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# THEORETICAL EVALUATION OF AGRIVOLTAIC SYSTEMS IN APPLE ORCHARDS: ECONOMIC FEASIBILITY UNDER HUNGARIAN CLIMATIC AND MARKET CONDITIONS

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The aim of this dissertation is to obtain a doctoral (PhD) degree in the scientific field of „Management and Business"

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# DECLARATION

I undersigned (name: **Chalgynbayeva Aidana**, date of birth: 11 December 1991) declare under penalty of perjury and certify with my signature that the dissertation I submitted in order to obtain doctoral (PhD) degree is entirely my own work.

Furthermore, I declare the following:

- I examined the Code of the Doctoral School of Management and Business Administration and I acknowledge the points laid down in the code as mandatory;
- I handled the technical literature sources used in my dissertation fairly and I conformed to the provisions and stipulations related to the dissertation;
- I indicated the original source of other authors' unpublished thoughts and data in the references section in a complete and correct way in consideration of the prevailing copyright protection rules;
- No dissertation which is fully or partly identical to the present dissertation was submitted to any other university or doctoral school for the purpose of obtaining a PhD degree.

Debrecen, 13 June, 2025

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signature

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# 1. INTRODUCTION

## 1.1. Motivation

Energy efficiency financing is crucial in achieving the European Union's climate and energy targets. It involves a combination of public funding from EU and national sources, accounting for 10% to 20% of the total, and private financing, which comprises the majority, ranging from 80% to 90%. This financial synergy is essential to reach the 2030 Energy and Climate targets, amounting to €3,000 billion by 2030. Pursuing energy efficiency goals, as outlined in the FF55 package and the REPowerEU initiative, necessitates substantial financial investments. The FF55 package anticipates an annual investment requirement of approximately €165 billion to attain the 2030 energy efficiency targets. Meanwhile, the REPowerEU initiative mandates €56 billion in additional investments, directed explicitly towards energy efficiency improvements, heat pumps, and the promotion of solar rooftop installations. In total, these initiatives entail cumulative investment needs of €1,150 billion by 2027 and €1,650 billion by 2030 for energy efficiency and demand-side enhancements [1]. Agrivoltaic systems, combining solar energy production and agriculture, offer a unique opportunity to contribute to both goals.

A recent study reveals that approximately 1.18 billion people are energy-poor, 60% more than the 733 million without electricity in 2020. About 1.2 billion individuals globally lack electricity access; an estimated 780 million may remain unconnected by 2030 without significant changes. In 2023, approximately 2.33 billion individuals experienced moderate to severe food insecurity. The figure has remained unchanged since 2020 despite the ongoing impacts of the COVID-19 pandemic, with over 864 million experiencing extreme food shortages. [2–5].

Photovoltaic (PV) systems are globally acknowledged as a leading sustainable energy solution with significant potential for widespread adoption. Significantly, 2022 marked a record-breaking expansion in recent solar power generation capacity additions, achieving a 35% increase over 2021 and reaching 230 gigawatts (GW). Projections indicate that global PV capacity will continue to rise, reaching an estimated 8,500 GWp by 2050 [6]. Therefore, agrivoltaics uses solar power generation technology and applies its power resources to agricultural production, including special pastoral construction, facility gardening and facility breeding. It is transitioning into an innovative production model integrating farming, power generation, and agricultural production activities.

This study explores the implementation of Industry 4.0 innovations in precision farming systems and evaluates the role of small-to-medium enterprises (SMEs) in advancing agricultural practices within rural communities. This integration has catalysed the development of an innovative "smart village" model, which empowers rural small and medium-sized enterprises (SMEs) to harness technology for enhanced public services and economic growth [7]. As noted by Maity et al.[8] that agrivoltaics (AV) provides several advantages, such as developing sustainable energy systems, enhancing agricultural productivity, and increasing financial prosperity for rural farming communities. Significant barriers exist, including high capital expenditure (CAPEX), potential environmental impacts and land-use conflicts. These systems improve land-use efficiency and can protect apple orchards from adverse climate conditions[9,10].

Hungary's advantageous geographical position is conducive to fruit cultivation [11]. To maximise yield, alongside geographical features, the technological conditions of fruit cultivation and the genetic traits of the cultivated varieties are crucial factors [12]. Research suggests that escalating climate variability will heighten the regularity of severe meteorological phenomena in Hungary, such as freezing rain, heightened forest fire risks, extended drought periods, and reduced biodiversity. These extreme weather events have become more frequent and impactful, often occurring at different times and locations than previously recorded [13]. In 2020, the accepted drought-affected area amounted to 243,371 hectares, 1.8 times larger than the previous year and over three times larger than in 2018. The size of the areas impacted by water supply systems varied significantly, ranging from 160 to 343.5 thousand hectares, primarily due to technical constraints. The analysis of total crop areas focused on those experiencing damage exceeding 500 hectares, while irrigated areas were evaluated using a lower threshold of 50 hectares. Notably, the most severe damage to apple and Virginia tobacco crops in 2018 occurred in August, whereas the peak damage in irrigated regions was observed in September. The temporal distribution of drought damage was significantly influenced by the predominance of non-irrigated crops such as maize, sunflower, lucerne, and soybean [14]. There are ongoing challenges in modernizing the electricity networks to support decentralized energy generation and fluctuating capacities in Hungary. Overcoming these challenges requires significant investments in balancing systems, grid infrastructure and energy storage solutions. Although the government has outlined plans to grow storage capabilities to 1,000 MW by 2026 and launch a 100 MW consumer-driven energy adjustment program by 2030, current regulatory frameworks for energy storage are insufficient to stimulate significant market-based commercial investments [15]. These changes affect health, biodiversity, essential infrastructure, agricultural productivity, and nearly all facets of life. Strategically deploying AVS offers Hungary a pathway to alleviate grid infrastructure constraints while advancing renewable energy production and harmonizing with agricultural activities. Hungary currently operates several large-scale PV systems, which could support the future implementation of AVS. AVS is expected to protect freezing rain events while simultaneously enhancing biodiversity. Adopting AVS in Hungary aligns with the nation's agricultural development policy, introducing a novel approach to agricultural expansion. However, the effective implementation of AVS requires addressing several critical factors, including technological progress, policy support, land availability and multi-stakeholder collaboration.

AVS attain their maximum energy efficiency of 22.41% during the winter, as lower temperatures positively impact system performance, primarily due to the thermal coefficient parameter. Conversely, higher temperatures and intense solar radiation in the spring lead to diminished performance, with energy efficiency recorded at 21.41%. The winter season also sees the highest exergy efficiency at 23.64%, while the lowest exergy efficiency at 22.59% occurs in the spring [16]. Despite the obstacles linked to funding energy efficiency initiatives, it is insightful to analyse the simultaneous increase in the adoption of conservation strategies and the expanding integration of clean energy technologies, specifically focusing on distributed renewable generation [17]. Modular technologies, such as wind and photovoltaic systems, are encompassed within distributed energy resources that users can install and manage on-site [18,19]. A holistic understanding of sustainability extends beyond economic considerations to include social and environmental dimensions [20]. Recent studies and pilot projects emphasize optimizing energy production alongside agricultural processes to achieve a sustainable balance between outputs rather than focusing solely on maximizing yields [21]. Key benefits include reduced desertification, improved water-use efficiency, microclimate stabilization, enhanced heat stress tolerance, and mitigation of excessive solar radiation [22–24]. Additionally, agrivoltaics can diversify farmers' income streams, ensure local electricity supply in rural areas, and enhance land productivity by as much as 70% [9,25]. Over the last decade, photovoltaic systems and energy efficiency measures have often been seen as economic rivals [26]. There is a gap in research relating to comparing cost-effective and energy-efficient solutions that approach near-zero energy consumption, characterized by very low energy use. This highlights the pressing need for a detailed economic assessment. Nonetheless, concerns persist regarding high investment costs, limited knowledge of long-term impacts, and potential crop and yield performance reductions.

In Hungary, the exploration of agrivoltaic systems remains in its early stages, providing an ideal opportunity to assess their potential benefits. Among various crops, apples are particularly well-suited for agrivoltaic implementation for several compelling reasons.

Apples are economically significant in Hungary, with a well-established market and high demand both domestically and internationally [27–29]. This economic value provides a strong incentive to optimize apple production through advanced agricultural techniques [23]. Additionally, apples are perennial crops, meaning they do not require annual replanting, thus reducing labour and resource inputs compared to annual crops like wheat or corn. Furthermore, research indicates that apple trees can tolerate and even benefit from partial shading, a condition inherent to agrivoltaic systems [30]. The strategic placement of solar panels can optimize light distribution, potentially enhancing apple yields and improving fruit quality by mitigating stress from extreme weather events [23].

Apples offer distinct advantages compared to other land uses, such as arable crops or grass. Arable crops often require full sunlight [31] and may not benefit from the shading effect of solar panels, whereas grass typically yields a lower economic return [32–34]. Thus, focusing on apples maximizes both agricultural output and energy generation, making it a more economically viable option.

This study aims to evaluate the economic feasibility and challenges of integrating agrivoltaic systems with apple cultivation in Hungary. By focusing on the economic aspects, the research will provide insights into the potential for enhanced profitability and sustainability of apple production when integrated with solar energy systems. Highlighting the economic advantages of apple cultivation in agrivoltaic systems, this study seeks to demonstrate a viable strategy for increasing the economic resilience of Hungarian agriculture.

### 1.2. Scope and limitations

The scope of this research encompasses the exploration of AVS in the context of Hungary, focusing on evaluating the economic competitiveness of solar technical adaptations with apple orchard farming and the long-term financial outcomes associated with AVS. At the beginning of my research, the focus was encapsulated in the title "Potential and economic effects of agrivoltaic systems on land use". This initial scope was broad, aiming to explore various aspects of agrivoltaic systems, including their general potential and economic implications across different types of agricultural land and crops.

However, as the research developed, several critical insights emerged. Firstly, preliminary analyses and literature reviews highlighted the specific suitability and benefits of integrating agrivoltaic systems with perennial crops, particularly apple orchards, due to their economic significance and compatibility with shading from solar panels. This area demonstrated significant untapped potential, especially in Hungarian agriculture, where apple cultivation is economically essential. In the meantime, data specific to Hungary's climatic conditions and market dynamics became increasingly relevant, suggesting that a targeted evaluation could provide more practical and impactful insights. This shift in focus was supported by new findings related to the economic feasibility of agrivoltaic systems when applied to apple orchards under these specific conditions.

Due to the facts mentioned above, the final research area was refined, resulting in the revised title: "Theoretical Evaluation of Agrivoltaic Systems in Apple Orchards: Economic Feasibility under Hungarian Climatic and Market Conditions." This new title reflects a more focused and context-specific study, emphasising the theoretical evaluation of economic feasibility tailored to Hungary's unique climatic and market conditions, thus ensuring that the research provides actionable insights and contributes meaningfully to the field.

However, during the research process, several limitations were encountered:

1. ***Data scarcity***: Current research on agroelectric systems shows a severe lack of reliable, in-depth data regarding agricultural outcomes and economic viability. The study's dependence on a particular chosen case study in Hungary limits its generalizability across different regions and contexts. The lack of comparative studies examining AVS and PV systems alongside conventional apple farming across various rural areas affects the understanding of the operational efficiency of these systems.

2. ***Uncertainties in key variables***: The study faced uncertainties associated with various factors, including electricity rates, apple productivity, observation period, producer prices, weather conditions and shading effects. These factors introduce variability that can affect the economic assessments. This study uses the ground-mounted photovoltaic (GM-PV) system's fixed feed-in tariff price of 0.082 Euro/kWh[1] (33 HUF/kWh) under the KÁT framework as an assumption for evaluating the AVS. Therefore, the KÁT tariff provides a more suitable benchmark for assessing the economic potential of AV systems, given the absence of a dedicated framework for agrivoltaic feed-in tariff rates in Hungary. This approach is necessary due to the absence of a specific feed-in tariff framework for AVS in Hungary, as they are not yet established within the current regulatory landscape. Using the GM-PV tariff as a reference point, this assumption is intended to reflect a realistic scenario for investing in the AV system, with adjustments made for inflation minus one percentage point. In contrast, the calculations for GM-PV

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[1] Current exchange (19/02/2025): 1€=401.75HUF

systems under the METÁR mechanism are based on a bid price of 0.050 Euro/kWh[2] (20 HUF/kWh). This figure is drawn from the average bid prices of the second METÁR tender and the weighted average of successful bids, noting that the maximum bid price allowed under METÁR (0.065 Euro/kWh[3] (26 HUF/kWh)) is 21% lower than the KÁT tariff. There is also a plausible concern that AV systems may not secure contracts in innovation tenders due to competition from GM-PV systems and may need to be combined with controllable loads, affecting cost considerations. These factors highlight the uncertainties and challenges in determining the economic viability of AV systems.

However, in contrast, AVS are not implemented all year round. This effort should include understanding shadow effects on apple orchards and collecting financial metrics across various geographic regions to enhance the generalizability of findings. Conducting longitudinal studies will be crucial to assess AV systems' sustainability and economic viability over time, considering weather conditions, producer prices, crop productivity and electricity rates. Furthermore, validating existing economic models and projections should be pursued through real data collection from ongoing agrivoltaics projects, especially in Hungary. This involves comparing apple yields from different locations with wholesale prices to ensure accuracy and relevance. Investigating factors influencing farmers' decisions to adopt AV systems is necessary, emphasising addressing knowledge gaps and developing compelling business cases to encourage acceptance and integration.

Additionally, research should explore the technical and social adaptations required for effective AV system implementation, considering local conditions and stakeholder engagement. Comparative analyses of AV and PV systems alongside traditional agricultural practices across diverse regions are needed to evaluate utilization efficiency and economic competitiveness. Finally, examining the complexities of integrating AV systems, particularly the interaction between energy production and agricultural outputs, will provide valuable insights. Addressing these areas in future research will deepen understanding of agrivoltaic systems, supporting their broader adoption and informing potential investors of their economic and environmental benefits.

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[2] Current exchange (19/02/2025): 1€=401.75HUF

[3] Current exchange (19/02/2025): 1€=401.75HUF

## 1.3. Research hypothesis

The evaluation of agrivoltaic systems in apple orchards is based on a sustainability framework that integrates economic, environmental, and social dimensions [35–37]. The model showed over 90% agreement with the production data from more than 50 operating solar panel systems in Hungary, consistent with findings from a wide range of studies in PV performance modeling. This high level of agreement underscores the importance of robust validation techniques, the careful calibration of model parameters, and the integration of localized climatic data [38].

In Hungary, where climatic and market conditions are evolving, the synergy between renewable energy production and traditional orchard management is expected to offer dual benefits, enhancing revenue streams while promoting sustainable land use. The economic performance of agrivoltaic systems is evaluated through a rigorous financial framework that incorporates key metrics such as capital expenditure (CAPEX), operational expenditure (OPEX), net present value (NPV), and internal rate of return (IRR). While much of the existing literature has emphasized the technical and environmental benefits of agrivoltaic systems, there remains a notable gap in comprehensive financial analyses that integrate these critical economic indicators.

This study addresses that gap by examining whether the dual income streams from renewable energy generation and agricultural production justify the higher CAPEX and ongoing OPEX associated with agrivoltaic investments. The analysis compares explicitly systems implemented on a 200-hectare scale with those on a 42-hectare scale under realistic market conditions and operational scenarios.

The financial performance evaluation goes beyond simple revenue assessment. It rigorously quantifies whether the initial investment and subsequent operational costs yield sufficient returns (as measured by NPV and IRR) to support the long-term economic sustainability of agrivoltaic systems.

One key challenge is reconciling the need for immediate profit returns with long-term sustainability goals, where an entrepreneurial spirit must drive the integration of innovative renewable energy practices with established agricultural methods. It is therefore necessary to examine whether the synergy between these internal (e.g., orchard management practices, microclimatic benefits) and external factors (e.g., governmental incentives, market conditions) can significantly enhance the overall performance of apple orchards.

To address this research gap, the dissertation proposes the following hypotheses:

**$H_1$: Scale-dependent capital efficiency**

After accounting for CAPEX differences, large-scale agrivoltaic systems will demonstrate a more favourable NPV and IRR profile than GM-PV systems or conventional apple farming.

Hypothesis 1 will be answered in Section 3.2. and 3.3. and Results 4.2 and 4.3. will summarise it.

**$H_2$: Nonlinear interactions of economic and environmental factors on agrivoltaic production costs**

The interaction of feed-in tariffs, investment costs, apple yield, and sunshine variability produces significant nonlinear effects on the unit costs of electricity and apple production in agrivoltaic systems, such that optimising these variables together reduces total production costs more effectively than optimising them individually.

The comparative financial analysis for different scales is presented in Section 3.2. and 3.3. and detailed results and interpretations are provided in Results Sections 4.2 and 4.3.

**$H_3$: Regulatory uncertainty**

Regulatory uncertainty and elevated subcomponent costs increase the levelized cost of energy (LCOE) and financial risk in agrivoltaic systems, rendering GM-PV systems more economically competitive unless substantial cost control measures and technological innovations are implemented.

This hypothesis is covered in Section 3.3, with supporting evidence discussed in Results 4.3.

**$H_4$: Impact of environmental factors on agrivoltaic feasibility in Hungary**

Hungary's solar irradiance levels and climatic conditions are sufficient to optimize the efficiency of agrivoltaic systems, thereby maximizing energy generation and minimizing the impact on crop yield, leading to improved economic outcomes over traditional farming methods.

The answer to Hypothesis 4 will be the outcomes of evaluating the comprehensive and empirical literature of the field. It will be examined in Section 3.1, with findings summarized in Results 4.1.

By empirically testing these hypotheses, this dissertation aims to provide a detailed financial analysis supporting the economic justification of agrivoltaic systems. The insights derived from comparing the 200-hectare and 42-hectare implementations will be instrumental in guiding investment strategies and policy decisions within the agrivoltaic sector.

### 1.4. Structural design and problem statement

In Section 1, the study is introduced, detailing the motivation and objectives behind the research. Section 2 explores the foundational principles and advanced applications of agrivoltaic systems, focusing on overhead configurations for both static and dynamic systems, examines global case studies and research innovations, analyzes the dynamics and policies of the European and Hungarian electricity markets, assesses trends and sustainability challenges in apple production, and evaluates the economic framework, viability, and sustainability implications of agrivoltaics. In section 3, material and research methodologies are detailed, encompassing a systematic review of agrivoltaics, cost-benefit aspects of integrating AVS at the Kaposvár solar photovoltaic park, and an assessment of the financial viability of agrivoltaic systems in apple farming. Section 4 examines and interprets the economic results, while Section 5 provides the conclusion.

Drawing on insights from the Fraunhofer Institute for Solar Energy Systems (ISE), the objective of my doctoral work was to investigate the economic performance of agrivoltaic systems by which three different systems – AVS, GM-PV systems, and traditional apple farming systems affect the economic aspect of competitiveness. The role of initial investment is regarded as a primary economic factor. In this doctoral study, we conducted three consecutive studies and applied the following specific objectives:

1. To evaluate AVS's economic, technical, infrastructure, environmental and agricultural impacts through a bibliometric review, focusing on economic assessments, crop production, livestock grazing, and PV-greenhouse integration while comparing results with previous studies and addressing key conclusions and limitations.
2. To evaluate the anticipated economic impacts of AVS, accurate data from a high-capacity PV project in the Kaposvár region of Hungary was utilized. Economic data from Schindele et al complemented [24] on GM-PV and AV systems, integrated with agroeconomic datasets from the Hungarian apple orchard. A sensitivity analysis used a baseline scenario to identify the barriers and enablers shaping the long-term integration of AVSs within agricultural frameworks, focusing on technical and economic viability and stakeholder acceptance.
3. To provide a systematic economic evaluation of AVS in apple cultivation, comparing its economic viability against both GM-PV systems and conventional apple production.

In the context of these comparisons, it's apparent that fluctuations in numerous economic variables can negatively impact the actual and opportunity costs and revenues linked with AVS. Key factors include CAPEX systems, the efficiency of PVs, the extent of PV coverage in AV systems, the influence of shading on agricultural yields, the prices of green electricity and the choice of plant species under AV systems. In terms of plant species, apple plantations were the chosen subject for this study due to several reasons:

- Horticultural produce such as apples could yield higher efficiency in AV systems due to their high per-hectare productivity, longevity, and enhanced resistance to extreme weather conditions, such as icy rain and intense summer sunshine.
- Despite the partial coverage, the apple yields are not anticipated to experience a decline when compared to traditional apple production.
- Apples constitute a significant component of Hungarian horticulture.

# 2. LITERATURE REVIEW

This chapter illuminates the concept of AVS. It presents a concise overview of the technical methodologies and global findings associated with AVS, specifically assessing its economic viability, and concludes with an examination of AVS applications in apple cultivation.

## 2.1. Introduction to agrivoltaic systems

Agrivoltaics embodies a dual-purpose land management strategy, synchronizing crop cultivation with photovoltaic power generation to establish a dual-output framework that enhances both energy and agricultural resource synergies [25]. Although the idea of integrating agriculture with photovoltaic systems was first introduced by Goetzberger and Zastrow, global interest in this topic began to significantly increase approximately 10 to 15 years ago, leading to the emergence of initial research projects in this field. The concept of agrivoltaics has been considered since the 1980s [24,39], though this idea was rarely discussed until the early 2000s [40].

Globally, there is a growing demand for food, feed, and energy from agricultural land. However, agrivoltaic systems (AVS) allow for the concurrent production of energy and food on the same land. Although AVS requires significant initial investment compared to conventional agricultural production, its economic viability is influenced by location factors, including the number of sunshine hours and fluctuations in the prices of electricity and farming products. The study [41] proposed a system where the PV modules were positioned 2 meters above the ground, with the spacing between the rows set at three times the height to ensure uniform irradiation distribution on the ground. In two experiments, the study found that 62% and 71% of the global irradiation reached the area beneath the PV modules when the row spacing was 3 meters and 4 meters, respectively, compared to a reference field without any modules. In 2021, the total installed agrivoltaics capacity globally reached approximately 14 GW, a significant increase from about 2.9 GW in 2018. Europe and North America were the leading regions, collectively dominating the global agrivoltaics market during this period [42]. Germany hosts at least eleven agrivoltaic systems currently in operation for research purposes. These systems are located in various regions and utilise different types of land. In Weihenstephan/Freising, Bavaria, vegetable growing is supported by a tracking PV array, commissioned in 2013, with a capacity of 22 kWp, and PV tubes installed in 2015, with a capacity of 14 kWp. In Gelsdorf, located in the Ahrweiler district of Rhineland-Palatinate, fruit growing utilises both tracking and fixed semi-transparent PV modules, which were commissioned in 2021 and have a capacity of 258 kWp. Additionally, Bavendorf in Baden-

Württemberg has implemented a system for fruit growing that includes tracking and fixed PV modules, which have been operational since 2022 with a capacity of 227 kWp. Heuchlingen, also in Baden-Württemberg, employs fixed PV modules for fruit growing, with a capacity of 113 kWp, and has been operational since 2023 [43].

### 2.2. Design and classification of agrivoltaic systems

The design considerations for agrivoltaic systems are outlined as follows. A key factor is light distribution within the system, which should be uniform. This can be achieved through increased row spacing, elevated installations, orientation toward the southwest or southeast [44], utilization of smaller or semi-transparent modules [43], special modules, and the rearrangement of modules or tracking systems.

