CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114153

Combination of Sustainable Agriculture and Renewable Energy Systems

Bernadett Rádli-Burján*,[a], Lóránt Kovács[a], Balázs Vehovszky[b], Zoltán Weltsch[b], Ferenc Magyar[a]

[a]Széchenyi University Group, ZalaZONE InnoTech Nonprofit Kft, H-8900 Zalaegerszeg, ZalaZONE tér 1
[b]Széchenyi István University, H-9026 Győr, Egyetem tér 1
bernadett.radli-burjan@zalazone.hu

It is now not a question anymore that the fossil fuel-based energy system of human civilization has to be converted into a sustainable energy cycle during the 21st century. In most cases, the introduction of related, novel energetical technologies and solutions leads to disadvantageous interferences with other fields of life. Perhaps the most critical example is the competition between the energy sector and the food industry for valuable agricultural land. Although the two utilization purposes are generally considered mutually exclusive, there are agro-energetical solutions where the two goals are not just indifferent, but they expressly increase each other's efficiency. Such solutions are the agro-photovoltaic systems, where photovoltaic panels are installed in a way that is advantageous for the crops below them. Some plants, such as berries, prefer shady to semi-shady environments, which can be optimally provided under partially covered PV fields. With the active control of the PV panels, ideal shading conditions and even mechanical protection can be ensured in case of extreme weather events. With the appropriate selection of the crop plants and the PV installation, cultivation processes are not hindered, can be highly automated, and the energy needs can be fully covered by the local PV system. From the above description, it is clear that the realization of efficient agro-photovoltaic systems is not just possible but really prosperous. This study offers a more detailed overview of currently realized solutions around the world, as well as a thorough planning process of an agro-photovoltaic project at the ZalaZONE test center, optimized for the Hungarian climatic and agricultural conditions and possibilities.

1. Introduction

A significant portion of global carbon dioxide emissions is currently attributed to the energy sector. One of the key pillars in the fight against climate change is the establishment of a sustainable energy system, in which the majority of energy production should come from renewable sources instead of today's fossil energy sources. Among these renewable energy sources, solar power plants currently represent the largest share, with an installed capacity of 1,418,969 MW in the world (IRENA, 2024).
The energy density of solar power plants is extremely significantly lower compared to power plants using other energy sources. The power density of solar panels typically ranges from 100 to 300 W/m^2 on average. However, the available area cannot be fully covered due to the shading caused by the rows overlapping each other. In 2016, the average power density of solar power plants projected over the total area was 5.7 W/m^2. (Miller et al., 2019) With the advancement in the manufacturing of solar panels, this value has somewhat increased, reaching 8.7 W/m^2 by 2020 (Chatzipanagi et al., 2023).
The installation of solar panels on rooftops is becoming increasingly popular and supported. Although, a significant portion of the installed capacity still comes from ground-mounted solar parks. To increase the proportion of renewable energy sources. Therefore, a considerable amount of land area is needed. The advancement of solar power plant installations is expected to withdraw significant areas from agricultural production. With the growth of the population, the demand for food increases; however, food production is becoming more challenging due to the effects of climate change. Globally, available arable land is decreasing due to desertification, extreme weather events, and droughts becoming more frequent. Arable land per capita

Paper Received: 12 July 2024; Revised: 12 August 2024; Accepted: 12 November 2024
Please cite this article as: Rádli-Burján B., Kovács L., Vehovszky B., Weltsch Z., Magyar F., 2024, Combination of Sustainable Agriculture and Renewable Energy Systems, Chemical Engineering Transactions, 114, 913-918 DOI:10.3303/CET24114153

