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Research Article

Design and Development of a Smart Pumped Hydro Storage System Utilizing the Unused Solar PV Power Output

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Abstract

The growing use of solar photovoltaic (PV) systems in decentralized energy setups has compounded issues related to intermittency, battery degradation, and the excessive curtailment of surplus generation. This study proposes and experimentally validates a smart hybrid energy storage architecture that integrates pumped hydro storage (PHS) with a PV–battery system to enhance energy management and lifecycle cost performance in rural electrification contexts. A case study was conducted for a rural household in Pakistan, near Kot Diji Fort, with an energy demand of 1754 Wh per day. The optimal size of the PV system was 400 Wp to ensure complete supply security. Extensive power management analysis showed a large mid-day surplus generation (456 Wh/day) due to battery saturation limitations. A closed-loop PHS subsystem was designed, constructed, and integrated to utilize this otherwise curtailed energy. When PV power was in excess, it was used to pump water during peak sunlight hours, and the stored gravitational potential energy was later converted into electricity during the evening peak period (7:00–9:00 PM). Experimental results established that PHS integration significantly reduced the battery depth of discharge, with the evening state-of-charge declining by only about 1%, thereby increasing battery service life. A comparative techno-economic analysis showed that a standalone PV–battery system has a levelized cost of energy of 33.24 PKR/kWh, whereas the integrated PV–battery–PHS system achieves a reduced cost of 27.56 PKR/kWh. The findings corroborate the claim that PHS hybridization improves renewable energy utilization, reduces lifecycle costs, and enhances storage resilience. The proposed framework offers a scalable and sustainable option for decentralized energy systems and supports increased renewable energy penetration with long-term energy security in off-grid and weak-grid areas.

I. INTRODUCTION

Well, the world is highly dependent on unstable fossil fuels [1], and within the Net Zero emissions mission, the target is to ensure that global warming does not exceed 1.50 °C above pre-industrial temperatures by 2050. This will require reducing CO_2 emissions by approximately 45% by 2030 to achieve net zero in 2050, with the remaining emissions offset through natural absorption in the ecosystem. Around 33% of all CO_2 emissions in 2023 were due to the power sector, with transport contributing about 21%. Major strategies include closing coal power plants, increasing the adoption of electric vehicles, and expanding renewable energy technologies to achieve environmental sustainability [2], [3]. The global use of energy is expected to grow by approximately 66% by 2050 [4], whereas solar and wind energy-although already mature and free of greenhouse gas emissions-remain intermittent and insufficiently flexible due to weather conditions [5], [6]. Energy Storage Systems (ESSs) are required to smooth out this variability, store surplus power for later use, and better align supply and demand. Co-location of ESSs with solar and wind systems will maximize the utility of renewables and facilitate renewable-based microgrids [7]. Renewable Energy Sources (RES) are inherently variable, but intelligent ESS implementation can effectively manage this variability. Current storage technologies such as batteries, flow batteries, and capacitors are rapidly advancing, supporting the transition to clean energy and reduced emissions [8], [9].

The water–energy nexus in this context refers to how the energy used to pump, treat, and distribute water is interconnected with the water required for power generation. According to the Electric Power Research Institute, nearly 4% of global energy is used for drinking water and wastewater services, indicating significant potential for cost and emissions reduction through renewable energy integration and improved storage. The energy situation in Pakistan is challenging production levels are low, financial conditions are poor, and demand continues to increase due to a population growth rate of approximately 3% annually. This paper, therefore, attempts to address these issues by promoting eco-friendly operations and renewable solutions that can benefit the water industry [10], [11].
Electrical blackouts are extremely frequent in Pakistan, particularly in rural and remote regions where the grid is unavailable for hours at a time or were electrification lags due to limited transmission capacity [12].

Ageing distribution systems and various operational issues contribute to recurring large-scale blackouts, often caused by engineering failures or transformer breakdowns that may require several days to resolve. To overcome power shortages, many households are installing solar PV panels with battery storage. Pumped-hydro storage is also highly effective in hilly areas such as those around Kot Diji Fort in Khairpur Mirs, Sindh. Combining pumped-hydro storage with solar PV allows excess midday PV output to be used for pumping water to an elevated reservoir, which can later generate hydroelectricity. This approach enhances energy efficiency and reduces long-term costs.

A. Renewable Energy

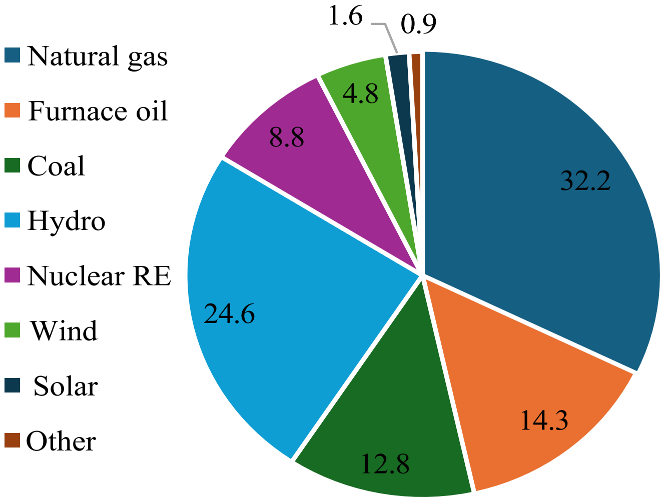


Fig.1 Percentage of Different Installed Energy Systems in Pakistan [4]

The origins of green energy are rapidly expanding worldwide as replacements for the existing energy mix to address the energy crisis and global warming through improved solar panels, larger wind turbines, taller towers, and more efficient dams. However, with their rapid deployment, a major emerging challenge is energy storage [13].

