Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28318

255 (2022) 27–33
April

Energy yield evaluation of a rainwater harvesting system using a novel agrophotovoltaics design

Fathia Chekired[a,*], Amina Richa[b], Sami Touil[b], Brendon Bingwa[c]

[a]*Unité de Développement des Equipements Solaires UDES/EPST CDER, Tipaza, Algeria, email: chekiredfathya@yahoo.fr*
[b]*Research Laboratory of Agricultural Production and Sustainable Development of Natural Resources, University of Djilali Bounaama, Khemis Miliana, Algeria, emails: a.richa@univ-dbkm.dz (A. Richa), s.touil@univ-dbkm.dz (S. Touil)*
[c]*Fraunhofer Institute for Solar Energy System ISE, Heidenhorfstr.2,79110 Freiburg, Germany, email: brendon.bingwa@ise.fraunhofer.de*

Received 30 July 2021; Accepted 14 January 2022

ABSTRACT

The aim of this study was to assess an agrivoltaic prototype design integrated with rainwater harvesting, installed at the Khemis Miliana demo site in Algeria. Agrivoltaics combines land-use for food and electricity production. Photovoltaic (PV) modules surfaces can be utilized as water catchment canopies to harvest rainwater for crop irrigation and/or drinking water. In the current investigation, light distribution under the PV modules was assessed, as well as the energy yield and applications of electricity produced, and rainwater harvesting potential. The design of the rainwater harvesting agrivoltaic system in a V-shape design was assessed and the energy yield was modeled and simulated. The energy yield assessment was performed to predict the performance of the V-shape design, as well as determining the best installation parameters and system layout. Agrivoltaic systems have great economic potential by allowing for electricity production and crop growth on the same land area. This would be a significant development in the sustainable development of society.

Keywords: Agrivoltaic; Energy yield assessment; Irradiance simulation; Photovoltaic system; Crop yield; Water consumption

1. Introduction

The terminology "agrivoltaic", alternatively known as agrophotovoltaics (APV), Agri-PV and APV, describes an Integrated Food-Energy System (IFES) approach in which photovoltaic (PV) modules are mounted at a height that allows for agricultural activity underneath [1]. The concept, first proposed in 1982 by Adolf Goetzberger and Armin Zastrow, contributes to resource efficiency, through dual land-use via energy and crop production on the same area of land [2]. The resource efficiency gained by agrivoltaics is more specifically quantified through applying the concept of the land equivalency ratio (LER), adapted from agroforestry (the practice of combining cultivation of trees and food crops). LERs are indicators of the productivity of the land, used to assess the value of mixed cropping systems. The approach allows for the comparison of productivity of mixtures of crops on the same land area vs. monocultures [3].

By extending LER to any system that mixes two (or more) types of production on the same land unit, Dupraz et al. [3] was able to measure the productivity of agrivoltaic systems. The results of the study showed that APV systems had the potential to be efficient, with a 35%–73% increase of land productivity for two APV systems with different panel densities (Ground Cover Ratio – GCR). Apart from the increase in the land-use efficiency, the multiple ecosystem services of agrivoltaic systems have been the focus of past and current research. Amaducci et al. [4], Marrou et al. [5] and Barron-Gafford et al. [6], among

* Corresponding author.

Presented at the International Virtual Conference on Water and Energy (ICWE 21), Hassiba Benbouali University of Chlef, Algeria, 25–27 May 2021

1944-3994/1944-3986 © 2022 Desalination Publications. All rights reserved.

others, have found that agrivoltaic systems have numerous effects on the agricultural, photovoltaic and water layers. The shading caused by the PV modules impacts the microclimate below, by potentially reducing air and soil temperature and increasing humidity and moisture. This subsequently results in a reduction in soil-crop evapotranspiration and reduced crop irrigation water requirements [4]. Shading additionally reduces heat and light stress on crops, thus preventing suppressed photosynthesis, allowing for greater carbon uptake for growth and reproduction. The presence of crops below PV modules additionally has the potential to improve module efficiency through a "transpirational cooling effect" [6].