Recent studies have evaluated the agricultural productivity of various horticultural crops under agrivoltaic (AV) conditions. Investigations have encompassed kiwifruit vines [45,46], wine grape [24,47], pear [48,49] and apple [10,50] and other horticultural crops like chiltepin pepper and cherry tomato [22] and additionally crops such as sweet pepper, tomato and cucumber [51], in combination with AV. However, the available data remain limited. Furthermore, several crops, including celeriac, potatoes, lettuce [59], winter wheat and grass clover [24,56–58] and corn [60], have been evaluated for their suitability to grow under the AV system. The outcomes of these studies have been variable, with photovoltaic (PV) panel shading inducing inconsistent effects on crop yields. Under unrestricted conditions, yield reductions of up to 20% have been reported [52,53]. However, slight yield improvements may occur in hot, dry climates, accompanied by lower soil and air temperatures within the AV setup. In a related study, Zisis et al. [54] investigated pepper plant (Capsicum annuum) grown under the shading of organic photovoltaic (OPV) panels with an efficiency of 2.1% and a transparency level reaching 19.4% that covered 22% of a Mediterranean greenhouse roof—and found that these conditions enhanced performance compared to mass fruit production. Moreda et al. [55] examined nine different vegetables under European conditions, noting that the yields were significantly affected by the weather conditions of the study year. In their comprehensive research, Barron-Gafford et al. [22] demonstrated that PV panel shading offers multiple additive and synergistic benefits, including reduced enhanced food production, drought stress on crops and a lower heat load on the panels. Collectively, these benefits have the potential to bolster the resilience of food and energy systems against increasing environmental stress, heat, and drought. Publications about AV's impact on agricultural productivity have been published by [9,22,47,52,56–61].

Overhead agrivoltaic systems are characterised by their installation above crop rows, with clearance heights ranging from 2 to 6 meters [43]. Bifacial solar panels are mounted on steel columns at a 20° tilt angle, featuring a row width of 3.4 meters, a row spacing of 6.3 meters, and a vertical clearance of 5 meters. These elevated structures result in higher CAPEX compared to interspace systems. Nonetheless, they minimally obstruct agricultural operations underneath. Further technical specifications are detailed in prior publications [25,62,63]. AVS also affect the microclimate. German preliminary standard DIN SPEC 91434 differentiates between elevated systems (Category I) and systems with ground-level elevation (Category II). The most important criterion is whether the systems have a vertical clearance of <> 2.10 m height. The clear height is described in section 3.9 of the DIN SPEC as the "free vertical area between the ground of the agricultural utilization area and the bottom edge of the lowest structural component when under dead weight deformation". In the EEG context, however, a further distinction is made regarding whether the systems are elevated vertically or horizontally. Furthermore, the systems can be categorised according to whether they have an integrated water system or whether it is still possible to cultivate below the modules. Figure 1 shows an example of a Category I agrivoltaic system. The clear height in Category I is at least 2.1 m [64]. These agrivoltaic systems are further categorised into two main types: static systems positioned above arable land or fruit trees/berries, and dynamic systems situated over arable land or fruit trees/berries.

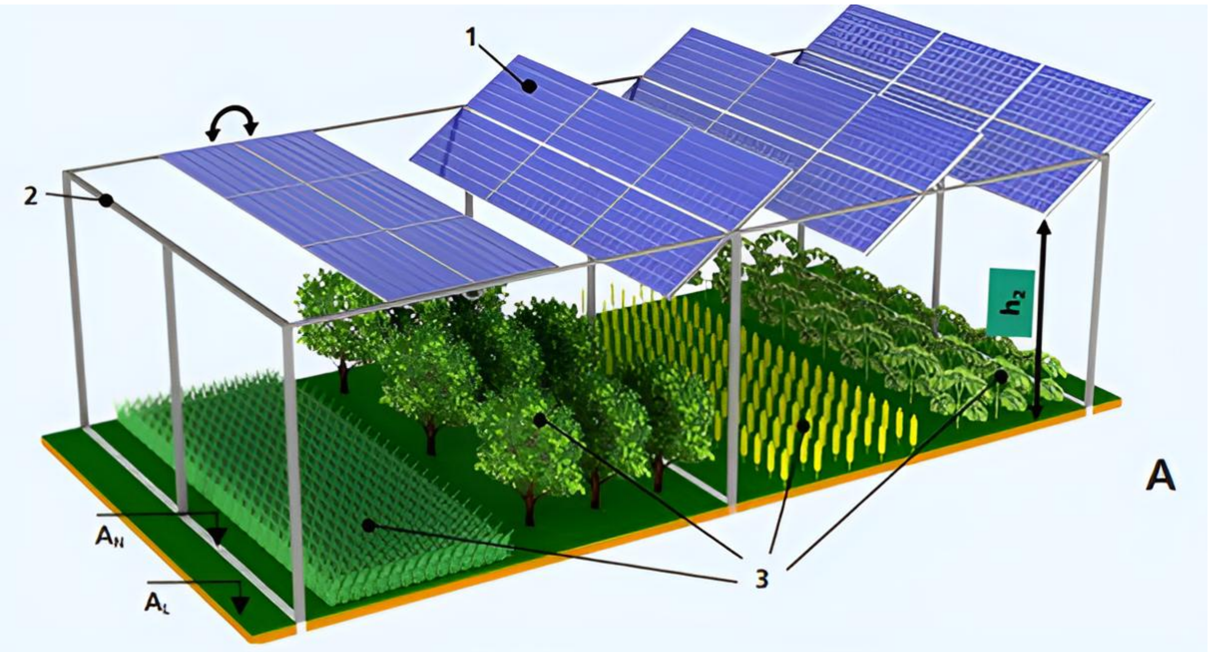

**Figure 1: Illustration of the category I agrivoltaic system with overhead configurations and vertical clearance above 2.1m according to DIN SPEC 91434:2021. Source: ©Fraunhofer ISE (2025)**

Chapter 5 of the DIN SPEC outlines the criteria and requirements essential for primary agricultural use within Agri-PV systems. These requirements encompass elevation, land loss, workability, water availability, light availability and homogeneity, residue-free construction and dismantling, soil erosion, profitability calculation, and land use efficiency. The main guidelines were [65]:

- Regarding elevation, photovoltaic (PV) modules in both categories must be installed and distributed uniformly across the project area. The elevation technique must ensure that the land remains workable in its previous use.
- Regarding land loss, the DIN SPEC stipulates that the reduction of arable land must not surpass 10% of the entire project area for Category I and 15% for Category II. Subchapter 3.5 of the DIN SPEC provides a more thorough and detailed explanation of areas that become unusable for agricultural purposes, including green strips formed by elevation or ram protection.
- Land use efficiency is defined as crop yield following the AVS's installation and operation, calculated for the entire project area. The impact of the agrivoltaic system on both land and yield losses must be considered. It is required that the agricultural yield must reach at least 66% of the benchmark yield; for details on determining this, see the study [65].

### *2.2.1. Overhead static systems – permanent crops*

Static systems installed over fruit trees or berries, often called orchard-agrivoltaics, partially replace existing plastic foils or hail nets. These systems facilitate cultivation between the module strips and can be dynamic or static. A commonly implemented static configuration involves semi-transparent fixed-tilt PV modules elevated approximately 3.5 meters above the orchard canopy, allowing for sufficient light transmission and crop management beneath the system (see Figure 2). This design is exemplified in the Kressbronn agrivoltaic project in Germany. Another configuration type includes vertical bifacial systems [66], where modules are mounted vertically, resulting in minimal land occupation. Integrating bifacial modules with an east-west orientation shifts energy peaks from midday to morning and afternoon, which can benefit the electrical grid.

**Figure 2: Illustration of static orchard AV system and annotation of its main parts. Picture from:** [67]

In orchard agrivoltaic systems, the modules partially substitute pre-existing plastic foils or hail nets [43]. This necessitates the module being positioned directly above the trees, meaning the crop layout determines the pitch and azimuth. Consequently, light management through lower ground coverage ratio (GCR) values is not feasible, necessitating the use of semi-transparent crystalline silicon (c-Si) modules. These modules feature spatially segmented cells, allowing sunlight to penetrate and reach the plants. The effective GCR must be considered in this context. For instance, an apple orchard with a row-to-row spacing of 3 meters, paired with a roof-type landscape east-west AV system (Figure 2) would result in an effective GCR of 0.67 with opaque modules unsuitable for crop growth. However, using modules with 50% transparency reduces the effective GCR to 0.33, significantly increasing light availability for the apples [68].

An example of this configuration is a 239 kWp system installed above an apple orchard in Kressbronn, Germany (Figure 3). This setup involved comparing two types of semi-transparent modules with transparencies of 51% and 40%. Initial results from Fraunhofer ISE indicated that the apple yields were more significant within the agrivoltaic system compared to the control setup. Interestingly, apples grown under the 40% transparency modules exhibited more intense redness than those under the 51% transparency modules during the first year [43].

**Figure 3: Agrivoltaic system in Kressbronn (2022) © Fraunhofer ISE**

### *2.2.2. Overhead dynamic systems*

Dynamic agrivoltaic systems, equipped with either one-axis or two-axis tracking mechanisms, are implemented across various crops, including vineyards, apples, wheat, and corn. Their primary advantage lies in custom tracking algorithms that dynamically regulate light exposure. During critical growth phases, these systems can adjust sub-optimally to let more light reach the crops. They can shift horizontally to form a protective canopy when needed, thus offering enhanced control over light and microclimate [69]. The research explored various tracking strategies to enhance system performance. For instance, smart-tracking techniques were employed during rainy seasons to maximise light availability and plant growth, while standard solar tracking was utilised during dry and hot periods to maintain optimal energy capture. However, they entail higher acquisition and operational costs than static systems [43], raising questions about the trade-off between electricity generation and improved light conditions. Additionally, continuous sun-tracking can result in more shading than static configurations for the same setup.

In a practical application shown in Figure 4, a 258 kWp pilot system was installed in 2021 at the Nachtwey organic orchard in Gelsdorf, focusing on various aspects such as light management, system design, and crop cultivation. This project includes four experimental setups: a control field with hail-protection nets, a standard agrivoltaic system, an agrivoltaic system with reduced crop protection, and a sheet covering. The project also explores public acceptance and social responsibility, investigating potential stakeholder conflicts regarding land use and distribution. The technical details of the system include a 3552 m² area with three rows of single-axis tracking, semi-transparent double-glass PV modules (225 Wp, 1148 modules), and supporting both self-consumption and grid feeding [43].

**Figure 4: Tracked agrivoltaic system at Nachtwey organic fruit farm (2021, 2023) © Fraunhofer ISE**

## 2.3. Case studies and advanced research perspectives on global agrivoltaics

The global upsurge in agrivoltaics can be attributed to support from government initiatives across the globe. Japan was at the forefront, launching the first program in 2012, and other countries such as Germany, France, China, South Korea and the United States have since joined the movement. More nations are predicted to embrace agrivoltaics in the coming years [70]. This literature review focuses on case studies and advanced research perspectives on global agrivoltaics, providing an overview of the field's current status, potential for growth, and challenges. It explores the experiences of various countries that have implemented AVS, reflecting on the impacts of government policies, economic feasibility, and social implications.

Overhead agrivoltaics in Japan were first introduced in 2004 by Akira Nagashima, who developed removable structures allowing crop rotation and flexibility. The Ministry of Agriculture, Forestry, and Fisheries reported 1,992 registered agrivoltaics farms covering over 560 hectares across 46 prefectures, excluding Toyama. As of March 2019, these farms have successfully cultivated more than 120 crop varieties, with Sakaki, myoga ginger, shiitake mushrooms, paddy rice and blueberries among the top ten crops [71–73]. With the implementation of the feed-in tariff (FIT) scheme in 2012, Japan witnessed a significant rise in agrivoltaics. The FIT has profoundly impacted policy, increasing Japan's renewable energy supply by 76% between 2012 and 2019. In agrivoltaics, shading typically varies from 10 to 55%, with a median range of 30 to 40% [71]. Therefore, the extensive adoption and economic benefits highlight the feasibility and agricultural variety that agrivoltaics can bring to Japan.

The Fraunhofer ISE conducted a 50 MWp agrivoltaic system in Maharashtra in 2018/2019. The project's economic viability was established, with the levelized cost of electricity (LCOE) projected at EUR 0.0243, including water-related expenses. Social impacts varied depending on the institutional framework, with potential outcomes ranging from significant benefits to extreme poverty among the farmers involved. Estimated land losses were 9% for soybeans, 4% for tomatoes, 6% for cotton, and 3% for bananas. Evaluations of crop productivity predicted an increase of 11% for tomatoes and 33% for cotton, while a yield reduction of 20% for bananas and 17% for soybeans [74]. The study discusses a detailed report compiled by the Indo-German Energy Forum Support Office (IGEF-SO) and the National Solar Energy Federation of India (NSEFI). This report encompasses multiple significant pilot projects throughout India and identifies 22 currently operational plants and three upcoming ones, primarily focusing on experimentation [75]. Regarding cost-effectiveness, agrivoltaic farms hold an advantage over traditional solar farms. This is due to the decreased spacing between rows, leading to lower costs per unit area, such as per acre. The monetary investment required to establish a 1-acre agrivoltaic farm can fluctuate depending on the costs per power unit during installation, as demonstrated by a sensitivity analysis with a range of $2/W to $0.25/W [47]. The financial metrics related to turmeric cultivation, including a price-performance ratio of 0.79 and a benefit-cost ratio of 1.71, indicate the project's feasibility and potential for success. The agrivoltaic project that includes turmeric cultivation exhibits a payback period of 9.49 years and a land equivalent ratio of 1.73, suggesting both efficient productive potential and rapid investment recovery for AVS [76].

China's agricultural sector has witnessed an impressive expansion in the construction of PV power stations in recent years. An installed capacity below 0.001 GW in 2009 escalated to a substantial 1.18 GW by 2014 [77]. These state-of-the-art structures enable the simultaneous cultivation of crops such as assorted vegetables, tea, diverse mushroom species and grapes [78], demonstrating the swift development and expansion of photovoltaic projects within China's agricultural sector. Research carried out by Jiang et al. [46] explored the impact of PV shading intensities of 19%, 30%, and 38% on kiwifruit cultivation within agrivoltaic systems at an experimental site in Fuxing township, Chengdu Plain, China. The study found that the 19% shading level optimised photosynthetic and water use efficiency in kiwifruit plants, with only marginal effects on crop development and yield. Growth parameters exhibited modest fluctuations, ranging from a 7.3% decrease to a 5.5% increase, while yield experienced limited reductions between 2.6% and 6.5%. These results indicate that light shading (19%) in integrated energy-agriculture configurations can enhance resource utilisation while maintaining near-baseline crop performance, offering a viable strategy for sustainable land use in similar agroecological contexts. Water productivity increased by 8.2% at this level, whereas the highest shading level significantly reduced it by 9.8%. These findings suggest that 19% PV coverage is optimal [46]. However, further research is needed to balance energy production with crop productivity, especially at higher shading levels.

In South Korea, it is estimated that between 80 and 180 km² of land is needed for efficient photovoltaic systems at a latitude of 33°, with an assumed efficiency of 18.3%. Although AVS were introduced in 2017 primarily for research, expansion plans are underway [79]. South Korean policymakers intend to launch 100,000 AVS projects, each with a capacity of 100 kWp, by 2030, aiming for a total market capacity of 10 GWp [24].

Jack's Solar Garden is the largest commercial agrivoltaics research site in the U.S., collaborating with institutions like the National Renewable Energy Laboratory to study the effects of solar-induced microclimates on plant growth. Various plants, including tomatoes, herbs and blackberries, are cultivated beneath the solar arrays alongside trees and pollinator-friendly vegetation [80]. Similarly, ReVision's Skowhegan solar farm in Maine has pioneered an innovative solar grazing initiative. In partnership with Michael Dennett of Crescent Run Farm, ReVision Energy integrates sheep grazing beneath solar panels. This approach reduces the use of fossil fuels for grass maintenance and enhances the economic viability of sheep farming [81]. Sun-Raised Farms, a North Carolina-based initiative, offers a sustainable solution for maintaining solar farms using locally sourced sheep. This approach supports the local production of pasture-raised lamb, reducing dependency on imports [82].

In Bierbeek, Belgium, an agrivoltaic system was implemented with 7-year-old pear trees cultivated under standardised intra-row and inter-row spacing configurations. Since July 2021, this system has utilised a MODBUS RTU-based data acquisition framework and PVGIS weather data to calculate irradiance. The 2021 economic forecast indicated a 10 tons/ha pear yield reduction, costing €6000/ha. Even with 600 MWh/ha annual energy, the LCOE was €200/MWh due to a CAPEX of €2.05/Wp, which exceeded the off-take price, suggesting that the project was not financially viable [83].

In Italy, REM Tec and the University of Piacenza developed a solar tracking system, Agrovoltaico®, which integrates with maize cultivation. Initiated in 2012 across two locations

(Monticelli d'Ongina and Castelvetro Piacentino), this system covers areas of 7 and 20 hectares, illustrating its potential for scalability in Northern Italy [84].

In France, there is a substantial focus on agrivoltaics, supported by national initiatives:

- Total Quadran collaborates with Agrosolutions on photovoltaic solutions over 200 hectares, establishing a research unit for economic modelling and challenge resolution [85].
- Cero Generation and EDF Renewables acquired Green Lighthouse Development, which holds a 2.4 GW capacity in France, with Cero also managing over 1.5 GW in Italy [86].
- Sun'Agri secured an allocation of 104 MW capacity distributed for 39 projects by the Commission de régulation de l'énergie (CRE), with about 40MW dedicated to AV projects, selling power at €0.0828/kWh [87]. The overarching goal of these projects is to support farmers in boosting crop yields while addressing the challenges posed by climate change.

### 2.4. European and Hungarian electricity markets: dynamics, policies, and trends

Initial estimates from the United Nations Task Team for the Global Crisis Response Group14 indicate that the dual impact of over two years of the Ukraine conflict and global energy crisis has led to a significant escalation in food and energy prices. These effects are seen across global commodities, inflation, and financial markets. Furthermore, the ongoing repercussions of climate change, resulting in diminished crop yields, rapidly intensify food and energy insecurity worldwide. Since 2020, the European electricity market has experienced a marginal price increase that has escalated dramatically [88,89]. Sweden deviates from this trend with more minor fluctuations and more considerable price reductions, potentially due to the substantial contribution of continuous biomass energy production [90,91]. In the first six months of 2023, the EU's average electricity cost was 289 EUR/MWh, varying from 114 to 475 EUR/MWh. In contrast, Hungary's electricity price during the same period was 116 EUR/MWh [92].

After the signing of the Paris Agreement in December 2015, the EU put forward rigid requirements for the renewable energy operation level of Member States, which triggered a new round of renewable energy construction upsurge in European countries in recent years. Among them, based on the tendentious incentive policies of the Hungarian government, the photovoltaic industry has developed rapidly in Hungary in recent years [93]. The MAVIR [94] (see Figure 5) dataset illustrates the growth of installed household PV capacity and total installed capacity from 2019 to early 2025, alongside the fluctuating contribution of solar production to total electricity consumption. The total installed capacity has increased significantly from 1.56 GW in 2019 to 7.76 GW by February 2025, demonstrating Hungary's commitment to scaling up solar energy. The installed capacity of household PV systems has shown consistent growth, reflecting strong policy support for decentralised solar adoption. A notable trend is the fluctuation in the ratio of solar production to total consumption. The share of solar energy peaked at approximately 12% in December 2024.

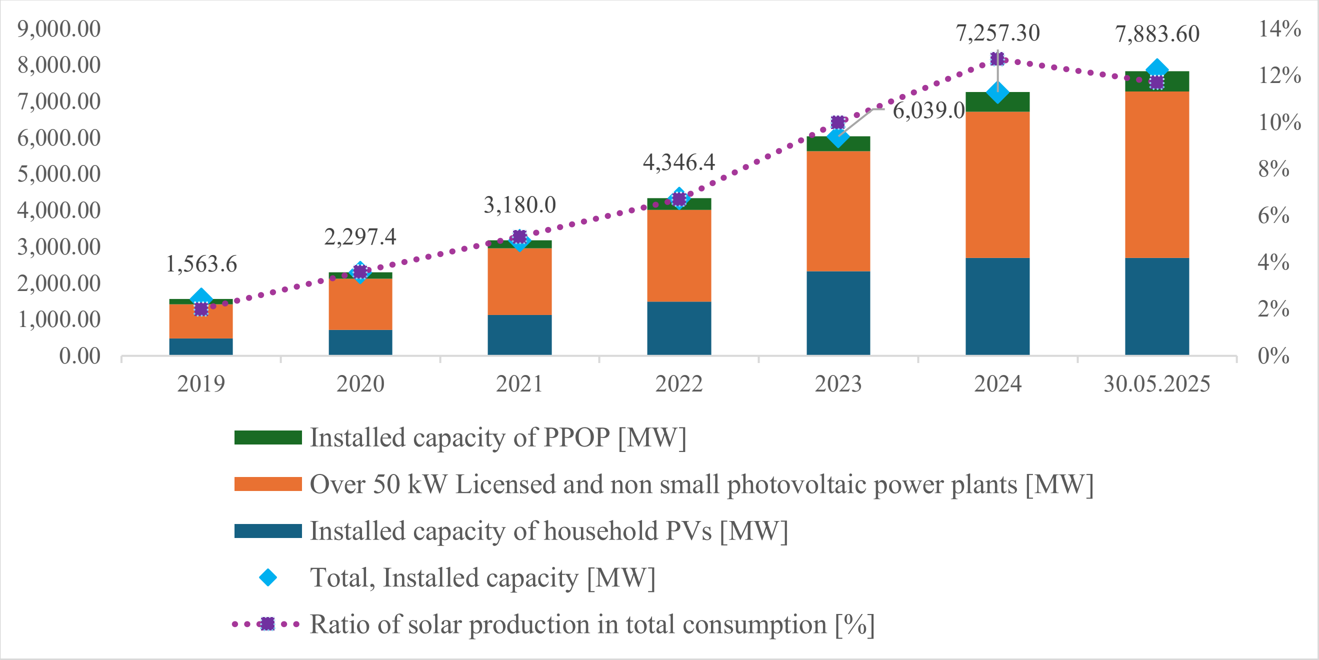

**Figure 5: PV installed capacity and share data change from 2010 to 2025.05.01 in Hungary. Source:** [94]

An economic analysis of agrivoltaic systems in apple cultivation indicates potential benefits such as additional revenue from electricity generation, reduced irrigation costs and financial risk and improved overall profitability and energy transition [43,49,62,95,96]. However, more comprehensive studies are needed to assess the long-term economic viability of such systems.

In Hungary, hailstorms represent a significant climatic hazard, posing risks to agricultural production and AV systems through potential mechanical damage to PV panels. Apple cultivation in Hungary primarily faces hail risks, drought, late frost, and heat. In northern Hungary, the chief risk factors are hail and late frost, along with waterlogging and continuous rainfall [97]. To mitigate these risks, the Hungarian government established the National Hail Damage Mitigation System (Országos Jégkármérséklő Rendszer, abbreviated as JÉGER) in 2018, operated under the coordination of the National Chamber of Agriculture (NAK). The system employs a network of 986 ground-based silver iodide generators comprising 223 automatic and 763 manual units distributed across the country to suppress the formation of large hailstones by cloud seeding [98].The primary objective of JÉGER is to reduce hail-induced agricultural losses, and according to the operator's reports, the system has demonstrably decreased the severity and frequency of hail-related crop damage since its implementation [99].

Despite the nationwide intention of coverage, however, the spatial distribution of the hail suppression units is not uniform. In certain regions, some protective stations have been decommissioned or never installed due to local public opposition, environmental concerns, or administrative decisions. These localized gaps, colloquially referred to as “holes in the system,” may lead to spatial disparities in hail protection efficiency. Consequently, AV installations located in or near these uncovered areas may face elevated exposure to hail damage compared to national average estimates. This highlights the need for spatially differentiated hail risk assessments when conducting feasibility studies or risk modeling for agrivoltaic investments. Incorporating localized hail occurrence probabilities and protection infrastructure coverage into risk analysis may significantly affect both the technical and economic evaluation of AV systems in Hungary.

