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Evaluation of groundwater pumping with solar energy for irrigation practice in Tunisia using homer energy

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ABSTRACT

In response to the increasing demand for water in irrigated areas, the use of groundwater pumping is emerging as a compelling alternative, particularly in arid and semi-arid regions. However, the costs associated with fossil fuel based pumping systems, as well as their negative environmental impact through the emission of harmful gases, have prompted a shift towards renewable energy. The main objective of this study is to analyze and optimize the feasibility of a groundwater pumping system using different energy sources by HOMER Energy. A farmer in the Nabeul region (Chiba) was selected for an in-depth analysis of water demand and pumping station sizing. The evaluations showed that a 3 kW photovoltaic panel installation per hectare could sufficiently meet the irrigation water needs of this farmer. After optimizing the proposed pumping systems, including diesel generator (DG), photovoltaic (PV) and hybrid (DG + PV) panels, it was determined that the most economical and environmentally friendly solution was the hybrid system. This system produces a power output of 3.3 kW, with CO2 emissions in the order of 5.117 kg per year. HOMER software is a powerful tool for optimizing energy-efficient irrigation practices and assessing the best mix of renewable and conventional energy resources to meet specific needs.

Keywords: groundwater, irrigation, solar energy, HOMER, Tunisia.

INTRODUCTION

Groundwater is an important natural resource in Tunisia, accounting for more than 70% of total water resources [Hammami Abidi et al. 2017]. It plays a crucial role in meeting the country's domestic, agricultural and industrial water needs. Tunisia is located in a semi-arid region with limited surface water resources, making groundwater an important source of water supply. The importance of groundwater in Tunisia is reinforced by the fact that it is relatively more reliable and less prone to seasonal fluctuations than surface water resources. Groundwater is also of great economic importance as it is used for irrigation, which is the backbone of the country's agricultural sector. However, overexploitation, mismanagement and pollution are major challenges to the sustainability of groundwater resources in Tunisia. There is therefore an urgent need to adopt sustainable groundwater management practices to ensure the long-term availability and usability of this vital resource [Besser and Dhaouadi 2022].

In Tunisia, groundwater pumping for irrigation is essential yet increasingly problematic due to over-extraction and aquifer depletion. According to Besser [2022], the rapid expansion of irrigated agriculture has led to unsustainable groundwater use, especially in regions like the Sahel and southern oases, where groundwater serves as the primary water source. Excessive pumping has significantly lowered water tables, with declines of over a meter per year in some areas [Liu et al., 2022]. This depletion exacerbates water scarcity and increases salinization risks, particularly along the coast, where seawater intrusion further contaminates freshwater aquifers [Rakib et al., 2020]. Despite regulatory policies, weak enforcement and widespread illegal well drilling worsen the strain on groundwater resources [Frija et al., 2015], highlighting the urgent need for sustainable water management practices to ensure agricultural resilience in the face of Tunisia's arid climate.

Solar energy is becoming an increasingly popular alternative to traditional energy sources for pumping groundwater around the world [Baghdadi et al. 2015; Gimpel et al. 2022]. This is particularly important in areas where electricity grids are unreliable or non-existent, and where access to water is critical for agriculture and other purposes. In recent years, there has been a significant increase in the use of solar-powered pumps for groundwater extraction, particularly in rural areas of developing countries [Kumar et al. 2015]. Solar-powered groundwater pumping is becoming increasingly popular and feasible in Tunisia. With abundant sunshine and the relatively high cost of traditional grid-connected electricity, solar-powered pumps can be a cost-effective and sustainable solution for small-scale irrigation and domestic water supply in rural areas. Several initiatives and projects have been implemented in Tunisia to promote the use of solar-powered pumps for groundwater extraction. For example, the United Nations Development Programme (UNDP) has supported the installation of more than 350 solar-powered pumps in rural areas of the country, providing reliable and sustainable access to water for agriculture and domestic use [Souissi 2021]. In addition, the Tunisian government has implemented policies to encourage the use of renewable energy, including solar pumps, through subsidies and tax incentives for installation and operation. Overall, solar pumps offer a promising solution for sustainable groundwater extraction in Tunisia, particularly in remote and rural areas where access to electricity and water is limited.

HOMER (Higher-Order Model Estimation and Reconciliation) is a suite of software tools for the analysis and optimization of energy systems [Brandoni, and Bošnjaković 2017] particularly in the context of microgrids and distributed energy resources [Okakwu et al. 2022]. It was developed by the National Renewable Energy Laboratory (NREL) and is freely available for download. HOMER allows users to model and simulate a wide range of energy systems, including photovoltaic and wind power systems, energy storage systems, and conventional generators [Canales and Beluco 2014]. The software uses optimization algorithms to find the optimal configuration of energy systems for a given set of inputs, such as load demand, fuel prices and equipment costs [Masud 2017]. HOMER also includes a comprehensive economic analysis module that can be used to evaluate the cost-effectiveness of different system configurations [Agyekum et al. 2022]. One of the key features of HOMER is its ability to perform sensitivity analysis, allowing users to explore how changes in input variables affect the performance and economics of the energy system [Agyekum et al. 2022; Onu et al. 2022]. This can be particularly useful for decision making and planning purposes, allowing users to assess the impact of different scenarios and assumptions [Wade et al. 2022].

