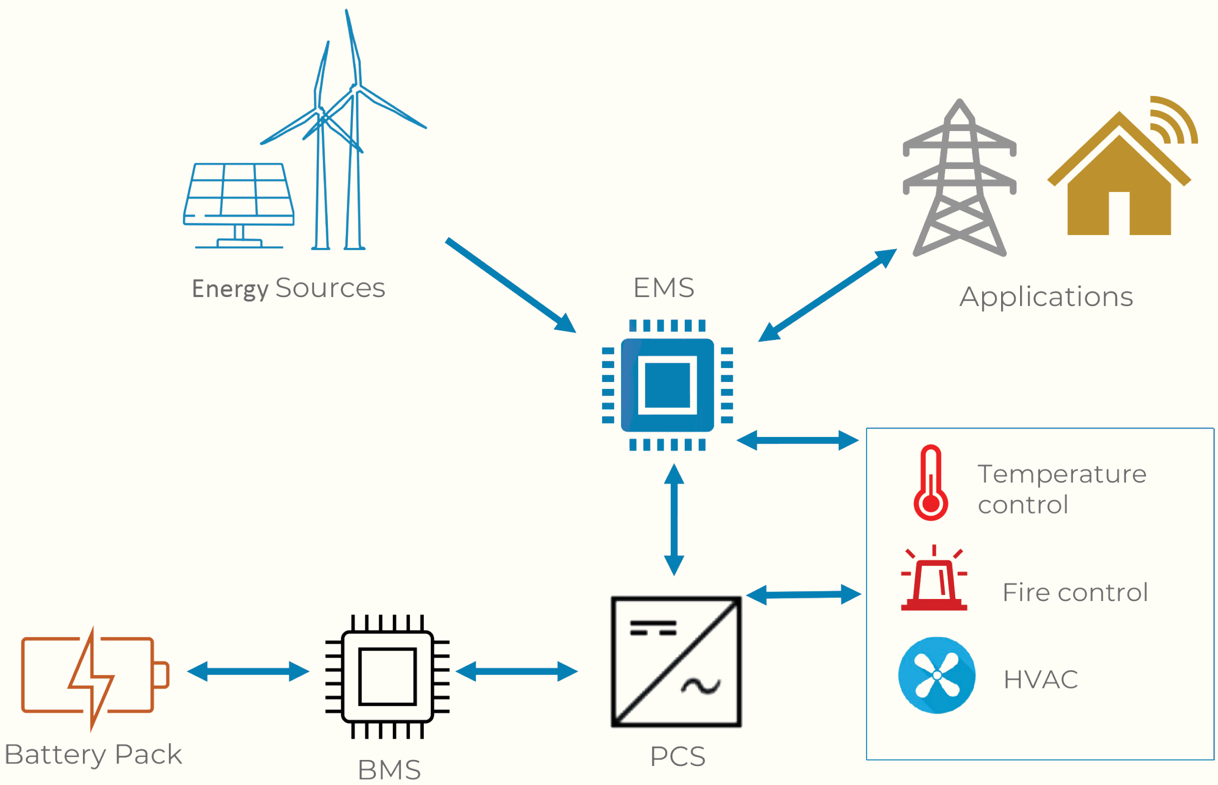


Figure 5 - Elements of BESS

Similarly, the BESS modeling design parameters are as follows.

Energy capacity: This is the maximum amount of energy that the battery can store, usually measured in megawatt-hours (MWhs) or gigawatt-hours (GWhs).

Max Power (Pmax): Max power is the power in kilowatts (kW) or Megawatts (MW) at full discharge measured at the connection point, i.e., excluding inverter losses.

Round-trip efficiency: The round-trip efficiency of the battery is the ratio of energy charged and discharged in the BESS. It is expressed as a percentage. The round-trip efficiency may represent the total DC to DC or AC to AC efficiency of the BESS incorporating all the losses, i.e., Self-discharges and other electrical losses.

Maximum State of Charge (SoC): Maximum SoC is a BESS's allowable minimum state of charge. This is expressed as a percentage of the Capacity defined.

Minimum SoC: Minimum SoC is the allowable minimum SoC of a BESS. This is expressed as a percentage of the Capacity defined.

PCS: Power conversion system comprised of inverters.

Depth of Discharge (DOD): The difference between the maximum and minimum state of charge is called depth of discharge.

Battery Cycle: A battery cycle refers to the complete process of charging a battery from its minimum SoC to its maximum SoC and then discharging it back to the minimum SoC again. Typically, a battery storage unit undergoes one cycle per day.

Battery Life: The expected lifespan of a battery is either expressed in years.

Cost Parameters: Various cost-related parameters such as capital, operating, maintenance, and replacement costs.

C-Rate: C-Rate is a unit which is used to express the rate at which a battery is charged or discharged. It represents the current relative to battery's capacity. 1C represents current will be fully charged or discharged in a battery in 01 hour.

Battery Energy Storage Systems (BESS) sizing varies depending on the intended applications. For frequency regulation, BESS sizes typically range from 10 to 40 MW, addressing short-term power needs with targeted discharge durations ranging from 15 minutes to 01 hour. In transmission upgrade deferral cases, where the goal is to delay utility investments in transmission system upgrades or avoid such investments, BESS sizes typically range between 10 to 100 MW, with targeted discharge durations of 2 to 8 hours. For providing electric supply capacity by deferring or avoiding new capacity additions, BESS can be sized up to 500 MW, with targeted discharge durations between 2 to 6 hours.

3. Use-Cases

BESS offers multiple applications, providing essential ancillary services such as Frequency Regulation, Peak Shaving, Grid Balancing and market arbitrage. Frequency regulation refers to a process where the alternate Current (AC) is maintained at a constant value of 50 Hz or 60 Hz, depending on the region. In Pakistan, the Normal operating range for frequency is 49.8Hz to 50.2Hz, and the Contingency Operating range is 49.3Hz to 50.5Hz as per the Grid Code 2023. Frequency regulation is essential to restore the balance between supply and demand. Failing to do so results in a malfunction that could cascade and cause widespread blackouts in the overall power system. There can be multiple reasons behind frequency deviations such as dynamic fluctuations in demand and generation that result in temporary imbalances and eventually cause frequency deviations. A significant contributor to frequency deviations is large scale integration of Renewable energy sources. Since REs are asynchronously integrated with power systems through power electronic devices, their inertial support to the power system is limited. This low inertia can lead to increased frequency oscillations that might exceed operating standards and eventually cause potential threat to uninterrupted power supply.

The primary responsibility of the System Operator is to ensure the system possesses adequate generation capacity to meet peak demand throughout the entire time horizon. Traditionally, costly thermal generators, known as peaking plants, have been employed to address this peak demand in accordance with the load curve. However, BESS also presents a cost-effective solution for meeting peak demand. Integrating REs with BESS empowers system operators to manage peak demand intervals efficiently. By strategically charging BESS during valleys of net demand and discharging them during peak demand intervals, the overall load factor of the system is enhanced, ensuring reliable demand management. This hybrid configuration of REs coupled with BESS has become increasingly economical, especially with the declining prices of BESS and REs. It can avoid costly peaking plants and fuel contracts, significantly advancing cost-effective and reliable peak demand management.

Market arbitrage using BESS involves taking advantage of price differentials between periods of low or high electricity demand or between regions with different electricity prices. BESS can be strategically charged when electricity prices are low and discharged when prices are higher to take market arbitrage opportunity. In this way, revenue can be maximized, and the costs of market participants can be minimized. In addition to this, stored energy in BESS during intervals of lower electricity prices can be used in ancillary service market for provision of ancillary services like voltage support and frequency regulation etc. However, this requires enactment of open market regulations entailed in the Competitive Trading Bilateral Contracts Markets (CTBCM) that are still pending in Pakistan. From the use cases of BESS described above, this study primarily focuses on two major applications: Firm Capacity and Peak Support, as these align well with the energy needs and dynamics of Pakistan's energy sector.

For the analysis of peak support case, hourly demand profiles from the National Transmission and Despatch Company (NTDC) and K-Electric (KE) during the fiscal year 2022 are utilized. Throughout the fiscal year 2022, the forecasted peak demand for NTDC was 24,755 MW, while KE's peak demand was 4,321 MW per the Indicative Generation Capacity Expansion Plan (IGCEP 2022) [9]. To facilitate comparison, both NTDC and KE demands are normalized, allowing for the analysis of relative trends. Normalization is achieved by dividing the respective hourly demands by the average demand of the entire fiscal year. Consequently, the peak normalized demand for NTDC reached 133 MW in quarter 3, while KE's demand peaked at 121 MW in quarter 2.

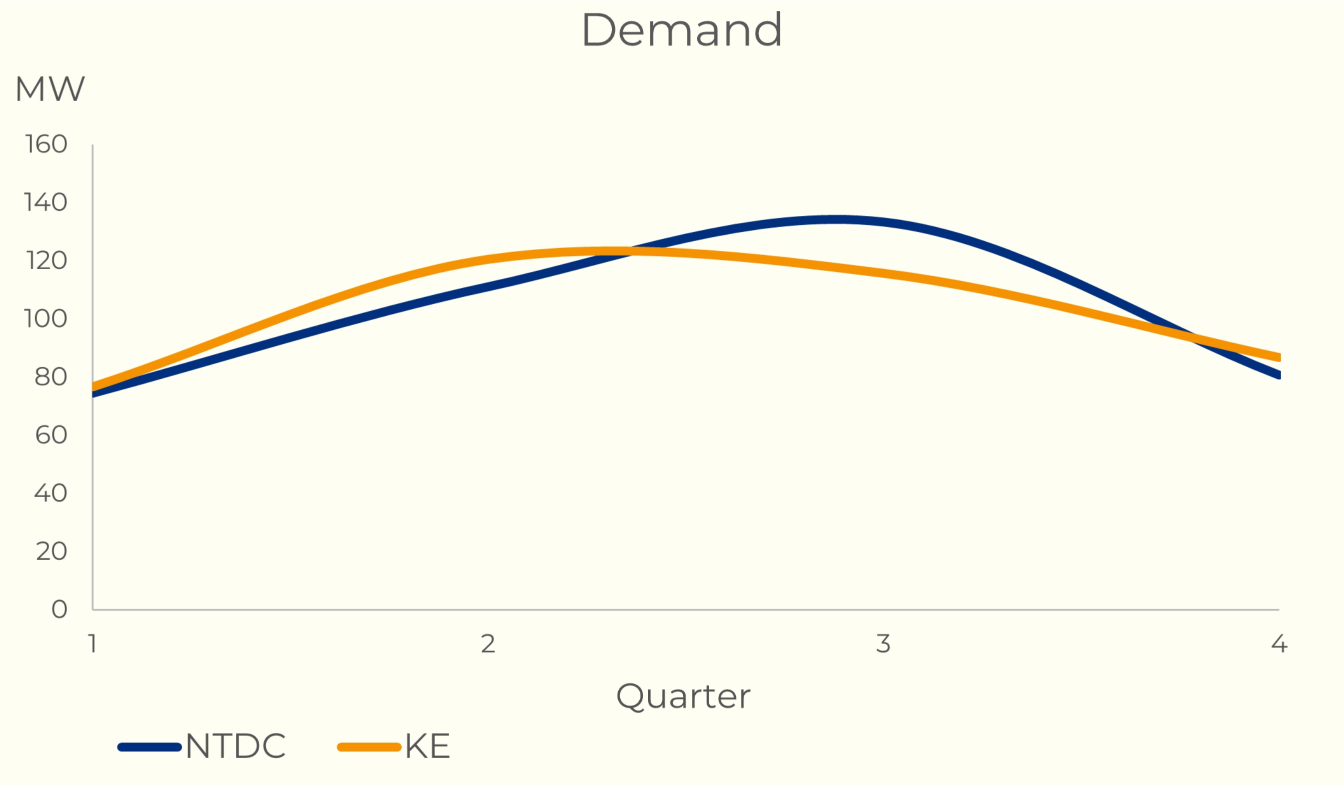


Figure 6 - Electricity Demand Pattern of NTDC & KE (Source: NTDC)

Note: these graphs have been normalized at 100 MW for the purpose of comparison

To meet this demand, an analysis of the generation profiles of REs is conducted quarterly. The analysis encompasses six REs i.e., net metering, utility-scale solar, and wind. Additionally, various hybrid profiles, incorporating specific combinations of wind and solar, are considered, as detailed in Table 2 below:

Power Plants	Variations	Capacity Factor (CF)
Solar Net metering	Solar only	17%
Utility-scale Solar	Solar only	22%
Hybrid-27	1:3 (wind-to-solar ratio)	27%
Hybrid-32	1:1 (wind-to-solar ratio)	32%
Hybrid-37	3:1 (wind-to-solar ratio)	36%
Utility-scale Wind	Wind only	40%
All the power plants (solar, wind, and hybrid) are 100MW		

Table 2: Power Plants Considered for analysis.