The objectives related to the agrivoltaic systems on apple trees are to modulate the shading provided to the crop by photovoltaic panels according to the physiological needs of the plants, and it requires the construction of protective structures, driven by algorithms that prioritise agricultural products over photovoltaic panels [100]. A well-engineered agrivoltaic system has the potential to serve as a protective measure against various environmental risk factors, including heavy hail, rainfall, and wind. However, it is essential to note that these panels cannot entirely substitute for hail protection nets, as studies have documented hail damage rates exceeding 60% without supplementary netting. Nonetheless, the structural design of agrivoltaic systems allows for the integration of additional hail nets, which can effectively reduce both protection costs and production risks. Furthermore, implementing agrivoltaic systems can significantly mitigate the risk of plastic and foil waste entering and contaminating the soil [10,25,101,102]. Recent developments in photovoltaic technology have significantly improved resistance to extreme weather conditions. Some modern solar modules are now designed to withstand hailstones up to 45 mm in diameter, exceeding standard requirements [103,104]. A study conducted in Germany on agrivoltaic (AV) systems in apple farming found that investment costs could be reduced by 26% by partially replacing traditional hail protection structures with AV systems. This also resulted in a 9% reduction in annual operating costs, mainly due to savings in land and maintenance. However, annual revenues decreased by 9% due to lower high-quality apple yields, leading to an overall 5% reduction in the total cost of apple production [23]. Complementary to this, trials conducted in Italy's Trentino region demonstrated that integrating frost and hail protection. The primary applications of agricultural netting systems are diverse, with hail protection being the most common at 40%, followed by shading (35%) and insect protection (30%). Other uses include windbreaks (12%), bird protection (9%), frost protection (8%), and rain protection (6%) [105]. In Hungary, about two-thirds of apples are allocated for industrial purposes, with 80-85% going to concentrate production, while one-third is for consumption, a less favourable ratio than the EU average [106]. Nationally, production variability and lower quality are due to the lack of frost protection in 89-94% of apple orchards and irrigation in only 25-33%. Hail nets cover just 2,000-2,500 hectares, suggesting that many apple orchards use outdated or extensive cultivation methods and are often neglected [107]. Under the hail net, temperatures were up to 1 K warmer below 5 °C, and 0.3–1.2 K cooler above 5 °C compared to outside. The net cooled air was around 15 °C by up to 1.2 K. Relative humidity was up to 3% higher but considered negligible. A black hail net (4.2 m ridge height) delayed late frost onset by two hours and reduced its severity by 1.2 K [108]. During the late winter to early spring period, flowering performance in pear trees improved relative to the control group, primarily due to the protective effect of the overhead PV modules, which reduced exposure to radiative frost and low temperatures [48]. Moreover, depending on the design, AV structures can support the integration of mesh netting to reduce insect penetration. Assuming future implementation of AV systems in apple orchards in Hungary, agrivoltaic systems could be equipped with hail-resistant modules, making them more suitable for regions like Hungary, where severe weather events are becoming more frequent. This situation leads to the development of agrivoltaic systems in Hungary, a dual production system in which green electricity and agricultural production are combined. Additionally, innovative financing methods are essential to stimulate investments in energy efficiency.

In Italy, a comparison was made between the GM-PV system and AVS. LCOE for an agrivoltaic system with a capacity of 500 kWh per square meter was determined to be €0.0895 per kWh, and the GM-PV system had an LCOE of €0.0847 per kWh. The analysis assumed that 80% of the generated electricity was directly utilized for self-consumption, with the remaining 20% being offset by the national grid operator. This consideration considered the annual average electricity price, transmission fees, and additional expenses [36].

In developing countries like India, CAPEX and LCOE are considerably lower compared to the typical European costs (e.g., LCOE: 0.02-0.07 €/kWh, CAPEX: 492-588 €/kWp) [74]. Across Europe, LCOE was evaluated at three locations, with weighted average cost of capital (WACC) adjusted by 25%, CAPEX and OPEX. In Northern Europe, LCOEs are mainly influenced by capital costs and can be reduced depending on the crop's ability to tolerate shading [109].

For the agrivoltaic system with a capacity of 520 kWh per unit, the projected LCOE stood at €0.0828 kWh per unit, while the GM-PV system had an LCOE of €0.0603 kWh per unit. As both solar systems primarily generate green electricity, LCOE is a crucial measure of competitiveness. AV had a 38% higher LCOE, mainly due to the increased CAPEX and the additional costs associated with agricultural products. The predominant investment costs for AV are attributed to PV modules, structural components, soil protection and site preparation. Yet, AVS incurred OPEX 13% less than GM-PV systems, as observed in the German experiences. The disparity in operational costs arose from the lower annual maintenance, surveillance costs, land costs and mowing for AV, although AV incurred higher repair servicing costs [24].

As per the results of Moreda et al. AVS could represent mutually beneficial opportunities for farmers and investors, with an Internal Rate of Return (IRR) exceeding 8% in the baseline scenario despite a 20% decrease in vegetable yields. In tropical regions, where geographic conditions and biomass productivity are more favourable, competitiveness is likely significantly higher than in advanced economies, potentially making AV systems more appealing to investors in these areas [55]. Bhattacharya et al. proposed using a Renewable Energy Portfolio (REP) system to regulate energy prices by valuing renewable electricity more than intermittent sources. This could raise regular electricity prices, affecting production and profits depending on historical electricity generation costs, supplier competition and consumer preferences.

Long-term policies in the United States promoting the growth of photovoltaic systems have started to yield results [110,111]. Similarly, Japan launched its "new energy promotion program" and "new sunshine plan" in the late 1990s [112]. Around the turn of the 20th century, the European Union began to elevate its renewable energy usage target consistently [113]. This led to a rapid surge in solar energy utilisation in major EU countries such as Germany, Italy, Spain, and France [114]. By 2020, the European Union's gross electricity consumption accounted for 14% of the global total [115].

Renewable electricity generation is gaining prominence in the EU from both energy policy and environmental perspectives. The Renewable Energy Directive establishes a compulsory target of 32% for the European Union, yet it does not include obligatory targets for individual member states. The Tradable Green Certificates (TGCs) scheme could be a market-based operationalisation of this target. Prior research [116,117] proposed that this system could potentially decrease the total cost of transitioning to renewable energy in the European Union by as much as 70% and significantly reduce CO2 emissions [118]. However, due to varying externalities between countries, this incentive may not be sufficient to reach the EU target, leading Karakosta and Petropoulou [119] to reinstate compulsory national targets.

Future studies in AV economics are expected to investigate the optimal configurations for solar panel coverage, the most suitable crops for different conditions, spacing, and arrangement, and the effects of price fluctuations in connected sectors like agricultural inputs and outputs, electricity markets and solar panel technology. In summary, the future economics of PV systems involve significant uncertainties. Technological progress and intelligent systems might reduce costs, while consumer preferences could increase prices. However, the added storage expenses might also increase costs.

### *2.4.1. Evolving dynamics of Hungary's renewable energy landscape and regulatory impacts on solar power integration*

Hungary has rapidly evolved into a country that prioritizes energy conservation and the utilization of renewable energy, a shift that carries significant implications for its economic growth [7]. Under the Green Program of the Hungarian National Bank (MNB), utility-scale renewable energy production has been scrutinized for potential support and developmental opportunities, emphasising bolstering environmental sustainability within the national financial system [120].

The recent enactment of Decree No. 7/2025 (I. 31.) represents a significant shift in Hungary's renewable energy policy by freezing the feed-in prices for solar power plants. This legislative change, effective retroactively from 1 January 2025, until the end of 2029, suspends the inflation tracking of feed-in tariffs within the Mandatory Feed-in Transmission System (KÁT), maintaining prices at 2024 levels unless inflation exceeds 6% [121]. This decision introduces considerable uncertainty into the renewable energy market, with potentially profound implications for investment and market dynamics.

In January 2025, the Hungarian government enacted Government Decree No. 7/2025, which suspends the annual inflation adjustment of the mandatory feed-in tariff (KÁT) for renewable energy producers until 2029, unless the annual average inflation exceeds 6% [122]. The government, through the Ministry of Energy, justifies this measure as a means to stabilize energy costs for residents and businesses while ensuring grid balance [123]. They argue that the temporary suspension of inflation adjustments will not adversely affect solar power operators' returns, due to the substantial additional income generated from the recent surge in energy prices. However, this optimistic view is not universally shared among market participants. The measure could negatively impact the return on investment for more than 2,700 industrial-scale solar projects, which collectively contribute over half of the country’s solar electricity output [124]. The price freeze is likely to prolong the payback period for new investments, particularly those heavily reliant on bank financing.

In response to these challenges, the regulation offers solar power operators the option to exit the KÁT system and sell their energy on the open market. This move is intended to encourage market liberalization and provides potential tax breaks and the opportunity to engage in long-term green power purchase agreements (PPAs). However, the substantial 42% Robin Hood tax poses a significant hurdle, reducing the appeal of market-based sales by limiting competitive pricing.

Beyond the immediate economic impacts, the freeze on feed-in tariffs raises broader concerns about Hungary's energy independence. With imports accounting for over 40% of the country's electricity supply, Hungary remains highly susceptible to external market fluctuations. Enhancing energy sovereignty by promoting the spread of renewable energy sources and encouraging market competition through tax incentives is crucial for developing a stable and sustainable energy market [121]. Furthermore, the full effects of these regulatory changes on the energy sector and investment climate are not yet fully apparent. Nevertheless, stakeholders advocate for reassessing the regulatory framework and introducing a more sustainable pricing mechanism to ensure the continued development of renewables in Hungary. Adapting support systems to align with changing market conditions will be essential for achieving both national and global sustainability objectives.

Hungary's energy landscape has undergone significant transformations, positioning itself as a model for green energy integration within the European context. As of 2025, the Hungarian energy mix has become notably diversified, with a strong emphasis on nuclear energy, solar, and wind power, reflecting a broader commitment to sustainable energy practices. According to Zsolt Hárfás, an expert quoted in Magyar Nemzet, both Hungarian and international frameworks underscore the necessity for parallel growth in nuclear and renewable capacities to meet escalating global energy demands [125].

The projected rise in global electricity demand by 2050, fueled by advancements in e-mobility, heat pump systems, and hydrogen technology, necessitates substantial investment in renewable energy. Hungary's proactive approach in this regard is evident in its energy statistics from the previous year: the Paks nuclear power plant alone accounted for approximately 47% of domestic electricity production. In conjunction with gas (20.4%) and coal (8.3%), base power plants provided 75.7% of the nation's electricity, while renewables, led by solar power and biomass, composed the remaining quarter. Government initiatives have propelled Hungary’s solar power capacity from 1.4 MW in 2010 to an impressive 7,550 MW by 2025, with expectations to reach 12,000 MW by the next decade. Industrial solar power plants contributed 5.7 TWh in electricity last year, translating to a 16.7% production share and a 17.8% capacity utilization factor [125]. This starkly contrasts the Paks nuclear power plant's utilization factor of 90.3%, highlighting the efficiency discrepancies between renewable and nuclear energy sources. However, when factoring in household and self-generated solar contributions, the total production share of solar energy in Hungary could potentially climb to 25%, potentially marking the highest in Europe.

According to the National Climate Change Strategy report, Hungary's goal is to elevate the contribution of solar energy in its primary energy framework, increasing its share from five per cent to twenty-one per cent by the year 2030 [126]. Successful achievement of this target would result in a reduction in Hungary's greenhouse gas (GHG) emissions by approximately 52 to 85% relative to 1990 levels [127]. Comparatively, the European Union's energy mix for 2024 shows nuclear power leading with 657 TWh, or 24.1% of total production, while solar energy, despite its substantial installed capacity of 302,000 MW, accounted for only 10.3% of production [125]. This disparity underscores the significance of installed capacity and energy production methods' availability and efficiency.

Globally, nuclear power represents 9.5% of approximately 30,000 TWh total production, with solar and wind contributing 5.4% and 7.8%, respectively. Despite these gains, fossil fuels—comprising coal, gas, and oil—still dominate, generating 60% of the world's electricity. Hungary's strides in renewable energy capacity, particularly in solar, position it as a potentially leading example in Europe, demonstrating the effectiveness of strategic energy diversification and investment in sustainable sources.

The newly ratified National Energy Strategy and the National Energy and Climate Plan (2030, with a perspective until 2040) project that, between 2000 and 2030, investments in Hungary's renewable energy sector, primarily PV plants, are projected to reach a total value of HUF 2,253 billion (€6,324 million). This will require debt financing of HUF 1,577 billion (€3,889 million), and a planned PV power capacity of 12 GW by the end of 2040 [128]. The share of renewable energy within the overall energy consumption is projected to be at least 45%.

Hungary has seen a continuous rise in the capacity of its large-scale solar power facilities, nearing an installed capacity of 1,800 MW. Including residential solar installations, the total PV capacity is about 2,800 MW (see Table 1). Although growth may slow in the year's second half, projections indicate that Hungary will surpass the 3,000 MW benchmark in 2022, reaching a significant point toward the 2030 target outlined in its energy strategy [129].

Currently, the largest PV installations in Hungary, boasting a capacity of 25 MW, operate in Kapuvár. This park is owned by a public stock exchange group in Israel, which maintains three

PV power facilities in Hungary: Nádasd, Kapuvár and Tuzsér. All three sites continually produce energy, with the PV panels functioning at an aggregate capacity of 57 MW [130].

**Table 1. List of photovoltaic power stations**

| Name of Plant | Area | Capacity | Construction cost | Project Developer |
|---|---|---|---|---|
| Kaposvár | 200 ha | 100 MW | € 99,919,101 | China National Machinery Import & Export |
| Tázlár Solar Park | 100 ha | 63 MW | €50,000,000 | MASPED Első Magyar Általános Szállítmányozási Zrt., "HO-ME 2000" Vagyonkezelő Kft., and MET Group |
| Felsőzsolca PV park | 45 ha | 20 MW | € 24,264,063 | Investment from EU's Cohesion Fund, MVM Group |
| Duna Solar Park | 40 ha | 17 MW | € 25,000,000 | MET Power |
| Mátra Power Plant, Bükkábrány | 32 ha | 16 MW | € 17,524,045 | MVM Group |
| Pécs Solar Park | 20 ha | 10 MW | € 11,323,229 | State support, the additional HUF 703 million provided by MVM Hungarowind Kft. |
| Total | 437 | 226 | € 228,030,438 | |

## 2.5. Key facts on European and Hungarian apple production: trends, challenges, and sustainability factors

AVS integrate crop cultivation with PV energy production, considering multiple environmental factors that influence crop growth, including shading effects, climatic conditions, and water availability [131]. The performance of crops under AVS is highly contingent on species-specific adaptability to shading, panel height, and spacing configurations.

Economic aspects significantly influence apple cultivation. A consumer trend towards locally produced food has been observed over recent years, which extends to fruit products. This rising demand creates a potential for expanding local production, achievable through adapted production systems like protected cultivation or tailored crop management [132,133]. Despite a decreasing market share of apples in Hungary [134], apples remain the most popular fruit variety in the country, considering production products. Nevertheless, fruit production is critical in the country's agricultural landscape [135]. Data from the Hungarian Central Statistical Office [136] suggests that in 2022, apple trees accounted for roughly 31% (24000 ha) of Hungary's fruit cultivation area, underscoring the apple's preeminent status in Hungary's fruit industry.

Typically, Hungary yields around 530 thousand tonnes of apples per year, although this output has varied between 350 and 780 thousand tonnes annually over the past decade [137]. Consumers' purchasing decisions heavily rely on the quality of the apple, determined by external features such as colour, size and shape, as well as internal quality traits like the characteristic taste of the variety, sugar content, texture, firmness, and juiciness [138].

Apple orchard productivity and economic viability are highly influenced by production system design, cultivar selection, and investment in protective and input technologies. In intensive apple production systems (around 800–1,200 trees/ha), balanced mineral and organic fertilisation has significantly enhanced yield performance and fruit quality [139]. Super-intensive orchard systems (2,500–4,000+ trees/ha), characterized by ultra-high planting densities and dwarf rootstocks, require high upfront investments but offer faster returns due to early and increased yields. However, these systems are particularly vulnerable to climatic risks such as hail, which can cause significant economic losses. Szabó (2016) demonstrated that installing hail protection nets in Hungarian super-intensive apple orchards is economically feasible, particularly when considering long-term yield protection and reduced market losses. This is highly relevant in agrivoltaic systems where structural integration of PV panels may offer dual benefits of energy production and physical crop protection. Furthermore, apple cultivars' selection and adaptability to specific production conditions significantly affect fruit quality outcomes such as firmness, sugar content, and shelf-life [140]. The impact of genotype-environment interactions must be carefully considered when evaluating the suitability of apple varieties for intensive and agrivoltaic systems, where light availability and microclimatic conditions may differ from conventional orchards [10]. Lastly, the economic efficiency of orchard investments has been extensively evaluated, emphasising that factors such as orchard type (intensive vs. super-intensive), input costs, market access, and yield reliability critically determine profitability [141]. Since 2002, Hungary's apple orchard area has declined from 41,000 to about 24,000 hectares, representing a 40% loss [136]. This decrease primarily impacted orchards with insufficient post-harvest and market infrastructure, obsolete varietal structures and outdated cultivation methods [142], a trend likely to persist. Of the current orchards, around 5,000 hectares are managed under semi-intensive or intensive systems aimed at fresh consumption, which contributes two-thirds of production. The remaining output is supplemented by selective harvesting in legacy or industrial-scale orchards. However, only ~20% of these operations meet contemporary agricultural standards, serving as the foundation of Hungary's apple sector. The adoption of agrivoltaic systems could serve as a viable strategy to protect apple blossoms from frost-induced floral damage, especially relevant in Hungary [107]. Furthermore, the decision to purchase is influenced by factors such as price, market availability, and distribution, which contribute to intense competition among different growing regions [143]. For producers, achieving high transport stability and storability is crucial [138].

Agrivoltaic systems can affect water availability and usage in apple orchards. Studies have demonstrated reduced evapotranspiration rates, increased soil moisture retention, and improved water use efficiency, thus supporting sustainable water management [144,145]. Several studies have reported positive effects of agrivoltaic systems on apple tree growth, including increased shoot elongation, larger leaf area, and enhanced photosynthetic activity, leading to improved fruit yield [140,146]. The shading effect of PV panels in agrivoltaic systems reduces water evaporation, minimizing irrigation requirements and optimizing water use efficiency [10]. Although site-specific assessments are necessary, studies indicate that these systems can lead to increased soil moisture [22,145], reduced evapotranspiration [60,147], diminished diurnal air temperature fluctuations and plant temperature variations and lower soil temperatures [147,148]. Weselek et al. (2021) researched near Lake Constance, Germany, where AVS was implemented on sandy loam soil. The study observed a reduction in photosynthetically active radiation by approximately 30% under the panels. During summer, soil temperature decreased beneath the AVS. Crop yields varied, with some increases noted during hot and dry conditions, suggesting that AVS can mitigate heat stress in such soils [53]. Fraunhofer ISE has conducted extensive simulations to analyze the impact of photovoltaic (PV) modules on light availability for crops situated between or under the modules. Two important metrics in these studies are photosynthetically active radiation (PAR) and the coefficient of variation [43]. Research by Fraunhofer ISE demonstrates that overhead systems generally provide more excellent PAR and lower coefficient of variation than interspace systems at equivalent pitch distances.

Research has shown that AVS can increase soil moisture retention by 14.7% in fixed installations and 11.1% in mobile setups [149]. AVS system capacity of 0.675 kWp implemented on lateritic and clayey loam soils in Odisha, India. The system cultivated turmeric under 70–75% shading. Findings indicated that the shading structure maintained a moderate microclimate, reducing temperature and evapotranspiration rates and enhancing energy and food production [76]. In a dry–hot valley eco-fragile area of Southwest China, researchers examined the early effects of AVS on soil quality. The study found that AVS significantly enhanced soil moisture, organic carbon, and nutrient levels. Gap cultivation (areas between panels) had a more pronounced positive impact on soil quality than under-panel cultivation [150]. A long-term study in Central Italy assessed soil property changes after seven years of ground-mounted photovoltaic panels. Results indicated a significant reduction in water-holding capacity and soil temperature under the panels. Additionally, soil organic matter decreased, and microbial activity was reduced, suggesting potential long-term impacts on soil health [151]. Hungary exhibits a variety of soil types across its major horticultural regions. In the north-eastern and eastern regions, notably around Debrecen and Nyírség, where apple orchards are concentrated, the dominant soils include:

- Sandy soils with alternating clay layers, characterised by low macronutrient and humus content and limited water-holding capacity [152].
- Clay loam soils and biotope soils, which exhibit higher moisture retention potential, especially when managed with water-conserving amendments [153].
- Brown forest soils and chernozems tend to have moderate to high water retention, depending on organic matter content and structure [154].

The influence of AVS on soil moisture is closely tied to shading, reduced evapotranspiration, and lower wind exposure. These benefits, however, interact with intrinsic soil physical properties such as texture, porosity, and organic matter content:

- In sandy soils, AVS can mitigate rapid moisture loss due to high infiltration and low retention, although water-holding capacity remains limited. Such soils benefit most from AVS when combined with conservation practices (e.g., mulch, water retainers) [152,153].
- In clay loam soils, AVS shading contributes to stable subsurface moisture by reducing surface evaporation, and the inherent fine texture enhances moisture retention at depth [153].
- In chernozem soils, AVS may enhance a favourable water balance, especially under organic or reduced-tillage regimes.

Although exact soil moisture values under AVS differ by region and setup, findings from Szalacsi (2022) indicate that moisture levels at 10 cm and 20 cm depths were consistently higher in treated orchard soils even though differences were not always statistically significant [153]. This aligns with findings from agrivoltaic research showing 5–15% higher soil moisture content under panels, depending on panel height, tilt, and shading density [155].

Moreover, AVS enhances irrigation efficiency, achieving a 328% improvement in water retention compared to full-sun agricultural plots [145]. The study site featured silty loam (Lu) soil, with a grain size distribution of 20-30% clay, 10-30% sand, and 50-70% silt. Laboratory results confirmed that the soil water retention curves for both the A and B horizons closely matched the idealized curve for silty loam. Volumetric water content (VWC) was measured at various pressure heads, and key indicators like field capacity (FC), available water content (AWC), and wilting point (WP) were derived [156]. The soil exhibited typical silty loam water retention properties, with a moderate ability to retain moisture, making it suitable for agrivoltaic systems in orchard settings. In a study of dryland agriculture, water-use efficiency under PV panels varied by crop type, reaching 157% for chilli, 65% for tomatoes, and 12% for lettuce at a panel height of 4 meters [60]. A global meta-analysis projected that agrivoltaic deployment on 22–35% of non-irrigated croplands could mitigate water stress for staple crops (e.g., wheat, maize) under moderate shading (20–30% coverage) [157]. Agrivoltaic systems have been shown to influence fruit quality attributes such as colour, size, firmness, and sugar content, with some studies reporting enhanced fruit quality in terms of increased sugar accumulation and improved colourations [158,159]. Therefore, given the compelling evidence of agrivoltaic systems' positive impact on apple tree growth, fruit yield, and quality attributes, as well as their potential economic benefits in terms of reduced irrigation costs, enhanced fruit quality, and increased overall yield, it is imperative to investigate the broader ecological and financial implications of these systems in diverse agricultural contexts. AVS presents a synergistic opportunity to optimize resource utilization and enhance economic viability. Elevating PV panels to a height of 2-5 meters makes it possible to maintain agricultural activities beneath them, thereby maximizing land use efficiency and promoting sustainable development in the agricultural sector [160], as shown in Figure 6.

