

Mobile Autonomous Energy Station with Battery Swapping for Agricultural Robotics: Design and Commercialization Prospect

Olga LIIVAPUU^{1*}, Yevhen IHNATIEV², Jüri OLT³

^{1–3}*Estonian University of Life Sciences, 56 F.R. Kreutzwaldi 56, Tartu, Estonia*

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Abstract – Innovation is a major driver of progress across all sectors, including agriculture, while intellectual property, particularly industrial property, plays a central role in supporting both innovation and economic development. The successful commercialisation of industrial property can contribute to economic growth by encouraging investment, creating new employment opportunities, and enabling the development of innovative products and services. This paper investigates the commercial potential of a novel autonomous, mobile, and environmentally sustainable energy station created at the Estonian University of Life Sciences. The process requires securing industrial property rights and managing them appropriately through the necessary legal procedures, followed by the initiation of technology transfer from academia to industry. In this case, the transfer takes place from a university to a commercial company. To facilitate commercialisation, a licensable technology portfolio must be prepared around the core licensing asset, which may include patents, utility models, and know how. In addition, the key value propositions of the product or technology must be clearly defined. The proposed mobile energy station consists of a solar power unit, operating as the primary non dispatchable source, with a maximum total output of 6.82 kW, a biomethane powered generator serving as a secondary dispatchable source, an energy storage system with a total capacity of 14.4 kWh, and a rapid battery swapping and charging system for an agricultural robot. By combining solar energy with generator support, the system is able to maintain continuous operation even in unfavourable weather conditions. The battery swapping and charging mechanism includes a platform alignment system, a motor driven trolley for battery transfer, and an automated locking and unlocking solution. The entire station is automated and managed by a programmable logic controller together with several embedded microcontrollers. The central SIMATIC PLC supervises the main control processes, including solar tracking drive operation, battery state of charge monitoring, generator control, and wireless communication with approaching robots.

Keywords – Environmental protection; intellectual property; renewable energy; research and development; sustainable innovation.

* Corresponding author.

E-mail address: olga.liivapuu@emu.ee

Olga LIIVAPUU <https://orcid.org/0000-0001-8611-9640>

Jüri OLT <https://orcid.org/0000-0003-4302-3176>

1. INTRODUCTION

Agriculture is increasingly affected by labour shortages driven by urbanisation, which limits production capacity and may threaten food security [1], even as demand for food continues to grow [2]. In response, new technologies such as agricultural robotics and automation are being viewed as promising solutions for filling labour gaps and supporting the transition to the next stage of development, Agriculture 5.0 [3]. Field robots are capable of carrying out tasks such as weeding, sowing, fertilising, crop protection, and harvesting with high precision, which improves the management of resources and reduces environmental impact [4]–[6]. The environmental footprint of agricultural operations can be further reduced by choosing electrically powered machinery. However, one of the main challenges in deploying autonomous electric agricultural machines is energy supply, especially ensuring uninterrupted operation over large fields given the limited capacity and energy density of onboard batteries [5], [7]. Equipping each robot with larger batteries is often not a practical solution because of added weight, higher cost, and diminishing returns [8]. As a result, the lack of a reliable mobile energy source creates both a technological and an operational barrier, since field robots may need to stop frequently for charging, significantly reducing their productivity [9].

One promising response to this challenge is a mobile energy station equipped with battery swapping capability [10]. In this concept, a solar powered mobile unit is positioned near the field so that robots can replace depleted batteries with charged ones directly on site, thereby minimising downtime [11], [12]. Battery swapping allows electric ground vehicles or robots to receive a fully charged battery within minutes, avoiding long charging interruptions and helping to overcome the problem commonly referred to as range anxiety. Because the energy supply is no longer tied to fixed plug in charging schedules, dependence on the electricity grid is reduced and energy management becomes more flexible [13]. Such stations effectively bring the charging infrastructure to the field, which is especially valuable in remote or off grid farms where electrical infrastructure is limited [11]. When renewable energy generation, such as solar panels, is integrated with energy storage, a mobile station can continuously recharge spare batteries and serve as an independent energy source for robots and other farm operations [14], [15].

