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System-level optimisation of hybrid energy powered irrigation system

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ABSTRACT

Renewable energy-powered irrigation systems have emerged as sustainable solutions, particularly for farmers in off-grid areas. While existing research often highlights tank storage-based systems as the most cost-effective option, large-scale deployment of water tanks incurs significant costs and maintenance challenges. Additionally, there is limited research on the feasibility and optimisation of battery-based irrigation systems, which are often deemed costly despite their potential benefits. This study addresses this gap by identifying the optimal storage solution for hybrid energy-powered irrigation systems through a system-level optimisation model. The model evaluates the suitability of three storage options: direct-coupled water tank storage, battery-coupled storage, and a hybrid battery-tank storage system. Optimisation criteria include life cycle cost (LCC), loss of power supply probability (LPSP), and loss of load probability (LOLP), ensuring a comprehensive assessment of both cost and reliability. Results indicate that the hybrid battery-tank storage system is the most reliable, followed by battery-only storage, while tank-only storage, despite its lower initial cost, poses scalability and maintenance challenges. The LCC over a 25-year project lifetime is £31 k for battery-tank, £26 k for battery-only, and £23.3 k for tank-only systems. Despite the lower cost of tank storage, its complexity and maintenance make it the least preferred option for large-scale systems.

1. Introduction

Recent increases in fossil fuel prices and inflation have affected the livelihood of millions of farmers in Pakistan. The majority of the smallholder farmers who live in off-grid locations face obstacles to adopting conventional electric-powered irrigation systems. The country's geographical location in Punjab and Sindh is on the perimeter of the Indus River, which is one of the world's largest irrigation systems. Despite being a geographically favorable location for agriculture, Pakistan is one of the inefficient food deficit countries in the world, and its global food security index is one of the lowest [1]. Water scarcity and energy demand pose tremendous challenges in Pakistan's agricultural landscape. The energy crisis significantly affects agriculture, leading to energy price hikes, food insecurity and poverty [2]. Integrating renewable energy systems with agricultural infrastructure emerges as a promising avenue for sustainable development here. The Pakistani Government passed legislation in July 2021 on a net zero strategy for the country by 2030, and a few recommendations in the mitigation plan are bringing on renewables in irrigation [3]. In compliance with the net zero targets, the researcher will need to make a significant effort to find a solution for the smooth integration of renewables into Pakistan's agriculture. As reported in Pakistan Vision 2025, the country has a broader vision of promoting a new irrigation policy to ensure efficient water usage for irrigation [4]. The farmers mainly adopt the traditional irrigation system, a barrier to productivity improvement. Using a PV-wind hybrid system reduces the storage capacity required compared to a single source, and renewable energy sources can be utilised more cost-effectively. Moreover, irrigation pumps integrated with hybrid energy systems can ensure sustainable farming and economic growth, hence eradicating energy poverty in rural sectors [5].

Though renewable energy-powered irrigation systems can improve the productivity of crops [6], the storage method to be used is still a challenge for large land areas. Most of the published research is on water tank-based systems without a detailed matrix on scalability and scope

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for large-scale systems. A few articles have raised concerns about water tank costs. For example, C. Soenen et al. conducted a techno-economic comparison between battery and tank-based water pumping systems, finding that the lifecycle cost (LCC) of tank-based systems is 22 % higher than that of battery-based systems. However, this study was limited to domestic water supply contexts [7]. An optimisation study carried out by A. Mazloumi et al. on a water tank storage-based solar-powered system showed that the cost of water supplied per litre for tank-based systems was lower compared to contemporary battery and diesel-based systems, but the tank size was limited to 10 m^3 [8]. A study of various storage systems showed that water tank storage incurs a comparatively lower cost, but the sizing of the tank can pose a challenge. For example, building a 200 m^3 water tank to meet daily water needs can be infeasible considering the required construction cost and the cost of materials, labour, and land area [9]. Furthermore, the cost of the tank-based systems increases to twice that of the battery-based systems when scaling up [10]. The mixed opinions that exist in selecting suitable storage for irrigation systems have necessitated the development of various optimisation models. There have been few published articles on optimising renewable energy-powered irrigation with battery or tank storage. The published literature mostly used the LCC and either loss of load or loss of power supply probability as optimisation criteria [11–14]. But for off-grid systems, both LPSP and LOLP must be considered for optimisation. Therefore, eliminating either one reliability criterion could be a limiting factor for off-grid systems, which has been addressed in this paper by considering both LPSP and LOLP as reliability criteria.

This article aims to identify the storage system for hybrid energy-powered irrigation, and to achieve this aim, the following objectives are carried out.

- Developing a system-level model that comprises an irrigation system, resource assessment, hybrid energy system, and output modules. The model can be used to design, size, and predict the performance of the hybrid energy for various applications.
- Optimising the hybrid irrigation system based on three criteria: life cycle cost (LCC), loss of power supply probability (LPSP), and loss of load probability (LOLP).
- Identifying the optimum storage solution for the hybrid energy-powered irrigation system.

While existing research predominantly focuses on water tank storage systems, often highlighting their cost-effectiveness, there is a significant gap in the exploration of battery-based solutions for irrigation. Large-scale deployment of water tanks incurs substantial costs and maintenance challenges, particularly in off-grid areas where infrastructure is limited. This paper addresses this gap by conducting a comprehensive feasibility and optimisation analysis of battery-based irrigation systems in comparison to traditional water tank systems. By evaluating the hybrid storage solutions on the basis of LCC, LPSP, and LOLP, this research provides critical insights into the most efficient and sustainable storage options for hybrid energy-powered irrigation systems. The findings contribute to the advancement of renewable energy integration in agriculture, offering scalable solutions that enhance reliability and cost-efficiency, thus supporting sustainable farming practices and energy security in rural regions. This study's innovative approach in combining both battery and tank storage systems demonstrates a significant improvement in the reliability and economic viability of irrigation solutions, paving the way for broader adoption and policy support.

The paper's organisation is as follows. Section 2 introduces the materials and methods, including the location of the study, the hybrid energy system working principle, and modelling methods. The hybrid energy system optimisation techniques are addressed in Section 3. Section 4 presents the results, the techno-economic analysis of various storage systems, the optimisation summary, the output generated from the HES, and CO_2 savings. Finally, Section 5 provides some discussion and concluding remarks.

2. Materials and methods

2.1. Site selection

The location of the study is in Sindh, Pakistan (latitude 25.8° and longitude 65.8°), where the average daily solar and wind resource potential is 6 kWh/m^2 and 1.3 kWh/m^2, respectively. The average daily peak sunshine hour is considered 6 h. However, the highest sunshine hour can be as high as 8 h during summer and as low as 4 h during winter. The clearness index of the location K_T value is 0.53–0.74. The average temperature is 27 °C during summer, the highest temperature rise occurs in May at 34 °C, and the minimum temperature at 16 °C is noted for January. The tilt of the PV module is considered 25° during model design. The vertical axis wind turbine is chosen for the hybrid energy system design due to its higher efficiency at low wind speed. However, due to the structural limitations of VAWT, a hub height of 10 m–20 m is recommended. A hub height of 10 m is considered in this study. The hourly annual variability of wind speed is over the range of 1–7 m/s.

In this study, a completely off-grid solar wind hybrid energy system has been designed. The energy system will deliver power to the irrigation pump to irrigate 5 acres of land for sugarcane cultivation. The daily peak water demand for sugarcane production is 293 m^3 required in July. The system level model is developed considering an average daily water demand of 208 m^3 to avoid oversizing the system. The HES runs a 4-kW irrigation pump for 12 h every day at a daily energy requirement of 48 kWh. The hybrid energy system design involved finding the wind turbine's rated power, peak power of PV, and required storage capacity to compensate for any power deficit caused by solar and wind unavailability and determining the optimum tank size to store any water residuals. The block diagram of the model is shown in Fig. 1.

2.2. Design of hybrid energy system

Hybrid energy systems (HES) consist of at least two or more energy resources integrated with energy storage and user loads [15]. The energy flow of a hybrid energy system with battery-tank storage is presented in Fig. 2 below.

The HES comprises solar PV, wind turbine, battery storage, irrigation pump load, and water tank. The MPPT charge controller supervises and controls the energy flow by extracting maximum power from PV and wind, protecting the battery from overcharging, and discharging, and meeting the load demand. The pump controller controls and monitors the tank's water flow, pressure, and level. The hybrid energy system works with five modes to ensure the load demand is met and to maintain the battery's state of charge to retain battery life [16].

The energy supplied by the hybrid system:

$$E_H = E_{PV} + E_{WT} \tag{2.1}$$

The energy supplied to the pump load:

$$E_L = \begin{cases} E_{PV} + E_{WT}\ , \ if\ E_H > E_{Lmin} \\ E_{PV} + E_{WT} + E_{BAT},\ if\ E_H < E_{Lmin} \end{cases} \tag{2.2}$$

The gross energy production from PV and WT can be calculated as:

$$E_G = \frac{E_{PV} + E_{WT}}{E_L} \tag{2.3}$$

Excess energy production when battery capacity is full that is, SOC = SOC_{max}, can be calculated as:

$$E_{excess} = \frac{[E_{PV} + E_{WT}] - E_L}{E_{PV} + E_{WT}} \tag{2.4}$$

The modes of operation are briefly described below.