There are a variety of options for energy storage, such as lithium-ion batteries commonly found in phones, laptops, and electric vehicles, which can supply power immediately. However, they are costly, and their long-term performance at grid scale remains uncertain [14]. Solar energy is now more prominent than ever, especially with the development of advanced perovskite solar cells, but it can neither store excess energy nor provide peak power without incorporating some form of storage solution [15].

This is why reliable storage technology is required to keep the grid running consistently. The future of energy storage will likely involve a combination of various technologies to ensure that large-scale storage and distribution become more effective.

TABLE I INSTALLED CAPACITY OF RE IN PAKISTAN [16]

Source	Installed Capacity (MW)	Total Share %
Fossil Fuels (Total)	24,688	59.4%
Natural gas	13,423	32.3%
Furnace Oil	5,943	14.3%
Coal	5,319	12.8%
Green Energy (Total)	16,872	40.6%
Hydro	10,264	24.7%
Nuclear	3,657	8.8%
Wind	1,995	4.8%
Solar	667	1.4%
Others	374	0.9%
Overall Installed Capacity	41,557	100%

B. Energy Storage Systems

Storage of energy is a necessity; we should expect our power systems to remain affordable and reliable as we become more reliant on variable renewables to achieve decarbonization targets. As we continue to transition to wind and solar, large amounts of energy must be stored to keep the grid stable. Short-duration needs are handled by batteries; however, longer-duration storage is required to maintain power during extreme weather events or other disruptions [17].

C. Pumped Hydro Storage System

Pumped hydropower storage (PHS) is a commercially tested technology that facilitates grid stability while offering both short- and long-duration energy storage. It was first developed in the early 20th century in Switzerland and has been widely deployed since the 1930s in countries such as the United States and Japan to support nuclear energy and peak generation [18]. Expansion of PHS increased during the 1980s and 1990s but declined in the late 1990s due to environmental concerns and limited suitable construction sites. Interest resurged after 2000 due to rising renewable energy demand and the liberalization of electricity markets [19], [20]. The earliest documented U.S. PHS system, installed by the Connecticut Electric and Power Company near New Milford, Connecticut, had a 230-ft (70.8-m) head and a 44,000-horsepower (33-MW) output-enough to power 30,000 homes in 1930 [21]. In 2015, the largest PHS facility in the United States surpassed 3,000 MW, nearly 100 times the capacity of the New Milford installation and equivalent to three nuclear generators. A PHS system consists of a pair of reservoirs, a pump, a hydro turbine generator, and water-transfer pipelines. Water is pumped from the lower reservoir to the upper reservoir, storing energy as gravitational potential energy. During periods of high demand, the stored water is released through a turbine to generate electricity, functioning as a large-scale water battery.

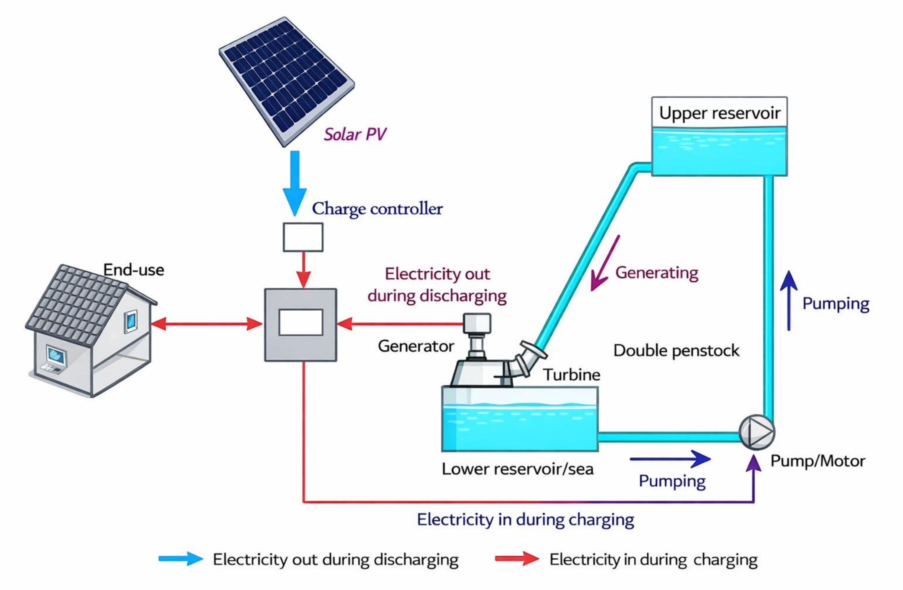


Fig.2 PHS System Utilizing Solar PV and Battery

The PHS systems are either closed-loop or open-loop, and this project uses a closed-loop system in which the same water moves around the reservoirs in a loop. In contrast, open-loop systems are connected to the lower reservoir and a river, whereas closed-loop systems require extensive construction works and human intervention. Although closed-loop systems have a greater environmental impact due to excavation, construction materials, and associated carbon emissions, they are necessary to provide solutions for large-scale energy storage.

Countries such as China are at the forefront of deploying PHS, while the US and Japan occupy the second and third positions in the number of facilities [22]. PHS plants are mostly large-scale and traditionally associated with conventional energy sources such as natural gas or coal. This project combines PHS with solar energy and battery storage to drive water to the upper reservoir using renewable power. The resulting hydroelectric power can serve domestic demand, charge batteries, or support local substations and businesses. As of today, PHS accounts for approximately 3% of the world's installed electricity generation capacity and nearly 99% of global electricity storage capacity, making it the most common mechanical energy storage technology.