The aim of this study is to design a solar pumping system for groundwater extraction for a farmer in the Chiba region (Nabeul-Cap Bon). This region is densely populated and groundwater is extensively used for irrigation purposes, resulting in over-exploitation. The study aims to analyze and optimize the feasibility of the solar pumping system using HOMER Energy software per hectare (unit scale) to provide an assessment for other farmers and decision makers in the region.

MATERIAL AND METHODS

Region of the study

The Chiba region (Latitude: 36.67694000; Longitude: 10.88794000) belongs to the Korba delegation, part of the Nabeul governorate in the Tunisian Cap Bon (Figure 1).

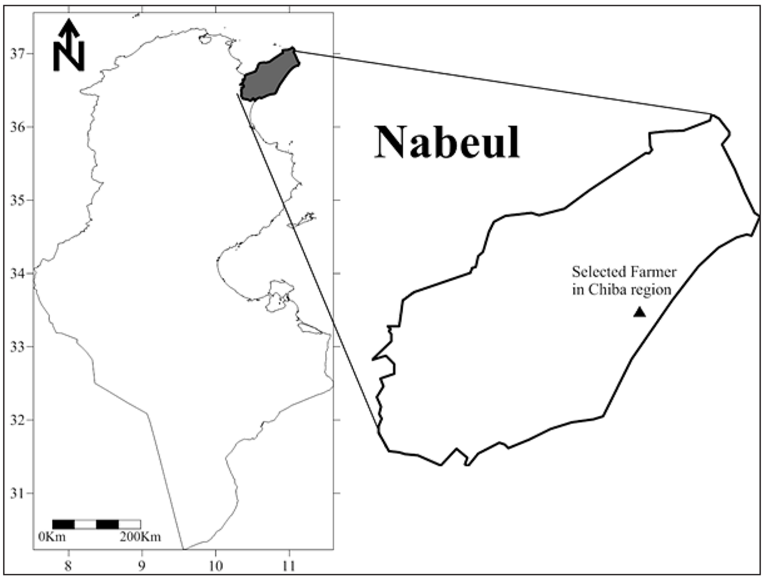


Figure 1. Location of the site in Chiba region

Climate

It is characterized by a semi-arid climate, with mild winters and hot, dry summers, mainly due to its eastern border with the Mediterranean Sea. The study area is characterized by a soil cover dominated by soils of light to medium texture, sandy-loamy, with good porosity, suitable for all types of crops.

Temperature

The region of Nabeul has a temperate climate. The average annual temperature is quite high, around 19 °C, with a range of maximum and minimum temperatures between 27.3 °C and 12.4 °C. On a monthly basis, the coldest month is February, with an average temperature of 12.4 °C, while the hottest month is August, with an average temperature of 27.3 °C.

Rainfall

Chiba is known for its temperate climate. The average annual rainfall is estimated to be about 463.7 mm. The wettest months of the year are October and September, while the driest months are June, July and August.

Wind

The average hourly wind speed shows considerable seasonal variation throughout the year. The windiest period of the year is from October 31 to May 2, with average wind speeds exceeding 18.5 km/h. The calmest period of the year is from May 2 to October 31. The calmest day of the year is August 12, with an average hourly wind speed of 15.1 km/h. The main average wind direction changes throughout the year, with the wind most often blowing from the northwest.

Solar radiation

Tunisia is one of the countries blessed with abundant solar energy. However, solar radiation data are not readily available due to the cost and calibration and maintenance requirements of the measurement equipment, which is a challenge for most projects in developing countries. This section deals with the total daily shortwave solar radiation reaching the Earth’s surface over a wide area, fully accounting for seasonal variations in day length, the Sun’s elevation above the horizon, absorption by clouds, and other atmospheric components. Shortwave radiation includes visible light and ultraviolet radiation. Average daily shortwave solar radiation from 2010 to 2020 shows extreme seasonal variations throughout the year (National Institute of Meteorology in Tunisia). The brightest period of the year lasts for 3.4 months, from May 6 to August 19, with shortwave solar radiation per square meter exceeding 6.8 kWh. The darkest period of the year lasts for 3.5 months, from 30 October to 12 February, with shortwave solar radiation per square meter falling below 3.5 kWh (Table 1).

Table 1. Means of solar energy for every month in Chiba region (2010–2020)

Solar energy (kWh/m²/month)	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	2.7	3.6	5.0	6.2	7.1	7.7	7.9	6.9	5.4	4.0	3.0	2.5

Note: National Institute of Meteorology in Tunisia.

Sizing of the solar pumping system

Sizing photovoltaic (PV) panels for irrigation systems involves calculating the electrical power required to operate the pump and ensuring that the solar array can generate enough energy to reliably meet that demand. This process involves several key steps, including determining the water requirements of the irrigation system, estimating the power consumption of the pump, and sizing the PV panels based on solar irradiance data and system efficiency [Cuadros et al. 2014; Bertsiou et al. 2022; Wang et al. 2023].

Step 1 – Calculate water requirements: The first step in sizing PV panels for irrigation is to determine the water requirements of the system. This takes into account factors such as crop type, acreage, soil type, climatic conditions, and irrigation method.

Step 2 – Calculate pump capacity: Once the water requirement is known, the next step is to calculate the power consumption of the pump needed to deliver that water.

