

AGRICULTURE ELECTRIFICATION, EMERGING TECHNOLOGIES, TRENDS AND BARRIERS: A COMPREHENSIVE LITERATURE REVIEW

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On a global scale, the agriculture sector is a major contributor to greenhouse gas emissions, and this holds true for the European Union as well. While a shift to renewable energy sources could reduce reliance on fossil fuels and enable electrified agriculture, there are significant challenges to overcome. These include the high initial costs and inconsistent energy output of renewable sources, as well as issues with acceptance and cost related to electric tractor technology and load-balancing batteries. To explore potential solutions and future prospects for electrifying agriculture, a literature review is conducted to identify emerging technologies and research trends in areas such as agrovoltatics, semi-transparent photovoltaic panels, energy storage systems and electric tractors. The review conducted will provide a valuable insight into future research and the implementation of emerging technologies, thus addressing the challenges faced by the agriculture sector during its transition to electrification based on renewable energy sources.

Keywords: Agriculture, battery technology, electrification, electric tractors, hydrogen, literature review, renewable energy sources (RES), semi-transparent photovoltaics.

1. INTRODUCTION

Agriculture electrification, the process of introducing a wider use of electricity to rural environments, has the potential to revolutionise the way we produce food and manage our natural resources, thus becoming an increasingly important area of research as the world looks to decarbonise the sector and

reduce greenhouse gas (GHG) emissions. According to the United Nations Framework Convention on Climate Change [1], in 2018, the agricultural sector contributed to around 24 % of the world's GHG emissions, but a study made in 2021 [2] determined that the emission level was much higher than

expected, reaching up to 34 %. With this in mind, the European Union (EU) has implemented several acts of legislation to support the decarbonisation of the farming sector, which includes the EU Green Deal [3] and the Farm to Fork Strategy [4].

These policies aim at reducing emissions not only in food production, waste management and in the use of artificial fertiliser, but also increasing the use of renewable energy, promoting sustainable energy production and electrification of machinery practices. However, application of electrification activities is not without its challenges and barriers.

Implementation of renewable energy sources (RES) in agriculture is highly dependent on the initial cost of energy supply and RES energy generation patterns. Furthermore, placing renewable energy generation infrastructure on a plot of land may result in a reduction of the cultivated area, which could subsequently lead to a decrease in crop yield. Alternative installation and operation strategies for renewable energy systems should be explored.

Moreover, integrating RES could be challenging due to seasonal load fluctuations within the system. The integration of efficient battery systems has the potential to enhance the utilisation of renewable energy, promote self-consumption and minimise the impact of load fluctuations on the energy supply system [5].

Electrification of agricultural machinery (mainly tractors) faces considerable development challenges regarding battery efficiency and charging possibilities in a rural environ-

ment. From the acceptance point-of-view, farmers' willingness-to-buy is heavily influenced by the cost of the equipment. Since the expense of lithium is high, the battery system accounts for approximately 30 % to 50 % of the overall cost of electric tractors, which can result in the initial cost of electric tractors being up to three times more expensive than comparably capable diesel-powered internal combustion engine vehicles [6]. Thereby, it is necessary to identify the factors that could impact the farmers' inclination to opt for an electric tractor, despite the high costs associated with the current technology.

It is important to understand the current state of knowledge on existing technologies and practices, as well as the ongoing research in this area. A literature review could provide an overview of the subject matter, and enable farmers to make evidence-based decisions regarding the implementation of electrification activities. With this in mind, the aim of the paper is to provide a comprehensive literature review of the current state of agriculture electrification with emphasis on wider use of RES, energy storage and electric tractors. Furthermore, throughout literature review the authors would seek answers to barriers related to agriculture and give better understanding about current bottlenecks from an energy point of view, thus identifying key areas for future research and development.

The paper is organised as follows: Section II describes literature selection methodology, Section III includes literature review and Section IV contains results and conclusions.

2. METHODOLOGY

In order to conduct a structured literature analysis, aspects of literature selection methods described by [7], [8] were used. The methodology used for this review is pre-

sented in next paragraphs.

The main sources of information were gathered through academic journal publications, therefore providing review of the lit-

erature related to agricultural electrification from different analysis and research perspectives.

The initial step that was established involved selecting the most suitable scientific publication databases. To evaluate relevant publications, IEEE Xplore, Scopus, and Web of Science databases were chosen. Scientific publications filtering process consisted of two aspects: publication period and keywords. Publication period of 2018–2023 was used, thereby content of the scientific literature would reflect the latest research and electrification development trends. Publication search using review related keywords (“agriculture electrification”, “agriculture electrification challenges”, “renewable energy sources in agriculture”, “electric machinery in agriculture”, “electric tractors”, “agriculture battery technologies”) on the chosen databases was performed in January–February 2023. Keywords were determined to reflect the main aim of this review – trends, challenges, barriers and solutions for

wider use of RES and electric machinery in agriculture.

