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Potential for using Solar-Powered Water Pumping Technology for Irrigating Sugarcane in Sri Lanka

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ABSTRACT

Purpose: *Price hike of petroleum and the non-coverage of national electricity supply in plantation sites are some shortcomings against implementing lift irrigation projects in highland sugarcane plantations. Solar energy can be used as an alternative energy source for diesel or national electricity dependent water pumping technology. The present paper demonstrates the potential of using solar-powered water pumping technology for irrigating sugarcane in Sevanagala, Pelwatta, Hingurana, Kantale, and Kilinochchi, in Sri Lanka.*

Research Method: *The study was conducted in Sevanagala, Pelwatta, Hingurana, Kantale, and Kilinochchi, sugarcane growing areas. Technical and economical evaluation was carried out to characterize the usability of solar powered water pumping technology respective to conventional furrow irrigation and drip irrigation under different water sources i.e., tube-wells, agro-wells, small water tanks, and runoff water harvesters. Solar irradiance ($W.m^{-2}$) and cloud cover (%) in each location were used to estimate the solar energy variations. NASA–MERRA-2 data set (GMAO, 2015) was used to derive solar irradiance for the period of 10 years from 2010 – 2019.*

Findings: *The solar irradiance and insolation in the sugarcane plantation sites are sufficient to operate solar-powered water pumping systems. The solar irradiance and insolation in study area ranged from 218.2 $kW.m^{-2}$ to 225.4 $kW.m^{-2}$ and 5.34 $kW.h.m^{-2}$ to 5.48 $kW.h.m^{-2}$ respectively. The solar technology will greatly reduce the operating costs of irrigation, despite the high initial costs. Kilinochchi and Kantale area showed the highest and lowest profitability in using solar powered irrigation respectively. Nevertheless, Sevanagala, Pelwatta and Hingurana show medium potential for implementing solar powered water pumping systems for irrigations.*

Research Limitation: *Limited availability of data on temporal changers of cost incurred on the irrigation practices and the fluctuation of market price of the solar powered water pumping systems were significant constraints experienced during the study period.*

Originality/ Value: *The results of this study are highly useful for decision makers in both plantation and national level in implementation of productivity improving programs in sugarcane plantation areas in Sri Lanka.*

Keywords: *Benefit cost ratio, Irrigation, Solar-power, Sugarcane, Water pumping*

INTRODUCTION

Supplementary irrigation is important to improve the current productivity levels of rain-fed sugarcane plantations in Sri Lanka (Wyseure *et al*., 1994). Runoff water harvesters, natural drainages,

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agro-wells, small tanks, and tube-wells available in some locations can be used as supplementary irrigation water sources (Wijayawardhana *et al*., 2013). Currently, some highland sugarcane famers use diesel and electric water pumps for irrigation. Price hike of petroleum and the non-coverage of national electricity supply in plantation sites are major shortcomings against implementing such irrigation projects. Solar energy can be used as an alternative energy source for the diesel or national electricity dependent water pumping technology (Mekhilef *et al*., 2013; Foster and Costa, 2014; Kumar *et al*., 2020). Studies in other areas of the world have shown that the photovoltaic system is the most suitable option among three popular energy types of diesel, electric grid connected, and the solar powered as it involves a low running cost (Foster and Costa, 2014; Korpale *et al*., 2016; Kumar *et al*., 2020). Due to vast increase in the technologies involved, solar irrigation systems have become an economically viable alternative to electric and diesel-powered water pumps in irrigation projects (Foster and Costa, 2014; Korpale *et al*, 2016; Aliyu *et al*., 2018). Unlike other photovoltaic applications, the irrigation pump usually runs during the day, does not use any backup batteries and can directly connected with the solar power system (Korpale *et al.*, 2016; Kumar *et al.*, 2020), thereby significantly reduces the entire cost of the irrigation system. However, the main technical drawback of the solar power system is the instability of the output power as changes in the irradiance level (Closas and Rap, 2017; Kumar *et al*, 2020) which caused mainly due to cloud cover (Korpale *et al.*, 2016; Dissawa *et al.*, 2019). Not only cloud cover, but the available solar irradiance varies during the time of the day, time of year, distance of sunlight travel across the air, atmospheric turbidity levels, land altitude, and nature of the terrain (Korpale *et al.,* 2016; Aliyu *et al*., 2018). As such, the solar irradiance and the available solar insolation in a given location change significantly throughout the year (Korpale *et al.*, 2016). On a sunny day at zero altitude, the solar irradiance on the equator is about 1000 W.m^2 (Barad *et al.*, 2017).

