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A COMPARISON OF LEVELISED COST OF ENERGY OF DIFFERENT ENERGY SOURCES FOR IRRIGATED SHALLOT FARMING IN SOME COASTAL REGIONS OF GHANA

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ABSTRACT
This study assessed the technical and economic viability of Poldaw wind pumps for irrigates shallot cultivation in the Keta Municipality in Ghana. Technical analyses of 4 versions of the Poldaw pump is conducted to determine if it they can supply the water requirements for irrigated shallot farming. The Levelized Cost of Energy (LCOE) of wind energy for irrigation over a period of 20 years is also calculated and compared with that of grid electricity, diesel, petrol and premix fuels as alternative energy sources for irrigated shallot farming in the area. At a hub height of 10 m, the 5.0 m Poldaw was found to be capable of supplying the daily water requirements for irrigated shallot farming in the area. In addition, its LCOE is better than those of petrol, diesel and premix fuel. Grid electricity lost its slight advantage on LCOE when the Poldaw pump was assessed for hub heights of 12 m and higher. The findings of the study suggest that the 5.0 m Poldaw pump is a viable alternative to pumps powered by other energy sources currently used for irrigated shallot farming in the Municipality.
Keywords : *Wind Powered Irrigation, Sustainable Faming, Wind Energy, Technical And Economic Analyses*

1. Introduction

All phases of production in modern farming involve energy input, including the use of energy directly in farm machinery, water management, irrigation, cultivating, and harvesting. However, high cost of energy, unstable supplies, and limited accessibility in farming areas, unstable fuel prices and shortages amidst environmental concerns are some of the challenges that face contemporary farming. Promoting sustainable agriculture to end hunger and achiever food security and improved nutrition (SDG 2), buttresses the need for alternative energy sources in farming. Solar energy and wind energy are two of the most popular non-polluting sustainable and renewable energy sources used in the agriculture sector. The process of converting solar energy into food for humans and animals through photosynthesis is really called agriculture, and it is a renewable energy conversion process. In the agricultural sector, solar energy has also been used for a variety of purposes, including drawing water for irrigation and watering livestock. Other uses include drying food and supplying electricity. Since ancient times, wind energy systems have also been utilized for irrigation and milling, and at the turn of the 20th century, they began to be employed to generate electricity. For irrigation and the hydration of farm animals, wind pumps have been erected in many nations, especially in rural areas.

Agriculture plays a central role in Ghana's economy and accounts for over 25% of total employment of its population in 2020 (TheGlobalEconomy.com, 2020). That notwithstanding, the structure of the sector is vulnerable for its heavy reliance on seasonal rainfall which lasts roughly for six-months and thus limits effective conventional farming season to only half yearly (R. E. Namara et al., 2011). The estimates for Ghana's irrigation potential range from 0.36 to 2.9 million hectares (Agodzo & Bobobee, 1994). The concept of irrigation is not a new phenomenon in Ghana. For instance, the Keta strip of the Volta Region farmers' experience of groundwater utilization for agriculture is well over 200 years (E. R. Namara et al., 2010). However, the sector is not well explored. A survey conducted by the Ghana Irrigation Development Authority (GIDA) concluded that, the Keta municipality has the largest informal irrigation system in Ghana with an estimated total of 4000 hectare (ha) cultivated all year round (Ahiabor, 2014). A variety of fresh vegetables, especially shallots, are produced all year-round in the municipality using irrigation. Farmers depend on irrigation using groundwater from wells that are drilled to a depth of about 1 m - 9 m to provide water for irrigation (Diaba, Kutsanedzie, & Deku, 2015). Initially, irrigation in the municipality made use of the human feet/hand-operated equipment, such as rope, calabash and buckets, making the system labor intensive.

However, due to good abstraction rates from these wells (as observed by Kortatsi (1994)) the traditional labor-inefficient shallow groundwater irrigation systems have given way to more efficient, albeit capital intensive systems. These systems have emerged due to the introduction of pumps powered by various sources of energy which are used to draw water from the wells to irrigate vegetable farms all year round. Adzraku (2017) found that, the main sources of energy for irrigation in the municipality are electricity from the grid (54.7%), and premix fuel (44.6%). The other sources include petrol and diesel, with no solar or wind energy, being deployed for lifting water in the region. This is in spite of the fact that the Municipality has some of the best wind resources in Ghana (Dzebre, 2019; Dzebre, Ampofo, & Adaramola, 2021; Energy Comission of Ghana, 2006; National Renewable Energy Laboratory (NREL), 2004).

2. Literature Review

Renewable Energy (RE) pumping systems have been of interest, particularly in developing countries over the years. Solar energy and wind energy are two of the most popular non-polluting sustainable and renewable energy sources used in the agriculture sector. The systems are either powered by electricity that is generated from the RE sources, as is the case of most (if not all) solar powered and some wind powered water pumping systems, or mechanically lift the water from ground sources, as is the case of Mechanical wind pumping systems. Figure 1 presents illustrations of Electrical wind and mechanical pumping systems.

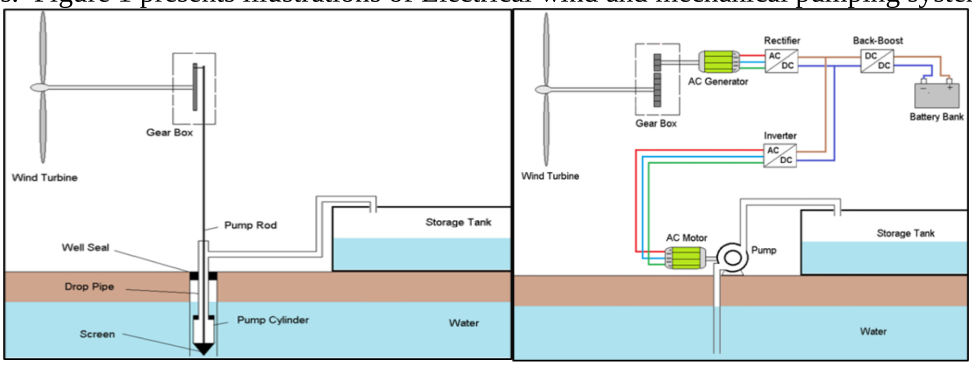

Fig. 1. Schematic representations of Electrical Wind (left) and Mechanical Wind (right) pumping systems (Achour & Kesraoui, 2021).

The Poldaw Wind Pump

The Poldaw wind pumps are low-cost mechanical wind pumps that were developed and intended principally for use in developing countries (NEALE Consulting Engineers, 2003). The pumps use a simple crank and rocker arrangement, with a rotor which develops high torque at low wind speed without the involvement of a gearbox. This however reduces the aerodynamic efficiency which is easily offset by making the rotor blades a bit longer. The elimination of the gearbox system in its design makes it simpler to build, less expensive and improves reliability at lower maintenance cost.

