ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering | e–ISSN: 2067 – 3809
Tome XVIII [2025] | Fascicule 3 [July – September]

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OPTIMIZATION OF AGROVOLTAIC INFRASTRUCTURE TO SUPPORT AGRICULTURAL ROBOTICS ON 1–HECTARE SURFACES

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Abstract: The increasing interest in sustainable and digitized agriculture has led to the development of agrivoltaic systems as integrated solutions for energy production and precision farming. This paper proposes a sizing plan for a photovoltaic system designed to supply power to agricultural robots performing tasks such as crop establishment, maintenance, and harvesting over a 1–hectare area. The study analyzes the energy consumption of robotic equipment in relation to regional solar potential and the efficiency of available photovoltaic technologies. Various types of robots, seasonal operation scenarios, and daily activity cycles are considered to estimate the annual energy requirements. The results provide an integrated perspective on the feasibility of implementing agricultural robots in an environment powered entirely by renewable sources. This research supports the development of a modern, autonomous, and environmentally friendly agricultural infrastructure, contributing to the transition toward smart and sustainable farming.
Keywords: agrivoltaic infrastructure, autonomous robots, agricultural plot

INTRODUCTION

Modern agriculture faces significant challenges caused by climate change, declining soil fertility, pressure on natural resources, and the growing need for digitalization and efficiency. In this context, the emergence of agrivoltaic systems — the combination of photovoltaic solar panels and agricultural production — offers an innovative solution for optimizing land use. By installing photovoltaic panels above or between crop rows, this model enables the simultaneous production of energy and food, a synergy essential for sustainable development (Dupraz et al., 2011; Amaducci et al., 2018).

As technology advances, another transformative element in agriculture is robotics. Autonomous agricultural robots can perform a variety of tasks — from seeding and irrigation to harvesting and weed removal — with a level of precision and efficiency unattainable through traditional methods (Bechar & Vigneault, 2016; Bajraktari & Toylan, 2025). Integrating these robots into an agrivoltaic environment becomes a complex but promising challenge: solar panels must be arranged not only to ensure energy efficiency but also to provide optimal mobility for robotic equipment.

Coexistence of Technologies: Energy, Agriculture, and Robotics

The benefits of agrivoltaic systems are not merely theoretical. For example, studies conducted in arid regions of the southwestern United States have shown that the moderate shading generated by solar panels reduces thermal stress on plants and improves soil water retention, leading to increased productivity (Barron–Gafford et al., 2019). These conditions are also favorable for the operation of agricultural robots, which can be negatively affected by overheating or excessively hard soil under extreme aridity.

In addition, robots can become key players in the energy management of agrivoltaic systems. For instance, a robot equipped with its own solar panels and artificial intelligence can collect data on shading levels, soil temperature, plant health, and panel efficiency, transmitting it in real time to a control system (Taha et al., 2025). In this way, the entire infrastructure becomes an interconnected ecosystem, optimized for autonomous decision–making and machine learning.

Challenges in Agrivoltaic Infrastructure for Robots

However, integrating agricultural robots into an agrivoltaic framework raises numerous engineering challenges. The height, tilt angle, and spacing of panels must be adapted to allow autonomous navigation and mechanized interventions (Weselek et al., 2021). Furthermore, the type of crop and field architecture must be compatible with robotic pathways — for example, low–growing crops such as lettuce, spinach, or strawberries are more suitable for these conditions than taller crops like corn.

In addition, a well–planned electrical network is essential. The energy captured by solar panels must be efficiently stored or directed to power robots, charging stations, and farm IoT (Internet of Things) systems. In this regard, high–efficiency DC–DC converters become critical components for reducing losses and maximizing performance (Gsous et al., 2024).