Battery swapping technologies have also been explored in other sectors, particularly in electric vehicles [16], [17]. Commercial trials began more than a decade ago, with Better Place launching an automated battery swapping service for EVs in 2007, and the concept gaining further momentum in China from 2008 onward in the bus [18] and taxi sectors [15]. Recent reviews indicate that battery swapping stations, or BSS, can complement conventional charging by drastically reducing refuelling time and enabling innovative business models such as Battery as a Service. At the same time, the wider adoption of BSS faces important challenges, including high initial investment costs and the lack of standardisation across manufacturers. Similar issues are likely to arise in agriculture, where a mobile battery swapping station would also require substantial investment in equipment, such as automated battery handling systems and charging racks, as well as interoperability between different robot models through standardised battery modules.

Although mobile energy stations offer clear technical potential, their successful commercialisation and adoption in agriculture depend on presenting a convincing value proposition to farmers and overcoming barriers to uptake. Earlier studies on agricultural innovation show that farmers tend to be cautious about new technologies unless they clearly improve economic performance and reliability [19]. More recent research has identified high upfront costs and uncertain returns on investment as the main barriers to the adoption of

agricultural robots [5]. Farmers also express concern about the complexity of maintaining advanced equipment and the availability of supporting infrastructure. A mobile energy solution can therefore only be viable if it is cost effective, reliable, and easy to integrate into everyday farm operations. Encouragingly, survey results suggest that farmers are willing to adopt technologies that demonstrably improve productivity when enabling conditions such as training, technical support, and proven reliability are in place.

Previous studies [20]–[25] indicate that many universities, particularly technical universities, are playing an increasingly active role in innovation, intellectual property protection, and technology transfer. Intellectual property protection, and industrial property protection in particular, involves managing rights through their acquisition, maintenance, monitoring, and enforcement in the countries where such rights are strategically important. Effective management therefore requires both specialised expertise and adequate resources. Universities, however, often face substantial challenges in intellectual property management and technology transfer [23]. Successful commercialisation also depends on a realistic assessment of the expected lifetime of industrial property rights [21], which varies according to the specific circumstances of each case. Earlier research has also examined the environmental sustainability of patented inventions [25], as well as the economic and organisational factors that influence the market introduction of new technical solutions. In this work, technical feasibility is considered together with market readiness in order to provide a more comprehensive assessment of how such innovations can move from the prototype stage to practical application in modern agriculture.

The aim of this study was to present an environmentally sustainable mobile energy station developed at the Estonian University of Life Sciences, based on solar energy, equipped with a biomethane backup generator, and integrated with an automated battery-swapping unit, and to evaluate its commercialisation potential together with the related intellectual property management challenges.

2. MATERIAL AND METHODS

The lifecycle of a patented product [21], [25] should be taken into account when planning production and commercialisation, as depicted in Fig. 1.

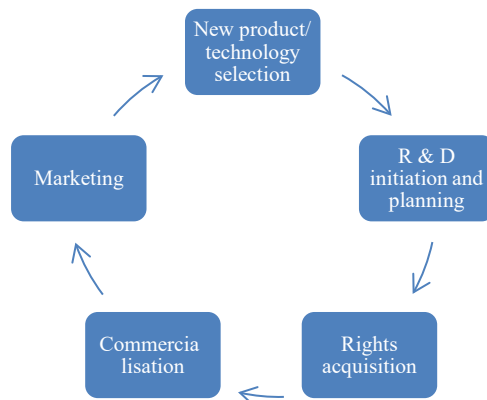


Fig. 1. Market model of life cycle of industrial property.

As shown in Fig. 1, this lifecycle comprises four main stages: (I) product introduction and planning, including market needs assessment, patent searches, and R&D; (II) rights acquisition, including patenting and prototype development; (III) commercialisation, including industrial production, licensing, and market launch; and (IV) market development, including market support, sales growth, gradual decline, and eventual product withdrawal, followed by upgrading or replacement with a new product. Accordingly, successful entry into a large-scale market requires a product that is patent-protected, technologically validated and refined for production, and supported by prior market preparation. In the case of agricultural machinery, the main sales argument is usually the specific cost of the technological operation, C_A , which is directly proportional to fixed and variable costs and inversely proportional to productivity [10], as follows:

$$C_A = \frac{1}{W} (C_F + C_V), \quad (1)$$

where

W productivity of the agricultural robot, ha h⁻¹;
 C_F fixed cost, € h⁻¹;
 C_V variable cost, € h⁻¹.

