Innovative Solar Photovoltaic Solutions for Water-Efficient Irrigation: A Comprehensive Algorithmic Approach

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***Abstract*—This study presents a pioneering integrated comprehensive model for photovoltaic solar pumping irrigation systems, addressing critical challenges prevalent in Egypt and other developing countries. These challenges primarily revolve around the scarcity of fossil fuels and the imperative need for optimizing renewable energy usage in agriculture, as well as rectifying irrigation inefficiencies in both established and emerging agricultural areas, where flood irrigation remains a predominant but resource-intensive practice. Our proposed model synthesizes principles from agricultural science, irrigation science, and photovoltaic solar engineering. To demonstrate its efficacy, we conducted a comprehensive case study in Egypt. The results underscore the transformative potential of our approach, revealing a substantial reduction in water consumption, approximately 30% lower than that of conventional flood irrigation methods in regions, such as the Nile delta and Nile valley. However, our findings also illuminate the inherent dependence of the proposed system on photovoltaic technology, which may entail certain limitations, particularly in areas characterized by inconsistent sunlight availability. As such, this study offers a holistic assessment of the proposed system's feasibility by juxtaposing its cost-effectiveness, in the context of the Egyptian case study, against the alternative of desalinating an equivalent volume of seawater. The analysis reveals considerable cost savings of up to 1.865 billion USD and a monumental conservation of 14.025 billion cubic meters of precious irrigation water resources, reinforcing the viability of our proposed system. In addition to these insights, our research presents a versatile modular simulator, empowering PV solar engineers to tailor water pumping systems for diverse land types. This multidisciplinary framework amalgamates PV solar, electronic, irrigation, and agricultural engineering models, offering engineers optimized solutions to achieve the pinnacle of solar pumping irrigation system design. In summation, this study bridges critical gaps in sustainable agriculture and renewable energy utilization, providing a robust solution for water-efficient irrigation practices while mitigating the pressing concerns of fossil fuel depletion and environmental conservation in Egypt and analogous regions.**

I. INTRODUCTION

Any reclaimed lands need irrigation system and estimation of prevailing crop water requirements to design water irrigation pumping system. Pumping system needs to be powered, the source of power must be consistent and reliable. Due to global fuel crises and raising fuel cost, the photovoltaic solar system as a source of power is considered very feasible. The region which is chosen for this research is in Ashmon- Monofya- delta of Nile river. Solar engineers need to use a lot of tools to estimate the pumped water needed for irrigation for any specific geographical location. The purpose of this proposal is to present a detailed tool, which depends on algorithm (with its equations) to size the solar pumping irrigation system. The simulator must run accurately in working conditions around the year (different insolation and different needs of the crops during the development of the farm green canopy). There are many models to estimate the plant water requirements. The Blaney–Criddle equation [1] is one of the popular methods to estimate evapotranspiration of the plant to determine the needed water during the different stages of development. Although it is recommended to use in periods not less than one month to be rational. The dependency of crop yield coefficient on water, soil type, and timing is explained as depicted by [2].in this work we will adopt the Penman-Monteith variation method [3]. It is recommended by the Food and Agriculture Organization [4]. and the American Society of Civil Engineers [5]. This model will determine the water requirements of the crop pattern we choose according to environmental and geographical location of Egypt. [6] and [7] discussed the Agroclimatic zones of Egypt and the prevailing crop patterns in each zone in great details. The crop combination had been chosen according to those patterns with balanced water consumption for the whole season. After estimation of irrigation water requirements of the crops, the amount of water must be pumped in different season will determine the size and hours power of the pump. The pump will be affected by its turn by the irrigation system and total dynamic head opposing the pumped water. The irrigation system must obtain good efficiency to save amount of water needed from the crops. This strategy will save both energy and water and it will be translated into money savings. A suggested irrigation system is employed here to overcome deep percolation and run off problems. It depends on raising conveyance efficiency and to raise the water transportation rate to targeted sector of the land. this will raise irrigation efficiency by flood irrigation widely used in Nile delta lands. Once the pumping power is determined the second stage or layer of analysis begins to determine the working region of the pump and to build a model of the pump considering efficiency of the pump versus different power levels. [8], National Renewable Energy Laboratory (NREL) pump model is analyzed and modified to more accurate Model. After pump power is determined the photovoltaic generated must be designed and simulated for a whole one year. This will allow us to estimate the injected power to the solar pumping irrigation system hourly basis. In that way the irrigation water sufficiency will be determined and feedback of the system will be considered to modify the design to cover any excess water needed for the cultivated land. In this study land of area 20 feddan will be a case of application. The needed water and all aspects of system design will be discussed in details. Two questions will be answered, first question will be: is the solar pumping system will be enough without storing any irrigation water, or must it be hybrid system or solar system with water storage backup. the second question is: are solar irradiance free data available on the web site like (Photovoltaic Geographical Information System of European Union -typical meteorological data TMY) will be accurate enough for solar engineers to be used for system design. And what tolerance will be compared to paid simulators and design applications.

II. Material and Methods

In order to design solar PV pumping irrigation system, we need accurately to determine the water requirements of crops which is cultivated each season. The crop pattern suitable for each region in Egypt depends on the location and weather of this location through the year. [6] had divided Egypt to 5 Evapotranspiration regions according to averages of 10, 20, and 30 years study of evapotranspiration ET_0 data for all lands in the country.

The average of ET_0 and least significant difference method

along with ET_0 for 30 years data determine best fitting zones classification ET_0 as shown in Fig. 1 The specific zone (Ashmon-Monofya) in which the study will be applied shown on google maps Fig. 2 The main tool will be used to analyze Irrigation schedules under various management conditions, and scheme water supply is CROPWAT platform (software developed by FAO). It uses Penman-Monteith method for calculating reference crop evapotranspiration which is used by its turn to calculate water requirements for each crop in decade period of time (each decade =10 days). Fig. 3 shows water losses in the canals. reference evapotranspiration [mm /day] ET_0 could be calculated using equation (1).

$$\begin{aligned} ET_0 = 0.408\Delta(R_n - G) \\ + \gamma\left[\frac{900}{T+273}\right]u_2\frac{(es-ea)}{\Delta} \\ + \gamma(1+0.34u_2) \end{aligned} \qquad (1)$$

Where,
ET_0: reference evapotranspiration [mm /day].
R_n: net radiation at the crop surface [MJ / m^2.day].
G: soil heat flux density [MJ / m^2.day].
T: mean daily air temperature at 2 m height [°C].
u_2: wind speed at 2 m height [m /s].
e_s: saturation vapor pressure [kPa].
e_s: actual vapor pressure [kPa].
$e_s - e_a$: saturation vapor pressure deficit [kPa].

Water application to the field is not totally efficient. Losses due to transporting water and irrigation method of the crops take place and waste big amount of water according to many factors.

TABLE I. Efficiency of the conveyance for different type of canals and lengths

Irrigation methods	Field application efficiency
Surface irrigation (border, furrow, basin)	**60%**
Sprinkler irrigation	**75%**
Drip irrigation	**90%**

Table I shows Efficiency of the conveyance for different type of canals and lengths. And Table II shows the field application efficiency of the different soil types. crop evapotranspiration ET_c is determined by multiplying ET_0 by crop coefficient k_c [9].