Step 3 – Preliminary PV panel sizing: Once the pump power requirement has been determined, the next step is to size the PV panels to provide the electrical power needed to run the pump. This involves estimating the daily energy consumption of the pump and then sizing the solar array to generate that amount of energy.

Step 4 – Solar Irradiance Data: Solar irradiance data for the location of the PV system is required to estimate the amount of solar energy available for power generation.

Step 5 – PV Panel Efficiency: The efficiency of the PV panels, along with other system components such as inverters and batteries, must be considered when sizing the solar array. PV panel efficiency is typically expressed as a percentage and represents the efficiency with which solar energy is converted to electrical energy.

Step 6 – Calculate panel size: Finally, the size of the PV panels can be calculated.

The choice of pumping system installation to meet the irrigation water requirements of crops and provide water for livestock on the farm is calculated in detail in the results section based on the study case of a farmer in the Chiba region.

Homer energy pro

HOMER (Higher-Order Model Estimation and Reconciliation) is a software suite for analyzing and optimizing energy systems, especially for microgrids and distributed energy resources [Singh et al. 2021; Pardo and Navarro-González 2024]. Developed by the National Renewable Energy Laboratory (NREL) in Colorado (USA), it is freely available for download. HOMER enables modeling of diverse energy systems, including photovoltaic and wind power, energy storage, and conventional generators. It uses optimization algorithms to determine optimal configurations based on inputs like load demand, fuel prices, and equipment costs [Chowdhury et al. 2022; Lin et al. 2023; Samir et al. 2024]. The software also includes economic analysis and sensitivity analysis tools, which help users assess cost-effectiveness and explore the impact of changing variables on system performance. HOMER is a valuable resource for the renewable energy sector and academic research [Probst et al. 2024].

The HOMER software is easy to use, with an interface similar to most software, with a menu at the top and icons that can be used without navigating through menus. The HOMER Pro 3.11.2 interface can be divided into three main areas:

- a system definition area.
- a zone for calculation results.
- a zone for resources (temperature, solar, wind).

The System Definition area allows the selection of the equipment to be included in the modeled system. The user can fill the window with the necessary data by clicking on the icon specified for this study:

- test site coordinates: those of the selected farmer in the Chiba region;
- type: dwelling with daily electricity;
- grid: we chose an off-grid installation;

- fuel price per liter: set at 2 DT (Tunisian dinar, with 1 DT equal to approximately 0.32 US dollars);
- choice of system: a photovoltaic (PV) system was chosen at a cost of 15.000 DT;
- storage: the battery chosen is an LGChem 3.3 kWh at a cost of 8000 DT;
- once these data have been entered, the HOMER software can be run as shown in Figure 2;
- a diesel-powered pump is used to extract groundwater by converting diesel fuel energy into mechanical power. The pump creates suction, lifting water from underground aquifers through pipes to the surface. It's commonly used in agriculture, construction, and remote areas, offering portability and efficiency but requiring regular maintenance and fuel supply.
- a photovoltaic (PV) system with a battery and generator setup for groundwater pumping combines solar energy, storage, and backup power. Solar panels convert sunlight into electricity to power the water pump during the day. The generator serves as a reliable backup during extended cloudy periods or high-demand scenarios, ensuring uninterrupted water supply. This system enhances energy reliability while reducing diesel fuel dependency and carbon emissions. It's ideal for remote or off-grid areas, supporting sustainable water extraction with flexibility and resilience against varying environmental conditions.
- a hybrid PV system with a battery and generator for groundwater pumping combines solar power, diesel energy, and energy storage for reliable and efficient operation. Solar panels provide primary power during daylight, reducing diesel usage, while excess energy charges the batteries for night time or low-sunlight conditions. The diesel generator serves as a backup, ensuring uninterrupted pumping during extended cloudy periods or peak demand.

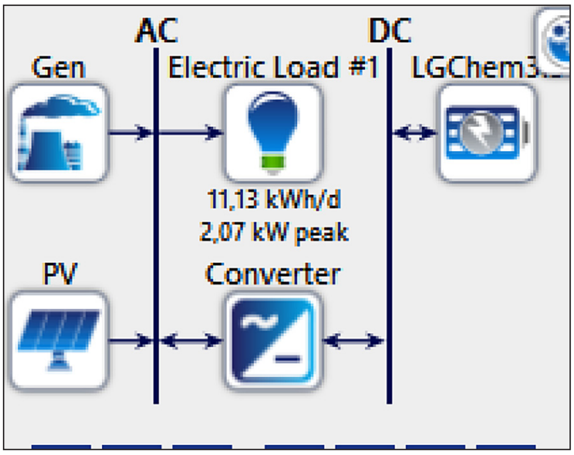


Figure 2. Components of the water pumping system implemented in the Chiba region

RESULTS AND DISCUSSION

Irrigation needs of crops

Given the suitability of the soil in the region and the agricultural vocation, the farm grows vegetables such as tomatoes, peppers, potatoes, fennel and cabbage, as well as fodder crops, using drip irrigation. The cropping calendar for the different recommended crops to be planted in the study area is shown in Table 2. This table provides information about the surface area allocation (%) of different crops planted across various months.

The net irrigation water requirement (NIWR) for the selected crops is determined from the water balance. The net irrigation water requirements for the selected crops are shown in the following table (Table 3). ET0 was estimated using the Penman-Monteith equation and Kc values were taken from [Allen et al. 1998].

