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RESEARCH ARTICLE - ENGINEERING

Performance Study of the Direct-Coupled Photovoltaic Water Pumping System for the Rural-Isolated Agricultural Region in Iraq

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Abstract

The rural-isolated agricultural region in Iraq and some developing countries lack access to electricity, and thus the primarily alternative is to use diesel water pumping systems to irrigate their crops. However, due to a rise in the oil's price on the international market, toxic pollution from burning oil, high maintenance costs, and short lifespans have been challenged to create more viable alternatives. Renewable energy can limit the use of fossil fuels, particularly by using the solar-powered water pumping system. This article aimed at finding an optimal design for a direct-coupled photovoltaic water pumping system in Iraq. The article presents the significant design aspect for an optimal system, such as the groundwater aquifer depth, installation aspect, cost, and irrigation efficiency. The design offers a combination of sprinkler and environmentally sustainable and cost-effective photovoltaic technology to reduce electricity and water use. A deep well to the storage system is adopted with, 40m maximum well depth, 90m^3 reservoir, 1200W submersible pump, and 1800 Wp, which can supply water to 12 greenhouses for three days. The yearly results show pumping efficiency is increased up to 42.6%, used water need is achieved at 10950 m^3, and unused energy is reduced by 48.8%.

Keywords: PVsyst; Solar Pump; Greenhouse; Irrigation; Well to the storage; Solar Pumping; Water system.

1. Introduction

One of the best solutions for remote areas' irrigation systems is the solar PV water pumping system, where grid connectivity is costly to reach or not even possible. Such a system needs to be suitable for the existing resources. Groundwater aquifer must be investigated accurately to get a vision for possible depth for well's depth, then the amount of the needed water will be considered according to the planted crop, area of the land, the amount of rain-falls in the area, soil type, and solar irradiation. This article introduces a study to design a solar PV water pumping from well to reservoir with the help of the PVsyst Software, as shown in Fig. 1. A DC direct coupling with an MPPT is adopted to reduce the overall system cost. The presented data is used to implement the first part of the PV solar pumping project responsible for pumping the water into a reservoir which is used to meet the crops needs for three days. The next part of the project will be into pumping this water through a smart irrigation network with twelve greenhouses.

Many researchers study the solar pumping system to provide clean drinking water to millions of unserved people worldwide and irrigate their crops[1]. System performance varies significantly during the rainy season[2]. Moreover, these systems' autonomy and the cost depend on sizing their component [3-5], but irradiance and temperature variation at the installation site must be considered for maximum performance [6]. Many techniques are introduced to decrease the cost and increase system reliability, such as using a directly-coupled PV water pumping system[7], using a ground reservoir, and shading part of it py the PV array to reduce the water evaporating, saving the water that enough for the next three days of irrigation. During the crops cycle, the designed system must guarantee to deliver the required water; the most worst-case scenario of the weather must be considered [4]. The theoretical and simulated data is used to implement an experimental system. The design results present and discuss many indicators like the water availability, well static head and drawdown loss, losses due to full tank, a method to enhance the system performance, and other design aspects are all considered. PVsyst is considered as a convenient tool used by many researchers, and its results were very close to the practical results. Program version 5.52 was used where also included a full explanation via diagrams. It is used to correct the problems of the system before conducting the field work [8-12]. The work in [13] took into account the power of radiation on the solar engine. While focus on the level of static water not accounting for costs of (drilling for wells, exploration and manpower) were not considered in[14]. The authors in [15], performed sensitivity analysis on 14 parameters and showed that the thermal parameters and hydraulic

Nomenclature			
GlobEff	effective global corrected for IAM and shading	WMiss	missing water, with respect to the user's needs.
EArrMPP	array virtual energy at MPP	BLDC motor	brushless DC electric motor
EPmpOp	pump operation energy	MPPLoss	loss with respect to the MPP running
ETkFull	unused energy (Tank full)	EPmpThr	energy loss under pump producing threshold
HPump	average total head at the pump	EPmpOvr	pump overload energy
WPumped	water pumped	ELowLev	pump stopped due to low level aspiration
GlobHor	horizontal global irradiation	EPmpAv	available useful energy at pump when running
WUsed	water drawn by the user	MPPT	maximum power point tracking
EOutConv	Energy at the output of the converter	EArray	Effective energy at the output of the array, according to the real Voltage operating point.

losses had a negligible effect on the model output and the optimal formation. In [16] the effect of temporal resolution of water consumption rate on model accuracy and optimum sizing (pv sys) was studied.
This work aims to provide farmers in Karbala city with a low cost, environmentally friendly, easy to maintain and resistant to irrigation problems in remote areas by using smart irrigation systems.