decreased by 48 % between 1961 and 2016 (Klokov et al., 2023). It is particularly important to minimize the withdrawal of arable land for energy production purposes. Agro-photovoltaic systems (APV) can offer a solution to this problem. These systems enable simultaneous agricultural production and energy generation on a given land area. APV-s can be divided into two main categories based on their agricultural utilization: those for livestock farming and those for crop cultivation. Livestock farming applications can be implemented alongside traditional solar power plant parameters; grazing typically occurs in many solar farms, often with small livestock (Kochendoerfer et al., 2022). Crop cultivation within solar power plants can be achieved by modifying the conventional solar power plant layout in two ways: increasing row spacing makes the inter-rows suitable for agricultural cultivation while raising support columns enables crop cultivation underneath the solar panels (Moreda et al., 2021).
Various design configurations of APV systems can achieve power densities ranging from 0.2 MW/ha to 0.9 MW/ha. In the European Union, there is a utilized agricultural area (UAA) of 157,262,140 ha. By employing APV systems with different power densities and utilizing less than 10 % of the UAA, the solar power installation targets set for 2030 could be achieved (Chatzipanagi et al., 2023). The size of the currently utilized areas, as well as those required to achieve further objectives for solar power plants with varying energy densities, is shown in Figure 1.

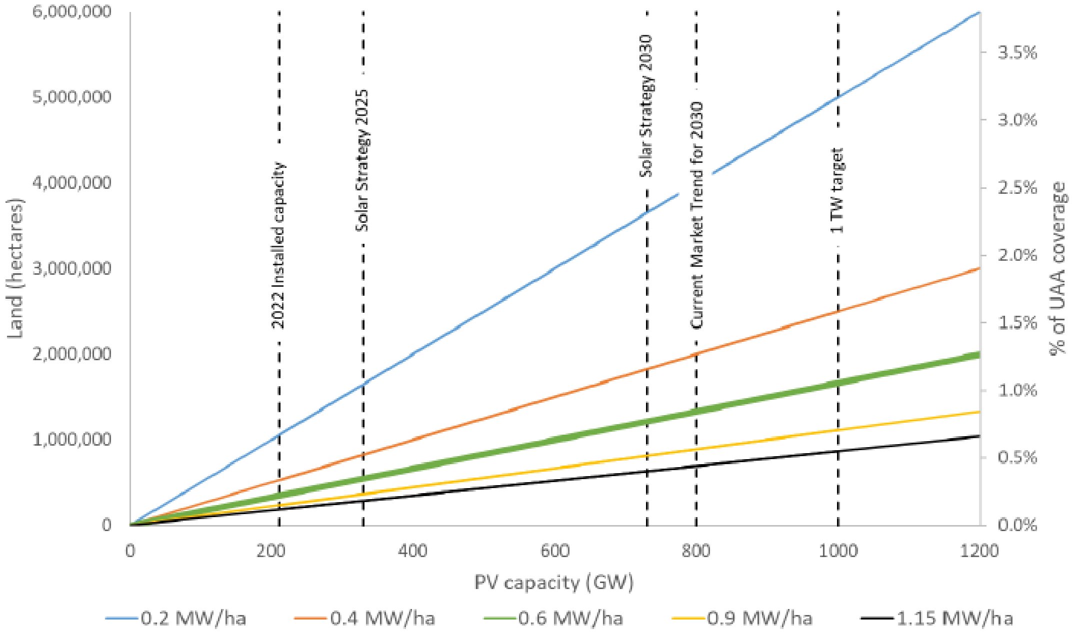

Figure 1: Land requirements and percentage of UAA coverage for APV systems for the accomplishment of the different EU PV installation targets (Chatzipanagi et al., 2023)

There is no universally accepted definition of APV systems; individual countries determine what constitutes an APV system within their jurisdiction. Among European Union countries, Germany, Italy, and France have the most advanced APV regulations. Overall, regulations consider only those systems as APV where the installation does not significantly reduce the agricultural production potential of the area and can be removed at the end of its lifespan without affecting the fertility of the soil (Chatzipanagi et al., 2023). In 2021, the Hungarian land law also included provisions for APV systems. Solar panel systems are considered agro-photovoltaic if their establishment and operation do not prevent the underlying land from being used as arable land according to its agricultural category (Hungarian Official Gazette, 2021).
APV systems are still largely in the research phase across most European countries. Hungary's climatic and agricultural characteristics have yet to be thoroughly evaluated from an agro-photovoltaic perspective. The objective of this research is to analyze the international context alongside Hungary’s specific agricultural and climatic conditions in order to identify the optimal crop types and solar power plant configurations.