The rotor size and hub height can be designed to meet the available wind resource, the pumps characteristics and water supply demand. They come in sizes of 1.5 m, 2.2 m, 3.5 m and 5.0 m rotor diameters. The water source that the wind pump will collect water from most frequently is a borehole. An elevated storage tank is the target of a traditional multiblade Poldaw pump's reciprocating or piston pump. In order to overcome the weight of the pump rods and the water in the rising main, the rotor must produce adequate torque when the piston pump is first started. Because of the rotating rotor's velocity, the torque demand drops after it starts to rotate. After then, the wind pump won't operate until the wind speed is roughly 2/3 of the start-up windspeed. A cut-in speed of 2.5 to 3.0 m/s is required for the Poldaw pump (NEALE Consulting Engineers, 2003) .

The Poldaw wind pump is also equipped with a tail vane mounted perpendicular to the plane of the rotor to keep it orientated into the wind stream and for automatic furling at high wind speeds to prevent damage. It is designed to furl at wind speeds above 50 m/s. Table 1 shows a summary of some generic features of the Poldaw wind pumps. Due to the simplicity of the Poldaw wind pumps, they can be easily fabricated.

Table 1 - Generic technical specifications of the Poldaw wind pump (Ejieji & Olayaki-Luqman, 2013).

Feature	Value
Number of blades	12
Tower height (m)	9 – 10
Typical rotor speed (rpm)	40 – 80
Starting wind speed (m/s)	2.5
Survival wind speed (m/s)	50
Service life (years)	20

Several studies, including have investigated the viability of RE systems, often in comparison conventional sources of energy. These in recent times include Mbarek, Ghamgui, Chaabane, Ooualha, and Tadeo (2023) who proposed a wind powered irrigation system for growing tomatoes and strawberries in Tunisia. Others include Jayanthi and Ravisankar (2005), Islam, Islam, Islam, and Razzaque (1995) and Amar and Elamouri (2014) who investigated the technoeconomic viability and efficiency of wind energy for water pumping for agriculture applications, Genç Mustafa (2011), who compared the economic viability of wind turbine and diesel water pumping systems is presented in Anatolia region of Turkey, Pam, Mansir, Borok, and Kolo (2013), who examined the performance of the Poldaw wind pump in northern Nigeria, and Paul, Oyedepo, and Adaramola (2012), who assessed the economic viability of the water pumping systems supplied by selected wind turbine models. Several others such as Nemouchi, Amrane, Nemouchi, and Boucetta (2024), Widiastuti and Wijayanto (2017), Abu-Aligah (2011), Poompavai and Kowsalya (2019), Mengi and Altas (2015), and Achour and Kesraoui (2021) have also focused on the development of conventional and smart hybrid systems to ensure continuous availability and improve system efficiency. A common conclusion from all these studies is that, standalone wind or solar-wind hybrid water pumping systems are viable. However, it is realized from the results of these studies that, performances of the systems are mixed, owing to the geographic dependent of the wind and solar resources. In addition, economic viability of the systems also often depends on country-specific economic factors and government policies. These observations are supported by findings of Kamwamba-Mtethiwa, Weatherhead, and Knox (2016) in their review of small-scale irrigation systems in Sub-Saharan Africa (SSA), where they reported and highlighted the geographically biased nature of system performances, and the limited availability of data that is needed to better assess the performance on such systems. This conclusion was also highlighted by Ziter (2009) in his assessment of selected wind pumping systems for agriculture purposes in selected developing countries. The conclusions of these studies underscore the need for studies on the performance of such systems under different conditions to better inform the their deployment and the formulation and adoption of appropriate policies and strategies to aid their success when deployed (Ziter, 2009).

However, few of such studies could be found in open literature on Ghana and often, with limited scopes. For instance, though Diaba et al. (2015) experimentally conducted a comparative evaluation of the cost of irrigation farming with Electrical wind, and grid electrical pumping systems in Keta and found that the grid electricity system was more expensive, their study was limited to just a Electrical wind system. The Agricultural Engineering Services Directorate (AESD) of the Ministry of Food and Agriculture of Ghana, in collaboration with the Village Infrastructure Project (VIP) manufactured and piloted the Poldaw wind pump in selected localities in Ghana. Though they concluded at the end of the project that mechanical wind pumping systems for irrigation are viable, albeit with higher initial cost their conclusion was based on a 5 years period analysis, far less than the typical 20 years lifespan of the Poldaw pumps (NEALE Consulting Engineers, 2003) . Furthermore, in addition to the relatively short periods of analyses, these studies did not consider all the energy sources that are currently commonplace in the pumped irrigation sector of the country. According to Renewable Energy Master Plan (REMP) of Ghana, insufficient research and data on technical and economic performance continue to hamper the development of wind irrigation in Ghana. The plan suggests that to promote wind irrigation systems, existing installations and studies that were done previously under the Village Infrastructure project should be reviewed, studies should be conducted to identify potential implementation areas. It also recommended research and development in wind irrigation technology.

In view of these, the aim of this study aim was to evaluate the technical and economic viability of mechanical wind pumping system as compared to other commonly used energy sources for pumped irrigation in areas along the coast of Ghana. The technical analysis assessed the ability of the Poldaw pumps to meet water requirements for irrigated shallot farming in the Keta Municipality in Ghana. The economic analysis calculated the Levelised cost of wind energy compared to other types of energy that are currently commonly used for pumped irrigation in the municipality. The Keta Municipality was chosen for this study as it has some of the best wind resources in Ghana. This is in addition, to the fact that it has the largest informal irrigation system in Ghana (Ahiabor, 2014), with shallot cultivation quite common in the area (Adzraku, 2017; Porter, Young, & Dzieor, 1997) .

This study expands on the previously identified limited scope of earlier studies in Ghana; mechanical wind pumps is assessed for the more typical 20 years lifespan of wind systems. In addition, a comparison is made with other currently used energy sources, not just grid electricity. It also attempts to generalize the findings to other coastal areas in Ghana.

3. Research Methods

3.1 Study area

The Keta Municipality, shown in Figure 2 is one of the Volta Region's fifteen (15) administrative districts. It lies within the latitudes 5.450°N and 6.005°N and longitudes 0.3°E and 1.05°E. The peninsula is located in the municipality. The peninsula is bordered to the east by the Ketu North and South Districts, to the north by Akatsi South Districts, to the east by the South Tongu District and the south by the Gulf of Guinea. It is essentially a 2.5-kilometer-wide stretch of sand bar that separates the Keta lagoon (to the north) from the sea (to the south). It has a total surface area of 1,096 km^2, of which water bodies and swamps cover 30%, interspersed with savannah woodland and short grassland mangroves (Ghana Statistical Service (2014a).