It is pertinent to mention that among the three hybrid systems, the most efficient configuration is Hybrid-37 (3:1 wind-to-solar ratio) owing to its higher capacity factor and cost optimality, which is further explained in the cost section of this report. In this study, the Hybrid-37 configuration is chosen among other hybrid systems for its higher capacity factor and economic feasibility. The analysis extends to the generation profiles of REs, examined hourly and yearly. Results indicate that solar exhibits significant daily variation with lower annual variation, while wind displays higher annual variation and more downward daily fluctuation. Comprehensive figures 7 & 8 illustrating the yearly and quarterly generation of REs alongside the demand profiles of NTDC and KE systems are presented below for clarity:

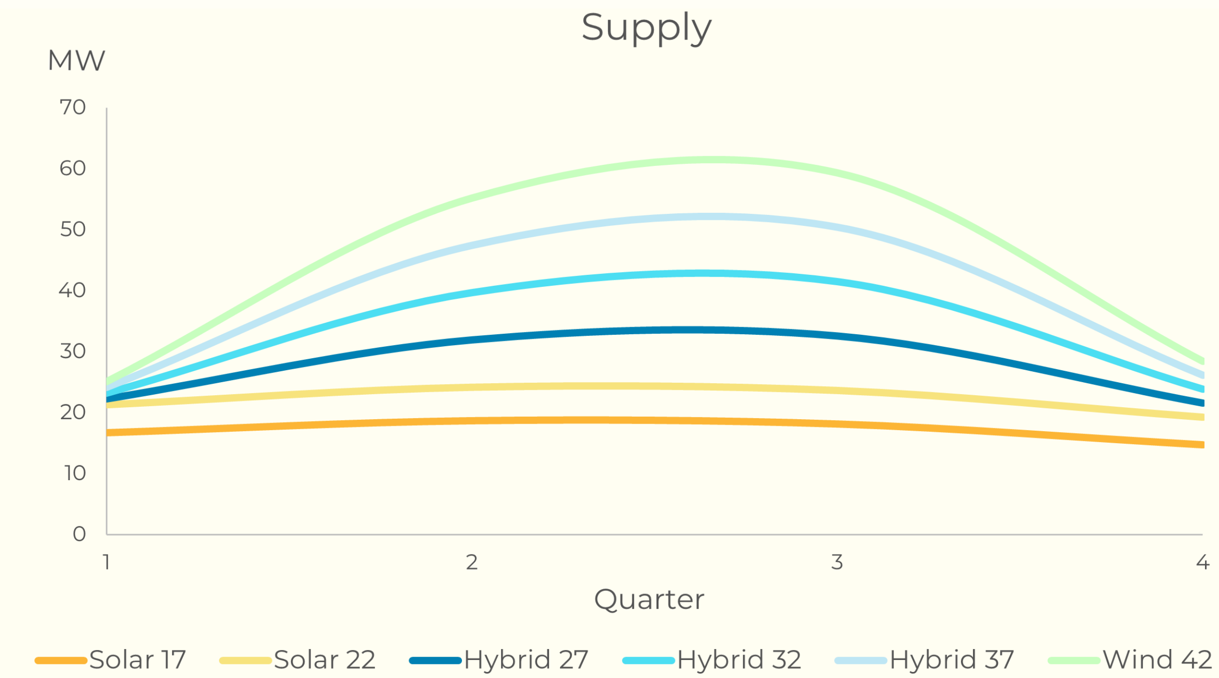


Figure 7 – Annual representative RE resource profiles

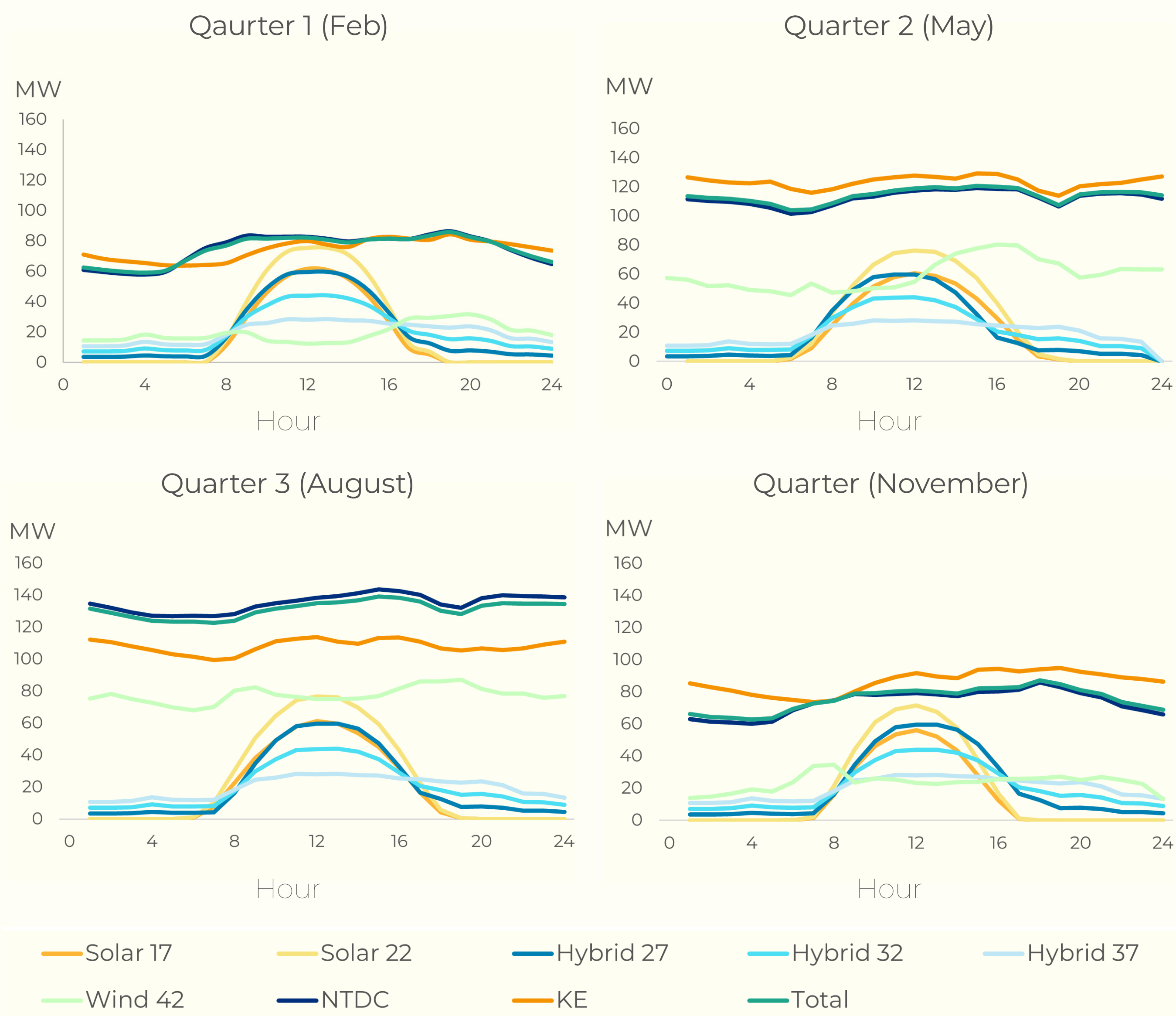


Figure 8 – Quarterly RE resource profiles against NTDC & KE demands

1. Firm Capacity

Expressed in kilowatts (kW) or Megawatts (MW), the firm capacity refers to the installed capacity that can reliably meet the demand during high-risk or peak intervals. The hybrid setting of REs paired with the BESS can contribute to the firm capacity. By adequately scheduling the charging and discharging of BESS, the energy stored in the BESS can be dispatched instantly when needed, ensuring consistent and robust capacity support. This configuration will provide a stable power supply even during variable generation intervals. In terms of applicability, this configuration of REs coupled with the BESS can be utilized to meet commercial load that usually lasts up to 08 hours, for instance, offices and markets. On a broader scale, this hybrid configuration can also be used as a customized package for industrial consumers having one or two working shifts in a day.

2. Peak Support

Peak support refers to the reliable and continuous supply of power from alternative sources to offset high demand from consumers, simultaneously helping ease out fluctuations in the grid and avoid strain on the system during peak usage times. Owing to fast response time, ramping rates, and flexibility in controlling the output, BESS can effectively meet spikes in demand and offer grid stability.

4. Modeling Parameters:

The primary goal of a power system planner is to meet the demand in a reliable and cost-efficient manner while maintaining the energy security of the power sector. Therefore, it is imperative to comprehend the modeling parameters for a system. This study utilizes the following modeling parameters to achieve its objectives:

4.1. Demand:

The key to crafting a well-thought-out and effective power generation plan is understanding and meeting the electricity demand cost-efficiently. Since a power generation plan aims to meet the demand, it is imperative to analyze and understand the demand and devise strategies accordingly. The constant demand can be called the baseline heart of power grids. Continuous demand involves consistent and steady electricity demand over a longer time horizon, and it can be predicted more accurately because of its stability. The continuous demand/load usually includes residential loads like lighting, basic electronics, public infrastructures, and some industries. The continuous demand exhibits gradual changes that can be predicted more efficiently, for instance, commercial and industrial loads, owing to their shift patterns.

In this study, the continuous demand includes 10 MW, 15 MW, 20 MW, and 30 MW of continuous demand.

4.2. Battery Size:

Measured in units like kilowatt-hours (kWh) or Ampere-hour (Ah), battery size is the total amount of energy that a battery can store, like the dam storage system in the case of hydel power plants where water is held in the reserve which can be used later. For optimizing the BESS, the sizing of the battery plays a pivotal role. The size of the battery depends on several factors like expected energy needs, i.e., the consumption patterns of a region or the system that needs to be powered up, the duration for which battery backup is needed, and the depth of discharge. Careful consideration of these factors is essential for optimizing a BESS. In this study, the BESS size varies as per the demand profiles and power plant configurations and described in the findings of the study.

5. Findings of study

This study explores the two use cases of the BESS coupled with REs, the firm capacity, and the peak support. For this, four distinct demand profile scenarios are analyzed, encompassing 10 MW, 15 MW, 20 MW, and 30 MW of continuous demand. As mentioned earlier, various combinations of REs coupled with BESS are considered and analyzed to find the best match for fulfilling the demand profiles effectively and efficiently.

The detailed findings of the study are mentioned below scenario-wise:

5.1. Firm Capacity

For the “firm capacity” use case, the scenarios include the integration of a standalone solar power plant with the BESS, a standalone wind power plant with the BESS, and integrating a hybrid power plant (Solar and wind) with the BESS. The scenario-wise analysis is presented below:

5.1.1. Solar with BESS

In the first scenario focusing on firm capacity, the analysis considers three solar power plants with capacities of 100

MW, 70 MW, and 50 MW in conjunction with demand profiles. Given that solar power plants typically operate with capacity factor of approximately 21% to 22 % and generate electricity solely during daylight hours, these specific plant sizes were selected to ensure firm power supply. Various Battery Energy Storage System (BESS) sizes were evaluated to create firm support packages. Let's delve into the analysis of the 100 MW solar power plant:

5.1.1.a. Solar 100 MW against 10 MW continuous demand

A solar power plant rated at 100 MW, paired with a 137 MWh BESS, can reliably provide a continuous power supply of 10 MW throughout the day. Considering that the solar plant is inactive for an average of 13 hours daily, the BESS capacity needed to sustain a consistent 10 MW output is determined to be 130 MWh. We assumed a round-trip efficiency of 95% for the BESS, based on industry standards. As depicted in Figure 9 below:

The analysis shows that a 137 MWh BESS, combined with a 100 MW solar power plant, effectively meets the continuous 10 MW demand. Notably, there are intervals during which solar generation exceeds demand by a factor of five to six. This surplus energy presents opportunities for utilization, such as selling to the market or supplying multiple consumers. However, capitalizing on these opportunities would require regulatory frameworks conducive to competitive trading, such as the implementation of Competitive Trading Bilateral Contracts Markets (CTBCM) in Pakistan.