II. METHODOLOGY

A. Prototype Site Location

Power blackouts are widespread across Pakistan, with outages lasting more than five hours daily in some areas, while many rural regions remain unelectrified due to limited transmission infrastructure [12]. Rapid population growth and rising per capita income have increased electricity demand, while outdated distribution systems cause frequent large-scale blackouts due to engineering faults or transformer failures. Many households rely on solar PV systems with batteries, although batteries typically last only two to three years and cost about 15,000 to 30,000 every three years, depending on load. Hilly areas near Kot Diji Fort, Khairpur Mirs, Sindh, have been identified as suitable locations for pumped hydro storage (PHS) installation. Solar PV generates maximum power during peak radiation, enabling unspent energy to drive water to a higher tank for later use in hydroelectric power generation. Field visits confirmed that elevated terrain and existing PV usage make the region technically feasible for PHS deployment. The integration of solar PV with PHS offers a reliable energy management solution and reduces long-term electricity costs for local communities.

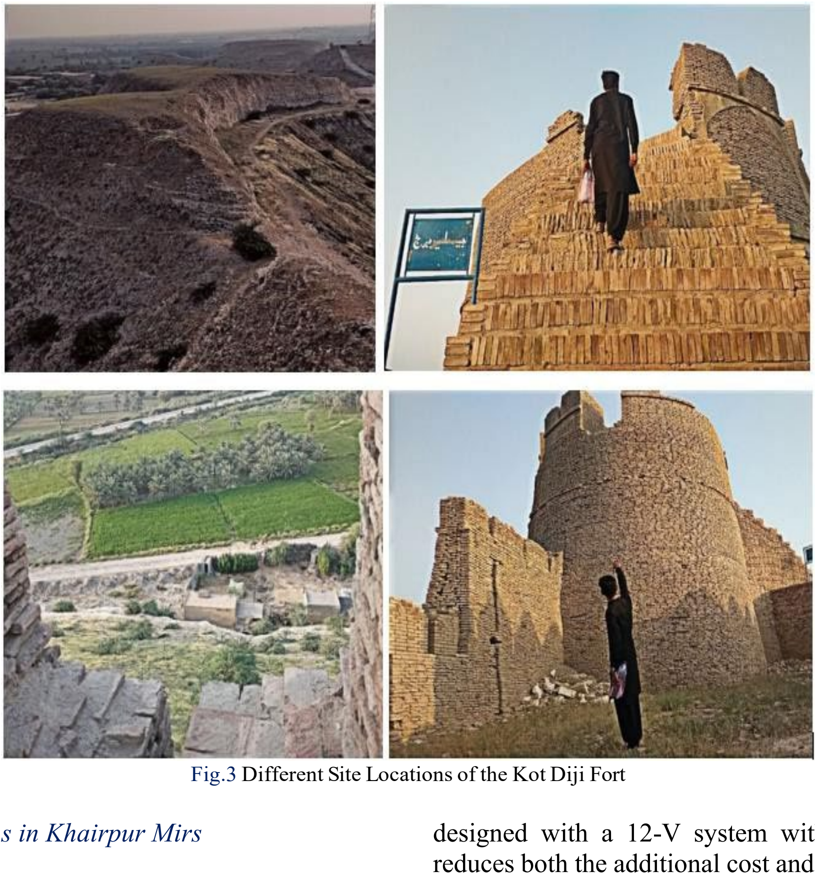


Fig.3 Different Site Locations of the Kot Diji Fort

B. House Load Variations in Khairpur Mirs

Calculations of loads were carried out to determine the estimated power required for a farmer's house in the Kot Diji Fort region, where most houses are directly DC-loaded through solar PV and batteries. The houses were therefore designed with a 12-V system without an inverter, which reduces both the additional cost and the system size by about 20%. The total load of the 12-V system was calculated based on the approximate daily usage time and is presented in Table 2, which indicates the daily power consumption.

TABLE II DAILY ELECTRICITY USED DAILY BASED ON (12-VOLT) AMPERES/HOUR AND AMPERES/DAY

Appliance	Quantity	Watts/Hr	Operation Hrs/day	Watts/day
Ceiling royal fan (AC+DC)	3	40	6	720
Pedestal Stand fan (DC)	2	30	10	600
Lighting (bedrooms)	4	8	6	192
Lighting (kitchen)/(hall)	1	8	4	32
Lighting (bathrooms)	1	5	2	10
Circulation Pump	1	100	2	200
Total Watts Per Hour = 191			Total Watts per Day = 1754	

Figure.4 illustrates the variations in the hourly loads of a farmer's house in a rural region, and the load trend is influenced by the daily activities of the family. The daily household energy usage is approximated as 1754 Wh, and the peak load demand occurs at 7 a.m. and 1 p.m. when the entire family is at home for breakfast and lunch. In the rural areas of Sindh, farmers typically rise at approximately 6 a.m., eat breakfast, and begin farming work. Both men and women participate in agricultural activities, thereby reducing the household load requirement between 8 a.m. and 12 noon to zero. As the family returns for lunchtime and students arrive back home from school, the load demand again increases to its peak. After lunch, the family returns to farming and other activities and continues until 5 p.m. They use a pedestal fan in the evening, sit outside on a cot, dine at 9 p.m., and talk about family matters until 11 p.m.