The contribution of agrivoltaic systems to resource efficiency is enhanced by the potential to close the loop in the Water-Energy-Food nexus by integrating water management solutions into the infrastructure. Due to similarities between rooftops and PV module array design and orientation, the surface of photovoltaic modules has the potential to be used for water collection. Santra et al. [7] was among the first to propose that the surface of PV modules can be employed to collect and store rainwater. This includes the need for designing and developing a PV system with rainwater harvesting, conduction and underground storage for cleaning panels and supplementing irrigation to the crops grown under the system. Furthermore, a 105 kWp agrivoltaic system was installed at the Central Arid Zone Research Institute in Jodhpur, Western Rajastan. With a total surface area of 651 m^2, the installation was found to have an efficiency of 70%–80% and the potential to provide 37.5 mm irrigation over an area of 1 acre (equivalent to 375 m^3 total water supplied). The design mimicked a typical rooftop and gutter setup, with a gutter placed along the lower edge of the PV modules [7]. Fig. 1 represents the agrivoltaic system with gutter for collecting rainwater installed at the Khemis Miliana demo site in Algeria.

The aim of this study was to assess an agrivoltaic prototype design integrated with rainwater harvesting, installed at the Khemis Miliana demo site in Algeria. The design of the rainwater harvesting agrivoltaic system in a V-shape design was assessed and the energy yield was modeled and simulated. The energy yield assessment was performed to predict the performance of the V-shape design, as well as determining the best installation parameters and system layout.

2. Agrivoltaic and rainwater harvesting design concept

The concept for a rainwater harvesting design developed by Fraunhofer ISE, deviates from the previously described approaches in which a rain gutter is attached to the mounting structure at the lower edge of the PV modules. In the Fraunhofer ISE design, the mounting structure is fixed in a "V-shape" that can be constructed to the required PV module tilt angle and allows for the mounting of any type of PV module. The design was proposed to create material-use efficiency and limit the shading effect of an additional structure on each module row (by having two rows share a single rain gutter) and close the loop in the Water-Energy-Food security nexus (Fig. 2).

3. Crop selection and role in system design classification

The shade tolerance of crops plays an important role in the agrophotovoltaics (APV) system design parameters, namely the PV module row distance, table height (distance from the ground to the lowest point of the PV modules), and the array orientation (azimuth), as these design factors dictate the amount and distribution of solar irradiation incident on the area below the PV modules. Although the impact of the agrivoltaic system shading on agriculture is not well understood, as studies of APV impacts on crop physiology, soil, and agricultural production are still in their infancy, an extensive amount of research has been done regarding the shade tolerance of crops [8] and is used as a basis for classifying crops into different categories based on whether they are (shade tolerant) and benefit from shading (+ category), (shade neutral) – where shading has no significant effect or (shade sensitive) and have a negative response to shading [9,10] (Fig. 3).

The selection of potatoes and strawberries (both in the "+" category and therefore shade loving) for cultivation in the agrivoltaic system therefore plays an important role in determining the design parameters of the agrivoltaic installation, with the selected height, pitch distance and system orientation selected, as described in the section below, to support crop growth and energy yield.

4. Agrophotovoltaics (APV) system layout

For the specific location for Khemis Miliana (Latitude: 36°15′06.8″N Longitude: 2°14′14.5″E), the pre-layout was designed taking into consideration the meteorological and

© UDBKM / Amina Richa & Sami Touil

Fig. 1. Agrivoltaic system with gutter for collecting rainwater.

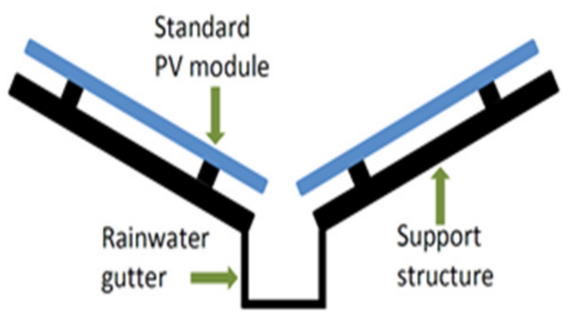

Fig. 2. Conceptual rainwater harvesting V-shape design.

