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Techno-Economic Optimization of Hybrid Photovoltaic Energy Systems for Sustainable Agricultural Irrigation in the Arabian Peninsula

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ABSTRACT

This study introduces optimal photovoltaic (PV) renewable energy systems to satisfy the agricultural irrigation demands across the Arabian Peninsula for a representative mixed-use farm. The investigated farm covers 30,000 m^2 and is utilized to grow palms and seasonal trees. Furthermore, water requirements were determined based on crop coefficients and weather data. The irrigation pumping power demand was calculated on an hourly basis and was equal to 19,800 kWh/year for the Al-Ahsa Farm. Two off-grid renewable energy system alternatives were considered: (1) PV-battery and (2) PV battery-diesel generator (DG). Both the off-grid systems were compared with a grid-connected system covering the same irrigation load. The optimization process was conducted using HOMER Pro, and the configurations that maximized reliability and minimized costs were identified. The hybrid PV-battery-DG system provided a good level of reliability with the lowest levelized cost of energy (LCOE) of 0.231 $/kWh in Neom (Saudi Arabia) owing to the favorable solar potential and relatively moderate irrigation requirements. Across the Arabian Peninsula, the minimum LCOE of approximately 0.211 $/kWh was noted in Sana'a because of the relatively low power demand for irrigation caused by favorable climatic conditions. However, a maximum LCOE of 0.302 $/kWh was noted in Sharjah owing to the hot climatic conditions and relatively higher loads. Compared to the conventional grid baseline, the optimized hybrid system decreases annual CO_2 emissions by 84.9%, dropping from 12.5 tons to 1.9 tons.

Keywords: sustainable irrigation systems; water-energy nexus; hybrid renewable energy systems; photovoltaic-powered agriculture; energy-economic optimization; climate change mitigation

1. INTRODUCTION

Energy consumption has increased in the last few years, demonstrating that demand will grow by over 2% in 2024, exceeding expectations over the last decades [1]. By implementing renewable energy systems and designing new frameworks to boost energy reliability, nations across the Arabian Peninsula are attempting to fulfill this surging electricity demand [2]. For instance, as the region's largest economy, Saudi Arabia is gradually transforming its energy sector, aiming for 50% reliance on alternative sources [3]. Nevertheless, the General Authority of Statistics published a report in the second half of 2025 stating that nine solar-based projects are presently operating with a combined capacity of approximately 6151 MW [4]. Contrastingly, total electricity production exceeded 441 TWh, leading to total clean energy production in Saudi Arabia representing <1% [5]. Farming in the remote areas of the Arabian Peninsula faces major energy challenges, particularly when extending the main power grid, which is expensive. Most off-grid agriculture is presently operated using diesel generators, which creates considerable difficulties, including high fuel costs in the long term and dense carbon emissions. The region's arid climate exacerbates these issues because extreme heat requires intensive water pumping, resulting in high seasonally fluctuating energy demands. These irrigation energy demands are closely associated with crop calendars, which account for two primary crop cycles in Saudi Arabia: summer planting (March-May) with harvests at the end of the third quarter, and winter cycles (September-November) with frequent harvests between May and July [6]. Table 1 lists the classification of common crops in Saudi Arabia, based on their primary growing seasons. Crops, such as watermelons and tomatoes, are planted during the summer cycle and crops, such as wheat and barley, are grown during the winter cycle. Alfalfa is listed in both categories because it is a perennial crop that remains in the field year-round and needs consistent irrigation during hot and cool months.