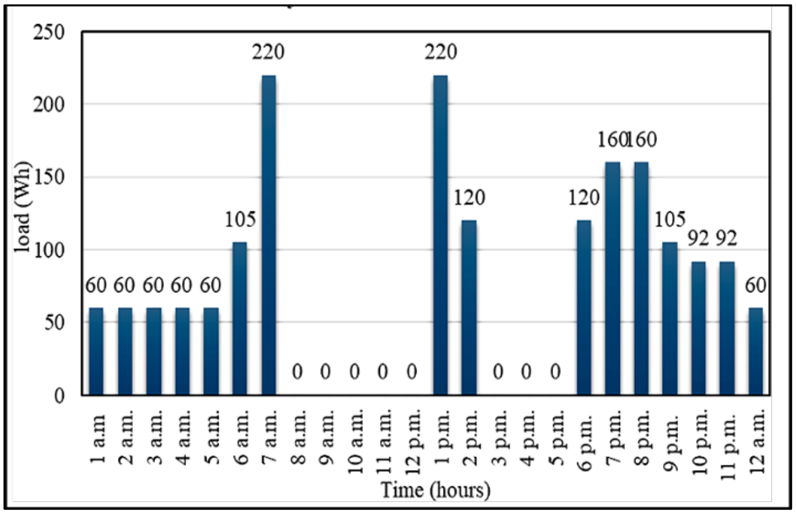
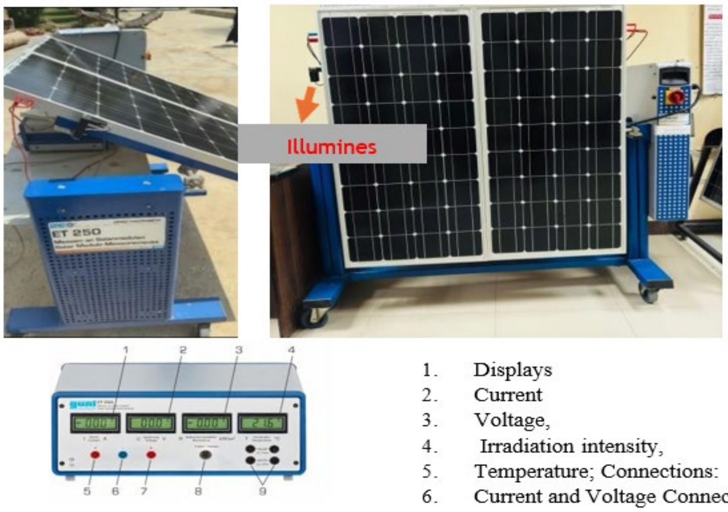


Fig.4 Hourly House Load of the Rural House of a Farmer's Family



1. Displays
2. Current
3. Voltage,
4. Irradiation intensity,
5. Temperature; Connections:
6. Current and Voltage Connection
7. Sensors Connection

Fig.5 Solar Irradiance Measurement Setup

C. Weather Data Assessment

Weather data assessment, specifically solar irradiance for the study location, was carried out using the ET 250 solar module measurement device, as shown in Figure 5. Two days of solar irradiance measurements were taken at 30-minute intervals between 9:00 a.m. and 3:00 p.m. Due to limited resources and equipment safety concerns, data collection was not performed after 3:00 p.m. The irradiance fluctuations for Day 1 and Day 2 are presented in Table III. On Day 1, the weather was sunny with an average irradiance of 750 W/m², whereas on Day 2, the average irradiance was 698 W/m². Figure 6 shows the variations in solar irradiance for Day 1 and Day 2. The peak solar irradiance on Day 1 was 830 W/m² at 11:30 a.m., while on Day 2 it was 870 W/m².

TABLE III VARIATIONS IN THE SOLAR IRRADIANCE FOR DAY 1 AND DAY 2

	Day 1	**Day 2**	**Average**
Time	**Irradiance (kW/m^2)**	**Irradiance (kW/m^2)**	**Irradiance (kW/m^2)**
09:00 a.m.	0.73	0.45	0.59
09:30 a.m.	0.78	0.53	0.655
10:00 a.m.	0.79	0.58	0.685
10:30 a.m.	0.79	0.61	0.7
11:00 a.m.	0.81	0.85	0.83
11:30 a.m.	0.83	0.84	0.835
12:00 p.m.	0.83	0.85	0.84
12:30 p.m.	0.81	0.84	0.825
01:00 p.m.	0.78	0.87	0.825
01:30 p.m.	0.73	0.71	0.72
02:00 p.m.	0.70	0.63	0.665
02:30 p.m.	0.63	0.67	0.65
03:00 p.m.	0.60	0.64	0.62

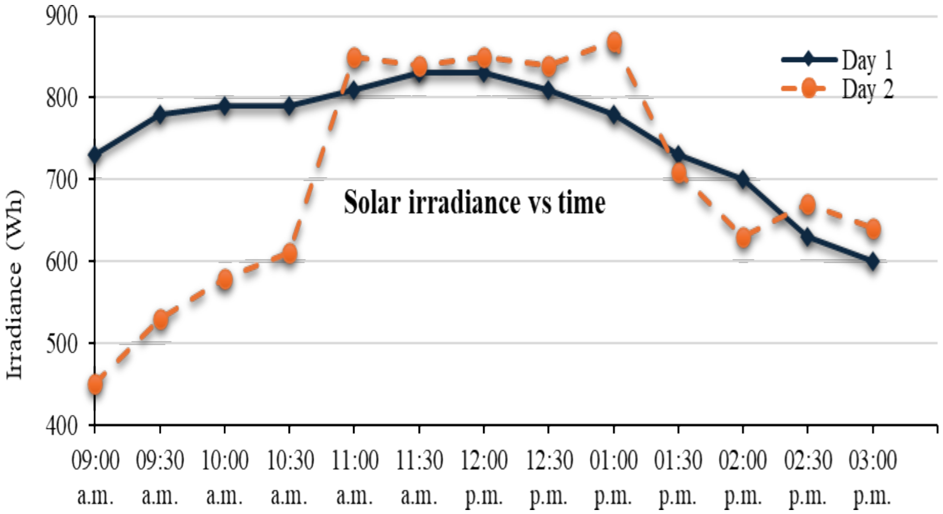


Fig.6 Solar Irradiance Data from 9 am to 3 pm

D. Design of the Solar Pv System

Figure.7 shows the complete design of the solar PV system. This system is designed to operate in combination with a battery to meet the power load demand. The system clearly consists of a solar panel, a battery, a charge controller, and a load. The solar panel converts solar energy into DC power to either charge the battery or supply the loads. The battery is used when solar radiation is insufficient, which occurs less frequently during the day. The charge controller disconnects the current flow between the battery and the load once the battery is fully charged, thereby extending the battery's lifespan and operating duration.