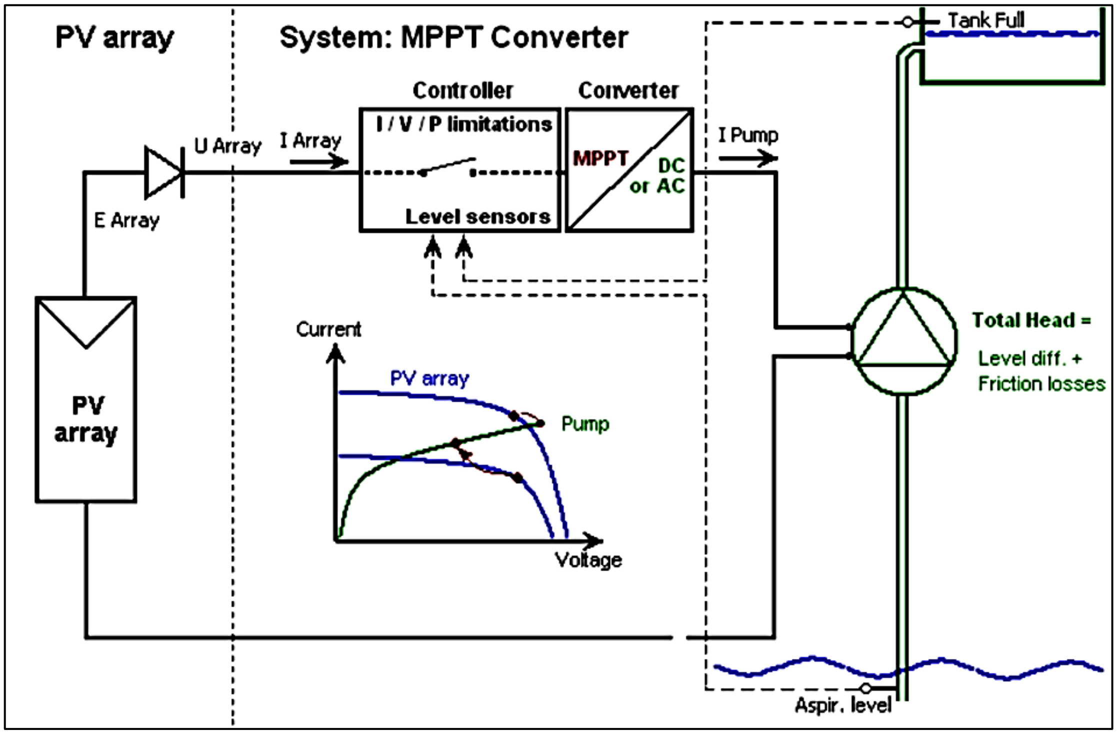


Fig. 1. System Design Block Diagram[8]

2. Design Methodology and Aspects

Many design aspects must be taken into consideration when planning to install a solar pump station, such as:

2.1. Water Needs

Four types of data are required to calculate the exact amount of the needed water, namely, rainfall data, climatic data, soil data, and crop data[17]. Many studies briefly discussed the water needs in Iraq for different crops. In [18], useful water irrigation needs calculations for four crops (Tomatoes, Wheat, White corn, and Barley). Many researchers in this field briefly discussed these data for a different Iraqi regions [19, 20]. The challenges have been discussed in[21].

2.2. Groundwater Aquifer Detection

Researchers investigate many regions in Iraq such as: Arabian Peninsula[22], Al-Khazir Gomal Basin[23], Bahr Al-Najaf depression[24], Northern Babylon Governorate[25], Kirkuk region[26], area between Al-Zubair and Umm Qasr[27], Badra–Al Al-Gharbi–Teeb areas[28], Al-Batin alluvial fan[29], Sulaymaniyah City[30], Galal Badra basin[31], Al-Dammam[32], and more. using 2D and 3D electrical imaging survey is more common in detecting the groundwater aquifer for choosing the best drilling site for the well. Figure 2 shows an example for the 2D and 3D survey results.