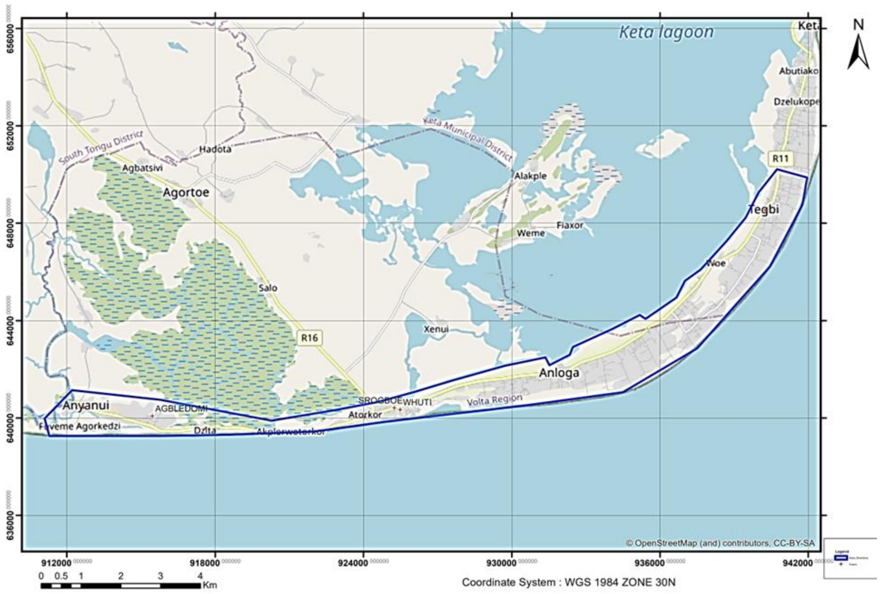

Fig. 2. Keta Municipality

The economic activities in the area depends essentially on fishing and the cultivation and sale of shallots and other vegetables (Porter et al., 1997). According to the Ministry of Food and Agriculture, Keta municipal is a central vegetable-producing area in the Volta Region, particularly for shallots grown in the flood plains along the Angaw and Keta lagoons, streams, and depressions created by wealthy farmers. The main shallot-producing areas include Anyanui, Agbledomi, Dzita, Whuti, Anloga, Woe, and Tegbi. Other vegetables, such as okra, tomato, and pepper, are also widely grown, either as pure stands or as intercrops, depending on the season, with the alluvial soils along the lagoons providing excellent growing conditions. The municipality's emerging crops include onions, carrots, and Asian vegetables. Because the lagoon water is too saline for agricultural use, horticulture relies on groundwater irrigation from the shallow fresh aquifer beneath the bar. Sandy soils cover most of the peninsula, but heavy saline clays prevail closer to the lagoon edge.

Irrigation is essential for farming due to the irregularity in rainfall in the area. The Keta municipality receives limited rainfall of less than 800 mm per annum (Addo, Nicholls, Codjoe, & Abu, 2018; Foloitse, Obeng-Koranteng, Osei, & L.P., 2017) which falls under sub-humid and semi-arid climate (C. Brouwer & Heibloem, 1986). There are two dry seasons and two wet seasons in the region. From March to June, there is the first rainy season. These four months of the year account for almost 75% of all rainfall (Foloitse et al., 2017). Rainfall abruptly stops in July and August for around six weeks. Therefore, rain fed farming is limited, making the use of groundwater irrigation from fresh water sources a necessity to ensure an all-year-round farming period.

3.2 Methodology

Technical Analysis

The aim of the study was to assess the technical and cost of the Poldaw wind pump for pumped irrigation cultivation of shallots in the Keta Municipality of Ghana. For the technical assessment, the average annual water requirement for shallot farming was estimated. Data on water output of the Poldaw wind pump at varying wind speeds were obtained from performance data of the pump. Wind data for the study was analyzed to determine if the required wind speeds to meet the desired water output rates prevail in the area.

Water Requirements for irrigation: This was estimated using a procedure outlined by the Food and Agriculture Organization (AQUASTAT, 2021; C. Brouwer & Heibloem, 1986). The quantity of irrigation water depends on the type of plant, soil type and weather conditions. The annual depth of water (in mm) required for irrigation for a specific plant was as

$$I_{water} = 365 \times P_{water} - R_{water} \quad (1)$$

where I_{water} is the yearly depth of irrigation water requirement for the plant in (mm), P_{water} is the depth of daily water requirement for the plant (mm) and R_{water} is the depth of annual rainfall in mm. For a known daily depth of water ($D_{water} = I_{water}/365$), the daily quantity of water required to irrigate a parcel of farmland can be expressed as

$$Q = D_{water} \times A_{land} \quad (2)$$

where Q is the volume of water in m^3 and A_{land} is the area of the farm in m^2.

Wind Resources Assessment: Wind statistics were collected at a height of 40 m heights, which differs from the heights of interest for this study. The Power law was used to adapt the available wind speeds to the wind turbine hub heights of 4 m, 6 m, 8 m, 10 m, and 12 m for this study. The power law is given as

$$\frac{v}{v_O} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (3)$$

where v_O is the measured wind speed at height h_o above ground level (a.g.l), v is the required wind speed at height h and α is the surface roughness coefficient expressed according to (Manwell, McGowan, & Rogers, 2010) as;

$$\alpha = [0.37 - 0.088ln(v_O)]/\left[1 - 0.088ln\left(\frac{h_o}{10}\right)\right] \quad (4)$$

The wind data were examined using the two-parameter Weibull probability density function. The Weibull distribution is the most commonly used method for modelling the distribution of wind energy. The Weibull Probability Density Function according to (Dzebre & Adaramola, 2019) is given as;

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (5)$$

where $f(v)$ is the probability of observing wind speed (v), k is dimensionless Weibull shape parameter, and c is the Weibull scale parameter (m/s). The Weibull parameter factor k and the Weibull scale factor c can be determined by the following expressions:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} 1 \le k \le 0 \quad (6)$$

and

$$c = \frac{v_m k^{2.6674}}{0.184+0.816k^{2.73855}} \quad (7)$$

where σ standard deviation expressed as

$$\sigma = \left[\frac{1}{n-1}\sum_{i-1}^{n}(v_i - v_m)^2\right]^2 \quad (8)$$

In addition to the mean wind speed of a site, the other useful characteristics wind speeds parameters are the most probable wind speed (v_f), and the wind speed carrying maximum energy (v_e). They can be estimated from the following expressions for Weibull distribution function:

$$v_f = c\left(\frac{k-1}{k}\right)^{1/k} \quad (9)$$

and

$$v_e = c\left(\frac{k+2}{k}\right)^{1/k} \quad (10)$$

Economic Analysis

The economic analysis was based on the premise of Rao (2019) that, the benefit of wind energy can be assessed by comparing the cost of generating energy using alternative technologies that are being substituted by wind turbines. This implies that, when a wind turbine is used instead of a diesel generator, the cost of producing energy with diesel can be equated to the value of electricity generated by the wind. (Rao, 2019). Therefore, in this study, the useful energy output of the wind pump was valued in terms of the amount of fuel an Internal Combustion Engine (ICE) would need to generate the same amount of useful energy as the wind pump. In the case of an electric pump, this refers to the amount of electrical energy the pump uses to produce useable energy that is comparable to that of the wind pump. The cost of generating the equivalent amount of power from these other sources of energy (fuel and grid electricity) were determined. Other costs; initial capital costs, maintenance costs among others for the Poldaw pumps, petrol, diesel, and electric submersible pumps were determined from literature, a market survey and interviews with experts on the subject. These were used to estimate the Levelised Cost of Energy (LCOE) of the various energy sources for comparison and discussion.