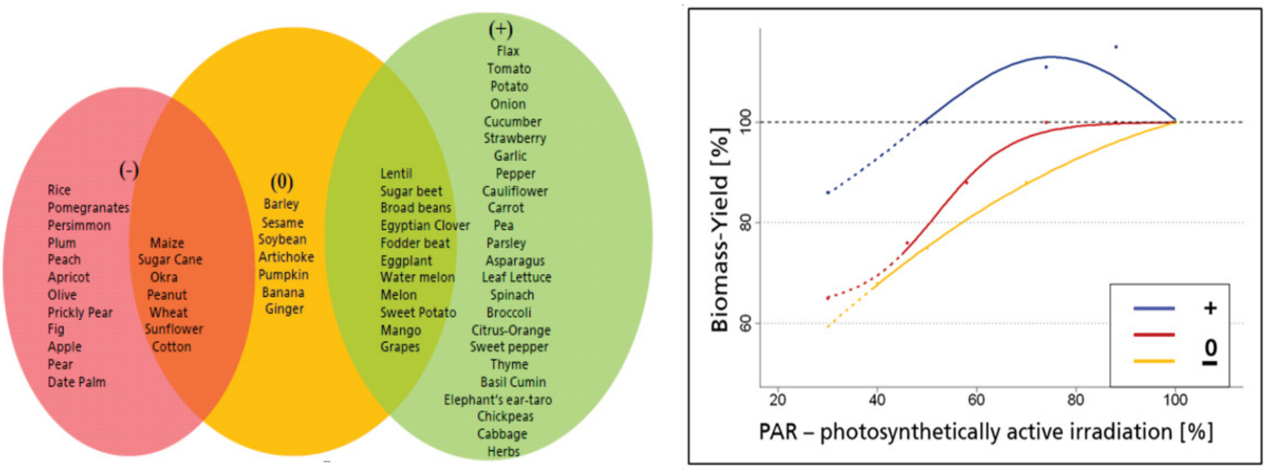

Fig. 3. Crop classification based on shade response (left) and crop response curve (right) [9,10].

climatic conditions–average Global Horizontal Irradiation (GHI) of 1,785 kWh/m^2, and hot dry summers and low rainfall during cold winters. Fig. 4 presents the proposed APV system Layout.

A target ground cover ratio (GCR) of 45%, achieved by setting module row spacing to 4.57 m, was proposed to allow sufficient solar irradiation to reach the target crops and thus minimize harvest losses. The table height of 2.5 m was selected to further allow the transmission of solar irradiation and in consideration of the dimensions of the agricultural machinery used to till the soil. The modules within each array are laid out relative to each other in portrait orientation. Module tilt angles between 0° and 30° were selected to be analyzed at 5° intervals and multiple array orientations were proposed (South: 0° to EW: –90°/90°). Several simulations were carried out to verify the pre-design parameters and optimize the system. The final installation parameters are presented in Table 1. It should be noted that only one row is composed of the PV modules as shown in Fig. 4. The four other rows represent the dummy modules based on the white PVC Board which have the same dimensions as the PV modules.

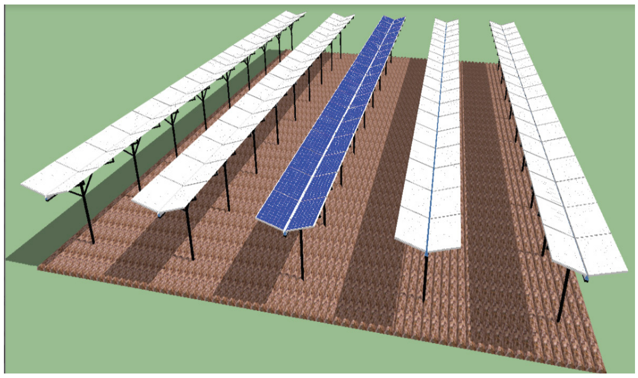

Fig. 4. Agrophotovoltaics (APV) system layout.