The gap between irrigated and rain-fed sugarcane yields at different locations in Sri Lanka shows different levels (De Silva, 2021), so the potential income from solar powered irrigation projects varies from one location to another. Nevertheless, the depth of the water table being changed spatially coursing the changes in energy requirement of the water pumping in different locations. As such, when planning a solar irrigation system, it is important to consider the inherent variability and economic benefits of solar irrigation systems (Boxwell, 2017; Aliyu *et al.*, 2018) in different locations, with special attention to the irradiance and solar insolation changes on temporal and special scales (Korpale *et al.*, 2016). Therefore, this study was conducted to determine the potential of solar pumping systems to irrigate sugarcane in different sugarcane growing areas in Sri Lanka, and to determine the economic feasibility of using solar irrigation systems under Sri Lankan conditions.

MATERIALS AND METHOD

Study Area

The study was conducted in *Sevanagala*, (latitudes 6 22'and longitudes 80 54'), *Pelwatta* (latitudes 6 43'and longitudes 81 12'), *Hingurana* (latitudes 7 13'and longitudes 81 12'), *Kantale* (latitudes 8 19'and longitudes, 81 02') and *Kilinochchi* (latitudes 9 25' and longitudes 80 20'). The study area is mainly located in the low country dry zone (Panabokke and Punyawardhana, 2010). Annual total rainfall varies from 1200 to 1900 mm (Shanmuganathan, 1990), and annual average temperature is about 28 °C. The dry periods spread from February to March and June to October (Wyseure *et al.*, 1994; Wijayawardhana *et al.*, 2014).