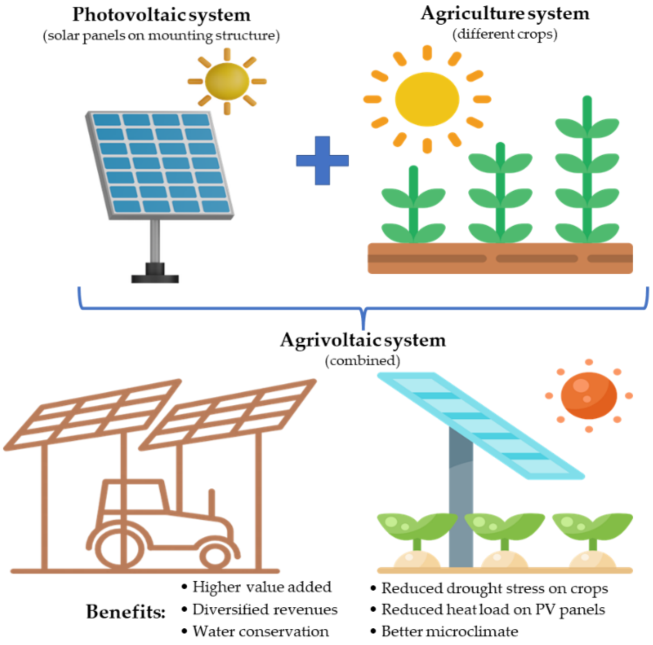

**Figure 6: Comparative illustration of agrivoltaic and photovoltaic systems on shared agricultural land. Source:** [40]

Beyond shading and water conservation, agrivoltaic systems also modify local microclimatic conditions. Elevated PV panels influence temperature, humidity, and wind patterns, which can further impact crop growth [145]. The extent of these changes depends on factors such as panel height, tilt angle, and regional climate conditions. Fixed-panel installations significantly lower soil temperatures than mobile tracking systems, allowing greater radiation penetration throughout the day [53]. For instance, shade-resilient crops like chilli (*Capsicum annuum*) and cherry tomatoes (*Solanum lycopersicum*) in Tucson, USA, demonstrated tripled and doubled yields, respectively, under stilt-mounted panels (3.3 m height, 1 m spacing), directly boosting farm income while generating solar power [22]. Conversely, shade-sensitive crops like durum wheat in Montpelier, France, suffered 11–29% reductions in dry matter and 8–11% yield losses under panels (4 m height, 1.64 m spacing), necessitating compensatory energy revenue or subsidies to offset agricultural deficits [9]. Similarly, lettuce in Kansas, USA, experienced 19–42% yield declines under 3.2–6.4 m panel spacing, highlighting the need for crop-specific adjustments to maintain profitability [161]. Maize exemplifies how system optimisation can mitigate trade-offs: in Japan, adjusting row spacing to 1.67 m under low-density AVS maintained yields at 3.54 kg/m², comparable to full-sun conditions [61]. Such adaptations are critical for balancing energy and agricultural revenue streams.

Economic assessments of solar agricultural farms further underscore the benefits of integrating energy and food production. In one case study, an agrivoltaic system exhibited a cost-benefit ratio 1.5. It achieved a 55% lower levelized cost of electricity compared to conventional surface-mounted systems while maintaining a similar payback period and higher NPV [162]. Similarly, stilt-mounted AVS designs mitigate shading impacts, even for shade-intolerant crops like corn. In Japan, low-density stilt configurations increased corn biomass by 4.9% and yield by 5.6% relative to controls, challenging assumptions that PV integration inherently compromises agriculture [61]. Even-lighting agrivoltaic systems, which ensure uniform illumination, achieved an average LER of 1.64 and were associated with a more than fivefold increase in farmer income [163]. However, the economic viability of AVS is highly sensitive to several external factors. Critical determinants include fluctuation of electricity price, financing structures, and crop yield variability, all of which can significantly influence the overall profitability of these systems. The FIT price and financing conditions were identified as the most important revenue drivers determining the economic performance of the agrivoltaic system, with a higher FIT price making traditional ground-mounted PV systems more profitable. The agrivoltaic system resulted in more balanced unit costs for electricity and apple production than standalone systems while allowing for more efficient land use [30].

The yield of apple orchards typically ranges between 25 and 40 t/ha, depending on the management type [164]. Nonetheless, these yields vary due to alternate and climatic conditions. These fluctuations can result in significant income volatility for apple producers, an uncertainty further exacerbated by fluctuating sales prices.

Commercial fruit cultivation, including permanent crops, is highly susceptible to environmental factors due to its location-specific nature and exposure to year-round weather conditions over an extended period. Consequently, extreme weather phenomena such as drought, hail, continuous heavy rainfall, severe frosts, strong summer sunshine or storms pose significant risks. These conditions can affect the health of perennial crops, resulting in yield reductions or even total crop failure, and can impact yields in subsequent years [25,165]. Weakened plants face an increased risk of secondary damage from fungi, bacteria, or insects [166]. The potential extent of yield losses depends not only on the severity and timing of the extreme weather but also on whether the orchard was already experiencing a low-yield year due to other factors. Adverse effects on future years can range from increased cultivation workload to substantial yield losses due to underdeveloped flower buds in the previous year [167]. Given the high added value of speciality crops, damage from these conditions presents substantial risks for farmers [168].

Predicted climate change could result in more frequent extreme weather conditions. As such, farmers would greatly benefit from a clear assessment of future conditions and concrete adaptation strategies. This necessitates improved data and information [168]. The subsequent analysis focuses on the extreme weather conditions and forecasts that pose the most significant risk to apple cultivation and their anticipated future developments.

Unlike permanent crops, as opposed to annual crops, present a higher investment risk due to the necessity of long-term commitment of capital and the uncertainty of future conditions [169]. From a business standpoint, enhancing yields per unit area is advantageous. Increasing yields on the same land area allows fixed costs to be spread over more produce, thereby improving cost efficiency. This strategy also enhances the ability to stabilize yield fluctuations and fulfil delivery commitments, which is crucial for businesses with strong customer loyalty [170]. Achieving this requires high planting densities and robust trees [171,172].

As previously noted, harvest outcomes are influenced by weather conditions and alternation, necessitating significant investment in crop protection. Consequently, more crops are being cultivated under protective conditions, which in turn demands increased investment [173]. In recent years, the workload associated with fruit cultivation has slightly risen, even though the area under cultivation and the number of farms has remained stable or decreased. This trend indicates an intensification of fruit cultivation practices, such as higher planting densities.

## 2.6. Economic framework of agrivoltaics: market dynamics, economic viability, and sustainability implications

The economic evaluation of AVS is significantly impacted by the correlation between electricity and agricultural market prices and their fluctuations. In the European Union and Hungary, renewable energy sources such as wind and PV are rapidly expanding, accounting for a substantial portion of the total energy mix. The unpredictability of their production times and limited storage capacity have led to increased volatility in electricity prices on the spot market, ranging from 0 to 500 EUR/MWh. Projections indicate a sharp rise in extreme electricity prices starting in 2026 [174], revenue from solar electricity is unpredictable, necessitating durable regulatory frameworks or storage solutions.

The study [175] outline the investment expenditures associated with GM-PV systems, noting that these can increase AVS compared to GM-PV systems by 6% [176] to 111% [43]. This wide range is due to the diverse applications of AVS, indicating that a generalized statement about its economic viability is not feasible. For example, AVS used for sheep grazing may closely resemble GM-PV configurations, whereas those designed for arable farming using elevated systems have significantly different requirements [177].

Investment costs for AV production can differ depending on technology, capacity, module type and size, and the specific crop utilised. For horticultural systems reliant on perennial species, including orchard crops such as apples, cherries or pears, which have production spans exceeding a decade, specialized technology for higher-mounted designs is required [178]. Key factors affecting investment costs include modifying the substructure, installing costs, and balance of system components and PV modules [36,55]. The structure costs are comparable to traditional hail protection systems, but can replace them, potentially reducing costs by about 60%. The minimum height of the AV system and its material and cost implications largely depend on the type of management within the system. The complexity of installation, especially at significant heights, further raises labour and cost expenditures. Care must be taken to avoid negatively impacting subsequent agricultural activities by ensuring soil and vegetation are minimally disturbed during installation [179]. In high-mounted apple orchards, construction and soil preparation costs, ranging from 243 to 500 € per kWp and 190 to 266 €, respectively, could increase by up to 10%, depending on the height and spacing of posts [43]. For the GM-PV system, standard module costs are around €220/kWp, and the mounting system costs approximately €75/kWp. For vertically mounted systems, the use of bifacial modules increases the module cost to up to €260/kWp. The more complex mounting systems also lead to additional costs of around €180 to €200/kWp [23,24]. For high-mounted AVS, the specialised modules are estimated at around €360/kWp. The cost of the mounting structure depends on the intended application and, therefore, the required height. Above arable land, where systems must be installed at particularly high elevations, costs can reach approximately €400/kWp. In the speciality permanent crops, where installation height is significantly lower, mounting system costs range between €130 and €220/kWp [180]. The values in Table 2 are rough estimates. The exact costs depend, among other factors, on the size of the system, the location, the distance to the grid connection point, and current developments in the PV module market. The provided values are intended only to give a rough overview of the relative sizes of the individual cost components and to enable an approximate comparison of the economic efficiency of different system designs. Vertical agrivoltaic systems are more expensive to install than conventional ground-mounted PV systems due to the use of bifacial modules and the generally costlier mounting structures. High-mounted agrivoltaic systems, on the other hand, are significantly more expensive because of their particularly tall and stable substructures as well as the specialized modules used.

**Table 2. Investment costs (Euro per kWp) and cost structure (% share) for different system types**

| **Cost Item** | **GM-PV share (%)** | **GM-PV Cost (€ / kWp)** | **Vertical AVS share (%)** | **Vertical AVS Cost (€ / kWp)** | **Elevated AVS (high-mounted) share (%)** | **Elevated AVS Cost (€ / kWp** |
|---|---|---|---|---|---|---|
| Modules | 38.46% | 220 | 36.63% | 252 | 29.17% | 360 |
| Mounting structures | 13.11% | 75 | 27.78% | 191 | 32.41% | 400 |
| Site Development, Planning, Infrastructure | 14.86% | 85 | 7.71% | 53 | 24.31% | 300 |
| Grid Connection | 16.43% | 94 | 13.66% | 94 | 7.62% | 94 |
| Cabling | 8.57% | 49 | 7.12% | 49 | 3.97% | 49 |
| Inverter | 5.42% | 31 | 4.51% | 31 | 2.51% | 31 |
| Fencing | 3.15% | 18 | 2.62% | 18 | 0.00% | 0 |
| Total |  | 572 [181] |  | 688[181] |  | 1234 [182] |

Recent fluctuations in steel prices have posed additional risks. Module prices vary with light transmission capabilities and design, with semi-transparent modules costing between 240 and 440 € and double glass modules priced at 326 € per kWp. Higher electricity production per installed capacity can offset these extra costs. Planting material and irrigation system costs remain unchanged. However, the absence of comprehensive building, nature, and landscape conservation legislation could increase authorisation costs depending on the country [23,24,183].

Conversely, costs for site preparations typically required for GM-PV systems, such as clearing, levelling, or additional soil compaction [177], and fencing [23], are avoided. Nonetheless, project development, site selection, and preparation involve higher complexity due to the need to coordinate among various stakeholders and their interests. The use of specialized modules in AVS, which are often not mass-produced, can further increase investment costs due to their higher purchase price [23].

The potential for increasing the economic efficiency of AV systems is seen in the cost reduction of the substructure by requiring lower mounting heights or by developing more material-efficient designs [30]. This possibility can arise, among other things, when AVS is used in conjunction with fruit and wine growing (see Chapter 2.5). A high self-consumption rate can also have a positive effect, saving expensive purchased electricity [43]. However, this possibility only exists for a specific system size (see Chapter 2.6). In addition, cost factors in the PV sector affect AVS's investment costs. These factors encompass the maturity level of the local PV industry, the components and costs associated with the balance of the system, the accessibility of financing mechanisms, and the applicable taxes and incentive structures [184]. Like GM-PV, AV systems and CopAPS benefit from economies of scale as the system size increases and the costs per installed capacity decrease and enhanced economic competitiveness compared to smaller installations. This cost advantage increases the likelihood that large-scale AVS projects will prevail in competitive tendering processes. Furthermore, this concentration presents a limitation for research and development (R&D), as the successful advancement of AV technology depends on exploring a wide range of system configurations and crop combinations [185]. However, this trend may inadvertently reduce support for smaller, decentralised systems, which are often better integrated into local agricultural settings and more likely to gain public acceptance, particularly in regions with small-scale or speciality crop cultivation. A disproportionate emphasis on large-scale projects may undermine AVS's social acceptance and hinder its integration into diverse agricultural landscapes. A balanced deployment strategy, particularly during the early funding and policy support phases, is essential to foster innovation and identify optimal synergies across varying AV applications. AVS can also benefit from learning effects and economies of scale as market presence increases.

These findings highlight the need for further research to evaluate the relative viability of AVS compared to GM-PV systems and ConAPS. Competitiveness is a multifaceted construct, the assessment of which inevitably depends on the methodological framework and the specific objectives of the study [186]. This analysis focuses on the economic dimension of competitiveness, employing a comparative framework to evaluate farm-scale financial performance metrics across AVS, GM-PV, and ConAPS.

# 3. MATERIAL AND METHODS

## 3.1. Systematic review methodology

This chapter employs a systematic review methodology to analyse existing literature relevant to the study's focus comprehensively. A well-defined research strategy is formulated to guide the selection of studies, including establishing specific criteria to ensure that only relevant and high-quality studies are included in the review. These criteria focus on study design, publication date, and significance to the research question. Data extraction involves extracting relevant data from the chosen studies to ensure that key variables and findings are accurately captured, facilitating thorough analysis and synthesis. Additionally, a bibliometric analysis was conducted to evaluate the quantitative aspects of the literature, including examining publication trends and citation patterns and identifying influential studies and authors within the field. This work delineates critical knowledge gaps by synthesising prevailing research trends and proposes priority research directions to advance scalable frameworks for future interdisciplinary investigations.

### *3.1.1. Research strategy and study selection criteria*

Aligned with PRISMA standards [187], this systematic review employs a reproducible analytical pipeline, integrating RStudio (v7.2.0) and Bibliometrix for data extraction, curation, and visualization. The protocol's design and validation rigorously follow PRISMA's evidence synthesis principles to ensure methodological transparency. The inclusion and exclusion criteria were established upon determining the research topic to align with the study's objectives.

A thorough literature search was performed from the beginning of the field through 15 November 2022, utilizing the Scopus database to access metadata on scientific papers concerning agrivoltaic systems without imposing a publication date limitation. Scopus was selected due to its comprehensive coverage of articles relevant to the research domain. For this systematic review, we focused on complete-text, peer-reviewed original research publications, including conference papers and journals, due to their high credibility achieved through stringent peer-review processes by journal editors and experts. Only studies published in English were included, given that Scopus data analysis reveals a strong preference for English in scholarly publishing, with 91.6% of articles issued in this language [188]. Key details of our dataset are summarized in Table 3.

**Table 3. Descriptive metrics and structural features regarding the collection**

| Description | Results |
|---|---|
| Period | 2011-2023 |
| Total documents | 121 |
| Sources (journals and conferences) | 59 |
| Number of authors | 382 |
| Total literatures | 5415 |
| Keywords by authors | 363 |

*Source:* [40]

Figure 7 shows the search terms employed for querying the Scopus database. Within each category, terms were combined using 'OR'; for the first group (KW1), only AVS synonyms were used, while sub-keywords for the other categories were connected using 'AND'.

Initially, the Scopus database search yielded 532 articles for potential inclusion. SLR method involved four stages: (i) using a predefined list of keyword strings to search for conference papers and peer-reviewed articles within the Scopus database; (ii) conducting a screening process based on titles, abstracts, and keywords, with a thorough review of the full texts for potential inclusion; (iii) reviewing the bibliographies or references of these articles to find additional relevant studies. The Scopus-derived BibTex files (*.bib) were partitioned into five keyword-specific subsets and systematically integrated into the RStudio environment to ensure modular data processing. During this process, 328 duplicate entries were eliminated before the screening phase.

Then, 204 records were selected and transferred from RStudio to MS Excel. From these, 151 records underwent eligibility assessment through full-text review. At this stage, 33 articles were excluded due to the unavailability of the full text. In the concluding step, 3 conference papers were added, and a snowball search was conducted to find additional pertinent articles. In total, 121 full-text articles were identified and analysed. The review process is illustrated in the flowchart presented in Figure 7.

The data was subsequently examined using Biblioshiny, an interactive web tool for bibliometric and visual analysis, enabling graphical displays of various potential results. The analysis encompassed keyword trend co-occurrence, top-cited papers, scientific output by country, thematic mapping, bibliographic connections, yearly publication trends, and co-authorship analysis by country. These findings underscored the key trends and current development status in terms of leading countries, authors, research papers, journals, and subject areas.

### *3.1.2. Eligibility criteria and data extraction*

In establishing the eligibility criteria for article selection, the focus was on ensuring the relevance and standard of the studies contained within the review. The criteria were designed to encompass studies that specifically address the multifaceted aspects of AVS, including technical, energy, economic, infrastructural, agricultural and environmental dimensions, as well as their associated benefits. Only peer-reviewed scientific and conference papers written in English were considered to maintain high academic rigour. Publications that did not meet these standards, such as non-peer-reviewed reports, non-English articles, books, and reviews, were excluded to ensure the integrity and focus of the review.

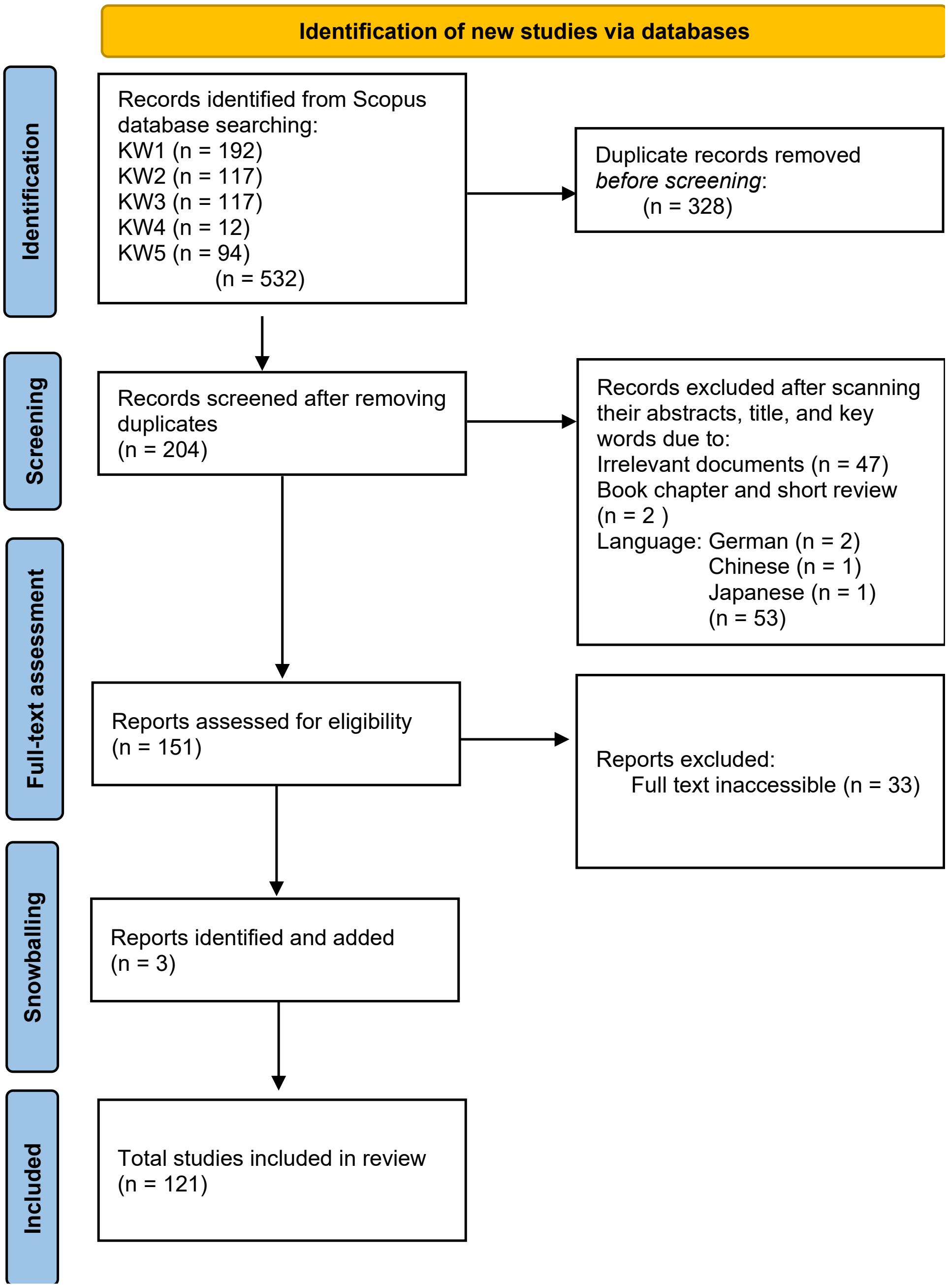

**Figure 7: Flowchart illustrating systematic review methodology. Source:** [40]

Data extraction was conducted manually by thoroughly reviewing each publication and recording relevant information into Microsoft Excel for subsequent analysis. Inclusion criteria prioritized peer-reviewed, English-language scholarly articles. Eligible articles were sequentially filtered to (1) exclude non-scientific publications, (2) exclude non-English publications, and (3) remove duplicate studies.

### *3.1.3. Bibliometric analysis*

Bibliometric analysis applies the quantitative analytical techniques of science to examining publications, including journal papers and the number of times they have been cited. This quantitative assessment is prevalent across almost all scientific disciplines, helping to assess the development, maturity, prominent authors, new trends within the research community, and conceptual and intellectual frameworks. Bibliometrix, an open-access software suite tailored for scientometric inquiry, consolidates core methodologies for bibliographic analysis. This platform enables multi-database data ingestion, advanced metric evaluation (e.g., co-authorship networks, thematic keyword clustering, citation linkages), and dynamic matrix generation to map scholarly interactions. Complementing this, SCOPUS, a comprehensive bibliographic database launched in 2004, supports granular querying across metadata fields (titles, abstracts, keywords, references) and streamlined export of curated datasets, enhancing reproducibility in large-scale bibliometric studies.

## 3.2. The financial viability of integrating agrivoltaic systems within apple farming practices

This section outlines the creation and application of an economic model specifically tailored to analyse the financial viability of integrating agrivoltaic systems within apple orchards under Hungarian conditions. The model is designed to simulate the economic outcomes and assess the integration's potential benefits and challenges.

The economic model incorporates a variety of inputs, such as initial capital investment, operational costs, and revenue streams from agricultural yields and solar energy production. Local climatic data, apple yield statistics, and solar irradiance levels are integrated to ensure the model accurately reflects Hungarian conditions. Data for the model was meticulously collected from agricultural reports, scientific papers, solar energy production databases, and Hungarian economic studies, providing a robust foundation for analysis. Key analytical techniques, such as discounted cash flow (DCF) analysis, are employed to calculate net present value (NPV) and IRR, providing insights into the project's financial viability.

To ensure reliability, the model undergoes validation through scenario testing using historical and hypothetical data and is benchmarked against existing agrivoltaic projects in other regions. This systematic approach provides a rigorous methodological background for evaluating the economic feasibility of agrivoltaic systems in Hungary, offering valuable insights for stakeholders considering this sustainable agricultural practice. The individual procedures are described below.