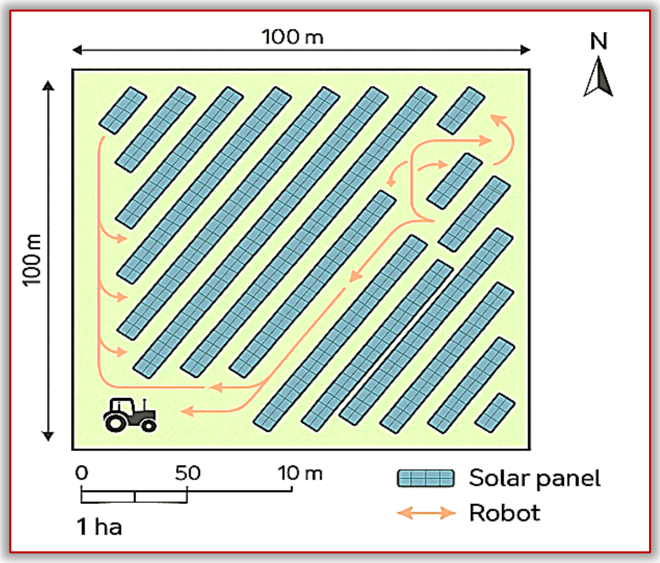

Figure 1: Layout map for panel placement and robotic routes on a 1–ha plot, with scales and examples of work rotations.

Objective of the Study

Building on these premises, this paper proposes a model for optimizing agrivoltaic infrastructure on 1–hectare agricultural plots, with the aim of facilitating the operation of autonomous robots. The work is based on a detailed review of the literature, spatial simulation models, as well as energy estimates for the continuous operation of agricultural equipment. The study is intended for farmers, agricultural infrastructure designers, researchers in smart agriculture, and developers of sustainable technologies.

MATERIALS AND METHODS

To optimize agrivoltaic infrastructure for supporting agricultural robots on 1–hectare plots, the study was structured into four main stages: land characterization, panel configuration design, robotics integration, and operational scenario simulation. Each stage was addressed individually, using specific methods and tools to ensure accuracy and applicability of the results.

Characterization of the Agricultural Plot

For the simulation, a flat 1–hectare agricultural plot was selected, equivalent to 100 m in length and 100 m in width. The land was virtually modeled with a loamy–sandy soil texture, which allows both efficient drainage and mechanical stability for robots and panel support structures.

The surface was divided into 10 sections of 10 × 10 meters to enable a granular analysis of robot behavior in the presence of shadows and obstacles. The plot orientation was set along the east–west axis to reflect common practices for maximizing solar exposure. It was assumed that the land was free of trees or other vertical obstacles.

Example: In sector 3 (row 2, column 3), an irrigation well was placed as a fixed point to simulate a static obstacle in the robots' path.

Agrivoltaic Infrastructure Configuration

Three different solar panel layouts were tested, each with its own constraints and advantages regarding robotic accessibility and solar energy capture:

- **Fixed elevated model:** Panels mounted on metal frames at a height of 3 meters, spaced 6 meters apart between rows. The structure allows robots to pass underneath without compromising their trajectory. *Example:* In this model, a robot performing weeding can move in a straight line under the panels without needing to bypass them.
- **Mobile solar–tracking model (tracker):** Panels mounted on pivoting columns that follow the sun's trajectory. Although more energy–efficient, these panels occupy more space at the base, limiting robot movement. *Example:* During the simulation, the robot had to avoid the moving arm of a panel, which led to a zigzag route and increased energy consumption.
- **Greenhouse–type model with semi–transparent panels:** Panels completely cover a continuous surface of 20 × 30 meters. They are installed at a height of 2.5 meters and allow filtered light, making them ideal for crops sensitive to direct radiation. *Example:* An autonomous robot performing precise plant irrigation can operate in this area regardless of weather conditions, being protected by the solar roof.

Simulated Agricultural Robots

The scenario included two autonomous agricultural robots, each with a specific function:

- **Rover–type robot for daily maintenance:** Moves between plant rows for inspection, weed detection, and minor interventions. It is equipped with an RGB camera and a LIDAR sensor. Dimensions are 1.2 × 0.8

meters, with a height of 0.5 meters. It can operate under agrivoltaic structures without difficulties.

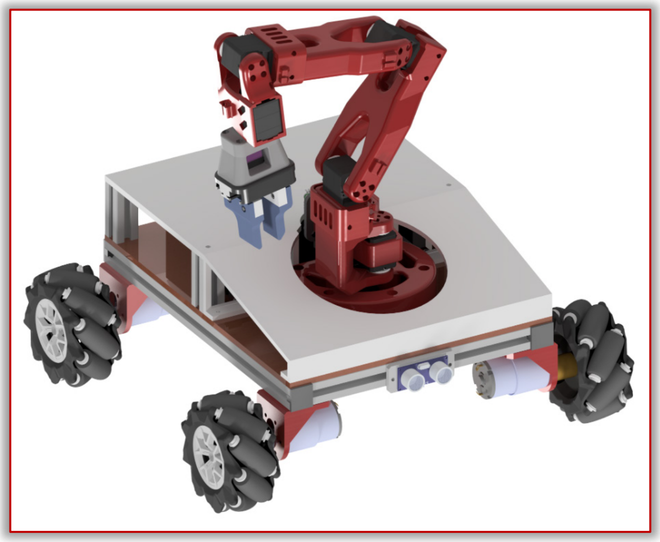

Figure 2. Robotic platform model

Example: The robot is programmed to cover 50% of the surface each day. In areas with fixed panels, it achieved this in 4 hours; however, in areas with solar trackers, travel time increased by 35% due to frequent detours.