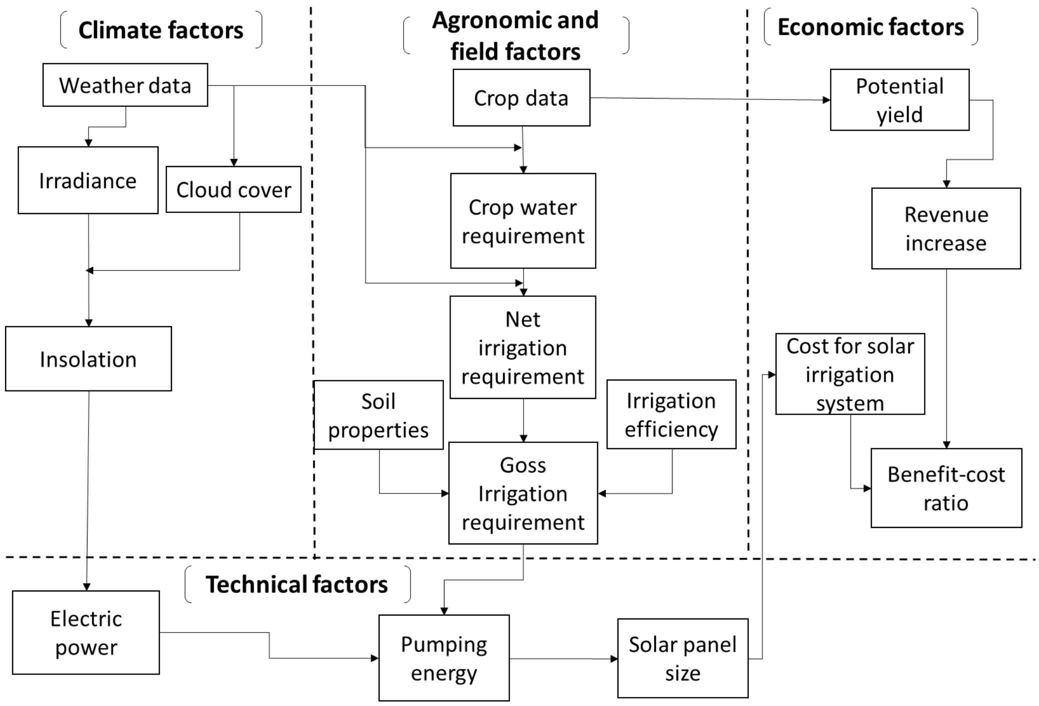

Figure 01: Conceptual framework of the modal

Conceptual Framework

The study was conceptualized aiming at evaluating of possible effects of local climate, water table depth, and efficiency of the irrigation method in different locations. Microsoft Excel based mathematical model was developed to perform the analysis. The conceptual framework used for the present analysis is shown in Fig. 01.

Data

Solar irradiance (W.m^{-2}) and cloud cover (%) for *Sevanagala*, *Pelwatta*, *Hingurana*, *Kantale* and *Kilinochchi* was taken from NASA–MERRA-2 data set (GMAO, 2015) for the period of 10 years from 2010 – 2019. The NASA dataset have been developed using satellite images (Putman and Suarez, 2011). The downloaded data set was verified by conducting goodness of fit test (Legates and McCabe, 1999; Eslamian, 2014) using actual data, which was recorded by the Campbell stokes sunshine recorders (Allen *et al.*, 1998) installed at the weather stations at *Sevanagala*, and *Pelwatta* sugarcane plantation site. Unfortunately, there is no such ground level data set for *Hingurana*, *Kantale,* and *Kilinochchi*. Index of agreement (d), root mean square error (RMSE) and percent bias (PB) were used as validation indices (Legates and McCabe, 1999; Marin *et al.*, 2011). R software was used for the calculations (Mauricio, 2020).

Solar Panel Energy Production

The main factor affecting the power generation of solar panels is the receiving solar insolation which dependent on the solar irradiance and the percentage of cloud cover (Allen *et al.*, 1998; Boxwell, 2017). The defused irradiance often increases under cloudy weathers (Korpale *et al.*, 2016). Solar insolation was computed by using Kasten and Czeplak model as given in the Equation 01 (Haegele, 2020).

$$Ig=Igc(1-0.75(n)^{3.4}) \quad [01]$$

where, Ig = Insolation (W.h.m^{-2}), I_{gc} = Irradiance (W.m^{-2}), and n = Cloud cover fraction which varied from 0 to 1 (GMAO, 2015).

Only a part of the solar energy, which was received by the top of the solar cell (panel) is converted into electrical energy (Kumar *et al.*, 2020). The energy conversion rate is given as the efficiency of the solar cell (Aliyu *et al.*, 2018), which depends on the semiconductor type. Solar cells are made up with monocrystalline, polycrystalline or amorphous-silicon semiconductor (Mekhilef *et al.*, 2013; Barad *et al.*, 2017; Boxwell, 2017). The conversion efficiency varies from 16% to 20%, depending on the type of semiconductor used (Mekhilef *et al.*, 2013). The power generation of a solar panel was estimated using Equation 02.

$$E = H \times W \times E_{Panel} \quad [02]$$

where, E = Daily electric generation (W.h), H = Daily insolation (W.h.m^{-2}), W = Panel area (m^2), E_{panel} = Efficiency of the panel (0.18).

Solar insolation usually reduces during the rainy season due to cloud cover (Allen *et al.*, 1998) (Boxwell, 2017). February to March and June to October are the dry seasons that have comparatively less could cover, and is the period irrigation practices are performed in sugarcane plantations in Sri Lanka (Wijayawardhana *et al.*, 2013). Based on the worst-case scenario (Boxwell, 2017; Siriwardena *et al.*, 2019), the lowest solar radiation value recorded during the dry period was chosen as the design parameter of H in Equation 02. Rainy seasons were omitted from the analysis (Foster and Costa, 2014).