Taking into account the efficiency of the irrigation system (efficiency = 0.85 for the drip

Table 2. Crop calendar in the case study of Chiba region

Crop	Surface area (%)	S	O	N	D	J	F	M	A	M	J	Ju	A
Potato	40						▨	▨	▨	▨			
Tomato	40							▨	▨	▨	▨	▨	
Pepper	20							▨	▨	▨	▨		
Potato (late)	40	▨	▨	▨	▨								
Cabbage	20	▨	▨	▨	▨	▨							
Fennel	30	▨	▨	▨	▨	▨							
Forage	10	▨	▨	▨	▨	▨							

Table 3. Net irrigation water requirements (NIWR) in mm/month

Description	S	O	N	D	J	F	M	A	M	J	Ju	A
ET_0 (mm/month)	123.3	96.6	65.1	55.9	59.7	61.4	78.9	94,2	125	145.9	174.6	163.6
P (mm/month)	65.7	77.9	46.9	41.5	39.7	38.1	55.3	33.1	23.1	13.6	5.6	23.7
Pe (mm/month) Pe = 0.8*P	52.6	62.3	37.5	33.2	31.8	30.5	442	26.5	18.5	10.9	4.5	19
NIWR=Kc* ET_0 -Pe												
Potato						-	15	81.83	81.5			
Tomato							-	43.2	125.25	138	118	
Pepper							-	44.15	112.75	120.41		
Potato (late)	2.88	10.15	37.36	11.52								
Cabbage	2.88	10.15	30.85	19.9	21.9							
Fennel	9.05	-	14.58	22.7	33.87							
Forage	-	19.8	30.85	22.7	19							
Total	14.81	40.1	113.64	76.82	74.77		15	169.18	319.5	258.41	118	

Note: P – precipitation; Pe – effective precipitation.

Table 4. Irrigation water volumes (m^3)

Description	S	O	N	D	J	F	M	A	M	Ju	J
Potato						-	705	3840	3835		
Tomato						-	-	2032	5894	6494	5552
Pepper							-	1038	2652	2833	
Potato (late)	135	477	1758	542							
Cabbage	67	239	725	470	517						
Fennel	319	-	514	801	1195						
Forage	-	233	362	267	223						
Total (m^3)	521	519	3359	2080	1935		705	6910	12381	9327	5552

irrigation system) and the area occupied by the crops, the amount of irrigation water required is shown in the table below. According to Table 4, the irrigation water requirement for the peak month of May is estimated to be 12.381 m^3. The average irrigation water requirement per hectare is 1.238 m^3/ha (Total surface = 10 ha). Water consumption also includes watering 25 animals, including goats and sheep. Knowing that each animal consumes 5 liters of water per day, the water requirement for animal watering is 4 m^3. The total water consumption of the farm is 1.242 m^3/ha.

Pumping height

To determine the required pumping flow rate per hour (or average hourly flow rate of the machine), the average daily water consumption is divided by five, assuming that the entire flow will be obtained more or less in 5 hours. This is based on average sunlight conditions [Ammar et al., 2012]. Therefore, the average hourly flow rate of the machine is 8 m^3/h per hectare. The geometric water elevation height EH is 17 m. The optimal diameter of the discharge pipe can be sought through Bresse formula [Gama et al. 2019]: $- 1.5\sqrt{Q}$, with: DN: nominal diameter in m Q: pumping flow rate in m^3/s. This formula yields a diameter of 70 mm. In practice, a commercialized diameter of DN: 63/75 is chosen with a head loss (HL) of 10 mm/m. The total pressure head is expressed as follows:

$$PT = 17 \times HL \qquad (1)$$

The total pressure head height (PT) is equal to 17.2 m. In our conditions, we chose a submersible pump with an AC motor. This choice was determined by the curves provided by the manufacturers; the efficiency of the chosen pump is about 75%, and that of the motor is approximately 80% at the nominal operating point [Mahmoud et al., 2024]. The total efficiency of the pump-motor group (EP) is therefore 60%.

So, the electrical energy required for the pump is [Cuadros et al. 2004]:

$$We = (Ch \times Q \times PT)/EP \tag{2}$$

where: Ch represents the hydraulic constant equal to 2.725 kg.h/m², Q represents the daily flow rate, PT represents the total pressure head, and Ep represents the efficiency of the pump. In the case of this study the daily energy required for the chosen pump is 3124 W/day.

Solar pumping system

The peak power Pp is the theoretical power, expressed in watts, that a PV module can produce under standard sunlight conditions (i.e., 1.000 W/m²) and temperature (i.e., 25 °C). To determine the value of this power, we need the geographical conditions of the site. These conditions are: latitude 30° 55' 23" North, longitude 6° 54' 15" West, elevation 1,103 m, and inclination angle 30°. The site's daily irradiation (Irr) is 2.5 kWh/m². The peak power of the PV generator [Cuadros et al. 2004] is given by the following equation:

$$Pp = We/(R \times Irr) \tag{3}$$

where: R is the efficiency of the inverter. Pp is equal to 1315 W.