### *3.2.1. Modell description and objectives*

Following the evaluation of solar potential across Hungary, the country was selected as the target region for this study due to its favourable conditions for PV development and its significant role in apple production within Central Europe. Figure 8 presents Hungary's Global Horizontal Irradiation (GHI) map, which illustrates the spatial distribution of solar energy potential across the country. This information is essential for identifying optimal PV and agrivoltaic system deployment locations. The study leverages data from the GM-PV system located in Mezőcsát, located in Borsod-Abaúj-Zemplén county in northeastern Hungary, and the Kaposvár solar photovoltaic park (more detail in Section 3.3.1. Project Description), situated in the southwestern part of the country (see Fig.8), alongside a conceptual apple plantation to analyse the economic potential of AVS. Figure 9 illustrates a theoretical agrivoltaic implementation map, showing selected solar park locations and their spatial relationship to agricultural zones. Apple cultivation in Hungary is highly sensitive to climatic variability, particularly concerning temperature extremes and precipitation patterns. The apple orchard is especially vulnerable to frost events, with critical damage thresholds occurring at 4 °C for buds, –2 °C for flowers, and –1 °C for fruits [189]. Furthermore, cool temperatures during the apple flowering period can reduce pollinator activity, while excessive humidity and rainfall may negatively affect fruit set and quality. Orchard farmers frequently employ protective structures such as crop protection nets and plastic coverings to mitigate these climatic risks. These adaptive measures suggest a high compatibility with AVS, which not only facilitates renewable energy generation but also offers microclimatic advantages such as frost protection and shading, potentially enhancing the resilience and productivity of apple orchards.

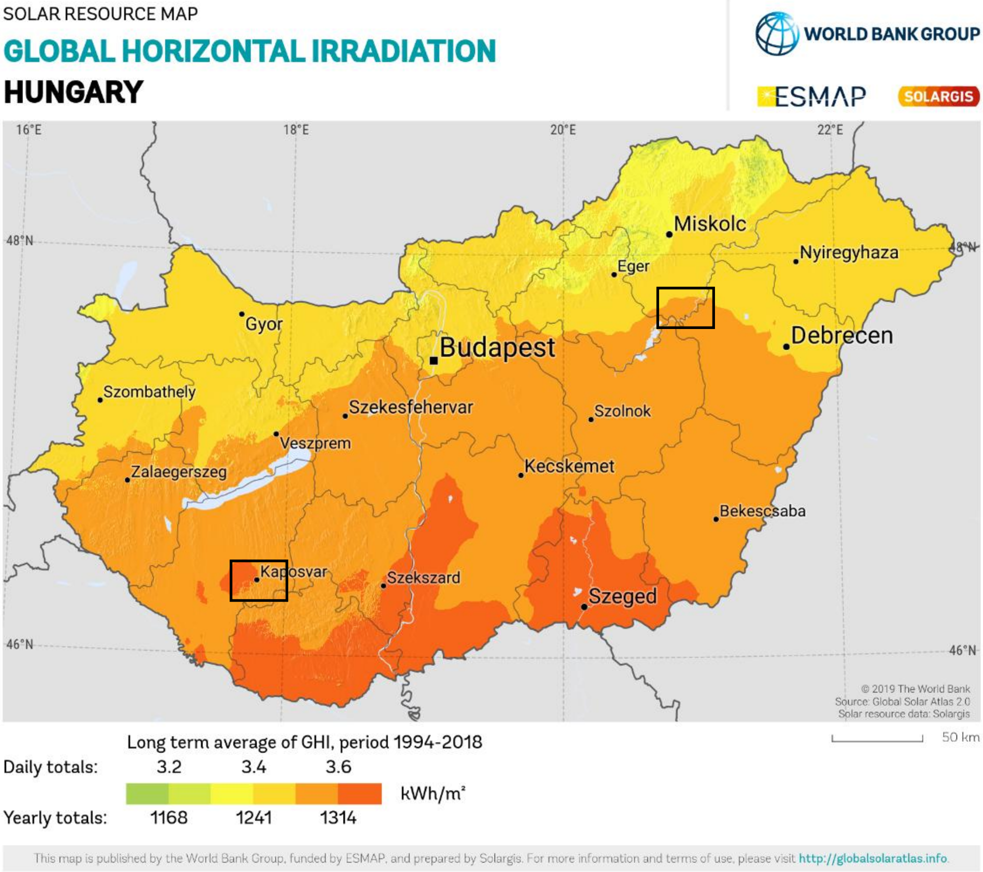

**Figure 8: GHI map of Hungary indicating solar energy potential across regions. Source:** [190]

**Figure 9: Theoretical agrivoltaic implementation map with solar park layout and total area allocation. Source:** [191]**. Image: © Airbus, CNES / Airbus, Maxar Technologies, 2025, Map data ©, 2025**

Table 4 presents a detailed overview of the AVS shed's dimensions, the integrated photovoltaic system's specifications, and the apple trees' design parameters, encompassing reference and estimated values. The validated dataset underpins high-fidelity simulations of the Mezőcsát AVS, a 42-hectare pilot project targeting 38,269 kWp total capacity (based on a peak capacity density of 911.16 kWp per hectare). The system design integrates photovoltaic arrays within apple orchard configurations, allocating 251.12 kWp for dual-use energy-agriculture operations. Phytotechnical designs incorporate financial forecasts, orchard layout parameters (tree spacing, canopy management), infrastructure specifications (panel mounting structures, shading optimization), and spatial allocation of PV capacity across the site.

**Table 4. Project overview**

| | | | |
|---|---|---|---|
| AVS shed area (ha) | 42* | Basic AVS shed capacity (kWp) | 251.12* |
| Length (m) | 1.64* | Basic AVS shed (width) | 26[1] |
| Width (m) | 1[1] | Basic AVS shed (length) | 106[1] |
| Weight (kg) of PV | 18.2[1] | Basic AVS shed area (ha) | 0.2756* |
| Area each panel (m$^2$) | 1.64* | Total Number of AVS Sheds | 239* |
| Apple tree design | | kWp/ha | 911.16* |
| Height of structures (m) | 5[1] | PV Capacity per 6 ha Plot (kWp/plots) | 5,467* |
| AVS width over the apple row (m) | 1.7[1] | Number of PV models | 866* |
| Space within rows (m) | 1[1] | The overall module surface area (m$^2$) | 866* |
| Row to row distance (m) | 3.6[1] | GCR | 31%* |
| Available space for PV system within rows | 2.6* | Plant capacity (kW) | 5,467* |

*Source:* [30]. *Note:* [1] [10,55,192–194], * *Own calculation.*

Figure 10 presents a fundamental design of a singular solar PV shed for an agrivoltaic infrastructure. The system features a vertical clearance of 5 meters and comprises conventional photovoltaic panels arranged within a modular framework. The unit spans a longitudinal dimension of 3.19 meters, supported by dual parallel arrays of 11 vertical supports each, ensuring structural stability and optimal light penetration. This empirical framework draws upon findings from [55], which investigates the interplay between spatial arrangement of arboreal elements (e.g., tree spacing) and irradiance capture efficiency, as well as its cascading impacts on photosynthetic efficiency and energy yield in hybrid agricultural-energy systems.

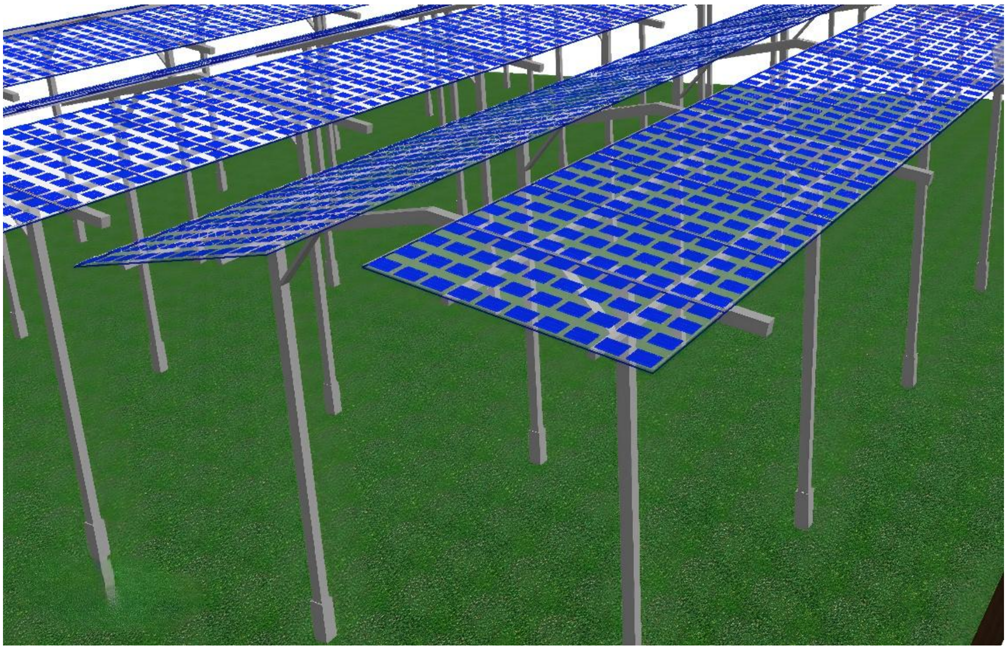

**Figure 10: The fundamental design of PV shed in an agrivoltaic apple orchard setting ©Fraunhofer ISE (2025)**

Figure 11 showcases a modular agrivoltaic configuration, where spatially distributed PV arrays are interspersed among apple trees. This design emphasizes the system's capacity to balance high-density solar energy harvesting with minimal disruption to orchard yields, validated through empirical studies on light partitioning and microclimate modulation.

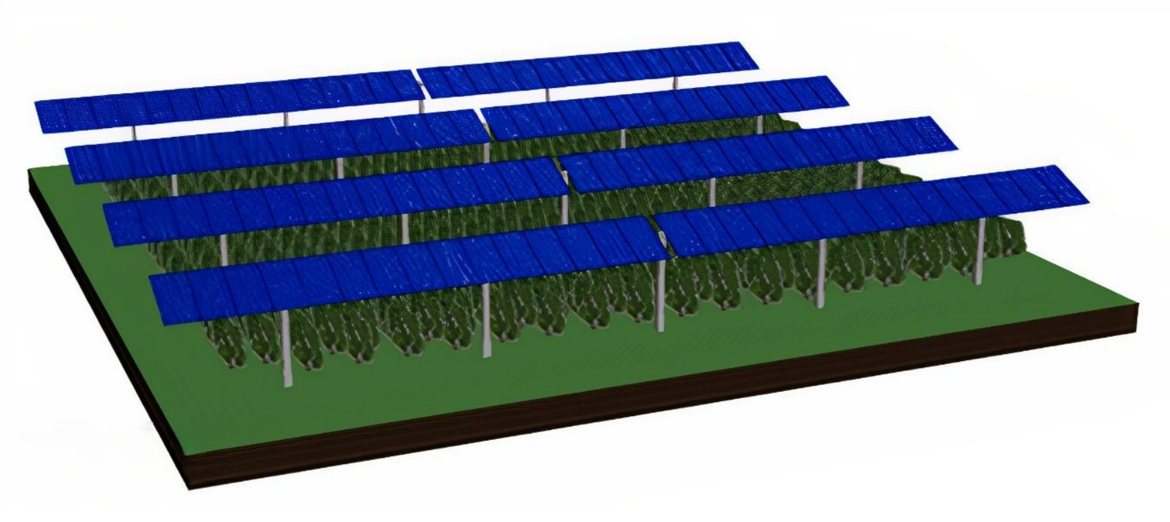

**Figure 11: Solar PV sheds on an agrivoltaic apple farm ©Fraunhofer ISE (2025)**

Table 5 details the 2023 GM-PV financial model, with CAPEX (€23.39M) covering hardware, labour, and balance-of-system components. The FIT rate (0.087€/kWh) reflects per-unit revenue generation and informs energy yield forecasts. The system demonstrates a 99% year-over-year operational efficiency improvement attributed to technological refinement. OPEX breakdown includes security infrastructure (insurance, surveillance) (€1.8/kW), maintenance

(€2.1/kW), and IoT-enabled monitoring (€0.8/kW), ensuring compliance with grid reliability standards and minimizing downtime.

**Table 5. Basic economic data for the proposed PV system in Hungary (2023)**

| Indicators | Value |
|---|---|
| Initial investment (€) | 23,386,364 |
| FIT rate (€/kWh) | 0.087 |
| Annual sunshine hours | 2,000 |
| Operational efficiency (Annualized) (%) | 99 |
| Maintenance OPEX (€/kW/year) | 2.1 |
| Risk mitigation costs (€/kW/year) | 1.8[1] |
| IoT-Enabled System Monitoring Costs (€/kW/year) | 0.8[1] |

*Source:*[30] *and* [1][55]

Table 6 presents fundamental data regarding apple cultivation in Hungary for 2023. The model is predicated on a super-intensive orchard system, which is characterized by substantial agricultural inputs, elevated yields and high-quality products [195]. A capital outlay of €42 million is anticipated to implement a vertically integrated, high-input orchard model in Hungary, reflecting advanced phytotechnical and resource management protocols. This investment encompasses establishing 2,800 Knipp apple trees per hectare, a supporting infrastructure comprising concrete columns and wires to accommodate a drip irrigation system and hail netting. The model accounts for two additional years after the apple orchard's initial planting and growth year. According to expert assessments and data from multiple years of Hungarian agricultural studies, the orchard is anticipated to reach maturity by the fourth year, yielding an average of 57.5 tons per hectare from years four to fifteen.

Since yield significantly impacts the economic viability of apple production, implementing various hazard mitigation frameworks is crucial in practice [106]. The drip irrigation system and hail net are key components in the super-intensive apple orchard, effectively minimizing environmental exposure risks. While frost protection is another method for mitigating weather risks, it is not included in this model, which may lead to increased CAPEX. In the context of this model analysis, the proposed super-intensive orchard assumes high standards in plant protection and cultivation technology, thereby enhancing yield stability and reliability.

**Table 6. Fundamental financial details of super-intensive apple farming in Hungary (2023)**

| Indicators | Value |
|---|---|
| Initial capital investment (€/ha) | 41,885 |
| Net cash flow (Year 2) (€ /ha) | –1,047 |
| Net cash flow (Year 3) (€ /ha) | –262 |
| Mature phase average yield (post-year 4) (tons/ha/year) | 57.5 |
| Consumption purposes ratio (%) | 90 |
| Premium grade apple yield (tons/ha/year) | 51.75 |
| Industrial-grade apple yield (tons/ha/year) | 5.75 |
| Market price (premium grade) (€ /t) | 288 |
| Market price (industrial grade) (€ /t) | 105 |
| Agricultural subsidy (SAPS) (€ /ha/year) | 183 |
| Annual production cost (€ /ha/year) | 11,518 |
| OPEX (excl. depreciation) (€ /ha/year) | 7,853 |

*Source: own data collection based on expert opinion and* [107,195].

Our comprehensive analysis is focused on 2024. Initial fruiting typically manifests after a 24-month growth cycle, a determinative interval for carbohydrate partitioning, rootstock establishment, and floral induction in temperate orchards. It allows us to evaluate the period from planting to the onset of commercial fruit production. By temporally aligning the PV infrastructure's maiden operational year with the apple orchard's growth cycle, this framework methodically assesses the co-evolution of energy and agricultural productivity during formative stages, addressing synergies and trade-offs in land-use efficiency.

Given the absence of operational AVS in the target area, this study's findings derive from conceptual modelling. The scenarios generated here establish a preliminary evidence base for policymakers evaluating dual-use solar-agriculture systems, particularly GM-PV integration, to balance energy transitions with food security objectives.

### *3.2.2. Financial indicators for the adaptation of agrivoltaics systems in Hungary*

The techno-economic assessment models investment viability through deterministic baseline forecasts and stochastic scenario testing, capturing systemic sensitivities to input variability. In addition to traditional profitability indices (NPV, IRR, DPP), the analysis contextualizes economic returns within sector-specific risks, such as policy shifts and commodity price fluctuations, to inform adaptive decision-making frameworks [196,197]. The analysis also includes evaluations of CAPEX, OPEX, and unit costs. Computational modelling frameworks are deployed to analyse input-output dynamics, focusing on parametric sensitivity and systemic interdependencies.

The fact that the yields from PV lead to stabilization is plausible due to the significantly higher and more stable income level from PV due to the fixed feed-in tariff price, tender mechanism or PPA terms. In addition, the calculation is highly dependent on the selected discount factor. The WACC method was used in the present model. The calculation of interest rates within a realistic range for the apple orchard and energy sector is based on an estimate of the effects of AVS on agricultural practices derived from literature, expert interviews, and exchanges between experts. The analysis neglected the shadow effects on apple orchards due to AVS and hail nets. As a basic estimate of how the yield quality and quantity change, studies on conventional apple systems were used to assume the implementation of AVS in Hungary.

For risk quantification, probabilistic modelling techniques such as Monte Carlo simulations are employed to reconcile deterministic system behaviours with stochastic variability [198], aligning with methodological frameworks applied in prior studies, such as those of Elkadeem et al. [199], to identify critical determinants of financial performance. Parametric uncertainties (e.g., market prices and yield fluctuations) are represented via probability distributions, enabling iterative sampling to explore probabilistic outcomes across divergent scenarios. This approach facilitates holistic risk characterization by embedding stochastic variables into predictive models, as delineated by the parameter ranges and central tendency assumptions in Table 7.

The @RISK 7.6 software (Palisade Corporation) operationalizes these simulations, parameterized with empirically derived inputs and probability distributions reflective of the observed variability. Each simulation executed 5,000 stochastic iterations to ensure statistical robustness. Sensitivity analyses were performed using standardized regression coefficients to rank input variables by their proportional impact on outputs, complemented by Spearman's rank correlation coefficients to assess monotonic relationships. Positive regression coefficients indicate direct proportionality between input escalations and output gains, consistent with the methodology described by Bai et al. [200].

**Table 7. Investment analysis indicators and market factor distributions**

| Parameters | Range/Value | Contextual Notes | Distribution type |
|---|---|---|---|
| *Investment analysis* | | | |
| PV system CAPEX (million EUR) | 14–23.4 | Subsidized scenario (40% grant): €14 million (Hungarian tender); Unsubsidized: €23.4 million. | Discrete uniform distribution |
| FIT rate (€/kWh) | 0–0.08–0.087–0.16 | Electricity prices may decrease to zero or negative due to changing demand or supply conditions, surplus renewable energy, government policies and grid constraints. Electricity storage remains economically unviable at scale. | Discrete uniform distribution |
| Annual sunshine hours | 1700–2000–2300 | Based on geographical conditions in Hungary [201,202] | Triangle distribution |
| Discount rate (%) | 0–6.8–8 | Hungary's discount rate range (0% to 6.8% to 8%) is influenced by the current 6.8% yield on 20-year government debt. The upper limit of 8% is considered a ceiling. | Triangle distribution |
| Inflation rate (%) | 3–4–6 | Current core inflation in Hungary (6%) is expected to decrease significantly to 4% in the short term and around 3 % in the long term [203]. | Triangle distribution |
| Mature apple orchard yield (tons per hectare) | 45–57.5–65 | Median yield: 57.5 tons/ha, based on empirical data and stakeholder consultations [107,195] | Truncated normal distribution |
| Consumption purpose ratio of apples (%) | 80–90–95 | High-quality fruit (Class I/II) dominates production, reflecting market demand and agronomic practices. Based on expert assessments and studies [107,195] | Truncated normal distribution |

*Source:* [30]

The project's timeline is expected to span from 2023 to 2053. After the initial investment year of 2023, the PV infrastructure is projected to remain operational for a 30-year. In contrast, the viable lifespan of an apple orchard is estimated at 15 years, necessitating two complete full replanting cycles to align with the PV system's operational horizon. The economic model generates critical financial metrics, including NPV, profitability index (PI), IRR, LCOE and apple production.

NPV and IRR constitute foundational pillars of DCF analysis, a methodology for evaluating long-term investments. The NPV is derived using the formula:

$$NPV = -I_0 + \Sigma_{j=1}^{t} DCF_n \qquad (1)$$

The calculation of the DCF is executed as follows:

$$DCF_n = \frac{C_n}{D_n} \qquad (2)$$

The annual CF is computed with this formula:

$$C_n = R_n - O_n - T_n \qquad (3)$$

where the nomenclature for Equations (1), (2) and (3) is defined in Table 8.

**Table 8. Nomenclature corresponding to Equations (1), (2), and (3)**

| Symbol | Description | Unit |
|---|---|---|
| $I_0$ | Initial capital investment (CAPEX) | € (euros) |
| NPV | Net Present Value | € (euros) |
| $DCF_n$ | Discounted Cash Flow in year *n* | € (euros) |
| t | Total duration of the analysis period | years |
| $C_n$ | Cash Flow in year *n* | €/year |
| $D_n$ | Discount factor in year *n* | – (unitless) |
| $R_n$ | Total annual revenue from PV energy and apple production in year *n* | €/year |
| $O_n$ | Annual operational expenditures (OPEX) in year *n* | €/year |
| $T_n$ | Annual corporate tax in year *n* | €/year |

The total yearly revenue from apple production ($R_a$) is calculated as follows:

$$R_a = (AY_c \times P_c + AY_i \times P_i + S) \times A \qquad (4)$$

The total yearly revenue from electricity ($R_e$) is determined by:

$$R_e = (P \times S \times E) \times F \qquad (5)$$

To model temporal financial flows, annual revenue and operational expenditures (OPEX) are inflation-adjusted using a 4% mean annual rate, ensuring all monetary values remain nominal.

The nominal adjustment for a given year *t* follows the formula:

$$R_i = R_{n-1} \times (1 + InfR) \qquad (6)$$

$$O_n = O_{n-1} \times (1 + InfR) \qquad (7)$$

Where nomenclature corresponding to Equations (4), (5), (6), and (7) is provided in Table 9.

**Table 9. Nomenclature for the variables and parameters used in Equations (4), (5), (6), and (7)**

| Symbol | Description | Unit |
|---|---|---|
| $R_a$ | Total yearly revenue from apple production | € (euros) |
| $AY_c$ | Annual per-hectare yield of apples for fresh consumption (Class I/II) | ton/ha |
| $P_c$ | Market price per ton of premium-grade (fresh consumption) apples | €/ton |
| $AY_i$ | Annual per-hectare yield of processing-grade (juice) apples | ton/ha |
| $P_i$ | Market price per ton of industrial-grade (processing) apples | €/ton |
| $S$ | Annual subsidy per hectare | €/ha/year |
| $A$ | Total cultivated orchard area under analysis | ha |
| $R_e$ | Total yearly revenue from electricity | € (euros) |
| $P$ | Installed photovoltaic (PV) capacity | kW or MW |
| $S$ | Annual sunshine hours | hours/year |
| $E$ | Annualized efficiency coefficient of PV system | dimensionless (0–1) |
| $F$ | Feed-in Tariff (FIT) rate | €/kWh |
| $R_i$ | Nominal annual revenue in year t | € (euros) |
| $R_{n-1}$ | Nominal annual revenue in previous year | € (euros) |
| $O_n$ | Nominal operational expenditure (OPEX) in year t | € (euros) |
| $O_{n-1}$ | Nominal operational expenditure in previous year | € (euros) |
| $InfR$ | Inflation rate | decimal (e.g., 0.04) |

The computation for the annual corporate tax base encompasses the combined annual revenue and OPEX, and the depreciation of the PV system and the apple orchard every year. The corporate tax rate in Hungary is currently fixed at 9%.

The discount factor is calculated using this formula:

$$D_n = (1 + r)^n \qquad (8)$$

The assessment of the financial viability of agrivoltaic systems relies heavily on selecting a suitable interest rate for carrying out dynamic financial analyses. In this study, we use the WACC, represented as $w$ in the analysis, as our chosen method.

