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Prospects of Hybrid Energy in Saudi Arabia, Exploring Irrigation Application in Shaqra

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Abstract: Dynamics in rainfall patterns due to climate change are posing a threat to crop production globally. The core issue of food security is expected to intensify, and improving crop yield using motorized power irrigation mechanisms can help in curtailing the impact of drought and changing weather patterns to meet the crop water requirement. To meet the energy demand of irrigation systems, this paper explores the use of hybrid energy sources, i.e., wind and solar energy, taking Shaqra Saudi Arabia as case study. This paper presents a systematic case study that evaluates crop water requirements for 3 different crops using the United Nations Food and Agriculture Organization's software CROPWAT 8.0 and converts the water requirement into energy demand to design the water pumping system. The energy requirement water pumping system is used to design a hybrid energy system using HOMER PRO 3.14.4 that can reliably meet the energy demand. The results suggests that, contrary to the common consideration in Saudi Arabia, a hybrid of wind and solar energy proves to be more cost effective and yields a higher amount of energy. The results suggest that a significant reduction in cost can be achieved with a hybrid energy system as compared to a solar PV system only.

Keywords: CROPWAT; hybrid energy; HOMER PRO; irrigation

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1. Introduction

Saudi Arabia is characterized by a desert climate and is typically classified as BWh, i.e., an Arid Desert climate. The temperature in the central region is extremely hot and dry, ranging from 27 °C to 43 °C in the inland areas and 27 °C to 38 °C in coastal areas [1]. The average annual rainfall in most parts of Saudi Arabia is below 150 mm throughout the year except the southwestern part, where the rainfall occurs between 400–600 mm annually [1]. Despite the climatic conditions and low rainfall, according to the United Nation Food and Agriculture Organization (FAO) Saudi Arabia produces 624 metric tons of Barley, 586 metric tons of Wheat and 144 metric tons of Sorghum [2]. The potential to convert the arid regions into fertile pastures can be exploited to conform with the Saudi Vision 2030 to meet the targets of green energy and food security [2].

The Kingdom of Saudi Arabia (KSA) Vision 2030 is a unique transformative economic and social reform, and it is based on sustainability development. It is a sustainable vision for the potential future of the kingdom, with sustainability in all sectors, including the energy and the agriculture sectors, from policy development and investment to planning and infrastructure. One of the 2030 vision's strategic goals is to increase the adoption of innovative and effective irrigation techniques to raise the efficiency of water in the irrigation sector for the purpose of food security. The 2030 vision aims to increase the share of renewable energy to meet the strategic target of energy mix to roughly 50% by 2030, while reducing dependance on fossil fuels [3].

The integration of renewable energy and irrigation systems can directly advance energy and food security. This can be achieved by meeting the current and future demand for both food and energy in a clean, environmentally sustainable, and inclusive manner, while contributing to climate resilience and adaptation based on the KSA 2030 vision, the United Nations 2030 Agenda for Sustainable Development, and the Paris Agreement on Climate Change. Renewable energy-based solar and wind energy can play a vital role in meeting the energy essentials of agri-food systems in Saudi Arabia. Saudi Arabia has abundant potential for exploiting solar energy, which has no Green House Gas (GHG) emission and is freely available, as the mean annual solar irradiation falling on the Arabian Peninsula is about 2200 kWh/m^2 [4]. Figure 1 shows the photovoltaic power potential for Saudi Arabia [5]. At the same time, the wind speed in most of the regions of Saudi Arabia is well-suited to produce power. Figure 2 shows the wind speed map of Saudi Arabia [6].

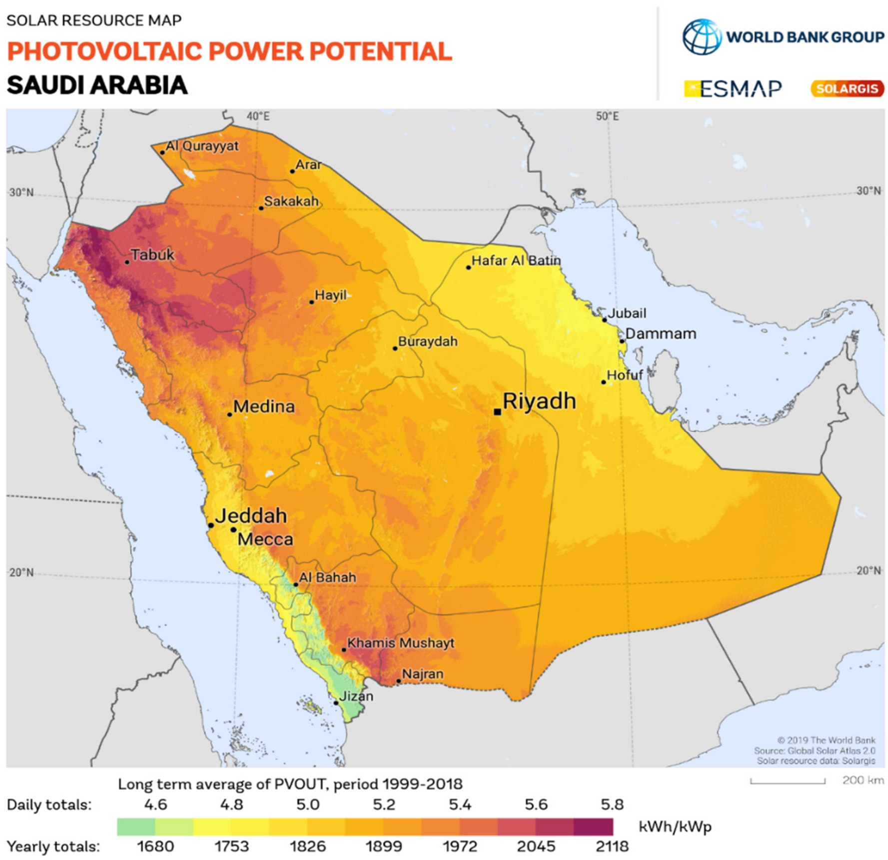

Figure 1. Map showing Solar PV potential of Saudi Arabia [5].