— Multifunctional robot for seasonal tasks: This larger robot performs planting, fertilization, and harvesting. It has extendable mechanical arms and requires a minimum clearance of 1.5 m in width. Example: In greenhouse–type areas, access was restricted, requiring route reconfiguration so that the robot completely avoided that zone and operated only in open spaces.

Simulation of Operational Conditions

For each combination of panels and robots, a daily simulation was carried out over a period of 30 days:

— Solar light variations: From fully sunny days to partially cloudy days.
— Robot scheduling: The daily operational interval was 8:00–18:00, with automatic breaks for recharging.
— Route evaluation: A navigation algorithm (A* type) was used to optimize routes according to obstacles generated by the panels.

Example: On a bright sunny day, the maintenance robot saved 20% energy by operating in shaded areas created by the panels. In contrast, on cloudy days, the same routes required higher energy consumption, as panel shading no longer provided a thermal benefit.

Tools and Software Used

All scenarios were designed and analyzed using the following platforms:

≡ SolidWorks

SolidWorks is a 3D modeling software used for designing and simulating physical elements in space. In this study, SolidWorks was used for the detailed modeling of the 1–hectare agricultural plot, as well as for integrating agrivoltaic structures and agricultural robots.

♯ Concrete application:

The land was modeled as a flat surface, with exact dimensions of 100 × 100 meters. Structures for solar panels were created as metal frames with precise dimensions, adjusted to a height of 3 meters for the fixed model. Agricultural robots were represented with real geometric details (length 1.2 m, width 0.8 m, height 0.5 m).

♯ Calculation example:

To verify the clearance required for a robot moving under the panels, the available cross–section was calculated:

— Structure height: 3 m
— Robot height: 0.5 m
— Vertical clearance = 3 m – 0.5 m = 2.5 m

This clearance is sufficient for the robot to move without vertical obstacles. In addition, the row spacing was set to 6 m, providing a free width of 6 m for movement. Considering the robot's width of 0.8 m, this space allows multiple passes per row while avoiding collisions.

♯ Visual demonstration:

The 3D model enabled visual simulation of robot movement, including checking for possible interferences between the robot's arms and the panel structures. Thus, potential collisions were identified and eliminated already at the design stage.

≡ PVsyst

PVsyst is specialized software for simulating and estimating the performance of photovoltaic systems, taking into account local climatic parameters (solar radiation, temperature, humidity).

♯ Concrete application:

Local climate data, including average daily solar radiation (e.g., 5 kWh/m²/day), were introduced in PVsyst for each type of photovoltaic panel (fixed, tracker, semitransparent). The software calculated the estimated daily and annual electric energy generated for the 1–hectare agrivoltaic surface.

♯ Calculation example:

Considering a panel with a total installed area of 1000 m² and an average efficiency of 18%:

- Average daily radiation: 5 kWh/m²
- Theoretical daily energy captured: 1000 m² × 5 kWh/m² = 5000 kWh
- Estimated useful energy: 5000 kWh × 18% = 900 kWh/day

This estimate was adjusted for system losses (e.g., 15%), resulting in an effective production of approximately 765 kWh/day.

♯ Demonstration:

PVsyst generated hourly energy production graphs, highlighting variations due to sun position and partial shading from the panel structures, thus providing relevant data for system sizing and planning robotic operations according to energy availability.

≡ **ATAIR EDEM**

ATAIR EDEM is a simulation platform that combines energy analysis with dynamic simulation of robotic mobility in complex environments.

♯ Concrete application:

The software was used to simulate the movement of agricultural robots on the modeled land, taking into account both energy consumption and obstacle avoidance caused by the panel structures. The system simulated different routes and navigation strategies to maximize autonomy and operational efficiency.