TABLE II. Indicative values of the field application efficiency (EA)

	Earthen canals			**Lined canals**
Soil type	**Sand**	**Loam**	**Clay**	
Canal length				
Long (> 2000m)	**60%**	**70%**	**80%**	**95%**
Medium (200-2000m)	**70%**	**75%**	**85%**	**95%**

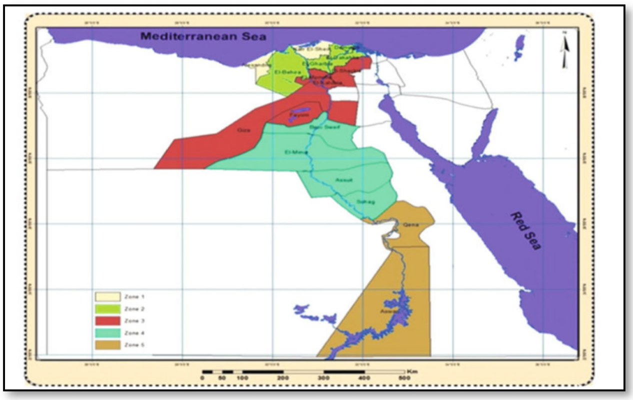


Fig. 1. Map of agroclimatic zones of Egypt using 10-year of ETo values

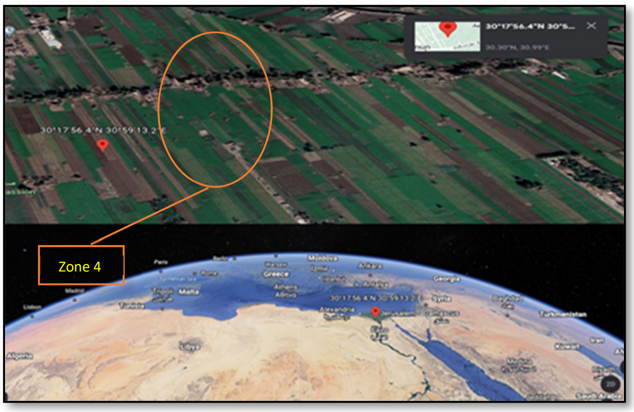


Fig. 2. The 4th agroclimatic zone

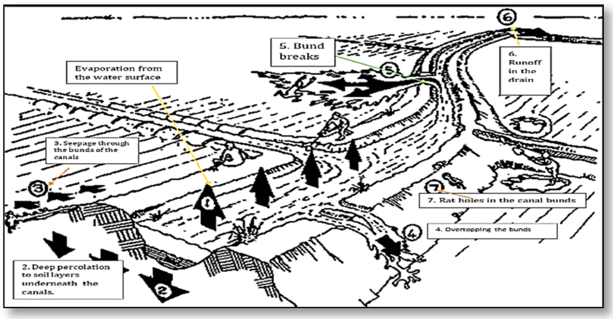


Fig. 3. Irrigation water losses in canals

To calculate the irrigation water which is used efficiently the following equation is used:

$$e = \frac{e_c \, x \, e_a}{100} \qquad (2)$$

(e) can be calculated, using the above formula

Where, e – scheme irrigation efficiency (%) e_c – conveyance efficiency (%), e_a – field application efficiency (%). A scheme irrigation efficiency of 50-60% is good; 40% is reasonable, while a scheme Irrigation efficiency of 20-30% is poor.to determine the useful water goes to the crops, a new term called crop evapotranspiration is calculated ET_c which is resulted from reference evapotranspiration multiplied by crop coefficient k_c. Where ET_c could be calculated as following formula:

$$ET_c = k_c \, x \, ET_0. \quad \ldots\ldots\ldots (3)$$

An indicative irrigation schedules could be designed using CROPWAT platform to determine the crop requirement of water in each stage of development. Fig. 4 shows soya bean irrigation schedule fixed interval (10 days) method.

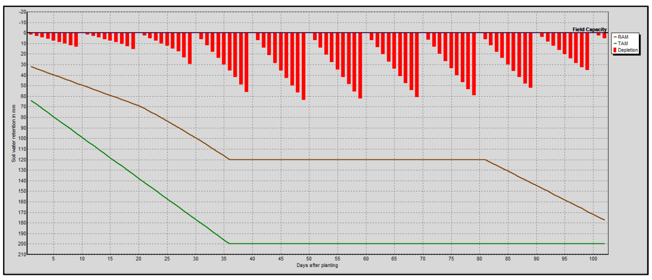


Fig. 4. soya bean irrigation schedule fixed interval (10 days) method

A. Cropwat and Climwat simulation for prevailing crops in 4th agroclimatic zone

Climwat is a weather program contains data from 20 weather station which are located in Egypt. Applying the FAO model (Penman-Monteith method) by using Cropwat program and Climwat application to investigate the cropping pattern irrigation water requirement according to the evapotranspiration of the crops. long term climatic data base of local weather stations near the location "Ashmon" will be used. The case study farm is targeted in this location. The solar water pumping irrigation system will be designed for this location. If drip irrigation along with High density poly Ethelene pipes are used the scheme irrigation efficiency will be:

$$e = .95 \text{ x } .9 = .855 \qquad (3)$$

i.e. around 85 % efficiency of water used will be useful for the crops. Each type of irrigation will affect this efficiency and accordingly the water consumption of the same area of planted land [10]. Although the calculated requirements from the FAO software application should be calibrated due to severe changes in climatic zones all over the globe [11].

Table III shows solar water pumping system irrigation water per decade per feddan (in cubic meter) needed for the crops and validated using results from Taha [11].

TABLE III. SWPS IRRIGATION WATER PER DECADE PER FEDDAN m^3

Crop	Validated irrigation requirements in cubic meter per feddan Whole season	Amount of water in cubic meter per decade per feddan
Wheat	1808.226	113.0141
Faba bean	1657.908	103.6193
Clover	2643.774	146.8763
Onion	3125.682	164.5096
Tomato	1609.272	100.5795
Potato	954.912	95.4912
Sugar beet	2550.954	134.2607
Cotton	3669.456	203.8587
Maize	2639.364	219.947
Soybean	2617.272	237.9338
Sunflower	2343.138	234.3138
Potato	2091.138	174.2615
Tomato	3001.908	230.916
Citrus	7104.636	197.351
Grape	4403.364	122.3157

B. Case study 20 feddan farm in Ashmon (Monofya- Nile delta- Egypt) water needs analysis

A farm land of 20 feddan which is old Nile Delta land (Clay black land) is considered to be equipped with solar photovoltaic pumping irrigation system. the estimated water requirement and crop pattern is the first step to correctly design this system. Fig. 5 shows the suggested crop pattern according to recommendation of [9], and [6]. also, careful consideration was taken to balance the amount of water for crop combination pattern in each season. Fig. 5 shows crop pattern for targeted region. The water requirements were rechecked with the results from [12] and a very good match with results was found. PV solar pumping irrigation system had widely been used in Egypt, [22] in her article states that it saves more than 30 % cost less than diesel generator pumping system cost considering 10 feddan irrigation system of nominal power of 7 kwp and life time cycle of 20 years for pv solar system and 10 years for diesel pumping system.