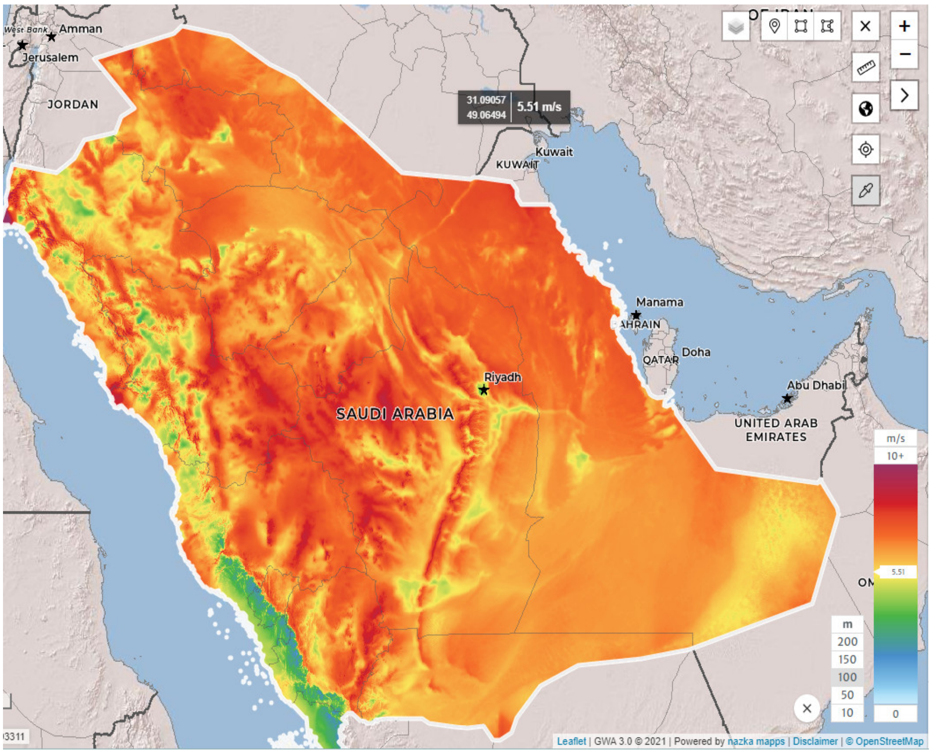

Figure 2. Map showing Wind speed and wind generation potential in Saudi Arabia [6].

Over the past decade, a significant advancement has been made in the field of renewable energy integration both with the grid and in island mode, driven by increasing cost of fuel and with the aims to reduce GHG emissions, reduce technology cost and encourage sustainable energy initiatives. Among these renewable energies are solar and wind energy, which have been leading candidates and are implemented for many applications, including lighting, cooling, water heating, crop/fruit drying, water desalination, operating irrigation pumps, and meteorological stations, etc., which is discussed in detail in [7,8]. The renewables are used at many levels in the power system, for example for planning and design [9], solar energy-related greenhouses [10], solar hydrogen [11], off-grid and on-grid optimization [12,13], and irrigation for very small and farms [13–15]. In addition, most of the previous studies on renewable-based irrigation are focused on solar energy and in a specific geographic location such as Namibia [16], Jordan [17], India [18], Saharan Africa [19], and Sudan [20–22].

Despite these studies' focus on the use of renewable energy for irrigation application, the literature shows that the focus of the use of renewable energy is limited to solar PV. This is mainly due to the high cost of wind generation in the past, but more recently wind generation has seen a drastic reduction in price [23]. The decade 2010 to 2020 saw dramatic improvement in the competitiveness of solar and wind power technologies [23]. Between 2010 and 2020, the cost of electricity from utility-scale PV fell 85%, followed by concentrating solar power (CSP; 68%), onshore wind (56%), and offshore wind (48%) [23]. This shows that onshore wind and solar PV are becoming cheaper, and hence the potential for exploiting the use of wind and solar PV is increasing large. Apart from the individual falling prices, due to the intermittent nature of wind and solar, where feasible, a hybrid of wind and solar can potentially increase monetary benefits and reduce capital investment. Solar PV will generate only during the day, whereas wind can possibly generate power all day (depending on the wind speed). In the past, studies considered wind-PV hybrid solutions, but they were not considered favorable due to the high cost of electricity [24,25]. However, more recent studies have conducted more detailed analysis of the wind-PV hybrid systems and identified locations with potential for hybrid energy systems in Saudi

Arabia [26]. Table 1 shows a comparison of different studies of isolated hybrid energy applications with different sources and their cost of electricity.

Table 1. Comparison of different renewable energy sources and Cost of Electricity (CoE).

Ref.	Location	RE Sources	CoE ($/kWh)
[27]	Saint Catherine, Egypt	PV/WT/FC/DG/Natural gas turbine/Biomass generator/Battery/Converter	0.532 $/kWh
[28]	Shafar, Yemen	PV/WT/DG/Battery/Converter	0.137 $/kWh
[29]	Hurghada, Egypt	PV/WT/DG/Battery/Converter	0.139 $/kWh
[30]	India	Biomass generator/PV/WT/Battery/Converter	0.195 $/kWh
[31]	Shanghai, China	PV/WT/Battery/Converter	0.0943 $/kWh
[32]	Hargeisa, Somalia	PV/WT/Battery/Converter	0.288 $/kWh
[33]	Tanzania	PV/DG/Battery/Converter	1.107 $/kWh
[34]	Gwagwalada, Abuja, Nigeria	PV/WT/DG/Battery/Converter	0.3145 $/kWh
[35]	Amritsar, India	PV/WT/DG/Battery/Converter	0.164 $/kWh
[36]	Busan, South Korea	PV/WT/Battery/Converter	0.399 $/kWh
[37]	Sudan	PV/WT/DG/Battery/Converter	0.387 $/kWh

The application of renewable energy sources in irrigation applications requires careful consideration of load. Most of the studies assume the load values without considering the detailed studies related to crop type, local strata, and other parameters. Keeping this gap in mind, this study is aimed at developing a solar wind-based, cost effective, and maintenance free pumping system for irrigation for Saudi Arabia. The primary objective of the project was to evaluate the techno-economic feasibility of the proposed system in terms of practical implementation under local conditions. This study explores the crop water requirement and then designs a pumping system for the irrigation system. The energy system is eventually designed using the load of the irrigation system. Section 2 outlines the methodology, Section 3 presents the case study with results, and Section 4 concludes the paper.

2. Materials and Methods

The primary task in designing any energy system is determining the energy requirement. The energy requirement for irrigation use is dependent on the water requirement for the crop. Once the crop water requirement is determined, the water requirement of the crop is converted into energy required by considering the area of the cropland and the depth of the borehole to ascertain the pump size required to pump the water from under the ground. Considering the energy requirement, an appropriate energy system is designed. The schematic of the proposed system is shown in Figure 3. A detailed process flow chart of the proposed methodology to design the hybrid renewable energy system for irrigation application by considering the crop water requirement is given in Figure 4.