2. Implemented systems

APV systems are anticipated to become key components of both sustainable energy systems and agriculture. To thoroughly evaluate the specific characteristics relevant to Hungary, it is beneficial to review systems implemented in other regions. Various APV solutions for crop cultivation have been deployed in numerous locations, with significant variation in their design, regulatory frameworks, and the types of crops cultivated.

2.1 Germany

In Germany, several primarily research-oriented APV projects have been realized. In the North Rhine-Westphalia region, one of these projects investigates East-West rotatable and fixed south-facing layouts employing various rainwater management methods. In these areas, faba beans are cultivated with different row and plant spacings. The growth of the plants is compared throughout the entire vegetation period with their development in control areas under different system types (Meier-Grüll et al., 2024).
A pilot project in Gelsdorf was implemented with semi-transparent fixed installation panels. In this 5 y project, 8 different apple varieties are planted under the APV system. Economic aspects, social acceptance, and apple yield are being examined (BayWa-re a, 2024).

2.2 Netherlands

A significant portion of agriculture in the Netherlands is dedicated to fruit cultivation. Ensuring adequate protection for orchards against hail, strong winds, and intense direct sunlight is of paramount importance. Various solutions involving plastic film and mesh are employed for this purpose, often requiring frequent replacement and improvement. APV systems, particularly, are seen as having considerable potential as they can provide protection against extreme weather conditions. One of Europe's largest APV systems was completed in Babberich, the Netherlands, spanning 3.3 hectares with an installed capacity of 2.67 MWp. The system comprises semi-transparent panels mounted on a fixed structure under which raspberries are cultivated (BayWa-re b, 2024). Additionally, in Wadenojen, there is a system with an installed capacity of 1.2 MWp, under which blueberries are cultivated (PV-Agri, 2024).

2.3 France

France is the first country to provide financial support specifically for the establishment of APV systems. Between 2017 and 2019, they supported APV projects with a total capacity of 15 MW (Chalgynbayeva et al., 2023). Among other developments, a 3.6 MW installed capacity system was established in St. Etienne, where cherries and spinach are grown under fixed-installation semi-transparent panels (PV-Agri, 2024). Additionally, numerous research infrastructures have been set up to study the interactions between various photovoltaic configurations, support structures, and crop types. Special emphasis is placed on the compatibility of viticulture with APV systems (Sun Agri, 2024).

2.4 India

In India the installed capacity of APV projects exceeded 14.5 MW in 2021. All established projects are experimental. Various crop cultures are being tested alongside different solar power plant configurations. The feasibility of crop cultivation within APV systems is being investigated in arid or semi-arid regions where agricultural production was previously not possible, even with irrigation, due to intense solar radiation. The regulatory environment is still in development, with multiple business models and corresponding support systems currently being formulated (Rahman et al., 2023).

2.5 China

China is a pioneer in this field, currently holding the largest installed agro-photovoltaic capacity in the world. More than 500 different APV projects have been established across the country, covering the full spectrum of agricultural applications. These include aquaculture, grazing, and crop cultivation systems (Silan et al., 2024). The development of APV systems is supported by both the energy and agricultural sectors. APV solutions are regarded as part of agricultural development and transformation efforts, with research indicating they could play a significant role in combating rural poverty (Trommsdorff et al., 2022).