Since the system works reasonably well, we tilt the field at an angle equal to the latitude, which is 30°. It is observed that December has the lowest average maximum hours of sunlight for this inclination, i.e. a maximum of 2.5 hours of sunlight per day. Therefore, the number of solar panels for our slope is:

$$N = Pp/320 \tag{4}$$

where: 320 is the power of a single photovoltaic panel [Cuadros et al. 2004]. In our case, the number of PV panels is 4.

Optimization with homer energy

To improve the quality of energy produced by a power generation system, a hybrid system is proposed [Maatallah et al. 2016; Babatunde et al. 2022]. An application of a hybrid system is simulated using the HOMER software to pump a certain amount of groundwater at our study site for optimization, which allows the determination of the type of actual hybrid system to be installed [Yousef et al. 2022; Hossain et al. 2024].

When the calculation is complete, the results are displayed and the most economical solution is listed first. A summary of the system and associated costs is displayed in the results area. Once all the data has been entered and the simulation started, a large number of results will be obtained. Since it is possible to enter different configurations for the same type of system, the results can be visualized in two ways: "categorized" and "total". When the "categorized" option is selected, the most economical option is displayed for each system category and therefore for each system type. For example, HOMER will only show the best option for a photovoltaic system with batteries, even if the simulation has been performed with different configurations (different number of panels, batteries). For the 'Total' option, HOMER will display all systems in the same list, with the first result being the most economical of all simulated system types. It is important to optimize each type of system to eliminate non-viable systems, which is achieved through multiple simulations to converge on an optimal system for each type. It is important to remember that the first result given by HOMER in the result list is always the most economical system found in terms of Net Present Cost among all simulated systems and configurations. As mentioned earlier, summaries of the systems and associated costs are displayed in the results area. The HOMER optimizer found 5 cases. The economic difference between the first four configurations is not very significant, about 3000 DT. We focus on this study (Table 5):

- the most economical solution: Exclusive diesel generator,
- the least economical solution: Exclusive photovoltaic panels,

Table 5. Summary of the optimization results in terms of performance for the three scenarios studied

System architecture	Power generator	Power installation	Generic flat plate
Diesel	2.3 kW	-	-
PV	-	6.5 kw	4
Hybrid	0.271 kW	3.175 kw	1

Table 6. Detailed price (DT) of the three installations (diesel, PV and hybrid) for irrigation water supply)

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Diesel						
Autosize genset	3 450.00	15 044.53	4 740.71	20 920.39	-81.18	44 074.45
System	3 450.00	15 044.53	4 740.71	20 920.39	-81.18	44 074.45
PV						
Generic flat plate PV	19 489.71		509.54	0.00	0.00	19 999.25
LGChem RESU [3.3kWh]	32 000.00	10 896.38	313.73	0.00	-752.94	42 457.17
System converter	725.57	132.56	0.00	0.00	-14.23	843.90
System	52 215.28	11 028.94	823.26	0.00	-767.17	63 300.32
Hybrid						
Autosize genset	3 450.00	11 073.66	3 578.80	15 332.95	-198.54	33 236.87
Generic flat plate PV	2 625.00		68.63	0.00	0.00	2 693.63
LGChem RESU [3.3kWh]	8 000.00	2 724.10	78.43	0.00	-188.23	10 614.29
System converter	81.25	14.84	0.00	0.00	-1.59	94.50
System	14 156.25	13 812.60	3 725.86	15 332.95	-388.37	46 639.29

- the intermediate solution: Hybrid installation with diesel generator and photovoltaic panels.

Cost

The cheapest solution is a diesel generator with a total price of 44,074.45 DT. The most expensive installation is PV panels with a price of 63,330.32 DT. The installation of a hybrid station has an intermediate price of 46,639.29 DT. The difference with the diesel installation is not significant. The most expensive components are the fuel consumption for the diesel and hybrid installations, while for the PV installation it is the batteries (Table 6).

Electrical production

Table 7 shows that the PV system produces the most electricity, significantly outperforming the other systems analyzed. Specifically, the PV system produces a significant amount of electricity while the hybrid system produces almost half of this amount, highlighting a notable disparity in energy output between these two systems. The annual electricity consumption of the diesel pump system is approximately 4000 kWh/year, which is identical to that of the hybrid system. This parity in energy consumption suggests that both systems have similar operational energy requirements, despite their different environmental impacts and emission profiles. In addition, the PV system not

Table 7. Electrical production of the three installations (diesel, PV and hybrid) for irrigation water supply

Parameter	Diesel	PV	Hybrid
Production (kWh/yr)			
Generic flat plate PV		9 536	1 284
Autosize genset		9 536	4 007
Total			5 292
Consumption (kWh/yr)			
AC primary load	4062	3 906	4 062
DC primary load	0	0	0
Total	4062	3 906	4 062
Quantity (kWh/yr)			
Excess electricity	1555	5 188	1 114
Unmet electric load	0	156	0
Capacity shortage	0	207	0
Renewable fraction	0	100	1.4
Max. renew. penetration	0	2 846	383

only meets its energy consumption requirements, but also produces an excess of 5188 kWh/year. This excess energy production demonstrates the efficiency and potential of PV systems to produce renewable energy well beyond their immediate needs. This excess energy can be redirected for a variety of uses, such as feeding back into the grid, powering additional applications, or stored for future use, increasing the overall sustainability and energy resilience of the system.