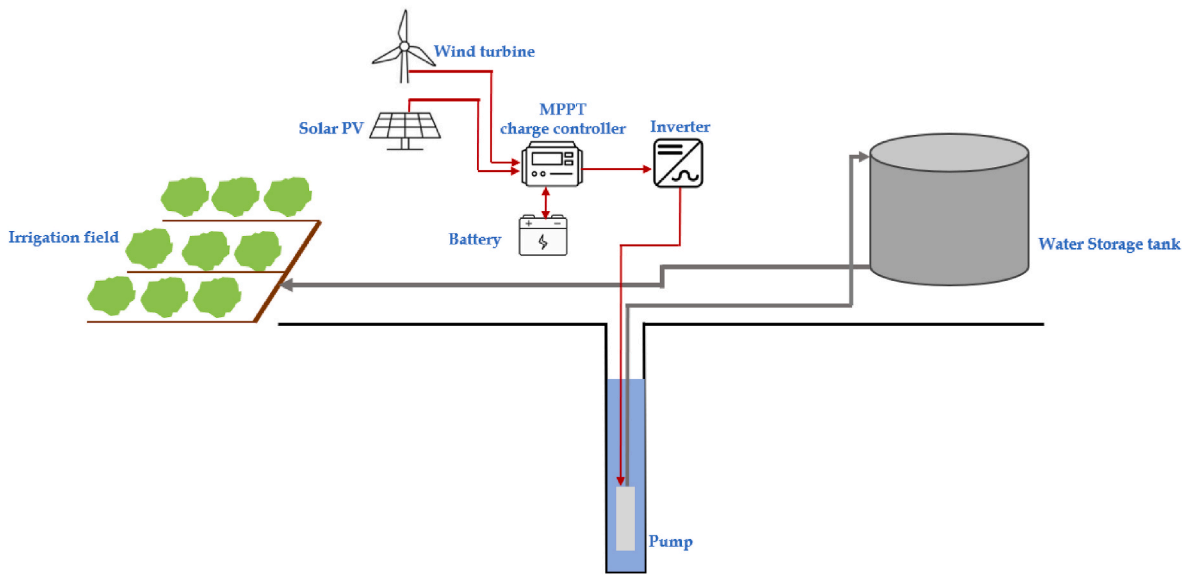

Fig. 1. Hybrid energy model block diagram.

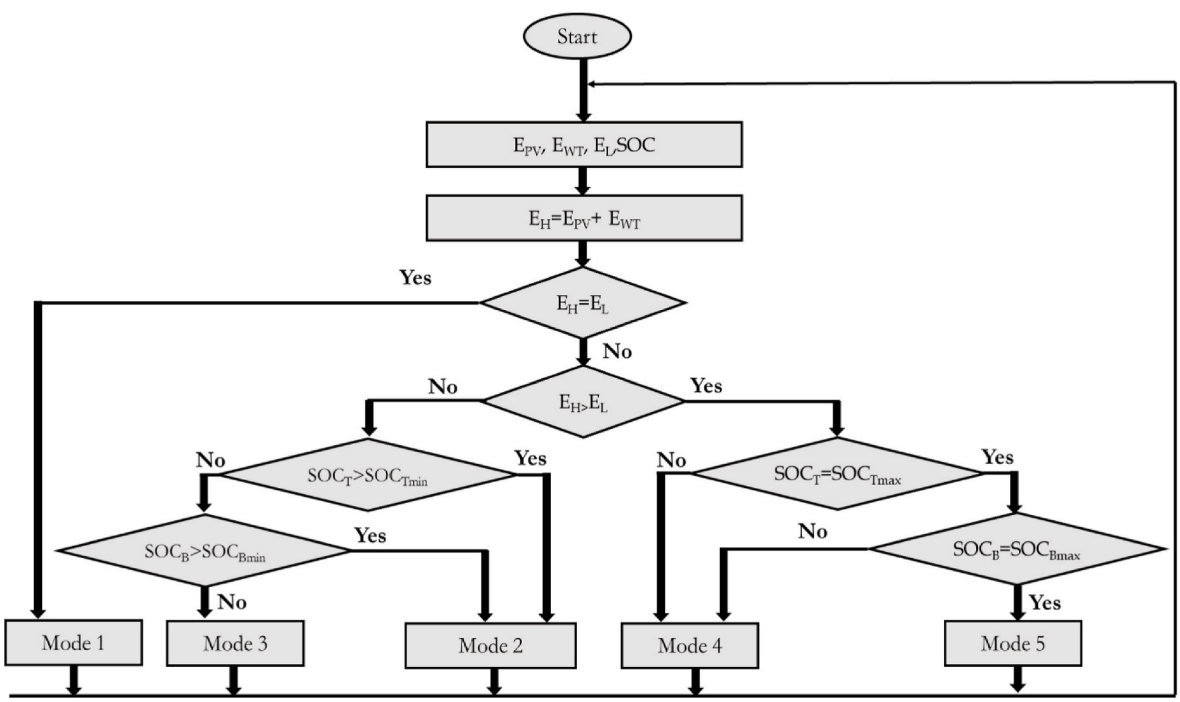

Fig. 2. Modes of operation of the hybrid energy system.

Mode 1: The energy supplied by the PV (E_{PV}) and wind turbine (E_{WT}) equals the energy demanded by the pump load. The available energy will be used to drive the pump, and the water residual in the tank will continue to rise if there is excess water.

Mode 2: The energy supplied by PV and WT is less than the load demand. If the tank water is above the minimum level, the water demand will be met by the tank water. If the tank water level reaches its minimum, the battery will compensate for the energy gap to drive the pump if the battery's state of charge (SOC) exceeds its minimum value (SOC_{min}).

Mode 3: The hybrid energy from PV and the wind is less than the load demand, and the battery state of charge and water tank level is less than the minimum threshold (SOC_{Bmin}) and (SOC_{Tmin}), respectively; both the battery and pump load are disconnected. The battery will be reconnected once it charges to its minimum value, and the pump load is connected again once sufficient energy is available to meet the load demand.

Mode 4: When the generated energy from PV and WT exceeds the load, and the state of the water tank level is less than the maximum threshold SOC_{Tmax}, the excess energy will drive the pump to fill the tank regardless of the state of charge of the battery, SOC_B. The excess energy will charge the battery once the tank reaches its maximum water level.

Mode 5: When the generated energy from PV and WT exceeds the load, and the charge state of the battery and water tank level reaches the maximum threshold SOC_{Bmax} and SOC_{Tmax}., the battery is disconnected. Hybrid energy sources supply the pump load, and the auxiliary load (if any) will absorb the surplus energy.

2.3. System-level model

Hybrid energy system performance depends on conditions such as daily or monthly temperature, weather data variation, and wind speed data. Modelling and analysing this complex system are critical to ensure the proposed system's reliability. The algorithm of the hybrid energy model is developed using Python. The developed model facilitates weather resource assessment, system sizing, and data analysis functionality, essential to processing the data and converting it into valuable information through statistical analysis, mathematical computation, and graphical representation. Hence, a system-level model is developed in Python version 3.7 at Spyder integrated development environment (IDE).

The model runtime dependency includes various scientific Python library packages such as Matplotlib, Pandas, NumPy, WindPowerlib, and PVLIB Python. The simulation is performed on an hourly basis to evaluate resource data, model battery and water tanks, and predict annual energy output from PV and wind turbines. The model utilises a numerically intensive computing Python library, 'Numba', which can be loaded by the program as a CPython interpreter. It is an open-source just-in-time (JIT) compiler which converts the Python and NumPy subset into faster machine code via the low-level virtual machine (LLVM) Python package. The simulations are run on Intel® Core ™ i7-7500U CPU @ 2.7 GHz–2.9 GHz Laptop. The system-level configuration is shown in Fig. 3 below. The model consists of four modules: irrigation module (IM.py), resource assessment module (RM.py), hybrid energy system module (HM.py) and output report generating module (OM.py).

a. **Irrigation module (IM):** The irrigation module performs a detailed analysis to define the irrigation system layout and pump capacity required for the irrigation system. It requires user inputs, such as weather data, available land area, types of crops to be irrigated, method of irrigation, and duration of irrigation. The output generated from this module is pump capacity for sprinkler and drip irrigation, required tank storage volume, pipe length and diameter and yield improvement.
b. **Resources assessment module (RM):** A detailed resource assessment is conducted to determine the solar and wind availability of the designated location. The model uses NASA's hourly database for wind resource assessment. For solar irradiance and temperature data, the model utilises PVGIS databases, which have a temporal resolution of 10 years and a spatial resolution of 5 km and are validated mainly using high-quality ground stations. The parameters assessed from this module are global irradiance mapping, the plane of array irradiance at various PV module tilts, average wind speed mapping, mean temperature, and clearness index. The outputs from this module are available solar and wind resource data, passed as input to the hybrid energy module.
c. **Hybrid Energy module(HM)**: This module performs the sizing and optimisation of the hybrid energy system. This module takes the required pump capacity (load) input from the irrigation module to determine the necessary PV, WT, battery, and inverter capacity. It calculates daily and monthly performance metrics such as energy production and produce graphs based on time, date, and test conditions.
d. **Output report module (OM):** The output report module generates automated PDF reports, including graphics, cost analysis, performance metrics, and tables. The report summarises the irrigation system requirements, the sizing of the hybrid energy system, the graphical presentation of resource assessment, expected energy production, yield improvement, and optimisation result output.