By using specified publication databases, period and keywords, 59 publications were retrieved. Following a full-text analysis, 28 publications were excluded due to the non-compliance with the agriculture electrification and publication duplications between the aforementioned databases. Thirty-one papers remained, which formed the basis for this review.

To compare the progress of electrification in the agricultural sector with that in other industries, as well as to gain additional insights on legislation and development priorities beyond agriculture electrification, supplementary information was collected by using documents and reports cited in the reviewed publications and other studies.

Starting with the next section and its subsections, analysis and results of literature review are presented and possible solutions for the aforementioned challenges are sought.

3. LITERATURE REVIEW: SEEKING SOLUTIONS TO AGRICULTURE ELECTRIFICATION CHALLENGES AND BARRIERS

3.1. Innovative RES Installations and Emerging Technologies

Due to energy intensive loads and physical nature of RES elements, traditional electricity generation element installations and operations in agriculture can be difficult to implement. First of all, energy consumption can be variable, irresolute and non-definable; thus, agriculture-customised power generation and storage solutions are needed. Second, due to the high power

consumption, RES elements can occupy large-scale territories, which could be used for crop fields and livestock pastures, thus decreasing the value of the land [9]. Therefore, innovative solutions to aforementioned problems have been developed, using new technologies, modelling skills and power system operations. This subsection will be devoted to review of these solutions.

3.1.1. Agrovoltaics

One of the most promising options for RES integration in the agricultural complex is using a synergy between PV panels and

farmlands – a method of installation called “agrovoltaics”. For the first time, this idea was put forward in the 1982 publication

[10], in which authors suggested that PV panels could be installed on the cultivated

land above the crops (see Fig. 1). Since then, this method has gained popularity.

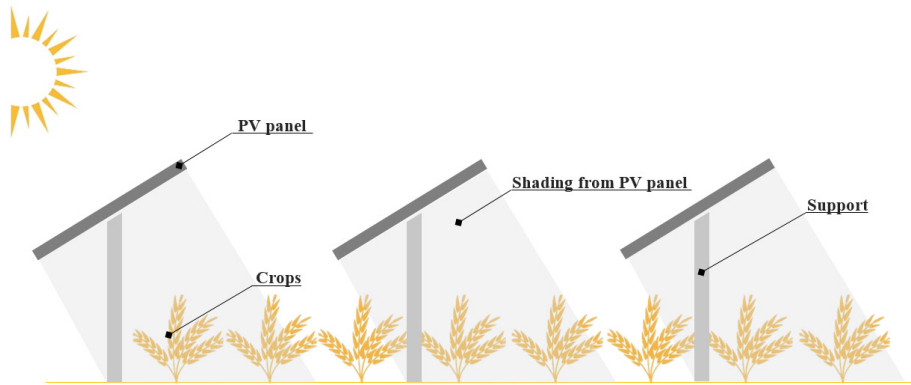


Fig. 1. Example of agrovoltaics installation method [5].

Its effectiveness is indicated in [11], where authors analysed United Nations Sustainable Development Goals (SDGs) and opportunities to reach them with the help of agrovoltaics. Additionally, the study compared it to roof PV panel and rooftop farming applications.

The authors determined that agrovoltaics can contribute to at least 10 of the overall 17 SDGs and, in comparison, gives greater contribution than rooftop PV and rooftop farming in the following activities:

- Agrivoltaics enables food and energy double income;
- It produces food locally;
- It brings more green view and offers a place to be with nature;
- Roof and agrovoltaics related farming work is not physically intensive and can create more jobs for females;
- Water used for PV panel cleaning can be used for crops underneath;
- It generates clean energy (less than rooftop PV);
- It is an emerging urban industry with economic potential;
- It reduces a heat island effect in cities;
- Partially it creates habitat space for animals, thus enriching urban biodiversity.

The main directions of agrovoltaics research are discussed and covered in [12], where authors summarised and analysed projects, technologies, field management implications and shading affect to crop growth using scientific publications done in the time frame from the 1980s until 2018. Since 2018, the ideas mentioned in the publication have been further developed by introducing innovative operational and technical solutions. For example, authors of [13] investigated agrovoltaics design features, which influenced microclimate under PV panels and temperature of PV modules by changing the panel height over the soil. The study concluded that the height of the installations and the microclimate under PV panels affected the efficiency of the panels themselves – when installing them at a height of 4 metres above the soybeans, the average temperature of the surface of the PV panels decreased by 10 °C. Agrovoltaics installation technique for growing individual plant groups can be effective from the point of the cooling of the modules due to the water vapour underneath them, which increases PV panel efficiency indicators and extends PV module lifespan. Although several authors point to the positive effects of agrovoltaics, publica-

tion [14] describes agrovoltatics techno-economic analysis using a neoclassical economic theory to determine PV panel negative effect of shading on crops, their growing efficiency and changes in land worth by using agrovoltatics installation. The method developed in the paper allows calculating not only the extent of crop yield reduction but also the ratio between profits from electricity generation and economic losses of crop yields.