3. Optimalization for Hungarian climate and agricultural needs

The usability of renewable energy sources depends on the geographical characteristics of a given area. In Hungary, the most significant renewable energy source is solar energy. The installed photovoltaic capacity is currently approaching 6 GW (MAVIR, 2024). This value is expected to continue growing, potentially reaching 12 GW by 2030 (National Energy and Climate Plan Hungary, 2023). A significant portion of these photovoltaic power plants is located on arable land temporarily withdrawn from agricultural production. This trend is expected to continue with future projects, resulting in numerous agriculturally usable areas being temporarily repurposed for energy production. Currently, agriculture is an extremely important sector in Hungary, with agricultural cultivation covering over half of the country's territory, amounting to 5.1 Mha (KSH a, 2024). Maintaining or possibly increasing the size of agricultural cultivated areas is an important strategic goal.

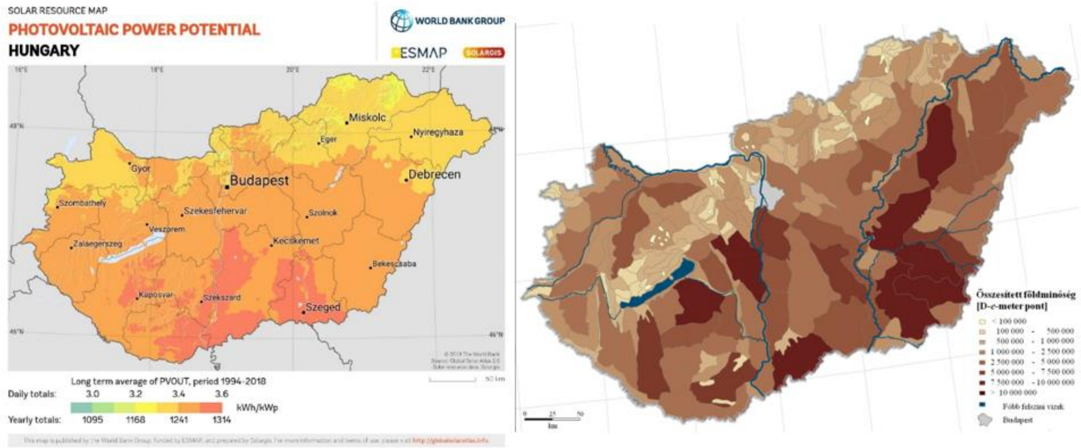

Figure 2: Photovoltaic power potential (left) (Solargis, 2024) and soil quality (right) (Tóth et al., 2014) in Hungary

If we examine the photovoltaic potential and the soil fertility of the country's territory, we can observe that areas with high-quality arable land often coincide with those with high photovoltaic potential. In these areas, the development of APV systems may be of particular significance.

3.1 Selection of crop culture

In APV systems, the structure of the solar power plant needs to be adapted for agricultural use. In the case of crop cultivation, this can be effectively achieved by elevating the solar panels (Lee et al., 2022). To ensure that the structure of the solar power plant meets the needs of the crops, the first step is to determine the crop culture to be cultivated.

The elevated solar panels cast shadows on the areas beneath them and influence the resulting microclimate. Typically, evaporation decreases, soil and air temperatures lower, and near-ground humidity increases (Weselek et al., 2021). The solar panels also provide mechanical protection against extreme weather conditions such as heavy rainfall or hail.

The optimal crop culture is shade-tolerant or sensitive to direct sunlight, can thrive in the microclimate created under the solar panels, and is typically installed with an irrigation system. Additionally, it may be beneficial to select crop cultures that are sensitive to extreme weather conditions and often require some form of mechanical protection or shading structure. These conditions are typically met by high-value fruits.

The volume of fruit production in Hungary is continuously decreasing. The size of areas cultivated as orchards decreased by 37.7 % between 2002 and 2022. A significant portion of these areas is used to grow long-day fruits, which are not optimal for cultivation in APV systems. The largest area cultivated with relatively high-value, shade-tolerant fruit is currently raspberries, which were grown on 203 ha in 2022 (KSH b, 2024).