The computation of the WACC is done through a specific formula:

$$w = E \times F \times D \times (1 - t) \times S \qquad (9)$$

Given that debt and borrowings are not taken into account in the calculations, the discount rate (noted as *r*) is computed exclusively from the cost of equity utilizing the formula:

$$r = FR + \beta + RP \qquad (10)$$

where the symbols and parameters of Equations (8), (9) and (10) are defined in Table 10.

**Table 10. Nomenclature corresponding to Equations (8), (9), and (10)**

| Symbol | Description | Unit |
|---|---|---|
| $D_n$ | Discount factor in year n | Dimensionless |
| $r$ | Discount rate | Decimal (e.g., 0.05) |
| $n$ | Particular year within the analysis period | Year (integer) |
| $w$ | Weighted average cost of capital | Decimal |
| $E$ | Cost of equity (expected return demanded by shareholders) | Decimal |
| $F$ | Proportion of equity financing in total capital | Decimal |
| $D$ | Cost of debt capital (pre-tax interest rate) | Decimal |
| $t$ | Corporate tax rate (used to calculate tax shield on debt) | Decimal |
| $S$ | Proportion of debt financing in total capital | Decimal |
| $FR$ | Risk-Free rate, typically based on sovereign bond yields | Decimal |
| $\beta$ | Beta coefficient (systematic risk relative to market) | Dimensionless |
| $RP$ | Equity risk premium (expected excess return over the risk-free rate) | Decimal |

The nominal return on equity (ROE) is determined by combining the risk-free rate with the industry beta and equity risk premium product, yielding a calculated value of 6.83%. Consequently, the expected nominal ROE is computed as follows:

$$r = 3 + 0.88 \times 2.95 = 6.83\% \qquad (11)$$

This computation integrates three key parameters:

1. The risk-free rate (R) of 3%, established using data from the Statista database [204], serves as the baseline return for a theoretically riskless investment.
2. The industry beta coefficient (β) of 0.88, specific to the Green & Renewable Energy sector, is obtained from the research [205] and quantifies the sector's systematic risk relative to the broader market.
3. The equity risk premium of 2.95%, derived from the study [206], reflects the additional return investors demand for assuming equity-related risk.

Every year within the designated timeframe, NPV is calculated by adding up DCF, called the Cumulative Discounted Cash Flow (CDCF). The project's breakeven point is indicated when the CDCF transitions from negative to positive. The CDCF for the concluding year, 2053, represents the project's overall NPV.

The formula to calculate the PI is:

$$P = \frac{\sum_{n=1}^{t} DCF_n}{I_0} \qquad (12)$$

where the nomenclature corresponding to Equation (12) is presented in Table 11. Investment could include purchasing equipment, setting up infrastructure, or any other initial costs associated with starting the project.

**Table 11. Nomenclature Corresponding to Equation (12)**

| Symbol | Description | Unit |
|---|---|---|
| $P$ | Profitability index (PI), a measure of investment efficiency | Dimensionless |
| $t$ | Total number of years in the analysis period | Year (integer) |
| $I_0$ | Initial investment cost in year 0 | € (euros) |
| $\sum_{n=1}^{t} DCF_n$ | The cumulative sum of discounted cash flows over the project lifetime | € (euros) |

IRR, the discount rate causing the NPV to become zero, is derived using MS Excel's IRR function, taking the series of yearly cash flows as input.

This analysis provides an in-depth insight into the per-unit electricity and apple production costs, excluding the costs associated with the PV systems.

The formula to compute the unit cost of electricity for a particular year ($Ue_i$) is:

$$Ue_i = \frac{Annual\ total\ cost \times Share\ of\ electrcity\ in\ total\ revenue}{Annual\ electrcity\ yield} \qquad (13)$$

The total annual cost is the aggregation of the OPEX and the yearly depreciation of the PV system and the apple cultivation.

Similarly, the unit cost of apple production for a specific year ($Ua_i$) is calculated using the following formula:

$$Ua_i = \frac{Annual\ total\ cost \times Share\ of\ apple\ production\ in\ total\ revenue}{Annual\ apple\ yield} \qquad (14)$$

The Levelized Cost of Electricity (LCOE) for agrivoltaic systems can be calculated using the following formula:

$$LCOE = \frac{\sum \frac{(I_0 + M_t + F_t)}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}} \qquad (15)$$

where the parameters used in Equation (15) are defined in Table 12.

**Table 12. Nomenclature from Equation (15)**

| **Symbol** | **Description** | **Unit** |
|---|---|---|
| $LCOE$ | Levelized Cost of Electricity, representing the average cost per unit of electricity generated | €/kWh |
| $I_0$ | Initial investment cost at year 0 | € (euros) |
| $M_t$ | Maintenance and operational costs at the end of the year t | € (euros) |
| $F_t$ | Fuel expenditures (if applicable) at year t | € (euros) |
| $r$ | Discount rate of the project | Decimal (%) |
| $t$ | Time period (year of analysis) | Year (integer) |
| $E_t$ | Electricity generated in year t | kWh |

In this formula, the numerator represents the total present value of costs (investment, maintenance, financing) over the lifetime of the agrivoltaic system, and the denominator represents the total present value of electrical energy generation over the same period. The result gives the levelized cost of electricity, which is a critical metric for assessing the economic viability of agrivoltaic projects.

### 3.3. Assessment of the cost-benefit aspects of integrating agrivoltaic systems at the Kaposvár solar photovoltaic park

Building upon the foundations of existing academic literature, this study utilises a dual-approach methodology, incorporating qualitative and quantitative analyses, to investigate the sensitivity analysis and comparison between GM-PV, ConAPS and AVS in investment decision-making. The research logic and conceptual framework of this paper are constructed accordingly.

The qualitative analysis segment explores factors influencing investment decisions regarding implementing GM-PV, ConAPS or AVS. Concurrently, the quantitative analysis segment is devoted to the aggregation and computation of data to determine the CAPEX and OPEX associated with these three systems. The fusion of qualitative and quantitative analysis offers an analytical tool for investors, facilitating informed decision-making.

### *3.3.1. Project Description*

A 2-hectare plot of land adjacent to the Kaposvár Solar Photovoltaic Park was selected as the baseline site for the theoretical implementation of the agrivoltaic system. The geographic location of the selected area is illustrated in Figure 12. The research involves extensive data collection from Kaposvár Solar Photovoltaic Park, including energy production and data from conventional apple yield for the financial performance of agrivoltaic systems. A detailed investment analysis evaluates payback periods, NPV, IRR, and sensitivity analysis under varying conditions. This study is focused on the conceptual assessment of an agrivoltaic system in the context of Hungarian apple farming. It is important to note that the analysis conducted herein relies on predefined assumptions and hypothetical scenarios, as the agrivoltaic system under investigation has not been implemented in an actual agricultural setting in Hungary at the time of this study. The assumptions encompass various aspects, including solar panel efficiency, crop productivity, climatic conditions, and economic parameters. While these assumptions are based on available data and literature, the results should be interpreted within these inherent limitations. The study serves as a valuable theoretical exploration, offering insights into the potential benefits and challenges associated with adopting agrivoltaic systems in Hungary. Future research endeavours may aim to validate these findings through empirical field trials and real-world implementations.

**Figure 12: Selected a 2-hectare area near the Kaposvár Solar Photovoltaic Park for theoretical agrivoltaic system implementation (identified via Google Maps). Source:** [207] **Image: © Airbus,CNES / Airbus,Maxar Technologies, 2025,Cartographic data © , 2025**

### *3.3.2. Data sources*

The study employs a rigorous economic modelling approach, combining agrivoltaic system performance data and investment analysis. The methodology employed for this study involved the application of benefit-cost analyses to assess the implementation of an agrivoltaic system in apple farming. The results of the benefit-cost analyses were expressed by comparing three systems: agrivoltaic systems, GM-PV systems, and ConAPS for the investment options. Economic analysis calculations considered the present value of benefits and costs over the project's lifespan, accounting for discount rates, inflation, and cash flows. This approach allowed for a rigorous assessment of the economic viability and long-term profitability of the agrivoltaic system in apple farming. Furthermore, sensitivity analyses were conducted to evaluate the robustness of the profitability estimates under various scenarios, ensuring the reliability of the economic evaluations. This study utilises AV system data, as Schindele et al. referenced [24]. The baseline scenario includes a capacity of 519.18 kWp/ha for AVS and 689.66 kWp/ha for GM-PV. These figures correspond to a 2-hectare area utilization, with the core parameters of the project outlined in Table 13 and Table 14. The synthesis of expert input and literature findings forms the foundation for the robust data and input parameters employed in this analysis. Table 13 presents the key input parameters and results pertaining to the assessment of AVS alongside PV systems in a given context.

**Table 13. Parameters for the baseline scenario**

| Parameter | PV | AVS | Units |
|---|---|---|---|
| Power capacity | 689.5 | 519 | kWp/ha |
| Land area | 2 | 2 | ha |
| CAPEX | 1031 | 1344 | th €/MWp |
| Sunshine hours | 1075 | 1075 | h/yr |

*Source:* [184]

**Table 14. The benchmark for comparative analysis of AVS and GM-PV Systems**

| Parameter | PV system | AVS | Units |
|---|---|---|---|
| Land area required for 1 MWp PV Capacity: | 1.45 | 1.93 | ha |
| Capital cost per MWp PV system installation: | 1031 | 1044 | th €/MWp |
| Capital cost per ha of PV system installation: | 516 | 672 | th €/ha |
| Capital cost per ha of apple plantation: | 5 | | th €/ha |
| Annual energy yield per ha of PV system | 741 | 558 | MWh/yr |
| Average electricity price in Hungary: | 9.5 | | €c/kWh |
| Average revenue from per ha apple orchard operations: | 2 | | th €/ha |

*Source:* [184]

### *3.3.3. Parameter sensitivity analysis*

The sensitivity analysis method provides a means to identify and quantify the impact of critical factors on the economic feasibility of investment projects amidst an array of uncertain elements. This approach is extensively implemented in investment decision research and analysis of agricultural revenue [24,196]. In the context of PV power generation projects and agricultural earnings, various studies have employed sensitivity analysis to determine that an augmentation in power generation capacity, loan ratios and agricultural profit can enhance the economic viability of PV projects within the agricultural sector. Conversely, rises in construction costs, OPEX, and loan interest rates impart a negative impact [208]. Moreover, scholars have noted the detrimental effect of photovoltaic module degradation rates and the beneficial influence of system efficiency [209], annual operational hours, electricity pricing, and power generation subsidies [210] on the economic performance of PV projects. We employed sensitivity analysis to evaluate the economic feasibility of choosing between an AV system, a traditional PV system, an AV system, and traditional apple production. This analysis aimed to determine whether the initial investment costs would yield a return under a 25-year operational horizon aligned with Hungary's projected lifespan of AV systems. This analysis demonstrates that AV configurations entail the highest initial capital expenditures for PV infrastructure and apple cultivation. These substantial upfront capital requirements present challenges in offsetting excess expenditures. However, sensitivity modelling indicates that surplus costs can be recuperated if two conditions are met: (1) agrivoltaic and GM-PV systems achieve an annual electricity output of 500 kWp per hectare, and (2) rising establishment costs for apple orchards (as hypothesized in this study) amplify comparative economic returns. The evaluation incorporated a systematic sensitivity analysis to quantify the effects of escalating operational costs and revenue streams. This approach enabled the identification of critical uncertainties influencing the financial feasibility of AVS investments, emphasizing variables such as energy yield variability, agricultural revenue fluctuations, and capital cost dynamics. We can propose specific recommendations for effectively leveraging their influence degree.

### *3.3.4. Scenario analysis*

The validated AVS and PV systems models were employed for scenario analyses to address hypothetical inquiries. These scenarios included large-scale GM-PV systems, considering the potential for AV systems, and evaluated ConAPS without PV systems. Therefore, these models and the resultant scenario analyses serve as effective tools for exploring the vast potential of integrating renewable energy technologies into agricultural practices. This study aims to identify optimal strategies for deploying such technologies to maximise energy production and enhance agricultural productivity.

Ultimately, it is paramount to sustainably enhance the yield of diverse horticultural crops and the quality of their produce. This point is particularly critical given the increasing global demand for high-quality food and the escalating pressures on natural resources. Moreover, the sustainable enhancement of crop yield and produce quality is a salient aspect of this discussion. As we navigate the twin challenges of increasing global food demand and diminishing natural resources, the role of sustainable agricultural practices, underpinned by renewable energy technologies, becomes ever more significant.

The analyses mentioned above were conducted using secondary data sources. These sources provide an efficient and cost-effective method for collecting large amounts of data, particularly when evaluating large-scale systems or long-term trends. As such, the value of using secondary data sources in executing these critical analyses is underscored. This study offers a cost-effective and efficient approach to managing large datasets, which is especially beneficial when examining large-scale systems or long-term trends. Furthermore, this study facilitates a broader perspective on the potential impacts and benefits of integrating renewable energy in agriculture.

### 3.4. Climatic background of the study areas

The Carpathian Basin, including the territory of Hungary, is undergoing significant climatic transformation due to global climate change. Observed and projected trends indicate a rise in mean annual temperatures, particularly during the summer months, accompanied by shifting precipitation patterns [211]. These changes are likely to impact agriculture, including apple orchards. In northeastern Hungary, rising temperatures have increased the risk of early budding in apple trees and drastically elevated summer heat accumulation, potentially leading to higher yield losses due to heat stress [212]. Additionally, the intensification of summer heat waves and reduced summer rainfall increase the risk of heat stress and drought, potentially lowering fruit quality and yields.

Regional analyses and meteorological data indicate that Mezőcsát, located in Borsod-Abaúj-Zemplén County in northeastern Hungary, is situated within a zone of elevated hail occurrence, particularly during the convective storm season from late spring through summer. This area is known for higher frequencies of severe weather events, including hail-producing thunderstorms. In contrast, Kaposvár, located in Somogy County in southwestern Hungary, experiences a relatively lower frequency of hail events, though it is not exempt from occasional hailstorms, as shown by periodic thunderstorm warnings issued by the Hungarian Meteorological Service [213]. During the endodormancy phase, which typically spans late autumn to mid-winter, apple buds and lignified aerial tissues exhibit high frost resistance. Empirical studies have shown that these tissues can tolerate temperatures as low as −20 °C without sustaining damage. However, once the chilling requirement is fulfilled and endodormancy transitions into ecodormancy, the metabolic activity of buds is reactivated by temperatures above 0 °C. This reactivation progressively reduces frost resistance, rendering flower buds increasingly vulnerable to cold spells, particularly in late winter and early spring [214]. The relationship between phenophases and meteorological variables, especially temperature, is well established in the literature, with the bloom period being the most closely studied.

The onset of blooming is primarily governed by the accumulation of sufficient chilling hours, usually between 800 and 1,200 hours below 7 °C, depending on the cultivar. Incomplete satisfaction of this chilling requirement, often the result of mild winters, can disrupt the typical blooming order of cultivars. Such disruptions reduce the effectiveness of cross-pollination and may impair fruit set. Furthermore, excessively high temperatures during bloom above 25–28 °C can also hinder fertilization [201,214]. Rapid pollen release under these conditions is accompanied by the desiccation of stigmatic surfaces, which reduces pollen adhesion.

Simultaneously, pollinator activity, especially among bees, declines at elevated temperatures, further lowering fertilization success. Key meteorological parameters influencing solar energy production include global horizontal irradiation, cloud cover, and precipitation patterns. Annual average global radiation in Hungary ranges between 1,200 and 1,500 kWh/m² (see Table 15. Comparative climatic parameters, with regional differences shaped by topography and atmospheric conditions.

To provide a localized climatic context, Table 15 compares the meteorological profiles of Mezőcsát (northeastern Hungary) and Kaposvár (southwestern Hungary). The comparison highlighted that key climatic parameters between Mezőcsát and Kaposvár reveal subtle but relevant differences that may influence photovoltaic energy yield and apple cultivation performance under agrivoltaic systems. Kaposvár demonstrates a marginal advantage in solar resource availability, with slightly higher global horizontal irradiation and marginally fewer months with high cloud cover. These factors contribute to a more favourable environment for PV energy production, potentially improving the energy yield and economic viability of agrivoltaic systems in this location.

Precipitation levels are nearly identical across both sites, suggesting a comparable water supply regime for apple cultivation. However, the slightly warmer average temperature in Mezőcsát could lead to earlier phenological development, such as bud break and flowering. This may increase susceptibility to late frost events, a known risk in Hungarian fruit production, especially when chill requirements are fulfilled prematurely.

Relative humidity, slightly higher in Mezőcsát, may exacerbate fungal disease pressure in orchard environments. In contrast, the lower humidity in Kaposvár could improve fruit quality and reduce plant stress under high-temperature conditions. In apple cultivation, environmental stressors such as intense solar radiation, elevated temperatures, and low relative humidity contribute significantly to developing physiological disorders, most notably sunburn [215,216].

**Table 15. Comparative climatic parameters**

| Climate Parameter | Mezőcsát | Kaposvár | Data Source |
|---|---|---|---|
| GHI(kWh/m²/year) | 1281.3 | 1323.7 | [217] |
| Cloud Cover (% or months) | 63% (7.5 months) | 64%(7.3 months) | [218,219] |
| Precipitation (mm/year) | 660.4 | 664.7 | [220,221] |
| Average Annual Temperature (°C) | 11.76 | 11.2 | [222,223] |
| Average Relative Humidity (%) | 75 | 71.36 | [223] |

Kaposvár, situated in southern Hungary, typically receives higher solar radiation, with an annual Global Horizontal Irradiation (GHI) of approximately 1323.7 kWh/m²/year, compared to 1281.3 kWh/m²/year in Mezőcsát. This GHI difference, although seemingly modest, translates into measurable disparities in energy yield over time. Kaposvár's southern latitude contributes to longer daylight hours, especially in summer, and higher solar elevation angles, which maximize solar panel exposure to sunlight.

Climatically, Kaposvár benefits from clearer skies and slightly fewer cloudy months (7.3 months vs. 7.5 in Mezőcsát), along with lower relative humidity (71.36% vs. 75%). These factors enhance the penetration and intensity of solar radiation. Though precipitation levels are nearly identical (664.7 mm/year in Kaposvár and 660.4 mm/year in Mezőcsát), the combined effect of lower humidity, higher irradiance, and more stable weather in Kaposvár creates optimal conditions for photovoltaic (PV) systems. Topographically, Kaposvár features flat terrain and better-developed solar infrastructure, supporting efficient and large-scale solar panel installation. In contrast, Mezőcsát, located in northeastern Hungary, faces greater atmospheric moisture, slightly cooler annual temperatures, and more rural, undulating terrain factors that marginally constrain its solar energy potential.

# 4. RESULTS AND DISCUSSION

This study's result and discussion section is divided into three key parts. The first part involves the SLR, which comprehensively analyses the existing literature. This review lays the groundwork for understanding the current knowledge landscape and helps identify further research areas. The second part of the results and discussion delves into the economic and investment analyses of two specific locations in Hungary: Mezőcsát, located in Borsod-Abaúj-Zemplén county, and the Kaposvár PV power plant. These detailed analyses incorporate various assumptions to predict the economic feasibility of implementing AV projects in these regions. Critical to these analyses is the calculation and interpretation of the NPV. The NPV measures the project's profitability, considering the investment costs and the anticipated future returns.

## 4.1. Descriptive statistical review of scientific literature through bibliometric analysis

The subsequent chapter presents the findings of the agrivoltaic bibliometric analysis. The results have been categorised into distinct sections to facilitate a more effective presentation. The process of identifying the individual pertinent application areas within the infrastructural, economic, environmental, technical, energy and agricultural sectors is delineated below. A list of the keywords used for the bibliometric search is provided in Appendix A. These keywords formed the basis for identifying and filtering relevant publications in the Scopus database.

Subsequently, instances of each application area are provided to offer a more comprehensive understanding. The bibliometric analysis then examines the literature's frequency, relevance, and temporal evolution. This analysis provides a quantitative evaluation of the global research trends and patterns in agrivoltaics, allowing for a better understanding of the current status of research and potential future directions. This methodical approach presents a holistic view of the existing literature in agrivoltaics, contributing to the broader literature review.

### *4.1.1. Developing trends in agrivoltaics research*

Figure 13 illustrates the lack of significant research publication activity related to agrivoltaics (AV) before 2011. Until 2011, this approach was primarily experimental, but during this year, the term "agrivoltaic" gained prominence in scientific literature. Globally, the concept is recognised by various names: in Germany, it is referred to as "agrophotovoltaics (APV)"; in France, Italy, and the United States, it is termed "agrovoltaics"; while in Asia, it is known as "photovoltaic agriculture" and "solar sharing" [84]. Today, "Agrivoltaic" is the internationally accepted terminology, with "AV" as the standardized acronym.

Over time, this innovative approach has provided energy for diverse agricultural applications such as crop drying, greenhouse cultivation, irrigation, and desalination. It facilitates the concurrent production of food and energy, offering substantial benefits to farmers.

Academic and industrial interest in agrivoltaics gained significant momentum post-2011 (see Figure 13) driven by its potential to reconcile energy and food production. Pioneering experimental installations were developed in the 2010s, with Japan, Germany, and France spearheading early pilot projects and foundational research [224]. As an interdisciplinary field, agrivoltaics encompasses a range of disciplines, addressing issues like solar infrastructure's long-term impacts on soil health, microclimate modification, and crop adaptability [225]. However, there is a scarcity of research focusing on agricultural parameters such as yield stability, crop-specific responses, and product quality under photovoltaic arrays. Since 2020, the scholarly focus has expanded to include socioeconomic and policy dimensions, analysing factors like cost-benefit ratios, community acceptance, and regulatory frameworks governing AVS deployment [24,163,226]. Despite the gradual worldwide installation of AV systems, limited scientific inquiry exists regarding their societal acceptance, economic feasibility, and farmer motivation.

Figure 13 captures the annual scholarly output in agrivoltaic research. Research activity in this domain began to emerge post-2011, experiencing rapid growth from 2021 onwards. The publication count from 2011 to 2020 increased slowly, reaching a peak in 2021 before declining in subsequent years. The increase in publications between 2020 and 2021 was 35.4%, while the decrease between 2021 and 2022 was 8.3%. This fluctuation may be attributed to the nascent and experimental nature of AVS, limited experience with certain crops like rapeseed, turnips, and legumes [43], and the concentration of studies in specific regions, coupled with a lower citation rate.