Calculation of Wind Power: The power available to a wind rotor is dependent on the speed of wind covering the cross-sectional area swept by the rotor blades (m^2). However, this available power is not utterly converted by the rotor since the wind cannot be brought to a complete halt. The theoretical maximum power that can be extracted by a wind rotor is only about 59.3% (known as Betz limit) of what is available in the wind (Pam et al., 2013). The rotor's efficiency, also known as the power coefficient, is defined by this restriction. The power generated by the wind in the case of the Poldaw wind pump was estimated as

$$P_r = C_r \times \frac{1}{2} \times \rho_a \times A \times v^3 \quad (11)$$

where P_r is the wind power to the rotor (W), ρ_a is the density of air given as 1.25 kg/m^3, C_r is the rotor power coefficient, A is the rotor sweep area (m^2) and v is the wind velocity in m/s. In practice real wind rotors have maximum C_r values in the range of 25%-45%, depending on the tip speed ratio of the rotors (Manwell et al., 2010).
For a mechanical pump, the power, P_p (W) required to pump water is expressed as

$$P_p = \frac{\rho_w \times g \times H \times f_w}{\eta_p} \quad (12)$$

where ρ_w is water density in (1000 kg/m^3), g is acceleration due to gravity (m/s^2), H is the pump head in (m), f_w is volumetric flowrate of water in (m^3/s) and η_p is efficiency of the pump. For any given wind speed, the power from the rotor must match the pumping power (i.e. $P_r = P_p$).

Equivalent Power from Other Energy Sources: The determining of the equivalent litres of fuel needed to generate the same amount of energy from the other fuel sources as the wind pump was determined according to (E.ON Next Energy, 2023) as follows

$$Volume\ of\ Fuel\ (L) = \frac{E_r}{C_f \times 1.02264 \times 3.6 \times \eta_{ICE}} \quad (13)$$

where E_r is amount of energy from by the wind pump (kWh), C_f is the net calorific value of fuel (MJ/L), 1.02264 and 3.6 are temperature correction and kWh conversion factors respectively and η_{ICE} is the overall efficiency of the Internal Combustion Engine (ICE) considering its thermal and mechanical efficiencies. The amount of fuel required by an ICE to deliver useful shaft power depends on its overall efficiency, which increases with the rating (Ejieji & Olayaki-Luqman, 2013). Efficiency values of 25% and 40% were assumed for the estimation of fuel consumption of petrol and diesel engines respectively. Calorific values of 36.9 MJ/L and 33.7 MJ/L were assumed for diesel and petrol respectively (European Automobile Manufacturers' Association (ACEA)). Premix fuel as assumed to have the same calorific value as petrol.

The Levelized Cost of Energy (LCOE): There are many economic performance indicators used assess the cost and benefits energy systems. These include the Levelized Cost Of Energy (*LCOE*), Net Present Value (*NPV*) and simple discounted Payback Period (*PP*) (Gu et al., 2018). However, this study simply took only the *LCOE* into account. Considerations that must be taken into account when determining LCOE, include financing, operating costs, maintenance costs, taxes, and support. The generalized expression for an energy system's *LCOE* during its lifetime is provided as(Gu et al., 2018):

$$LCOE = \frac{Net\ Present\ value\ of\ cash\ flow}{Present\ value\ of\ energy} \quad (14)$$

$$LCOE = \frac{\sum_{t=0}^{n-1} PV_{CE}}{\sum_{t=0}^{n-1} PV_E} \quad (15)$$

$$PV_{CF} = \frac{C_t}{(1+r)^t} \quad (16)$$

$$PV_E = \frac{E_{an\ t}}{(1+r)^t} \quad (17)$$

where PV_{CF} is the present value of the cash flow, PV_E is the present value of the energy, E_{an_t}. is the annual energy from the system in year *t*, *n* is the economic life of the system, *r* is the discount rate and C_t is the total cost in USD ($) to the setup in year *t*. C_t could further be expressed as

$$C_t = I_t + L_t + M_t + Tx_t - Sp_t \quad (18)$$

where I_t is the total investment expenditure (including installation and transportation cost among others), L_t is the financial loan cost, M_t is total operation and maintenance cost, Tx_t is the total tax paid and Sp_t is the total support and incentives, all in the year *t*. For a self-financed project ($L_t = 0$), Sp_t and Tx_t assumed to be zero, equation (25) becomes

$$C_t = I_t + M_t - Sp_t \quad (19)$$

In assessing the *LCOE*, the following assumptions are made in this study:

a) Cost of supportive gadgets common to all water lifting systems are ignored in the analysis. This is because they will have equal effects on the *LCOE* determination. They include, cost of borehole or well, distribution pipe lines, water storage tanks, sprinklers, etc.
b) Whereas the life expectancy for a Poldaw wind pump is 20 years, that of the other fuel pumps is assumed to be 10 years. The project period is therefore taken to be 20 years, with diesel, petrol, premix and electric pumps replaced after 10 years.
c) It is assumed that the diesel, petrol and premix pumping machines employ centrifugal pumps with an efficiency of 75%, while the submersible electric powered pump has an efficiency of 90% (Joe Evans, 2012).
d) A discount rate of 11% is assumed based on the Government of Ghana 31-year borrowing rate (Finance, 2012) adjusted upwards to reflect non-government borrowing.

2.3 Data Sources

Wind data

Hourly averaged data for December 2012 to December 2013 at a height of 40 meters, for Anloga, a town in the Keta Municipality were used in the study. The data was sourced from the Energy Commission of Ghana. Details of the instrumentation used for data collection are summarized in Table 2. The raw data (obtained in 10-minute temporal resolution) were postprocessed with the Windographer software. Data from the two anemometers at each height were combined using the combine anemometers feature in the software. Missing data points were filled with synthesized data from anemometers mounted at 50 m and 60 m during the same period on the same mast.

Table 2 - Selected Details of Observational data and instrumentation.

Period	13 months (December 2012 - December 2013)
Data time step	10 minutes
Mast location	5.7861 °N and 0.9188 °E
Mast type	NRG 60m XHD
Measurement heights	40 m, 50 m, 60 m
Anemometer type	NRG #40C

Data on Cost of energy in Ghana.