Nevertheless, the reviewed concept is seen as a promising option for renewable

energy integration in the agricultural sector. Agrovoltatics can contribute to at least 10 of the 17 United Nations SDGs and offer benefits, such as food and energy double income, local food production, job creation, clean energy generation, and reduction of a heat island effect in cities. However, the impact of shading from PV panels on crop yield and the overall economic viability of agrovoltatics are also important considerations that have been addressed in the above-mentioned studies.

3.1.2. Transparent and Semi-transparent PV Panel Modules

In order to avoid the negative effects of shading, at the same time to cover as little area as possible for RES installations, innovative semi-transparent and transparent PV panel modules can be used.

First fully transparent PV panel module was made in 2014 at the Michigan State University. Due to low efficiency, this technology has to be further developed to reach its efficiency from initial 0.4 % to potential

5 % and to find the possibility to be used in real agriculture conditions [15], [16].

More widely implemented technology is semi-transparent PV panels, the development of which began in the 1970s by creating the first thin-film solar technology. Nowadays, a wide transparency and efficiency range of semi-transparent PV panel technologies (see Table 1) are available to be used for agricultural purposes.

Table 1. Semi-transparent Solar Cell Technologies [15], [17]

Solar PV technology	Light transparency (%)	Efficiency (%)
Screen printing dye synthesised cell	60 %	9.2 %
Near-infrared heterojunction organic cell	55 %	1.7 %
Polymer cell	66 %	4.02 %
Perovskite cell	27 %	13 %
Electrophoretic technique cell	55 %	7.1 %
Dip-coater cell	70 %	8.22 %
Quantum dot cell	24 %	5.4 %

The authors of [18] and [19] identified the use of semi-transparent PV cells on greenhouse roofs as the main application of the technology. Paper [18] provides the development of an energy balance model to determine the impact of heat, air, and moisture flow and circulations in greenhouses with these PV panels. The study concluded that the roof design and place-

ment of the panels were significant factors affecting the circulation. Another publication [19] conducted a pilot project using semi-transparent PV panels (47 % transparency and 8.25 % efficiency) on a tomato greenhouse roof. The results showed the following:

- There was no negative impact on tomato yield from PV panels;

- The shading from the PV panels resulted in a 1–3°C decrease in air temperature on clear days, due to the 35–40 % reduction of solar irradiation under the panels. In addition, the panels had no effect on greenhouse humidity level.
- PV panels were composed of three modules with a peak power of 170 Wp each, the annual generated electric energy of the panels was 637 kWh and payback period for the panels was calculated to be 9 years.

Considering all the above, semi-transparent PV panel technology has shown

3.1.3. Battery Systems

RES variability such as fluctuating solar radiation or wind speed can pose challenges for electricity supply stability. Energy storage systems, including batteries, are crucial components in maximising RES self-consumption level. They store surplus energy, ensuring a steady power supply during low energy generation periods. This enhances reliability of energy supply, as well as promotes effective and efficient energy utilisation. To better understand current and future battery technologies and address challenges and solutions for their implementation in agriculture, this paragraph conducts a comprehensive literature review on battery

technologies. Pilot projects suggested that the panels have no significant impact on yield and provide only a slight decrease in air temperature. The efficiency and transparency of semi-transparent PV panels have a wide range, making them readily available for use in agricultural conditions. Nevertheless, further research is needed to improve the efficiency of fully transparent PV panel technology and reach its potential efficiency. In addition, further pilot projects using semi-transparent PV panels in different geographical conditions would provide additional valuable information for their integration potential.

technologies.

At the onset, it is crucial to acknowledge the existence of a multitude of energy storage technologies, each possessing its own qualities and benefits. Selection of battery technology for agriculture electrification is dependent upon a number of factors, including but not limited to the electricity consumption profile and character, as well as the economic viability and efficiency of the technology [20]. The most widely used battery technologies, along with their benefits, drawbacks, and practical applications, are presented in Table 2.