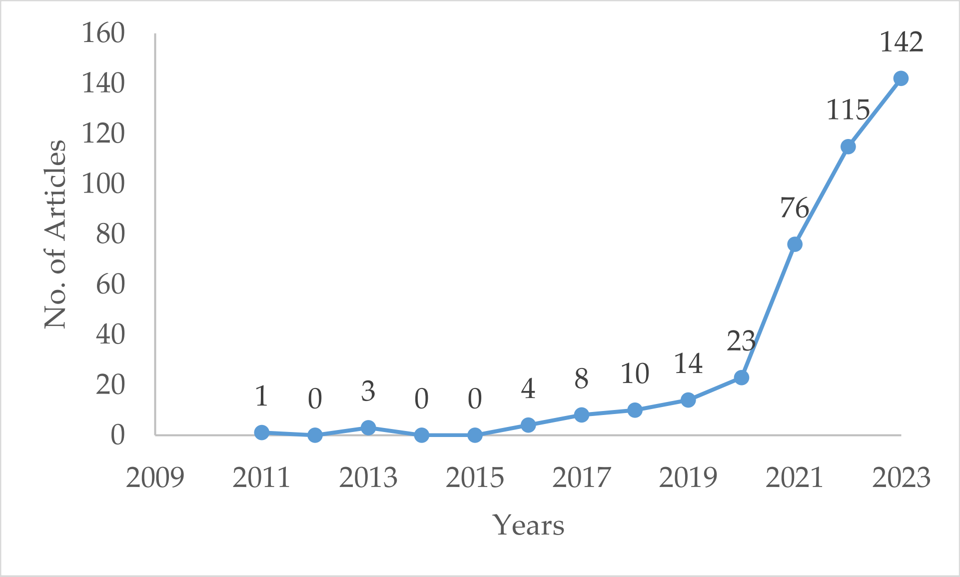

**Figure 13: Yearly output of scientific works. Source:** [40]

### *4.1.2. Leading ten journals by relevance*

Bibliometric analysis offers a fascinating perspective, particularly when pinpointing the journals scholars frequently use to share their research findings. Regarding the most significant journals according to publication count, Table 16 enumerates the top 10 journals based on the H-index encompassing an extensive array of research fields. It reveals that the three highest-ranking journals are responsible for more than 46.6% of publications. The analysed literature originated from seven publishers, with the highest concentration of articles (11 conference papers) published in AIP Conference Proceedings, a journal managed by the American Institute of Physics. Applied Energy (Elsevier) ranked second, contributing nine articles. These two journals represent prominent platforms for agrivoltaic research, reflecting the field's interdisciplinary nature and relevance beyond narrowly defined domains. Additional sources, as detailed in Table 16, yielded fewer than eight publications each, underscoring the importance of AV-focused scientific conferences for accessing cutting-edge advancements in this evolving field. Notably, most journals in Table 16 hold Q1 rankings, signalling strong academic interest from high-impact publishers. Exceptions include Sustainability and Energies, which remain reputable outlets for agrivoltaic studies despite lower quartile placements. This distribution highlights a broader shift toward interdisciplinary research bridging sustainable agriculture and renewable energy systems, with implications for enhancing land-use efficiency and decarbonizing agricultural practices. The prominence of top-tier journals further validates agrivoltaics as a dynamic and socially impactful area of study, poised to address global challenges in food security and clean energy transition.

**Table 16. Overview of key journals on agrivoltaic systems research**

| Journal/Proceedings | Publisher | Country | H index | SJR | TP |
|---|---|---|---|---|---|
| AIP Conference Proceedings | American Institute of Physics | United States | 75 | 0.19<br>(Not yet assigned quartile) | 11 |
| Applied Energy | Elsevier | United Kingdom | 235 | 3.06 (Q1) | 9 |
| Agronomy | John Wiley & Sons. | United States | 138 | 0.69 (Q1) | 8 |
| Energies | MDPI | Switzerland | 111 | 0.65 (Q1/Q2) | 7 |
| Sustainability (Switzerland) | MDPI | Switzerland | 109 | 0.66 (Q1/Q2) | 7 |
| IOP conference series: Earth and Environmental science | IOP Publishing Ltd. | United Kingdom | 34 | 0.2<br>(Not yet assigned quartile) | 4 |
| Renewable Energy | Elsevier | United Kingdom | 210 | 1.88 (Q1) | 4 |
| Scientific Reports | Nature Publishing Group | United Kingdom | 242 | 1.01 (Q1) | 4 |
| Journal of Cleaner Production | Elsevier | United Kingdom | 232 | 1.92 (Q1) | 3 |
| PLOS ONE | Public Library of Science | United States | 367 | 0.85 (Q1) | 3 |

*TP: the number of total publications. Source:* [40]

#### *4.1.3. Geographical and authorial distribution of publications*

Publications on agrivoltaics, focusing on sustainable farming and renewable energy, have been authored by scholars from 32 different countries. Table 17 ranks the top ten countries based on their productivity in this field, measured by the number of articles produced. A significant factor contributing to this is that Scopus predominantly indexes articles published in English, which is also the language of choice for 90% of the publications in our research database.

Table 17, which details each country's scientific yield, sheds light on their contributions to agrivoltaics. The USA, a global leader in renewable energy consumption [227], accounts for approximately 14.2% of the publications. US research initiatives are investigating the feasibility of integrating photovoltaic energy generation with various agricultural practices, such as crop cultivation and soil restoration, cattle and sheep farming, among others [145,228–230]. One US study highlights the significance of incorporating solar energy applications in agriculture into broader, multi-sectoral policy frameworks [231]. With its increasing demand for clean energy like solar energy, China holds the second place in the number of scientific papers produced. Given China's large population and corresponding food requirements, coupled with the ongoing evolution of its photovoltaic industry policies and services, photovoltaic projects have steadily been launched across its various regions [165,232,233]. In Europe, several countries have recently begun implementing agrivoltaic projects. France led the way by introducing a support scheme for agrivoltaics in September 2017, auctioning 15 MW of agrivoltaic capacity between 2017 and 2019. Germany is also contemplating the adoption of agrivoltaics. A German study compared the cost structures of agrivoltaic systems and standard PV systems, finding that the capital expenditure for agrivoltaics was 73% higher. In comparison, operational expenses were 13% lower than standard PV systems [24]. The decision to implement agrivoltaics is influenced by geographical factors, the country's laws, crop selection and agrivoltaic objectives.

**Table 17. Number of agrivoltaic articles published per country**

| Countries | Number of articles | Countries | Number of articles |
|---|---|---|---|
| USA | 15 | SPAIN | 4 |
| CHINA | 11 | AUSTRALIA | 3 |
| GERMANY | 9 | BELGIUM | 3 |
| FRANCE | 8 | FINLAND | 3 |
| SOUTH KOREA | 8 | PAKISTAN | 3 |
| JAPAN | 7 | NETHERLANDS | 2 |
| ITALY | 6 | SINGAPORE | 2 |
| CANADA | 5 | THAILAND | 2 |
| INDIA | 5 | TURKEY | 2 |
| MALAYSIA | 5 | UK | 2 |

*Source:* [40]

In this study, we have highlighted the most frequently cited papers in agrivoltaic systems. Table 18 summarizes the ten most frequently cited scholarly articles, presenting key metadata such as author initials, publication year, publishing journal, digital object identifier (DOI), total citations, and annual citations. Interestingly, most of these articles do not come from the journals mentioned in Table 16. Table 18 features the most impactful articles in terms of citations within the 11-year study period from 2011 to 2022. We performed a two-stage citation analysis, first highlighting the article with the most citations and then considering the average annual citations to evaluate the article's impact on the scientific community. The articles listed were selected through co-citation analysis, identifying the most frequently paired citations in the sample and offering insight into the pivotal works that have shaped the field in recent years.

Increasing citations annually indicate the growing interest in this research area. Older papers generally have the advantage in this analysis due to the additional time they have had to accumulate citations compared to more recent publications. The paper by Dupraz et al. (2020) [9] from France, UMR System and INRA stands out with 256 citations and an average of 21.33 citations per year, making it the most influential work in agrivoltaic systems.

In assessing the impact of these articles, the annual citation count was also considered to identify emerging trends in the field. Despite being relatively recent, the paper by Schindele et al. (2020) [24] titled "Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications" has made a significant contribution to discussions on the economic, social, and policy aspects of agrivoltaic systems, with an average citation of 25.67 per year.

**Table 18. Articles with the highest citation in agrivoltaic systems research**

| Paper | Titles | DOI | TC | TC per Year |
|---|---|---|---|---|
| [9], RENEW ENERGY | Combining solar photovoltaic panels and food crops for optimizing land use towards new agrivoltaic schemes | 10.1016/j.renene.2011.03.005 | 256 | 21.33 |
| [52], EUR J AGRON-a | Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels | 10.1016/j.eja.2012.08.003 | 143 | 14.30 |
| [148], AGRIC FOR METEROL | Microclimate under agrivoltaic systems is crop growth rate affected by the partial shade of solar panels | 10.1016/j.agrformet.2013.04.012 | 135 | 13.50 |
| [59], APPL ENERGY | Agrivoltaic systems to optimize land use for electric energy production | 10.1016/j.apenergy.2018.03.081 | 117 | 23.40 |
| [145], PLOS ONE | Remarkable agrivoltaic influence on soil moisture micrometeorology and water-use efficiency | 10.1371/journal.pone.0203256 | 86 | 17.20 |
| [147], EUR J AGRON | How does a shelter of solar panels influence water flows in a soil crop system | 10.1016/j.eja.2013.05.004 | 80 | 8.00 |
| [24], APPL ENERGY | Implementation of agrophotovoltaics techno-economic analysis of the price-performance ratio and its policy implications | 10.1016/j.apenergy.2020.114737 | 77 | 25.67 |
| [234], APPL ENERGY | Increasing the total productivity of land by combining mobile photovoltaic panels and food crops | 10.1016/j.apenergy.2017.09.113 | 75 | 12.50 |
| [235], SCI REP | Solar PV power potential is most significant over croplands | 10.1038/s41598-019-47803-3 | 75 | 18.75 |
| [47], SUSTAINABLE ENERGY TECHNOL ASSESS | Agrivoltaic potential on grape farms in India | 10.1016/j.seta.2017.08.004 | 71 | 11.83 |

*TC: Total Citations. Source:* [40]

The table above conveys information in both absolute and relative measures, using two metrics: TC and TC per year. In terms of total citations:

- Dupraz et al. (2011) [9] tops the list with 256 citations. This paper first introduced an agrivoltaic system, combining solar panels and food crops within the same field. The authors quantified potential synergies between these dual land uses by comparing photosynthesis's relatively low intrinsic efficiency (~3%) with the higher energy conversion rates of commercial monocrystalline PV systems (~15%). Their analysis projected a global land productivity enhancement of 35–73% across distinct agrivoltaic configurations. Economically, they predicted a land equivalent ratio (LER) of 1.7 for agrovoltaic systems, suggesting substantial productivity gains.
- Marrou et al. (2013) [52] and Marrou et al. (2013) [148] follow, with 143 and 135 citations, respectively. These investigations examined diverse crop systems, encompassing both short-growth-cycle species, such as lettuce [52] and cucumber, and long-growth-cycle crops, including durum wheat [148].

In terms of TC per Year:

- Schindele et al.(2020) [24] stands out as a critical techno-economic evaluation of agrivoltaic systems, comparing the additional investment costs of AV and GM-PV systems. Despite higher investment costs for AVS, the economic analysis within agrivoltaic systems is a significant source of interest.
- Amaducci et al. (2018) [101] explored the potential for doubling land productivity with agrivoltaic systems compared to the separate production of GM-PV modules and corn. Despite a 15-40% reduction in radiation available to crops under agrivoltaic systems, the benefits included decreased soil evaporation, reduced dry-year crop losses, and increased average yield.
- Dupraz et al. (2011) [9] continues to be influential in the field, with the TC per year index of around 21.33%.

#### *4.1.4. Keywords dynamics*

The assessment of keyword co-occurrence and their interconnections, using a method known as Keywords Plus, is presented (Figure 14). This method reveals the high prevalence of shared keywords in scholarly articles and conference papers, with over half of the authors' keywords being reflected in the Keywords Plus sets. Because of its comprehensive coverage of the authors' keywords, the Keywords Plus method was selected for our analysis.

Rstudio Biblioshiny was employed to analyze the co-occurrence of authors' keywords, providing an in-depth understanding of the primary keywords related to agrivoltaic systems in agricultural activities, both in greenhouses and open fields. In this context, a circle's size corresponds to a term's occurrence frequency. Hence, the more prevalent a word or phrase is in the collective list of author keywords, the larger its associated circle.

The distance between terms measures their correlation, with a smaller distance indicating a stronger linkage. The frequency of concurrent occurrence of the terms determines this correlation. Different clusters are represented using various colours.

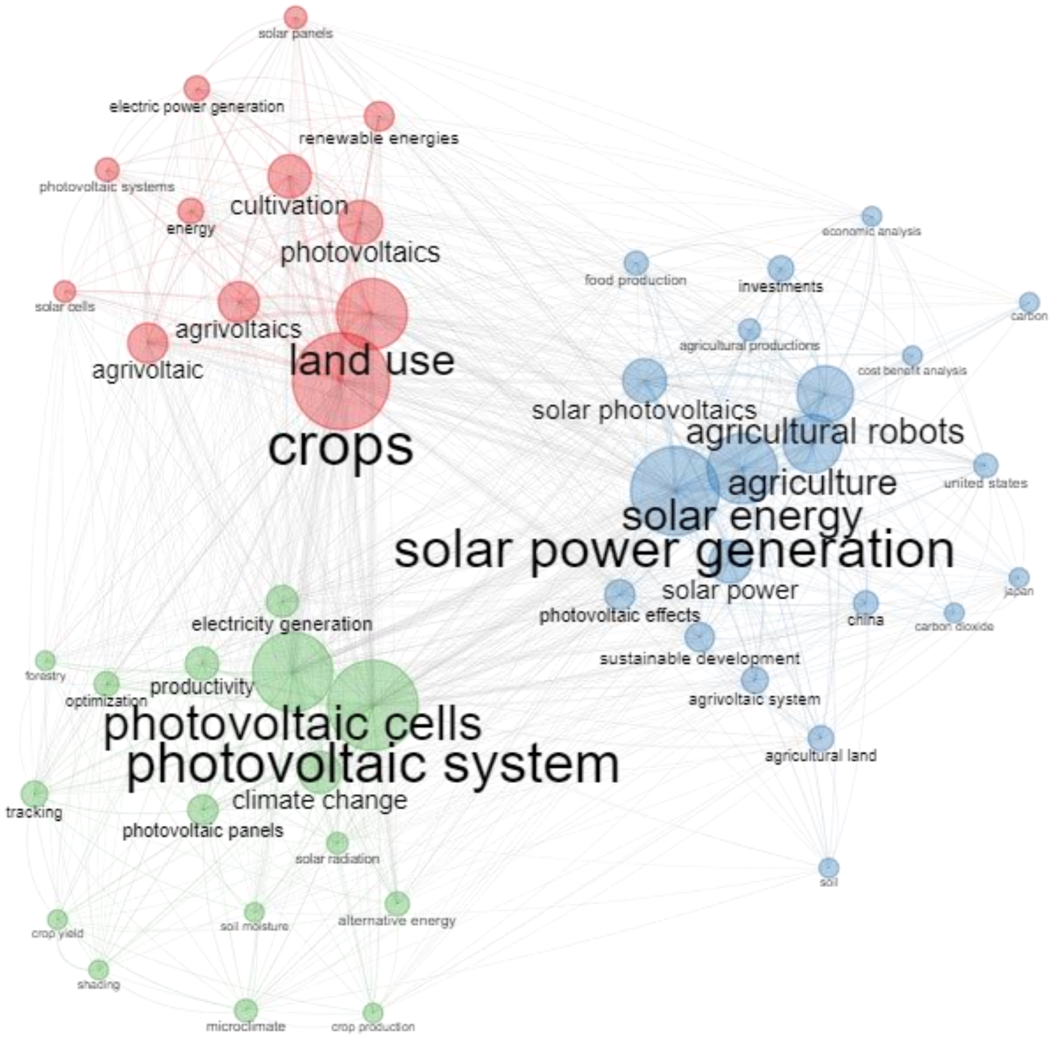

**Figure 14: Network of co-occurring keywords. Source:** [40]

The conceptual map presents a sophisticated network of terms within which three distinct thematic clusters can be identified. The first cluster (denoted in red) revolves around land use for solar power generation and crop cultivation, characteristic of a standard AVS. The second cluster (in light blue) is closely tied to the first, concentrating on examining various field types, such as those involving agricultural robots and carbon dioxide. Concurrently, topics like investment, cost-benefit studies, economic analysis and agricultural land usage are explored independently. The third cluster (highlighted in light green) pertains to investigating photovoltaic systems equipped with tracking mechanisms. These are positioned within a microclimate where the crops experience multiple periods of shading throughout the day, regardless of their location.

#### *4.1.5. Thematic analysis and evaluation*

In conducting thematic evaluations, the study examines the conceptual framework of academic publications in AVS. This analytical approach facilitates the mapping of prominent and evolving topics within the discipline while also revealing temporal shifts in research priorities [236]. The methodology argues that terms (keywords or phrases extracted from titles or abstracts) co-occurring within documents form a semantic network. This network is initially structured as a co-occurrence matrix, where off-diagonal values represent the frequency of term pairs co-appearing, serving as a measure of their associative strength [237]. Such matrices can be interpreted as adjacency matrices, enabling their visualization as undirected weighted networks.

Using the simple centre algorithm, community detection was applied to temporally segmented co-occurrence matrices to identify distinct research themes [238]. This technique isolates clusters of tightly interconnected terms, each representing a cohesive research theme or subtopic. Post-analysis, outcomes are visualised through strategic diagrams [239], which categorises themes into four typologies based on their quadrant placement[240], depending on the quadrant they fall into:

- Core Themes (upper-right quadrant): Exhibiting strong centrality and density, these well-established themes signify mature, influential areas driving advancement.
- Foundational Themes (lower-right quadrant): Characterized by high centrality but low density, these themes represent cross-disciplinary concepts that underpin diverse research directions.
- Niche or Peripheral Themes (lower-left quadrant): These underdeveloped themes occupy marginal positions with low centrality and density, often signalling emerging or declining interest.
- Specialized Themes (upper-left quadrant): Featuring high density but low centrality, these themes are internally robust yet isolated, reflecting focused, self-contained research with limited broader impact.Motor Themes (upper-right quadrant): These

themes demonstrate high centrality and density, indicating their development and significance in research.

Figure 15 categorizes five principal research themes into four distinct quadrants based on their centrality and density metrics. The upper-right quadrant represents motor themes, defined by their high centrality and density, which signify their pivotal influence and advanced development within the field. Notably, "crops" is positioned here, reflecting its prominence in recent literature and critical role in advancing agrivoltaic research. In contrast, the lower-right quadrant contains basic and transversal themes, which serve as foundational concepts bridging diverse subdomains. "Solar power generation" exemplifies this category, acting as a cross-cutting topic that intersects with various applications in the field.

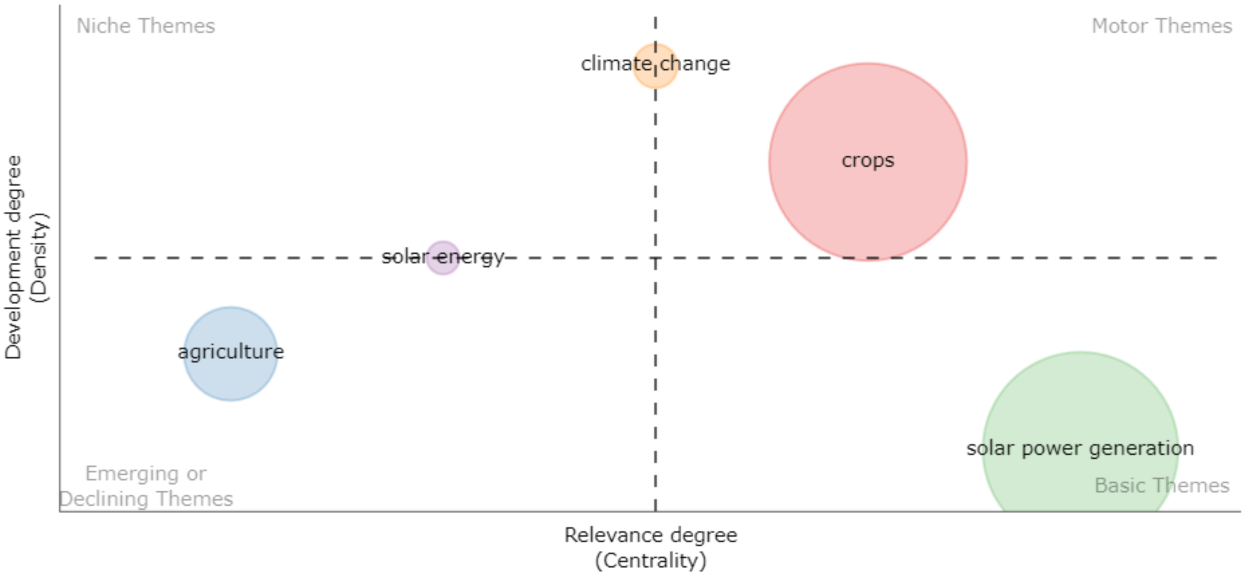

**Figure 15: Conceptual diagram of themes. Source:** [40]

The lower-left quadrant highlights emerging or declining themes, with "agriculture" identified as an evolving area of interest. This theme underscores innovative explorations into integrating agricultural practices with photovoltaic systems, enabling dual land use for crop production and renewable energy generation. Conversely, the upper-left quadrant features niche themes such as "solar energy" and "climate change," marked by high thematic density but limited centrality. Though frequently cited, these topics represent specialized foci within agrivoltaics, suggesting deep expertise in specific areas rather than broad interdisciplinary connections. This framework illustrates the dynamic interplay of themes shaping agrivoltaic research, from foundational concepts to cutting-edge innovations.

Figure 16 illustrates a co-word analysis designed to visualise the conceptual structure of a research domain by examining term co-occurrences across a corpus of academic publications. The analysis employs multiple correspondence analysis (MCA), a statistical method that reduces multidimensional data into a simplified two-dimensional representation. Natural language processing (NLP) techniques were applied to identify and extract relevant terms from article titles and abstracts. This approach transforms complex datasets with numerous variables into an interpretable spatial map, where the proximity of keywords corresponds to their conceptual similarity. Terms positioned nearer the graph's central axis reflect topics that have received substantial research attention over time.

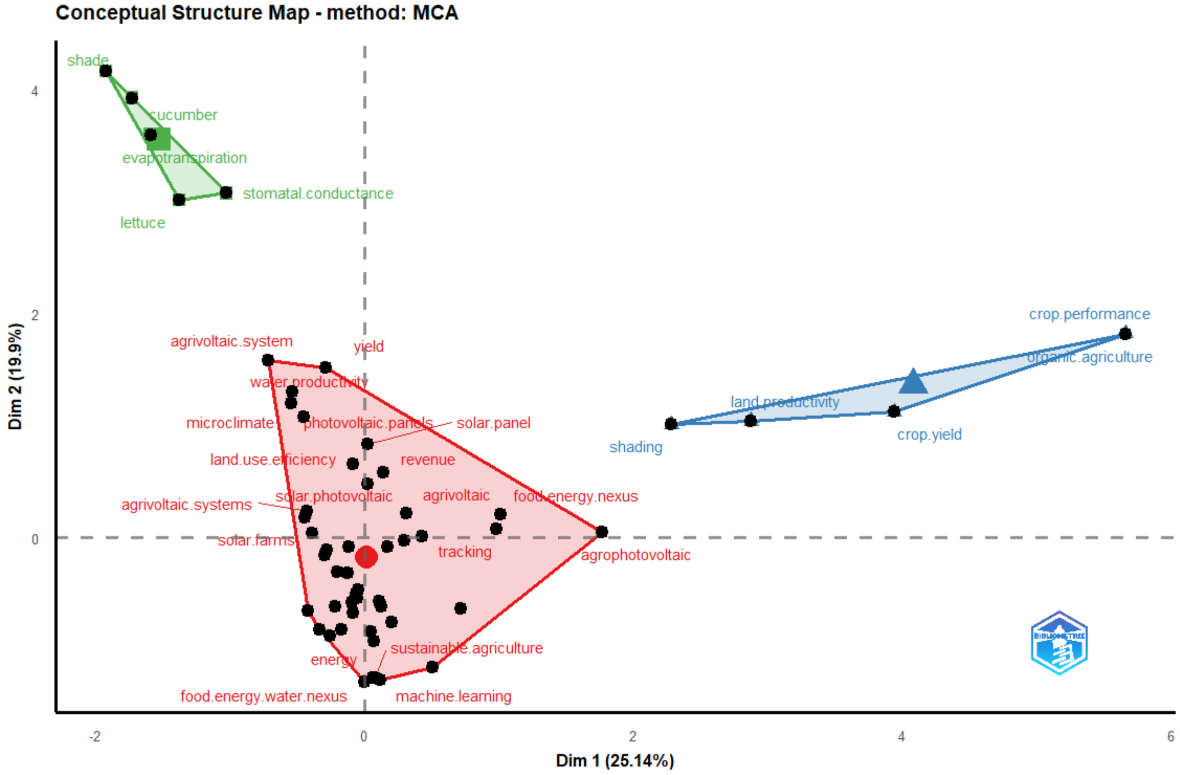

**Figure 16: Analysis of high-frequency keywords through multiple correspondences.**

**Source:** [40]

Cluster interpretation relies on the spatial arrangement of keywords across dimensions, with closer distances indicating stronger thematic relationships. The dominant cluster (red), comprising 42 keywords, revolves around themes such as "agrophotovoltaics," "agrivoltaic systems," "energy production," "sustainable agriculture," and "photovoltaic panel efficiency." A secondary cluster (blue) featuring five keywords highlights studies on "organic agriculture," "shading effects," "crop yield optimization," and "land productivity." A third cluster (green), also with five keywords, centres on research involving "cucumber cultivation," "lettuce growth," "shade adaptation," and "evapotranspiration dynamics." This visualization aids in identifying interdisciplinary connections and emerging trends within the field.