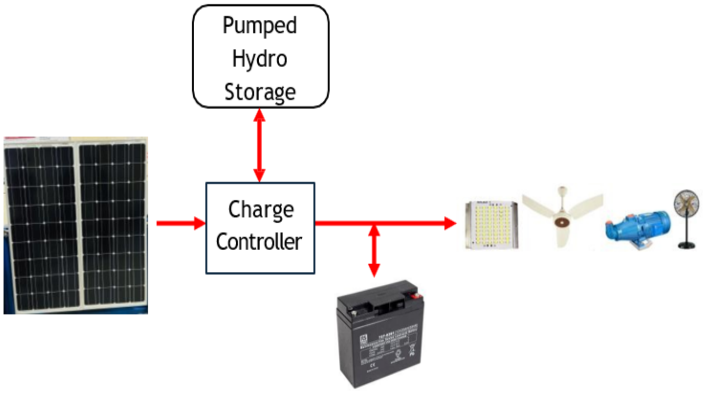


Fig.7 Complete Setup of the Solar PV System

E. Design of Pumped Hydro Storage System

Figure. 8 depicts the design of the pumped hydro storage system, which consists of a closed-loop configuration with two reservoirs: an upper reservoir and a lower reservoir. The basic principle of this operation is that an external pump is first used to fill the lower reservoir. Then, when the battery is fully charged and the load demand is zero-typically between 10 a.m. and 12 noon, and between 3 p.m. and 5 p.m.-the same water is pumped to the upper reservoir. A prototype was built as a proof of concept in the workshop laboratory of the Department of Mechanical Engineering, Mehran UET SZAB Campus, Khairpur Mirs, for experimental testing. Table IV presents the specifications adopted for the prototype.

TABLE IV COMPLETE SPECIFICATION DATA ABOUT THE MODEL

Item	Specification
2-tanks	Height = 2 ft, diameter = 1 ft
The upper tank’s height (from the ground)	Height = 5 ft
Solar PV	20 Watt
Battery	12-V, motorcycle battery
Charge controller	Usually used for a 100-watt solar panel
Turbine	3 watts
Pump	3 watts
Pipe (used from the upper tank to the turbine)	1 inch
Pipe (from the outlet of the turbine)	1.5 inch

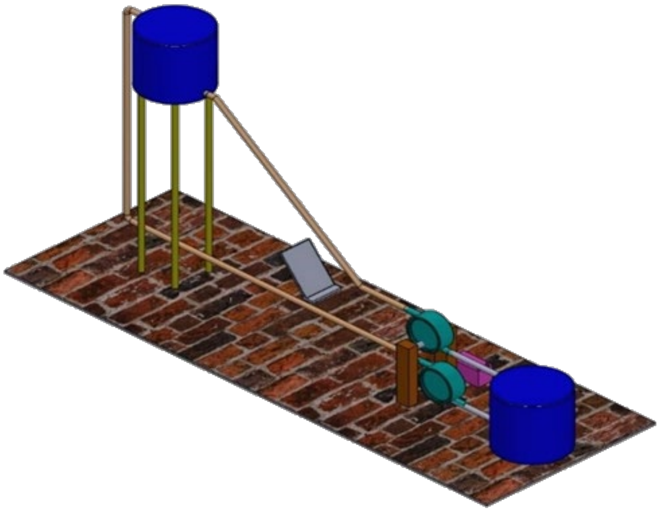


Fig.8 Pumped Hydro Storage System, 3D Models

F. Fabrication of Pumped Hydro Storage System

First, the project stand base was fabricated from iron material by welding in the workshop, and tires were attached to allow easy movement of the entire setup. The stand used in the project is shown in Fig. 9. After fabrication, the tanks and other components were assembled by placing the tanks on the stand. Holes were drilled at the lower part of the tanks to allow water to pass through a flexible pipe between the upper and lower tanks. The turbine and pump were attached using screws, and the complete structure is shown in the subsequent photographs.

Fig.9 Photo of the Stand with its Base and Assembly Snaps

G. Energy Management of the System

The energy supplied by the sun is high during daylight hours; however, after 6 p.m., when the sun sets, solar energy becomes completely unavailable. The battery system is capable of supplying energy after 6 p.m., but it cannot operate throughout the entire night and requires replacement approximately every three years. The system consists of two storage tanks, a turbine, a centrifugal pump, a battery, solar PV panels, a charge controller, and two float switches. It includes a solar panel connected to the charge controller and battery through positive and negative terminals, with both backup and load connections also linked to the charge controller. Solar irradiance reaches the solar panel and generates DC power, which is routed to the charge controller, where the flow of energy to the battery is regulated, and additional power and current are supplied to the load. Once activated, the pump initially uses solar power and transitions to battery power only after solar energy is depleted.

The system uses two 30 L tanks, with the pump transferring water from the lower tank to the upper tank via flexible tubing. When the upper tank fills and subsequently empties, it behaves like a battery-charging and discharging cyclically. The upper tank stores gravitational potential energy, which is released as water flows downward through a hydro turbine, producing kinetic energy (KE) that is then converted to electrical energy (EE). Integrating the pumped storage system with the battery and solar PV reduces the load on the battery during nighttime hours and extends its operational life.

H. Mathematical Formulation

A mathematical formulation was developed to numerically calculate the hydropower generation, the power required to pump water, and the time needed to fill the upper reservoir.