5. Photovoltaic system description

The stand-alone photovoltaic system installed on the Kemis Meliana site was composed of photovoltaic panels of 9.9 kWc consisting of 36 modules of 275 Wc (Mono-facial Polycrystalline, Jinko JKM275PP) configured in the form of two "strings", each having 18 modules in series. It should be noted that the PV energy produced from the first string was transferred directly through the DC/AC inverter to feed a high-pressure pump with a nominal mechanical power of 4KW-3HP/380V that pumps water to be used to irrigate crops. The other string was utilized to feed other loads like outdoor lighting of the agrophotovoltaics (APV) installation through the battery charger and the DC/AC inverter, while the energy surplus was used to charge the battery bank which will supply the loads in case of low irradiation conditions. The conversion of the continues current delivered by the PV modules into AC current was done by a photovoltaic solar inverter (5KVA/48V) and a battery regulator (100/70A) which was used to charge the battery bank from the PV power source. The AC-DC inverter, which was equipped with a maximum power point tracking (MPPT) control, was not limited to transforming the DC power generated by the solar modules into AC power in the form of a sinusoidal voltage of the desired frequency (230 V/50 Hz), but it also exploits the power delivered by the PV generator optimally by forcing it to operate at its maximum power point. The PV system was located at the University of Khemis Miliana (Algeria). The specifications of the PV system components are summarized in Table 2.

6. Agrophotovoltaics (APV) system performance simulation

A key step, prior to the installation of the APV system, was the performance analysis and optimization of the proposed design through Irradiation Simulation (IS) using a suite of software and tools developed and adapted by Fraunhofer ISE. The key performance indicators included the expected Global Horizontal Irradiation GHI at module surface, the electrical yield and the amount and distribution of solar irradiation below the PV modules (Photosynthetic Available Radiation – PAR).

Table 1
Rainwater harvesting agrophotovoltaics (APV) equipment and layout parameters

Rainwater harvesting APV equipment and layout parameters	Characteristics
Module length	1.65 m
Module width	1 m
Module area	1.65 m^2
Modules per string	18
Total number of strings	10
Total modules	180
Total module surface area	297 m^2
Total module area E facing modules (90° azimuth)	148.50 m^2
Total module area W facing modules (270° azimuth)	148.5 m
Table height (from ground to the lowest part of module)	2.5
Module tilt angle	15°
Pitch distance (distance between rows)	4.57 m
Ground cover ratio	45%
Module orientation (north = 0°, east = 90°, south = 180°, west = 270°)	EW
Field area	604.098 m^2

Table 2
Specifications of the installed PV system components

Source	Type	Number	Rating
Solar PV array	Mono-facial polycrystalline (mSi) Si 275W	36 (2 strings of 18 modules)	9.9 kWp
Battery bank	Gel	04	Batteries of 400 Ah, 12 V
Battery controller	With MPPT controller	01	48 V
DC-AC Inverter	Single phase	01	48 V/230 V
Pump	Pump HP	01	4 kW

6.1. Site meteorological data

It could be noticed that at Khemis Miliana in 2014, the best monthly average radiation is about 6.56 kWh/m^2/d in June. The lowest is 3.39 kWh/m^2/d in February. The average temperature varied between 11°C in January and 29°C in August. Fig. 5 presents irradiation and ambient temperature for Khemis Miliana site during year 2014.

6.2. Simulation methodology and tools

6.2.1. Solar irradiation and meteorological data

Irradiation and meteorological data for the site was acquired from SolarGIS, covering the time 1994–2019. Global horizontal irradiation (Ghor), diffuse horizontal irradiation (Dhor) and other meteorological parameters were provided as 15 min average values in this data set. The full year of 2014 was used for the calculations, as annual sums of global horizontal irradiance (Ghor) and diffuse horizontal irradiance (Dhor) are closest to the long-term average Ghor and Dhor.

6.2.2. Energy yield assessment

- *Radiance*: Fraunhofer ISE developed appropriate methods and tools based on Radiance, a light simulation, raytracing software developed at the Lawrence Berkeley Labs, USA. The Radiance calculation scheme uses absolute properties of radiance and irradiation in adequate physical units of W/m^2 sr or W/m^2. Models of the natural light sources sun and sky create a complete sky radiance distribution for any pair of global and diffuse irradiation (Ghor and Dhor) given as input values. Radiance can both render images and provide numerical values of local irradiation as "seen" by virtual irradiation sensors. Using Fraunhofer ISE's raytracing tool, irradiation levels were calculated for each time step for each solar cell within one module. Such single irradiance values were then aggregated to module irradiance values.
- *ZENIT*: ZENIT is Fraunhofer ISE's in-house modelling tool for electrical yield estimation for PV power plants. The software includes meteorological tools, such as irradiation transposition models, and PV system related tools, such as PV low-light performance curves and inverter efficiency models and established procedures to calculate PV energy loss mechanisms [11].