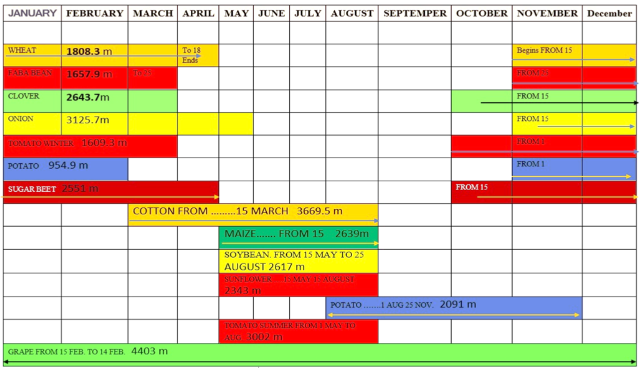


Fig. 5. crops pattern combination with balanced water needs calculated for all seasons

C. Water requirements and Novel irrigation design proposed

As calculated in previous paragraph the net irrigation water and gross irrigation water required is accurately determined. In this paper a 20 feddan cultivated with summer Tomato will be considered. A novel irrigation technique is proposed here instead of flood irrigation. The model is to raise the field efficiency and get same effect and efficiency similar to surge irrigation. According to results from research articles / papers [13] [14], [4], the main purpose of surge irrigation is to reduce water required for irrigation by cut off 2 phenomenon: run off water, and deep percolation. The main procedure used to do that is controlling the speed of water and amount of water during irrigation. The water is let to flow through half the furrow then stopped and transferred to another part of the field, this process seals the soil and make flow faster and leakage less. This technique according to above articles saves 30 to 52% of flood irrigation size. with the same principle the proposed irrigation system will apply water to basins of lands. The area of each them is one kirat, which is 175 m^2 (the feddan is 24 kirat and equals 4200 m^2). to rapidly apply the water and control the flow rate, a high-density poly Ethelyn pipes of 5’’ are used as main irrigation line. sub irrigation lines of only 4 inches. the end lines are controlled by valves. The number of valves opened each time simultaneously will control the pressure and speed of irrigation flow. experimentally timing and quantity will determine the exact period of time to apply water to several basins. using this technique will cut off the deep percolation and reduce run off problem. The feasibility study for these irrigation lines is calculated, it will not exceed 0.3 % of the land value (the asset). On the other hand, the cost of water desalination to equalize same amount of saved irrigation water will be very high. According to [15], the real cost of water production is not less than 51₵$ up to 59 ₵$. Fig. 6 shows the main pipe line layout and sublines to each kirat in the land to control irrigation scheme and surge irrigate each kirat with reduced amount of water. The final field irrigation efficiency will reach from 85% to 90 % according to the nature of old land in Nile delta. considering winter Tomato and Maize respectively with water needs every decade of 150 and 318 m^3 / decade. If applying water savings of 32 % as minimum to the irrigation scheme, water needs for the crops per decade will be reduced to be 102 and 216.2 m^3/ decade per one feddan. Water amount saved per season for both crops will be 1360 m^3 for one feddan and for 20 Feddan 27191 m^3.

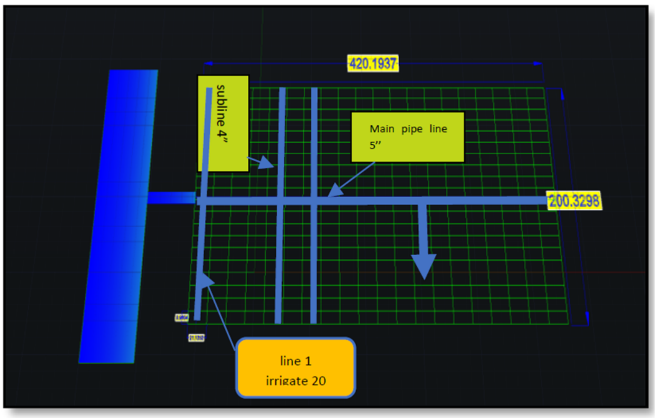


Fig. 6. Irrigation System schematic for 20 Feddan land

D. water requirements after calculations in summer and winter season.

1) Total water needs per 10 days for 2 feddan = (Tomato)102 x 2 = 204 m^3 (winter season).

2) Total water needs per 10 days for 2 feddan = (Maize) 216 x 2 = 432 m^3 (summer season).

The total requirements will be estimated based on max. needs and with irrigation cycle of 10 days. Due to intermittent nature of solar energy the system will be designed to cover 1.0 days of autonomy over the basic requirements i.e.

water requirements = 432 m^3 x 2.0 = 864 m^3 /decade. in summer and 408 m^3 /decade in winter.

Finally, regarding the water reduction, the cost-effectiveness analysis found a minimum overall treatment cost of 0.12 \$/m^3 up to 0.133 \$/m^3 [16], [17] for the treatment of an actual sewage waste water (SWW) using the combined ABR-AS-UV/H2O system at optimum operating conditions. knowing that irrigation consume 85% of available water at least from the Nile river and other resources, the total amount of savings will reach savings in cubic meters of water as follows

Savings = 55 billion m^3 x 0.85 x 0.3 = 14.025 billion m^3.

cost in $ for treatment this water amount:

cost = 14.025 billion m^3 x 0.133 \$/m^3 = 1.865 billion USD. this savings could be achieved every year applying the proposed system. Fig. 7 shows One kirat area of 20 Feddan which is whole farm. Surge irrigation plan and land division is shown in Fig. 6,8. The general overlay of the main pipes and sub pipes are illustrated, the main problems of deep percolation and run off will be totally solved by controlling amount and speed of water flow in the fields using valves in each line.

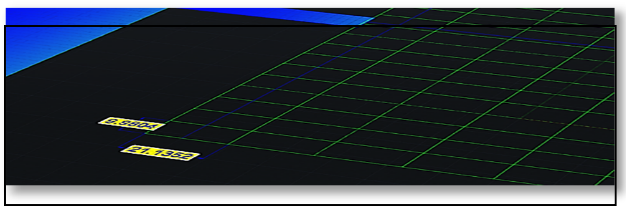


Fig. 7. One kirat land of 20 Feddan whole farm irrigation division

E. Hydraulic power and Total dynamic head (TDH) calculations.

Using the similar procedures used by [18] A.A. Tayebi (2018), [19] Jenkins Thomas, (2013b). [20] Buschermohle (2009), to calculate TDH the following equations are used to determine TDH for each feddan:

$$TDH = P_L + V_r + \left[L_t + \sum\left(n_f . f_e\right)\right] \times \frac{F_L}{30.48} \quad meter\ head \tag{4}$$

where P_L − Pumping level (ft) or m, V_r − Vertical Rise (ft) or m, F_L − Friction loss of head per 100feet of pipe or 30.48m of pipe, L_t −Total length of pipe (ft) or m, f_e −Fittings equivalent of pipe (ft) or m, n_f −Number of same fittings.

$$H = k\left(\frac{V^2}{2g}\right) \tag{5}$$

Where H- head loss (m), V- velocity of flow (m/s) K- head loss coefficient, g- gravitational acceleration (9.81 m/s2). According to data sheets of pipe lines manufacturers (flow rate of water – speed Q- diameter of the pipe- Fittings equivalent of pipe length), volume of water outlet desired is around 120 m^3/h, i.e. Q=0.0333m^3/s , and since the diameter of the main pipe is 5”, then the velocity of water is:

$$V = \left(\frac{0.0333}{\pi x r^2}\right) = \left(\frac{0.0333}{\pi x 0.127^2}\right) = 0.658\ m/s^2 \tag{6}$$

considering lifting the water from the main canal (Vertical Rise) is 1 meters and pumping level of 5-meter Hight as shown in Fig. 8 then we get:

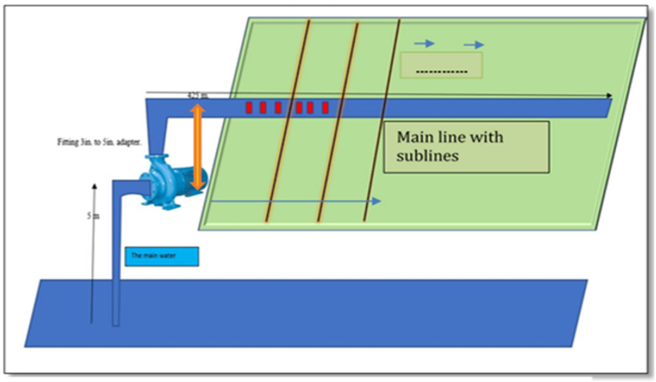


Fig.8 Pump lifting and main/ sub lines distribution

$$TDH_n = 5 + 1 + 2x1.1\,x\frac{(0.658)^2}{2 \times 9.8} + \frac{(42 \times n + 27.35) \times 3.7 + (100 \times 16.1)}{100} \times \frac{3.281}{30.48} \tag{7}$$

$$TDH_1 = 5 + 1 + .0527 + \frac{(42\times1+27.35)\times3.7+(100\times16.1)}{100} \times \frac{3.281}{30.48} = 8.06 \tag{8}$$

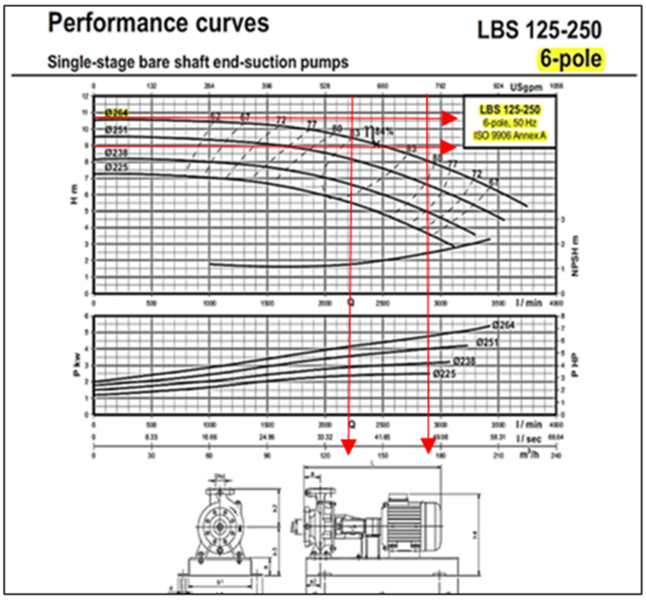
- *TDH* is in meter head of water. Where n is the feddan number from 1 to 10. to the right of the main irrigation pipe line and the same values are used for feddan 11 to 20. Applying the former equation to the 20 pieces of land we get Table IV of TDH which the pump must generate to deliver irrigation water to the basins. The TDH against pump power for each land piece of 1 Feddan in PSI and Bar is shown.

TABLE IV. TOTAL DYNAMIC HEAD FOR 5" PIPE LINE AND 4" SUBLINES

feddan number (n) TDH_n	TDH in meter head of H2O	TDH in psi	TDH in bar
TDH_1	8.06	11.46132	0.78988
TDH_2	8.23	11.70306	0.80654
TDH_3	8.4	11.9448	0.8232
TDH_4	8.56	12.17232	0.83888
TDH_5	8.73	12.41406	0.85554
TDH_6	8.9	12.6558	0.8722
TDH_7	9.07	12.89754	0.88886
TDH_8	9.23	13.12506	0.90454
TDH_9	9.4	13.3668	0.9212
TDH_{10}	9.57	13.60854	0.93786

Table V shows the main water heads from manufacturer data sheet which will affect pumping against speed, power and water flow of the pump block. Fig. 9,10. show Different heads and discharge of the pump with different speeds of motor. Using basic data from the Manufacturer data sheet table and the affinity lows. A coding program written by MATLAB is used to calculate all these curves and represent graphs to visualize the data. Using the max. TDH and highest water demand in crop pattern per decade, accompanied with the data sheet of the pump, the appropriate pump could be chosen. the following Table V pump curvatures are used.

TABLE V. PERFORMANCE DATA OF LUBI PUMPS WITH DIFFERENT HEADS



In order to get discharge rates at different speeds of the pump we use basic data from the Manufacturer data sheet table and the affinity lows:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{9}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{10}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{11}$$

where P, Q, N, H are power of the pump, flow rate of water, N speed of the pump shaft rpm., head of water respectively.

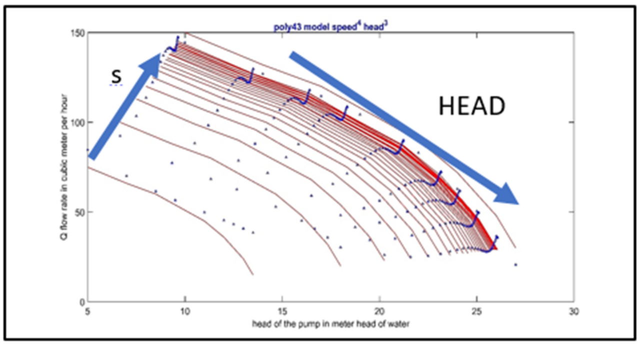


Fig. 9. Different heads and discharge of the pump with different speeds of motor

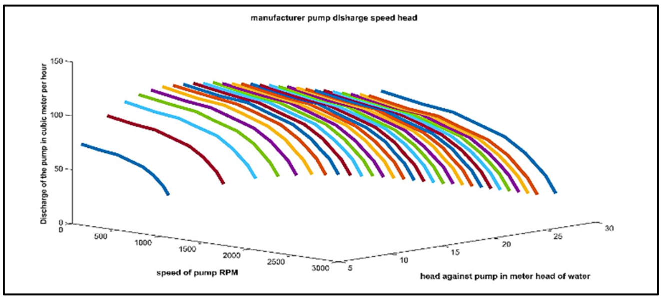


Fig. 10. Manufacturer pump output3D curves Discharge vs Speed vs head of water

F. Pumping system model and novel approach

1)National Research Energy Laboratories (NREL) PV pump sizing

NREL defines a method to approximate the required size of a PV pumping system [21], This is not solely for irrigation use, but any pumping system. The method assumes average daily efficiencies for all system components and uses an average daily solar radiation. The main equation used in this method is:

$$P = 1000\frac{\rho g h V \eta_r}{G_{T,D}\eta_{PV}\eta_{.S}} \tag{12}$$

Where P- PV array power (peak Watts), ϱ- Density of water (1000 kg m−3), g- Acceleration due to gravity (9.81 m s^{-2})

h- Total pumping head (m), V- Daily pumped Water (m3)

$G_{T,D}$- Daily solar radiation on PV surface (kW-hr m^{-2})

η_r- Array efficiency at 1000 W m−2 at 25 ℃, $\eta_{PV}\eta_{.S}$ - Array efficiency and Subsystem efficiency (%)

2) Novel modeling approach

based on the NREL Model if we could separate each system output with its efficiency and apply it to the pump equation it will be more realistic results and more accurate, therefore the following model is used:

$$P_h = \frac{Q\ X\ H\ X\ \varrho\ X\ g}{1000} \tag{13}$$

$$P_h = P_{shaft}\ X\ \eta_P \tag{14}$$

$$P_{shaft} = P_{PV} \tag{15}$$

Where $P_h -$ Hydraulic power submitted from pump to the pumped liquid, Q −Flow rate of liquid (cubic meter per second), H −head of water in meters, g −acceleration of earth gravity 9.8 m/s^2, P_{shaft}- power delivered from motor shaft to the pump shaft in watts, η_P- Efficiency of the pump, P_{PV}- electric power delivered from solar pv system to the motor block, η_{motor} − Efficiency of the motor.