2.3.1. PV and wind turbine model

The PV system is modelled using the PVLIB Python library [17]. PVLIB Python is an open-source library for simulating the performance of PV systems initially developed by Sandia National Laboratories as a part of the PV Performance Modelling Collaborative. It contains functions and classes to calculate the irradiance transposition, clear sky irradiance, cell temperature, maximum power point tracking, DC power output and AC-DC power conversion of the PV system. The power output from wind energy is modelled using windpowerlib, an open-access library developed by oemof developer group. The library provides several classes, such as height correction, temperature and air density correction and power output calculation [18]. The detailed discussion of the PV and wind turbine model has been excluded as the main focus of this article is the optimisation of battery and tank storage for hybrid energy systems.

2.3.2. Battery model

Two types of batteries are typically used to design hybrid energy systems: lead-acid and lithium-ion batteries. The design is based on a sealed gel-type lead-acid battery with a longer lifetime, low discharge rate and rated capacity of C_{20} (20 h discharge rate) [19]. Battery charging starts when the power generated from PV and wind turbines exceeds the load power. The SOC is determined based on the energy balance between the wind and PV hybrid energy systems and by observing the charging and discharging of the battery. After meeting the load demand, any surplus energy will be utilised to charge the battery. The model applies the Coulomb counting algorithm, to estimate the state of charge for battery, SOCB (t) in a hybrid energy system.

The state of charge (SOC) is 1 when the battery is fully charged. The allowable depth of discharge (DOD):

$$DOD_B = 1 - SOC_{Bmin} \tag{2.5}$$

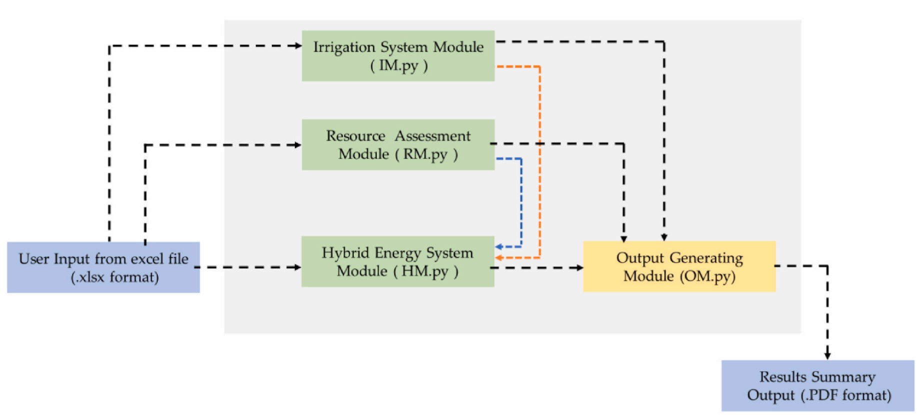

Fig. 3. System level model of the hybrid energy system.

Battery constraint: $SOC_{Bmin} \leq SOC_B\ (t) \leq SOC_{Bmax}$. The minimum state of charge for the battery is considered 50 % for lead-acid batteries.

The state of charge at time t, $SOC_B\ (t)$ of the battery is calculated as:

$$SOC_B\ (t) = SOC_B(t_0) * (1 - \delta_t) + \left(\frac{I_{BAT}\eta_{CH}\Delta t}{C_{BAT}}\right) \tag{2.6}$$

Battery discharging occurs when the power generated from PV and wind turbines cannot meet the load demand.

$$SOC_B\ (t) = SOC_B(t_0) * (1 - \delta_t) + \left(\frac{I_{BAT}\eta_{DCH}\Delta t}{C_{BAT}}\right) \tag{2.7}$$

Here δ_t is the battery self-discharge rate, η_{CH} is the battery charging efficiency, which is considered 0.85 and the battery discharging efficiency η_{DCH} is considered 1, C_{BAT} is the battery capacity in ampere hour (Ah) and I_{BAT} is the battery charging/discharging current, Δt is the 1-h interval. I_{BAT} is negative during discharge.

2.3.3. Tank model

The tank model represents the water level in the tank while filling or emptying the tank to meet the water demand. The tank operation is analogous to the charging and discharging of the battery. The tank modelling aims to identify the water deficit, state of charge (water) and excess water volume produced in hourly intervals over one year. The state of charge (SOC_T) is 1 when the tank is fully charged. The allowable depth of discharge (DOD_T):

$$DOD_T = 1 - SOC_{Tmin} \tag{2.8}$$

Tank constraint: $SOC_{Tmin} \leq SOC_T\ (t) \leq SOC_{Tmax}$. The minimum state of charge for the tank is considered 5 % of the total capacity. The state of charge (SOC_{Tmax}) is 1 when the tank reaches its maximum level. At any time, t, tank state of charge can be calculated as:

$$SOC_T\ (t) = \frac{Q_{res}(t)}{Q_{max}} \tag{2.9}$$

$Q_{res\ (t)}$ is the water residual in the tank at time t and Q_{max} is the maximum water capacity of the tank. Hourly volume of water pumped into the tank, $Q(t)$ in m^3 can be calculated as,

$$Q(t) = \frac{E_L \times 0.367 \times \eta_{sys}}{TDH} \tag{2.10}$$

E_L is the available energy from HES, TDH is the total dynamic head 45.95 m, 0.367 is the conversion faction from litre to m^3, η_{sys} is the pumping efficiency of 55 %. Water residual in the tank can be calculated as [20]:

$$Q_{res}\ (t) = \begin{cases} Q_{res}(t_0) + Q(t) - D(t), Q_{res}(t_0) + Q(t) - D(t) > 0 \\ Q_{res,min}, otherwise \end{cases} \tag{2.11}$$

$Q_{res,min}$ is the minimum water level maintained at the tank. The water demand, D represents the daily water consumption by the irrigation system. Water deficit at time t is calculated as:

$$Q_d\ (t) = \begin{cases} |\ Q_{res}(t_0) + Q(t) - D(t)|, Q_{res}(t_0) + Q(t) - D(t) < 0 \\ 0, otherwise \end{cases} \tag{2.12}$$

The excess water produced at any time can be calculated as:

$$Q_e\ (t) = \begin{cases} Q_{res}(t_0) + Q(t) - D(t) - Q_{max}, if\ Q_{res}(t_0) + Q(t) - D(t) > Q_{max} \\ 0, otherwise \end{cases} \tag{2.12}$$

3. Hybrid energy system optimisation technique

There are several techniques for hybrid energy modelling, such as linear programming, iterative methods, probabilistic approach, dynamic programming, or multi-objective optimisation. This study uses the nondominated sorting genetic algorithm (NSGA II) based multi-objective optimisation technique [21]. Optimisation aims to determine the PV wind optimum ratio, which provides minimum cost at an acceptable loss of power supply probability and loss of load probability.

Due to the intermittent nature of PV and wind, the energy system must deliver the necessary power to the load as required, and at the same time, the cost of the system should be minimal. In the preceding section, the reliability and cost analysis methods are presented.