Irrigation Depth and Area

The irrigation depth (gross irrigation requirement) of conventional furrow irrigation and drip irrigation was calculated by dividing the net irrigation requirement by the corresponding irrigation efficiency of furrow irrigation and drip irrigation as 60% and 90%, respectively. The net irrigation requirement for a single irrigation was computed using the Equation 03 (Wijayawardhana *et al.*, 2017).

$$NIR = \frac{(Mf - M50\%)}{100} \times BD \times D \quad [03]$$

where, NIR = Net irrigation requirement (m), Mf = Moisture content of soil at field capacity (w/w), $M50\%$ = Moisture content of soil at 50% moisture depletion level (w/w), BD = Bulk density of soil (Mg.m^3), D = Root zone depth (m).

Irrigation interval was calculated using Equation 04 (Meyer *et al.*, 2011).

$$T = \frac{NIR}{ET_{max}} \quad [04]$$

where, T = Irrigation interval (days) NIR = Net irrigation requirement (m), and ET_{max} = Maximum crop evapotranspiration (worst case scenario). The possible maximum evapotranspiration rate of sugarcane crop under Sri Lankan condition was previously estimated as 6 mm/day (Wyseure *et al.*, 1994; Wijayawardhana *et al.*, 2014).

Irrigation area was calculated based on Equation 05, assuming the irrigation period (days) equal to irrigation interval (days).

$$IA = \frac{A}{T} \quad [05]$$

where, IA = Irrigation area (m^2.day^{-2}), A = Land area (10,000 m^2), and T = Irrigation interval (days)

Pumping Capacity

Required pumping capacity was estimated as per the Equation 06.

$$W = GIR \times IA \quad [06]$$

where, W = Pumping capacity (m^3.day^{-1}), GIR = Gross irrigation requirement (m), and IA = Irrigation area (m^2.day^{-1}).

Energy Requirement for Water Pumping

The Figure 02 shows the hypothetical setup of the water pumping system. Pumping distance (l) is the distance from the water pump to the highest elevation point in the area (Aliyu *et al.*, 2018). h_1 and h_2 are delivery head and suction head of the water pump respectively. The design was completed for one hectare of sugarcane field.

As shown in Figure 02, the total head of the pumping system is calculated using Equation 07 (Holden and McGuire, 1998; Ali., 2011).

$$H=h_1+h_2+h_f \quad [07]$$

where, H = Total head (m), h_1 = Elevation difference (m), h_2 = Suction head, and h_f = Friction head loss which is a function of l (m) and the pumping discharge rate ($m^3.sec^{-1}$). The parameter h_f was determined as per the procedure given by (Holden and McGuire, 1998).

Required hydraulic energy was computed using the Equation 08 (Chandel *et al.*, 2015).

$$E_h=W\times\rho\times G\times H \quad [08]$$

where, E_h = Hydraulic energy, W= Volume of water which was determined by the Equation 06 (m^3), ρ = Water density (1000 $kg.m^{-3}$), G = Acceleration due to gravity, H = Total head (m)

Theoretically, the total energy that must be provided by the solar panel system should be equal to the hydraulic energy which was calculated according to Equation 08. However, in actual situations, water pumps and related electric wiring systems waste certain amount of energy (Kumar *et al.*, 2020). This loss must also be compensated by the solar panel system (Kumar *et al.*, 2020). Therefore, the total power supplied by the solar panel system was readjusted according to the efficiency of the water pump (70%) and electrical circuits (90%), respectively (Barad *et al.*, 2017).

Economic Evaluation

The economic evaluation was done based on the benefit cost analysis over the investment of the solar irrigation system. The analysis involves only the hardware cost comprising of solar panels, electric wirings and pumps (Foster and Costa, 2014). The prices of solar panels and water pumps are obtained through market surveys and internet markets prices prevailed during June to October 2020.

As there is a significant variation in the response of sugarcane to irrigation practices among different locations in Sri Lanka which leads to a variation in income in different rates (Kodituwakku *et al.*, 2014; De Silva, 2021), the financial benefit is calculated in each sugarcane plantation site according to Formula 09 (Kodituwakku *et al.*, 2013). Expected yield increases due to irrigation in *Sevanagala*, *Pelwatta*, *Hingurana*, *Kantale,* and *Kilinochchi,* were taken from annual reports of the Sugarcane Research Institute (2018) and De Silva *et al.* (2021).