During field operation, the battery of an electric agricultural robot gradually becomes discharged. Recharging the battery takes time, and this reduces the share of time that can be used for effective work. As a result, the productivity of the agricultural robot decreases. The productivity of the agricultural machine or robot is better characterized by hourly productivity, W , in hectares, which is expressed as follows:

$$W = 0.1 v_m B_h \tau, \quad (2)$$

where

v_m travel speed, km h⁻¹;
 B_h operating width, m;
 τ working time utilisation factor.

The working time utilisation factor is calculated as follows:

$$\tau = \frac{t_w}{t_d} = \frac{t_w}{t_w + t_{0.1} + t_{0.2} + t_p + t_r}, \quad (3)$$

where

t_w effective working time of the agricultural robot, h;
 t_d total operating time, h;
 $t_{0.1}$ travel time from the energy station to the working row, h;
 $t_{0.2}$ travel time from working row to the energy station, h;
 t_p time spent turning at the headland and moving from one working row to another, h;
 t_r time required for recharging the battery of the agricultural robot, h.

If an electricity network had to be extended to every individual field, the fixed costs in Eq. (1) would become excessively high. In that case, the use of electric robots in such locations would not be economically attractive. A mobile energy station would therefore be an attractive solution.

The product presented in this study, namely a mobile energy station, was developed at the Estonian University of Life Sciences and includes legally protected components. The energy station is a trailer-mounted unit [26] equipped with solar photovoltaic panels, an energy storage system, a backup generator, and an automated battery-swapping device. The main purpose of the battery-swapping device is to reduce the time t_r . By reducing t_r , it becomes possible to increase the working time utilisation factor τ in Eq. (3) and, consequently, the productivity W in Eq. (2). As a result, the specific cost of the technological operation, C_A , given in Eq. (1), can be reduced.

The energy station is designed to serve autonomous field robots during operation by providing on-site restoration of their energy supply through automatic battery exchange, that is, by replacing a discharged battery with a charged one without human intervention [27]. The station is conceived as a modular, multifunctional service centre. In addition to energy generation, it can also perform various agricultural tasks by using different modules, for example for fertilisation, plant protection, and other field operations.

Evaluation procedure. The system was evaluated through a combination of simulations and field experiments, focusing on two key aspects: the station's ability to support continuous robot operation and the practicality and benefits of battery swapping compared to conventional charging. During field trials, a small autonomous robot (prototype rover) operated on a test plot, repeatedly performing assigned tasks and periodically returning to the station for battery exchange. Key parameters recorded included solar energy production, robot energy consumption, battery swapping time, and operational downtime. These data were used to estimate the number of robots that a single station can effectively support under different conditions. Additionally, a scenario-based analysis was carried out for a notional 15-hectare farm employing robotic weed control. The simulation covered an entire growing season and compared two approaches: one utilizing the proposed mobile battery swapping station and another relying on a stationary charging point located at the field edge. The evaluation considered metrics such as productive working time, idle time, and fuel consumption, with the baseline scenario assuming a diesel generator for charging. This approach provides a basis for quantifying the efficiency improvements and potential fuel savings offered by the proposed system. The commercialisation discussion is a preliminary assessment based on the prototype manufacturing cost, potential user groups, alternative charging options, and intellectual property readiness; it is not a full economic or socio-economic analysis.

3. RESULTS

The power station is equipped with a total of 22 photovoltaic panels mounted on its roof and deployable side wings, providing a peak capacity of up to 6.82 kW. To optimize energy yield, the panels incorporate an automatic solar tracking system that follows the sun's position throughout the day [28]. This tracking is implemented through an astronomical algorithm combined with a dual-axis actuation mechanism, which continuously adjusts the panel orientation to optimize incident solar radiation. The generated solar energy is stored in an onboard lithium iron phosphate (LiFePO₄) battery bank with a total capacity of 14.4 kWh. LiFePO₄ batteries were selected due to their long cycle life and enhanced safety characteristics, particularly their lower susceptibility to overheating under agricultural operating conditions. The batteries are managed by a battery management system (BMS), which monitors the state of charge and overall condition of each module. To ensure operational reliability, the system also includes a secondary controllable generator with a capacity of 6.5 kW. This generator is designed to start automatically during extended periods

of low solar irradiance or during peak demand. Such a hybrid configuration (solar plus generator) ensures uninterrupted operation even under unfavourable weather conditions, in accordance with best practices for off-grid energy systems.