3) Determining efficiency of the pump η_P.

Using polynomial fitting technique based on least square fitting and by interpreting each power in KW and its own efficiency from manufacturer data sheet we could model the efficiency as a function of power, the power is represented by the following Linear model Poly5 equation:

$$\eta_P\ (\mathrm{x}) = P_1{*}x^5 + P_2{*}x^4 + P_3{*}x^3 + P_4{*}x^2 + P_5{*}\mathrm{x} + P_6 \tag{16}$$

Goodness of fit:

SSE: 31.31 (SSE is the sum of the squared differences between each observation and its group's mean.)

R-square: 0.9461, Adjusted R-square: 0.9077, RMSE- 2.115, where p1 to p6 are polynomial coefficients.

P_1 = 2.202, P_2 = - 42, P_3 = 308.7, P_4 = -1092, P_5 = 1866, P_6 = -1169.

Fig. 11 shows the goodness of fitting plotted, it is polynomial fitting using linear fitting of 5th degree. According to Table IV heads in meters is carefully studied. Considering max head will range from 8 to 9.57 meter, the flow rate of the pump will range from 120 to 177 m^3/h . The minimum flow rate will be considered and an average equivalent sun hour of 5.2 ESH will be taken in consideration. Although the unbalanced solar radiation will also affect the system as the break horse power of the pump is 2.6 kw so any power below that limit the pump won't be able to lift the water. another issue that the efficiency of the motor which will be approximated to 86.6 % and the MPPT inverter which is 98% and the wires which will be 97%. Accordingly, initial estimation will be 8.25 kwp system to pump the needed water for the farm with 1 day of autonomy.

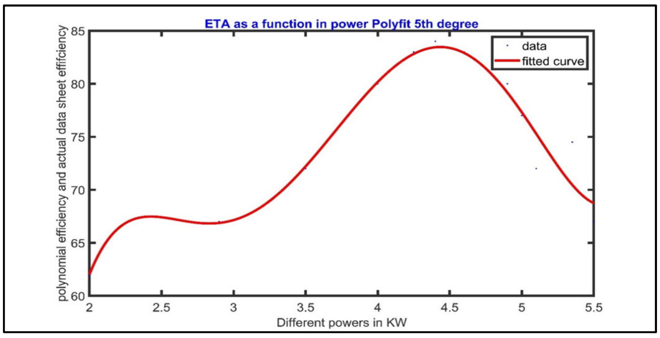


Fig. 11. Efficiency curve fitting as a function of power in kw using LSE

G. solar generator analysis and design.

1) Irradiance models (Level 1 algorithm).

The irradiance model utilized in this work will be the Isotropic Irradiance Model, the Hay and Davis model, along with the air mass modifier.

2) Isotropic Irradiance Model.

Using Lui and Jordan Isotropic Irradiance Model [25, 26]. AS following sets of equations:

$$a_M = 90^\circ - \theta_M \tag{17}$$

$$G_M^{tot} = G_M^{dir} + G_M^{dif} + G_M^{alb} \tag{18}$$

$$G_M^{dir} = SF \cdot DNI \cdot \cos(AOI) \tag{19}$$

$$\cos(AOI) = \cos(a_M) \cdot \cos(a_S) \cdot \cos(A_M - A_S) + \sin(a_M) \cdot \sin(a_S) \tag{20}$$

$$G_M^{dif} = SVF \cdot DHI \tag{21}$$

$$SVF = \frac{1 + \cos(\theta_M)}{2} \tag{22}$$

$$G_M^{alb} = \alpha_{gnd} \cdot (1 - SVF) \cdot GHI \tag{23}$$

$$AOI = \measuredangle (A_M, a_M)(A_s, a_s) \tag{24}$$

Where A_M Is Module azimuth [°], a_M − Module altitude [°].

A_S − Sun azimuth [o], a_S − Sun altitude [o], G_M^{tot} − Total irradiance on square meter of the panel [W/m^2]. G_M^{dir} − the direct normal irradiance [W/m^2]. G_M^{Dif} − the diffused irradiance [W/m^2]. SVF is Sky view factor. DHI is Diffuse horizontal irradiance [W/m^2]. G_M^{alb} − Albedo irradiance [W/m^2]. α_{gnd} − the albedo coefficient. GHI Is the global horizontal irradiance [W/m^2]. θ_M − module tilt angel in degrees[o]. (θ_z) or AOI is the angle of incidence [o].

In above model the diffuse irradiance is isotopically distributed in the earth's atmosphere. No circumsolar ring around the sun is considered or horizon brightening components.

3) Hay and Davies anisotropic irradiance model equation.

As stated by Hay et al. [28] they Calculate monthly mean solar radiation for horizontal and inclined surfaces Using following set of equations:

$$G_M^{tot} = \left(DNI + DHI.\frac{DNI}{DNI_{EX}}\right).SF \cdot \cos(AOI) + DHI.\left(1 - \frac{DNI}{DNI_{EX}}\right).SVF + \tag{25}$$

$$DNI_{EX} = S.\left(\frac{R_{av}}{R}\right)^2 \tag{26}$$

Where DNI_{EX} is Extraterrestrial direct normal irradiance on horizontal plan Empirical formula [W/m^2].

S Extraterrestrial radiation on horizontal plan [Wh/m^2]. R_{av} is Average sun- Earth distance [m], R is Actual sun- Earth distance [m]. *DNI* is Direct normal irradiance hourly basis [W/m^2]. DHI is Diffuse horizontal irradiance hourly basis [W/m^2]. SF is Shading factor. SVF is Sky view factor. In this method diffuse Irradiation is considered to be composed of 2 components:

a- Isotropic diffuse irradiance.

b- circumsolar diffuse irradiance.

4) Airmass Modifier.

Airmass (AM) is defined as the mass of atmosphere above Earth in which the light will travel and suffering of dispersion and spectral distribution according to the wave length of the components [32] King et al., [37] De Soto et al., [34].

$$G_{M-AM}^{tot}(i) = M(i)\left(G_M^{dir}(i) + G_M^{dif}(i) + G_M^{alb}(i)\right) \tag{27}$$

where M(i) - the Airmass Modifier, i - hourly index of the airmass modifier, $G_{M-AM}^{tot}(i)$ -Total Irradiance on Module affected by airmass modifier [W/m^2].

$$M = \sum_{j=0}^{4} a_{am,j}(AM)^j \tag{28}$$

$$M = 0.935823 + 0.054289(AM) - 0.008677(AM)^2 + 0.000527(AM)^3 - 0.000011(AM)^4. \tag{29}$$

Where $a_{am,j}$ a string of constants

$$AM = \frac{1}{\cos(\theta_z)} \tag{30}$$

5) solar cell (one diode) 5 parameters model (Level 2 algorithm).