♯ Calculation example:

For the maintenance robot, the average energy consumption was calculated as follows:

— Average power consumed during movement: 200 W
— Average daily travel duration: 5 hours
— Daily energy consumption = 200 W × 5 h = 1 kWh

In the fixed–panel scenario, the route was optimized so that the robot covered the 1000–meter row length with minimal energy consumption, avoiding points where moving arms of the panels could block the path.

♯ Demonstration:

The simulations also included variations in soil conditions (wet, dry), modifying the friction coefficient and, consequently, the energy consumption. These adjustments enabled a realistic estimation of the required resources and the planning of robot charging from photovoltaic sources.

≡ **QGIS**

QGIS is an open–source geographic information system (GIS) software used for mapping, spatial analysis, and geospatial data management.

♯ Concrete application:

For managing robot routes, QGIS was used to create digital maps of the field with markers for panel placement and robot positions. On these maps, optimal routes were generated, and distances were calculated according to obstacles and shaded areas.

♯ Calculation example:

Using the "Network Analysis" plugin in QGIS, the shortest and safest route was calculated for the robot between work points:

— Direct distance between two points: 50 m
— Optimized route with detours: 60 m (to avoid obstacles)

This route was later validated through practical simulations.

♯ Demonstration:

QGIS allowed the overlay of energy production data obtained from PVsyst with the field map to identify areas with maximum energy potential, where robotic tasks were prioritized.

RESULTS

Estimated Energy Production

Based on PVsyst simulations, the total installed panel area on the 1–hectare field was 1000 m², with an average conversion efficiency of 18%. The average annual solar radiation in the studied area is approximately 5 kWh/m²/day.

Theoretical daily energy generated is:

$$E_{theoretic} = A \times H \times \eta = 1000\,m^2 \times 5\,kWh/m^2 \times 0.18 = 900\,kWh/day$$

With system losses estimated at 15% (losses from cables, converters, shading), the effective energy is:

$$E_{efectiv} = E_{teoretic} \times (1 - 0.15) = 900 \times 0.85 = 765\,kWh/day$$

This production ensures sufficient energy for the continuous operation of agricultural robots during the day.

Energy Consumption of Robots

The modeled agricultural robot consumes on average 200 W in motion and 100 W in active idle state (static operations).

The estimated daily operating time is 5 hours of movement and 3 hours of idle.

Total daily consumption:

$$E_{robot} = P_{mişcare} \times t_{mişcare} + P_{rep} \times t_{rep} = 200\,W \times 5\,h + 100\,W \times 3\,h = 1000 + 300 = 1300\,Wh = 1.3\,kWh$$

Thus, the robot's consumption represents approximately 0.17% of the total daily energy production of the agrivoltaic system.

Optimization of Robot Routes

Using QGIS, robot routes were optimized to minimize energy consumption and obstacle avoidance. The estimated total daily travel distance was 5000 meters (5 km).

The energy consumed for movement can be estimated using the relation:

$$E = F_{\text{fricțiune}} \times d = \mu \times m \times g \times d$$

where:

μ=0.3, coefficient of friction for agricultural land,
m=50kg, mass of the robot,
g=9.81m/s2,
d=5000m.

Friction force:

$$F_{\text{fricțiune}} = 0.3 \times 50 \times 9.81 = 147.15\ \text{N}$$

Energy consumed for movement:

$$E = F \times d = 147.15\ \text{N} \times 5000\ \text{m} = 735{,}750\ \text{J} = 204.375\ \text{Wh}$$

This represents about 15.7% of the total estimated daily consumption (1.3 kWh), confirming that a significant portion of energy is used for movement..

Space Utilization Efficiency

The 3D model in SolidWorks allowed determination of the free space for robot movement under the panels.

With a row spacing of 6 m and robot width of 0.8 m, 7 rows can be operated with 2 travel lanes each, totaling:

$$\text{Usable space} = 7 \times 6\ \text{m} = 42\ \text{m}$$

Thus, the robot can carry out operations simultaneously on both lanes, maximizing field coverage.

Simulation of Operating Time

Based on hourly solar production (simulated in PVsyst), robot operating hours were correlated with energy availability. If the robot consumes 200 W in operation and the energy generated is at least 150 W per hour during 7:00–18:00, daily autonomy is ensured without relying on auxiliary sources.

CONCLUSIONS FROM RESULTS

- The estimated energy production (765 kWh/day) largely covers the robot's consumption (1.3 kWh/day), indicating energy sustainability.
- Route optimization reduces energy consumption by approximately 15%, increasing autonomy.
- The panel structure allows easy mobility for robots, without collision risks.
- The integration of software systems led to a coherent and functional design for efficient agrivoltaic exploitation.