All energy sources are connected to a common direct current (DC) bus, which supplies power to charging devices and, when necessary, can also provide energy to external equipment (Fig. 2).

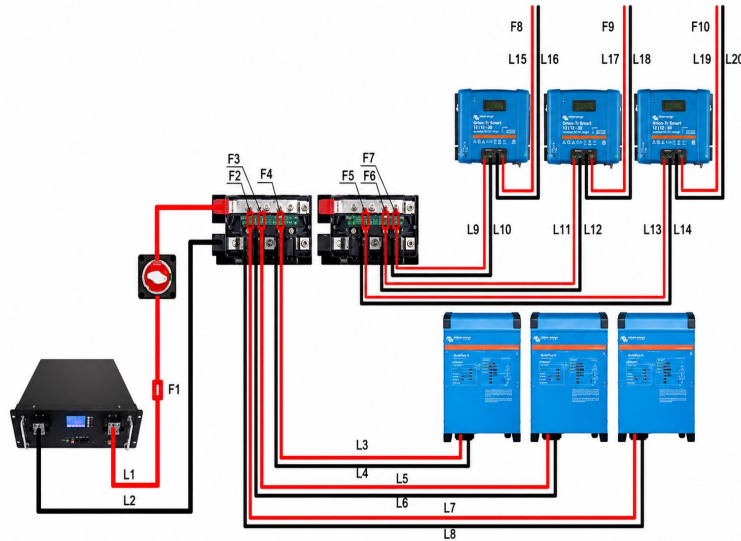


Fig. 2. Energy flow diagram. The busbars route power out via paired red and black conductors:

Lines L3–L8 connect to three blue inverters lined up horizontally along the bottom right; Lines L9–L14 connect to three blue MPPT solar charge controllers mounted above the inverters; Lines L15–L20 extend upward from the MPPT controllers through top switches/fuses labeled F8, F9, and F10.

In the given system, the agricultural robot is a medium-sized autonomous ground vehicle with a total mass of approximately 500 kg. Its main battery (51 V, 100 Ah lithium-ion, approximately 5 kWh) is housed in a standardized cassette format [29]. The robot's battery swapping and charging unit (Fig. 3) is mounted on the rear side of the power station platform, where the robot aligns itself upon arrival. The system includes a motorized carriage for transferring the robot's battery, as well as an automated locking and release mechanism that secures and disengages the battery cassettes [26].

When the agricultural robot requires a charged battery, it approaches the platform by following alignment sensors and ascends via a ramp. After the robot is secured to the frame of the battery swapping unit (Fig. 3), its depleted battery is released and pulled into the energy station using a transfer carriage equipped with a belt drive, gripper, and electric locking mechanism. The energy station contains two charging slots. The depleted battery is placed into one of the available storage ports for recharging. Subsequently, a fully charged battery is retrieved from the storage slot by the carriage and inserted into the robot's battery frame. The duration of the battery exchange process is comparable to systems described for electric vehicles and drones, typically taking up to 4 minutes. After the swap, the robot's onboard systems verify the status of the charged battery via the CAN bus [33], and the energy station releases the robot to resume its agricultural tasks in the field. By the time the robot returns for the next exchange, the previously removed battery is recharged to the required level, or

alternatively, a third backup battery is used in rotation [26]. This swapping strategy (two batteries per robot) ensures that the robot experiences virtually no downtime when restoring its energy supply.