3.1. Reliability of the hybrid energy system

Several methods are available to determine the reliability of the hybrid energy system, such as loss of load probability (LOLP or LOL), loss of power supply probability (LPSP or LPS), and unmet load. This research uses both LOLP and LPSP to assess system reliability. LOLP presents the probability that the water produced by the hybrid energy system is insufficient to meet the water demand. It is calculated by the ratio of the volume of water deficit to the volume of water demanded within the specified time such that [13]:

$$LOLP = \frac{\sum_{t=1}^{N=8760} Q_d\ (t)}{\sum_{t=1}^{N=8760} D\ (t)} \tag{3.1}$$

Furthermore, the loss of power supply probability is used to assess power reliability. LPSP presents the probability that the energy produced by the hybrid energy sources is insufficient to meet the irrigation pump load and any auxiliary load demand [22]. It can be calculated as [23]:

$$LPSP = \frac{\sum_{t=1}^{N=8760} (P_L(t) - P_T(t))}{\sum_{t=1}^{N=8760} P_L(t)} \tag{3.2}$$

Here, P_L is the load power at any time t, P_T is the total power from PV, WT and battery, and N is the number of hours a year. LPSP occurs when $P_L > P_T$. The total power P_T can be calculated as,

$$P_T = [\eta_{MPPT}(P_{PV} + P_{WT}) + P_{BAT}]\eta_{INV} \tag{3.3}$$

$$P_{BAT} = [SOC(t-1) - (1 - DOD)]\left[\frac{C_{BAT}V_{BAT}}{\Delta t}\right] \tag{3.4}$$

3.2. Cost analysis of the hybrid system

Once a technology has been identified as technically feasible, it is vital to assess its economic feasibility. The life cycle cost (LCC) approach is used to evaluate the cost of the HES system. The lifecycle cost comprises the initial cost of capital and the net present value of maintenance and replacement costs. The project lifetime is considered 25 years. The objective function of the lifecycle cost can be expressed as:

$$LCC = CAPEX + OPEX + R_C \tag{3.5}$$

The CAPEX includes the cost of HES components. The CAPEX can be calculated as:

$$CAPEX = PV_{Wp}UC_{PV} + WT_{WP}UC_{WT} + BAT_{cap}UC_{BAT} + INV_{WP}UC_{INV} + CC_PUC_{CC} + T_vUC_T \tag{3.6}$$

PV_{wp} = total PV capacity required.
UC_{PV} = per unit cost of PV
WT_{WP} = wind turbine capacity required
UC_{WT} = unit price of wind turbine
BAT_{cap} = total battery capacity required in Ah
UC_{BAT} = battery unit price
INV_{WP} = inverter power required

UC_{INV} = unit price of inverter
CC_P = charge controller capacity
UC_{CC} = unit price of charge controller
T_v is the volume of the tank and UC_T is the cost per m^3 of the tank. The unit cost of components is shown in Table 1 [24]. The operational cost in the first year is considered 2 % of the initial cost of each component (IC_n) and d_r is the discounted factor. The discounted operation and maintenance cost over the project lifetime, $t = 25$ years is:

$$OPEX_n = \sum_{1}^{t} \frac{0.02\, IC_n}{(1 + d_r)^t} \tag{3.7}$$

$$OPEX = \sum_{1}^{n} OPEX_n \tag{3.8}$$

R_{Cm} is the replacement cost of the m^{th} component and IC_m is the cost of each component. The components are battery, inverter, charge controller and pump set. The replacement of the battery and inverter will be required every six years within the project's lifetime.

$$R_{Cm} = \sum_{1}^{t} \frac{IC_m}{(1 + d_r)^t} \tag{3.9}$$

$$R_C = \sum_{1}^{m} R_{Cm} \tag{3.10}$$

4. Results and analysis

The results and analysis have five sub-sections: First, a sensitivity study of various input variables on the lifecycle cost of hybrid energy system is performed in section 4.1. Then, in section 4.2, the cost of the water tank is studied based on available market data in Pakistan. Following the tank cost analysis, the techno-economic performance of the various storage systems is shown in section 4.3. The optimisation summary and annual energy yield are presented in sections 4.4 and 4.5, respectively.

4.1. Sensitivity analysis of life cycle cost

The LCC of hybrid energy systems depends on four significant variables: energy input, discount factor, battery days of autonomy and daily duration of operation. A sensitivity analysis is conducted for battery-only storage systems to explore the dependence of these variables (Fig. 4). The midpoint values of 0 % are shown in Table 2, where the LCC is £26 K. The PV: WT ratio is 0.8:0.2, and battery days of autonomy is one day. The vertical axis represents the LCC at relative changes of input variables in the range of +75 % to −75 %, as shown in the horizontal axis. The analysis shows that the resulting LCC is highly sensitive to energy input, duration of operation and battery days of autonomy.

For this study, the duration of the operation is considered 12 h daily, and when it decreases, the pump capacity needs to be higher to balance for a lower duration of usage, and therefore the LCC increases. The higher battery days of autonomy minimise the benefits of a longer duration of operation. The days of battery autonomy beyond one day incur higher LCC, whereas decreasing the DOA below one day compromises the hybrid system's power reliability, which is discussed further in section 4.3.

Though reducing the energy input can lower the LCC significantly, the power reliability of the system also goes up over 20 %. Therefore, the sizes of the system to be chosen, keeping in mind the LPSP of the system, must maintain within 10 % – 12 % maximum.

Table 1
Unit cost of components.

Component	Unit price
PV	$0.25£/W_P$
WT	$0.4£/W_P$
INV	$0.25£/W_P$
BAT	£0.5/Ah
CC	$£0.1/W_P$
Water tank	$£80/m^3$

4.2. Water tank cost analysis

Based on the Pakistan market study of tank cost, a scatter plot showing the relation between water tank size and cost is shown in Fig. 5a. The graph shows a polynomial relationship between the tank cost and tank size. An illustration of the normal probability density function (PDF) is helpful in understanding the cost further. An illustration of the data's normal probability distribution function and its 2-sigma value for water tank cost is presented in Fig. 5b.

The cost of a water tank varies between $£52/m^3$ to $£135/m^3$. The average tank cost was found to be $£90/m^3$ with a standard deviation of $£21/m^3$. The width of the curve shows that 95 % of the data falls within the ±2 standard deviation (±2 σ) around the mean (μ). At the μ ±2 σ value, the cost is within the range of $£48/m^3$ to $£131/m^3$, which shows a wider variation. To avoid overpricing, this study considers a tank cost of £80/m3, which is slightly lower than the average cost.

4.3. Techno-economic analysis of HES performance

A load sensitivity study of battery coupled and direct drive watering in various cases is presented in this section to assess the techno-economic feasibility of storage used. The load represents the respective water demand. Table 3 shows the configuration of multiple instances.

In case 1, a battery-coupled irrigation system with one day of autonomy is considered, and the initial SOC of the battery is 0.6. Case 2 refers to the direct drive irrigation system with tank storage. The initial status of the water tank is 5 % of the maximum tank capacity. Case 3 considers both battery and tank-based systems. The HES system performance is evaluated in this section for PV: WT energy input ratio at 0.8:0.2, respectively.

4.3.1. Battery only system

A techno-economic analysis is performed for different cases to evaluate the best scenarios that offer the most optimised solution. Case 1 offers the base solution where the yearly water deficit is 6.3 %, implying almost 94 % water availability at one day of battery autonomy. A sensitivity analysis is shown in Fig. 6a to reveal the parameters that affect the LCC. Reducing the autonomy by less than one day lowers the LCC, but the overall power supply reliability exceeds 12 % limit. Therefore, at least one DOA is selected where the LCC is £26 k and increasing beyond one day, and the LCC goes up by £4 k. The peak monthly water deficit of 1229 m^3 occurs in July (Fig. 6b). The maximum hourly deficit shown in Fig. 7a occurs on 26^{th} July at 21 m^3 at a complete loss of load, and the maximum daily total water deficit of 123 m^3 occurs two days after (28^{th} July). The battery state of charge on that day was at a minimum of 0.5, with a depth of discharge of 50 %. Though depending on the temperature derate factor and rate factor of the battery, the maximum state of charge may go above 1, here it is assumed the maximum SOC limits to 1. Battery experiences frequent charge and discharge cycles in June–August due to the higher demand around this period (Fig. 7b). The power reliability (LPSP) slightly increases over the 12 % limit. However, due to the water deficit being within the limit of 10 %, a slightly higher LPSP is considered acceptable.

4.3.2. Tank only system

In case 2, for the tank-only storage, the initial stage of the tank is considered 5 % of its volume, which is the minimum water level that needs to be maintained; the remaining condition is the same as in case 1.

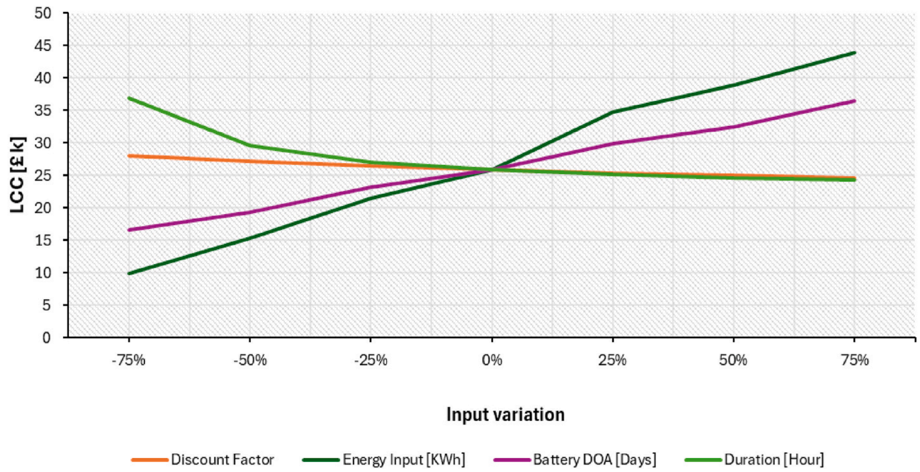

Fig. 4. Sensitivity study of various input variables in hybrid energy system.