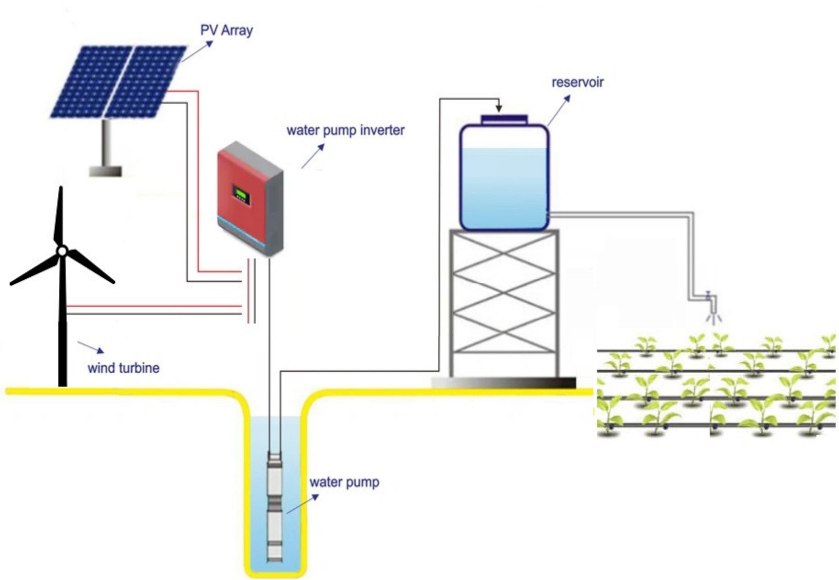

Figure 3. Hybrid-Energy water pumping system.

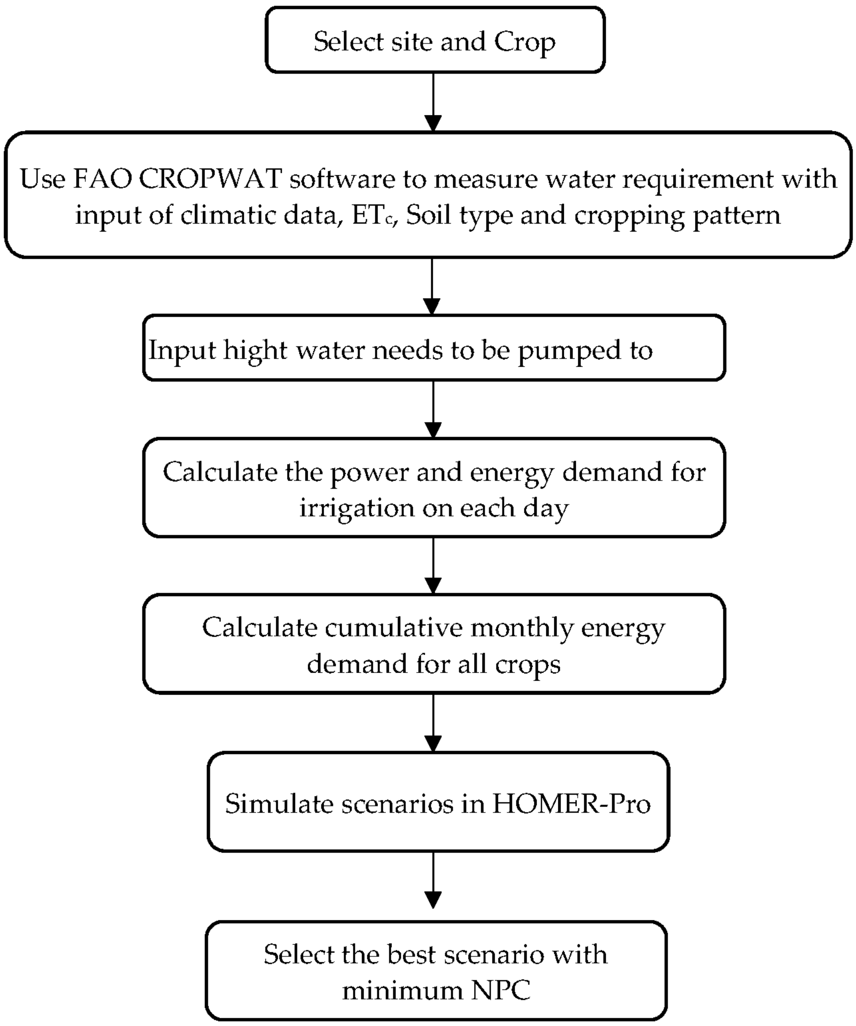

Figure 4. Methodology for design of Hybrid Renewable Energy System for Irrigation Application.

This study considered Wheat, Barley, and Sorghum, which are three primary crops of Saudi Arabia, and calculated their crop water requirement. Crop water requirement is calculated using the United Nations Food and Agriculture Organization's (FAO) software CROPWAT. CROPWAT considers several factors such as evapotranspiration (*ETo*), climatic data, soil type etc. to find the crop evapotranspiration to determine the crop water requirement.

The Penman-Monteith equation is considered to be the sole standard method for the computation of evapotranspiration *ETo* from meteorological data [38]. It is a commonly used method that determines the evapotranspiration from the hypothetical grass reference surface and provides a standard against which evapotranspiration in different periods of the year or in other regions can be compared and to which the evapotranspiration from other crops can be related [38]. The climatic data is available in the FAO software CLIMWAT 2.0, and it contains historical data. The crop water requirements are calculated from the planting date until the harvest date using the climatic data, *ETo*, soil type, and crop coefficients (*Kc*). The crop water requirement is calculated using the equation below [39];

$$ETc = Kc \times ETo \quad (1)$$

where *Kc* is the crop coefficient and *ETo* is the reference evapotranspiration. Crop irrigation requirements are determined by considering rainfall estimates and the availability of an irrigation system. Each crop will have its own crop coefficient, and the crop water requirement is evaluated individually.

The term crop water requirement refers to the amount of water required to maintain the requisite moisture level in the soil by supplying the water lost through evapotranspiration (*ETc*) [20]. Therefore, the crop water requirement is the *ETc* through different seasons. However, when calculating the irrigation requirements, consideration should be given to all sources of water supply, e.g., rainfall [20]. If there is no rainfall, the *ETc* is considered to be the water required for the crop, whereas in the case of rain or deep seepage, the Net Irrigation Water Requirement (*NIWR*) will be less, as given in (2) [40]:

$$NIWR = ET_o - R_{eff} \quad (2)$$

Once the crop water requirement is determined, the energy requirement for each day is calculated in order to pump the water. To calculate the power requirement, the total water discharge calculated using the CROPWAT is used as in (2) [41];

$$P = QgH\rho / 3.6 \times 10^6 \quad (2)$$

where Q is the flow of water (m^3/s), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), and H is the differential head (m). Using (3), the power required to lift water is calculated in kW, which can be converted to daily energy.

The calculated energy requirement is used to simulate the wind and solar energy system design using Homer-Pro software, which has been developed by the National Renewable Energy Laboratory USA. In a study by Sinha and Chandel [42], the authors concluded that amongst the software for designing hybrid renewable energy systems, HOMER is one of the most widely used with a maximum combination of renewable energy systems and performs optimization and sensitivity analysis, which makes it easier and faster to evaluate the many possible system configurations [42]. The Homer-pro software simulates scenarios for different energy system architectures as provided by the user and provides the optimum solution. The optimality of the system is determined by the Homer-pro based on the Net Present Cost (NPC). According to the architecture, Homer-pro simulates different sizing and combination of different components and determines the systems with minimum net present cost. The user can define constraints and carry out sensitivity analysis according to the need of the project. According to Homer-pro, the NPC of a component is the present value of all the costs of installing and operating the component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime [43]. HOMER calculates the NPC of each component in the system, and of the system as a whole [43]. The costs included in the NPC include the capital cost, the cost for maintenance, and the cost for replacing the equipment; the remaining cost is the salvage cost. NPC can be calculated as given in (3).

$$NPC = \sum (C_{capital} + C_{maint} + C_{repl} - C_{salv}) \quad (3)$$

where $C_{capital}$ is the initial capital cost, C_{maint} is the maintenance cost throughout the life of component, C_{repl} is the replacement cost, and C_{salv} is the salvage cost. Thus, the NPC is constituted of the costs throughout the life of project, excluding the salvage cost.