Table 2. Overview of Existing Battery Technologies [20]

Technology	Life cycles	Advantages	Limitations	Main applications	Applicability in agriculture*
Li-ion	~3000	High energy density and efficiency, fast response time, no memory effect	Expensive and safety issues depending on the type	Portable devices and electric vehicles (EVs)	+++
Flow batteries	<20000	Nearly unlimited longevity	High maintenance, complex monitoring and control	UPS, EVs, load balancing	++
LiFePO ₄	<2000	Safe and stable voltage discharge	Due to low capacity, it is used as preliminary energy storage	High load current devices	++

LiMn ₂ O ₄	<700	High power output level and safer than LiCoO ₂	Low energy capacity	Power tools	+
Lead-acid	<3000	Cheap and freely available	Low-energy density and high environmental impact	Emergency lighting and electric motors	+
NaS	~4500	High efficiency and life cycle	High operating costs and temperature	Load balancing, EVs	+
NaNiCl ₂	<3000	Long life cycle and high energy density	High maintenance costs and temperature	Load balancing and EVs	+
Double-layer capacitor	~1000000	High power density, long life cycle and fast response time	Complex water and thermal control, high initial cost and low efficiency	EVs, backup power applications and load balancing	+

**Rating was developed by the authors of the review from the analysis of existing battery technologies*

Battery technologies have undergone significant advancements, thanks to massive investments in financial resources. Despite their progress, all battery technologies face a common challenge – scarcity of raw materials. Lithium-ion batteries are currently the leading energy storage technology, but their main component material, lithium, presents a potential concern for the future. It is projected that the global lithium supply will only suffice market demand until 2100. To overcome this challenge, sodium-ion batteries are emerging as a promising alternative by using more available raw materials – sodium salts. Sodium-ion sources are abundant in nature, derived from sea water or salt deposits, and are cheaper than lithium.

Moreover, the energy capacity of a sodium-ion battery is heavily reliant on the size of its sodium-based solution, thus limiting its applicability to portable smart devices. Despite being larger and heavier than lithium-ion batteries, a sodium-ion battery could still be utilised as a cheaper option for large-scale renewable energy storage in the agricultural complex, where equipment size and weight are not significant limiting factors. Efforts are underway to enhance the capacity, stability, and rate performance of sodium-ion technology

through research and experiments. The goal is to make this technology commercially viable in the near future [21].

A significant progress in calculating economic assessments for RES and battery configurations has been done in recent years, using general consumption and generation data, as evidenced by the numerous publications in this area (as listed in [22]). However, the economic feasibility of incorporating RES and related technologies into agriculture energy consumption remains poorly understood due to a shortage of research and data. This was highlighted in a questionnaire of Swedish farmers conducted as part of publication [23], which found that technical and economic risks, including potential deterioration of battery performance and uncertainty around investment aid and the size of investment required, represented major barriers to battery integration in agriculture.

As a result, there is a pressing need for more extensive and wide-ranging studies on the techno-economic viability of these elements in agricultural environments. This includes evaluating the economic synergies that can be achieved through the combined use of conventional energy elements, such as photovoltaic panels, wind generators, and lithium-ion batteries, with emerg-

ing technologies and installations, such as agrovoltaics, semi-transparent photovoltaic

panels, next-generation battery technologies and electric tractors.

3.2. Electric Tractors

Electric tractors have the capability to revolutionise the transport and agriculture industries by reducing the reliance on fossil fuels and improving the use of locally available renewable energy resources. However, the effective implementation of this technology requires a thorough understanding of the current state of development, thus identifying electric tractor acceptance potential. The next paragraphs will be devoted to comprehensive literature review of the availability and efficiency analysis of electric tractors.

Broadly speaking, these tractors can be classified into three major categories [24]:

- Battery electric tractors: operated by an electric engine and energy stored in

batteries;

- Hybrid electric tractors: a combination of internal combustion engine and electric engine with a battery system;
- Fuel cell electric tractors: operated by an internal combustion engine, which uses hydrogen as the main source of fuel.

Electric tractors are a subject of discussion in the field of agriculture and agricultural technology, with many experts examining their various capabilities and limitations. Each of the named types of electric tractors has their own advantages and disadvantages regarding power capacity, efficiency and other aspects (see Table 3).

Table 3. Advantages and Disadvantages of Battery Electric and Hybrid Electric Tractors [6], [24]–[26]

Battery electric tractors		Hybrid electric tractors		Fuel cell electric tractors	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Zero emissions	Limited battery life and long recharge time	Long continuous working hours	Release of emissions	High fuel consumption efficiency	Limited lifetime
High torque	High initial cost	High fuel efficiency	High complexity	Zero emissions	High initial and maintenance costs
Low running costs	High energy consumption during heavy loads	Energy generation during regenerative braking	High initial cost	Existing tractors can be modified to use hydrogen instead of diesel	Hydrogen production and storage issues
Long lifetime	Negative effect of hot climate on the battery				

Economic arguments at this point do not allow making a decision in favour of electric tractors. Hence, alternative approaches must be explored to encourage farmers to shift from diesel-based tractors to environmentally friendly machinery. To gain insight into the extent of demand for electric tractors and the underlying motivations for their adoption, the authors of the publication [27] carried out a comprehensive questionnaire of

farmers to elicit information regarding their willingness and preferences for purchasing an electric tractor. They concluded that the demand for electric tractors was influenced by costs, the size of the farming area, farmers' age and technical skills, engine characteristics, and other preferences. In particular, lower initial and maintenance costs were found to be a motivator for farmers to purchase electric tractors.