Diameter of the tanks = 0.6 m
Height of the tanks = 0.3 m
Diameter of the pipe = 0.0254 m
Distance between the upper tank and turbine inlet (Z_1) = 0.9 m
Distance between the turbine outlet and lower tank (Z_2) = 0.6 m
The volume of the tank (V) is calculated as:

$$V = \pi \times (d/2)^2 \times h$$

To begin, we first determine the discharge through the penstock. Assume that the discharge through the pipe is $5 \times 10^{-6}\ \mathrm{m^3/s}$.
Hydraulic power:
$P_{hydraulic} = \rho \times g \times Q \times H$
Where: H is the total head, and ρ is the density of water that is equal to 1000kg/m3.
Mechanical power:
$P_{mechanical} = P_{hydraulic} \times \eta_{hydraulic}$
Electrical power:
$P_{electrical} = P_{mechanical} \times \eta_{generator}$

I. Case Study

A case study was conducted to numerically calculate the PV power generation, hydraulic power generation, and pumped power based on the power load demand described in the case study.

III. RESULTS AND DISCUSSION

This study presents the findings on PV power production and its control with respect to load demand. Excess PV power is used to pump water into a hydropower system, which will be utilized at a later stage when the load demand exceeds the capacity of the PV system to supply power; this approach reduces reliance on the battery system and allows for minimal battery storage. The advantages of hydropower in reducing battery requirements and its impact on project cost over its lifespan are also discussed.

A. Capacity and Cost of the Power System Based On 1754 W/Day of Load

Capacity and cost analyses of the PV–battery system and the PV–battery system integrated with a pumped hydro storage system are carried out using the installed cost of pumped hydro storage and Excide Battery [1].

B. Capacity and Cost of the PV-battery Systems

TABLE V CAPACITY AND COST ANALYSIS OF THE PV-BATTERY SYSTEM

Component	Installed Capacity	Lifetime (Years)	Cost/component (PKRs)	Cost/Year (PKRs)
PV Modules (Monocrystalline)	400 W_P	25	16000	640
Battery at 83.3% DoD (Exide HP 200)	12 V & 130 Ah	2	36400	18200
Charge Controller (Victron MPPT 75/15)	600 W	10	19000	1900
Wires	Solar Wire + Connectors	10	5000	500
Structure	Iron	25	15000	600
Miscellaneous	-	25	10000	400
Total Cost			101,400.00	22,240.00

Table V presents the analysis of the PV–battery system cost and capacity. The numerical analysis demonstrates that the optimal PV capacity is 400 Wp to meet the peak load demand and charge the batteries during depletion in the absence of solar irradiance. The unit energy cost was determined by dividing the total installed component cost by the system lifespan (in years) and then by the annual power consumption of the load demand.

TABLE VI UNIT COST OF ENERGY FOR A RURAL FARMER HOUR

Total Energy load per Year (kWh/year)	669
Total Cost Per Year (PKRs/Year)	22,240.00
PKRs/kWh	33.244

The unit cost of energy, as shown in Table VI, is calculated as the annual instalment of the overall installation cost-excluding the discount rate-divided by the overall annual load demand of the energy required by the house of a rural farmer. The unit price of energy is 33.244 PKR/kWh.

C. Capacity and Cost of the PV–Battery Systems Integrated with PHSS

The capacity and cost of the PV–battery system integrated with the pumped hydro storage system are presented in Table 7, based on a 70% cycle efficiency at an optimal three-hour operating period, depending on the PV generation and the hourly load demand. The system consists of a reservoir capacity of 40 m^3, a gross power production of 550 W, and a rated 150 W turbine that generates approximately 127 Wh of hydropower energy per hour. Table VIII shows the unit energy consumption cost for the PV–battery system combined with the pumped hydro storage system. The unit cost of electricity was determined to be 27.56 PKR/kWh.

TABLE VII CAPACITY AND COST ANALYSIS OF THE PV-BATTERY SYSTEM INTEGRATED WITH PUMPED STORAGE

Component	**Installed Capacity**	**Lifetime (Years)**	**Cost/component (PKRs)**	**Cost/Year (PKRs)**
PV Modules (Monocrystalline)	400 W_p	25	16000	640
Battery at 83.3% DoD (Exide HP 150)	12 V & 90 Ah Installed, in market 100 Ah available	2	26800-2680	12060
Pumped Hydro Storage System	550 W (Reservoir Capacity)	50	50000	1000
	4 m x 4 m x 2.5 m (Tanks)			
	150 W (Turbine Rated)			
Charge Controller (Victron MPPT 75/15)	600 W	10	19000	1900
Wires	Solar Wire + Connectors	10	5000	500
Structure	Iron	25	15000	600
Miscellaneous	-	25	10000	400
Total Cost			139,120.00	17,100.00

TABLE VIII UNIT COST OF ENERGY USING PV-BATTERY AND PUMPED HYDRO FOR A RURAL FARMER PER HOUR

Total Energy load per Year (kWh/year)	669
Total Cost Per Year (PKRs/Year)	17,100.00
PKRs/kWh	27.56