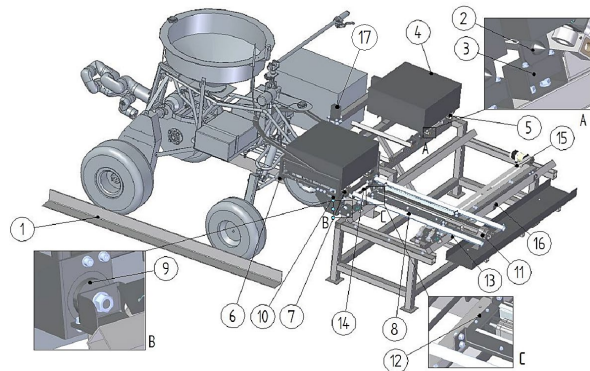


Fig. 3. Model of the battery swapping unit with the agricultural robot docked to it: 1 – directional guide for robot wheels; 2 – conical pin-catcher; 3 – locking element; 4 – battery container; 5 – roller of the battery container; 6 – frame carrying the battery container on the robot; 7 – longitudinal guide; 8 – battery cart; 9 – conical guide on the frame of the battery swapping unit; 10 – locking element; 11 – linear actuator; 12 – gripper; 13 – sensor determining the zero position of the battery cart; 14 – plate equipped with catches; 15 – belt transmission equipped with a stepper motor reducer and pulleys; 16 – sensor registering the position of the battery cart; 17 – sensor of the battery container's state.

The station's automation and control are managed by a programmable logic controller (PLC) and several embedded microcontrollers operating as an integrated system. A central PLC (Siemens SIMATIC) coordinates the main technological processes, including the operation of solar tracking drives, monitoring battery charge levels, starting and stopping the generator, and wireless communication with approaching robots. When a robot signals a low battery level, the PLC prepares a charged battery and instructs the robot to enter the service area. Real-time technological operations, such as carriage movement and locking mechanism control, are executed using Arduino-based controllers. The station is equipped with a safety system that includes emergency stop buttons, infrared sensors for obstacle detection during battery transfer, and interlocks that prevent movement in the case of a mobile trailer during the battery swapping process. Communication between the robot and the station is established via short-range wireless connection (Wi-Fi Direct) and a handshake protocol, ensuring that the robot remains immobilized, with its drives disabled, during the battery exchange for safety purposes.

A functional prototype of the mobile energy station (Fig. 4) has been constructed, featuring a platform base area of 12 m² and a height of 1.9 m in the folded state, extending up to 3.5 m when the panels are deployed. The supporting frame is made of high-strength aluminum alloy (6082-T6) to reduce overall weight while maintaining the structural capacity to support solar panels and battery equipment. During the design phase, finite element analysis was employed to verify the frame's resistance to dynamic loads, such as transport over field roads, as well as to strong winds during operation [28]. Calculations indicated that at a wind speed of 15 m s⁻¹ (54 km h⁻¹), the control system should automatically fold down the solar array to reduce wind exposure; this functionality was implemented to protect the structure [28]. The mass of the unloaded trailer is approximately 850 kg. After installation of the complete energy, control, and battery-swapping equipment, the total operating mass of the fully equipped station was measured as 4480 kg. The station must therefore be transported by a towing vehicle rated for this load.

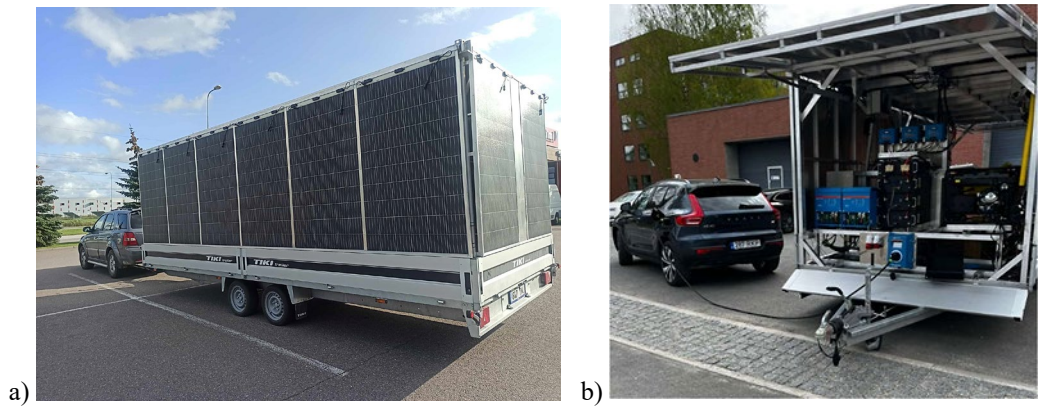


Fig. 4. Prototype of the mobile energy station: (a) coupled to a towing vehicle; (b) charging an electric car.