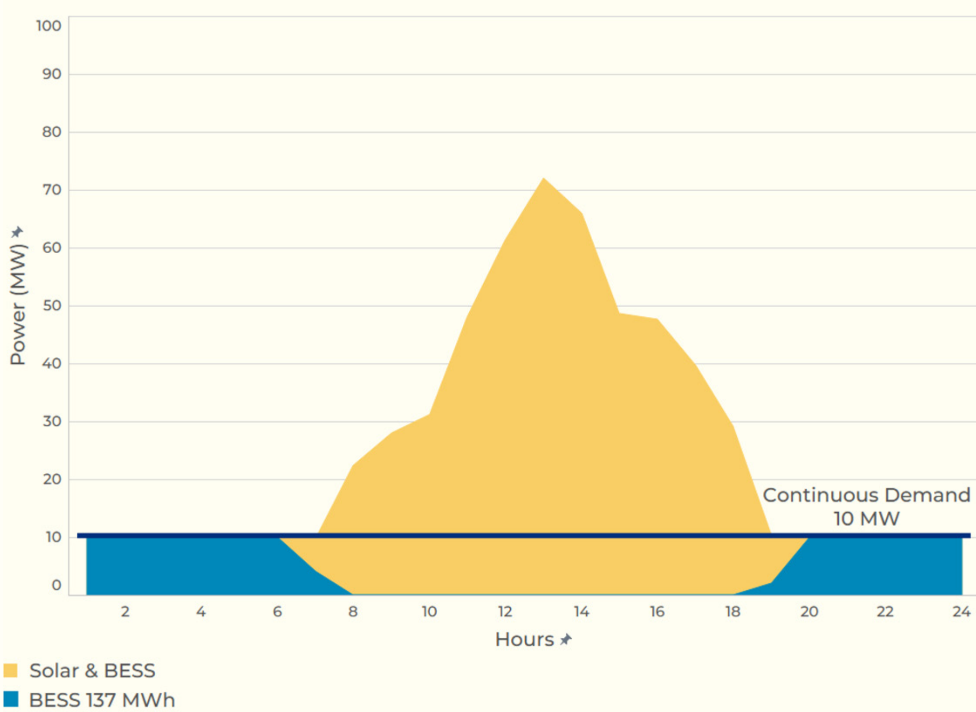


Figure 09 – 10 MW Firm support – All day

For detailed information on Levelized Cost of Energy and other cost parameters, please refer to the methodology section of this report under section 6.

5.1.1.b. Solar 100 MW against 15 MW continuous demand

In the next iteration, the continuous demand of 15 MW needs to be served. For this demand, a solar power plant of 100 MW is paired with 206 MWh BESS to ensure a consistent supply of 15 MW all day. The information is presented in the figure below:

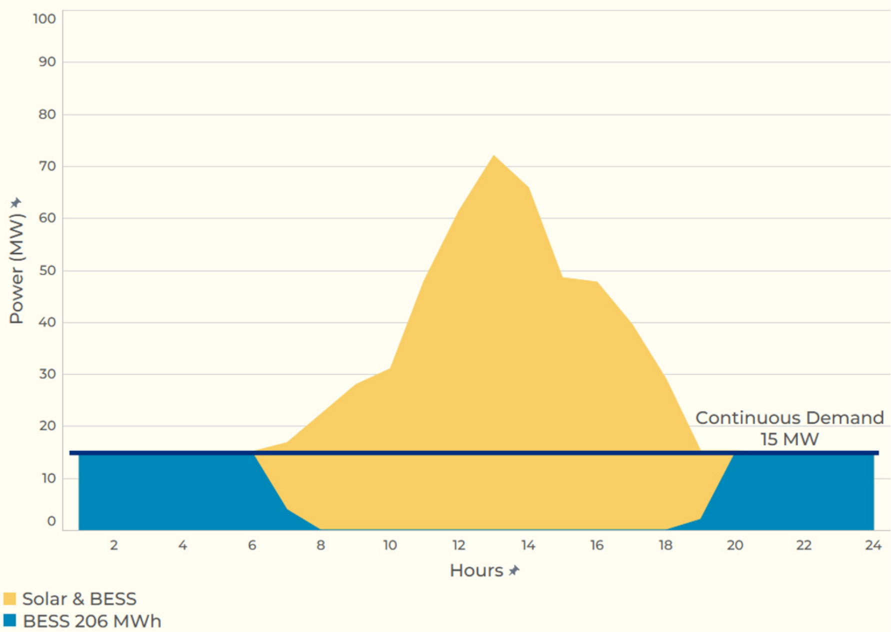


Figure 10 – 15 MW Firm support – All day

5.1.1.c. Solar 100 MW against 20 MW continuous demand

To ensure a consistent supply of 20 MW, a solar power plant with a capacity of 100 MW is integrated with battery energy storage systems (BESS) totaling 276 MWh. The sizing of BESS is determined by identifying periods of solar generation downtime and optimizing BESS charging schedules accordingly. It's worth noting the significance of BESS charging and discharging strategies, which can vary based on control algorithms such as fast or slow charging, depending on the C-Rate. For the purposes of this report, standard charging and discharging procedures are assumed. The configuration is shown in the figure below:

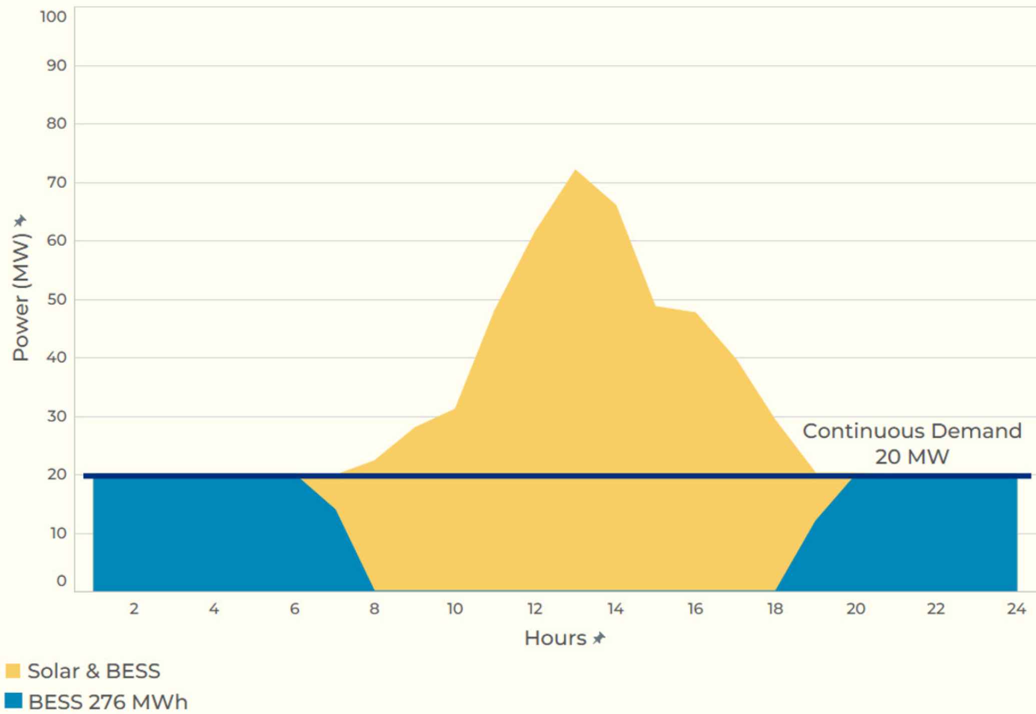


Figure 11 – 20 MW Firm support – All day

5.1.1.d. Solar 100 MW against 30 MW continuous demand

In the last scenario of 100 MW solar power plant, the continuous demand of 30 MW is considered. The analysis shows that a solar power plant of 100 MW is not capable of meeting consistent demand of 30 MW with any size of BESS as there is not enough generation to charge the BESS after serving the demand of 30 MW during daytime. However, a 100 MW solar power plant coupled with BESS of size ~127 MWh can provide firm support of 30 MW up to 14 hours. For this setting, 04 hours of backup is assumed from the BESS having capacity of ~31.7 MW (with 95 % round-trip efficiency) the configuration is shown in the figure below:

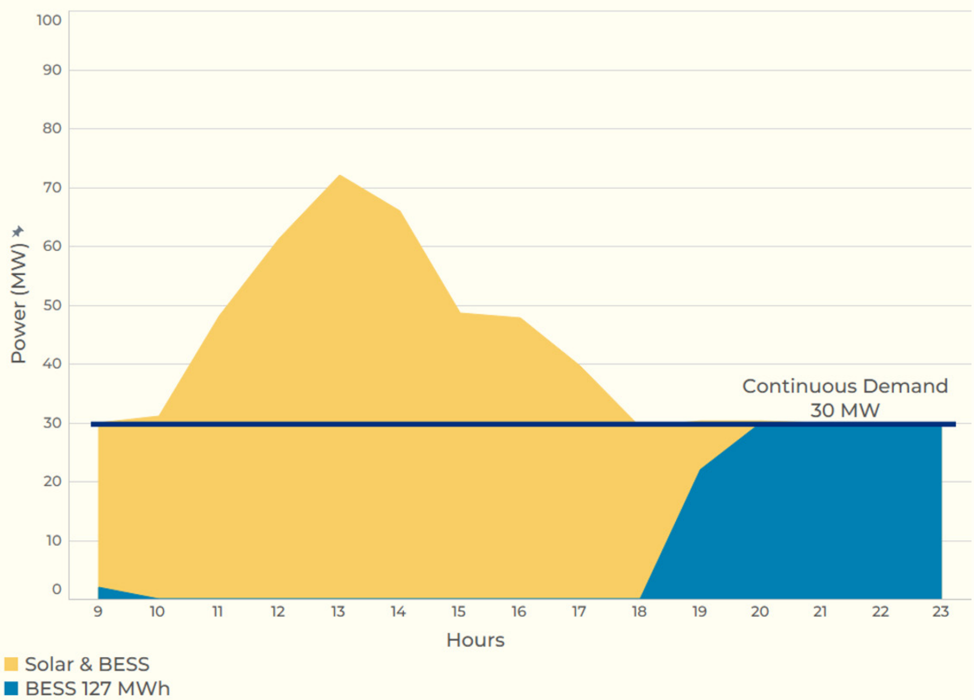


Figure 12 – 30 MW Firm support – 14 hours

5.1.1.e. Solar 70 MW against 10 MW continuous demand

In the second iteration, we explore the feasibility of a 70 MW solar power plant in optimizing combinations with Battery Energy Storage Systems (BESS) to effectively meet the specified demand profiles. Initially, we analyze the performance of a 70 MW solar plant coupled with a 137 MWh BESS to provide a consistent supply of 10 MW, as depicted in Figure 15 below:

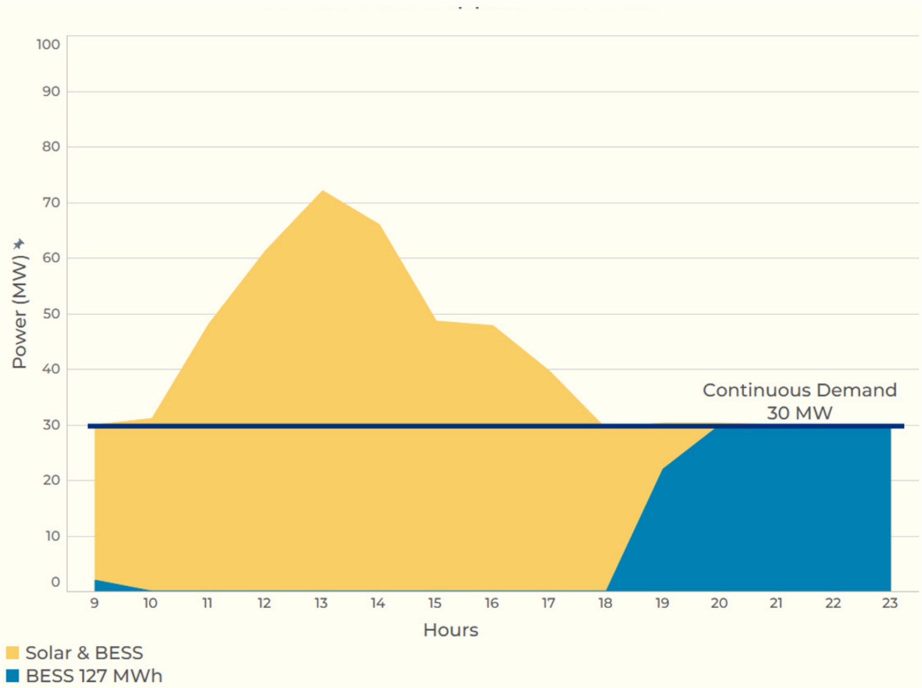


Figure 13 – 10 MW Firm support – All day

In contrast to solar power plant of 100 MW, a solar power plant of 70 MW can also meet the continuous demand of 10 MW when coupled with 137 MWh BESS and the surplus energy has also reduced as compared to 100 MW solar power plant. The comparison between LCOEs for both the settings is detailed in the methodology part under section 6.