However, relying solely on solar power systems can cause a shortage in power supply owing to the stochastic nature of solar energy availability. Although solar panels produce the most electricity in the middle of the day, watering crops at noon causes the water to evaporate quickly. The power supply does not perfectly match the watering schedule given that plants require irrigation early in the morning or late at night. Moreover, water pumps are

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Table 1. *Classification of winter and summer crops grown in Saudi Arabia*

Summer crops	Winter crops	Ref.
Watermelon	Onions	6
Cantaloupe	Garlic	
Cucumbers	Carrots	7
Okra	Wheat	
Tomatoes	Barley	
Dates	-	8,9
Mango	Citrus	10–12
-	Potatoes	13,14
Alfalfa	Alfalfa	15

heavy machines that pull massive surges in power to start up. Standard solar inverters can shut down when subjected to heavy loads beyond their limits. To prevent this, batteries and backup generators can be utilized to handle high power demands without causing a voltage drop. Locations such as Saudi Arabia do not have steady water sources; therefore, keeping these hybrid systems running smoothly needs high-quality management[16]. Farming in the area relies almost entirely on groundwater. In summer, for instance, the situation becomes more challenging because water use for people and crops markedly increases while rainfall is almost zero. Consequently, pumping out excessive water without replenishment from rain puts huge strain on underground reserves[17]. Heavily relying on the conventional grid to power these pumps markedly increases the carbon footprint of the farm. On-site renewable energy is a safer choice considering that the main power grid is not always reliable during an energy crisis. When the weather is hot and dry, farms require more energy for pumping, especially during a weak rainfall season and summer peak in evapotranspiration[18], which increases the energy demand for irrigation. Therefore, rural areas require standalone power sources, such as solar panels, battery storage, and hybrid systems[19]. Table 2 summarizes previous research that has explored the implementation of renewable energy systems in the agricultural sector. These studies provided a global perspective on the economic and environmental benefits of solar-powered irrigation.

The above literature survey reveals that previous studies have evaluated the viability of solar-powered irrigation systems in arid regions. However, most of these studies were limited to a single location, single PV-based pumping configuration, or fixed pumping load. However, limited attention has been paid to assessing irrigation water requirements as a function of the local weather conditions of the farm area and subsequently translating these variable water requirements into location-dependent pumping power demands. The novelty of the present study is that it links local crop distribution and seasonal crop calendars with hourly irrigation water needs and pumping power demands across several locations in the Arabian Peninsula. Additionally, it compares PV battery and PV battery-DG systems under the same irrigation load and presents regional economic maps to reveal how the system cost and performance differ spatially. This study aimed to:

- Determine the water requirements of local crops in the Arabian Peninsula under different weather conditions.
- Develop hourly and seasonal electricity demand profiles for irrigation across the Arabian Peninsula.
- Optimize the PV-battery and hybrid PV-battery–DG system to satisfy the same irrigation load.

2. METHODOLOGY

2.1. Farm Description. This study modelled a typical mixed-use farm in the arid climate of Saudi Arabia using the Saudi Arabian agricultural calendar as a representative baseline because KSA covers nearly 80% of the Arabian Peninsula. The total farmland area was set at 30,000 m^2 and divided into four main sections to account for various crop water requirements and seasonal irrigation profiles. Date palms cover 13,500 m^2, or 45% of the land. These trees require a constant water supply throughout the year. Tomatoes and barley comprise 9,000 m^2 (30%) of the local food and grain supply. Alfalfa covers 4,500 m^2 (15%) of the land for livestock feed. Seasonal crops grew over the last 3,000 m^2 (10%). This smaller section switches between wheat and watermelon based on the time of year. Notably, the farm area was determined based on a field visit to a local farm in Al-Ahsa, whereas the crop types were selected based on the crops commonly cultivated across farms in the Arabian Peninsula. Moreover, to provide a meaningful comparison of water and pumping power requirements farm size and crop types were fixed. The weather conditions, which vary noticeably from location to location across the Arabian Peninsula, primarily affects these requirements.