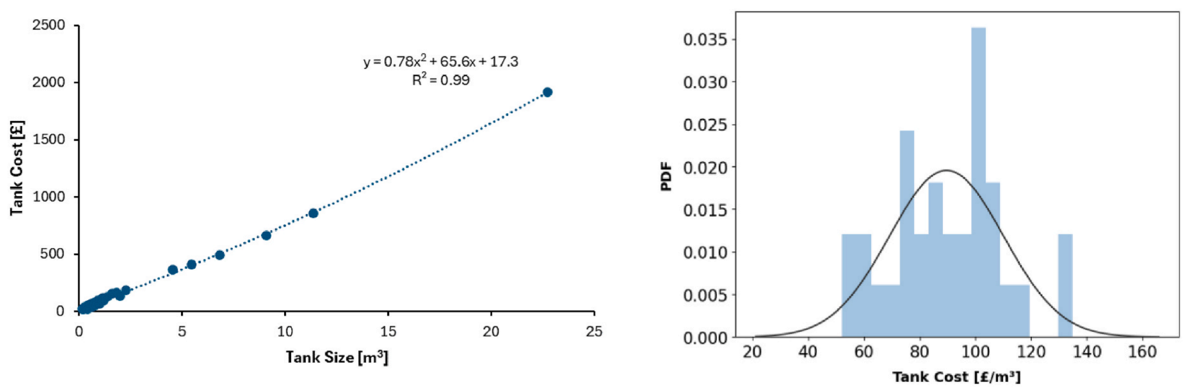

Fig. 5. a. Tank cost based on market study (left), b. Probability distribution of tank cost/m^3 (right).

Table 2
Sensitivity analysis parameter.

Parameter	Value
Energy Input	48 kWh
Battery days of autonomy	1 day
Usage of operation	12 h
Discount factor	5 %
LCC	£26 k

As shown in Fig. 8a, the LCC is highly sensitive to tank size. On tank days of autonomy, for one day, the LCC is £34 k for plastic water tanks only, which might rise significantly if the tank material changes. The tank construction is the next cost-intensive part, which adds further complexity as the tank size increases. Compared with a battery-based system in case 1, the water deficit at tank autonomy 0.5 day incurs nearly the same monthly peak deficit (8 %) as the battery-based system. Decreasing the tank size beyond this point approaches the monthly peak deficit towards its 10 % limit.

The water deficit is highest in July (Fig. 8b), and the maximum hourly water deficit of 23 m^3 is noted on 22nd July (Fig. 9a). The

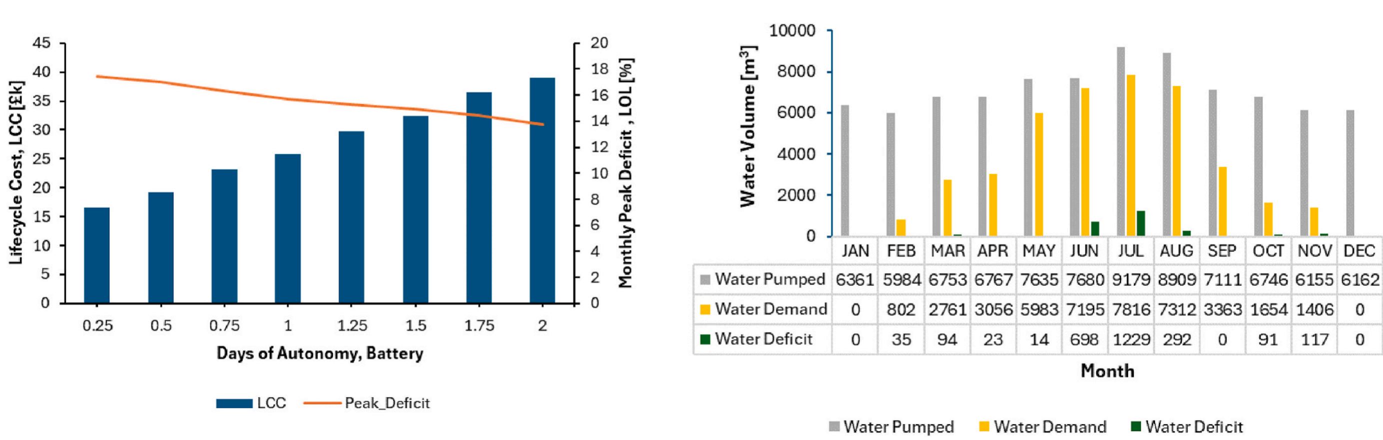

Fig. 6. a. Sensitivity analysis of LCC and LOLP (left), b. Monthly water pumped, water demanded and deficit (right) of battery only storage system.

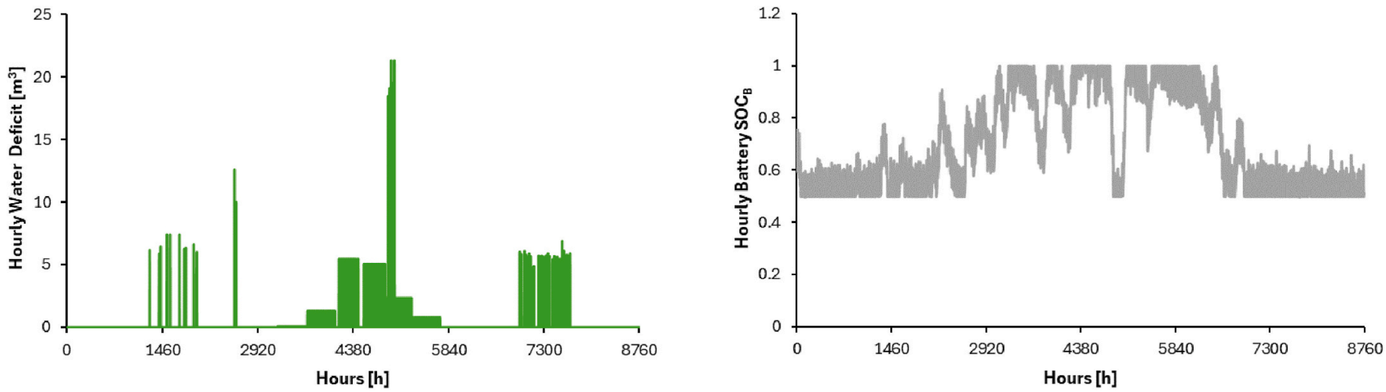

Fig. 7. a. Hourly water deficit (left), b. Hourly state of charge of the battery (right) of battery only storage system.

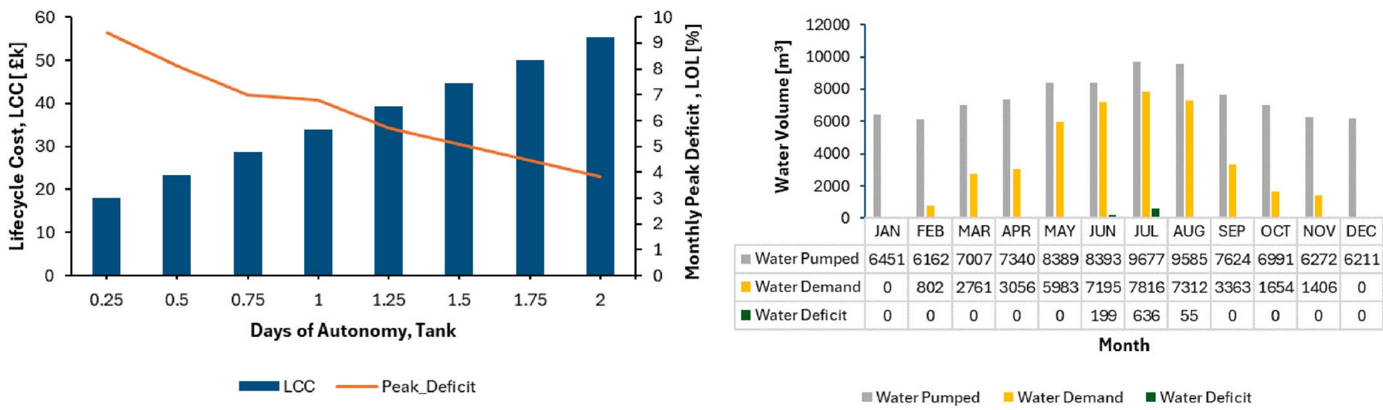

Fig. 8. a. Sensitivity analysis of LCC and LOLP (left), b. Monthly water pumped, water demanded and deficit (right) of tank only storage system.

maximum daily water deficit of 137 m^3 occurred on 26th July. The tank water residual is shown in Fig. 9b, which represents the maximum discharge of the tank that occurs during peak irrigation month in May to July and in the remaining time, mostly the residuals drop to 50 % of its maximum volume.

From November to February, the tank is primarily full due to less water demand; hence, the loss of load probability is lower. The additional tank autonomy seems to oversize the capacity, exceeding the requirement.