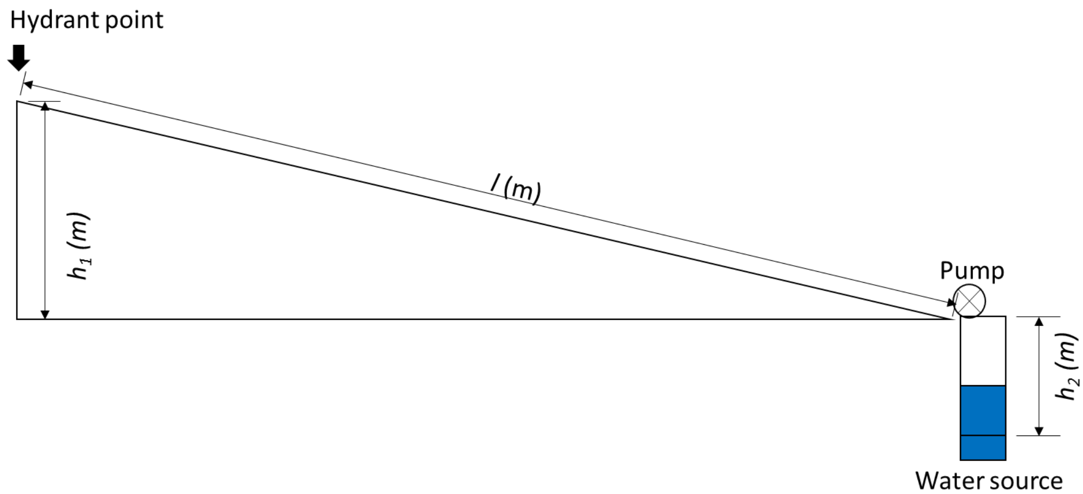

Figure 02: Hypothetical setup of the water pumping system

$F=(Y_{irri}-Y_{rf}) \times P$ [09]

where, F = Expected financial benefit due to irrigation (LKR/ha), Y_{irri} = Average yield of irrigated sugarcane in each location (ton.ha^{-1}), Y_{rf}= Average yield of rain-fed sugarcane in each location (ton.ha^{-1}), P = Selling price of sugarcane in year 2020 (LKR 5,500 per ton).

RESULTS AND DISCUSSION

Goodness of Fit Test

The Figure 03 shows the scatter plot diagrams and statistics of the goodness of fit test conducted between satellite-based irradiance data (model data) and actual irradiance data (observed data) recorded in *Sevanagala* and *Pelwatta* plantation sites. The conducted goodness of fit test clearly showed that the satellite-based irradiance data, used for this evaluation was accurately well. The calculated index of agreement (d), root mean square error (RMSE) and the percent bias (PB) between actual data and satellite-based data have clearly shown an ensured agreement between two data sets (Legates and McCabe, 1999; Xystrakis and Matzarakis, 2011). This shows that it is very reasonable to use satellite-based solar radiation data for non-gauge areas such as *Hingurana*, *Kantale,* and *Kilinochchi*.

Solar Irradiance and Insolation

Average daily solar irradiance (kW.m^{-2}) and insolation (kW.h.m^{-2}) in each month in *Sevanagala, Pelwatta, Hingurana*, *Kantale,* and *Kilinochchi,* is shown in the Table 01 and Fig. 04. Annual average irradiance was ranged from 218.2 kW.m^{-2} to 225.4 kW.m^{-2}. The minimum irradiance was recorded during the month of November in all the locations which varied from 193.3 kW.m^{-2} to 198.6 kW.m^{-2}. Nevertheless, the minimum insolation was recorded in the month of November in all the locations ranging from 4.6 kW.h.m^{-2} to 4.8 kW.h.m^{-2} (Figure 04).

However, minimum solar insolation levels during the dry spell (insolation values which used in this model) were 5.34 kW.h.m^{-2}, 5.42 kW.h.m^{-2}, 5.41 kW.h.m^{-2}, 5.48 kW.h.m^{-2}, and 5.40 kW.h.m^{-2} in *Sevanagala, Pelwatta, Hingurana, Kantale,* and *Kilinochchi,* respectively (Table 01).