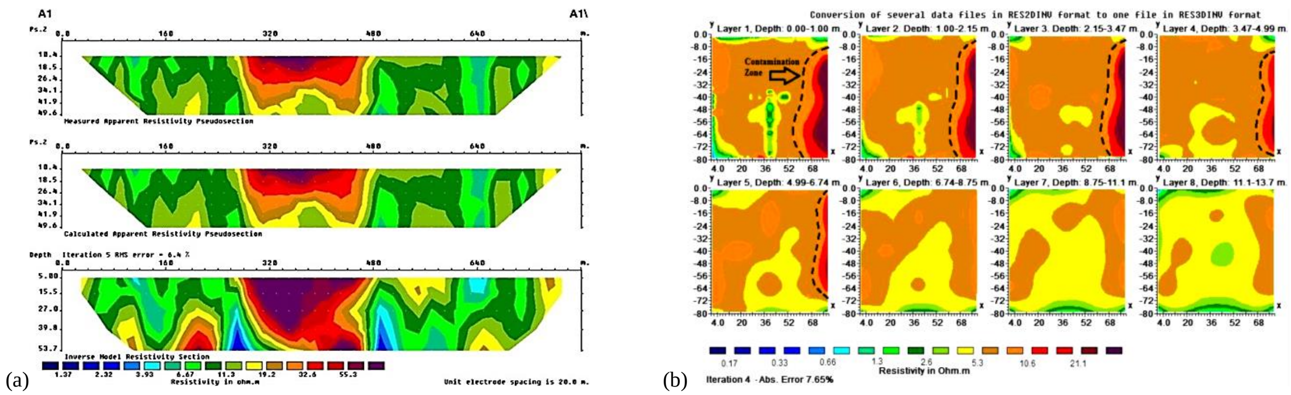
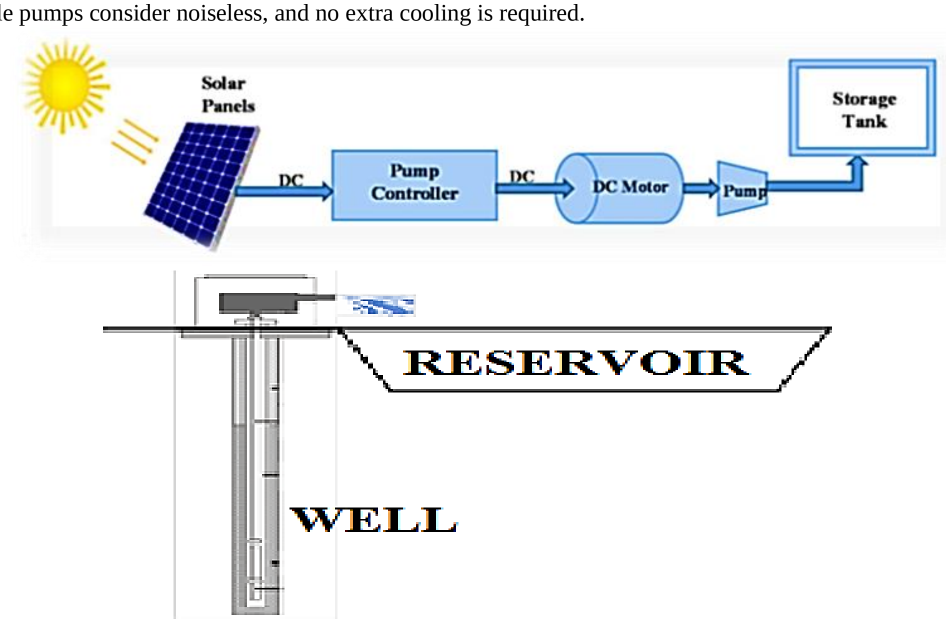


Fig. 2. Electrical resistivity imaging survey for detecting groundwater aquifer, a) Sample 2D survey image[33], b) Sample 3D survey image[34].

2.3. Pumping Unit Specification

In this article, we adopt a well to storage method with a submersible pump. Some significant aspects are taken into consideration in designing the pumping unit, such as;

- The maximum pump head and the flow rate are compatible with well's depth and the required water.
- There is no need to store the energy in batteries since the water will be saved in a big reservoir and used whenever required, even at night.
- It is possible to pump water more than the required for one day and save it.
- Using direct coupling with Maximum Power Point Tracking (MPPT) can reduce the installation and maintenance cost., The PVsyst software can simulate Grid-connected, standalone, pumping, and DC Grid systems[35]. as shown in Fig. 3a.
- As shown in Fig. 3b, using a reservoir with ground level is not costly since it is only required an excavation and concrete coating layer.
- Submersible pumps consider noiseless, and no extra cooling is required.



(a)

(b)

Fig. 3. Pumping unit station; a) the pumping unit block diagram, b) reservoir level.

2.4. Photovoltaic System

The solar panels are the primary power source for the system. They are affected by many environmental factors and come in different efficiency and sizes after calculating the required water and deciding its depth and the reservoir capacity. PVsyst Software simulates the system to calculate the required PV power, sizes, and methods of connecting the array.

2.5. The Reservoir

The reservoir volume was calculated to save the amount of water required for the crops for one day. So, the system adopts a high safety factor to supply water whenever maintenance is required or on cloudy days. The reservoir is also designed to be underground for cost reduction since it is built by excavating into the required size, then coated with concrete or any rubber coat. Also, The PV panel array will be installed over the reservoir to reduce the evaporating losses, to cooling the PV array, and to save the cleaning water in the cleaning process