Fig. 12, 13 shows solar and pumping algorithms. [29] proposed a set of equations which determine the values of the solar cell/panel 5 parameters as shown in Fig. 14 Javier used the following boundary equations accompanied with some simplifications. Accuracy of the values is very near or better than accuracy determined by other methods.

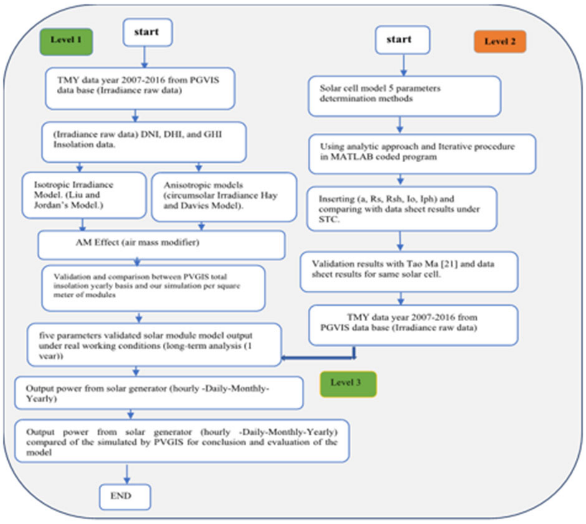


Fig. 12 PV solar generator Algorithm and design

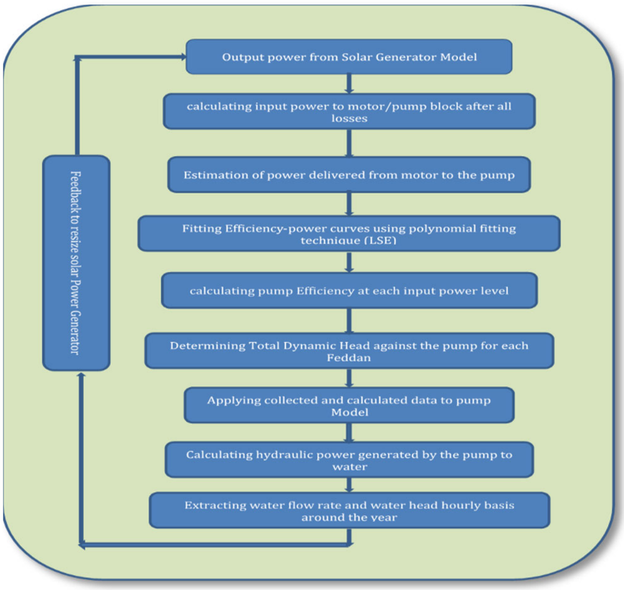


Fig. 13. Pump algorithm to determine water flow rate and head hourly basis in a year

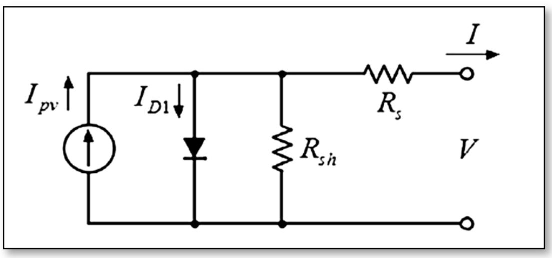


Fig. 14 one diode 5 parameters solar cell model.

Boundary conditions and their equations are:

a)One diode 5 parameters solar cell model equation:

$$\mathrm{I} = \mathrm{I_{pv}} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{V}+\mathrm{IR_S}}{\mathrm{aV_T}}\right)-1\right]-\frac{\mathrm{V}+\mathrm{IR_S}}{\mathrm{R_{Sh}}}. \tag{31}$$

b)Short circuit boundary condition:

$$\mathrm{I_{SC}} = \mathrm{I_{pv}} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{I_{SC}R_S}}{\mathrm{aV_T}}\right)-1\right]-\frac{\mathrm{I_{SC}R_S}}{\mathrm{R_{Sh}}} \tag{32}$$

c)Open circuit boundary condition:

$$0 = \mathrm{I_{pv}} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{V_{oc}}}{\mathrm{aV_T}}\right)-1\right]-\frac{\mathrm{V_{oc}}}{\mathrm{R_{sh}}}. \tag{33}$$

d)Maximum power point differentiation condition:

$$\left(\frac{\partial \mathrm{I}}{\partial \mathrm{V}}\right)\Bigg|_{[\mathrm{I_{mp}},\mathrm{V_{mp}}]} = -\frac{\mathrm{I_{mp}}}{\mathrm{V_{mp}}}. \tag{34}$$

Where (I) is Solar cell total current [A], $\mathrm{I_{pv}}$Photo voltaic generated current[A], $\mathrm{I_0}$Diode saturation current[A],

$\mathrm{V_T}$ Thermal voltage of the diode [V], a Ideality factor of the solar cell, $\mathrm{I_{SC}}$Short circuit current of the solar cell [A], $\mathrm{V_{oc}}$ Open circuit voltage of the solar cell [V], $\mathrm{R_s}$ Series resistance of the solar cell [Ω], $\mathrm{R_{sh}}$ Shunt resistance of the solar cell [Ω].an implicit expression of the series resistor, $\mathrm{R_S}$, as a function of the initial known parameters:

$$\frac{\mathrm{aV_TV_{mp}}(2\mathrm{I_{mp}}-\mathrm{I_{SC}})}{\left(\mathrm{V_{mp}I_{SC}}+\mathrm{V_{oc}}(\mathrm{I_{mp}}-\mathrm{I_{SC}})\right)(\mathrm{V_{mp}}-\mathrm{I_{mp}R_S})-\mathrm{aV_T}(\mathrm{V_{mp}I_{SC}}-\mathrm{V_{oc}I_{mp}})} = \exp\left(\frac{\mathrm{V_{mp}}+\mathrm{I_{mp}R_S}-\mathrm{V_{oc}}}{\mathrm{aV_T}}\right) \tag{35}$$

final expression of the shunt resistor, $\mathrm{R_{sh}}$, as a function of Rs and the initial parameters:

$$R_{sh} = \frac{(V_{mp}-I_{mp}R_S)(V_{mp}-R_S(I_{SC}-I_{mp})-aV_T)}{(V_{mp}-I_{mp}R_S)(I_{SC}-I_{mp})-aV_TI_{mp}} \tag{36}$$

Where $\mathrm{V_{mp}}$ is Maximum power point voltage [V], $\mathrm{I_{mp}}$ is Maximum power point current [A]. These equations are validated by applying the methodology and iterative algorithm suggested by Shaker et al. [38], to determine the values of the 5 parameters:

e)initiating a value for ideality factor (a) from 1 to 1.5, increasing by 0.05 each time.

f) Solving symbolic Equation for series resistance using MATLAB coding program.

g)Solving symbolic equations for shunt resistance using MATLAB coded program.

h)apply all values to MPP and use the data sheet of the manufacturer to get best estimation of the parameters.