Raspberries are water-intensive plants that prefer cooler, more humid areas. Hungary is currently at the southern limit of its cultivability. They are typically planted with irrigation and mechanical protection. The height of the plantations does not exceed 2 m, and they are cultivated with small machinery or by hand (Csihon and Gonda, 2020). Therefore, raspberries are an excellent candidate for overhead APV systems in Hungary.

3.2 Optimal solar structure

In APV systems, the traditional structure of solar power plants must be adapted to the needs of crop cultivation. This typically affects the supporting structure, as well as the type and arrangement of the solar panels. The height to which the supporting structure is elevated is determined by the typical height of the crop culture and the height of the machinery required for cultivation (Weselek et al., 2019).

The type and arrangement of the solar panels should be adjusted to the light requirements of the crop culture (Schindele et al., 2020). For crops with higher light requirements, the distance between rows and panels can be increased, and partially transparent solar panels can also be used. Another solution is the use of tracker-supported structures, where the panels can be rotated not only to follow the sun but also according to the needs of the plants (Imran et al., 2020).

4. Planned system at ZalaZONE

Hungary's first agro-photovoltaic system is currently in the planning phase, and the preparation of professional decisions for this design process required an analysis of the international examples presented in earlier stages and the possibilities specific to Hungary. The planned system is expected to be completed in Q2 2025 and will provide an opportunity for a more detailed investigation of the optimization of agro-photovoltaic systems for Hungarian conditions.

The planned agro-photovoltaic test environment will be located on an open green area adjacent to the ZalaZONE Automotive Proving Ground in Zalaegerszeg (46°53'32.6"N 16°50'07.6"E), covering an area of 1,250 m². It is planned to install 9 north-south oriented rows of solar panels, under which raspberries will be planted. To facilitate raspberry cultivation, the solar panels will be elevated to a height of 2 m above the ground. Two types of solar panels will be installed in the system: 80 % of the panels will be regular, while 20 % will be partially transparent. The solar panels will be mounted on tracker-supported structures, allowing them to be rotated in an east-west direction. This will enable the investigation of the effects of different rotation programs on raspberry cultivation.

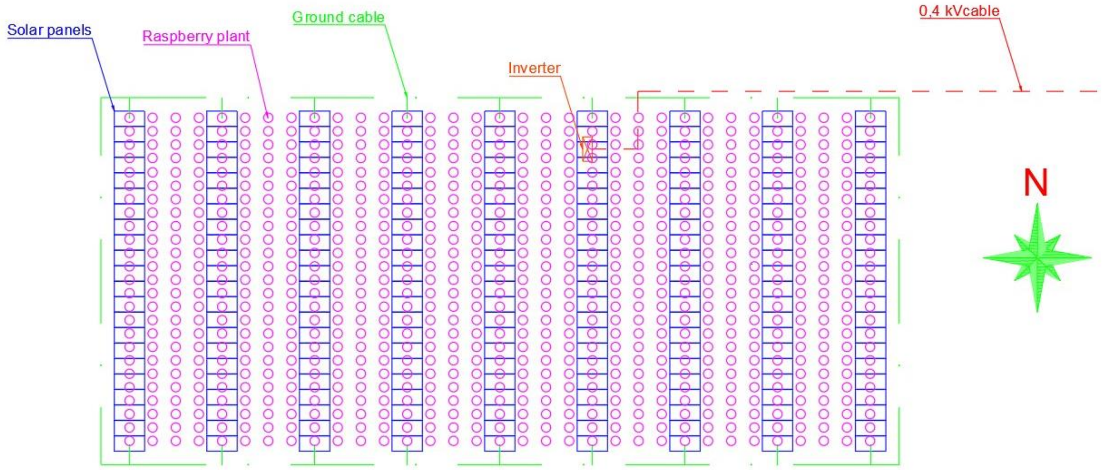

Figure 3: Planned test system at ZalaZONE

The planned installed capacity of the solar power plant is 99 kWp, which will connect to the existing internal network via a 100 kVA inverter. The plant is designed to reduce self-consumption and will not feed into the public grid. The system will enable the investigation of the impact of crop planting on electricity generation.