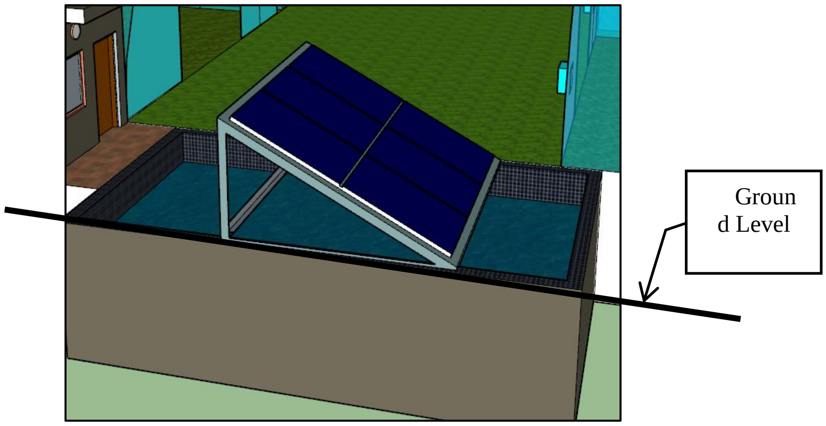


Fig. 4. Vertical section for the reservoir

3. Result and Discussion

As a case study, we consider tomato crop grown in a certain area has a total growing season of 150 days and the following monthly crop water needs [36], the average water need is 157.2 mm/month which is equal to ≈5m^3/1000m^2/day (or less if the greenhouse is used). For implanted area (3500 m^2), the water need will be equal to 30 m^3/day. By considering a reservoir that save water for three days, its capacity will be 90 m^3. According to the studied well, as shown in Baghdad's suburban area, which has a static level depth 18.0 m, Diameter 30 cm, pump depth 42 m, maximum pumping depth 40 m, and specific drawdown a 0.50 m/m^3/h.
The used submersible pump manufactured by Lorentz, PS1200 SJ5-8, has centrifugal multistage. It has a BLDC motor associated with MPPT. The other specification as follows (H Pump= 36 mWater, WPumped= 5.8 m^3/h, EPmpOp= 1200W, and Pipe PE50 Dint =54 mm).
The used PV panels array consists of six panels, Si-Poly VSPS-300-72-A by VOLTEC SOLAR, connected in two parallel strings. Each string consists of three panels. Each panel has a nominal power of 300 Wp that make the EArrMPP is 1800 Wp @STC and 1623 Wp @ 50 °C. Each panel has VMPPT = 98V and IMPPT =17A, making the array able to supply 294V, 34A.
The PV array is installed on a fixed structure, as shown in Fig. 5, facing the south with an elevation angle (33°N). The elevation angle was selected for optimal yearly production, which is equal to the location latitude. PVsyst Software simulates all the presented data, and the yearly pumping results were as shown in Table 1. From these results, we can conclude the following:

- The selected site has a decent amount of Globe,
- the EArrMPP is enough to supply the system with energy even at the low Glob or months such as November- F
- February in the selected site.
- The E Pump is enough to operate the motor through the whole year,
- The H Pump is more than 20m,
- the average of WPumped is more than 900 m3 (≥ 30m3 per day),
- the W Used to indicate that all the produced water is useful and there is no loss (W Miss=0), thanks to the big reservoir.

(a) (b) (c)

Fig. 5. Photos for the well under study; a) the well, b) the PV array structure, and c) the PV array

Table 1. Pumping system main results

	GlobEff (kWh/m²)	EArrMPP (kWh)	EPmpOp (kWh)	ETkFull (kWh)	H Pump (meterW)	WPumped (m³/day)	WUsed (m³/day)	WMiss (m³/day)
January	133.6	228.1	138	72	21.93	31.17	30.00	0.000
February	147.8	247.3	121.9	104.6	22.04	30	30.00	0.000
March	177.6	289.1	134.4	129.5	21.81	30.02	30.00	0.000
April	179.8	288.4	130.5	137.3	21.44	30.02	30.00	0.000
May	201.9	312.2	133.3	156.6	21.57	30	30.00	0.000
June	207.2	310.8	129.1	158.8	21.6	30	30.00	0.000
July	209.8	310	133.1	156.3	21.6	30	30.00	0.000
August	212.9	313.7	134	158.5	21.58	29.99	30.00	0.000
September	198.5	299.4	131.9	145.3	21.64	29.97	30.00	0.000
October	184	286.9	134.2	132.5	22.17	30	30.00	0.000
November	148.2	244.5	129.4	97.5	22	29.96	30.00	0.000
December	123.9	210.4	133	61.8	21.93	30	30.00	0.000
Year	2125.1	3340.8	1582.7	1510.6	21.76	30.1	30.00	0.000

In Table 2 and during summertime, we notice that:

- There is a high array of virtual energy at MPP (EArrMPP) due to high solar irradiation in this period.
- High EPmpThr due to zero flowrate (Reservoir is full) due to high solar irradiation in this period.
- EPmpOvr equal to zero indicates that EArray is not excessing the pump's maximum power (good indication).
- E PmpAv (EOutConv – EpmpThr) is sufficient.
- ELowLev is zero, indicating that the pump does not stop due to low level in the well (it is mainly based on the drawdown speed of the well, if this factor increased, the pump safety will be an issue since practically that mean the motor will be out of the water and it may sucking dirt from the well's button).
- High ETkFull, and EPmpOp (EPmpAv- ELowLev - ETkFull) which refer to an abundant production.

In Table 3, monthly hourly sums for EPmpOp in kWh is listed. The results show that the pump energy is increased for the late morning, where the solar irradiation is enough to start the pumping process and stops when the reservoir is full. It is also showing that most of the abundant production happens from 8 am to 12 pm.