D. Power Management Analysis

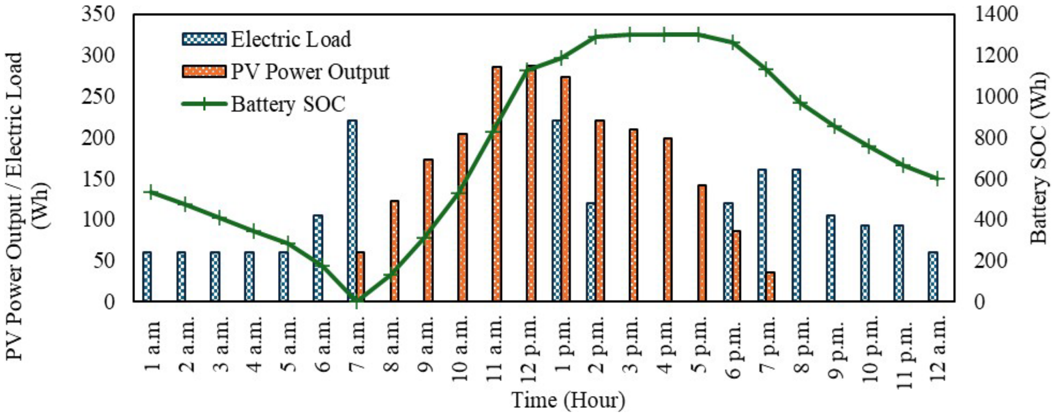


Fig.10 Power Management with PV-Battery System

Figure 10 shows the hourly PV power output, load demand, and battery state of charge. A PV capacity of 400 Wp will produce a maximum of 287 W at noon at the study site. The total PV energy generation is 2298 W, ensuring a 100% reliable power supply to the farmer's house. The actual equipment loading is 1754 W and 1842 W, considering 5% self-power consumption. This leaves an unused output of 456 W in the given example. To utilize this excess power for pumping water and subsequently generating electricity, a pumped hydro storage system is incorporated, thereby eliminating reliance on battery storage.

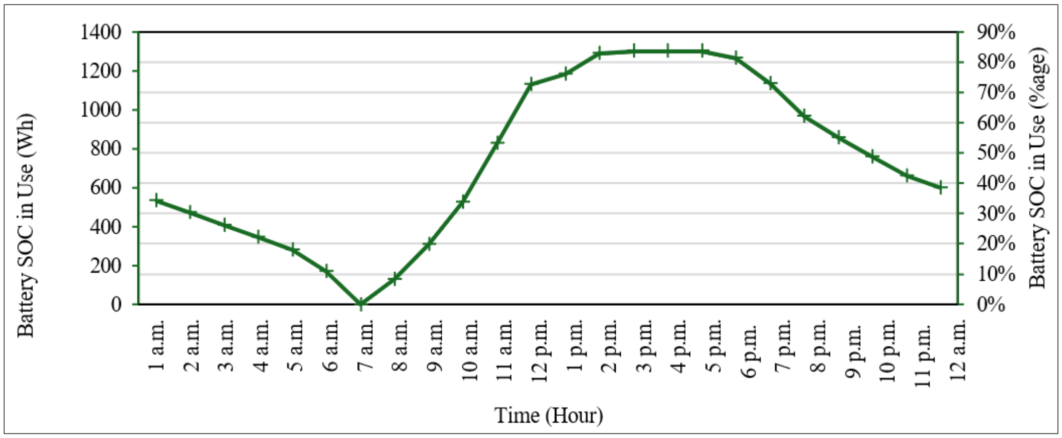


Fig.11 Battery State of Charge in Use

The hourly battery state of charge in Wh and percentage is shown in Figure.11. The PV power remains unused during the three hours before the batteries reach their optimal charge level at 2 p.m. and before they are fully charged at 5 p.m. This period is suitable for regulating water to the upper reservoir, which will be required later for hydropower generation. Figure.12 shows the hydropower produced between 7 p.m. and 9 p.m. (a total of three hours) and its effect on the battery state of charge. Hydropower reduced battery discharge between 6 p.m. and 7 p.m., and the load demand between 7 p.m. and 8 p.m. and 8 p.m. and 9 p.m. was supplemented by hydropower, resulting in an increase in battery charge. Consequently, the battery state of charge decreased by only 1% from 6 p.m. to 9 p.m., indicating the benefit of installing the pumped hydro storage system.