6.3. Modeling steps

The aggregated module irradiance values acquired by the ray tracing tool (Radiance) serve as input into ZENIT and the

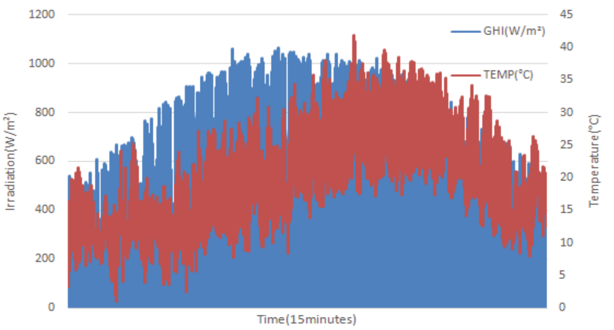

Fig. 5. Irradiation and ambient temperature for Khemis Miliana site during year 2014.

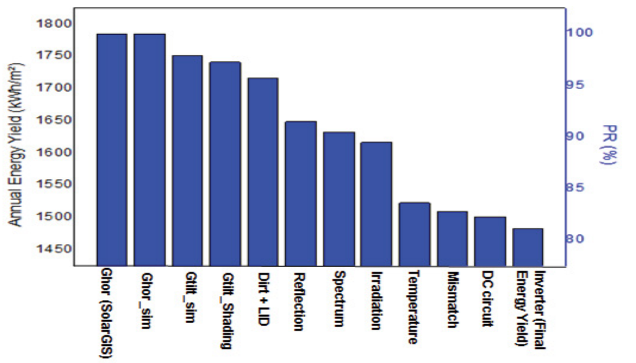

Fig. 6. Energy yield assessment.

calculation of PV power generation. To achieve the aggregate module irradiance, the following module steps are taken:

- The initial input of the Global horizontal irradiance (Ghor) from SolarGIS.
- Simulated Ghor on a sensor point over the PV array, set at 7 m above ground (Ghor_sim _7 m above). The setting of a sensor point at some value above ground is a standard modeling action in Radiance.
- Simulated irradiation incident on a sensor point over the PV array, in the same plane as the PV modules (Gtilt_sim).
- Irradiation incident at the level of the PV modules and considering any shading effects (Gtilt_Shading). Gtilt_ sim and Gtilt_shading show the cricital losses from the different design of PV module's tilt angle. The final value serves as the initial input for ZENIT which then firstly simulates losses from the effect of soiling and Light Induced Degradation (Dirt + LID). Applying Non-Standard Test Conditions (STC) operation of the PV modules, reflection, spectral, irradiation and temperature losses are factored in.
- Finally, the losses associated with module connections, DC circuit and inverter, are calculated.

7. Simulation results

The modeling steps explained in section 6.3 and associated energy losses are summarized in Table 3. Gain/Loss represents the % losses or gains from the modeling steps. PR is the Performance Ratio.

The steps up to "Gtilt_shading" were from Radiance light tracing simulation. The irradiation on the sensor point 7 m above ground (Ghor_sim (7 m above)) presented a loss of 0.64% (11.36 kWh/m^2) from the unimpeded global horizontal irradiance value of 1,775.48 kWh/m^2. The subsequent steps in the light tracing simulation up to Gtilt_ Shading resulted in total losses of 48.64 kWh/m^2 (2.77%) and gave the final aggregated module irradiance value of 1,715.48 kWh/m^2 equating to a module Performance Ratio (PR) of 97.23%. The value of 1,715.48 kWh/m^2 was the input value into ZENIT and the first step considered the expected soiling and LID effects which resulted in losses of 1.50%. The non-standard test conditions (STC) operation of the PV modules resulted in further cumulative losses of 12.15% for a specific yield of 1,492.18 kWh/kWp. The final losses resulting from module interconnections, cabling and inverter inefficiencies modeled to give the final overall expected system annual specific yield of 1,455.91 kWh/kWp equating to a PR of 81.13% (system losses of 18.87%). Fig. 6 presents the Energy yield Assessment of the proposed APV system.