Additionally, farmers with prior experience with electric tractors demonstrated a positive willingness-to-pay.

The trend towards sustainable and environmentally friendly agricultural practices has been driving the growth of the electric tractor market. According to [28], the global tractor market is expected to grow by 5.7 % each year by 2026. Furthermore, this growth is driven by increasing demand and the adoption of electric tractors. With increasing demand, manufacturers of electric tractors are contributing to market growth with supply of this environmentally friendly technology. The state of the market has been addressed by [24], [28] and [29], in which the authors identified the state of the market for electric tractors as well as the current assortment of them. Although the tractor market offers conventional tractors with electric engines, the market is limited to only low power engine technologies (40–50 horsepower electric tractors), despite their positive impact on energy costs and climate impact [30]. As [31] points out, <50 horsepower tractors are able to perform light ploughing and bailing, but are unable to perform heavy duty tasks like equipment transportation, harvesting, cultivation, hard ground ploughing and other activities.

Moreover, a significant part of the electric tractor market consists of autonomous tractors, which requires the farmers' relatively high technical, planning and programming skills [32]. While bearing in mind that electric tractor willingness-to-buy is influenced by farmers' age and skills factor, an excessively high supply of autonomous electric tractors can potentially slow down their acceptance rate and use by con-

sumers simply because their operating principle would be drastically different from the use of conventional tractors.

Additionally, the lack of charging infrastructure and distance between charging stations and tractors in the field pose significant challenges in the aforementioned publications. One possible conceptual solution to this challenge could be the use of on-board battery packs or trailers with spare batteries and mobile charging option [33].

As a result, the agriculture industry has the potential to be transformed by the introduction of electric tractors, which would reduce dependence on fossil fuels and increase efficiency. Although the reviewed publications cover valuable insights into the capabilities and demand for electric tractors from a consumer perspective, lack of comprehensive examination of the connection between RES and the use of electric tractors can be seen.

Future research should investigate the feasibility of utilising renewable energy as a reliable and efficient power source for electric tractor charging infrastructure. By applying different business models, one of the ways could be to develop a comprehensive, commercialised and techno-economically compatible renewable energy system package (RES elements, battery system and power flow control system) for charging specific types of electric tractors and related equipment. It would greatly facilitate the determination, planning, and implementation of RES for electric tractor charging purposes. Furthermore, it would be advisable to examine how a wider range of electric tractors in the market could influence farmers' willingness to purchase them.

3.3. Initial Cost and Economic Assessment of RES

Due to the global economy's rapid movement towards greater use of RES and overall decarbonisation, the agricul-

tural sector sooner or later will become a climate-neutral industry. But based on currently available solutions and technologies –

at what price? By reviewing scientific literature, this paragraph will examine the economic analysis of the use of different RES and will find out whether the current solutions economically justify the introduction of them to the farming sector.

Authors of publication [34] proposed a simple solution to the diesel powered irrigation system by replacing the existing water pumping system to water storage, distribution and control system by using PV panels as a source of electricity. Economic analysis showed that the system had a payback period of just 3 years on 100 % capital expenditure investments, additionally creating a nearly carbon free environment.

Another publication [35] focused on determining optimal configuration of energy generation elements using diesel generators, PV panels, inertia storage (flywheel) and electrochemical storage (battery). Taking into account electricity consumption profile of the site, a solar irradiation level in the studied region (Tunisia), equipment costs and other aspects, the results of the study clearly showed that PV-Diesel-Battery-Flywheel configuration had lower operating costs and cost of energy than in other configurations (PV-Diesel-Flywheel and Diesel-Battery-Flywheel). In PV-Diesel-Battery-Flywheel configuration, initial and maintenance costs were approximately two times lower than 100 % RES system, but in most optimal configuration 16.2% of overall costs consisted of diesel fuel purchases (at the contemporary unprecedentedly low price of 0.52 €/litre). Similar approach was made in [36], where authors

modelled a Pakistan off-grid agricultural site in HOMER software using hydro, biogas and solar energy elements. By using determined load profiles, solar irradiation levels, biomass availability graph and generation element specifications and restrictions, a solar-biogas-hydro system showed the lowest cost of energy as well as net present costs related to other system configurations (“biogas-hydro”, “solar-biogas”, “solar-hydro” and “biogas only”).

Although the above reviewed publications offered optimisation solutions, as well as discussed the comparison of different results from an economic point of view, regional economic and climatic conditions play a major role in RES efficiency and economic justification in those publications. It means that results cannot be applied in different regions outside their research directions. In the course of collecting scientific publications related to RES economic assessment, lack of specific literature was observed regarding impact of individual energy generation elements. Instead, authors offer a universal type of solutions, in which the economic assessment is calculated using not for agriculture suitable energy consumption or energy generation characteristics, but offering calculations that can be used for universal consumption and electricity generation profiles (publications in detail can be found in [8]). It is unclear whether a universal approach to economic assessment of RES implementation and business models can be suitable for this sector due to the rural and possibly off-grid conditions, along with energy intensive variable loads.