5. Conclusions

Agri-photovoltaic systems enable the combined optimization of energy and food production, addressing the conflict between sustainable energy transition and agricultural land use. Successfully implemented agro-photovoltaic solutions in various parts of the world, such as Germany, the Netherlands, France, India, and China, demonstrate that these systems can function effectively under different climatic and agricultural conditions.

Based on the analysis of Hungary's conditions, it can be concluded that, given the country's significant agricultural output and solar potential, APV systems hold considerable promise. To maximize the land-use efficiency of these systems, it is essential to carefully select appropriate crop types, optimize solar power plant configurations, and adapt agricultural production processes to the conditions beneath the solar panels. Our findings indicate that an elevated solar panel structure, combined with the cultivation of high-value fruit crops, is the most suitable approach for Hungary's specific climatic and agricultural conditions.

Acknowledgments

This work was financially supported by the National Laboratory for Cooperative Technologies. The authors would like to thank ZalaZONE Automotive Proving Ground for providing the research infrastructure.

References

Hungarian Official Gazette, 2021, Amendment of Act CXXIX of 2007 (Act LX of 2021). <https://www.kozlonyok.hu/nkonline/MKPDF/hiteles/MK21098.pdf>, accessed 11.05.2024.

BayWa-re a., 2024,. First Agri PV research Facility for Apples in Germany: <baywa-re.com/en/news/details/first-agri-pv-research-facility-for-apples-in-germany/>, accessed 22.05.2024.

BayWa-re b., 2024, Solar Installation Bear Fruit for Netherlands Agri PV: <baywa-re.com/en/cases/emea/solar-installations-bear-fruit-for-netherlands-agri-pv>, accessed 22.05.2024.

Chalgynbayeva A., Gabnai Z., Lengyel P., Pestisha A. and Bai A.,2023, Worldwide Research Trends in Agrivoltaic Systems- A Bibliometric Review. Energies, 16, 611.

Chatzipanagi A., Taylor N., Jaeger-Waldau A., 2023,. Overview of the Potential and Challenges for Agri-Photovoltaics in the European Union. European Commission, Joint Research Centre, Ispra, Italy.

Csihon Á., Gonda I., 2020, The technology of fruit cultivation (in Hungarian). Debrecen University Press, Debrecen, Hungary, 139-149.

Imran H., Riaz M. H., Butt N. Z.,2020, Optimization of Single-Axis Tracking of Photovoltaic Modules for Agrivoltaic Systems. 47th IEEE Photovoltaic Specialists Conference, (pp. 1353-1356). Calgary, AB, Canada.

IRENA, 2024, Renewable Energy Statistics. International Renewable Energy Agency, Abu Dhabi, UAE.

Klokov A. V., Loktionov E. Y., Loktionov Y. V., Panchenko V. A., and Sharaborova E. S.,2023,. A Mini-Review of Current Activities and Future Trends in Agrivoltaics. Energies, 16, 3009.

Kochendoerfer N., Hain L., Thonney M. L.,2022,. The Agricultural, Economic and Environmental Potential of Co-locating Utility Scale Solar with Grazing Sheep. Cornell University, Ithaca, NY, USA.

KSH a., 2024, Agricultural land use in Hungary by cultivation types, <ksh.hu/stadat_files/mez/hu/mez0008.html>, accessed 06.12.2024.

KSH b., 2024, Harvested area of major fruit crops and grapes (in Hungarian), <ksh.hu/stadat_files/mez/hu/mez0014.html>, accessed 06.10.2024.

Lee H. J., Park H. H., Kim Y. O., and Kuk Y. I.,2022,. Crop Cultivation Underneath Agro-Photovoltaic Systems and Its Effects on Crop Growth, Yield, and Photosynthetic Efficiency. Agronomy, 12, 1842.