2.2. Study Area and Input Data. The Arabian Peninsula is characterized by diverse topography and climate[28,29]. High mountains rise over 2,000 meters along the Red Sea coastline, from Tabuk in the northwestern corner to Sana'a in the west of the south, whereas the land steadily descends eastward, flattening to <200 m near the Arabian Gulf. This geography directly controls the wind and temperature patterns in the region. The central and southern inland areas trap large amounts of heat. Average temperatures in these regions regularly exceed 30 °C. Contrastingly, the northern regions and high-altitude western mountains experience cooler climates, typically ranging between 15 and 25 °C. The main input data used for irrigation and energy models included ambient temperature, rainfall, wind speed, solar radiation, and terrain elevation. These inputs were employed to estimate the crop water demand, pumping electricity requirements, and photovoltaic (PV) power generation.

3. MATHEMATICAL MODELING

Figure 1 illustrates the standalone solar-based power system utilized to supply the farm irrigation load. The system was divided into two primary parts. Solar PV panels receive solar radiation and generate electricity, thereby acting as primary power sources. The PV system was connected to batteries that stored extra energy for use after sunset or on cloudy days. The irrigation load was connected to the AC side. Additionally, a diesel generator (DG) was included, which serves as a backup source to provide

Table 2. *Previous related research articles*

Location	System type	Direct Impact	Other affected factors	Ref.
Nicaragua	PV Irrigation	Monthly earnings increased from $25 to $546; electricity bills decreased from $33 to $2.90/month; one-year loan payback.	Types increased of livestock (8–12 cows)	20
Philippines	PV Irrigation	Diesel savings of 11–380 L/ha/year, return on investment ranging from 30% to nearly 3,000%, and an average payback period of approximately 3 years.	Annual GHG emissions are cut by up to 27 tons/ha. The initiative was socially accepted by 69% of farmers.	21
Pakistan, Punjab	PV Irrigation	With unit cost of PV around 0.12$/kWh, over 6.5 million liters of diesel is saved annually	It cuts about 18,000 tons of CO_2 emissions each year and saves roughly 40% on water	22
Iraq, Wasit	5.0 MW Wind Farm	Net present value of approximately $11.3 million. An internal rate of return of 25%, and a payback period of a little over 6 years.	The project will reduce greenhouse gas emissions by almost 32,000 tons every year.	23
Philippines	PV Irrigation	Net Present Value of USD 4,517/ha over 25 years. Eliminates annual fuel costs of USD 394/ha.	Reduced operational and maintenance costs from USD 375/ha to USD 140/ha; eliminated health Risks from diesel fumes.	24
Mexico	Distributed Energy System	The farm is now generating approximately £57,000 in net annual profit.	Enables energy independence and creates a new revenue stream from selling surplus electricity back to the grid	25
Rwanda	PV system	Market for solar PV in pasteurized milk processing is USD 4 million	This initiative enhances product quality and reduces spoilage. Additionally, this increases value chain stability and encourages investment in rural areas.	26
Japan, Shizuoka	Agrivoltaics	Produces 5 tons of crops and 8,000 kW of electricity annually.	Provides 90% shade for high-quality matcha.	27

power when the PV generation and battery storage are insufficient. Thus, the system's aim is to ensure continuous operation when solar energy is insufficient. The study determines water requirements using crop coefficients and weather data based on a re-parameterized FAO-56 Penman-Monteith model[30], as provided in the supplementary material. The supplementary material also presents the mathematical models of the main system components, including the PV array, battery, and converter. In addition, it describes the economic models used in the analysis, including the Net Present Cost[31] (NPC) and Levelized Cost of Energy[32] (LCOE).

4. OPTIMIZATION FRAMEWORK

Optimization was performed using HOMER Pro version 3.18.4. Several configurations of the two systems (PV-battery and PV-battery-DG) were simulated on an hourly basis for 1 year using the irrigation load and weather data of each location. HOMER simulates all possible configurations of the PV array, battery, converter, and DG. The hourly balance between power supply and demand was monitored during the simulation. Configurations that could not meet the irrigation load were rejected, whereas the feasible configurations were ranked based on the minimization of the NPC. Thus, the objective function can be expressed as:

$$F = \min(NPC) \tag{1}$$

The objective function is subjected to several optimization constraints, including the component-allowed capacities and battery limitations, which are expressed as:

$$N_{i,min} \leq N_i \leq N_{i,max} \tag{2}$$

$$SOC(t)_{min} \leq SOC(t) \leq SOC(t)_{max} \tag{3}$$

where (N_i) represents component i (which includes the PV, battery, and DG), and $(N_{i,min})$ and $(N_{i,max})$ are the minimum and maximum capacities of each component, respectively. Eq. (3) shows that for each time step, the battery SOC should be between the minimum and maximum limits (Table S.1 provides the minimum and maximum battery limits). Moreover, the annual capacity shortage, which was set to 0%, is another constraint. This means that optimized systems are necessary to completely meet electricity demand, and the annual unmet load should be zero. A diesel generator was utilized as a backup system when the PV and battery storage were insufficient. Finally, the study was repeated in several locations across the Arabian Peninsula, and economic contours were developed to map the system costs. Figure 2 illustrates the complete steps of the optimization process.

5. RESULTS AND DISCUSSION

In this study, the irrigation load was estimated and satisfied with two solar-based renewable energy systems (RESs): (1) a

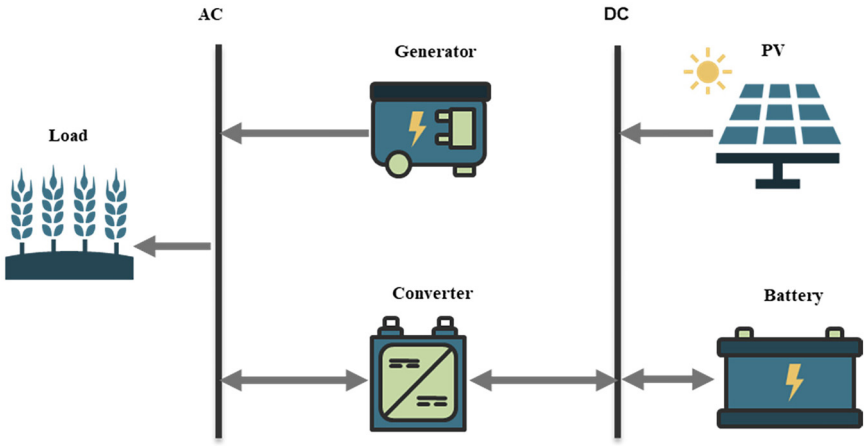

Figure 1. Schematic diagram of the considered solar-based renewable energy system

PV-battery and (2) hybrid (PV-battery-DG) systems. A grid-connected scenario was utilized as the baseline for the analysis. The optimization findings for Al-Ahsa, as an example, will be presented and discussed. The findings across the Arabian Peninsula countries are subsequently presented as maps.

5.1. Optimization Results for the Al-Ahsa . Al-Ahsa was selected as an example because of crop variety. The studied farm grows date palms year-round and plants tomatoes and watermelons in certain seasons. This mix of crops, along with local climate data, causes the water pumping needs to change throughout the year. Figure S.1 (a) illustrates the solar radiation in Al-Ahsa, which has lower values in the winter months and higher values in summer, peaking in July, with values reaching 1 kW/m^2. Figure S.1 (b) shows the ambient temperature, which influences irrigation needs. In summer, when temperatures exceed 45 °C, evaporation markedly increases. Consequently, tomatoes and watermelons require more water, leading to the highest electricity use in July (Figure 3). Two solar-based RESs were simulated and optimized for Al-Ahsa considering the solar radiation, temperature, and irrigation load shown in Figure 3.