The majority of Ghana's energy (grid power) comes from thermal sources, which rely on fossil fuels and have a significant impact on tariff determination (Volta River Authority, 2023). Additionally, as fuel is exchanged in foreign currencies on the global market, the cost of producing energy is impacted by exchange rates. Non-residential users include those who irrigate using electricity. The Public Utilities Regulatory Commission (PURC), an organization required by Ghanaian law to do this task, evaluates electricity pricing on a quarterly basis. Additionally, the Ghanaian petroleum downstream sector is governed by the National Petroleum Authority (NPA) [26] playing a key role in the determination of fuel prices at the pumps. Table 3 shows the cost of electricity, petrol and diesel in Ghana.

Table 3 - Average electricity tariffs for non-residential users and fuel costs as of 31/01/2023 (Goil Company Limited, 2023; National Petroleum Authority, 2023; Public Utilities Regulatory Commission Ghana, 2023).

Item	Unit cost (GH¢)	USD ($)
Average cost of electricity for non- residential users	1.33 /kWh	0.13 /kWh
Diesel	15.52 /L	1.55 /L
Petrol	13.6 /L	1.36 /L
Premix	5.85 /L	0.59 /L

*Average Exchange rate in January 2023: 1 US$ = 10.00 GHS (CEIC Data, 2023)

3 Results

3.1 Water requirement for shallot farmland.

For the study analysis, a farmland size of 1 ha (10,000 m^2) was assumed. The daily water needs of the standard grass crop (the reference crop evapotranspiration), for sub-humid climates with temperatures above 20 ^{o} C is averagely 7 mm/day, which is approximately the same for onions (C Brouwer, Prins, Kay, & Heibloem, 1988). Therefore, the daily water requirement for the shallot was taken to be 7 mm (2555 mm/year). A rainfall depth of 700 mm/annum means an additional 1855 mm/annum is required for an all-year shallot farming in the Keta municipality. The deficit translates into 50800 L/ha/day (i.e., ~5 L/m^2/day) of water using Equations 1&2. For reasons of sustainability during abstraction, well or borehole depth of 10 m or more shall be assumed as deep enough to meet the water needs. Table 4 summarizes this information.

Table 4 - Irrigation water requirement for shallot production in Keta.

Item	Quantity	Reference
Farm land size	1 ha or 10,000 m^2	Assumed
Required depth of water for shallot, $\boldsymbol{P_{water}}$	7mm/day or 2555mm/year	(C Brouwer et al., 1988)
Depth of rainwater, $\boldsymbol{R_{water}}$	700 mm/year	(Foloitse et al., 2017)
Depth for irrigation, $\boldsymbol{I_{water}}$	1855 mm/year	Equation (1)
Daily Quantity of irrigation water required	50.8 m^3/ha/day or 5 L/m^2/day	Equation (2)

3.2 Wind Resource and Technical Performance of the Poldaw wind pump.

On the basis of the analytical modules in the preceding part, the site wind characteristics and Weibull parameters are estimated. Table 5 shows that for heights of 4 m, 6 m, 8 m, 10 m, and 12 m, respectively, the yearly mean wind speeds are 3.53 m/s, 3.86 m/s, 4.12 m/s, 4.22 m/s, and 4.50 m/s. To roughly assess Ghana's potential for wind energy, the site's Weibull shape parameter of 2 is assumed, as was done in prior research.

Table 5 - Site wind speed characteristics and Weibull parameters at different heights (a.g.l).

Parameter	4 m	6 m	8 m	10 m	12 m
$\boldsymbol{v_m}$ (m/s)	3.53	3.86	4.12	4.22	4.5
$\boldsymbol{k}$	2.00	2.00	2.00	2.00	2.00
$\boldsymbol{c}$ (m/s)	3.98	4.35	4.64	4.87	5.07
$\boldsymbol{v_e}$ (m/s)	5.63	6.16	6.16	6.74	7.17
$\boldsymbol{v_f}$ (m/s)	2.82	3.08	3.28	3.45	3.58

As shown in Table 5, when height increases from 4 to 12 meters, the wind speed conveying the greatest energy rises from 5.63 to 7.17 meters per second. The relevance of v_e is that it is closely related to the intended or rated wind speed of a wind turbine, and the closer their values are, the better. Additionally, as the height a.g.l rises from 4 to 12 meters, it can be shown that the annual most probable wind speeds (v_f.) range from 2.82 to 3.58 meters per second. Figure 3 likewise displays this. The Poldaw wind pumps can be built at any of these heights because of their cut-in speeds, which range from 2.5 to 3 m/s. However, consideration of physical features of the wind pumps and further cost/benefit analysis may be required to arrive at a good installation decision. Figure 3 also shows that wind speeds above 10 m/s are very rare for hub heights at 12 m a.g.l and below in the Keta municipality.

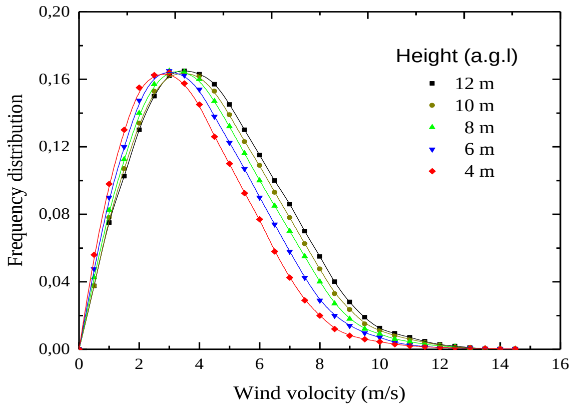

Fig. 3. The annual Weibull probability density frequency for wind speed at different heights a.g.l.

Figure 4 shows the performance of the available versions (1.8 m, 2.2 m, 3.5 m and 5.0 m) of Poldaw wind pumps installed at 10 m hub height (v_m= 4.22 m/s) and pump head of 10 m in the Keta municipality. These estimates are reached by assuming an overall (rotor, shaft and pump energy conversion) efficiency of 0.1 (Equation 19) and a consideration of water requirement for irrigation in the area as discussed in the previous section.

As could be seen from the graph, the quantity of water lifted by the 1.8 m, 2.2 m, 3.5 m and 5.0 m wind pumps are respectively 11,067 L/day, 16,533 L/day, 41,846 L/day and 85,399 L/day. Thus the 5.0 m version could lift 104%, 416% and 672% more water than the 3.5 m, 2.2 m and 1.8 m versions respectively. These figures compare favorably with existing technical data published in various documents (Agricultural Engineering Services Directorate (AESD), 2016) (NEALE Consulting Engineers, 2003). Figure 3 also shows that 1.8 m, 2.2 m, 3.5 m and 5.0 m wind pumps can respectively irrigate 0.22 ha/day, 0.33 ha/day, 0.84 ha/day and 1.70 ha/day.