Table 2. Losses in the pumping system

	EArrMPP kWh	EPmpThr kWh	EPmpOvr kWh	E PmpAv kWh	ELowLev kWh	ETkFull kWh	EPmpOp
January	228.1	0.022	0	210	0	72	138
February	247.3	0.13	0	226.5	0	104.6	121.9
March	289.1	0.31	0	263.9	0	129.5	134.4
April	288.4	0	0	267.8	0	137.3	130.5
May	312.2	0.305	0	289.9	0	156.6	133.3
June	310.8	2.084	0	287.9	0	158.8	129.1
July	310	1.345	0	289.4	0	156.3	133.1
August	313.7	0.079	0	292.6	0	158.5	134
September	299.4	0.075	0	277.2	0	145.3	131.9
October	286.9	0.111	0	266.7	0	132.5	134.2
November	244.5	0.194	0	226.9	0	97.5	129.4
December	210.4	0.609	0	194.8	0	61.8	133
Year	3340.8	5.264	0	3093.5	0	1510.6	1582.7

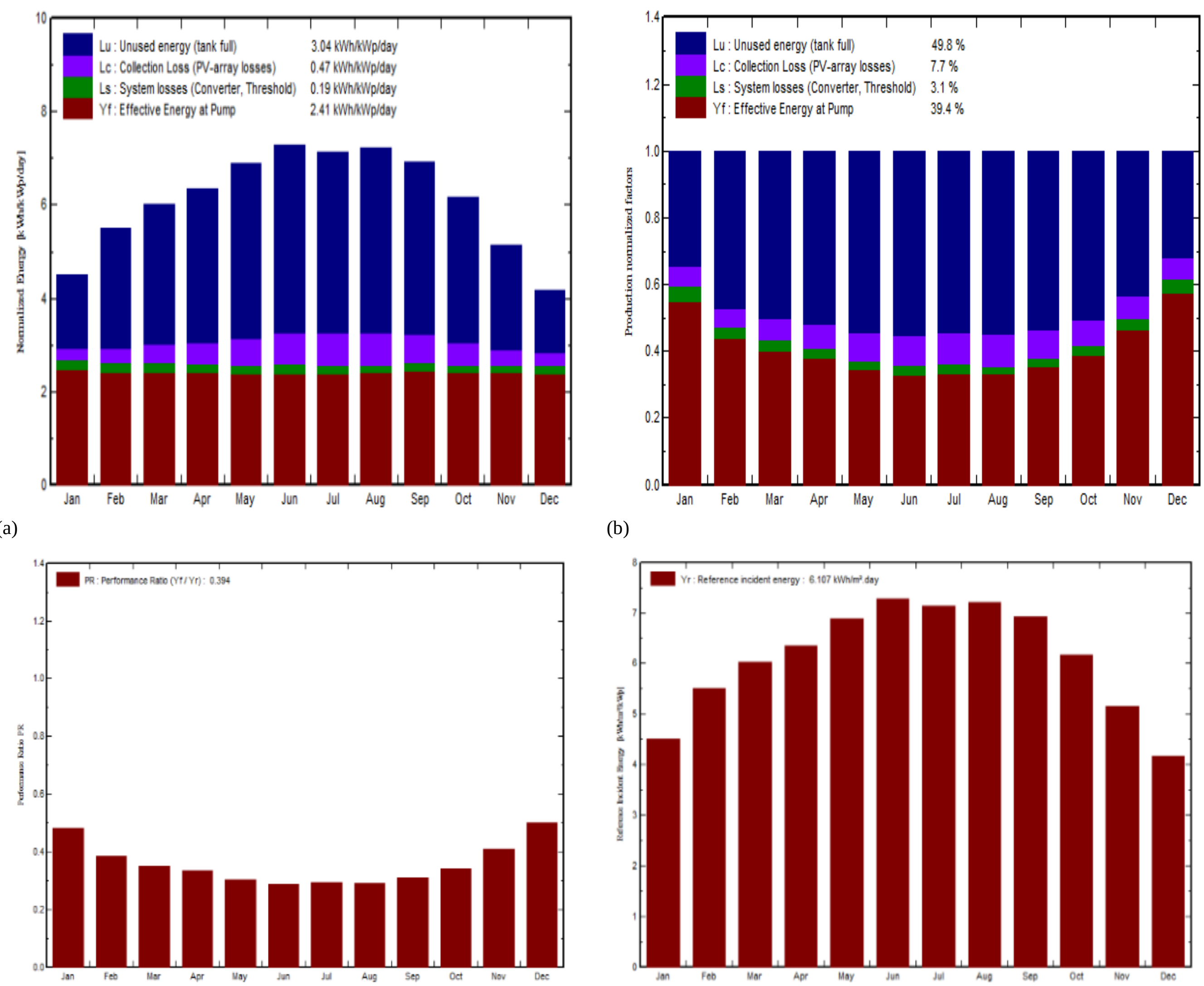
Table 3. Monthly Hourly sums for E_PmpOp [kWh]