5.1.1.f. Solar 70 MW against 15 MW continuous demand

In the scenario where a continuous demand of 15 MW is required, a 70 MW solar power plant paired with a Battery Energy Storage System (BESS) of approximately 206 MWh capacity proves capable of supplying firm support for the entire day. Since there are intervals when solar generation is twice or thrice than the demand to be served the battery sizing can vary however for this report, BESS size of 206 MWh is considered. The configuration is shown in the figure below:

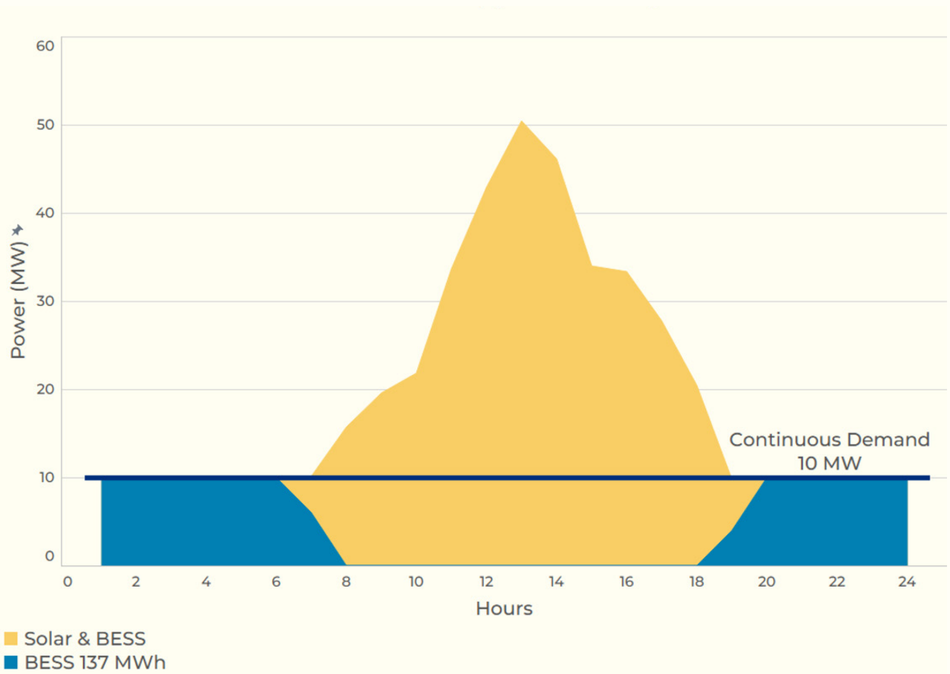


Figure 14 – 15 MW Firm support – All day

5.1.1.g. Solar 70 MW against 20 MW continuous demand

In the next iteration, the generation profile of 70 MW solar power plant is analyzed against the continuous demand of 20 MW, in this case the firm support of 20 MW can be supplied up to 14 hours by pairing BESS of ~85 MWh. The analysis is illustrated in the figure below:

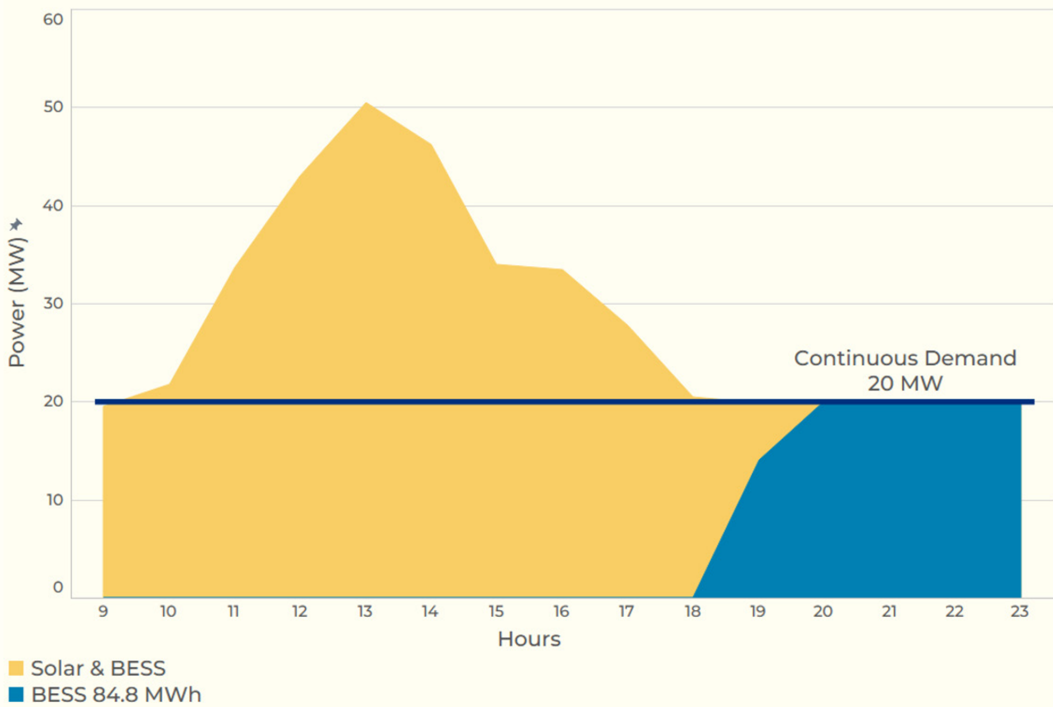


Figure 15 – 20 MW Firm support – 14 hours

5.1.1.h. Solar 50 MW against 10 MW continuous demand

In the final iteration, a 50 MW solar power plant in conjunction with demand profiles to find the optimal configuration for a hybrid power plant is examined. To meet a continuous demand of 10 MW, pairing the 50 MW solar power plant with a Battery Energy Storage System (BESS) of approximately 137.5 MWh ensures a consistent supply throughout the day. The analysis is illustrated in the figure below:

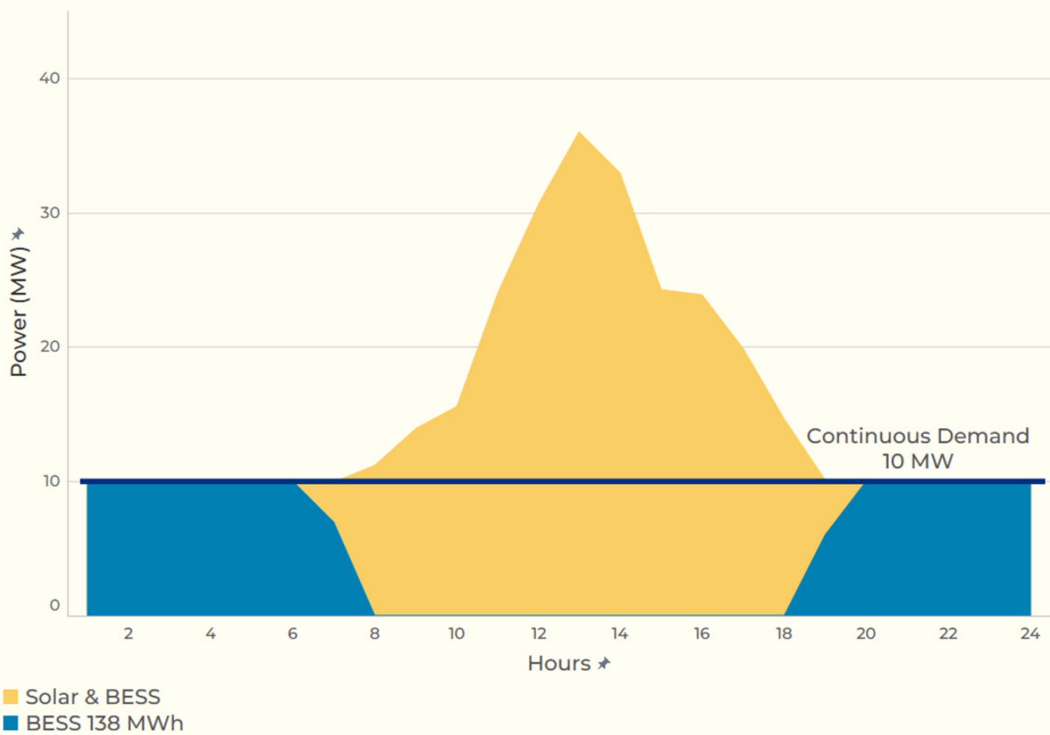


Figure 16 – 10 MW Firm support – All day

5.1.1.i. Solar 50 MW against 15 MW continuous demand

For the continuous demand of 15 MW, solar power plant of 50 MW paired with the BESS of 64 MWh can provide the firm support of 15 MW for up to 13 hours reason being not enough generation from solar power plant. This is illustrated in the figure below:

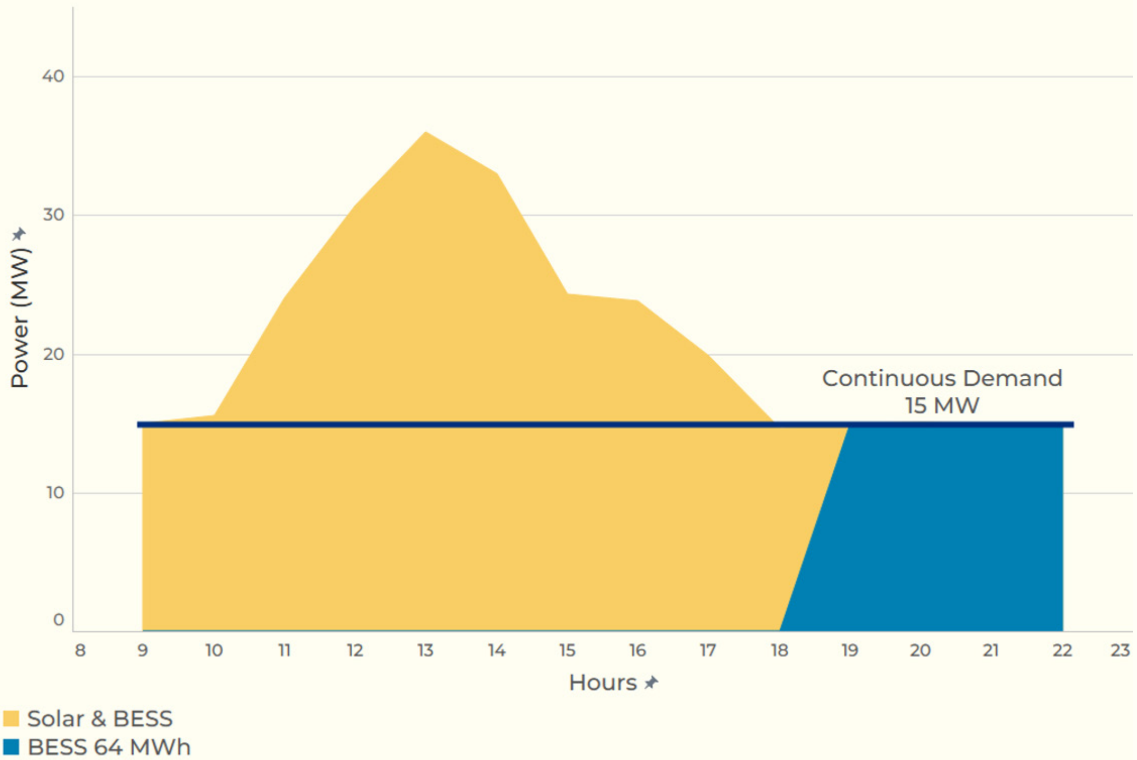


Figure 17 – 10 MW Firm support – 14 hours

The analysis reveals that combinations of solar power plants ranging from 100 MW to 50 MW, paired with varying sizes of Battery Energy Storage Systems (BESS), show the potential for hybrid setups to provide firm support. While all combinations highlight the feasibility of solar-BESS integration, some configurations offer firm support for limited durations. This hybrid proposition presents an opportunity for Renewable Energy (RE) developers to tailor offerings to bulk power consumers, particularly export-based industrial sectors. As industries face mounting pressure to reduce Scope 2 and Scope 3 emissions and meet science-based targets (SBTs) to remain competitive in global markets, securing access to clean energy becomes imperative especially for export-based industry. The firm support scenarios outlined in this report serve as a valuable reference for the development of customized products, positioning them as critical assets in Pakistan's electricity market, particularly following the implementation of Competitive Trading Bilateral Contracts Markets (CTBCM).