If the total power required to meet the energy requirement is represented by 'P_{tot}', and the wind, solar, and battery power are represented by 'P_{wind}', 'P_{sol}', and 'P_{Bat}', respectively, then according to (4),

$$P_{tot} = P_{wind} + P_{sol} + P_{Bat} \quad (4)$$

The Homer Pro considers both generation sources, i.e., wind and solar PV, and optimizes the size of either wind alone, solar PV alone, each with a battery, or a hybrid of both with and without a battery to obtain the minimum NPC. The system design with the minimum NPC is the optimum design. The results of the Homer Pro give the size of the wind, solar PV, and battery systems for practical implementation.

3. Case Study

As discussed above, the site selected for the purpose of designing the hybrid energy system for irrigation application is the Shaqra region in Saudi Arabia. Three primary crops of Barley, Wheat, and Sorghum are selected as case studies. The area for each crop is taken as 1 hectare. The climatic data is taken from FAO CLIMWAT for CROPWAT software [44]. The nearest weather station to the Shaqra region is Gassim. The data from the weather station is given in Table 2.

Table 2. Climatic data for Gassim Weather Station [44].

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	*ETo*
	°C	°C	%	km/day	h	MJ/m²/day	mm/day
January	6.5	18.4	52	216	6.8	13.4	2.84
February	8.2	21.6	43	216	7.9	16.7	3.77
March	12.3	26.4	36	259	6.7	17.5	5.26
April	16.9	30.9	31	302	7	19.6	6.98
May	22	36.9	24	302	8.3	22.4	8.79
June	23.7	40.5	16	259	10.3	25.5	9.47
July	24.5	41.4	16	259	10.2	25.2	9.61
August	24.4	41.1	13	216	10	24.2	8.6
September	22.4	39.4	17	173	8.5	20.6	6.96
October	17.2	33.9	23	216	8.2	17.8	6.31
November	12.4	25.8	38	216	8	15.2	4.37
December	7.8	20.1	51	216	5.4	11.3	2.97
Average	16.5	31.4	30	238	8.1	19.1	6.33

From the above, the average temperature in the region tends to be between 16.5 °C and 31.4 °C. However, the highest temperature can go up to 41.4 °C, and with global warming extreme events are becoming more frequent, and a further increase in temperature is expected. Further to these parameters, rainfall is another important parameter that determines the need for crop water requirement. The rainfall data is given in Table 3.

Table 3. Rainfall data for Gassim Weather Station [44].

	Rain	Eff Rain
	mm	**mm**
January	18	17.5
February	10	9.8
March	59	53.4
April	37	34.8
May	4	4
June	0	0
July	0	0
August	0	0
September	0	0
October	4	4
November	20	19.4
December	31	29.5
Total	183	172.3

The total annual rainfall for the region is 183 mm, which is significantly low and promotes aridity. Considering these climatic conditions, crops require a secondary source of water, which is through irrigation. The calculation of the irrigation requirement is made using CROPWAT software and the results for Barley, Wheat, and Sorghum are given below in Tables 4–6; the irrigation schedule is shown in Figures 5–7.

Table 4. Crop Water Requirement for Barley [44].

Month	Decade	Stage	*Kc*	*ETc*	*ETc*	Eff Rain	Irr. Req.
			Coeff	**mm/day**	**mm/dec**	**mm/dec**	**mm/dec**
March	1	Init	0.3	1.43	14.3	14.9	0
March	2	Deve	0.35	1.86	18.6	20.7	0
March	3	Deve	0.7	4.06	44.7	17.7	27
April	1	Mid	1.07	6.86	68.6	14	54.5
April	2	Mid	1.2	8.37	83.7	12.2	71.6
April	3	Mid	1.2	9.1	91	8.5	82.4
May	1	Mid	1.2	9.9	99	3.9	95.1
May	2	Mid	1.2	10.66	106.6	0.1	106.5
May	3	Late	1.19	10.82	119	0	118.9
June	1	Late	0.96	8.89	88.9	0.1	88.8
June	2	Late	0.65	6.12	61.2	0	61.2
June	3	Late	0.36	3.43	27.5	0	27.5
				Total	823	92.2	733.5

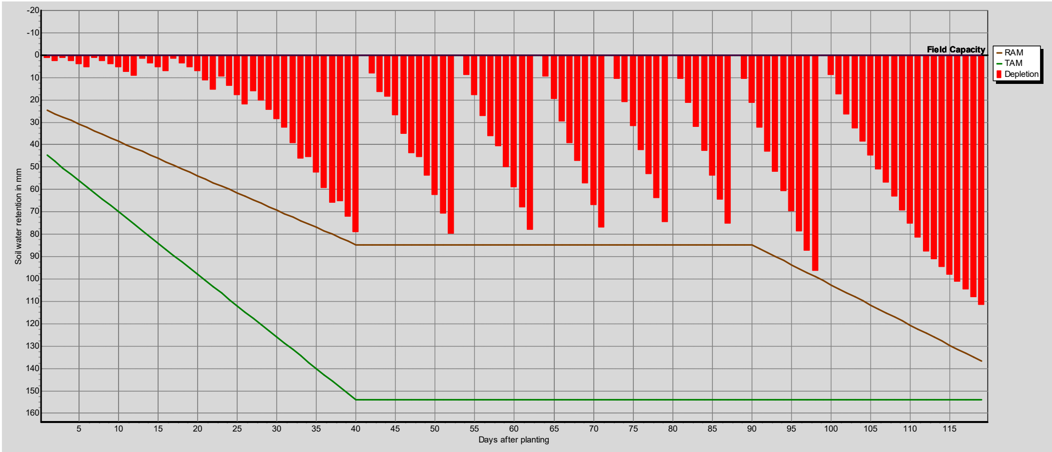

Figure 5. Irrigation Schedule for Barley (x-axis show days after planting and y-axis show soil water retention in mm (TAM represents Total Available Moisture and RAM represents Readily Available Moisture).

Table 5. Crop Water Requirement for Wheat [44].