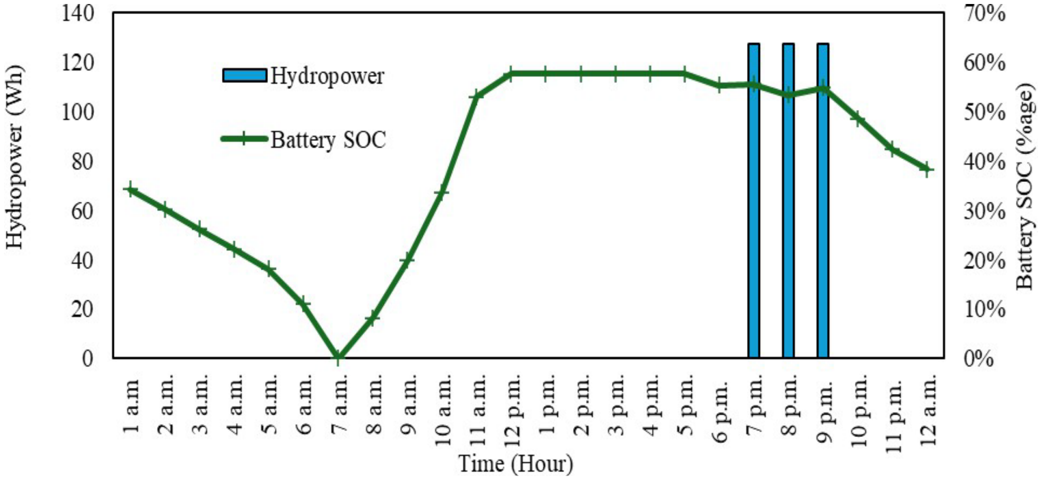


Fig.12 Hydropower Generation and Effect on Battery

IV. CONCLUSION

Pumped hydro storage (PHS), in combination with a photovoltaic (PV)–battery system, provides an effective solution to renewable energy variability and grid stability by integrating long-duration storage with flexible, fast-response storage. A PV–battery system integrated with PHS was developed to supply the energy needs of a farmer’s house, where the appliance ratings, specifications, and usage times are provided in Table II. The household load profile is determined by family activities, as illustrated in Figure 4, with a total daily energy consumption estimated at 1754 Wh/day. In this study, the focus is on energy management, and solar irradiance was recorded over two days to analyze the trend of daytime energy production, as shown in Figure 6. The excess PV energy generated during the day remains unused after the battery is fully charged, as seen in Figure 10. The battery typically reaches full charge at approximately 1:00 p.m., after which the unused solar energy is used to pump water from the lower reservoir to the upper reservoir. Figures 12 show the real-time state of charge (SOC) of the battery. The PHSS reduces the battery load between 7:00 p.m. and 9:00 p.m. Without PHSS, the SOC declines after 7:00 p.m. and continues to drop until morning; however, with PHSS installed, the battery does not experience an increase in depth of discharge (DoD). The reduction in battery SOC is only 1% between 6 p.m. and 9 p.m., demonstrating a clear benefit of the pumped hydro storage system. Based on the analyses in Table VII and Table VIII, integrating PHSS is economically advantageous compared to using a standalone PV–battery system. The unit energy cost of the PV–battery system is 33.244 PKR/kWh, whereas the integrated PHSS with the PV–battery system yields a lower unit cost of 27.56 PKR/kWh, making it more affordable. Pumped hydro storage can provide large quantities of energy over long discharge durations, complementing the battery, which supplies rapid response and short-term storage. Although infrastructure cost and site suitability may pose challenges, the combination of PHS and PV–battery systems enhance energy security, reduces carbon emissions, and supports the development of sustainable energy solutions for the future.

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Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation

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REFERENCES

[1] Z. Hyder *et al.*, "Experimental evaluation of torrefied sawdust pellets as a potential solid fuel in Pakistan," vol. 14, no. 2, pp. 39–48, 2025.
[2] B. Hadjerioua, *Report Covers Costs of Various Storage Technologies, Including Pumped Storage Hydro*, 2019.
[3] G. E. Odor, C. D. Dirisu, N. C. Omekawum, and A. Isaac, "Implementing carbon capture technologies and strategies in the cement industry: A complete review," *Transport*, vol. 8, p. 15, 2025.
[4] J. P. Dorian, H. T. Franssen, and D. R. Simbeck, "Global challenges in energy," *Energy Policy*, vol. 34, no. 15, pp. 1984–1991, 2006.
[5] Y. Yang, S. Bremner, C. Menictas, and M. Kay, "Battery energy storage system size determination in renewable energy systems: A review," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 109–125, 2018.
[6] M. A. Hannan *et al.*, "Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues," *J. Energy Storage*, vol. 42, 103023, 2021.
[7] L. Al-Ghussain, R. Samu, O. Taylan, and M. Fahrioglu, "Sizing renewable energy systems with energy storage systems in microgrids for maximum cost-efficient utilization of renewable energy resources," *Sustain. Cities Soc.*, vol. 55, 102059, 2020.
[8] K. M. Tan *et al.*, "Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration," *J. Energy Storage*, vol. 39, 102591, 2021.
[9] A. N. Abdalla *et al.*, "Integration of energy storage system and renewable energy sources based on artificial intelligence: An overview," *J. Energy Storage*, vol. 40, 102811, 2021.
[10] R. B. Sowby, N. Morehead, and S. Burdette, "Review of energy management guidance for water and wastewater utilities," *Energy Nexus*, vol. 11, 100235, 2023.
[11] A. Rehman and Z. Deyuan, "Pakistan's energy scenario: A forecast of commercial energy consumption and supply from different sources through 2030," *Energy Sustain. Soc.*, vol. 8, no. 1, p. 26, 2018.
[12] M. Hamza and A. M. Khan, "Challenges and opportunities of industrial revolution 4.0 in renewable energy sector of Pakistan: Case study," *Pak. J. Eng. Technol.*, vol. 4, no. 2, pp. 32–37, 2021.
[13] S. Shah, T. Aized, M. Sumair, and S. M. S. Rehman, "Sustainable energy generation-Scenario development for Pakistan in the context of WWF's 2050 vision," *Environ. Prog. Sustain. Energy*, vol. 42, no. 6, e14176, 2023.
[14] J. Tian *et al.*, "A critical review on inconsistency mechanism, evaluation methods and improvement measures for lithium-ion battery energy storage systems," *Renew. Sustain. Energy Rev.*, vol. 189, 113978, 2024.
[15] Z. Q. S. Nwokediegwu, K. I. Ibekwe, V. I. Ilojianya, E. A. Etukudoh, and O. B. Ayorinde, "Renewable energy technologies in engineering: A review of current developments and future prospects," *Eng. Sci. Technol. J.*, vol. 5, no. 2, pp. 367–384, 2024.
[16] S. Khanum, *Optimization of Hydropower for Sustainable Energy in Pakistan*, Ph.D. dissertation, Centre of Excellence in Water Resources Engineering, UET, 2019.
[17] L. Peng, G. He, and J. Lin, "Role of pumped hydro storage in China's power system transition," 2024.
[18] A. Mdallal, M. Mahmoud, and A. H. Alami, "Developments of pumped hydro energy storage systems," in *Renewable Energy-Volume 4: Energy Storage Systems-Mechanical, Hydro, and Thermal*. Academic Press, 2026, pp. 231–247.
[19] J. P. Deane, Ó. Gallachóir, B. P. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," *Renew. Sustain. Energy Rev.*, vol. 14, no. 4, pp. 1293–1302, 2010.
[20] F. Mustafayev, P. Kulawczuk, and C. Orobello, "Renewable energy status in Azerbaijan: Solar and wind potentials for future development," *Energies*, vol. 15, no. 2, 401, 2022.
[21] S. Lykins, *Valuation of Potential Pumped Hydro Energy Storage Projects Based on Known Economic and Service Criteria*, M.S. thesis, Univ. of North Dakota, 2023.
[22] E. Barbour, I. G. Wilson, J. Radcliffe, Y. Ding, and Y. Li, "A review of pumped hydro energy storage development in significant international electricity markets," *Renew. Sustain. Energy Rev.*, vol. 61, pp. 421–432, 2016.