4.3.3. *Battery-tank system*

A sensitivity study was carried out to understand the impact of tank days of autonomy (DOA) on LCC and LOLP. The battery days of autonomy are fixed for one day. The result shows (Fig. 10a) that the LCC at the tank days of autonomy 0.25 days (52 m^3) is £5 K higher than the complete battery-based system costing £31 k where the cost of water tank is 13 % of LCC with a total water deficit of 1066 m^3. The monthly peak water deficit decreased by more than 50 % in July compared to the battery-only storage system (Fig. 10b) and by more than 15 % compared to the tank-only storage. Reducing the tank size furthermore will raise the peak daily deficit close to the 10 % limit, which for present scenario is 7 %.

The hourly water deficit occurring before April and beyond September for battery-based systems has now improved due to dual energy storage (Fig. 11a), and the deficit during these months is now zero. The battery state of charge over the year shows that during high peak load periods (May–August), the battery goes through several charge-discharge cycles (Fig. 11b). However, in the remaining months,

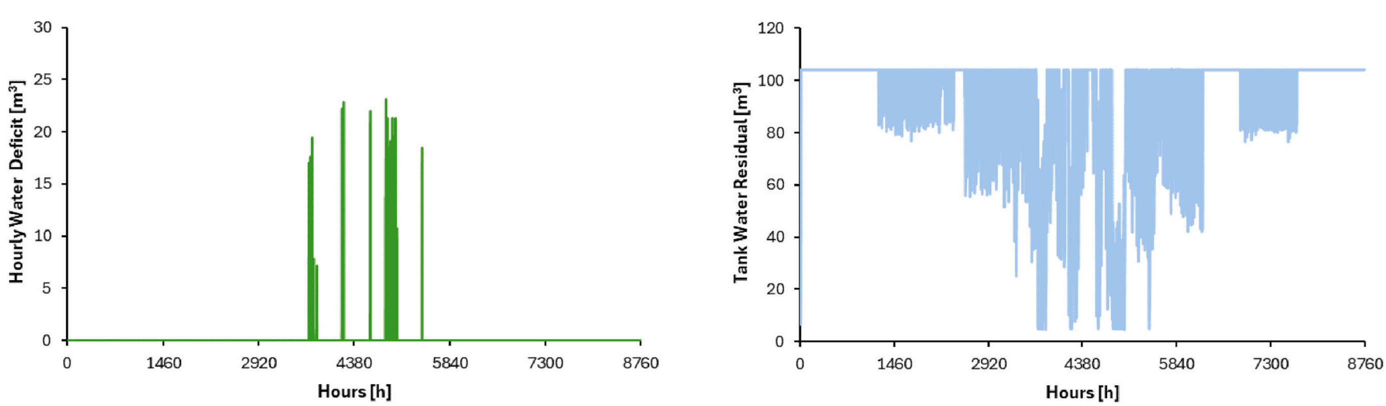

Fig. 9. a. Hourly water deficit (left), b. Hourly water residual in the tank (right) of tank only storage system.

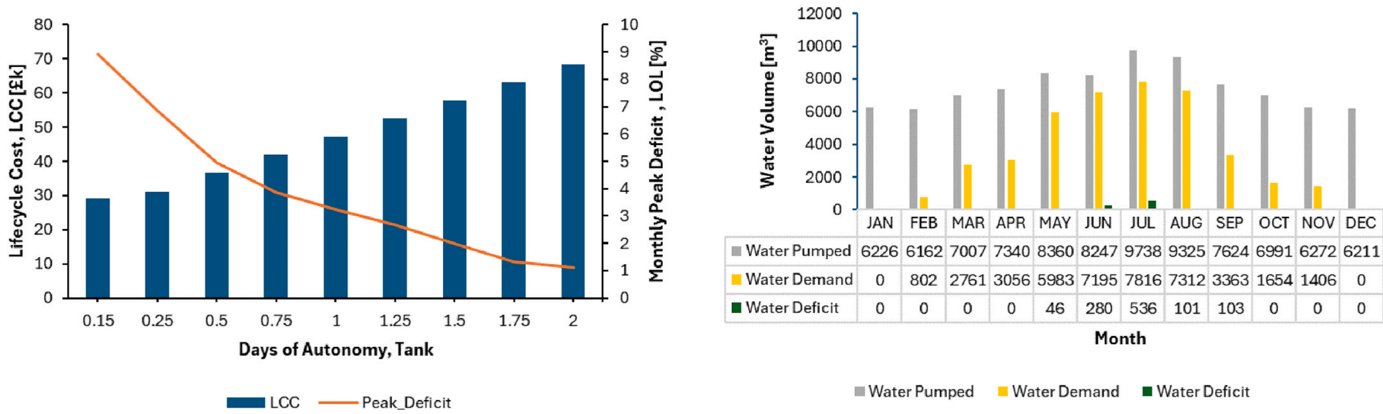

Fig. 10. a. Sensitivity analysis of LCC and LOLP (left), b. Monthly water pumped, water demanded and deficit (right) of battery-tank storage system.

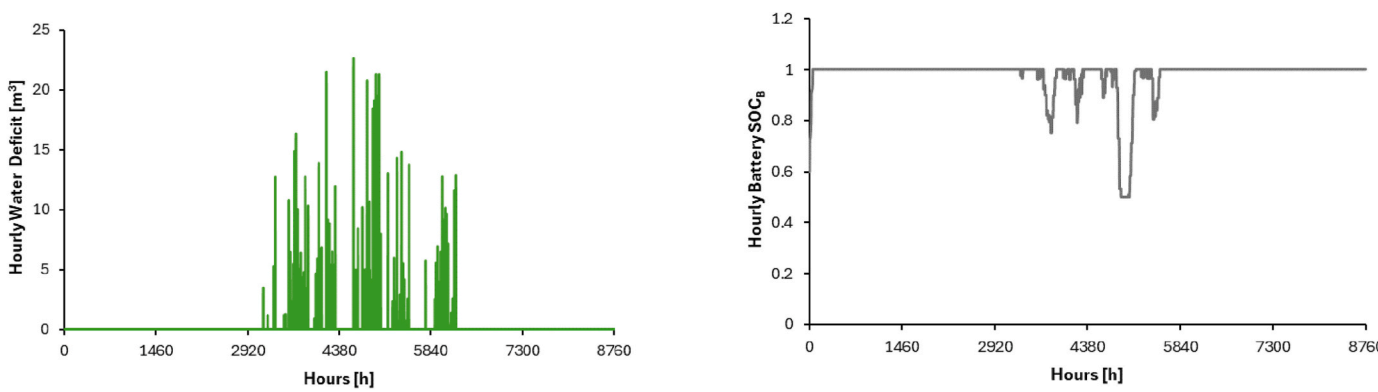

Fig. 11. a. Hourly water deficit (left), b. Hourly state of charge of the battery of battery-tank storage system.

the battery mostly remained charged due to low daily load demand, indicating room for adding a few auxiliary loads in these months. Hourly water residual in the tank shows (Fig. 12) a higher frequency of events that the tank water residual drops down to a minimum threshold of 5 % of the water volume (3 m^3). If the results are compared with the tank-based system, the overall LOLP is 2.6 %, close to the LOLP of the tank-based system (2.2 %), and the LCC is £7 k higher than the tank-based system due to the additional cost of the battery. The monthly peak water deficit is nearly the same as tank-based (7 %). Though lower battery days of autonomy reduce LCC, it is essential to realise that in case of future expansion of the off-grid system, the option would be limited with lower days of autonomy. Moreover, here, it is assumed that the efficiency of the irrigation pump remains fixed, which will vary with a possible increase in water deficit. Therefore, battery days of autonomy minimum of one day is recommended to keep the scope for an additional charge-discharge cycle if the water demand or the motor efficiency changes. Overall, the best performance was achieved for the battery tank-based system. The overall system reliability improved in this case, and the overall LPSP is <1 %.

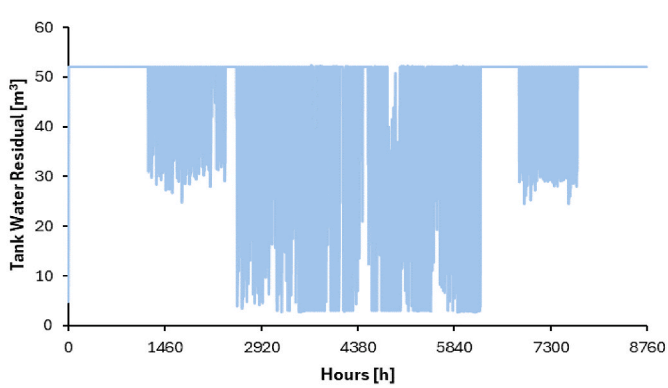

Fig. 12. Hourly water residual in the tank of battery-tank storage system.