4. RESULTS AND CONCLUSIONS

In this paper, a literature review has been performed that summarised agriculture electrification related to economic

assessment of RES and emerging technologies in the following categories: agrovoltatics, transparent and semi-transparent PV

panel modules, energy storage systems and electric tractors. In each category, the current state, recent research developments, and the author's vision to enhance existing technologies have been reflected, as well as future research activities aimed at achieving full electrification of the sector through synergy between the wider use of RES and the afore-mentioned technologies.

Regarding agrovoltaics, the literature suggests that this approach to installing PV panels is effective in mitigating the adverse effects of inefficient use of agricultural land for PV panel installation. Studies indicate that irrigation below PV panels has a positive effect on the cooling of the PV panels, thus increasing their efficiency and lifespan. On the other hand, authors point out that such an installation can drastically shade the plants below and it is debatable whether the value of the energy produced by the PV panels is higher than the reduction in yield of the plants below.

Considering transparent and semi-transparent PV panels, results from pilot projects have shown that by installing them on the roofs of the greenhouses, PV panel light absorption has no significant impact on yield and provides only a slight decrease in air temperature inside a greenhouse. Nevertheless, authors insist that further research is needed to improve the efficiency of this technology, thus making it possible to apply it for other agriculture-related purposes.

The review summarised the advantages, disadvantages and applications for existing battery technologies and indicated that the selection of battery technology is mainly dependent upon the following factors: electricity consumption profile, economic viability and efficiency of the technology. The analysis shows that significant progress in calculating economic assessments for RES and battery configurations has been made, using general consumption and generation

data; however, the economic feasibility of incorporating RES and related technologies into agriculture energy consumption remains poorly understood due to a shortage of research and data. As a result, there is a pressing need for more extensive and wide-ranging studies on the techno-economic viability of these elements in agricultural environments. In addition, new battery technologies are predicted to replace commonly used lithium-ion batteries with more accessible and cheaper battery technologies.

According to the reviewed literature, there is a significant potential for sodium-ion battery technology to replace the use of lithium-ion batteries in the agriculture sector. This can be justified by the fact that sodium sources are more abundant in nature than lithium and cheaper to acquire and process. Moreover, the energy capacity of a sodium-ion battery is heavily reliant on the size of its sodium-based solution. Nevertheless, it could still be utilised as a cheaper option for large-scale renewable energy storage in the agricultural complex, where equipment size and weight are not significant limiting factors.

As a result of this review, the advantages and disadvantages of the three main types of electric tractors (battery electric, hybrid electric and fuel cell electric) have been summarised. Moreover, according to the reviewed questionnaire, farmers' willingness to replace diesel-based tractors with electric tractors was mainly affected by the following factors: costs of the tractor, the size of the farming area, farmers' age and technical skills, engine characteristics, prior experience with electric tractors and other preferences. After analysing publications describing the current electric tractor market, it has been determined that the market is limited to low-power engine technologies that are only capable of performing light

tasks. Heavy-duty tasks such as equipment transportation, harvesting, cultivation, hard ground ploughing, and other activities cannot be carried out by these tractors.

Additionally, a significant portion of the electric tractor market consists of autonomous tractors, which require farmers to have high technical skills. However, an oversupply of autonomous electric tractors can potentially slow down their adoption and use by consumers, as their operating principles are drastically different from those of conventional tractors. The lack of charging infrastructure and distance between charging stations and tractors in the field pose significant challenges in the reviewed publications, but these can be overcome with the help of on-board battery packs or trailers with spare batteries and mobile charging. While the reviewed publications provide a valuable insight into the capabilities and demand for electric tractors from a consumer perspective, there is a lack of comprehensive examination of the connection between RES and the use of electric tractors. Further research should focus on exploring how RES can be used as a reliable and efficient source of electricity for tractor charging infrastructure. Addition-

ally, research should examine how changes to the current electric tractor market can affect farmers' willingness-to-buy more environmentally friendly solutions.

Looking at the literature related to the initial cost and economic assessment of RES, publications address the evaluation of different energy sources and their overall performance in various operating configurations. Nevertheless, a shortage of publications that offer a reliable direction for the development of agriculture can be observed, and most of the analysis in the available literature is heavily reliant on regional economic and climatic conditions. As a result, the solutions of the reviewed publications would be challenging to apply and justify in different economic and climatic environments. Instead, the authors offer a universal type of solutions, in which economic assessment is performed using not for agriculture suitable energy consumption or generation characteristics, but offering calculations that can be used for universal consumption and electricity generation profiles. It is unclear whether a universal approach to economic assessment of RES implementation and existing business models can be suitable for successful agriculture electrification.