The optimization results are presented in terms of PV size (kW), battery capacity (kWh), DG capacity (kW), NPC, LCOE, payback period, and CO_2 emissions. The hybrid PV-battery-DG system has the lowest cost. The optimal PV-battery-DG system comprises a 17.9 kW solar array, 37 kWh battery storage, and an 11-kW DG as a backup source. This hybrid design reached a NPC value of 61.4 k$ and LCOE of 0.240 $/kWh. It recovers its costs in 2.5 years, outperforming the fully renewable (PV-battery) system, taking nearly 5.2 years to pay back the initial investment. Using PV and DG system provides an economical and more reliable alternative but with higher emissions equal to 1.9 ton/yr. Contrastingly, the PV battery system has zero direct operating emissions; however, it needs larger PV (34 kW) and battery (124 kWh) capacities, which increases the NPC to 103 k$, and LCOE to 0.405 $/kWh. Thus, a hybrid system is more suitable when cost and reliability are the primary priorities, whereas a fully renewable PV battery system is preferable when eliminating emissions is the main target. A grid-connected system was studied to benchmark the two solar-based systems. The farm uses 19,800 kWh of electricity annually, and the Saudi agricultural electricity rate is 0.048 $/kWh. This means that the

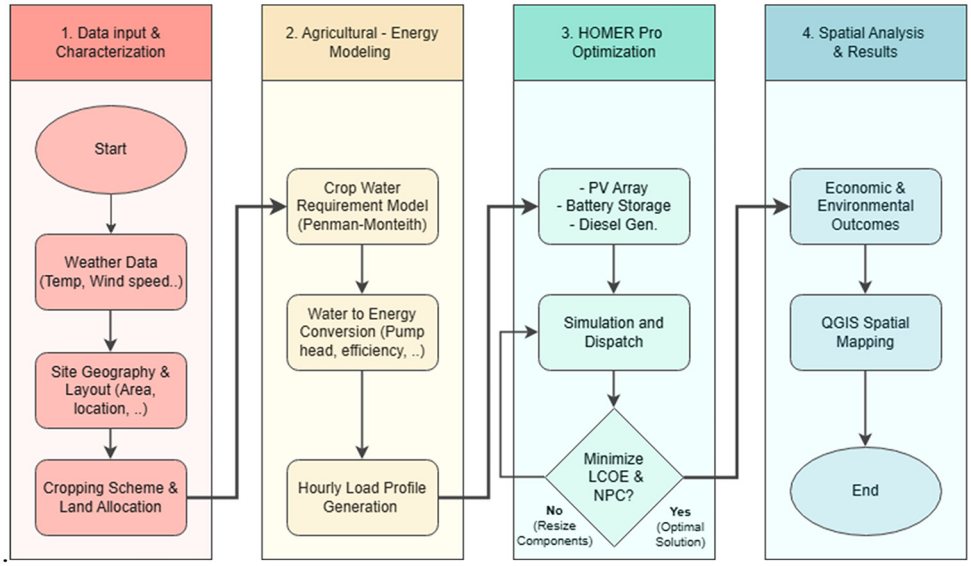

Figure 2. Flowchart of the system optimization process

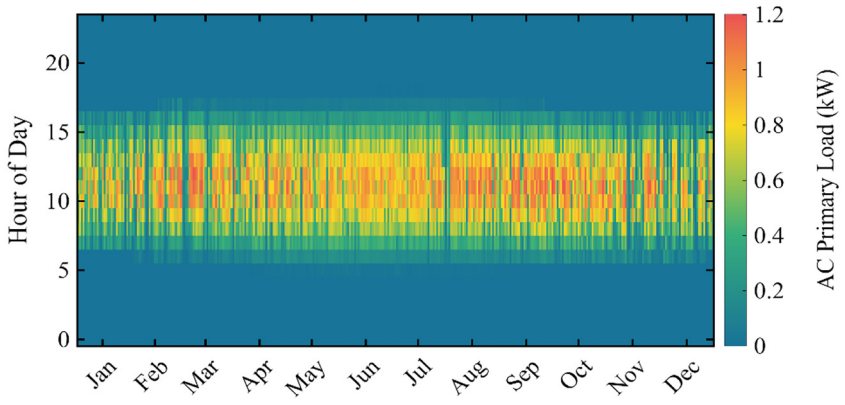

Figure 3. Primary load in the Al-Ahsa Area (kW)

farm spends approximately $950.4 per year on energy, covering only the running costs. Additionally, the use of conventional grids has a substantial environmental impact. Each year, this system produces approximately 12.5 tons of carbon dioxide (CO_2). Moreover, additional results for Al-Ahsa are provided and discussed in the supplementary material including annual energy generation (Figure S.2), hourly power generation (Figure S.3), cost breakdown (Figure S.4), and hourly system performance (Figure S.5).