5.1.2. Wind with BESS

In contrast to solar power plants, wind power plants show low diurnal variations and significant yearly variations in their generation. The reason behind this varying generation pattern of wind power plants is that during windy seasons, the variations are minimal as per the topography of the region in which they exist, while in low wind periods, the generation is minimal. Therefore, integrating the BESS with a standalone wind power plant in an area with such variations is not technically feasible. This is evident from the results of the scenario in which a wind power plant of 100 MW is coupled with the BESS units of 20 MW and 60 MW, as shown in Figure below:

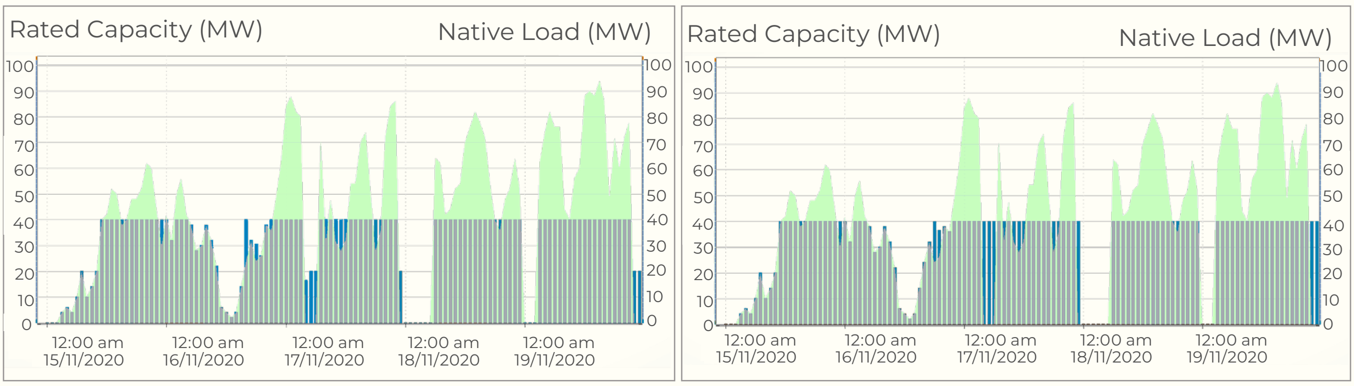


Figure 18 - Comparison of 40 MW demand served by 20 MW 4h and 60 MW 4h BESS with Wind

The extent to which a wind power plant can meet demand depends on seasons, i.e., wind seasons. For instance, a wind power plant of 100 MW coupled with 80 MWh BESS can meet the continuous demand of 10 MW and 20 MW during May and August when the wind speed is higher. However, this configuration cannot meet the demand during February and November when the wind speed is minimal, as depicted in Figures 19 & 20 below:

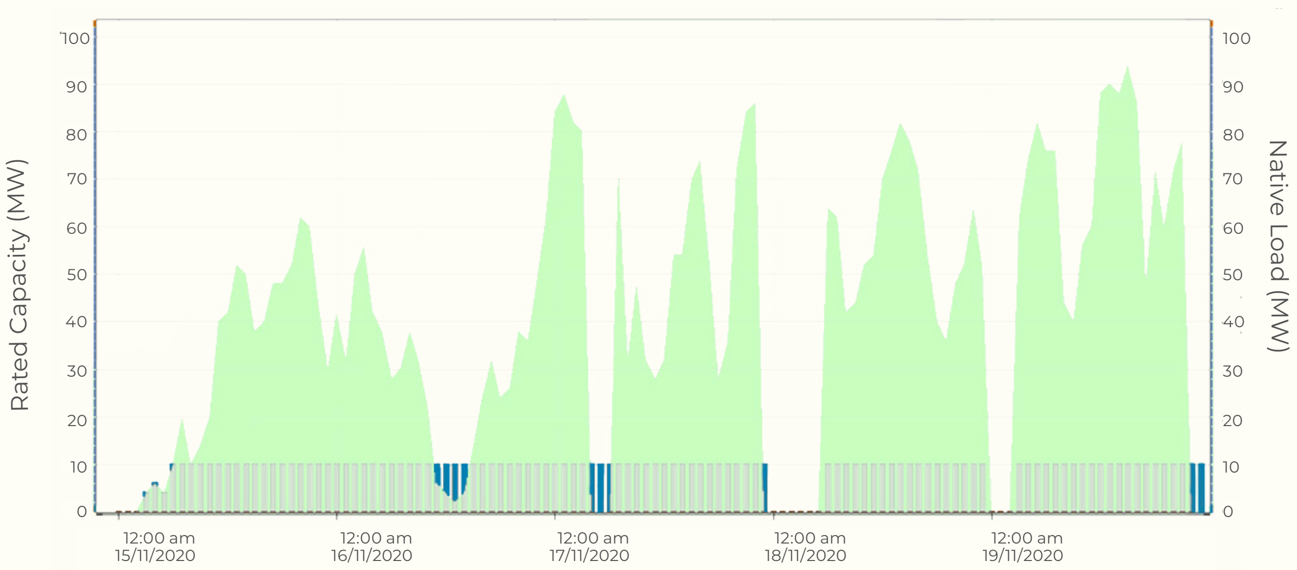


Figure 19 - 10 MW demand served by 20 MW, 40 MW 4h BESS with Wind

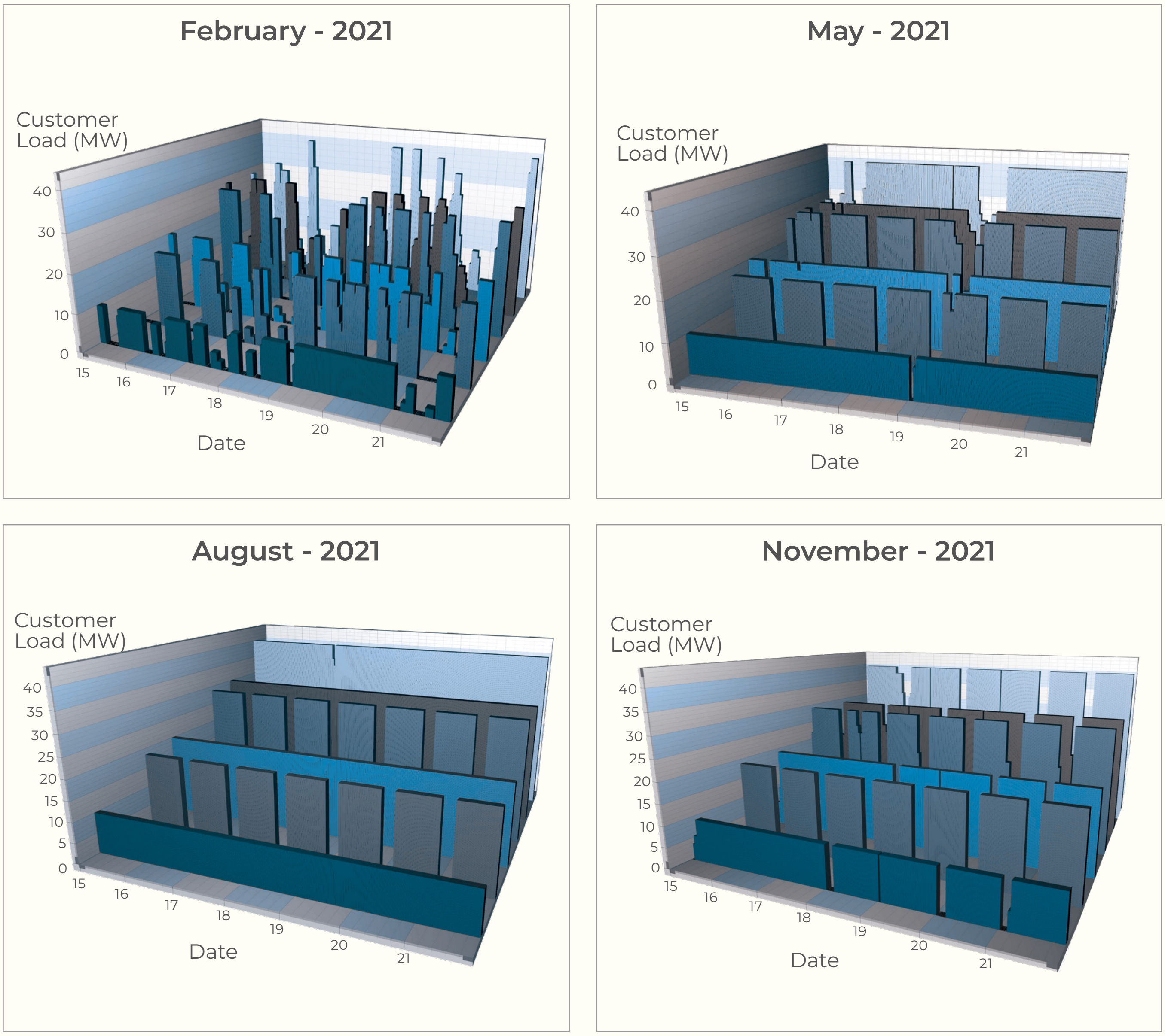


Figure 20- Demand served with wind and 20 MW & 4h BESS system

Similarly, a wind power plant of 100 MW coupled with the three BESS units of 20 MW, each with a capacity of 240 MWh, can meet the continuous demands of 10, 20, 30, and 40 MW during the high wind months, i.e., August and May. However, this system is not able to meet the demand requirements during low wind periods, as shown in Figure below:

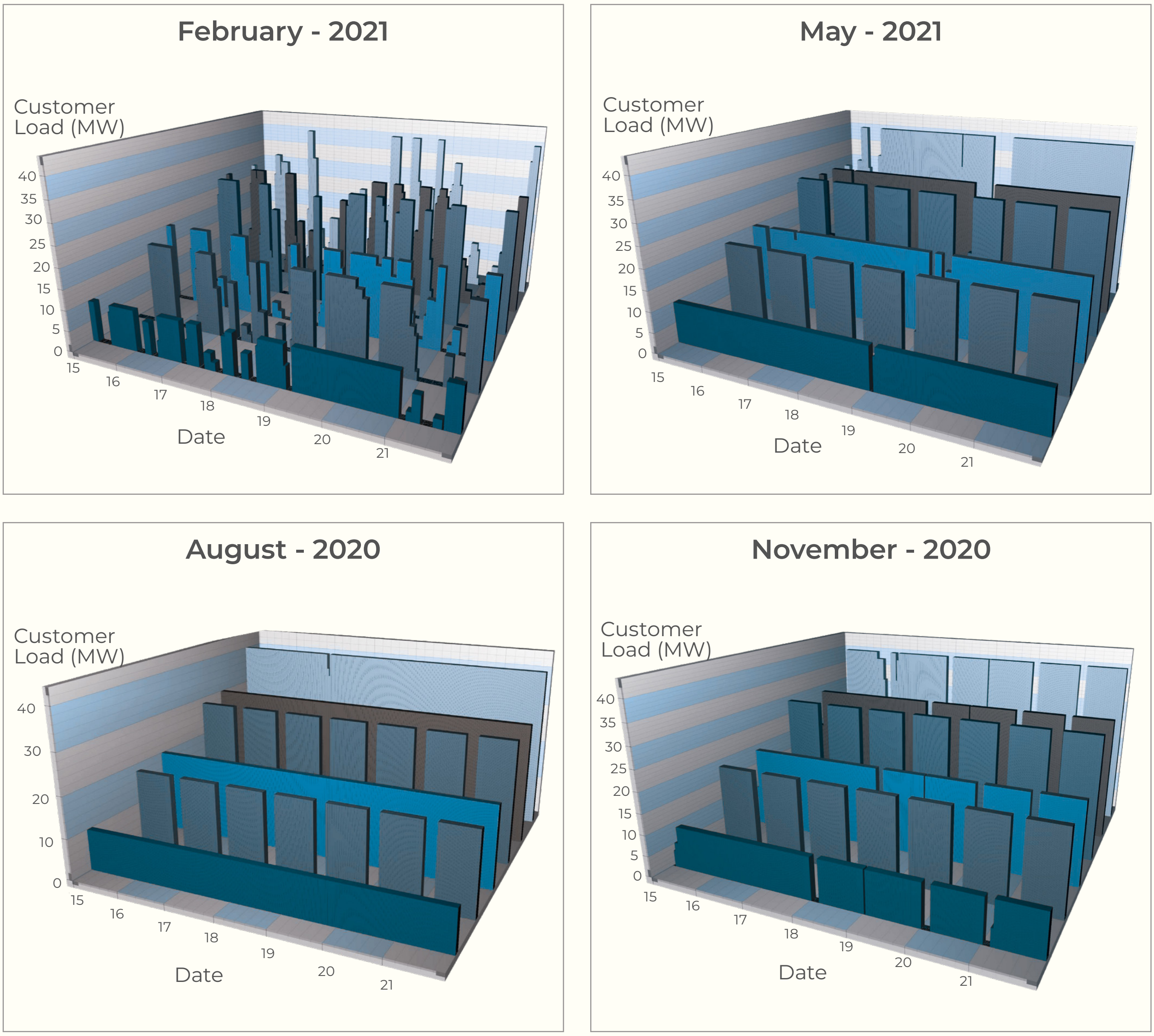


Figure 21 - Demand served with wind and 60 MW & 4h BESS system

5.1.3. Solar and Wind (Hybrid-37) with BESS

The hybrid model of solar power plants coupled with wind power plants has appeared as an influential contributor to sustainable power generation. In a wind farm, where turbines are strategically spaced at a considerable distance from each other (approximately 8 to 15 times the rotor diameter), incorporating solar panels within these gaps yields synergies. This approach maximizes energy yield from the land, providing a reliable, enhanced, and consistent power output compared to standalone wind or solar power plants.