4.4. Hybrid energy system optimisation summary

The purpose of optimisation is to find the configuration at the lowest cost at acceptable loss of power supply probability (LPSP) at ≤ 12 % and loss of load probability (LOLP) at ≤ 10 %. The optimised PV and wind hybrid ratio is found to be 0.8:0.2, 0.9:0.1 and 1:0. With the increasing wind turbine ratio, the required swept area increases and therefore, the turbine's cost rises. At PV: WT ratio of 0:1 (no PV), the loss of power supply probability is more than 60 %, and LOLP is more than 80 %. With PV: WT ratio of 1:0 (no wind turbine), the LOLP varies between 2 % and 6 %. However, a hybrid system ensures higher power reliability than the one that runs only PV or wind for all three cases. Fig. 13 presents the cost contribution for each element in the total CAPEX of the HES. The inverter and charge controller are the lowest cost elements of the system.

The cost of batteries dominates the CAPEX contribution by 37 % (Fig. 13a) for battery-based systems, whereas for battery tank systems (Fig. 13b), the cost component of tank and battery is almost at same proportion at 26 % and 27 % respectively. The CAPEX is higher for the

Table 3
Cases considered in this research.

Case no.	Tank volume (m^3)	Battery capacity (kAh)	Storage type
Case 1	–	8.8	Battery
Case 2	104	0	Tank
Case 3	52	8.8	Battery + Tank

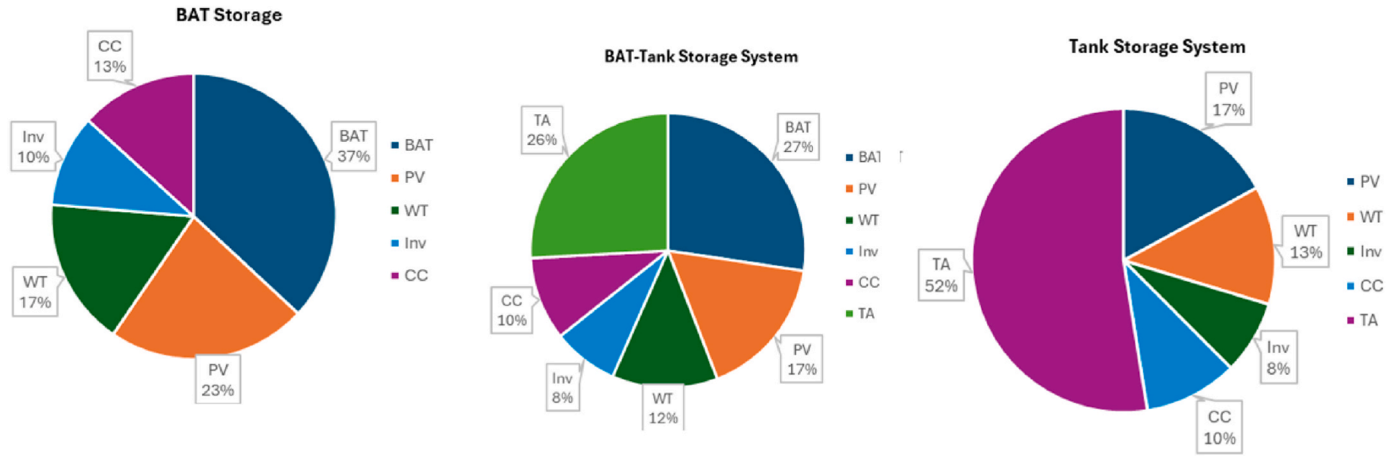

Fig. 13. Cost distribution a. Battery based system (left), b. Battery-tank based system (center), and c. Tank only storage system (right).

tank-only system (Fig. 13c) because the water tank comprises more than 50 % of the total cost. However, the maintenance cost is the lowest for tank-only systems, which rises by more than three folds for battery and battery and tank-based systems. Compared with the battery-based system, the LCC of battery-tank-based system increased by 20 % to £31 k for a tank size of 52 m^3. The reason for higher LCC for battery tank storage systems is that the water tank cost ranges between £80/m^3 and £100/m^3 [25]. Furthermore, this study considers plastic water tanks, but the price can rise by more than 50 folds for steel tanks [26].

The optimisation results are shown in Table 4 for all cases at all three ratios. The total system capacity, combining solar and wind, and the required battery capacity will remain the same regardless of the storage type. The most optimum storage would be a battery tank-based system, and the second optimum system would be battery-only. The least preferred storage solution would be a tank only due to the higher tank size requirement and complexity associated with its construction and cost.

The optimum day of battery autonomy is found one day, and the optimum tank size is 25 % and 50 % of the average daily demand for battery-tank and tank-only storage systems, respectively. Hence, the battery capacity required is 8.8 kAh, and the tank size is 52 m^3 and 104 m^3. Depending on the daily load demand, the optimisation outcome will vary. However, the given example can be used as a reference when designing the hybrid system for any load profile.

The proposed model will work for any geographical location. The user needs to input the latitude, longitude, climate database, and time zone to generate the weather data, and the model will automatically produce the results accordingly. For economic data, users can select either standard component prices or local market prices based on their specific equipment manufacturers. This flexibility ensures the model's adaptability to various geographical locations and economic conditions. The optimisation results for the solar-wind hybrid ratio will vary based on location-specific solar and wind resource availability. For example, in the United Kingdom, with higher wind resource availability, the optimised ratio might be 70%–80 % wind and 20%–30 % solar. In contrast, in Pakistan, where solar resources are more abundant, the optimised ratio could be 80 % solar and 20 % wind. The battery-tank combo system remains the preferred storage option across different locations, ensuring maximum reliability and cost-effectiveness.

The hybrid energy system is designed to meet both primary and auxiliary loads. Any surplus energy is stored in the battery to provide backup in case of a lack of available solar or wind resources or to meet any deficit during nocturnal load demand. Users provide the energy input requirements and usage patterns, allowing the model to generate a comprehensive load profile. This ensures efficient energy management and system optimisation to maximise resource utilisation at minimum cost.

The model currently supports four crops: sugarcane, cotton, wheat, and rice, which are the primary crops in Pakistan. It can be customised for other crops by providing the specific irrigation requirements. The model runs simulations at hourly intervals, a standard practice in the research community. While more frequent intervals (e.g., 30-min or 15-min) could yield more precise results, they would significantly increase data processing and runtime. Therefore, hourly intervals are used for technical feasibility, ensuring reliable and accurate predictions without significant concerns.

Table 4
Optimisation summary.

PV: WT	PV capacity [kW]	WT capacity [kW]	Turbine swept area [m^2]	Annual energy [MWh]	LOLP [%]	CAPEX [£k]	LCC [£k]
Battery only storage							
0.8:0.2	10.8	5	25	21	6.27	11.9	25.8
0.9:0.1	12.2	2	13	21	6.09	11.5	25
1:0	13.7	0	0	22	6.54	10.4	23.8
Tank only storage							
0.8:0.2	10.8	5	25	21	2.15	15.8	23.3
0.9:0.1	12.2	2	13	21	2.11	15.4	22.7
1:0	13.7	0	0	22	2.98	14.3	21.3
Battery-tank storage system							
0.8:0.2	10.8	5	25	21	2.58	16	31
0.9:0.1	12.2	2	13	21	3.43	15.6	30.5
1.0:0	13.7	0	0	22	4.35	14.5	29

4.5. Output power generated from PV and WT

The annual PV and WT output for 80 % PV and 20 % wind energy ratio is shown in Fig. 14. The correlation between the monthly average daily solar and wind energy density was found to be 0.7, indicating a moderate positive correlation and a weak complementary relation. Therefore, the wind speed is also comparatively lower during low solar irradiance months in the winter. However, the complementarity is observed during June and July, when the solar power density decreases compared to April, whereas wind power density rises by almost twofold.

The monthly temperature increase during summer (28 °*C*- 30 °*C*) causes the overall energy production from PV to decrease as the open circuit voltage of the PV decreases with increasing temperature. Throughout the year, PV production is more uniform than WT. Wind generation shows fluctuation over the year except in the peak summer months (June and July), whereas PV production tends to decrease comparatively in these two months, which shows a complementarity of wind and solar energy over this period. The annual energy produced from the hybrid system is 21 MWh from an energy input of 16 kW. The system is oversized by 17 %, which is essential in an off-grid system to ensure battery charging.

The annual energy output will differ based on the PV module's specifications and the characteristics curve of the wind turbine chosen. Regardless, the hybrid system operates efficiently within the reliability limit of 12 % and the overall annual water deficit below 10 %. A valuable insight will be looking at the CO_2 saving of the hybrid energy system. The HES can replace over 150 tonnes of CO_2 over the project's lifetime. As shown in Fig. 15, the annual CO_2 emission reduction potential for the battery-based system is 0.4 tCO_2/kW_P and 0.3 tCO_2/kW_P compared to the electricity and diesel-based irrigation systems, respectively.