The results were compared to Tao et al. [30], using shell SQ175-PC solar cell at STC conditions. Excellent matches were found in key points in the I-V and I-P curves. After solving the symbolic equations and getting accepted values for parameters in STC, the photon current equations are fed by Irradiance model output data to determine the generated power of the solar generator throughout the year in an hourly, daily, monthly, and yearly manner. In this paper we used a set of equations suggested by Zekry et al. [38] to simulate working solar panels in different environmental working conditions.

6) solar generator Model including cables/inverter losses (Level 3 algorithm).

Based on Zekry et al. model [38], the following set of equations to simulate behavior of solar cell/panel in working conditions:

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_S}\left(e^{\frac{q(V+IR_S)}{nk_BT}} - 1\right) - \frac{V + IR_S}{R_{Sh}} \tag{37}$$

$$\mathrm{I_{ph(STC)}} = \mathrm{I_{SC(STC)}}\left(\frac{G}{G_{STC}}\right) \tag{38}$$

$$\mathrm{V_{OC}} = \mathrm{V_{OC(STC)}} + \mathrm{K_V}(\mathrm{T} - \mathrm{T_{STC}}) \tag{39}$$

$$\mathrm{I_S} = \mathrm{I_{S(STC)}}\left(\frac{T}{T_{STC}}\right)^3 e^{\frac{-qE_g}{nk_B}\left(\frac{1}{T}-\frac{1}{T_{STC}}\right)} \tag{40}$$

$$\mathrm{I_S(STC)} = \frac{\mathrm{I_{SC(STC)}}}{\left(e^{\frac{qV_{OC\,(STC)}}{nk_B T_{STC}}} - 1\right)} \tag{41}$$

Where E_g is the band gap energy of the semiconductor [eV]; G is the surface irradiance of the cell [W/m^2]; G_{STC} is the irradiance under STC (T = 25˚c and P =1000 W/m^2) ; $I_{S(STC)}$is the nominal saturation current [A]; $I_{SC(STC)}$ is the short circuit current per cell at STC [A]; k_B is the Boltzmann's constant [J · K $^{-1}$]; K_I is the temperature coefficient of short circuit current [%/°C]; K_V is the temperature coefficient of open-circuit voltage [%/°C]; n is the diode ideality factor; STC is standard test conditions at which (T_{STC} = 25 °C); T is the absolute temperature in Kelvin [k]. The output power generated hourly will be fed to cables and inverter, for simplicity, the losses must be included in the system of equations by simply multiplying the maximum output power P_{max} by 0.97 x 0.97 to account of the 3 percent loss for both cabling and inverter.

H. Economical aspect of the system.

Egypt is expected to spend EGP 55 billion in annual diesel subsidies during the fiscal year FY 2022/23 after the government's Wednesday decision to raise diesel prices for the first time in 30 months by EGP 0.5 per liter, Prime Minister Mostafa Madbouly has said [32]. According to study [33] conducted in Wadi El-Natrun desert The cost of solar energy/m3 of extraction water under the solar photovoltaic panels system was about 0.36 LE/m3 while using the convention diesel energy leads to cost of about 1.79 LE/m3 . Thus, it can be noticed that the cost of utilization of solar energy represented by 20% of usage of diesel energy.

I. Simulation and general block diagram of system architecture.

As shown in Fig. 12, the algorithm [35] is composed of 3 layers or levels of calculations and models. Each of them is to predict and evaluate certain parts of the whole simulation system. The accuracy and results of each layer of processing depends on the previous layer's results and accuracy, so each level is validated separately. The final generated power (level3) accounted for the whole system's performance. Fig. 13 shows the motor pump algorithm after sbmittng energy from the solar generator block, a feedback signal in the algorithm to reconsidering the size aspect of the solar generator.

III. RESULTS AND DISCUSSION

A. Irradiance model validation, results and discussion

Isotropic and Anisotropic Irradiance Models are used, the calculations based on 8760 hourly basis data point per year (TMY 2007 - 2016). The simulation outputs total 8760 hourly insolation energy in plan radiation points, Fig. 15. This data is integrated into daily, monthly and yearly results and compared with the total in plan insolation depicted by PVGIS European data tool for year 2016 Table VI. PVGIS 2016 energy per square meter is: 2282.1 KWh/ m^2 ,and for year 2020 resulted in 2377.579 KWh/m^2, while TMY data simulated in this work (incident power on horizontal plan using TMY 2007 - 2016) simulated by anisotropic model and isotropic model are: 2164.2 KWh/ m^2 and 2160.1 KWh/ m^2 respectively. percentage difference PVGIS results year 2016 and this work are 5.6477 % and 5.5039 % consecutively. While for 2020 percentage difference PVGIS results and this work are 9.11 % and 9.02 % consecutively. Also, Analysis shows increase of in plan radiation between PVGIS results year 2016 and 2020 by 4.02 %. as shown in Fig. 16.

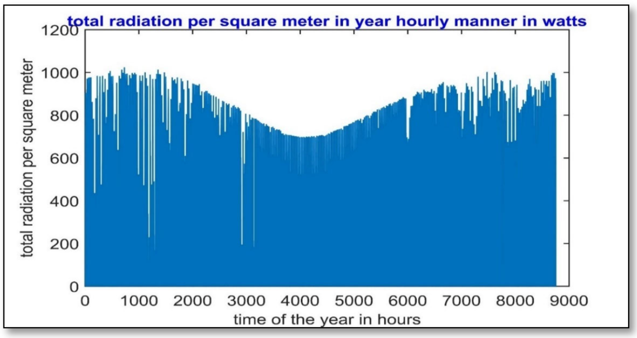


Fig. 15. Total radiation power per sq. meter hourly basis in a year

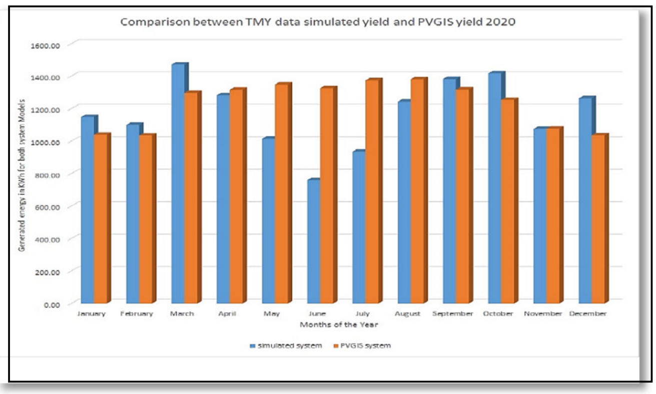


Fig. 16. Monthly energy output for 8.25 kwp system simulated in this work

TABLE VI. MONTHLY GENERATED ENERGY FROM PVGIS AND SIMULATED SYSTEM IN THIS WORK

	system used simulated	PVGIS simulation	Ratio
Months	**KWh**	**KWh**	**Ratio %**
JAN	1039.33	1148.65	110.52%
FEB	1034.11	1099.50	106.32%
MARCH	1296.5	1471.26	113.48%
APRIL	1316.24	1282.36	97.43%
MAY	1348.12	1014.50	75.25%
JUNE	1326.06	759.46	57.27%
JULY	1374.18	934.65	68.02%
AUGUST	1381.09	1243.24	90.02%
SEPTEMPER	1317.45	1382.32	104.92%
OCTOBER	1253.72	1417.08	113.03%
NOVEMBER	1075.87	1074.63	99.88%
DECEMBER	1035.09	1263.05	122.02%
Total	14797.76	14090.71	95.22%

Table VII shows the final 5 parameter extraction results using same analytic approach used by Javier Cubas [29]. the same solar panel data sheet used by Tao Ma to extract cell parameters is tested in this simulation. Tao Ma used numerical methods [30], [31]. The results are very close and final simulation for solar panel under different insolation conditions are almost identical to Tao Ma results as depicted in Fig. 17. Using and validating analytic approach to extract solar cell parameters in STC proving 99.999% matching with Tao Ma and data sheet results Table VII.