To ensure operational reliability, the system includes a secondary biomethane-powered generator (6.5 kW) capable of automatically starting during extended periods of low solar irradiance or under peak load conditions. This hybrid solution, combining solar power and a generator, enables uninterrupted operation even under unfavorable weather conditions, as recommended in the design of off-grid energy systems. All energy sources are connected to a common direct current (DC) bus, which supplies power to charging devices and, when necessary, can also provide energy to external equipment.

TABLE 1. TECHNICAL SPECIFICATIONS OF THE ENERGY STATION

Parameter	Unit	Value
Solar panel power	kW	$22 \times 0.310 = 6.82$
Inverter Quattro voltage	V	48
Number of phases		3
LiFePO ₄ battery voltage	V	48
Battery pack capacity	kWh	$3 \times 4.8 = 14.4$
Battery charge controller		MPPT
Battery Management System (BMS)		Yes
Generator	kW	6.5
Dimensions (l × w × h)	m	$6.5 \times 2.2 \times 2.8$
Mass in field-work configuration	kg	4480
Direct CO ₂ emissions (solar-only mode)	g h ⁻¹	0

The prototype is constructed using standard industrial components, including photovoltaic panels, inverter/charger, batteries, and a PLC, in order to ensure reliability and ease of maintenance. The total manufacturing cost of the prototype is approximately € 30 000, with battery modules accounting for about 40 % and solar panels together with control electronics approximately 30 % of the total cost. Although the overall cost is not insignificant, it is comparable to that of mid-range agricultural machinery. A potential approach to further cost reduction is the use of second-life electric vehicle (EV) batteries, i.e., repurposed batteries from electric cars. As demonstrated by Eissa and Chen [8], integrating second-life batteries into photovoltaic container systems can be economically advantageous. The proposed

technical solution is compatible with such batteries, provided they are available, which could reduce initial investment costs and enhance sustainability through the reuse of previously utilized components.

Measured field-test results. The mobile energy station prototype successfully demonstrated continuous robot operation with minimal downtime during field trials. In a typical test scenario, the robot operated autonomously for 10 hours on a soil monitoring task and required three battery swaps within this period. Each swap was completed in under 4 minutes, consistent with the designed cycle time of 223 seconds. The locking sensors and alignment system proved to be effective, with the robot consistently achieving successful docking on the first attempt with an accuracy of approximately 50 mm. Over dozens of swapping cycles, the success rate of proper connection alignment was 100 %, with no instances of dropping or jamming observed. These results confirm the reliability of the mechanical solution, in line with other automated swapping prototypes reported in the literature.

Measured energy results. During periods of maximum solar irradiance (around midday), the photovoltaic system delivered a measured continuous power output of approximately 5.6 kW under clear sky conditions. In summer test conditions, the average daily energy production ranged between 38 and 42 kWh, enabling the charging of approximately 10 robot batteries per day (each about 5 kWh) while simultaneously maintaining the station's own energy storage at full capacity. The station's energy balance on a sunny summer day showed that approximately 38 kWh was generated by the panels, of which around 29 kWh was used for battery charging, including robot battery swaps, while the remaining energy covered the station's internal consumption or was stored for nighttime use. On cloudy days, daily production decreased to approximately 18 kWh; in such cases, the generator was automatically activated in the late afternoon to supplement the energy supply. In one test instance, the generator operated for 2 hours, providing an additional 10 kWh. This hybrid operating mode ensured that the robot was able to complete its work schedule even when solar energy alone was insufficient, which is a critical requirement for practical agricultural applications. By comparison, a purely solar-based system would require reducing workload or suspending operation during heavily overcast conditions. These results support existing approaches to hybrid renewable energy systems, which emphasize the importance of backup generation or energy storage in ensuring operational reliability.