	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H
January	0	0	0	13.2	24.1	29	27.2	12.7	11.8	9.2	6.7	4	0	0	0
February	0	0	3.5	14.9	24.5	30.1	20.4	7.6	6.1	5.7	5	4	0.1	0	0
March	0	0	8.5	20.5	28.7	32.3	13.5	6.5	6.3	5.9	5.4	4.7	2.2	0	0
April	0	2.9	11.8	21.5	28.4	26.9	7.6	6.6	5.9	5.6	5.4	4.5	3.5	0	0
May	0	5	14.4	24.2	31.8	19.8	5.8	5.8	5.8	5.8	5.6	4.7	4.5	0	0
June	0	4.8	13.9	23.6	30.6	18.6	5.7	5.7	5.7	5.7	5.5	4.7	4.5	0.3	0
July	0	4.2	12.9	22.7	30	24.7	5.9	5.9	5.9	5.9	5.7	4.9	4.5	0.1	0
August	0	3.6	12.7	23.2	31.1	25.1	5.8	5.8	5.9	5.9	5.7	4.8	4.5	0	0
September	0	2.4	12.8	23.7	31.4	27.5	5.7	5.7	5.7	5.7	5.4	4.4	1.6	0	0
October	0	0.1	11.3	23.6	32	33.8	6.2	5.9	5.9	5.8	5.3	4.4	0	0	0
November	0	0	8.4	20.5	28.1	33.2	13.4	7.4	6.4	5.8	4.8	1.3	0	0	0
December	0	0	0.8	13.8	23.5	28.6	28.1	12.7	11.2	8.7	5.6	0	0	0	0
Year	0	22.9	110.9	245.5	344.1	329.6	145.2	88.2	82.4	75.7	65.9	46.5	25.4	0.3	0

While in Fig. 6, four bar-charts are listed that represent the following: Fig. 6a shows the yearly normalized energy [kWh/kWp/day](the nominal power 1800 Wp), it is shown in the red bar constant adequate energy at the pump, and there is a sufficient amount of the unused energy due to the filled reservoir. Thus there is a chance to increase the reservoir capacity. Fig. 6b shows that the normalized production and loss factors. It is shown that the unused energy due to the full tank is 49.8 %, the collection loss 7.7 %, the system loss is 3.1%, and the sufficient energy at the pump is 39.4%. From these results, it can be concluded that the system had more used energy even at the radiation months, it also shows a low collector loss even with using a fixed structure, and due to the optimized selected angle (Elevation angle ≈ Latitude), it can be more improved if there is a seasonal adjustment to the PV array. Fig. 6c shows that the system performance is increased from October to Apr, and this obvious since the site in the northern hemisphere and there a low radiation in these months, so the system used most of the input power. Fig. 6d proves that, where it showed high incident energy in summer that reaches ≥ 7kWh/m^3/day, but the temperature is an important matter too. PV system efficiency describes in the summer due to the high temperature, as shown in Fig. 7. The figure also shows that the PV Panel power is reduced from 316W @ cell temperature 10°C into 245 W @ cell temperature 70°C under irradiation 1000 W/m^2, and this is mean that there is around 22% reduction in the PV Panel efficiency.

In Fig. 7a, the effective energy at the output of the array in (kWh/day) seems linear when the GlobEff ≤5 kW/m^2.day, but after this point the curve is negatively deflected. Also, Fig. 7b shows that daily array output energy is fluctuated through the year except the time period from the May to the end of Oct, and that because the select site (Karbala) has clear sky in this time of the year.

To summarized the system's total efficiency and discussed the major points that could enhance the system performance, Fig. 9 is introduced. The GlobHor is 1968 kWh/m^2 at the selected site; after adding the global incident in the collector plane and multiply the result by the total collector area (6 Panels * 2m^2), the results will be 23.9 kW. Due to the used polysilicon cells, which offer only 15.11% efficiency, the collected power equals 3,823 kWh. There is room for enhancement here by choosing a more efficient panel. The figure shows a different type of loss, but the second effect is the PV losses due to 11.1% temperature. This design's most significant loss is unused energy due to tank full, 48.8 %, but this percentage is accumulated over the year. It can be enhanced by enlarging the reservoir capacity, which is a matter of depth only. To be exact most of this percentage came from the high irradiation months (May to September), and by considering the pump life cycle and the quantity of the required water for this site, it considers acceptable.



(a) (b) (c) (d)

Fig. 6. The system performance, a), b) Normalized Production and Loss Factors, c) Performance Ratio, and d) Reference Incidence Energy in collector plane