The comparison of these energy systems highlights the advantages of PV systems in terms of both energy production and environmental impact. While the hybrid and diesel systems have comparable energy consumption levels, the ability of the PV system to produce a significant surplus of clean energy highlights its potential as a superior solution for sustainable energy generation. This analysis highlights the importance of continued investment and development in photovoltaic technology to realize its full potential in reducing dependence on fossil fuels and minimizing environmental impact.

According to Figure 3, the production of electrical energy follows the trend of the variation of the water demand of the crops. Production peaks in the summer months, with a marked decrease in the wettest months.

Fuel production

Fuel consumption is a critical factor for both the diesel and hybrid systems. As shown in Figure 4, the range of fuel consumption is more pronounced for the hybrid system, while for the diesel system, consumption remains relatively constant over the months. For the diesel system, 75% of the recorded fuel consumption values are between 0.3 liters per hour (l/h) and 0.45 l/h. This narrow range indicates that the diesel system maintains a steady fuel consumption rate, reflecting its operational consistency and predictability.

In contrast, the hybrid system shows a wider range of fuel consumption values, with 75% of the recorded data varying between 0 l/h and 0.4 l/h. This wider range of variation suggests that the hybrid system experiences more variation in fuel consumption. This variation could be due to different operating conditions, different load requirements, or the efficiency of the hybrid system in different scenarios.

Despite these variations, an average fuel consumption value of approximately 0.4 l/h over the

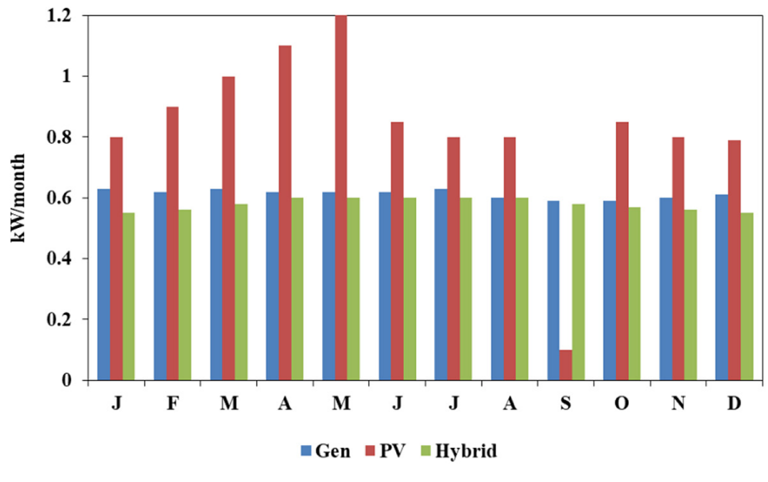
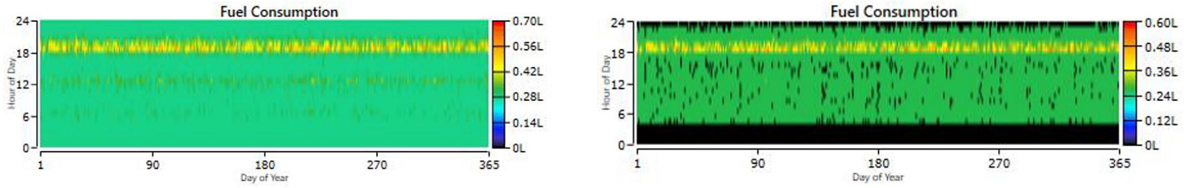


Figure 3. Monthly average electrical production (kW/month) for the three studied scenarios (Diesel (Gen), PV and Hybrid (PV+Gen)



a) Diesel installation **b) Hydrid installation**

Figure 4. Monthly and daily diesel and hybrid fuel consumption

year can be considered for both the diesel and hybrid systems. This average provides a useful benchmark for comparing the fuel efficiency of the two systems on an annual basis.

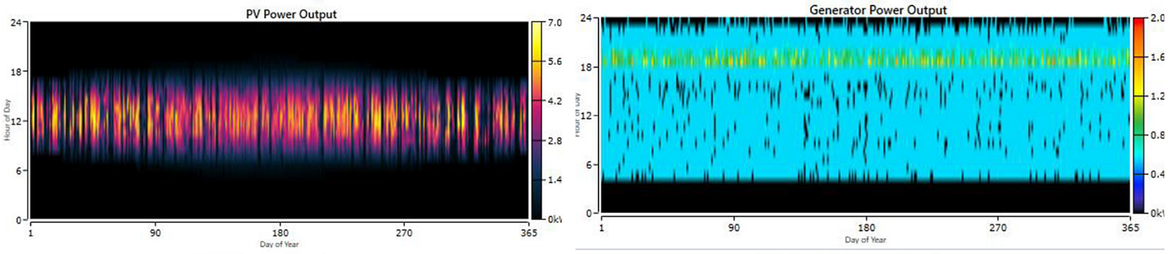
Power output

The diesel plant has the highest number of operating hours, running continuously for 8760 hours per year, which is equivalent to full-time operation throughout the year. This continuous operation underscores the reliability of the diesel system and its role as a consistent energy source, albeit at a significant environmental cost due to its fuel consumption and emissions (Table 8). In stark contrast, the photovoltaic (PV) panels have the highest energy production at 9536 kWh/year (Table 8). Remarkably, this high production is achieved with the fewest operating hours of any of the installations. PV panels typically operate only during daylight hours, and their efficiency can be affected by factors such as weather and seasonal variations. Despite these limitations, their ability to produce more energy with fewer operating hours underscores the efficiency and effectiveness of solar energy as a renewable resource.