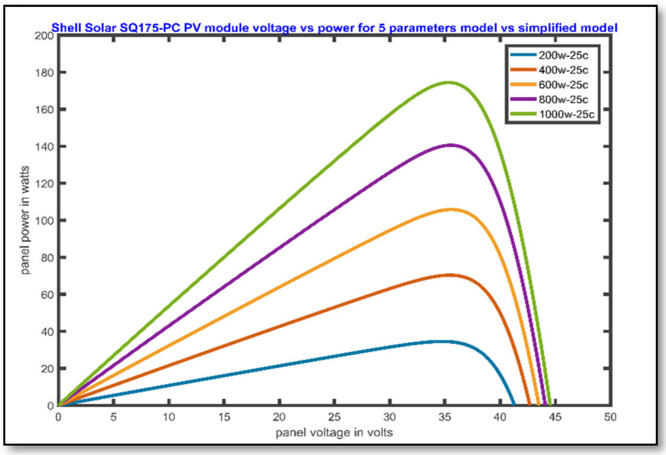


Fig. 17. Fixed temperature and different irradiance panel output

TABLE VII. CALCULATED PARAMETERS OF PV CELL/MODULE VS TAO MA RESULTS

Cell parameter	Iph	Io	Rs	Rp	Vt	n
Tao Ma results	5.449	1.20E-09	0.010	2.725	0.028	1.086
Study results	5.4493	1.30E-09	0.0097	2.7354	0.02567	1.09

B. solar generator section final results.

In this paper we tried to explain a method to practically evaluate the output of PV generator depending on available radiation data on the internet network for free, this method use sets of models for each level starting from irradiance data processing to solar parameter extraction and long term energy yield, using available TMY data from PVGIS website, although the raw data available ending in year 2017, the generated output power simulated, compared to the calculated energy yield in year 2020 was very near 4.78% difference (taking in consideration aging factor loss of efficiency 10 % in 20 years), this tool could be used as a whole system simulator to accurately calculate the energy generated from PV solar water pumping system or any other system without any need to use paid tools or programs. Through coding the stated equations above in MATLAB programming language. And using the flow chart explained in details second step is to insert the TMY data, and some iterating procedure, the goal is to extract the solar cell 5 unknown parameters, then use the solar cell model in simulating program fed by climate data. the final results turned to be decently accurate, moreover if the available weather data is more recent it will reduce the difference between simulated output and PVGIS results. The novelty of this methodology that it uses all models from the very beginning (5 parameter model) through long term evaluation to design and to predict solar system output. this tool could be used by engineers to design solar systems. all models could be interchangeably used with different known models to test as many models as required for research.

C. pumping system results and discussion.

In this section the final stage of the study will determine exactly every hour in the year the amount of water which will be pumped to the crops. The 8.25 K_{wp} system daily supply of water could be easily calculated. starting with the average daily power generated by the solar system after cables and inverter losses. In order to determine the power level supplied to the pump, motor efficiency from manufacturer data sheet is considered. for simplicity the average efficiency of the motor data sheet is considered. It is rounded to 86.6 %. when the pump shaft receives power from the motor shaft it will turn the impeller to generate hydraulic power. The hydraulic power will be delivered to the water in form of water flow and head of water. The governing factor of the pump block performance (water flow rate) is the efficiency of the pump. In preceding section, a polynomial had been fitting efficiency curve using least square error technique. According to efficiency power function the efficiency will be allocated for each input power level. Applying all calculated data to the pump model suggested in last section, Hydraulic power generated from pump impeller is obtained. Finally, water flow rate and head generated by the pump is obtained. As final goal, the pumped water is compared to water requirements determined using Penman-Monteith variation method. A feedback is sent to the beginning of the algorithm to correct solar generator sizing according to the new calculated data. The preceding algorithms (in Fig. 12, 13.) are used to accurately determine the flow rate and head of the pump each feddan hourly basis at any time of the year as depicted in Fig. 12, 13. It is worth mentioning that all power input to the pump should be limited to maximum power in the pump curve in the data sheet which is 5.5 kw. If the power input is more than that limit the fitting curve will act randomly and output will be faulty. It is very important also when taking average, it should be relative to non-zero power points (based in hours 12 hours will be dark in night). Fig. 18 shows the irrigation water of the solar pumping irrigation system. It depends on power delivered from motor to pump in an hourly basis, also it depends on efficiencies of the pump with respect to delivered power from the motor, and finally the discharge rates of the system all over the year is shown.

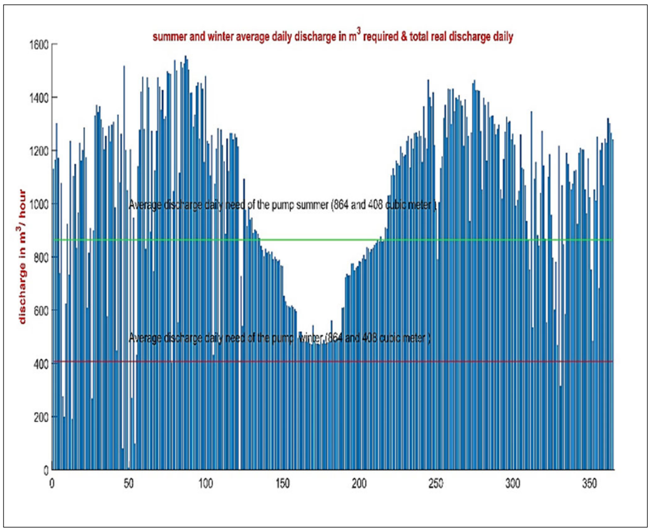


Fig. 18. summer and winter average daily discharge need and daily discharge

IV. CONCLUSIONS

A. Analytic approach which is used to extract solar parameter of the cells is decently accurate and gives satisfying results. Using and validating analytic approach to extract solar cell parameters in STC proving 99.9% matching with Tao Ma and data sheet results.

B. TMY data which is used in this study for one-year analysis, decreases around 9% compared with PVGIS 2022-year Irradiance data results. However, energy yield simulation returns 4.78% less than PVGIS results.

C. The algorithms used in this study are agile and modular, many other models could be plugged instead of applied ones used in this paper, and will represent good tools for engineers to predict performance of solar pumping irrigation systems, Programming Code is available [39].

D. Solar pumping irrigation system can't be used as stand-alone system except, if water is stored as days of autonomy or a hybrid system is used.

E. This work has limited accuracy due to free TMY data availability (till 2017 only).

F. As a future work, using another irradiance data type (processed total Irradiance) from PVGIS, which are updated till year 2020 could enhance accuracy of this model, however part of testing will be eleminated.

G. Time complexity of this algorithms is high to process real working conditions over one year, more than 15 coded Matlab programs tested for entire 48 hours to process the amount of input data using HP work station Laptop.

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