As per the analysis, the optimum configuration for this hybrid setting is 3:1 (wind to solar), which results in a capacity factor of around 36 percent. However, the capacity factor and hybrid configuration may vary depending on the spatial differences and topography of the region under consideration. Therefore, in this study, a hybrid power plant of 100 MW is considered with a wind-to-solar ratio of 3:1, having a capacity factor of around 36 percent. To analyze how this hybrid power plant, when coupled with the BESS, will meet the demands, a single unit of BESS with 80 MWh capacity is considered. The results show that this configuration successfully met the continuous demand of 10 MW. However, the continuous demand for 15 MW was only fulfilled during the third and fourth quarters of the year because of the unavailability of wind during the first quarter. The results are shown in figure as follows:

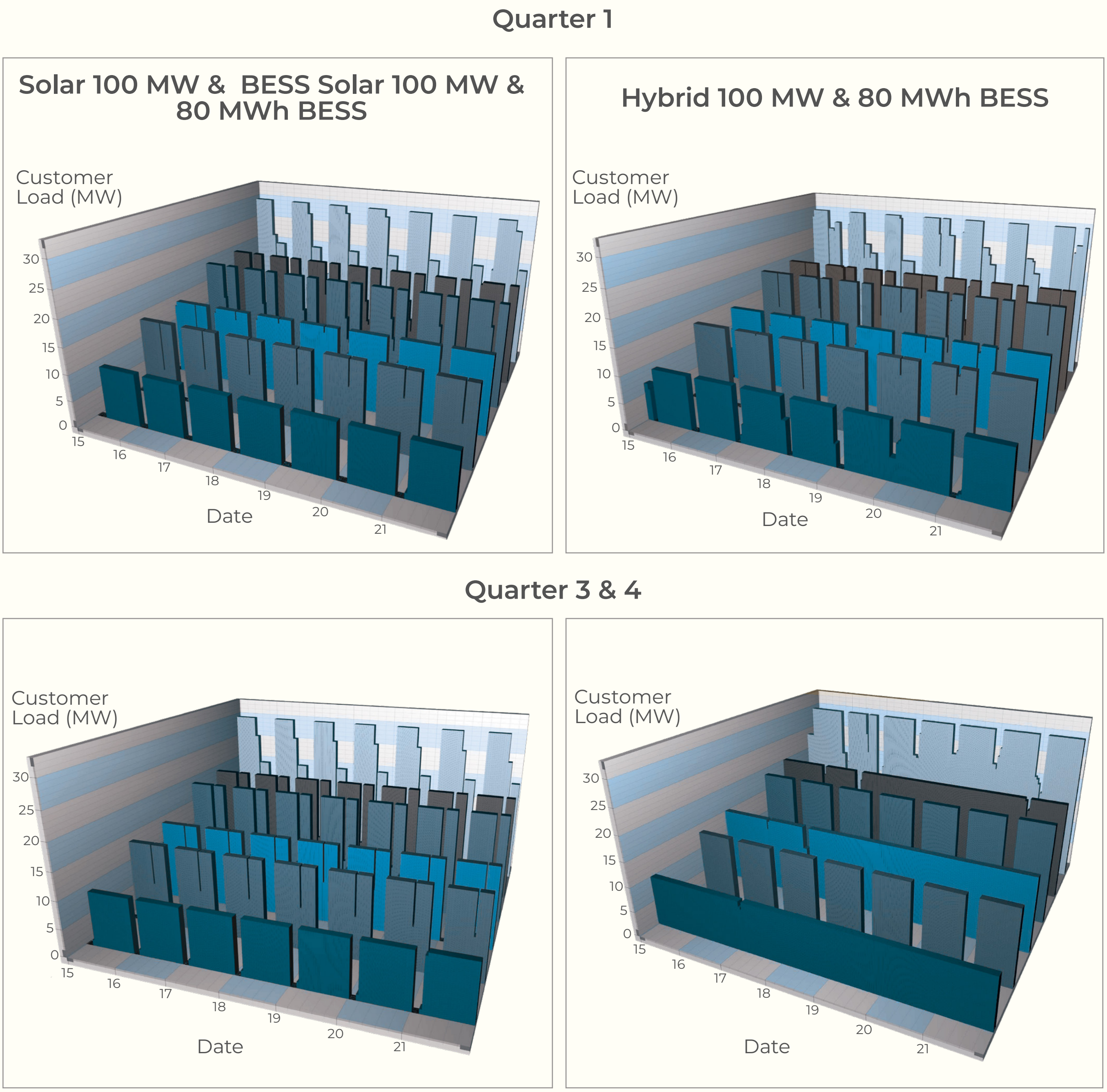


Figure 22- Comparison of solar and hybrid systems for quarterly firm support

5.2. Peak Support

For the use case on Peak Support, the demand of overall Pakistan is analyzed. The annual demand curves for NTDC and KE are plotted hourly throughout FY 2022-23. To compare NTDC and KE's demand, the demand profiles of both NTDC and KE are normalized. During the first quarter, NTDC experiences a peak demand that is relatively higher than KE but subsequently undergoes a steep decrease compared to KE. Likewise, in the third quarter, NTDC and KE exhibit low demand until the fourth quarter, when KE's peak demand surpasses that of NTDC as shown in the figure below:

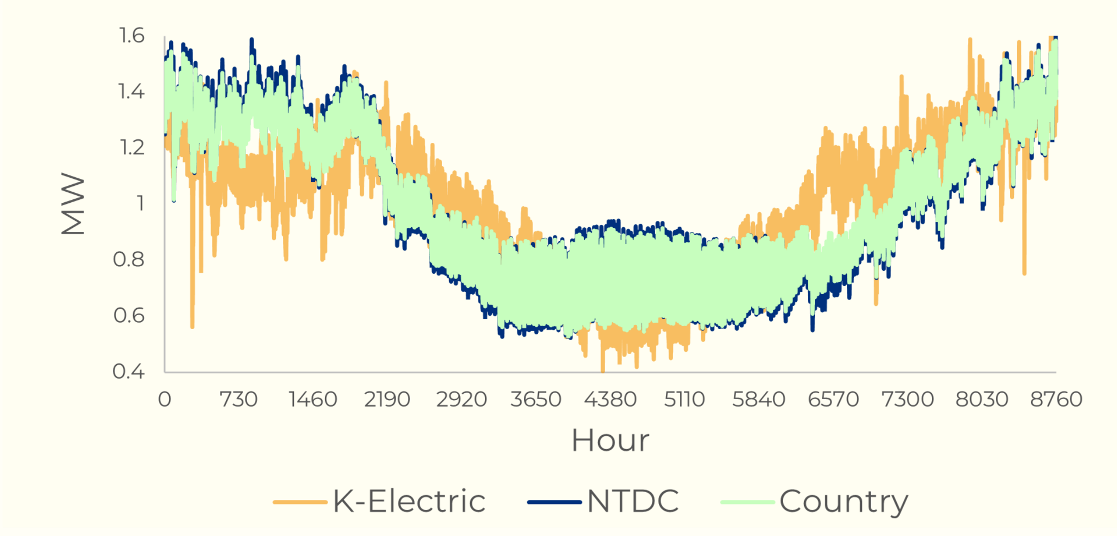


Figure 23 – Annual Demand Profiles

Note: this graph has been normalized at 100 MW for the purpose of comparison

The quarterly demand profiles of NTDC and KE are also plotted as shown in figure below:

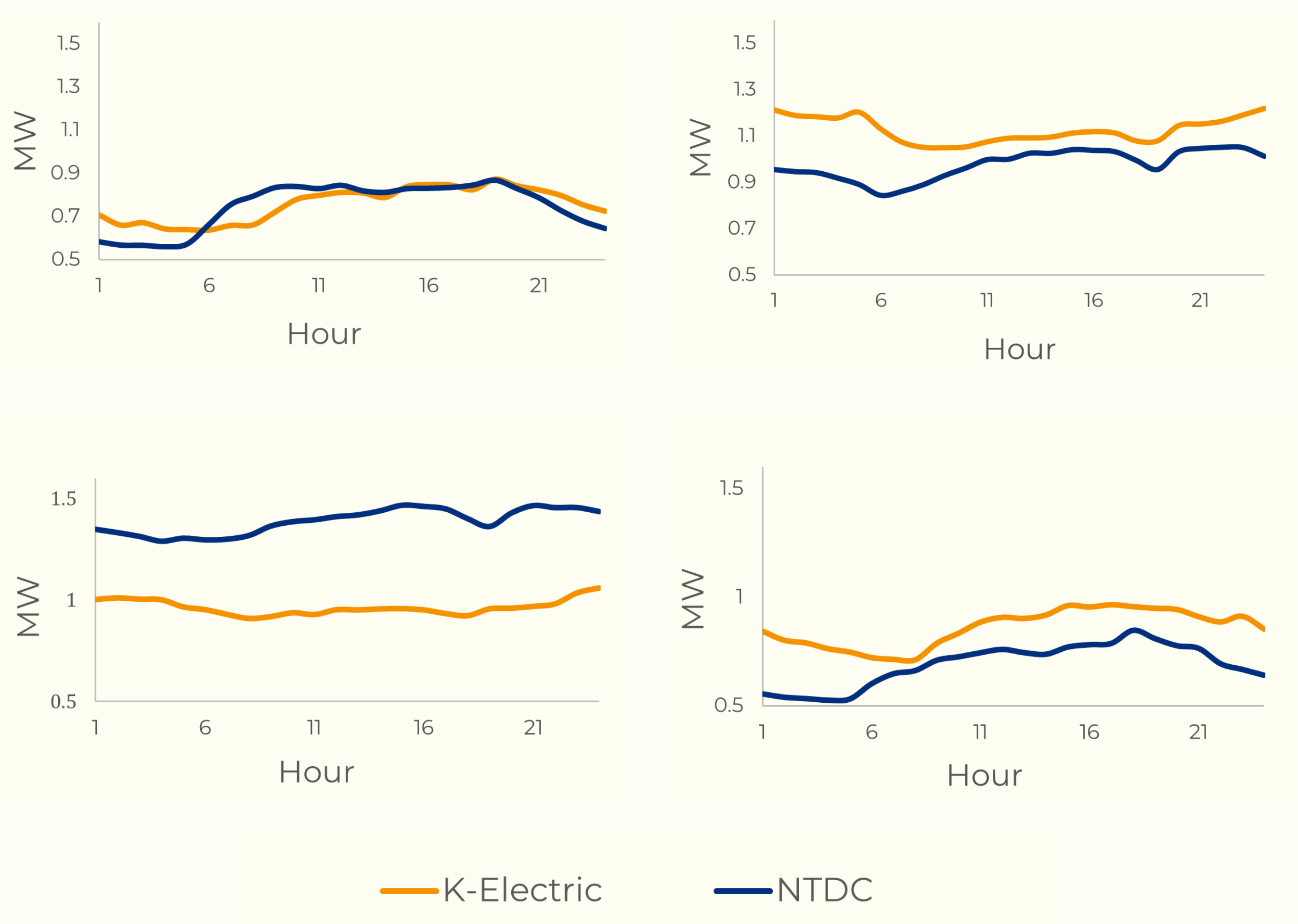


Figure 24 – Quarterly Demand Profiles

Based on the demand profile of Pakistan, six demand profiles (10 MW continuous, 15 MW step and continuous, 20 MW step and continuous, and 30 MW continuous) are created to analyze how the hybrid proposition of BESS coupled with REs fulfill these demand profiles as shown in figure below:

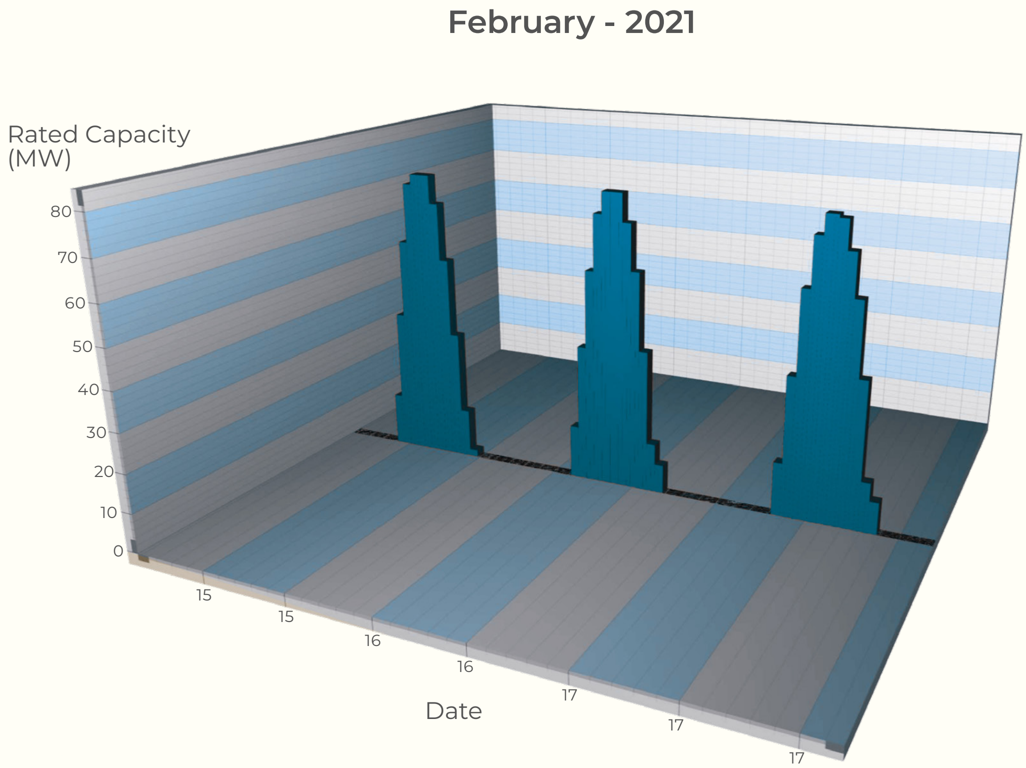


Figure 25 – Daily demand profiles for Peak Support 10, S15, 15, S20, 20, 30 (MW)

5.2.1. Peak Support – Solar

The Solar power plant (100MW) coupled with 80 MWh BESS can effectively meet the daily peak requirements as shown in the figure below:

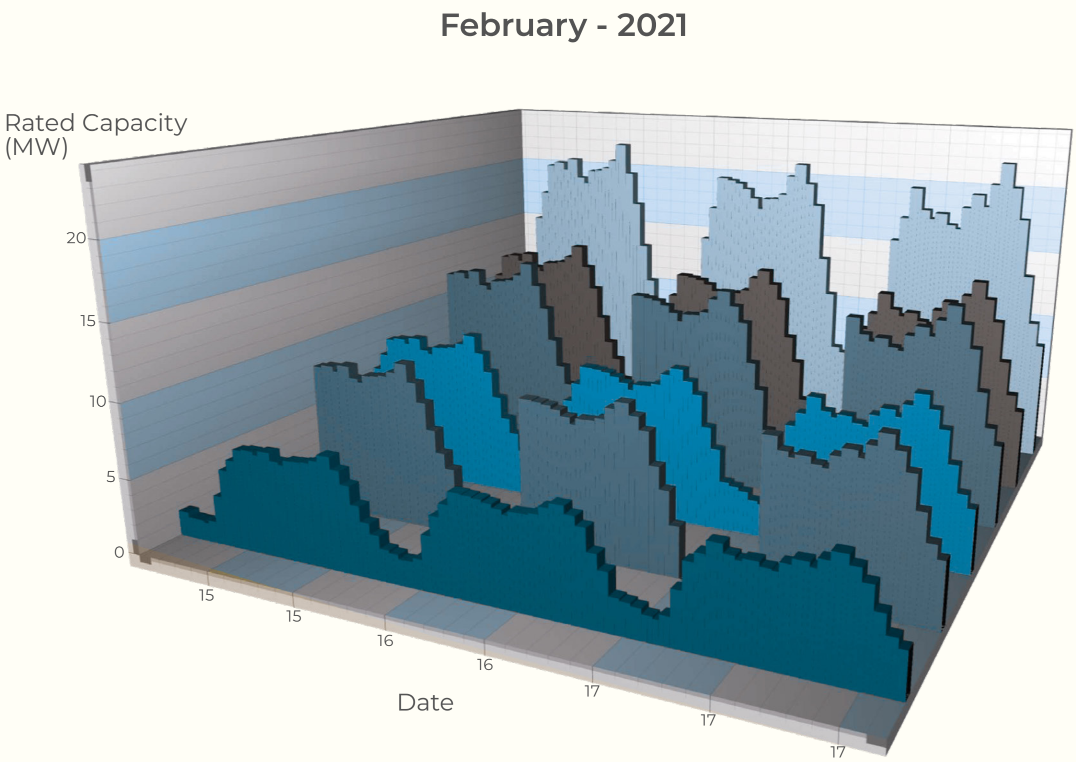


Figure 26 - Generation Profile of Solar plant coupled with 80MWh BESS

5.2.2. Peak support – Wind

In contrast to the Solar power plant coupled with the BESS, the wind power plant coupled with the BESS cannot meet the daily peak requirements due to wind seasons and inconsistencies in the generation during summer months. This is clear from the generation profile of 100 MW wind coupled with 80 MWh of BESS, as shown in Figure below:

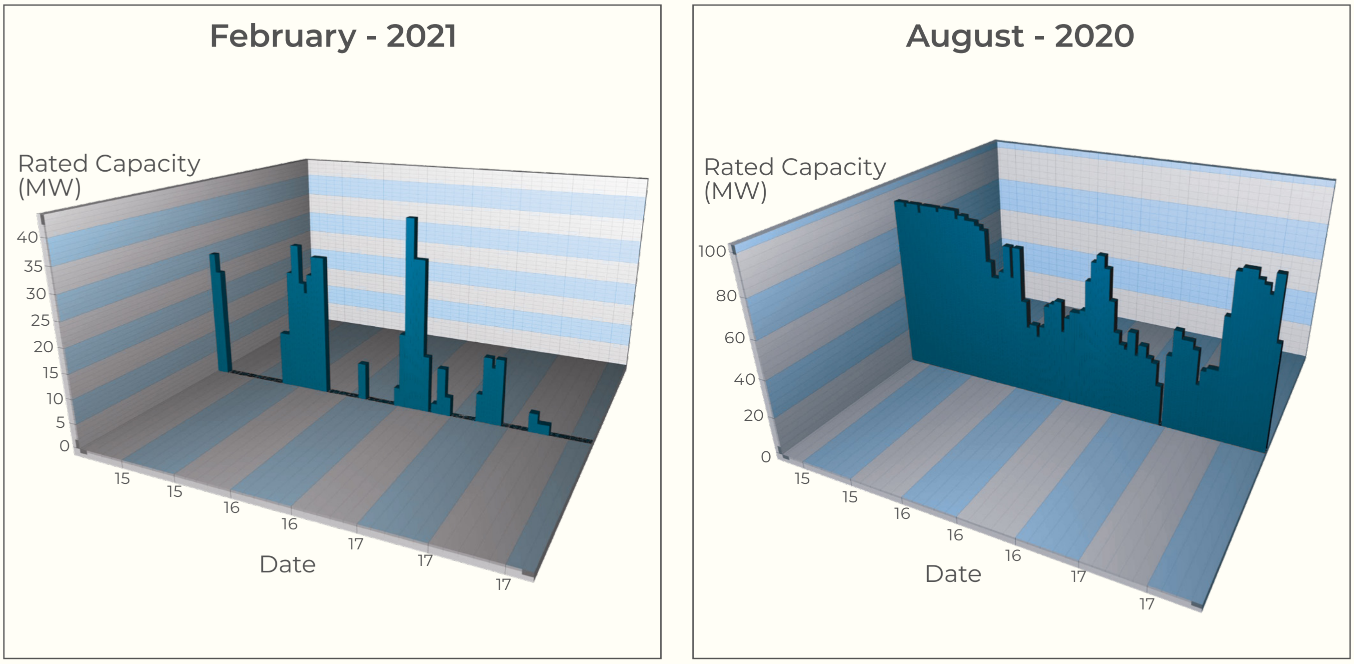


Figure 27 – Generation Profile of 100MW Wind with 80 MWh BESS

5.2.3. Peak support – Hybrid

The 100 MW hybrid power plant with a wind-to-solar ratio of 3:1, when coupled with 80 MWh BESS, effectively met the daily demand. However, the LCOE of this hybrid system is higher than standalone other REs (Wind and Solar) with BESS settings. The generation profile of this hybrid setting is shown in Figure below:

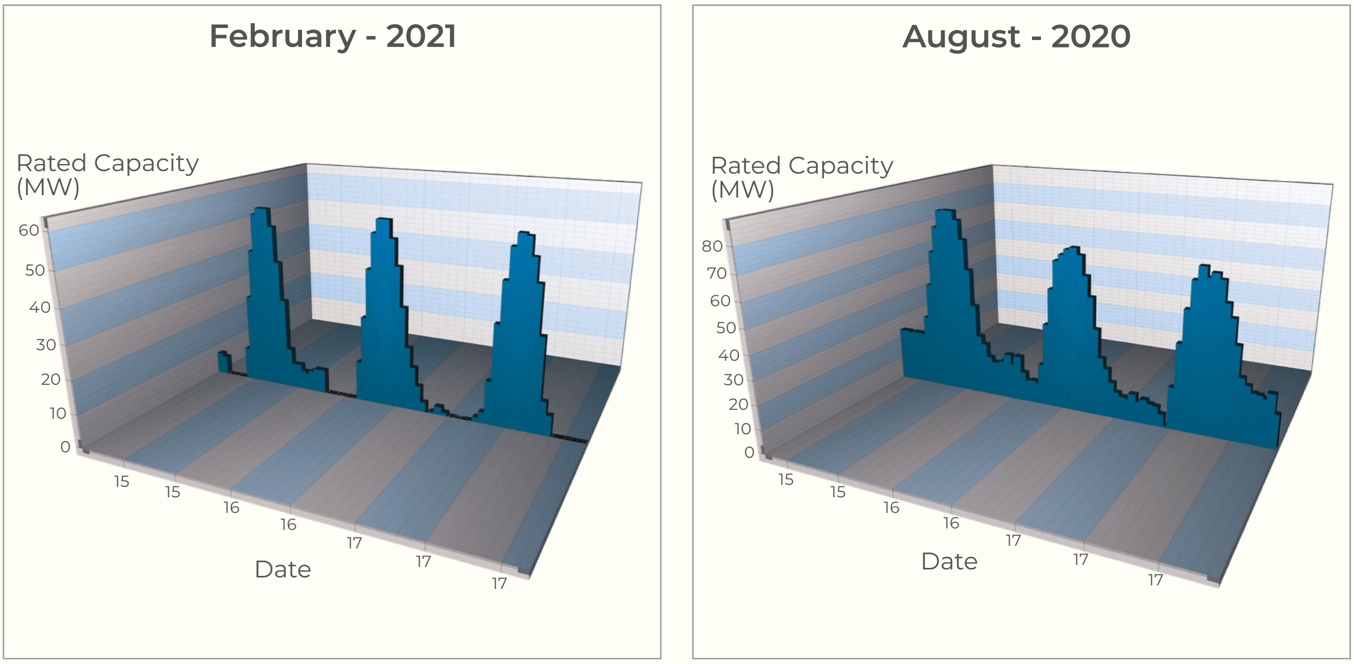


Figure 28 - Generation Profile of 100 MW Hybrid plant with 80MWh BESS

5.2.4. Peak support – Summer & Winter Variation

The overall analysis of use case cases reveals that the hybrid proposition of a wind power plant coupled with the BESS is well suited for peak demand during summer; the hybrid power plant with a 3:1 wind-to-solar ratio coupled with the BESS can provide peak support during winter months. Whereas, owing to a consistent generation profile throughout the year (ideally, the sun is shining all days), a solar power plant coupled with the BESS is well suited for annual firm capacity and wind with the BESS for daily firm capacity support. Similarly, a wind power plant coupled with the BESS is suitable for annual peak support, and a solar power plant with the BESS is well suited for daily peak support.