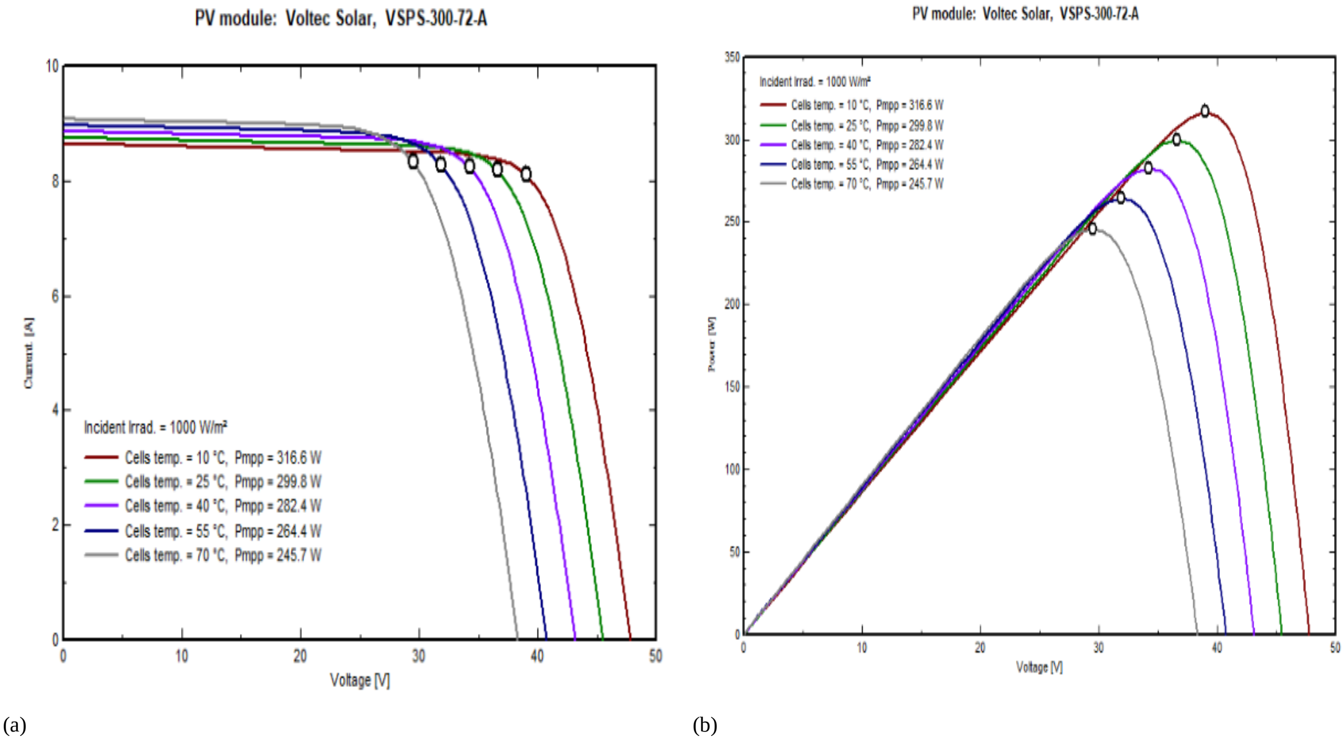


Fig. 7. The Temperature effect on the used PV panels (Model: VSPS-300-72-A), a) Current vs. Voltage@ different temperatures, b) Power vs. Voltage @ different temperatures

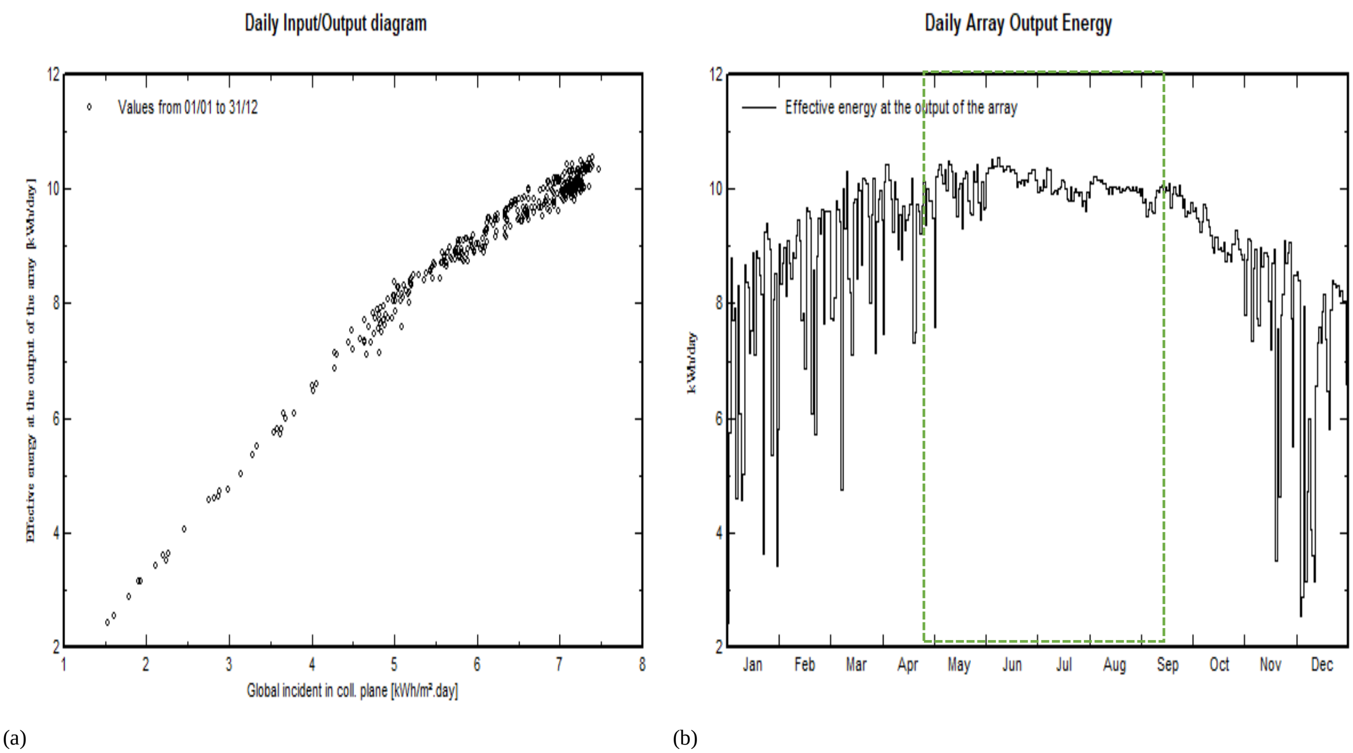


Fig. 8. The PV system performance, a) daily input/output diagram, b) daily array output energy