8. Results analysis and discussion

The proposed rainwater harvesting agrivoltaic system would be the first system using the V-shape configuration with a central rain gutter, to collect and channel rainwater into storage. As this is untested in the field and the most appropriate design for installation is unknown, a preliminary design was first proposed, based on existing research and data regarding rooftop rainwater harvesting system design, PV system performance and water flow dynamics. The V-shape design was proposed considering the potential advantages over the other system designs with modules in a single plane with a rain gutter attached to the lower edge. The V-shape firstly allows two modules with opposing orientation, to use one gutter to maximize the collection of water, relative to the changing inclination and direction of incoming rainfall and is expected to collect more rainfall than modules oriented in a single plane. The design was incorporated into a full agrivoltaic system with the module tilt angles, table height (height from ground to point at the lowest module edge) and array orientation, resulting in tilt angle of 15°, height of 2.5 m and an East-West orientation (–90°/90° azimuth). While the optimal tilt angle for a standard south facing system (2° azimuth) in Khemis Miliana was 32°, a tilt angle of between 10° and 20° was expected to be sufficient to allow effective runoff of rainwater from the module surface to the rain gutter and have limited module to module shading. Initial simulations were conducted to verify the expected losses associated with the module tilt angle and the angle of 15° was defined. The system height of 2.5 m was defined according to the expected agricultural activity below the PV modules (machinery size and final crop height and light requirements).

Previous research on agrivoltaic system orientation and the effect on the solar irradiation amount and homogeneity, determined the chosen East-West orientation.

Table 3
Modeling steps leading to the specific annual energy yield in Khemis Miliana

Modeling step	Annual energy yield	Gain/Loss (%)	PR (%)
Ghor (SolarGIS)	1,775.48 kWh/m^2		
Ghor_sim (7 m above)	1,764.12 kWh/m^2	–0.64	100
Gtilt_sim (7 m above)	1,726.40 kWh/m^2	–2.14	97.86
Gtlt_Shading	1,715.48 kWh/m^2	–0.63	97.23
Dirt + LID	1,689.75 kWh/m^2	–1.50	95.73
Non-STC operation of PV modules			
Reflection	1,617.94 kWh/m^2	–4.25	91.48
Spectrum	1,601.76 kWh/kWp	–1.00	90.48
Irradiation	1,585.74 kWh/kWp	–1.00	89.48
Temperature	1,492.18 kWh/kWp	–5.90	83.58
Mismatch	1,480.24 kWh/kWp	–0.80	82.78
DC circuit	1,472.10 kWh/kWp	–0.55	82.23
Inverter	1,455.91 kWh/kWp	–1.10	81.13

As shown by Beck et al. [12] changing the module array orientation from south facing (azimuth of 0°) to south-west/south-east (45° or –45° azimuth) or east-west (–90°/90° azimuth) improves the distribution of solar irradiation below the PV modules, resulting in homogenous distribution of light [12]. The final pre-design parameters required optimization by running preliminary simulations (not including full electrical yield assessment or ground level irradiation) at combinations of various module tilt angles between 0° and 20° and system orientations, resulting in the final orientation presented here. The final orientation then underwent full EYA using Radiance and ZENIT.

In the next steps of the project, the final EYA annual specific energy yield of 1,455.91 kWh/kWp at the inverter will be compared with the actual yield obtained through continuous operation on the project site.

9. Concluding remarks

The long-term aim of this work is to demonstrate that an agrivoltaic pilot can increase the available pool of non-conventional water resources together with conventional water resources of river basins in scarce or low water quality areas. Furthermore, that it can increase quantity, quality, and efficiency through cost savings and that such a system can reduce loses where remote sensing communications protocols are implemented. More specifically, the objectives of the pilot in the Cheliff Plain, Algeria were to set up a system for the monitoring of low-quality water uses (high salinity groundwaters) and apply it to modern irrigation practices. The goal was to save water and nutrients, with the aim to increase crop productivity and improve soil quality and environmental effects though more efficient water management in agriculture. In line with these overarching objectives, the rainwater harvesting agrivoltaic system needs to be analyzed for its potential to provide energy to isolated areas and to reduce irrigation needs through shadowing and test opportunities to integrate smart water management systems into the mounting structure.