Month	Decade	Stage	*Kc* Coeff	*ETc* mm/day	*ETc* mm/dec	Eff Rain mm/dec	Irr. Req. mm/dec
March	1	Init	0.3	1.43	14.3	14.9	0
March	2	Init	0.3	1.58	15.8	20.7	0
March	3	Deve	0.3	1.77	19.4	17.7	1.8
April	1	Deve	0.49	3.17	31.7	14	17.7
April	2	Deve	0.79	5.55	55.5	12.2	43.3
April	3	Mid	1.09	8.28	82.8	8.5	74.2
May	1	Mid	1.2	9.9	99	3.9	95.1
May	2	Mid	1.2	10.66	106.6	0.1	106.5
May	3	Mid	1.2	10.9	119.9	0	119.8
June	1	Late	1.19	11.01	110.1	0.1	109.9
June	2	Late	0.97	9.23	92.3	0	92.3
June	3	Late	0.67	6.42	64.2	0	64.2
Jul	1	Late	0.4	3.9	31.2	0	31.2
				Total	842.8	92.2	756.1

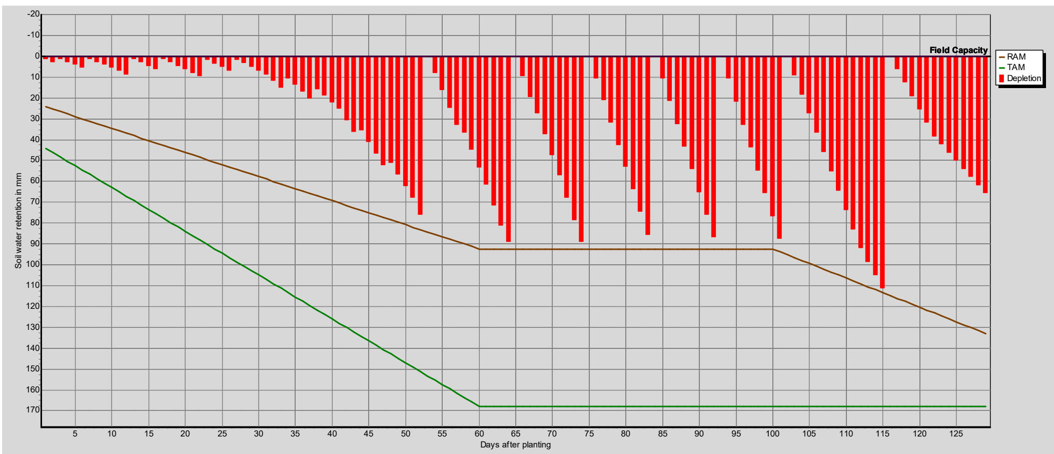

Figure 6. Irrigation Schedule for Wheat (x-axis show days after planting and y-axis show soil water retention in mm (TAM represents Total Available Moisture and RAM represents Readily Available Moisture).

Table 6. Crop Water Requirement for Sorghum [44].

Month	Decade	Stage	*Kc* Coeff	*ETc* mm/day	*ETc* mm/dec	Eff Rain mm/dec	Irr. Req. mm/dec
March	1	Init	0.3	1.43	14.3	14.9	0
March	2	Init	0.3	1.58	15.8	20.7	0
March	3	Deve	0.43	2.51	27.6	17.7	9.9
April	1	Deve	0.66	4.21	42.1	14	28
April	2	Deve	0.87	6.09	60.9	12.2	48.8
April	3	Mid	1.04	7.91	79.1	8.5	70.6
May	1	Mid	1.06	8.72	87.2	3.9	83.3
May	2	Mid	1.06	9.39	93.9	0.1	93.8
May	3	Mid	1.06	9.59	105.5	0	105.5
June	1	Late	1.01	9.37	93.7	0.1	93.6
June	2	Late	0.87	8.22	82.2	0	82.2
June	3	Late	0.72	6.82	68.2	0	68.2
July	1	Late	0.62	5.95	17.9	0	17.9
					788.3	92.2	701.6

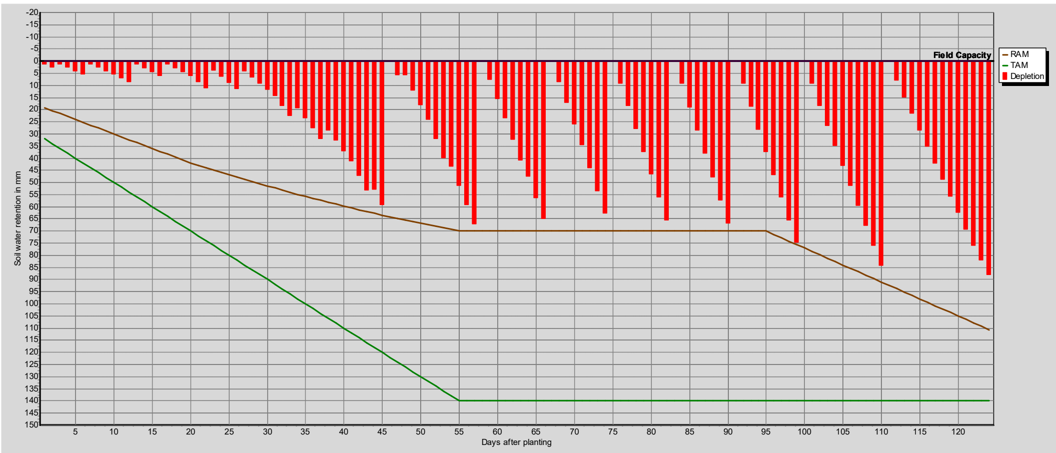

Figure 7. Irrigation Schedule for Sorghum (x-axis show days after planting and y-axis show soil water retention in mm (TAM represents Total Available Moisture and RAM represents Readily Available Moisture).

From the above irrigation schedule, several irrigations are required for each crop. Considering the above calculations, the pump size is calculated to meet the energy demand. The depth of the borehole in the region is considered using local interviews. The borehole depth in the area ranges from 60 m to 100 m, and for the purposes of this study, a borehole depth of 80 m is assumed. The highest load demand is observed in wheat, where a maximum of 1.8 kW pump is required to meet the crop water requirement at any given time for 1 hectare area. The combined energy requirement for all 3 crops is given in Figure 8.

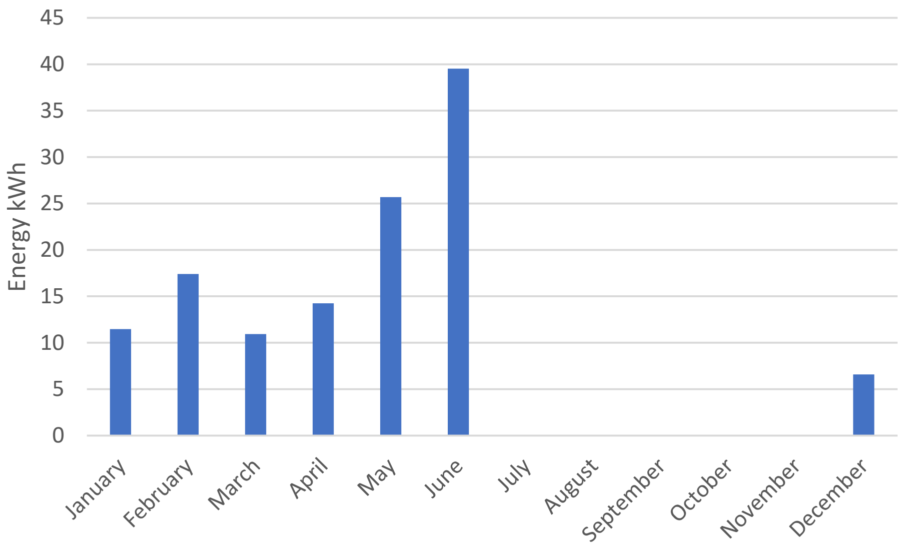

Figure 8. Energy requirement for all 3 crops.