The hybrid system, on the other hand, has performance metrics that are closer to those of the diesel system, but with some differences. Although it operates for fewer hours and produces less energy than the diesel system, its overall performance is relatively comparable. This suggests that the hybrid system, which is likely to use hydrogen-based technology, offers a viable alternative with a lower environmental impact, although it cannot match the energy output or operational consistency of the diesel system. Figure 5 shows that the PV system is the most powerful with an average of 4 kWh/day. The performance values for the diesel and hybrid systems are 2 kWh/day and 1.65 kW/day, respectively.

Table 8. Electricity production of the three installations (diesel, PV and hybrid) for irrigation water supply

Parameter		Diesel	Hybrid
Hours of operation	hrs/yr	8760	6613
Number of starts	starts/yr	1	600
Operational life	yr	1.71	2.27
Capacity factor	%	27.9	19.9
Fixed generation cost	DT/hr	0.442	0.442
Marginal generation cost	DT/kWh	0.251	0.251
Electrical production	kWh/yr	5618	4007
Mean electrical output	kW	0.641	0.606
Minimum electrical output	kW	0.575	0.575
Maximum electrical output	kW	2.07	1.8
Fuel consumption	L	2667	1955
Specific fuel consumption	L/kWh	0.475	0.488
Fuel energy input	kWh/yr	26247	19 237
Mean electrical efficiency	%	21.4	20.8
Photovoltaic			
Rated capacity	kW	6.5	
Mean output	kW	1.09	
Mean output	kWh/d	26.1	
Capacity factor	%	16.8	
Total production	kWh/yr	9536	
Minimum output	kW	0	
Maximum output	kW	6.71	
PV penetration	%	235	
Hours of operation	hrs/yr	4386	
Levelized cost	DT/kWh	0.267	



PV installation **Hybrid installation**

Figure 5. Daily electricity produced (kWh/day) by the three plants (diesel, PV and hybrid) used to supply water for irrigation

Table 9. Battery characteristics production of PV and hybrid systems

Parameter		PV	Hybrid
Batteries	qty.	4	1
String size	batteries	1	1
Strings in Parallel	strings	4	1
Bus voltage	V	51.1	51.1
Autonomy	hr	24.4	6.1
Storage wear cost	DT/kWh	0	0
Nominal capacity	kWh	12.9	3.22
Usable nominal capacity	kWh	11.3	2.83
Lifetime throughput	kWh	21264	5 473
Expected life	yr	10	10
Average energy cost	DT/kWh	0	0
Energy in	kWh/yr	2170	559
Energy out	kWh/yr	2073	533
Storage depletion	kWh/yr	11.3	1.97
Losses	kWh/yr	109	28
Annual throughput	kWh/yr	2126	547

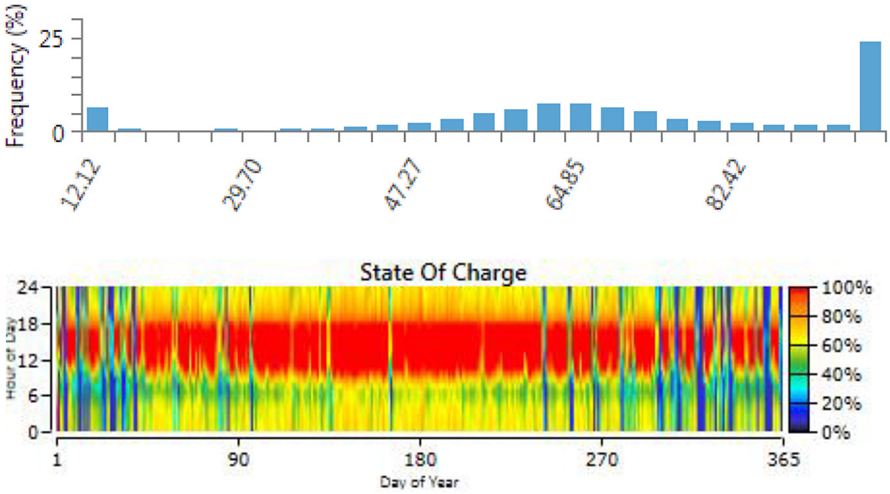
Battery

The diesel plant has the highest number of operating hours, running continuously for 8760 hours per year, which is equivalent to full-time operation throughout the year (Table 9). This continuous operation highlights the reliability of the diesel system and its role as a consistent power source, albeit at a significant environmental cost due to its fuel consumption and emissions.