Model-based capacity estimate. Based on field tests and energy modelling, a single mobile station can support approximately 2–3 robots performing light-duty tasks or 1–2 robots in more energy-intensive operations, with the main limitation being the daily energy budget of about 50–55 kWh, including solar production, battery storage, and occasional generator support. A high-power robot (≈ 5 kW) can consume most of this capacity alone, whereas lower-demand tasks (≈ 2 kW) allow energy to be distributed among multiple robots. Efficient battery swapping logistics are essential; experiments showed that, with two charging ports, batteries can be charged and exchanged in parallel, and a 5-kWh battery can be recharged to 90 % in about one hour, enabling continuous operation of two robots with staggered swap cycles.

Scenario-analysis results. The battery swapping approach significantly improved robot uptime and task efficiency compared to conventional charging. In the scenario analysis, a robot using the swapping station achieved an average of 9.6 productive hours out of a planned 10-hour day, with only about 4 % of time spent on battery exchanges. In contrast, a robot relying on a stationary charging point remained productive for only 5.5–6 hours, losing 1–2 hours to travel and charging-related downtime. Over a 100-day season, this corresponds to approximately 150 additional working hours per robot, or about 19 % more operational

time, consistent with findings in the literature that reduced downtime substantially increases system throughput. An additional advantage is reduced soil compaction and crop disturbance. As the station operates along field edges or access paths and robots remain within the crop area, unnecessary back-and-forth movement across the field is minimized. Combined with the inherently lower ground pressure of small robots, on-site energy replenishment supports improved soil health, reinforcing a key sustainability benefit of agricultural robotics.

Scenario-based environmental estimate. From an energy perspective, the solar-based station replaces a significant share of diesel fuel otherwise required for generator-based charging, with estimated seasonal savings of about 500 liters of diesel, corresponding to roughly 1.4 t of CO₂ emissions. In field tests, the generator contributed only around 10 % of total energy under the least favorable weather conditions, indicating that its role could be further reduced with increased solar or storage capacity. These results highlight the environmental benefits of the system, as it enables electrified agricultural operations powered largely by renewable energy, while the lightweight construction also reduces fuel consumption during transport.

Preliminary commercial assessment. The prototype manufacturing cost is approximately € 30 000, as detailed above; this is a one-off prototype cost and not a validated mass-production price. Potential users include farms operating several robots and agricultural service providers or contractors. Relevant alternatives include stationary grid-connected charging, diesel-generator charging at the field edge, larger onboard robot batteries, and extension of the electricity network to the field. The scenario results indicate that battery swapping may improve robot utilisation and reduce fuel and labour requirements. However, a defensible payback period under mass-production conditions cannot yet be calculated because validated series-production costs, annual utilisation, maintenance costs, energy and labour prices, financing conditions, and service-life data are not yet available. The possible socio-economic effects, including reduced operator demand, reduced fossil-fuel use, and lower field traffic, are therefore discussed qualitatively and require a separate economic and socio-economic study.

4. DISCUSSION

The development and testing of the mobile energy station demonstrate that field-based battery swapping for agricultural robots is technically feasible [26]. The results show that a well-designed swapping system can maintain near-continuous operation of 2–3 robots powered mainly by solar energy, representing an important step toward autonomous, low-emission agricultural operations. More broadly, this approach supports sustainable farming practices by reducing dependence on fossil fuels and enabling the use of smaller, lighter machines that are less harmful to soil structure [4].

Despite these advantages, several challenges must be addressed before large-scale commercialization. One of the primary issues is cost and economic viability, particularly the specific cost of technological operations (EUR ha⁻¹). The mobile energy station introduces an additional capital expense, and reducing this cost through economies of scale or service-based models will be essential. For example, an “energy-as-a-service” approach, where the station is provided as a service and charged per hectare or robot operating time, could convert upfront investment into operational expenditure, similar to battery-as-a-service models in the electric vehicle sector [7], [30].

Another key challenge is standardization and compatibility. Currently, agricultural robot manufacturers employ different battery systems in terms of voltage, form factor, and chemistry. A mobile swapping station would be most effective if it could serve multiple robot

platforms, which requires either standardized battery modules or adaptable interfaces. In the long term, this may necessitate industry-wide agreements or consortia to define interoperable battery standards. In the interim, solutions such as platform-specific adaptations or interchangeable adapters can be used, although they increase system complexity. Encouragingly, the concept of modular battery packs for small tractors and robots is already emerging. The proposed design accounts for this by using a versatile carriage and gripper capable of handling modules of varying dimensions within a defined range, with adjustable gripping points. Future developments, such as machine vision, could further enhance flexibility by enabling automatic identification and handling of different battery types [13].