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REFERENCES

1. World Health Organization. (2018). *COP24 Special Report: Health and Climate Change*.

Geneva: World Health Organization.

2. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 2, 198–209. doi: 10.1038/s43016-021-00225-9.
3. Directorate-General for Agriculture and Rural Development. (2021). *Factsheet: Green Deal Targets for 2030 and Agricultural Production Studies*. Brussels: European Commission.
4. European Commission. (2022). *Farm to Fork strategy*. Available at: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en
5. Rahman, M.M., Khan, I., Field, D.L., Techato, K., & Alameh, K. (2022). Powering Agriculture: Present Status, Future Potential, and Challenges of Renewable Energy Applications. *Renewable Energy*, 188, 731–749. doi: 10.1016/j.renene.2022.02.065.
6. Malik, A., & Kohli, S. (2020). Electric Tractors: Survey of Challenges and Opportunities in India. *Materials Today: Proceedings*, 28 (4), 2318–2324. doi: 10.1016/j.matpr.2020.04.585.
7. Webster, J., & Watson, R. T. (2002). Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Quarterly*, 26 (2), xiii–xxiii.
8. Lazdins, R., Mutule, A., & Zalostiba, D. (2021). PV Energy Communities—Challenges and Barriers from a Consumer Perspective: A Literature Review. *Energies*, 14 (16), 4873. doi: 10.3390/en14164873.
9. IRENA & FAO. (2021). *Renewable Energy for Agri-food Systems – Towards the Sustainable Development Goals and the Paris Agreement*. Abu Dhabi & Rome: IRENA & FAO. doi: 10.4060/cb7433en.
10. Goetzberger, A., & Zastrow, A. (1982). On the Coexistence of Solar-Energy Conversion and Plant Cultivation. *International Journal of Solar Energy*, 1 (1), 55–69. doi: 10.1080/01425918208909875.
11. Jing, R., Liu, J., Zhang, H., Zhong, F., Liu, Y., & Lin, J. (2022). Unlock the Hidden Potential of Urban Rooftop Agrivoltaics Energy-Food-Nexus. *Energy*, 256, 124626. doi: 10.1016/j.energy.2022.124626.
12. 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. doi: 10.1007/s13593-019-0581-3.
13. Williams, H.J., Hashad, K., Wang, H., & Zhang, K.M. (2023). The Potential for Agrivoltaics to Enhance Solar Farm Cooling. *Applied Energy*, 332, 120478. doi: 10.1016/j.apenergy.2022.120478.
14. Feuerbacher, A., Laub, M., Högy, P., Lippert, C., Pataczek, L., Schindele, S., ... & Zikeli, S. (2021). An Analytical Framework to Estimate the Economics and Adoption Potential of Dual Land-Use Systems: The Case of Agrivoltaics. *Agricultural Systems*, 192, 103193. doi: 10.1016/j.agsy.2021.103193.
15. Husain, A.A.F., Hasan, W.Z.W., Shafie, S., Hamidon, M.N., & Pandey, S.S. (2018). A Review of Transparent Solar Photovoltaic Technologies. *Renewable and Sustainable Energy Reviews*, 94, 779–791. DOI: 10.1016/j.rser.2018.06.031.
16. Lozanova, S. (2022). *Transparent Solar Panels: What this Emerging Technology could Mean for Installers*. Available at <https://www.greenlancer.com/post/transparent-solar-panels>
17. Lie, S., Bruno, A., Wong, L.H., & Etgar, L. (2022). Semitransparent Perovskite Solar Cells with > 13% Efficiency and 27% Transparency Using Plasmonic Au Nanorods. *ACS Applied Materials & Interfaces*, 14 (9), 11339–11349. doi: 10.1021/acsami.1c22748.
18. Hassanien, R.H.E., Li, M., & Yin, F. (2018). The Integration of Semi-transparent Photovoltaics on Greenhouse Roof for Energy and Plant Production. *Renewable Energy*, 121, 377–388. doi: 10.1016/j.renene.2018.01.044.
19. Ravishankar, E., Booth, R.E., Saravitz, C., Sederoff, H., Ade, H.W., & O'Connor, B.T. (2020). Achieving Net Zero Energy Greenhouses by Integrating Semitransparent Organic Solar Cells. *Joule*, 4 (2), 490–506. doi: 10.1016/j.joule.2019.12.018.