A sensitivity analysis was utilized to determine the performance of the hybrid system under uncertain future conditions. Figure 4 illustrates a sensitivity analysis wherein key parameters are varied by ±50% to evaluate their effect on the LCOE. The solar-scaled average was the most sensitive factor; when it reduced, the LCOE considerably increased. Furthermore, the nominal discount rate strongly influenced costs, with a 50% increase resulting in a sharp increase in energy costs. Other factors such as the electric load, expected inflation rate, and project lifetime had minimal impact, with changes observed to be below 0.02 $/kWh. The diesel fuel price had minimal effect (±0.01 $/kWh) because the system used a high share of renewables (79.4%). Therefore, fuel price changes did not markedly affect LCOE.

5.2. Generalization Upon Arabian Peninsula. The performance of the considered systems was assessed across the Arabian Peninsula to evaluate the economics and reliability of these systems in supplying power for agricultural loads. The simulation was repeated using the same planted area and crops as discussed in Section 2.1. Thus, the pumping electricity requirement was determined across the region to meet the same farm irrigation requirements. Figure 5 illustrates the annual load distribution across the Arabian Peninsula (MWh). The gradient color indicates high values mainly in the northeastern and central regions above 18,000 kWh. The load decreased toward the south, dropping below 11,640 kWh.

The two systems, (1) the PV-battery system and (2) PV-battery-DG system, were optimized using HOMER Pro for several locations across the Arabian Peninsula. Higher solar radiation usually lowered the required PV size and LCOE, whereas