Finally, simplicity, reliability, and safety in agricultural environments remain critical. Farming conditions involve dust, mud, vibration, and varying weather, requiring the swapping mechanism to be robust and well-protected. Any failure in the field can interrupt operations and potentially affect crop yield. Although prototype testing under controlled conditions has been promising, extensive long-term validation across different crops and climates is necessary. Farmers expect near-continuous reliability, and maintenance requirements must be minimal; ideally, the system should include self-diagnostics and support preventive maintenance. From a safety perspective, handling high-capacity batteries involves risks such as short circuits and thermal failures. The station design incorporates safety interlocks and a fire suppression system around the battery bank as precautionary measures, consistent with safety considerations highlighted in battery swapping research.

From a farm management perspective, the adoption of a mobile energy station together with agricultural robots requires a shift in operational practices. Farmers and personnel need training to deploy, operate, and monitor the stations, while tasks such as relocating the station between fields, managing charging (when not relying solely on solar energy), and scheduling battery swaps introduce additional complexity into daily routines. Studies on technology adoption indicate that ease of use and technical support are critical factors for acceptance; therefore, commercial solutions should incorporate user-friendly interfaces, such as control panels displaying battery status and energy storage levels, as well as remote support capabilities. At the same time, a well-integrated system can reduce labor requirements not only by replacing tractor operators but also by automating fuel and battery logistics. This aligns with broader smart farming trends, where processes are increasingly automated and synchronized [31]. In this context, the proposed station functions as an autonomous field-based charging unit that can be scheduled and managed via software, forming part of a broader farm management system coordinating robot operations and energy supply.

From a commercial perspective, given the rapid growth of agricultural robotics and the increasing emphasis on sustainable farming, mobile energy stations may occupy a market niche, subject to further market and economic validation [32]. Early adopters are expected to include large-scale farms and service providers or contractors.

In terms of innovation readiness levels (IRL), the proposed concept has reached the prototype demonstration stage, corresponding to approximately IRL 5–6 on a nine-level scale, where level 9 represents full commercial deployment. Future work should focus on scaling testing to multiple robots operating simultaneously, improving ergonomics and safety, including enhanced weather protection, and conducting extensive reliability trials. Advancing toward commercialization will require close collaboration with stakeholders, including farmers and agricultural service providers, to pilot the system under real-world conditions. This will also support the development of training materials and support services, which are essential aspects of non-technical readiness. Further refinement of both the technical design and business model, including potential leasing options, will be necessary to meet market requirements. As highlighted in the literature, successful adoption in agriculture depends not

only on measurable performance but also on trust, ease of integration, and clear cost-effectiveness, which in turn require transparent data on system performance and achieved savings.

5. CONCLUSION

This study demonstrates that a solar-powered mobile battery swapping station can effectively support agricultural robots, offering a sustainable and efficient alternative to conventional charging. The solution addresses practical energy constraints in field operations and, with careful consideration of cost and user needs, has the potential to accelerate the commercialization of agricultural robotics. Overcoming the remaining challenges will require continued innovation and collaboration between engineers, farmers, and policymakers; however, the pathway toward integrating clean energy with automation in agriculture is becoming increasingly clear.

As the energy station is designed to support agricultural robot operations, its value proposition can be summarized as follows:

1. Environmentally friendly, as it utilizes renewable energy sources;
2. Energy independence, enabling robot operation in fields without access to low-voltage grid infrastructure;
3. Reduced specific cost of technological operations due to improved utilization of working time compared to conventional methods;
4. No directly equivalent commercial product was identified in the sources reviewed; this was not an exhaustive market survey, and stationary charging, generator-based charging, grid extension, and larger onboard batteries remain alternative solutions;
5. Effective management of intellectual property supports and stimulates innovation;
6. Provides opportunities for the intellectual property holder to collaborate with industrial partners in manufacturing development;
7. Enables the intellectual property holder to offer exclusive rights for production, sales, and use;
8. Supports technology transfer to interested industrial partners, including licensing of the developed prototype, along with intellectual property, technical documentation, and know-how.

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