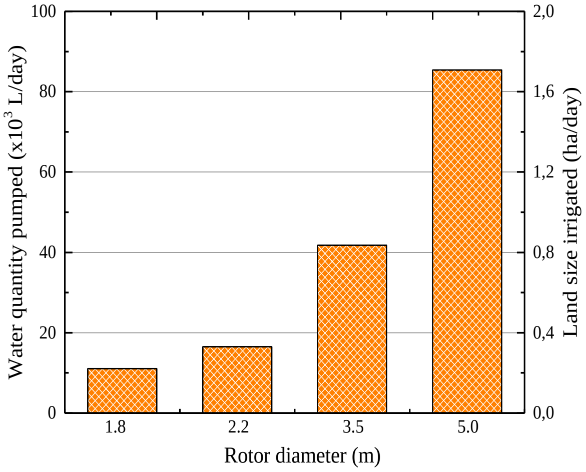

Fig. 4. Performance of Poldaw wind pumps at v_m= 4.22 showing estimated water quantities and farm size it could irrigate in Keta.

3.3 Power from wind pumps and quantity of fuel required to generate equivalent amount of power

The wind energy available to the rotor for conversion into mechanical energy is analyzed based on analytical modules in Section 2.2. The following assumptions are made; mean ρ_a=1.2 kg/m^3, C_r= 0.4 and η=1 in the absence of any load. Figure 5 shows the annual energy available for the pumping of water. It could be seen that the annual energy converted from the available wind energy by the 1.8 m, 2.2 m, 3.5 m and 5.0 m wind pumps are respectively 402.2 kWh, 600.8 kWh, 1520.6 kWh and 3103.3 kWh. Thus, these energies are available for the lifting of water. It could also be observed that the energy conversion profile shown in Figure 5 is not very different from what is displayed in Figure 4 for the estimated quantities of lifted water.

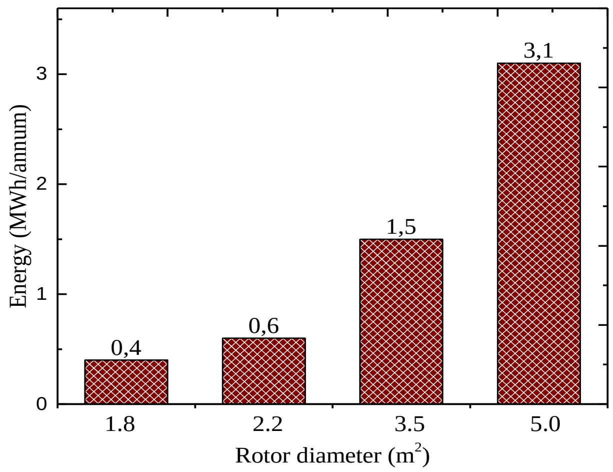

Fig. 5. Wind energy conversion by Poldaw wind pumps at 10 m hub height (v_m= 4.22 m/s) in the Keta municipality.

The volume of fuel an Internal Combustion Engine (ICE) will consume to deliver an amount of power equal to that of the wind pump is also determined with equation 20 and presented in Table 5.

3.4 Economic analysis

Table 6 lists the prices for the gasoline, premix, diesel, and electricity needed to provide energy gains comparable to those reported by the Poldaw wind pumps. Premix is the least expensive of the four energy sources, and then, in that order, diesel, gasoline, and electricity. Table 7 additionally includes other cost elements that were obtained for the study.

Table 6 - Energy and cost equivalence of the existing sources of energy for water pumping at Keta compared to estimated energy produced by the Poldaw wind pumps

Poldaw wind pump		**Equivalent Annual fuel/ electricity requirement**							
Rotor Diameter	**Energy kWh/yr**	**Petrol Liters/yr**	**US$/yr**	**Premix Liters/yr*[1]**	**US$/yr**	**Diesel Liters/yr**	**US$/yr**	**Electricity kWh/yr**	**US$/yr*[2]**
1.8 m	402.19	211	287.3	211.25	123.6	120	186.2	442	73.8
2.2 m	600.80	315	428.4	315.00	184.3	180	279.4	661	102.8
3.5 m	1520.63	795	1081.2	795.00	465.1	454	704.2	1,673	237.4
5.0 m	3103.33	1,621	2204.9	1,621.25	948.4	926	1437.5	3,414	468.9

*[1] The premix fuel is assumed to have the same colorific value as petrol

*[2] This includes the monthly service charge which comes to US$14.9 /annum

Table 7 - Prices of components and services.

Item	Unit Cost	M_t cost	Remarks (unit cost)
Poldaw D1.8	$ 1,352	$ 50 /annum	Market survey
Poldaw D2.2	$ 1,699	$ 50 /annum	Market survey
Poldaw D3.5	$ 2,852.	$ 60 /annum	Market survey
Poldaw D5.0	$ 3,920	$ 60 /annum	Market survey
Diesel water pumping machine	$ 103.0 /kWh	20 % of total cost/yr	Market survey
Petrol water pumping machine	$ 26.6 /kWh	20 % of total cost/yr	Market survey
Premix water pumping machine	$ 103.0 /kWh	20 % of total cost/yr	Assumed
Submersible pump for water	$ 232 /kWh	5% of total cost	Market survey
Grid power	$ 10 /kWh	5% of total cost/year	Assumed.
Installation Cost	10% of total cost	N.A	Assumed
Transportation/shipment cost	10% of total cost	N.A	Assumed

LCOE of Other Energy Sources.

Table 8 shows the *LCOEs* for the different sources of energy for water pumping in the Keta municipality as compared to the four models of the Poldaw wind pump that were considered in this study. It can be seen from the table that, can be seen from the table that, in contrast with the other energy sources, the *LCOE* for wind steadily decreases with increased rotor diameter of the Poldaw wind pump, and thus power generated, which should be expected as wind power increases with increasing rotor diameter. Thus, the 5.0 m Poldaw is the most economical of the Poldaw wind pumps analyzed in this study, and the 1.8 m rotor, the most expensive. Based on this, it can be seen that the 5.0 m Poldaw pump is better than the other energy sources (with the exception of grid electricity), an observation that is consistent with those of an analysis by the AEDS (Agricultural Engineering Services Directorate (AESD), 2016) . However, it should be noted that, per the results, the gains of grid electricity over the 5.0 m wind pump are quite marginal, and could be eroded with increasing electricity prices, and wind pumps mounted at increased heights with better wind speeds.

Table 8 - Comparison of the LCOEs of energy sources for irrigated shallot farming.