The energy requirement given above is used to design the hybrid energy system. The case study considers island mode for a microgrid with the primary source to be either Solar PV, Wind, or a hybrid of both. As almost all electricity generation in Saudi Arabia is generated using fossil fuels; grid energy is not an ideal candidate to support cause of Vision 2030. Therefore, only a microgrid in island mode is considered.

Prior to discussing the result of the case study, it is important to understand the potential of each source i.e., wind and solar PV. It is generally understood that a wind speed of above 5 m/s is required for wind turbines to operate. Therefore, prior to considering the wind energy, evaluation of wind sources is required. Homer-pro uses wind speed data from NASA to evaluate wind generation. A plot of the average wind speed over a year from the dataset used by Homer-pro is given in Figure 9. From Figure 9, it can be observed that the average wind speed in Shaqra is above 5 m/s throughout the year. This shows that Shaqra has significant potential for wind generation.

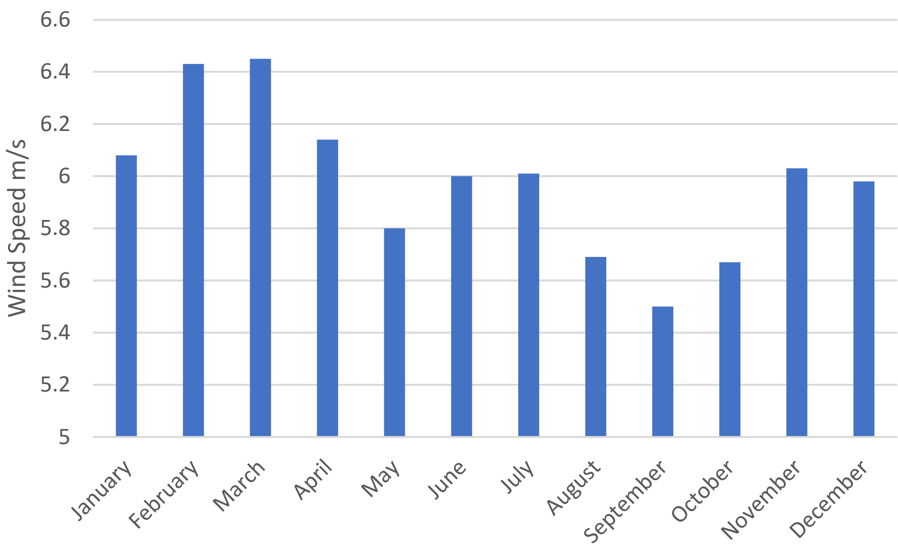

Figure 9. Average wind speed in Shaqra.

Similarly, solar irradiance for Shaqra given in Figure 10 shows an average daily irradiance of 5.73 kWh/m²/day. With high values of both wind speed and solar irradiance, Shaqra has potential for a hybrid energy system. The case studies given below evaluate the techno-economic feasibility of hybrid system.

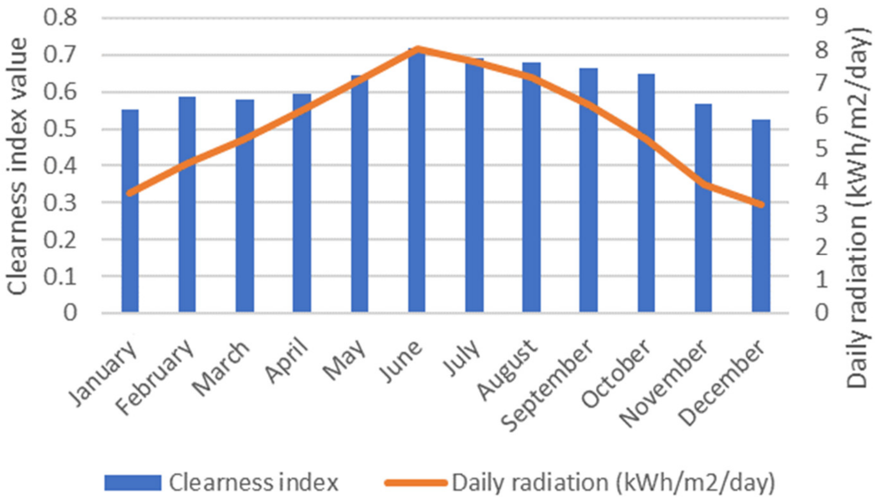

Figure 10. Solar irradiance in Shaqra.

The microgrid considered in this case study consists of a solar PV module, a wind turbine, battery storage, a convertor and the irrigation load. The architecture of the system is shown in Figure 11, below. Where 'PV' represents a solar PV module, 'G3' represent generic a 3 kW wind turbine with a hub height of 17 m and AC output, and 'S4KS25P' is the battery storage. The term generic model refers to non-proprietary dynamic models that can be used to represent wind turbine generators (WTGs) with similar physical and control topology, regardless of the manufacturer [13]. The Homer generic flat plate PV modules used in this study are of 1 kW capacity and have a lifespan of 25 years with a derating factor of 80%.

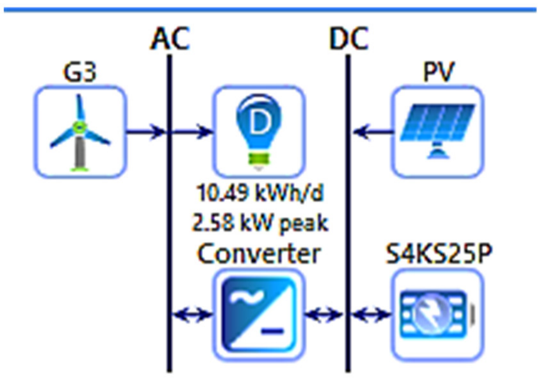

Figure 11. Architecture of island microgrid.

The price of solar PV has dropped from USD 4731/kW to USD 883/kW and for wind from USD 1971/kW to USD 1355/kW between 2010 and 2020 [23]. Therefore, in this study, the cost of PV is taken as USD 883/kWh, and for wind turbines, it is taken as USD 1355/kWh. The O&M cost for PV modules is taken as $10 and for the wind turbine as $180. For energy storage, a Surrette S4KS25P type is used and connected as a central storage system, and the capital cost of one battery is taken as $1250, while the O&M cost for the battery is assumed to be 15$/year [37]. The results of the simulation are given below in Figure 12.