5. Discussion & conclusion

This paper aims to identify suitable storage for an irrigation system for a solar wind-based hybrid system. A system-level hybrid energy model has been developed to carry out the optimisation. The model is optimised based on three criteria: lifecycle cost, loss of power supply probability (LPSP), and loss of load probability (LOLP). The optimisation depends on the solar and wind energy ratio and the respective storage systems. The proposed system is designed based on average rather than peak load demand to avoid unnecessarily oversizing HES capacity without compromising reliability. The LPSP and LOLP show consistency with the published results on various renewable energy-powered systems [27]. Though few studies consider the reliability limit of 0 % [28], it is often not required for irrigation applications, especially for a battery-tank-based system that provides multiple storage capacities. The LPSP and LOLP might vary during bad weather conditions or system loss. Furthermore, no additional source might be available, such as a diesel generator, to ensure battery charging. Therefore, the hybrid system needs to be oversized, and 17 % of the system is considered a reasonable choice here [29].

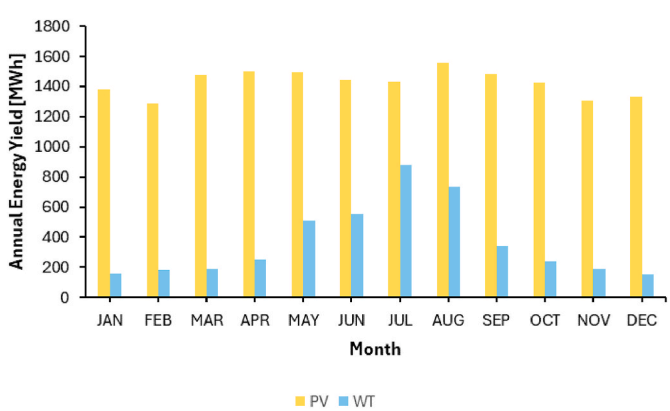

Fig. 14. Annual energy production.

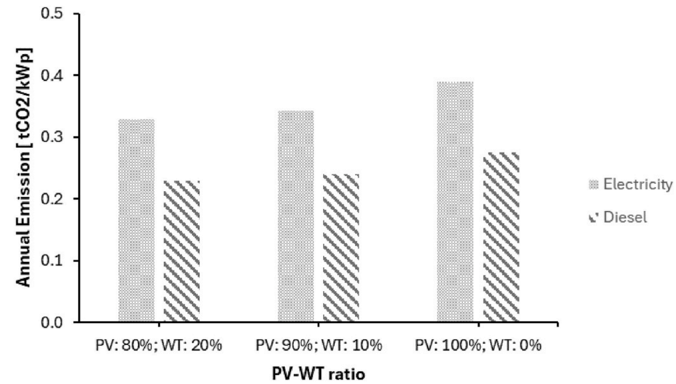

Fig. 15. Annual CO_2 emission saved.

The results indicate HES can bring a positive outcome in eradicating food poverty in Pakistan. The agriculture sector in Pakistan faces challenges due to insufficient crop production due to improper water management, which leads to water scarcity for irrigation [30]. Implementing hybrid energy-based irrigation systems will ensure the water deficit is within a tolerance level at LOLP of ≤10 %. Moreover, the availability of energy resources to run the pump will provide an enhanced window for daily irrigation operation from 6 to 12 h.

The HES ensures efficient use of resources and productivity improvement compared to conventional irrigation systems [31] but due to a lack of knowledge among farmers, they still consider conventional irrigation a viable option in the location under study [32]. Educating local farmers to convey the benefits of HES can play a vital role in this context. Though convincing the farmers to use a battery-tank combo or battery storage instead of a direct-driven or conventional system might be challenging, few initiatives can be taken in this regard. For instance, dissemination activities can be arranged to reach out to the farmers, such as organising workshops to convey information on how the hybrid system will improve productivity and save costs. To financially support them, low-profit and long-term business loans by micro financing can be arranged to incentivise them to invest in the hybrid energy system. Furthermore, a community-based approach could be applied. Farmers can form a cooperative and invest in the hybrid system. Banks and NGOs can play a crucial role in providing financial and logistical support. Highlighting the long-term advantages, such as reduced energy costs, enhanced reliability, and increased productivity, will help overcome potential resistance. The government can also benefit long-term by reducing the agricultural load from grids [33].

For optimise use of a hybrid energy system, integrating demand-side management is recommended. Load shifting based on resource availability ensures efficient use of the hybrid system. For less energy-intensive irrigation, a portable hybrid energy system can be employed, allowing multiple users to benefit from it on a rental basis. Ensuring adequate storage capacity involves balancing the PV-to-wind ratio based on local resource availability. Regular monitoring and management of energy flows will maintain cost-effectiveness and reliability, ensuring the system efficiently meets primary and auxiliary load demands.

The paper's key contribution is that a system-level optimisation model is developed to identify an appropriate storage system for off-grid water pumping systems for irrigation applications. The finding of this research justifies the usage of battery tank storage for the irrigation system. The water storage tank can provide extra backup with a battery-based system. Therefore, adding a tank is an optimum choice. The second preferred storage would be battery only, which can still provide the required LPSP and LOLP, as discussed in the results.

Using tank-only storage would be the least preferred option due to the various challenges incurred with large-scale systems. For instance, a report published by the USA Environmental Potential Agency found significant water quality problems associated with water storage tanks that cause chemical and biological hazards and physical damage. Examples are sediment build-up, microbial growth and stagnation. Proper maintenance and monitoring could be challenging for large-scale tanks [34]. It is essential to control waterborne microbes before using the water for irrigation. Algae and biofilm lead to poor water quality and may decrease plant growth and production of toxic substances. A range of chemical, ecological, and physical water treatment options are available, and they must be adopted before using water for irrigation [35]. Though typically, the cost of bigger water tanks falls per m^3, the largest-size plastic tanks are more expensive [36]. A custom-made water tank can be an option, but the material cost can be quite expensive, along with labour costs and transportation [37]. Furthermore, water tank efficiency is often overlooked, which creates additional water deficits [38]. On the contrary, there is considerable cost reduction potential for large-scale watering systems that use battery storage and tank combo as a sustainable solution. For battery storage, replacement cost is a significant barrier, and therefore, continuous research and development are required to improve battery efficiency and reduce costs. As reported by IRENA, the installation cost of battery-based systems will fall by more than 50 % by 2030. Lithium-ion batteries could be a better option in future, as they have installation cost reduction potential below £160 per kWh over the next five years [39]. Though initial costs with lithium-ion batteries are about 2.5 times more than lead-acid, the higher round trip efficiency of lithium-ion batteries could result in lower LCC [40].

The main findings of this paper are.

- The optimised ratios of PV and WT are 80 %–100 % for solar energy and 20 %–0 % for wind energy. The CAPEX of the hybrid system is dominated by the cost of the battery and the water tank. Battery size can be reduced if the hybrid system has no nocturnal load, but the one-day autonomy will be compromised in that case. It is important to note that the cost and LOLP will vary depending on the meteorological data of the location, hence the optimisation outcome.
- The result indicates that the battery tank combo is the most optimum storage system, followed by battery-only storage. Tanks are the least preferred storage method due to the higher tank size requirement and complexity associated with construction and cost.
- The optimum day of battery autonomy is found one day, and the optimum tank size is 25 % and 50 % of the average daily demand for battery-tank and tank-only storage systems, respectively.
- The HES can replace over 150 tonnes of CO_2 over the project's lifetime, and the annual CO_2 emission reduction potential of 0.4 tCO_2/kW_P and 0.3 tCO_2/kW_P compared to the electricity and diesel-based irrigation systems.
- The battery-only storage system has the lowest CAPEX of £11.9 K. The CAPEX of tank-only or battery-tank storage systems is about 1.3 folds higher than the battery-only HES.

To conclude, the outcome of this work can have an essential contribution to sustainable agriculture development for designing renewable irrigation systems. Currently, no hybrid energy-powered battery-tank storage-based irrigation system is used at the location under study. By deploying the hybrid energy system proposed in this paper, farmers can improve yield by atleast by four folds. This research provides valuable insights for policymakers and stakeholders to promote renewable energy integration in agriculture, enhancing productivity and sustainability. For the developer and investor, the finding of this paper is beneficial in determining the storage when developing a large-scale system. The strength of this paper is that the optimisation model developed here can be used for any location in the world if the weather data and cost information are available. Furthermore, this paper considers plastic water tanks, which are comparatively cheaper than other materials, such as steel. So, the finding here can be used as a benchmark to compare with other tank materials. More importantly, though the optimisation is carried out for irrigation watering systems, the study can be replicated for domestic water supply, rainwater harvesting or livestock farming applications.

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CRediT authorship contribution statement

Marzia Alam: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muhammad Imran:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Muhammad Sultan:** Resources, Investigation, Conceptualization. **Umar Manzoor:** Writing – review & editing, Supervision, Resources. **Zafar Ali Khan:** Writing – review & editing, Supervision, Resources. **Ahmed Rezk:** Writing – review & editing, Resources, Project administration. **Abed Alaswad:** Writing – review & editing, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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