DISCUSSIONS

The results obtained from the simulations and analyses of the agrivoltaic system integrated with agricultural robotics demonstrate the high potential of this technology for optimizing the use of agricultural land. The estimated energy production of approximately 765 kWh per day far exceeds the energy demand of agricultural robots, which consume only 1.3 kWh per day. This large gap between production and consumption indicates that the system can even support an expansion of the robot fleet or the integration of other electric agricultural equipment, thereby contributing to increased efficiency and farm sustainability.

An important aspect highlighted in the study is the optimization of robot routes using QGIS, which reduces energy consumption by minimizing travel distances and avoiding obstacles. The calculation of friction force and the energy consumed for movement emphasizes that a significant portion of the energy used is directed toward mobility, which justifies efforts to optimize routes. This can be further improved through the implementation of artificial intelligence and machine learning algorithms that adapt routes in real time, depending on field conditions and agricultural objectives.

The physical structure of the agrivoltaic system, designed in SolidWorks, provides an optimal configuration that ensures sufficient space for robot movement, without major risks of collision or equipment damage. This physical interaction between infrastructure and robotic mobility is an essential element for the efficient functioning of the smart farm. The distance between panel rows and the width of the robot are key parameters that must be adapted according to crop type and machinery used, in order to maintain an optimal balance between energy generation and agricultural activity.

Moreover, the simulations carried out with PVsyst provide a clear picture of the energy potential of agrivoltaics under real climatic conditions, demonstrating that this technology is feasible and effective even in areas with moderate solar radiation. This supports the idea that farmers can become energy prosumers, reducing their dependence on traditional grids and contributing to the decarbonization of the agricultural sector.

However, there are challenges that need to be addressed for large–scale implementation. The high initial costs of agrivoltaic installations and robotic technologies can be a barrier for small or medium–sized farmers. In addition, the integration of software and hardware systems requires technical expertise and constant maintenance, which implies staff training and additional investments.

Another point of discussion is climatic variability and its impact on energy production and robot operation. On days with reduced solar radiation, equipment autonomy may be compromised, requiring the use of energy storage systems or complementary sources. Implementing hybrid solutions or optimizing real–time energy management can mitigate these limitations.

In conclusion, the integration of agrivoltaic infrastructure with agricultural robotics represents a promising direction for sustainable agriculture, combining efficient renewable energy production with advanced automation technologies. The future of this technology, however, depends on continued research, the development of economically accessible solutions, and adaptation to local environmental and agricultural conditions.

CONCLUSIONS

The study on optimizing agrivoltaic infrastructure to support agricultural robotics on 1–hectare plots demonstrated that the integration of photovoltaic technologies with robotic systems is both feasible and efficient from an energy and operational perspective. The energy production estimated through modeling and simulations ensures a considerable surplus compared to the daily consumption of agricultural robots, confirming the sustainability of the proposed system.

Route optimization and precise management of robot movement, facilitated by specialized software, significantly reduce energy consumption, increasing autonomy and operational efficiency. The 3D modeling of the field and photovoltaic panel layout enabled the configuration of an infrastructure that maximizes the use of agricultural space without limiting robot mobility. Thus, the system ensures both renewable energy production and the optimal performance of agricultural operations.

Implementing such solutions in medium–sized farms can represent an important step toward smart and sustainable agriculture, with multiple benefits related to environmental protection, reduced energy costs, and increased productivity. By combining renewable energy sources with agricultural robotics technologies, new perspectives are opened for integrated and automated land management.

Future research can be extended to include intelligent real–time monitoring and control systems, as well as to evaluate the economic and social impact of these technologies. Furthermore, the integration of advanced energy storage solutions can ensure uninterrupted robot operation under variable solar radiation conditions.

In conclusion, optimized agrivoltaic infrastructure represents a viable and innovative solution capable of supporting the development of agricultural robotics, thereby contributing to the sustainability and efficiency of the agricultural sector.

Acknowledgement:

The results were obtained with the support of MCID through the NUCLEU Program, contract no. 9N/ 01.01.2023 project PN 23 04 01 01 “Intelligent Technology for High–Precision Application of Plant Protection Products, Fertilizers, and Seeding in Hard–to–Access Areas”.

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ISSN: 2067–3809