Architecture					Cost				System	
PV (kW)	G3	S4KS25P	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
6.56	1	6	2.03	CC	$17,482	$0.357	$340.92	$13,075	100	0
10.4		7	2.87	CC	$18,552	$0.379	$201.87	$15,942	100	0
	5	18	2.56	CC	$40,860	$0.834	$1,187	$25,517	100	0

Figure 12. Homer-pro simulation results for hybrid renewable energy system.

This microgrid requires 10 kWh/day and has a peak of 2.58 kW. In the proposed system, the contribution of wind and solar PV generation is given in Figure 13. It can be clearly seen from Figure 13 that despite having only one G3 wind turbine, it produces more than 50% of the PV generation. On the other side, it can be clearly seen that the capital cost of the hybrid generation system is $13,075, which is lower than solar only option, i.e., $15,942, and the wind only option, i.e., $25,517. Apart from the capital cost, the cost of electricity for the hybrid system is $0.357, while for the solar only generation system it is $0.379 and for the wind only generation system it is $0.834. This shows that not only in the technical aspects but also in the economic aspects there is a clear superiority of the hybrid energy generation system. The optimization algorithm of Homer Pro shows that a significant reduction in sizing of solar PV from 10.4 kW to 6.56 kW is achieved, with a reduction in energy storage from 7 to 6. Thus, a hybrid renewable energy system of wind and solar PV generation and battery storage is the optimum choice for this case study.

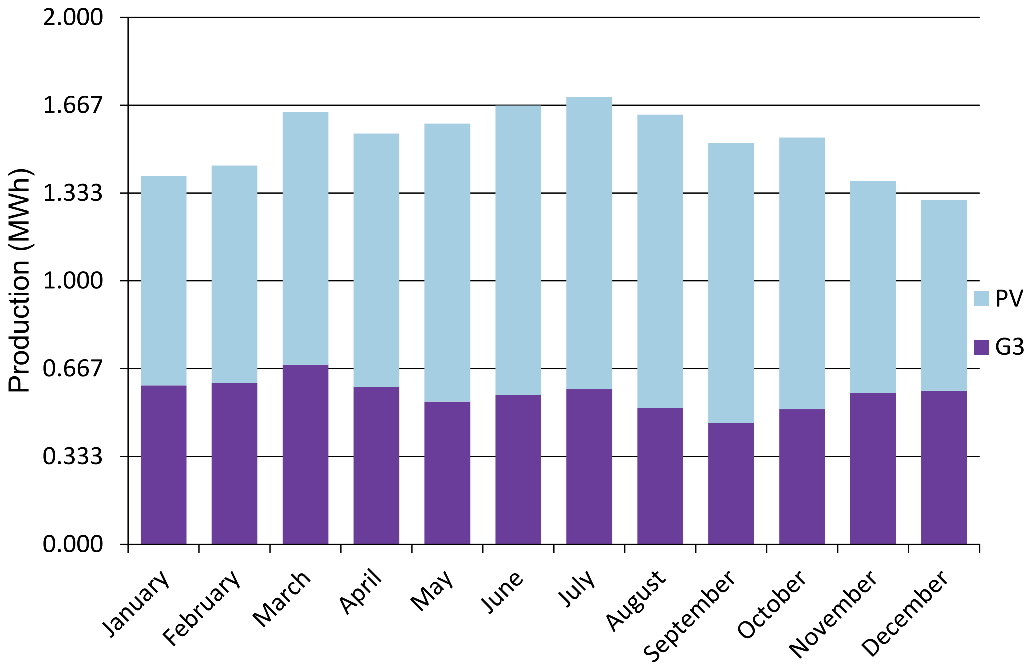

Figure 13. Share of wind and PV generation in total power production.

Daily generation profiles of the PV system show that due to the high solar irradiance, the solar generation stays high but with reduced daylight hours; particular reductions in generation during November, December, and January are observed. This can be observed in Figure 14.

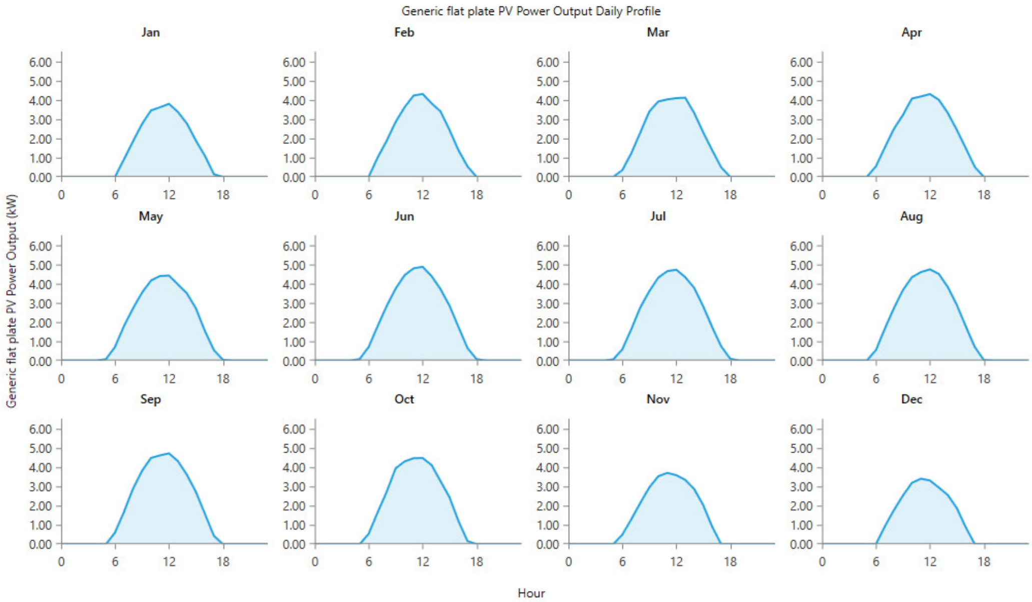

Figure 14. PV daily output profiles.

The generation profile of the wind turbine shows that, unlike the solar profile, the wind turbine generates power throughout the day and throughout the year. The wind generation tends to remain between 0.5 kW and 1.5 kW except for the hours after midnight till early morning. The generation profile of the wind turbine is given in Figure 15.