MAVIR, 2024, Energy mix - change and distribution of gross installed capacity by primary source (in Hungarian), <mavir.hu/documents/10258/268442107/BT_2015-20240501_ig_BR+NT_HU_v1.pdf/f266f25b-d220-f204-b095-4818e4eda318?t=1715935130637> accessed 06.11.2024.

Meier-Grüll M., Jedmowski C., Hoelscher K., Müller C., Raumann L., Pieters B., Gerber A., Trommsdorff M., Berwind M., and Muller O.,2024, Agri-Horti-PV Research System in North Rhine-Westphalia Including PV Trackers and Integrated Rainwater Harvesting. AgriVoltaics World Conference, 1-9, DOI: 10.52825/agripv.v1i.632.

Miller L.M., Keith D. W., 2019, Corrigendum: Observation-based Solar and Wind Power Capacity Factors and Power Densities. Environmental Research Letters, 14, 7.

Moreda G.P., Muñoz-García M.A., Alonso-García M.C., Hernández-Callejo L., 2021, Techno-Economic Viability of Agro-Photovoltaic Irrigated Arable Lands in the EU-Med Region: A Case-Study in Southwestern Spain. Agronomy, 11, 593.

National Energy and Climate Plan Hungary, 2023, <commission.europa.eu/system/files/2023-09/HUNGARY%20-%20DRAFT%20UPDATED%20NECP%202021-2030%20_HU.pdf>, accessed 06.06.2024. (in Hungarian)

PV-Agri.,2024, Zimmermann References, <pv-agri.de/en/references/>, accessed 22.05.2024.

Rahman A., Sharma A., Postel F., Goel S., Kumar K., and Laan T.,2023, Agrivoltaics in India. International Institute of Sustainable Development, Winnipeg, Manitoba, Canada.

Schindele S., Trommsdorff M., Schlaak A., Obergfell T., Bopp G., Reise C., Braun C., Weselek A., Bauerle A., Högy P., Goetzberger A., Weber E., 2020, Implementation of Agrophotovoltaics: Techno-Economic Analysis of the Price-Performance Ratio and Its Policy Implications. Applied Energy, 265, 114737.

Silan J.G., Xu S., Apanada M.J., 2024, 05 23, World Resources Institute. <wri.org/insights/agrivoltaics-energy-food-production-asia>, accessed 11.06.2024.

Solargis, 2024, Photovoltaic power potential Hungary, <solargis.com/maps-and-gis-data/download/hungary>, accessed 27.05.2024.

Sun Agri, 2024, Viticulture: Piolenc, <sunagri.fr/en/project/piolencs-experimental-plot/>, accessed 22.05.2024.

Tóth G., Rajkai K., Bódis K., Máté F., 2014,. Soil Quality of Hungary's Micro-Regions According to the D-e Meter Arable Land Classification Method (in Hungarian). Tájökológiai lapok, 12, 183-195.

Trommsdorff M., Dhal I.S., Özdemir Ö.E., Ketzer D., Weinberger N., Rösch C., 2022. Agrivoltaics: solar power generation and food production, In: Solar Energy Advancements in Agriculture and Food Production Systems. Elsevier, London, United Kingdom, 159–210. DOI: 10.1016/B978-0-323-89866-9.00012-2.

Weselek A., Bauerle A., Hartung J., Zikeli S., Lewandowski I., Högy P. , 2021, Agrivoltaic System Impacts on Microclimate and Yield of Different Crops Within an Organic Crop Rotation in a Temperate Climate. Agronomy for Sustainable Development, 41, 59.

Weselek A., Ehmann A., Zikeli S., Lewandowski I., Schindele S., Högy P., 2019, Agrophotovoltaic Systems: Applications, Challenges and Opportunities. A Review. Agronomy for Sustainable Development, 39, 35.