Windpump Rotor Diameter	**Wind LCOE** ($/kWh)	**Petrol LCOE** ($/kWh)	**Premix LCOE** ($/kWh)	**Diesel LCOE** ($/kWh)	**Grid LCOE** ($/kWh)
1.8 m	0.58	0.72	0.32	0.48	0.20
2.2 m	0.47	0.53	0.32	0.52	0.20
3.5 m	0.29	0.53	0.32	0.48	0.19
5.0 m	0.20	0.71	0.32	0.48	0.16

When analyzed at higher hub heights, where wind speeds are better, the LCOE of the 5.0 m Poldaw pumps reduces. Figure 6 shows the relation between hub height, wind speed, and the LCOEs of for the 5.0 m Poldaw Wind Pump and Grid electricity. As can be seen from the figure, when mounted at 12 m, the LCOE of the 5.0 m Poldaw Pump is on par with that of grid electricity, and it only continues to reduce with increasing hub heights. However, it should be noted that our analyses did not take into account the possible increased cost of installation at these heights.

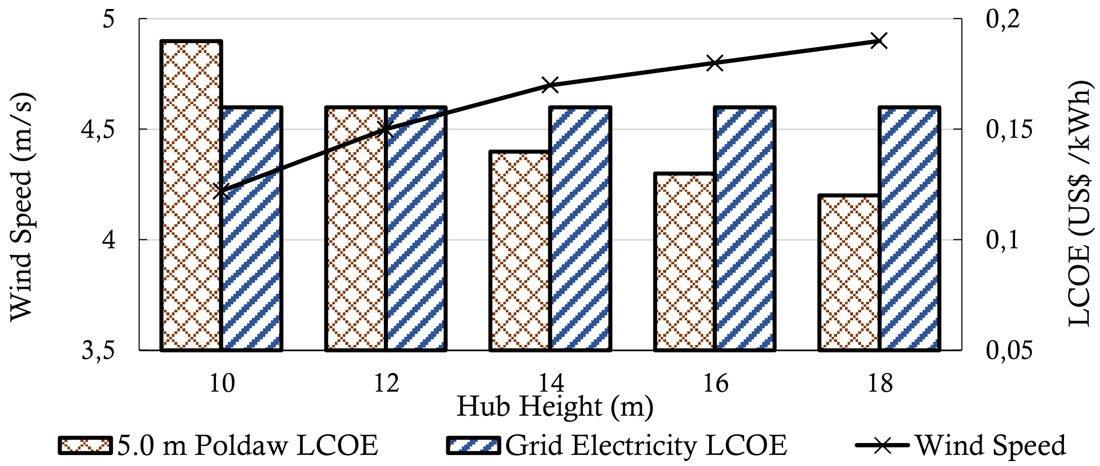

Fig. 6. Mean wind speed and LCOE of grid electricity and Wind energy at different turbine hub heights.

Owing to the location dependence of wind speeds, it was necessary to assess the generalizability of the findings of this study to the other locations in the municipality. Average wind speeds were deemed as the variable that can significantly influence the generalizability of the results in the municipality as all the other variables (at least for the economic analysis) can be assumed to be fairly constant throughout the municipality; prices of fuel (from the same retailer) and electricity prices do not vary throughout the country; prices of other components and labor were also assumed to be not significantly different throughout the municipality. For the technical performance, depth of wells vary between 1 ft – 9 ft in the municipality (Diaba et al., 2015). Therefore, the borehole depth of 10 m can be assumed as deep enough to meet the water needs (of a hectare of shallot farm) at any location in the municipality. Therefore, average wind speeds were the only variable that was used to judge the generalizability of the findings. The variation of the average wind speeds in the municipality was assessed with a wind speed map shown in the Figure 8. The map was generated with data and tools from earlier wind resources assessment studies in Ghana (Dzebre, 2019; Dzebre et al., 2021). It can be seen from the map that average wind speeds in the easter coastal areas of Ghana where the Keta municipality is located start from 3.7 m/s. Locations that are closer to the coast in the area tend to have average wind speeds above 4.2 m/s making them ideal locations for the use of Poldaw pumps. For areas further from the coast, the pumps will probably have to be mounted at higher heights in order for them to be viable. The map also shows that western coastal areas have average wind speeds around 3.0 m/s which might not be ideal for the use of the pumps.

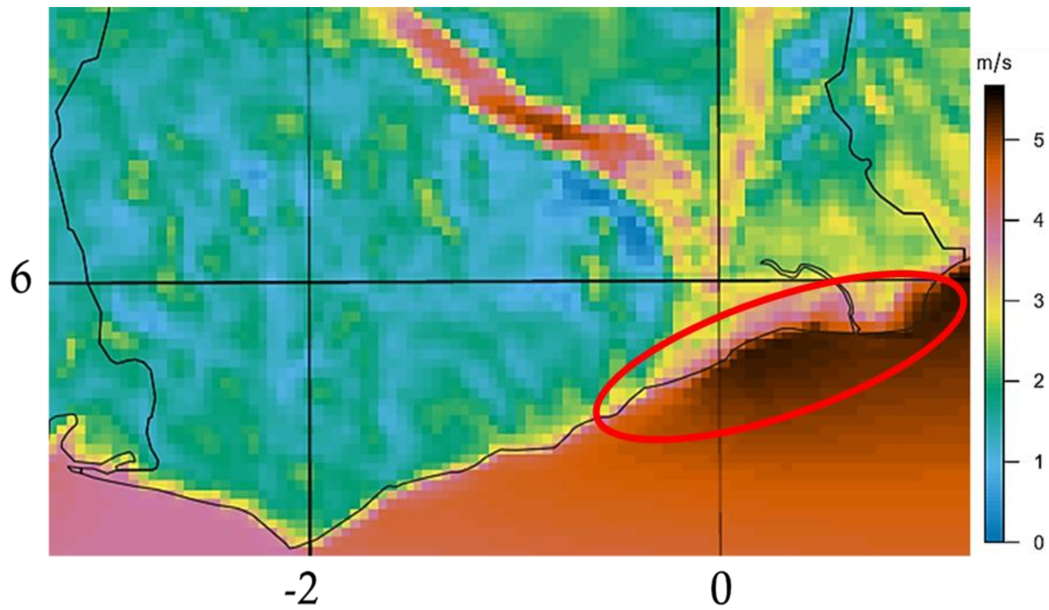

Fig. 7. Average wind speeds at 10 m

4. Discussion

This aim of this study was to assess the technical viability and cost of the Poldaw Mechanical wind pump for the cultivation of shallots, a popular crop that is produced via irrigated agriculture in the Keta Municipality in Ghana. It was found that when, when mounted at a hub height of 10 m, the 5.0 m model of the Poldaw pump, out of the 4 models assessed, meets and exceeds the daily water requirements for a hectare of shallot farmland (Figure 3). However, average wind speeds of around 4.2 m/s at 10 m hub height are required for this. In terms of cost, the 5.0 m model is again the least expensive of the 4 models analyzed, though it has the highest initial capital cost. In comparison with the other sources of energy that were analyzed in this study, energy from the 5.0 m Poldaw pump, when mounted at 10 m, provides the cheapest source of energy, with the exception of grid electricity. It is on par with grid electricity when mounted at 12 m, and cheaper when mounted at heights exceeding 12 m.