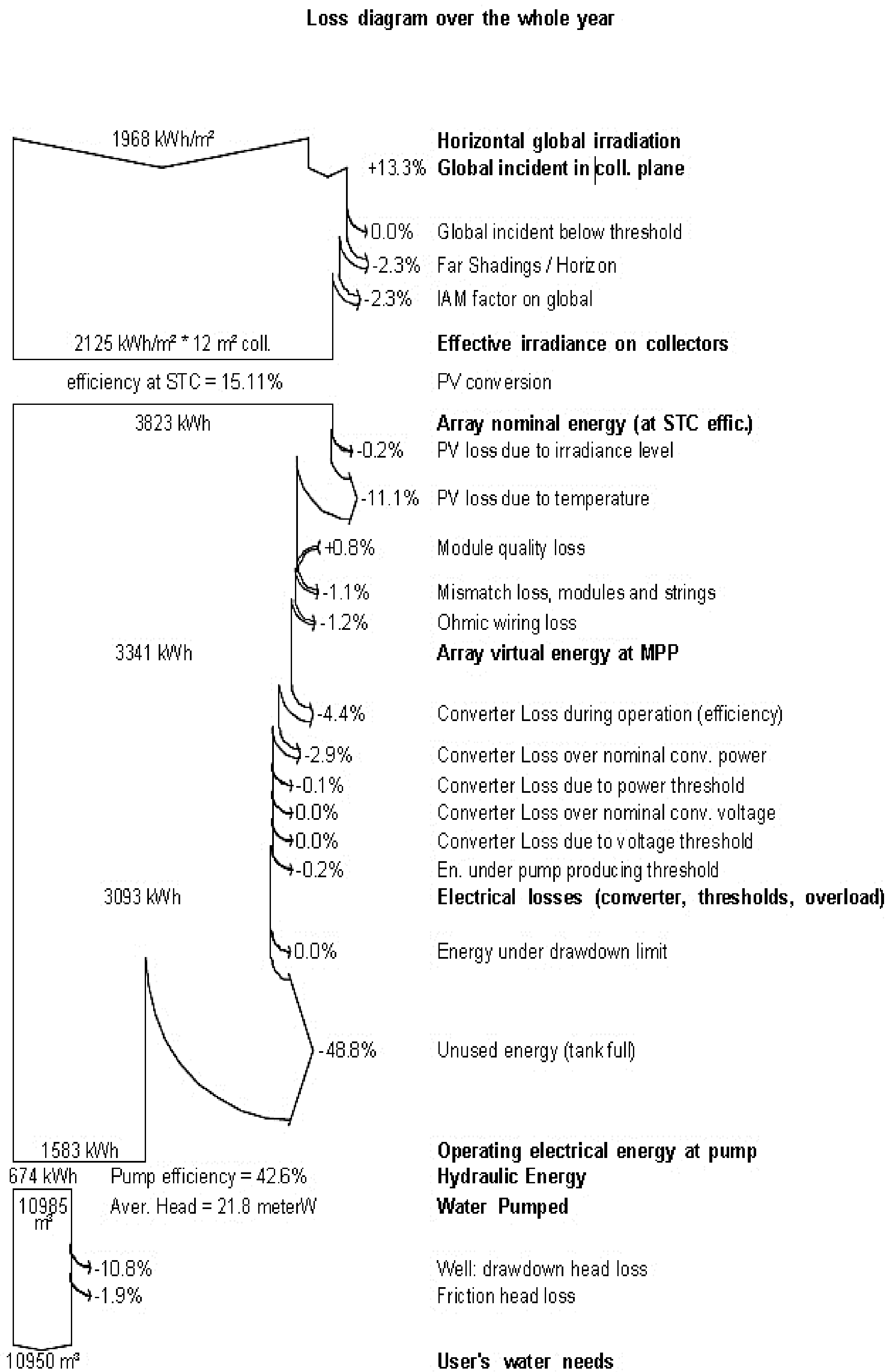


Fig. 9. Loss Diagram over the whole year

4. Conclusion

In this study a simple and optimized design of a solar PV water pumping system is presented. Estimating and understanding the effects of the selected parameters is achieved via photoelectric simulation. It is very useful to evaluate the performance and analyze the design mechanism and understand it through the results of the (pvsystem) program step by step. Based on geographical, geophysical data, and water requirements of crops designers and researchers understand the mechanism for designing a water pumping system by using the simplest methodological math operations performed by this work. The simulation program provides results' predictions for the field through pre-design and development. To further improve the system significantly, the results are analyzed and used to implement a real project in the (holy) city of Karbala. For validation, factors affecting system performance, such as cell temperature, solar irradiance, and tank capacity, were discussed to improve system performance. A step-by-step procedure for designing such a system was presented to simplify the design and computational design for designers.

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