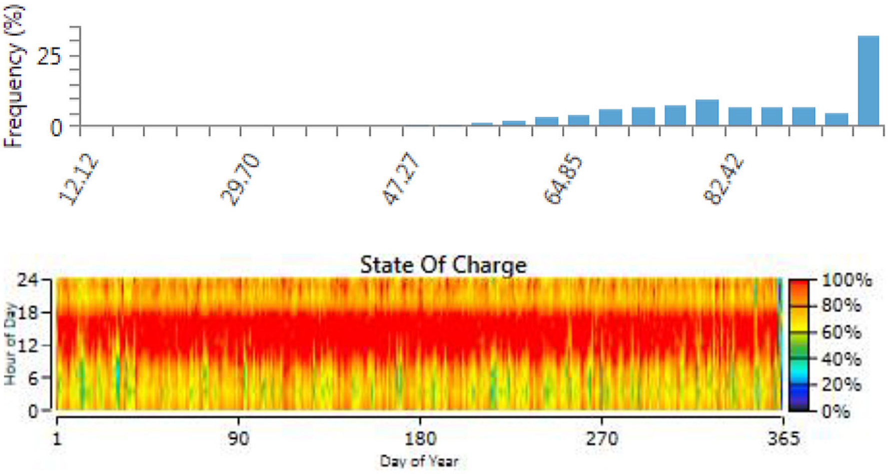
In contrast, the photovoltaic (PV) panels have the highest energy production at 9536 kWh/year. Remarkably, this high production is achieved with the fewest operating hours of any of the installations. PV panels typically operate only during daylight hours, and their efficiency can be affected by factors such as weather and seasonal variations. Despite these limitations, their ability to produce more energy with fewer hours of operation underlines the efficiency and effectiveness of solar energy as a renewable resource.

The hybrid system, on the other hand, has performance metrics that are closer to those of the diesel system, but with some differences. Although it operates for fewer hours and produces less energy than the diesel system, its overall performance is relatively comparable. This suggests that the hybrid system, which is likely to use hydrogen-based technology, offers a viable alternative with a lower environmental impact, although it cannot match the energy output or operational consistency of the diesel system.

According to Figure 6, the average state of charge of the PV batteries is between 60 and 80% on all days of the year. For the hybrid system, it is between 70 and 80%. The variation of the state of charge is more significant for the PV system.



a) PV installation



b) Hybrid installation

Figure 6. Battery state of charge and frequency of use of PV and hybrid systems

Table 10. Summary of emissions from three irrigation water supply systems (diesel, PV and hybrid)

Parameter		Diesel	PV	Hybrid
Carbon dioxide	kg/yr	6982	0	5.117
Carbon monoxide	kg/yr	44	0	32.3
Unburned hydrocarbons	kg/yr	1.92	0	1.41
Particulate matter	kg/yr	0.267	0	0.195
Sulfur dioxide	kg/yr	17.1	0	12.5
Nitrogen oxides	kg/yr	41.3	0	30.3

Emissions

Photovoltaic panels do not produce any emissions during their operation, making them a clean energy source. According to Table 10, the diesel system has the worst environmental indicators of the energy systems analyzed. This includes high levels of CO_2 emissions as well as other pollutants typically associated with fossil fuel combustion, such as NOx and particulates. In contrast, the hybrid system, which likely refers to a hydrogen-based energy system or metal hybrid storage, is less polluting than the diesel system. It produces fewer harmful emissions, contributing to a lower environmental impact. However, it's important to note that while the hybrid system is cleaner, the amount of CO_2 emitted is not significantly different from the diesel system. This suggests that while the hybrid system has environmental benefits, there is still room for improvement in reducing its carbon footprint. The comparison underscores the critical need for continued advances in clean energy technologies to significantly reduce emissions and mitigate environmental impacts. Transitioning from fossil fuels to renewable energy sources such as PV panels, and improving the efficiency and sustainability of alternatives such as hybrid systems, are essential steps in addressing climate change and promoting a healthier environment.

The optimization of the installation of photovoltaic panels for groundwater pumping in the Chiba region using HOMER Po 3.11 resulted in: The best scenario in terms of amortization of the installation is one using commercial fuel (2 DT/l), but under maximum operating conditions, the power generated does not exceed 2.3 kW.

The best scenario in terms of power output is a photovoltaic installation with a power of 6.5 kW. The hybrid installation scenario provides an intermediate power of 3.175 kW. Therefore, the most optimized scenario is the simulation of a hybrid system, the most cost effective, with a power of 3.175 kW and a cost of 47.000 DT.

CONCLUSIONS

Solar energy, abundant and renewable, holds great promise as a sustainable energy source worldwide. However, its use in the agricultural sector remains underexploited, particularly in developing regions such as Tunisia. Solar-powered groundwater pumping offers a promising and economically viable alternative for farmers in such areas. A detailed study of a solar-powered groundwater pumping system for a farmer in the Chiba region of Cap Bon, Tunisia, demonstrated the practical application of solar energy in agriculture. The study used HOMER Energy software to perform rigorous economic and technical evaluations, providing a detailed assessment of the power requirements for crop irrigation based on specific water requirements per hectare. The optimization results showed that a hybrid system combining a diesel generator with photovoltaic panels produced the most favorable economic and technical results in terms of cost (approximately 46 kDT) and energy efficiency (approximately 3.3 kWh). This is largely due to the low cost of fuel in Tunisia, which makes the use of fossil fuels for groundwater pumping more economically viable.

Looking forward, it is essential to extend this analysis to a broader basin scale. Such an approach would allow a comprehensive assessment of the overall energy and economic requirements for solar pumping systems. This would facilitate the development of tailored solutions that can increase the adoption and efficiency of solar energy in agriculture across larger regions, ultimately contributing to more sustainable agricultural practices and energy use in Tunisia. Especially as Tunisia positions itself as a leader in solar energy in North Africa and strives to meet its goal of generating 30% of its electricity from renewable sources by 2030.

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