The findings of this study are largely in agreement with conclusions from several studies (Amar & Elamouri, 2014; Fang et al., 2023; Gopal, Mohanraj, Chandramohan, & Chandrasekar, 2013; Islam et al., 1995; Jayanthi & Ravisankar, 2005; Kamwamba-Mtethiwa et al., 2016; Lara, Merino, Pavez, & Tapia, 2011; Mbarek et al., 2023; Pam et al., 2013) that, wind powered pumps are technically and economically visible for irrigation purposes. However, the results show that average wind speeds of 4.22 m/s, higher than what has been suggested in some literature such as Amar and Elamouri (2014), are required for the wind pumps to be viable. This is lends credence to the conclusion of authors such as Ziter (2009) and Kamwamba-Mtethiwa et al. (2016) that studies such as this are needed better judge the feasibility of wind pumping systems in different localities. In addition, the results further emphasize the fact that, not only does performance depend on wind conditions, but also on the water requirements for the crops to be cultivate, thus justifying the need for crop specific studies such as those of Mbarek et al. (2023) on a wind powered irrigation system for growing tomatoes and strawberries in Tunisia. Furthermore, it is realized that viability also depends on the design of the pumps; a larger pump in this case was better than relatively smaller pumps of the same design. This is also in agreement with the findings of Kamwamba-Mtethiwa et al. (2016) in their review of wind pumping systems in Sub-Saharan Africa.

In the context of studies in Ghana, results validate the suggestions of Diaba et al (2015) that Mechanical wind pumps are economically more viable for irrigation, and the subsequent findings of the 5-year study by the Agricultural Engineering Services Directorate that, the 5.0 m Poldaw wind pump provides the cheapest source of energy compared to all the other versions of the Poldaw Pump. In addition, we find that in comparison to not just diesel, but also petrol and premix fuel, the Poldaw pump remains the cheapest option over its 20 years lifespan, even though it does not have any cost subsidies. Premix fuel for instance, is quite heavily subsidized in Ghana, enjoying up to 80% subsidies at some point within the last 5 years (Acheampong, 2022). The cost of electricity is also quite regulated. Therefore, the diminutive ($0.04/kWh) cost advantage of grid electricity on the Poldaw pump at 10 m height can easily be eroded with the introduction of subsidies on the wind pumps, which will make the wind energy for irrigation even more competitive with the other energy sources. It is also found that that the eastern coastal areas of Ghana, especially the Keta Municipality, which was the focus of this study, has good potential for wind powered irrigation development with the adoption of the Poldaw (and possibly other) wind pumps.

A potential challenge towards the adoption will be the initial cost of the wind pump may be extremely expensive for smallholder farmers. However, unlike to electric pumps or fossil fuel-powered pumps, the Poldaw wind pump has a lifespan of over 20 years. The purchase, installation, and repairs of water storage reservoirs, drip materials, and drilling boreholes are not limited to specific seasons or periods. Once these items are purchased and installed, they can be used for many years. In addition, a potential solution to the cost issue could be cooperatives of local farmers, with the option to acquire the windmill through individual donations, securing bank loans, or utilizing any other form of financial assistance provided by governmental or non-governmental entities. Furthermore, engaging the local community experts like metal fabricators, RE experts, Agriculture extension officers and farmers in the design and development of the systems can improve decision-making processes regarding the location, design and operation of the wind pumps, with cost saving possibilities. When the project is managed locally using local resources, the sustainability of the project can be enhanced and will encourage the adoption of the pumps, as in addition to the economic benefits through the cost reduction of irrigation in the municipality, there is also the potential to mitigate carbon emissions through the decrease in the usage of fossil fuels.

Further to the increased use of RE in irrigation, the integration of wind pumps with solar panels to create a hybrid system has been gaining increased attention recent times, and this gives way to the possibility of increased integration between wind pumps and other renewable energy sources. Such systems result in the development of hybrid systems capable of functioning even under low wind speeds, providing a more dependable water supply for irrigation purposes.

5. Summary and Conclusion

Ghana has a number of policies governing the energy sector. These include the Renewable Energy Master Plan (REMP), the Renewable Energy Act 2011, National Energy Strategy. National Energy Policy, Energy Sector Strategy and Development Plan, Sustainable Energy for All and Ghana Energy Development Access Project. In regards to wind energy for irrigation, the REMP outlines the challenges, some of which include, high capital costs, low efficiency, limited operation and maintenance skills, lack of spare parts availability and insufficient research and data on technical and economic performance. The plan suggests research and development in wind irrigation technology to promote wind irrigation systems. Among others it recommends that existing installations that were done previously under the Village Infrastructure project should be reviewed, studies should be conducted to identify potential implementation areas and niche markets, and local human resources and manufacturing firms should be trained to manufacture, install, operate and maintain the systems.

This study is in response to some these recommendations and was aimed at filling some of the gaps that have been identified in studies that have been conducted on wind powered irrigation in the Keta Municipality of Ghana. The municipality has the largest informal irrigation system in Ghana with an estimated total of 4000 hectare (ha) cultivated all year round (Ahiabor, 2014). Though some studies in the past (Agricultural Engineering Services Directorate (AESD), 2016) have examined the feasibility of wind powered pumping for irrigation in the Municipality, none of them have looked at wind in comparison to the other the energy sources that are employed for the purpose of lifting ground water in the municipality. In addition, none of them have examined the sensitivity of results to varying rotor diameters or hub heights of the wind pumps; factors that significantly impact the performance of wind power technology. Therefore, this study evaluated compared the Levelised Cost of Energy (LCOE) of common sources of energy (as identified by Adzraku (2017)) in addition to wind, for irrigation at Anloga in the Keta Municipality of Ghana.

From the results, it is concluded that, the Poldaw Mechanical wind pump is a good alternative to electricity, and fossil fuel powered pumps for irrigated shallot farming in the Municipality and surrounding areas in the southeastern parts of Ghana. Whereas the 5.0 m version of Poldaw Pump is the most viable of 4 models tested.

A key limitation of this study is that, the efficiency of the wind pumps was assumed to be constant over its operational lifetime, something that been observed to decrease with time (Tu, Mo, Liu, Gong, & Fan, 2021). However, in relation to the relative costs of the various energy sources, we do not think this should significantly affect the conclusions of this study; the efficiency of the other pumps was also assumed to be constant over the 20 years span considered in this study. However, we recommend this is looked into in future studies. Other metrics of economic assessments such as Payback Period should also be assessed in these studies. In addition, we recommend assessing the irrigation water needs, average wind speeds and well depths in other parts of Ghana to judge the applicability of the findings of this study nationwide. The AESD has manufactured versions of the Poldaw pump locally in the past. A performance assessment of these locally fabricated pumps to explore possible design changes that can reduce their fabrication and maintenance costs to encourage their adoption should be looked into. Finally, given the significant solar potential in Ghana, the integration of wind pumps with solar panels to create a hybrid system is warranted, going forward.

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