20. Hannan, M.A., Wali, S.B., Ker, P.J., Abd Rahman, M.S., Mansor, M., Ramachandaramurthy, V.K., ... & Dong, Z.Y. (2021). Battery Energy-Storage System: A Review of Technologies, Optimization Objectives, Constraints, Approaches, and Outstanding Issues. *Journal of Energy Storage*, 42, 103023. doi: 10.1016/j.est.2021.103023.
21. Nurohmah, A.R., Nisa, S.S., Stulasti, K.N.R., Yudha, C.S., Suci, W.G., Aliwarga, K., ... & Purwanto, A. (2022). Sodium-Ion Battery from Sea Salt: A Review. *Materials for Renewable and Sustainable Energy*, 11, 71–89. doi: 10.1007/s40243-022-00208-1.
22. Rotella Junior, P., Rocha L.C.S., Morioka S.N., Bolis I., Chicco G., Mazza A., & Janda K. (2021). Economic Analysis of the Investments in Battery Energy Storage Systems: Review and Current Perspectives. *Energies*, 14 (9), 2503. doi: 10.3390/en14092503.
23. Lane, A.L., Boork, M., & Thollander, P. (2019). Barriers, Driving Forces and Non-Energy Benefits for Battery Storage in Photovoltaic (PV) Systems in Modern Agriculture. *Energies*, 12 (18), 3568. doi: 10.3390/en12183568.
24. Ghobadpour, A., Monsalve, G., Cardenas, A., & Mousazadeh, H. (2022). Off-Road Electric Vehicles and Autonomous Robots in Agricultural Sector: Trends, Challenges, and Opportunities. *Vehicles*, 4 (3), 843–864. doi: 10.3390/vehicles4030047.
25. Lagnelöv, O., Dhillon, S., Larsson, G., Nilsson, D., Larsolle, A., & Hansson, P.A. (2021). Cost Analysis of Autonomous Battery Electric Field Tractors in Agriculture. *Biosystems Engineering*, 204, 358–376. doi: 10.1016/j.biosystemseng.2021.02.005.
26. van Leeuwen, L.B. (2020). Hydrogen or Battery Tractors: What Potential for Sustainable Grape Growing? *I V E S Technical Reviews*. doi: 10.20870/IVES-TR.2020.4381.
27. Lombardi, G.V., & Berni, R. (2021). Renewable Energy in Agriculture: Farmers Willingness-to-Pay for a Photovoltaic Electric Farm Tractor. *Journal of Cleaner Production*, 313, 127520. doi: 10.1016/j.jclepro.2021.127520.
28. Caban, J., Vrabel, J., Šarkan, B., Zarajczyk, J., & Marczuk, A. (2018). Analysis of the Market of Electric Tractors in Agricultural Production. *MATEC Web of Conferences*, 244, 03005. doi: 10.1051/mateconf/201824403005.
29. Scolaro, E., Beligoj, M., Estevez, M.P., Alberti, L., Renzi, M., & Mattetti, M. (2021). Electrification of Agricultural Machinery: A Review. *IEEE Access*, 9, 164520–164541. doi: 10.1109/ACCESS.2021.3135037.
30. Dhond, R., Srivastav, U., Patil, B.T., & Vaishnav, H. (2021). Comparative Study of Electric Tractor and Diesel Tractor. *IOP Conference Series: Materials Science and Engineering*, 1168, 012003. doi: 10.1088/1757-899X/1168/1/012003.
31. Tractor Junction. (2021). *Tractor Horsepower Guide—How Much Horsepower is enough for Tractor?* Available at <https://www.tractorjunction.com/blog/how-much-horsepower-is-enough-for-tractor/>
32. Ghobadpour, A., Boulon, L., Mousazadeh, H., Malvajardi, A.S., & Rafiee, S. (2019). State of the Art of Autonomous Agricultural Off-road Vehicles Driven by Renewable Energy Systems. *Energy Procedia*, 162, 4–13. doi: 10.1016/j.egypro.2019.04.002.
33. Dar, A.L. (2022). An Introduction to Electric Tractor. *VIT University*. doi: 10.13140/RG.2.2.29165.26087.
34. Desai, A., Mukhopadhyay, I., & Ray, A. (2021). Techno-economic-environment analysis of solar PV smart microgrid for sustainable rural electrification in agriculture community. In *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, (pp. 2281–2285), 20–25 June 2021. IEEE Xplore: IEEE. doi: 10.1109/PVSC43889.2021.9518454.
35. Belouda, M., Jouini, Y., & Mami, A.K. (2022). Optimal configurations of a photovoltaic-diesel electrical production system with electrochemical and inertial storage for an isolated agricultural site electrification. In *2022 5th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, (pp. 73–78), 22–25 March 2022. IEEE Xplore: IEEE. doi: 10.1109/IC_ASET53395.2022.9765929.

36. Aziz, M.S., Khan, M.A., Khan, A., Nawaz, F., Imran, M., & Siddique, A. (2020). Rural electrification through an optimized off-grid microgrid based on biogas, solar, and hydro power. In *2020 International Conference on Engineering and Emerging Technologies (ICEET)*, (pp. 1–5), 22–23 February 2020. IEEE Xplore: IEEE. doi: 10.1109/ICEET48479.2020.9048222.