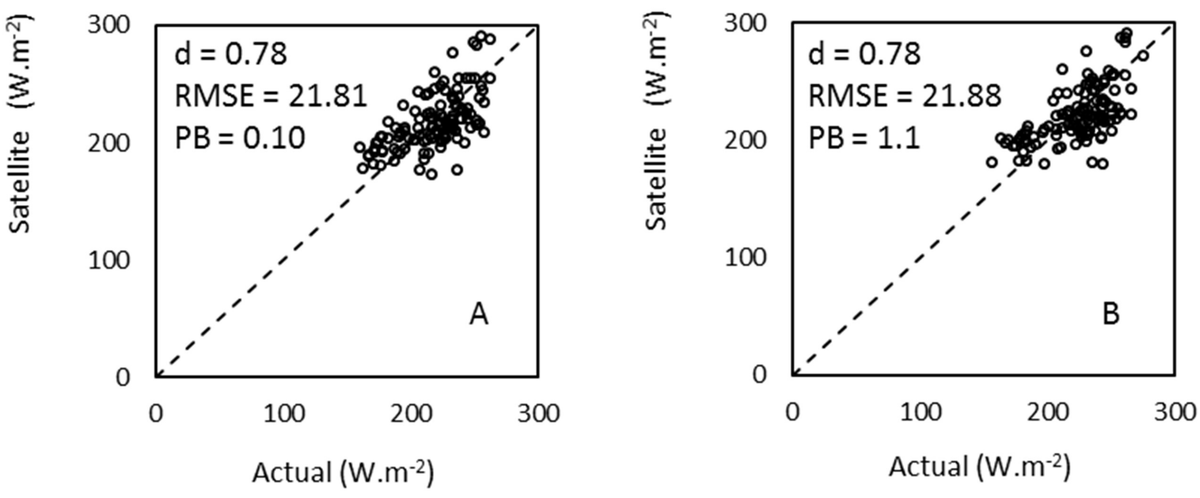

Figure 03: Index of agreement (d), Root mean square error (RMSE) and percent bias (PB) between the satellite based and actual solar irradiance (W.m^{-2}) in Sevanagala (A) and Pelwatta (B)