The initial steps in the application of the system at the project site in Khemis Miliana were the conceptual design, performance analysis and optimization. The current report introduced the concept of agrivoltaics and the rainwater harvesting functionality, subsequently proposing an innovative "V-shape" design to capture rainwater, while maintaining sufficient energy yield and optimal shading to the ground below. The predesign and optimization provide final design parameters of a system-oriented EW (–90°/90° azimuth), module tilt angle of 15°, table height of 2.50 m and array spacing of 4.57 m. The simulation of the given parameters for the system Energy Yield Assessment resulted in an annual specific yield of 1,455.91 kWh/kWp and a performance ratio of 81.13%.

These results provide an expected energy yield that will be compared to actual field measurements collected over the course of the research project. The actual field measurements will also contribute to the validation and optimization of the modeling tools used in the simulations. Additionally, several alternate system designs and orientations will be simulated and analyzed to compare the expected performance of the V-shape design to standard agrivoltaic approaches that use PV modules configured in a single plane. It is recommended that the rainwater harvesting capacity and the irradiation levels and distribution below the PV modules, should also be simulated in a future study.

In closing, agrophotovoltaic systems have great economic potential by allowing for electricity production and crop growth on the same land area. It can be reasoned that this would be a significant advancement in the sustainable development of society.

Acknowledgement

This paper was supported by the PRIMA program under Grant Agreement No. 1821, WATERMED 4.0, Call 2018 Section 1 Water. The PRIMA program is supported by the European Union. We appreciate the support provided by General Directorate for Scientific Research and Technological

Development (DGRSDT) /Ministry of Higher Education & Scientific Research (Algeria).

References

[1] S. Schindele, M. Trommsdorff, A. Schlaak, T. Obergfell, G. Bopp, C. Reise, C. Braun, A. Weselek, A. Bauerle, P. Högy, A. Goetzberger, E. Weber, Implementation of agrophotovoltaics: techno-economic analysis of the price-performance ratio and its policy implications, Appl. Energy, 265 (2020) 114737, doi: 10.1016/j.apenergy.2020.114737.

[2] A. Goetzberger, A. Zastrow, On the coexistence of solar-energy conversion and plant cultivation, Int. J. Sol. Energy, 1 (1982) 55–69.

[3] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes, Renewable Energy, 36 (2011) 2725–2732.

[4] S. Amaducci, X. Yin, M. Colauzzi, Agrivoltaic systems to optimise land use for electric energy production, Appl. Energy, 220 (2018) 545–561.

[5] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, J. Wery, Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels, Agric. For. Meteorol., 177 (2013) 117–132.

[6] G.A. Barron-Gafford, M.A. Pavao-Zuckerman, R.L. Minor, L.F. Sutter, I. Barnett-Moreno, D.T. Blackett, M. Thompson, K. Dimond, A.K. Gerlak, G.P. Nabhan, J.E. Macknick, Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands, Nat. Sustainability, 2 (2019) 848–855.

[7] P. Santra, P. Pande, S. Kumar, D. Mishra, R.K. Singh, Agrivoltaic system: crop production and photovoltaic-based electricity generation from a single land unit, Indian Farm., 68 (2018) 20–23.

[8] S. Touil, A. Richa, M. Fizir, B. Bingwa, Shading effect of photovoltaic panels on horticulture crops production: a mini review, Rev. Environ. Sci. Biotechnol., 20 (2021) 281–296.

[9] Essam. Evaluation of Agrophotovoltaic Technical and Economic potential in Egypt including Optimization of System Technology and Harvest, 2014. Available at: https://dokumen.tips/documents/by-ramy-essam-uni-kassel-by-ramy-essam-ramyessamhotmailcom-june-18-2014.html

[10] T. Obergfell, Agrovoltaik – Land wirtschaft unter Photovoltaikanlagen. Eine Machbarkeitsstudie für den Standort Deutschland. Agrovoltaic – Agriculture Under Photovoltaic Facilities. A Feasibility Study for Germany, Master Thesis, University of Kassel, 2012.

[11] V.S. Chulz, S. Munz, K. Stolzenburg, J. Hartung, S. Weisenburger, S. Graeff- Hönninger, Impact of different shading levels on growth, yield and quality of potato (*Solanum tuberosum* L.), Agronomy, 9 (2019) 330, doi: 10.3390/agronomy9060330.

[12] M. Beck, G. Bopp, A. Goetzberger, T. Obergfel, C. Reise, S. Schindele, Combining PV and food crops to agrophotovoltaic – optimization of orientation and harvest, EUPVSEC Proc., 1 (2012) 4096–4100.