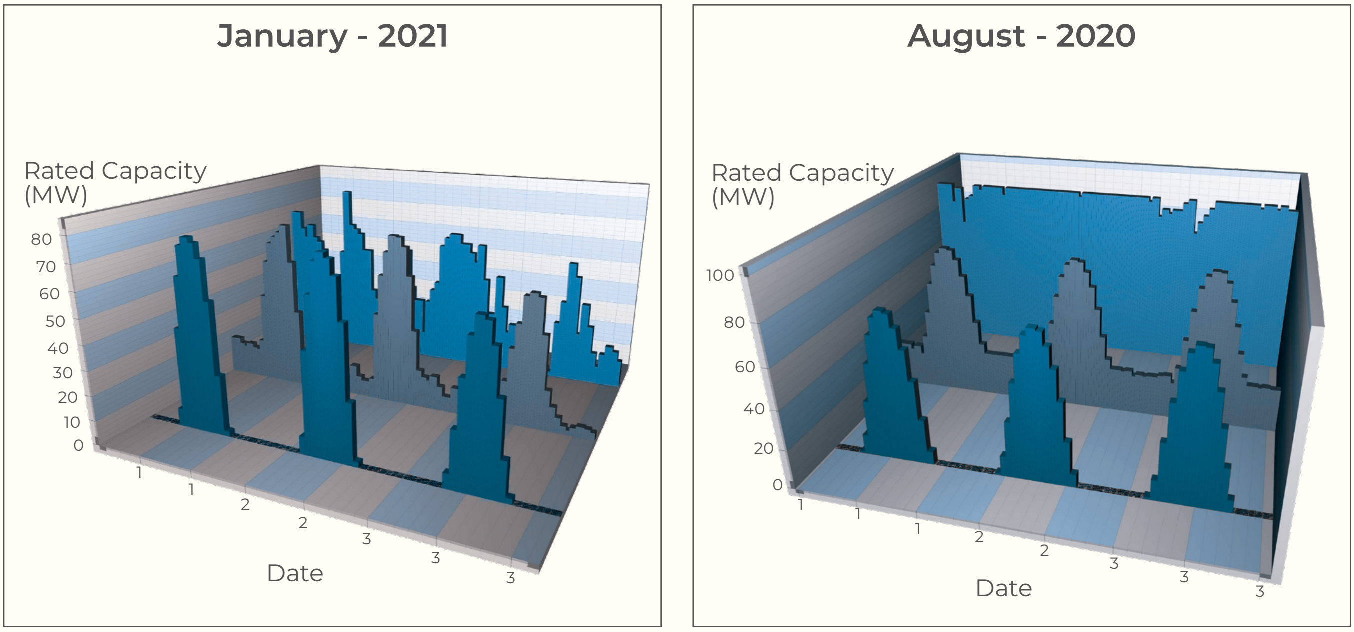


Figure 29 – Systems suitable for Seasonal peak support

	Yearly		Daily	
Use Case	**Solar**	**Wind**	**Solar**	**Wind**
Firm Capacity	Ideal			Ideal
Peak Support		Ideal	Ideal	

Table 4: Ideal use case based on diurnal and yearly variation

6. The Techno-economic analysis (TEA)

Techno-economic analysis (TEA) is a technique for evaluating the economic feasibility of specific technologies. TEA combines the technical and financial parameters to assess the overall performance, costs, and benefits of implementing a technology. In electrical power generation projects, TEA helps decision-makers better understand the economic implications and benefits associated with adopting such technologies. In this study, the scope of TEA encompasses understanding a vital metric, i.e., the Levelized cost of energy (LCOE) of integrating the BESS with REs, which is described below:

6.1 Levelized Cost of Energy (LCOE)

The LCOE is a critical metric used to assess the per unit cost of generating energy from a power plant throughout its life. It is a standard way of evaluating and comparing the cost competitiveness of different energy generation technologies (such as solar, wind, coal, natural gas, etc.)

LCOE is the lowest cost at which the electricity must be sold to cover all costs incurred over a plant's lifespan and achieve a break-even point. The electricity tariff allows the power plant to recover its initial investment and ongoing operational expenses.

For a clearer insight into how LCOE reflects the costs associated with generating electricity and meeting investor expectations, it's essential to familiarize ourselves with critical terms such as:

- **Equity:** Ownership stake in a company representing shareholders' residual interest in assets after deducting liabilities.
- **Debt:** Borrowed funds that require repayment with interest over a specific period, usually involving a

creditor-lender relationship.

- **Return on Equity:** Measure of profitability showing the percentage return earned on shareholders' investment in a company.
- **Return on Debt:** Indicator of the efficiency of debt utilization, representing the interest payments made on borrowed funds relative to the debt amount.
- **Discount rate:** The rate used to find the present value of future cash flows, considering the time value of money and risk factors.

6.1.1 Methodology: LCOE calculation for Solar/Wind and Batteries

LCOE considers all the expenses related to setting up a power plant, encompassing capital expenditure, operational and maintenance costs, and fuel expenses, and then computes a levelized cost for each unit of electricity the power plant generates throughout its lifespan. The LCOE comprises two main components: fixed costs and variable costs. The variable costs include fuel cost and the variable component of operations and maintenance cost (VO&M), usually expressed in $/MWh (US Dollars per Megawatts). Whereas fixed costs include capital cost, fixed operations and maintenance cost (FO&M), return on equity (ROE), return on equity during construction (ROEDC), insurance, and debt servicing, usually expressed in $/kW-year (US Dollars per kilowatt-year). The levelized cost calculation for the BESS is analogous to that for wind/solar. The only difference is that the levelized cost for BESS uses charging costs as fuel costs and takes the discharged electricity instead of generated electricity. For the analysis of LCOE, all the cost assumptions/per unit rate of electricity generated by REs has been taken from NEPRA latest tariff determinations. The USD to PKR exchange rate considered is 1USD=280 PKR. These assumptions are summarized in the table below:

#	Technology	LCOE (Cents/kWh)	LCOE Rs/kWh)
1	Solar	4	11.2
2	Wind	4.5	12.6

Table 5 – Reference Tariff determinations by NEPRA

For the optimization of BESS, key input parameters are taken from the energy consultants and publicly available report by World Bank "Guidelines to implement battery energy storage systems under public-private partnership structures" as listed in the table below:

Parameter	Value
Build Cost ($/kWh) *	300
VO&M Charge ($/kWh)	7
Economic life (yrs.)	10
Technical life (yrs.)	10
Max Cycles	8000
Capacity Degradation (%/1000 cycles)	10.9
Max SoC (%)	95
Min SoC (%)	5
Charge Efficiency (%)	95
Discharge Efficiency (%)	95
*Inclusive of DC/AC and EPC costs	

Table 6 – Input parameters for BESS Modelling

The formula to calculate LCOE involves dividing the total present value of costs (both initial and ongoing) by the total electricity output over the plant's lifespan. The result is the cost of generating each unit of electricity averaged over the plant's lifetime.

$$LCOE = \frac{\sum[Capital\ cost + O\&M\ cost + Fuel\ cost) \times (1+r)^{-t}]}{\sum Energy\ (MWh)\ \times (1+r)^{-t}}$$

The LCOE is calculated as formulated in the following equation:

Were,

Capital cost: Total capital expenditures in year t;

O&M cost: Total operations and maintenance costs in year t;

Fuel cost: Fuel costs in year t;

Energy: The amount of electrical energy produced in MWh in year t

r: Discount rate (the rate at which money is discounted over a period, i.e., the rate that time adds or drops value to the money per time period); and

$(1 + r)^{-t}$: The discount factor for year t.

6.1.2. Scenario Wise LCOE

The LCOE for firm support scenario of solar power plant paired with BESS are mentioned in the table below, the exchange rate is considered as 1USD = 280PKR.

Solar 100 MW		
BESS (MWh)	LCOE (US cents/kWh)	Firm Support
137	6.84	10 MW all day
205	8.25	15 MW all day
277	9.70	20 MW all day
127	6.62	30 MW 14 hours
Solar 70 MW		
BESS (MWh)	LCOE (US cents/kWh)	Firm Support
137	8.1	10 MW all day
205	10	15 MW all day
85	6.5	20 MW 14 hours
Solar 50 MW		
BESS	LCOE (US cents/kWh)	Firm Support
137	9.6	10 MW all day
64	6.6	15 MW 14 hours

Table 7 – Scenario-wise costs for Solar-Battery Systems

The LCOE for each peak support scenario (REs coupled with BESS) is calculated with various capacity factors of REs and sizes of BESS as shown in Table below:

LCOE (US Cents/kWh)			
Scenarios	With 20 MW BESS	With 40 MW BESS	With 60 MW BESS
Solar Net Meter	7.35	9.5	11.65
Utility-scale solar	6.65	7.3	8.9
Utility-scale wind	5.42	6.34	7.25
Hybrid 1	5.55	6.93	8.3
Hybrid 2	5.48	6.6	7.8
Hybrid 3	5.45	6.48	7.5

Hybrids 1, 2, and 3 represent hybrid power plants with solar-to-wind ratios of 1:3, 1:1, and 3:1, respectively. Plant size is 100MW

Table 8 – Scenario-wise costs for Solar-Wind-Battery Systems

7. Conclusion and Future scope

The integration of Renewable Energy sources, complemented by Battery Energy Storage Systems (BESS), stands as a transformative solution to address the evolving dynamics of electricity demand in Pakistan. This study highlights the importance of tailoring electricity generation strategies to suit the unique requirements of various sectors and the broader national context, thereby ensuring both operational efficiency and long-term sustainability. The use case on Firm Capacity highlights the opportunity for RE developers to develop customized products that can be sold bilaterally in the power market. The firm capacity can be ensured by optimal combination of REs especially solar power plant with BESS that can be customized as per the demand profiles of industries. This hybridization offers cleaner energy and an opportunity to reduce reliance on thermal power plants. The surplus energy can be utilized either by direct selling into power market or to charge the battery that can be used to take advantage of market arbitrage. However, this requires enactment of open market regulations entailed in the Competitive Trading Bilateral Contracts Markets (CTBCM) that are still pending in Pakistan. The use case on Peak support suggests that optimum hybridization of REs and BESS is well suited for peak shaving instead of using costly peaking plants that are majorly based on take or pay contracts.

Central to the success of this hybrid approach is the precise determination of BESS size and the establishment of optimal charging and discharging schedules. These pivotal steps not only guarantee cost competitiveness but also empower the system to seamlessly meet predefined demand profiles, offering a reliable and consistent power supply.

Moreover, the hybridization of REs with BESS presents an unparalleled opportunity to craft tailored solutions for bulk power consumers, notably those within the export industry striving to meet stringent Scope 2 and Scope 3 emissions targets. Through the adoption of REs coupled with BESS, these consumers can enhance their energy autonomy, reduce dependency on fossil fuels, and champion environmental stewardship.

Looking forward, intensified research and development endeavors should prioritize the refinement of BESS sizing and scheduling methodologies within hybrid RE configurations. Rigorous feasibility assessments and pilot initiatives are indispensable to confirm the scalability and efficacy of these integrated solutions in real-world scenarios.

Furthermore, fostering collaboration among governmental entities, industry stakeholders, and research institutions is imperative to propel innovation and foster widespread adoption of REs coupled with BESS. This collaborative ethos will foster the creation of bespoke energy solutions tailored to the diverse needs of various sectors and consumers, ultimately ushering in a resilient, sustainable, and low-carbon energy landscape for Pakistan.

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