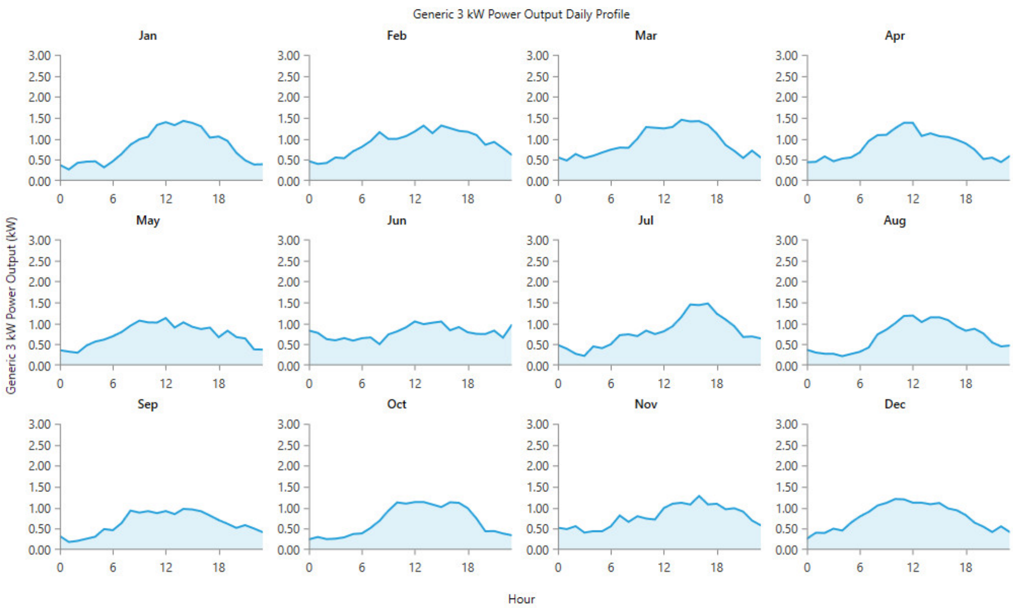

Figure 15. Wind turbine daily output profiles.

Total energy produced by PV is 11,542 kWh/year, whereas, for the wind turbine, the generation is 6837 kWh/year. This shows that the potential of wind generation in the region is significantly high. Hybridization of wind and solar PV benefits the system by reducing the NPC and cost of electricity. This establishes the fact that a reduction in the cost of wind turbines is making the hybridization of renewable energy sources technically and financially viable, and in future, with further reduction in the cost of PV and wind turbines, the scope of hybridization is expected to broaden.

The above shows that a hybrid renewable energy system is feasible in Shaqra, Saudi Arabia. It is usually perceived that the solar only solutions are always cost effective in Saudi Arabia, but this study shows that for irrigation applications, the hybrid of Wind and Solar PV can provide a good solution, which can be cost effective and environmentally friendly. As shown above, the CoE for this study is 0.357$/kWh for a hybrid energy system and 0.379$/kWh for solar PV only systems. A comparison of the CoE of the case study with global averages from different regions is given in Table 7. It is clear from the comparison that most of the studies show a higher CoE for hybrid energy sources. The cases where the CoE is lower is mainly due the fact that studies have included a diesel generator (DG) in their studies, which shaves the peak load, and a significant amount of renewable energy is reduced that is exclusively required to cater to the peak load. Although the addition of DG brings the cost down significantly, considering the drive for decarbonization, its detrimental impact on the environment restrains the use of DG. Despite all this, it can be clearly seen that the suggested site in Saudi Arabia has one of the lowest CoE for a hybrid of wind and solar PV.

Table 7. NPC and COE of the optimal HRES configuration plan in different regions all over the world.

Country	Location	RE Sources	NPC (M$)	CoE ($/kWh)	Ref.
Yemen	Shafar	PV/WT/DG/Battery/Converter	0.722	0.137	[27]
Egypt	Hurghada	PV/WT/DG/Battery/Converter	0.822	0.139	[29]
India	Silchar	PV/Biogas generator/Pumped hydro energy	0.813	0.4864	[45]
Australia	Sydney	PV/WT/Battery/Converter	0.093	1.502	[46]
Colombia	Puerto Estrella	PV/DG/Battery/Converter	0.836	0.473	[47]
Bangladesh	Chorasariadho,	PV/WT/DG/Battery/Converter	0.335	0.37	[48]
KSA	Rafha,	PV/DG/Battery/Converter	28.5	0.170	[49]
India	Amritsar,	PV/WT/DG/Battery/Converter	0.010	0.164	[35]
Canary Islands	Lanzarote,	PV/DG/Battery/Converter	0.473	0.404	[50]
Malaysia	Pulau Banggi	PV/WT/DG/Battery/Converter	8.54	0.276	[51]
South Korea	Busan,	PV/WT/Battery/Converter	26.09	0.399	[36]
Canada	Vancouver	PV/DG/Natural gas generator/Biomass/Battery/Converter	29.3	0.285	[52]
Sudan	Dongola	PV/WT/DG/Battery/Converter	24.16	0.387	[37]
Indonesia	Lhoknga Aceh Besar	PV/WT/DG/Battery/Converter	0.371	0.481	[53]
Saudi Arabia	Shaqra	PV/WT/Battery/Converter	0.0174	0.357	Current Study

4. Conclusions

This paper presents a systematic study to design a hybrid energy system for irrigation application. A case study of the Saudi Arabian city of Shaqra is presented, where crop water requirement is calculated using CROPWAT software and the crop water requirement is converted into energy requirement. Local knowledge and interviews are used to determine the borehole depth, and the energy system is designed using Homer-pro software.

The aim of study was to conduct a techno-economic feasibility of the hybrid energy system in Shaqra. The results suggest that technically, sufficient wind is available in the region along with high solar irradiance to offer a hybrid solution, which can support the load requirements. It can be concluded from the case study that the addition of a small amount of wind energy in the system can offset a much larger amount of solar PV generation. This is essentially due to the availability of wind throughout the day and night as compared to limited daylight hours for PV. Financial comparison shows that overall, the NPC for the hybrid energy system is $17,482, whereas for solar PV NPC it is $18,552 and for wind only $40,860. This shows that hybrid generation is always the best option due to the optimal energy mix and the availability of wind throughout the day. Further to the reduced cost, the wind profile and power generation profile show that wind generation can provide the necessary support to the PV generation to achieve a high level of reliability. Overall, the results of this case study are highly supportive of a wind-solar hybrid energy system for irrigation application.

The study was limited in scope to the use of wind and solar PV generation due to the application area. In future studies, a multidimensional approach with a higher agricultural load and with farm loads considering electric tractor loads, along with options of more renewable energy sources integration, will be considered.

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Nomenclature

ETo	Evapotranspiration
Kc	Crop coefficients
ETc	Crop water requirement
NIWR	Net Irrigation Water Requirement
R_{eff}	Effective Rainfall
Q	Flow of water/Discharge (m^3/s)
ρ	Density of water (kg/m^3)
g	Acceleration due to gravity (m/s^2)
H	Differential head (m)
FAO	Food and Agriculture Organization
GHG	Green House Gas
NPC	Net Present Cost
$C_{capital}$	Initial capital cost
C_{maint}	Maintenance cost
C_{repl}	Replacement cost
C_{salv}	Salvage cost
P_{tot}	Total power required to meet the energy requirement
P_{wind}	Power generated by wind
P_{sol}	Power generated by solar PV
P_{Bat}	Power supplied by battery
KSA	Kingdom of Saudi Arabia
CoE	Cost of Electricity

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