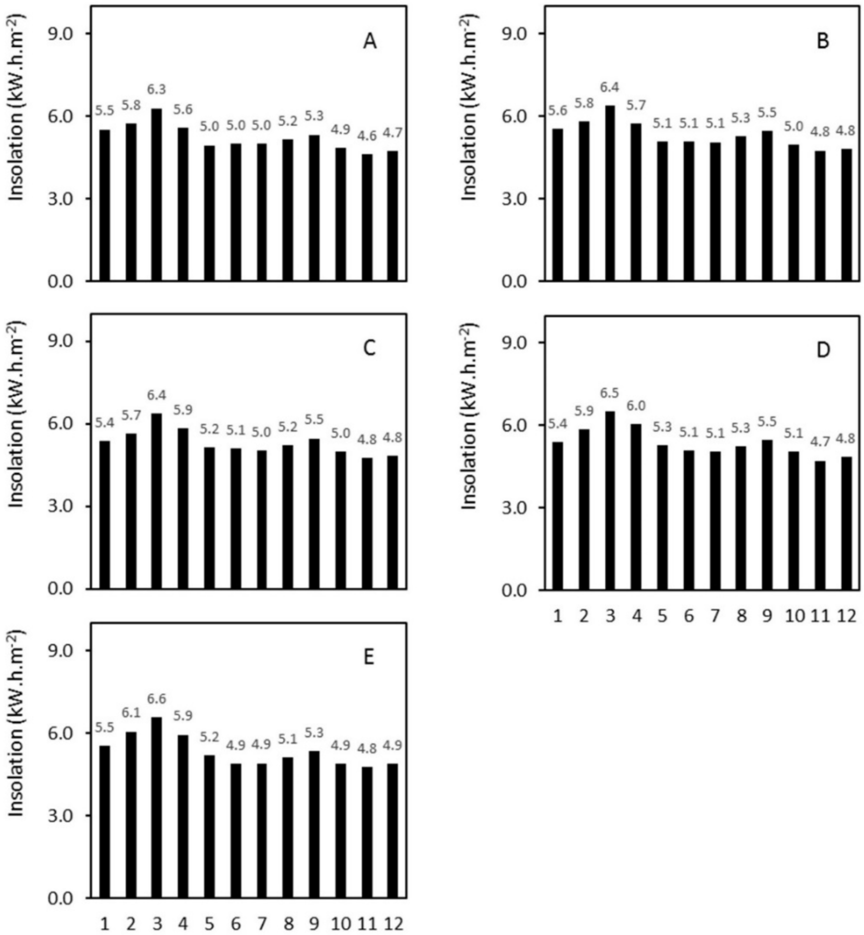

Figure 04: **Average daily solar insolation (kW.h. m^{-2}) in Sevanagala (A), Pelwatta (B), Hingurana (C), Kantale (D), and Kilinochchi (E): 1 – 12 in Figure 4-A-E are months from January to December**

Table 01: **Variation of daily irradiance, insolation and solar panel electric power generation rates in Sevanagala, Pelwatta, Hingurana, Kantale, and Kilinochchi.**

Location	Irradiance (annual daily average) kW.m^{-2}	Irradiance (daily average during dry spell) kW.m^{-2}	Solar insolation during dry spell kW.h.m^{-2}	Solar panel power generation rate during dry spell kW.h.m^{-2}
Sevanagala	218.2±4.6	222.7±5.0	5.34±0.13	0.97±0.03
Pelwatta	222.3±4.5	226.6±4.9	5.42±0.11	0.98±0.05
Hingurana	225.4±4.3	226.0±4.3	5.41±0.11	0.97±0.05
Kantale	224.5±4.3	228.2±4.0	5.48±0.10	0.99±0.06
Kiloinochchi	222.7±3.8	225.0±3.6	5.40±0.10	0.97±0.07

Size of the Solar Array

Table 02 shows the solar panel requirement (m^2) as per the depth of the water table and efficiency of the irrigation method. It clearly showed that the required solar panel array size (m^2) is highly varied with the depth of the water table by means of water source type, while slightly varied as per the efficiency of irrigation method in all the locations. *Kilinochchi* area requires lesser solar panel requirement while *Kantale* and *Hingurana* require the highest. In average, solar panel array size required for water pumping from an agro-well was 70% lesser than that of the deep tube-well. It leads to dramatically reduce the cost of investment for the solar power pumping system often by similar fraction. Usually, drip irrigation consumes lesser water due to its high irrigation efficiency, thus the drip irrigation system can be operated with smaller solar panel arrays respective to conventional furrow irrigation in all locations. Conventional furrow irrigation has nearly 60% efficiency while drip irrigation has 90% irrigation efficiency (Wijayawardhana *et al.*, 2014).

Benefit – Cost Ratio

Table 03 shows the variation of cost of solar powered water pumping system and corresponding benefit cost ratio for both tube-well and agro-well under furrow irrigation and drip irrigation condition in *Sevanagala*, *Pelwatta*, *Hingurana*, *Kantale,* and *Kilinochchi*. Accordingly, 648,000 LKR to 730, 000 LKR initial investment (per hectare) is needed for the installation of a solar powered water pumping system to be fixed to operate with a tube-well under conventional furrow irrigation method. Depth of the water table of the well positively correlates with the energy need for lifting of water and thereby increasing of cost for solar powered water pumping system (Table 02 and 03). Consequently, shallow water sources such as agro-wells or localized internal tanks are required only 290,000 LKR to 345,000 LKR initial investment for the installation of a similar solar powered water pumping system. This finding coincides with the findings reported by Almeida *et al*., (2019). Average tube-well water table depths were 52.0m, 52.5m, 56.4m, 59.0m, and 40.7m in *Sevanagala, Pelwatta, Hingurana, Kantale,* and *Kilinochchi,* respectively.