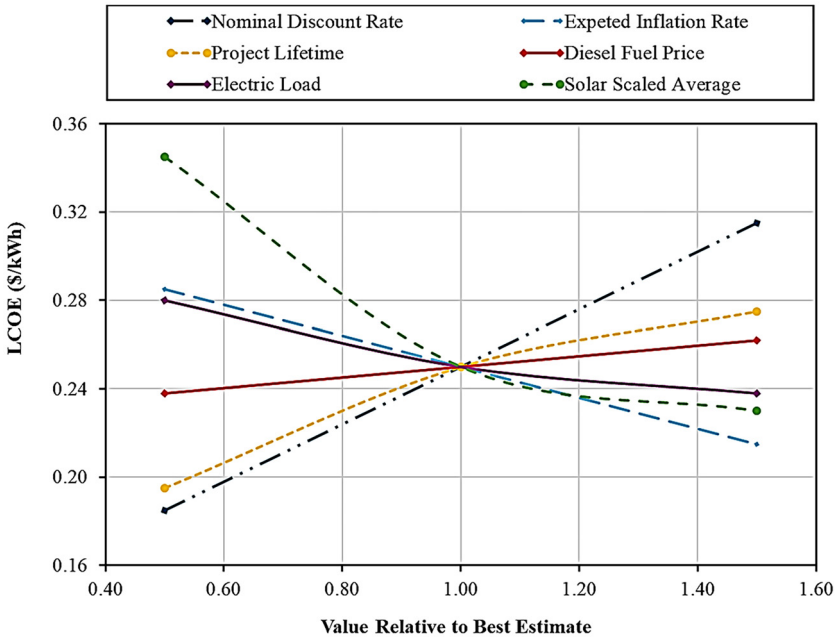

Figure 4. Sensitivity analysis

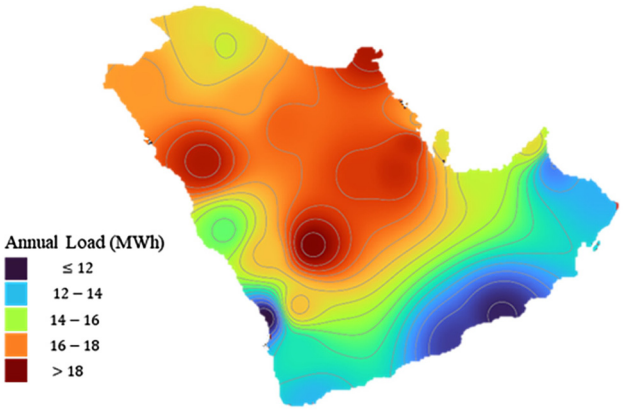

Figure 5. Energy requirements for irrigation across the Arabian Peninsula

a higher irrigation demand increased the required system capacity. Additionally, temperature affected the results because it can decrease PV performance and increase water demand. Thus, each location exhibited a different cost, depending on the balance between solar resources, climatic conditions, and irrigation load. The PV-battery system alone had high costs, with an LCOE ranging from 0.338 $/kWh to 0.743 $/kWh and an NPC ranging from <75 k$ to >120 k$. However, the addition of a diesel generator stabilized and lowered these expenses. This lowered the LCOE to a range of 0.211-0.302 $/kWh and reduced the NPC to a range of 30.7–70.1 k$. This massive reduction makes the hybrid system more practical for agricultural use anywhere on the peninsula. In Saudi Arabia, Neom exhibited low LCOE values for PV-battery and hybrid PV-battery-DG RESs, as the location has favorable solar energy potential and a relatively moderate irrigation load. In this case, the LCOE for Neom was found to be 0.366 $/kWh for PV-battery system, whereas it is reduced to 0.231 $/kWh for the hybrid PV-battery-DG system. Moreover, the minimum LCOE across the Arabian Peninsula for the hybrid system was observed in Sana'a (LCOE = 0.211 $/kWh) due to the relatively low irrigation load. However, a maximum LCOE of 0.302 $/kWh was observed in Sharjah, owing to hot weather conditions and a relatively higher load. For the PV-battery system, the minimum and maximum LCOE values across the Arabian Peninsula were found in Qatar and Salalah, with values of 0.338 and 0.743 $/kWh, respectively.

6. CONCLUSIONS

This study examined the application of RESs for irrigation in the dry Arabian Peninsula. For the same farm area and crops, the pumping power requirement was estimated under the variable weather conditions of the region. Two solar-based systems were assessed to meet the irrigation energy requirements: (1) PV-battery and (2) PV-battery-DG systems, which were optimized and compared with a grid-connected scenario. The conclusions of this study are summarized as follows:

- For the same farm area and crops, the water and pumping power requirements differ according to the weather conditions of the location, which affect the RES size and economics.
- The grid-connected system has the highest environmental impact, producing 12.5 tons CO_2/year. The fully renewable PV-battery system achieves zero direct emissions but needs larger PV and battery capacities, which increases the system cost.
- The hybrid PV-battery-DG system provides the best overall performance by balancing costs and reliability, while reducing CO_2 emissions by 84.9%.
- For Saudi Arabia, Neom attained the lowest LCOE for both systems, with values of 0.366 and 0.231 $/kWh for the PV-battery and PV-battery-DG systems, respectively.
- Across the Arabian Peninsula, the lowest LCOE for the hybrid system was achieved in Sana'a, reaching approximately 0.211 $/kWh, whereas the maximum value of 0.302 $/kWh was found in Sharjah for PV-battery-DG systems.

Although this study provides useful techno-economic insights, it has several limitations. The study was conducted for a farm area of 30,000 m^2 based on the representative crop patterns explained in Section 2.1. Future work could examine additional factors influencing irrigation water and power demands, such as various soil and crop conditions, detailed irrigation schedules, water storage options, and alternative hybrid configurations, such as PV-wind-battery or PV-hydrogen systems.

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