The average benefit cost ratios under tube-well were 1.8, 1.4, 1.7, 1.3 and 4.0 in *Sevanagala, Pelwatta, Hingurana*, *Kantale*, and *Kilinochchi,* respectively. If the irrigation method changed in to high-efficient drip irrigation system, the benefit cost ratio was increased by 20% in average compared to furrow irrigation. *Pelwatta* and *Kantale* areas show the lowest benefit cost ratio for a tube-well system. The highest benefit cost ratio for any combination of irrigation method shows in *Kilinochchi* due to shallow ground water levels interacted with the highest yield increment, indicating the highest potential area for implementing solar powered water pumping projects for irrigating sugarcane. It is clear that, the *Kantale* area recorded the lowest benefit cost ratio, showing the lowest potential area for implementing of solar powered water pumping projects.

Table 02: Solar panel size (m²) for conventional furrow irrigation and drip irrigation method as per the water sources type.

Location	Solar panel size (m²)			
	Conventional furrow irrigation		Drip irrigation	
	Tube well	Agro well	Tube well	Agro well
Sevanagala	30	09	20	06
Pelwatta	30	09	20	06
Hingurana	32	09	21	06
Kantale	32	09	22	07
Kilinochchi	25	09	17	06
Average	29.8	09	20	6.2

Table 03: Variation of cost of solar powered water pumping system, expected annual revenue and the benefit cost ratio (B/C) in tube-well and agro-well under furrow irrigation and drip irrigation condition in Sevanagala, Pelwatta, Hingurana, Kantale, and Kilinochchi.

Irrigation method	Total initial cost (LKR/ha)	Cost /ha / year (LKR)	Revenue (LKR/ha/ year)	B/C ratio
Furrow irrigation		Tube well		
Sevanagala	729,990	65,699	100,000	1.52
Pelwatta	729,990	65,699	80,000	1.22
Hingurana	766,656	68,999	100,000	1.45
Kantale	766,656	68,999	80,000	1.16
Kilinochchi	638,325	57,449	200,000	3.48
Drip irrigation				
Sevanagala	546,660	49,199	100,000	2.03
Pelwatta	546,660	49,199	80,000	1.63
Hingurana	564,993	50,849	100,000	1.97
Kantale	583,326	52,499	80,000	1.52
Kilinochchi	491,661	44,249	200,000	4.52
Furrow irrigation		Agro-well		
Sevanagala	344,997	31,049	100,000	3.22
Pelwatta	344,997	31,049	80,000	2.58
Hingurana	344,997	31,049	100,000	3.22
Kantale	344,997	31,049	80,000	2.58
Kilinochchi	344,997	31,049	200,000	6.44
Drip irrigation				
Sevanagala	289,998	26,099	100,000	3.83
Pelwatta	289,998	26,099	80,000	3.07
Hingurana	289,998	26,099	100,000	3.83
Kantale	289,998	26,099	80,000	3.07
Kilinochchi	289,998	26,099	200,000	7.66

Notes: The calculations were done using the market prices in the year 2020.

Since the benefit cost analysis conducted was merely based on the prevailing market price of solar pumping systems in 2020, for a 10 years' useful life, and hypothetical sugarcane farmland, having 65m water delivery distance and 10 m elevation difference (Fig. 02), the actual cost of the solar irrigated water pumping system in a given location may slightly vary according to the land geometry and exact elevation deference from water source to pumping location. Many studies have indicated that the use of solar powered water pumping for deep well and high elevated area are not economically and strategically important (Closas and Rap, 2017). However, the solar panel efficiency can be increased nearly by 17% with the use of of axis tracking system, but the total cost of the system increases by 19% in average (Aliyu *et al.*, 2018).

CONCLUSION

The results of the analysis clearly noticed that the solar powered water pumping for sugarcane irrigation has a great potential in Sri Lanka. The findings can be used as a theoretical guidance when designing similar kind of lift irrigation projects with the latest and efficient irrigation technologies. Use of tube-wells for irrigating sugarcane with solar powered system may not economically feasible since it comprises of higher cost and lower benefit cost ratio compared to agro-well or other shallow water sources.

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Conflicts of interest

Authors don't have any conflict of interest with the content of this paper.

Declaration

Authors declare that the work described in this manuscript has not been published before.

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