### *4.1.6. Discussion*

Previous studies have explored the efficiency of cultivating crops beneath solar panels. In recent years, the European Union has witnessed a proliferation of agrivoltaic projects, many of which remain experimental. However, while advances have been made in the field, with France emerging as a leader in successful agrivoltaic integration [24], there are still areas where further exploration is necessary.

This study highlights a rising trajectory in AVS research, with notable expansion since 2020 and peak productivity occurring in 2021. A systematic analysis of 121 interdisciplinary studies examined agrivoltaic systems, addressing economic viability, agricultural practices, system design, and crop-soil dynamics concerning food and water security. The review also underscored adaptation strategies and the role of AVS in mitigating climate impacts through accumulated empirical insights [52,148,241,242]. However, gaps persist in long-term, large-scale data to comprehensively assess system-wide effects.

Earlier literature reviews, such as [243], evaluated 98 studies but emphasized technical dimensions over economic and financial analyses. Our findings align with a prior similar review [244], which synthesized interdisciplinary outcomes, while advancing the discourse by integrating economic, environmental, infrastructural, technical, and agricultural dimensions. Distinctively, this study categorizes research into themes like AVS economic assessment, crop and livestock productivity under AVS, and photovoltaic greenhouses. Methodologically, the inclusion of Scopus-derived data and analytical tools (e.g., keyword co-occurrence networks, thematic mapping, and correspondence analysis in Figures Figure 14, Figure 15, and Figure 16) enabled a nuanced exploration of research trends, knowledge linkages, and thematic priorities. Another review highlighted energy management decisions, particularly solar PV system and agricultural practices, stressing light intensity optimization and stakeholder perspectives.

Agrivoltaic systems may alleviate competition for arable land [25], with studies reporting elevated soil moisture beneath PV panels, a 90% biomass increase in late-season crops, and 328% greater water efficiency in shaded areas. Research has prioritized shade-tolerant plant selection, PV shading effects on growth, and water conservation synergies [145]. Further investigation is warranted to optimize these interactions across diverse environmental contexts. While AVS offers promise in balancing land-use demands, its economic, environmental, and social trade-offs require rigorous quantification at varying scales. Weselek et al. [25,53] emphasize that crop responses to shading depend on climate, soil, precipitation, and system design, necessitating localized studies for context-specific insights. Current research remains nascent, with ongoing efforts to identify optimal crop-PV configurations for different climates.

This study contributes a bibliometric synthesis and systematic review of AVS productivity, structural designs, water efficiency, and electrical outputs, addressing critical gaps in AVS economics. Integrating multidisciplinary findings advances understanding of dual land-use systems and their potential to reconcile energy and agricultural needs amid climate challenges. This fills a gap in the research landscape regarding the economics of agrivoltaics.

## 4.2. Assessment of the techno-economic performance of agrivoltaic systems: A Proposed Case Study for Mezőcsát

The results of the investment analysis and analysis of electricity and apple production costs are presented in the following chapter. The calculations' parameters can be found in section 3.2 if not explained below. In the first step, the structure of the costs and the revenues is discussed to assess the profitability, viability and financing capability, as well as the effects on income volatility in the next step. This is done for the AVS, GM-PV and ConAPS cases. The focus will be on agricultural and electricity production costs.

### *4.2.1. Financial projection*

The financial projection results detailed in Table 19 comprehensively evaluate the economic viability and performance of the PV system under study.

**Table 19. Financial Forecast and Projections**

| Total revenues (in 1000) | €356,451 |
|---|---|
| Tax Rate | 9% |
| *NPV* | 82,737,901 |
| *DPP* | 5.30 |
| *PI* | 4.61 |
| *IRR* | 0.27 |
| LCOE | 0.78 €/kWh |

The tax rate, set at 9% [245], is a numeric representation of the portion of the PV system's annual revenue subjected to taxation . A positive NPV of ~€83M attests to the financial attractiveness of the project, signifying that it is expected to generate a surplus beyond the initial investment. With an IRR of 27%, the project is poised to yield an annual return exceeding this threshold, establishing its financial appeal. A PI of 4.61 emphasizes the financial soundness of the project, indicating that for every unit of capital invested, an additional €0.41 of net present value is projected to be generated. In the context of the Hungarian case study, the LCOE for agrivoltaic systems remains relatively higher compared to conventional PV systems. The LCOE remains consistently at the level of 0.78 €/kWh, regardless of subsidies, underscoring the inherent financial viability of self-investment in the PV system. This is primarily due to the additional infrastructure required to integrate agricultural activities with solar energy generation, as well as increased installation and maintenance costs. Moreover, the sensitivity of the LCOE to the discount rate reinforces the importance of considering the temporal dimension in project evaluation. Lastly, the LCOE's dependence on capital costs and solar resources underscores the necessity of prudent financial planning and maximising the utilisation of local solar resources to enhance the cost-effectiveness of PV systems. Despite the relatively higher LCOE, the projected revenue of €356,451,041 from the agrivoltaic system, including both photovoltaic electricity generation and apple cultivation, demonstrates the economic viability of dual land-use strategies within the Hungarian context. This revenue estimation is derived from theoretical financial modelling, incorporating key assumptions such as energy and agricultural yield calculations, market electricity prices, agricultural productivity, policy incentives, and the expected operational performance of both components over their lifespan. However, it is crucial to acknowledge that these financial projections are inherently subject to uncertainties, including market fluctuations, potential regulatory adjustments, and environmental conditions, all of which may influence actual financial outcomes. Consequently, while agrivoltaic systems may entail a higher cost structure compared to conventional PV systems, their broader socioeconomic and environmental contributions—particularly in terms of sustainable energy production and enhanced agricultural output—may substantiate their feasibility, especially under policy environments that promote integrated land use solutions.

#### *4.2.2. Investment analysis*

Lower investment costs, lack of electricity production, revenue from crop sales, and vulnerability to weather conditions primarily define traditional agriculture. Conversely, agrivoltaic systems introduce an additional revenue stream through electricity generation, and the solar panels' shading effect can offer some crop protection against weather elements. While GM-PV systems are designed to maximize electricity generation per area, agrivoltaics strive to integrate agriculture and solar energy production within the same space. The challenge lies in developing an optimal design that caters to both facets. AVS are approximately 80% more costly per installed capacity than GM-PV. Most investment costs are attributed to the PV modules, substructure, installation, and surface preparation. The cost components that see the most substantial proportional increases for AVS compared to standard GM-PV systems are specialized modules, a more complex and elevated substructure, and floor-protecting installation methods. CAPEX and OPEX for AVS exceed those of conventional GM-PV installations. However, partial cost mitigation in AVS is achievable by removing perimeter fencing infrastructure. In Hungary's apple cultivation sector, the choice between AVS and traditional PV systems depends on stakeholder priorities, resource limitations, and site-specific conditions, necessitating a context-sensitive strategy that balances horticultural productivity with energy generation efficiency.

A comparative financial assessment of AVS and GM-PV systems (each occupying 42 hectares) reveals significant disparities in CAPEX and OPEX. AVS incurs higher cumulative costs due to agricultural infrastructure investments, including orchard establishment and maintenance [24]. These cost ratios align with prior findings in analogous studies[24]. Revenue analysis within AVS demonstrates a pronounced dominance of photovoltaic income over agricultural returns[161]. While agricultural yields generate revenues in the order of thousands, PV energy production contributes millions [36]. In some instances, agricultural output accounts for only 4–6% of total AVS revenue [47], underscoring the economic reliance on energy generation.

Table 20 presents a detailed chronological financial evaluation of the proposed AVS project, highlighting critical operational milestones. In 2024, the system will initiate concurrent PV energy generation and orchard establishment. Apple commercialization commences in 2026 following a three-year maturation period for the orchard. The original orchard reaches its end-of-life phase in 2038, with replanting occurring in 2039 to sustain agricultural continuity. Key evaluation years include 2046 (mid-project assessment) and 2053 (project termination, concluding financial analysis). PV revenue accumulation begins in 2024, while agricultural income starts in 2026. Annual cash flow after tax is derived by deducting corporate tax from total revenues. DCF and cumulative DCF metrics, calculated using cumulative discount factors, provide insights into the project's long-term economic viability and temporal financial performance.

The AVS project's CAPEX across the 42-hectare site totals 25,146 thousand EUR, with the PV system accounting for 93% of this investment. During the initial operational year (2026), when the apple orchard reaches maturity and the PV system becomes fully operational, revenue distribution is heavily skewed toward energy generation, with the PV system contributing 90% of total income and apple production representing the remaining 10%. Over the analysis period, the PV system's revenue share gradually declines to 85%, primarily due to an annual efficiency loss of 1%. In contrast, OPEX is predominantly driven by apple production, constituting 60–64% of the total OPEX throughout the project lifecycle.

**Table 20. Financial planning of agrivoltaics implementation - expenditures and revenues**

| Expenditures and Revenues (unit of measurement: thousand EUR): | | Investment year | Operational years | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 2023 | 2024 | 2026 | 2038 | 2039 | 2046 | 2053 |
| 1. CAPEX for PV System | | 23,386 | | | | | | |
| 2. CAPEX for Apple Plantation | | 1,759 | | | | | | |
| 3. CAPEX after 15 Years for New Apple Plantation | | - | | | | 3,168 | | |
| 4. Annual OPEX | | | | | | | | |
| OPEX | OPEX for PV | - | 180 | 198 | 354 | 375 | 567 | 889 |
| | OPEX for Apple | - | 44 | 357 | 571 | 0 | 782 | 845 |
| Total Annual OPEX: | | - | 224 | 555 | 925 | 375 | 1348 | 1735 |
| 5. Annual Revenues | | | | | | | | |
| Output and revenues | PV Energy Generated | - | 6,592 | 6,988 | 9,917 | 10,211 | 12,524 | 15,361 |
| | Apple | - | 0 | 713 | 1,490 | 0 | 2374 | 2668 |
| | | | | | | | | |
| Total annual revenues | | - | 6,592 | 7,701 | 11,407 | 10,211 | 14,898 | 18,029 |
| Corporate Tax | | | 492 | 498 | 729 | 519 | 925 | 1,146 |
| Annual CF (after taxpaying) | | -25,146 | 5,876 | 5,935 | 8,263 | 6,149 | 10,526 | 12,481 |
| Discount factors (DF, cumulative) | | | 1.068 | 1.219 | 2.694 | 2.878 | 4.570 | 7.258 |
| Discounted cash flow (DCF) | | -25,146 | 5,500 | 4,868 | 3,067 | 2,136 | 2,243 | 1,720 |
| DCF (cumulative) | | -25,146 | -19,645 | -9,455 | 36,464 | 38,601 | 56,648 | 70,157 |

*Source:*[30]

Consequently, the project demonstrates financial viability, as indicated by the positive NPV of +70,157 thousand EUR and a profitability index (PI) of 3.79. These figures exceed typical values for apple farming [134,135] but remain lower than those for GM-PV projects. The project's IRR of 25% further highlights the economic feasibility and attractiveness of integrating AVS into apple cultivation in Hungary. Compared to a German case study on agrivoltaic apple farming [23], the NPV in Germany was significantly higher. This divergence may be explained by several factors, such as differences in agricultural practices, a higher FIT rate, and distinct legal frameworks in Germany, despite comparable climatic conditions. Evaluating each technology's specific characteristics and adaptability to the regional context is essential to ensure optimal implementation. This ratio illustrates the low sensitivity of AVS to agricultural revenue, implying a risk of diminished farming incentives within the system [246]. However, it also highlights the potential financial gains for farmers. Malu et al. [47] demonstrated that farmers cultivating grapes in India saw a more than fifteenfold increase in PV revenue. However, further research is needed to ascertain the magnitude of this effect.

External factors, including market dynamics and environmental conditions, can significantly impact economic outcomes. The favourable financial metrics, such as the positive NPV, high PI, and attractive IRR, indicate that the AVS implemented in apple cultivation is economically viable. This system demonstrates considerable potential for financial returns, especially when accounting for land conservation benefits and government subsidies. However, the growth in investment indicators is relatively more modest compared to AVS associated with grass production, primarily due to the differing economic characteristics of the crops involved. Descriptive statistics for the output variables used in the Monte Carlo simulations are presented in Table 21. These variables include the NPV, the unit cost of apples in 2027, and the unit cost of electricity in 2025. These were selected as key indicators because they directly reflect the profitability and cost-efficiency of both the agricultural and energy components of the system.

The mean values represent the most likely or average outcomes across 10,000 iterations, while the variance, standard deviation, and coefficient of variation quantify the level of uncertainty, risk, and potential variability in the model's results due to input fluctuations.

The high coefficient of variation observed in the NPV (102.77%) indicates considerable financial risk associated with the agrivoltaic investment. This elevated uncertainty primarily arises from the compounded effects of fluctuating market prices for apples and electricity, variations in crop yield influenced by climatic and agronomic factors, changes in subsidy policies, and fluctuations in electricity tariffs over the project's lifetime.

Similarly, the unit cost of apples in 2027 (UCa2027) demonstrates substantial variability (coefficient of variation of 130.99%), driven largely by yield variability, the distribution between premium and processing-grade apples, and volatility in agricultural market prices. These factors significantly affect production costs per unit output in the first harvest year.

The unit cost of electricity in 2025 (UCe2025), with a coefficient of variation of 126.08%, is influenced by uncertainty in annual energy generation (affected by weather variability and system efficiency), operational and maintenance costs, and the FIT rates applicable during the initial year of operation.

**Table 21. Statistical summary of the simulated output variables**

| Output variables | Mean | Variance | Standard Deviation | Coefficient of Variation (%) |
|---|---|---|---|---|
| NPV | 102.6 (Million EUR) | 11, 114, 267, 648.2 | 105.4 (Million EUR) | 102.77 |
| UCa2027 | 170.58 (€/t) | 49, 927.84 | 223.45 (€/t) | 130.99 |
| UCe2025 | 0.0128 (€/kWh) | 0.0003 | 0.0161 (€/kWh) | 126.08 |

*Legend: UCa2027 refers to the unit cost of apples in 2027 (the year of the first harvest); UCe2025 signifies the unit cost of electricity in 2025 (the initial year of operation). Source:* [30]

Figure 17, a spider diagram offers a comprehensive visualisation of the intricate effects of input variability on the NPV in agrivoltaic systems integrated into apple orchards. An increase in electricity prices leads to a significant rise in investment indicators in 40% of the cases. In contrast, higher discount factors, which reflect increased financing costs, are associated with a consistent decline in NPV. The effect of other economic indicators on the studied phenomenon appears minimal. The simulations employ stochastic processes for input and output calculations, an inherent feature of each simulation run. In contrast to deterministic simulations, which yield linear output changes in response to inputs, stochastic simulations introduce nonlinearity, thus depicting trends shaped by the respective input distributions. This emphasizes the sophisticated and probabilistic nature of the relationship between input variations and NPV outcomes in agrivoltaic systems.

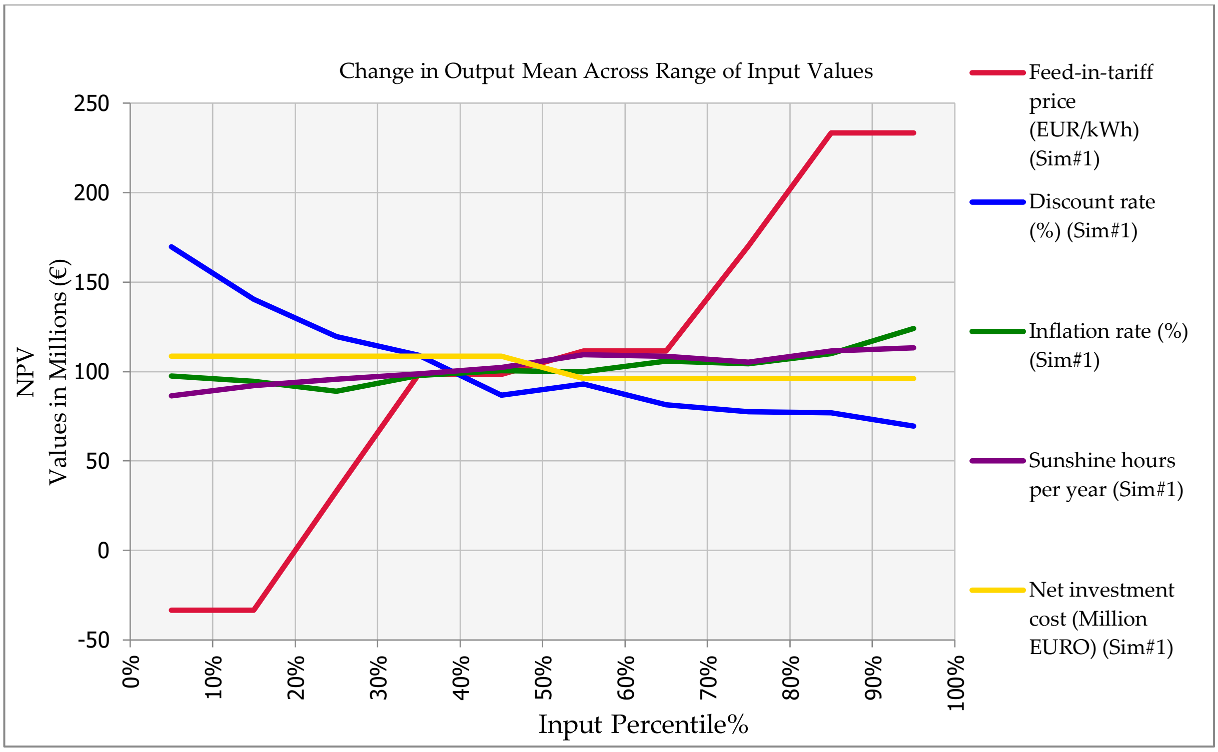

**Figure 17: Variation in output averages across a range of input values with respect to NPV. Source:** [30]

The Tornado diagram, presented in Figure 18, is a powerful visual tool for assessing the impact of different factors on the NPV. It is clear from the diagram that the FIT price is the most influential parameter, with a strong positive correlation coefficient of 0.87. This means that as the FIT price increases, the NPV also increases, indicating that higher FIT prices lead to higher profitability for the agrivoltaic system.

On the other hand, the discount rate and net investment costs show a negative correlation with the NPV, with correlation coefficients of -0.26 and -0.11, respectively. This implies that an increase in these factors results in a decrease in the NPV. The discount rate is essentially the cost of capital, which includes the interest paid on loans and the required rate of return for investors. Therefore, a higher discount rate means the project is more expensive to finance, reducing its profitability. Similarly, higher net investment costs, including purchasing and installing the agrivoltaic system, also lower the NPV.

These findings underscore the pivotal role of financial parameters, such as the FIT price and financing conditions, in determining the economic viability of agrivoltaic systems. Additionally, they highlight the importance of government subsidies in promoting the adoption of such systems. The government can play a critical role in making agrivoltaic systems more attractive to farmers and investors by providing subsidies or other financial support. This can help to offset the higher investment and operational costs associated with these systems, thereby improving their NPV and overall profitability.

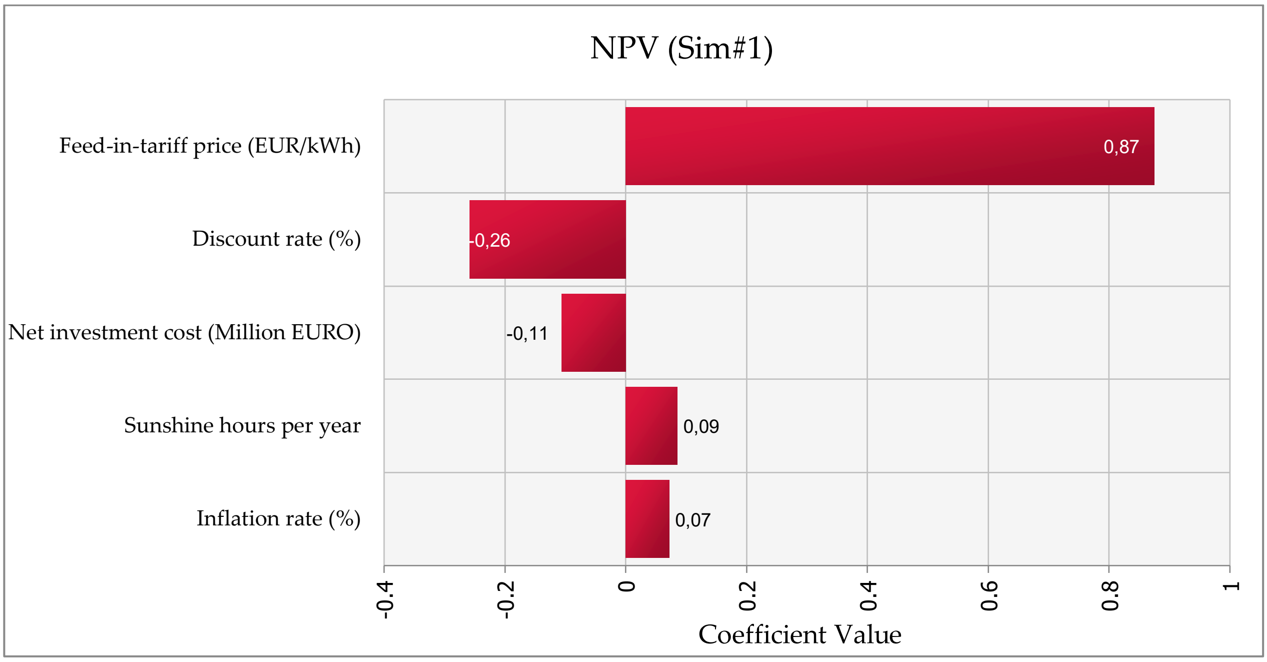

**Figure 18: Spearman rank correlation coefficients of the analyzed input and output data relating to the NPV. Source:** [30]

As depicted in the Tornado diagram of Figure 19, input and output unit price variations have distinct effects on the NPV, with coefficients of +0.91, -0.31, and +0.09, respectively. A coefficient of +0.91 for the output price suggests a strong positive relationship. In other words, an increase in the output price, which could be the price of electricity sold or the price of apples sold, tends to result in a significant increase in the NPV. This implies that the project becomes more profitable as the revenue generated from the sale of outputs increases. The coefficient of -0.31 for the input price indicates a negative relationship. This means that as the costs of inputs (such as the cost of setting up the AVS or the cost of maintaining the apple orchard) increase, the NPV decreases. Higher input costs reduce the project's profitability as they increase the overall expenditure. Lastly, the coefficient of +0.09 for a unit price change shows a relatively weak positive correlation. This suggests that minor changes in unit prices can have a slight positive effect on the NPV, but the impact is not as substantial as the output price or as detrimental as the input price. These coefficients underscore the sensitivity of the NPV to price changes in agrivoltaic systems, highlighting the importance of efficient cost management and strategic price setting in maximizing profitability.

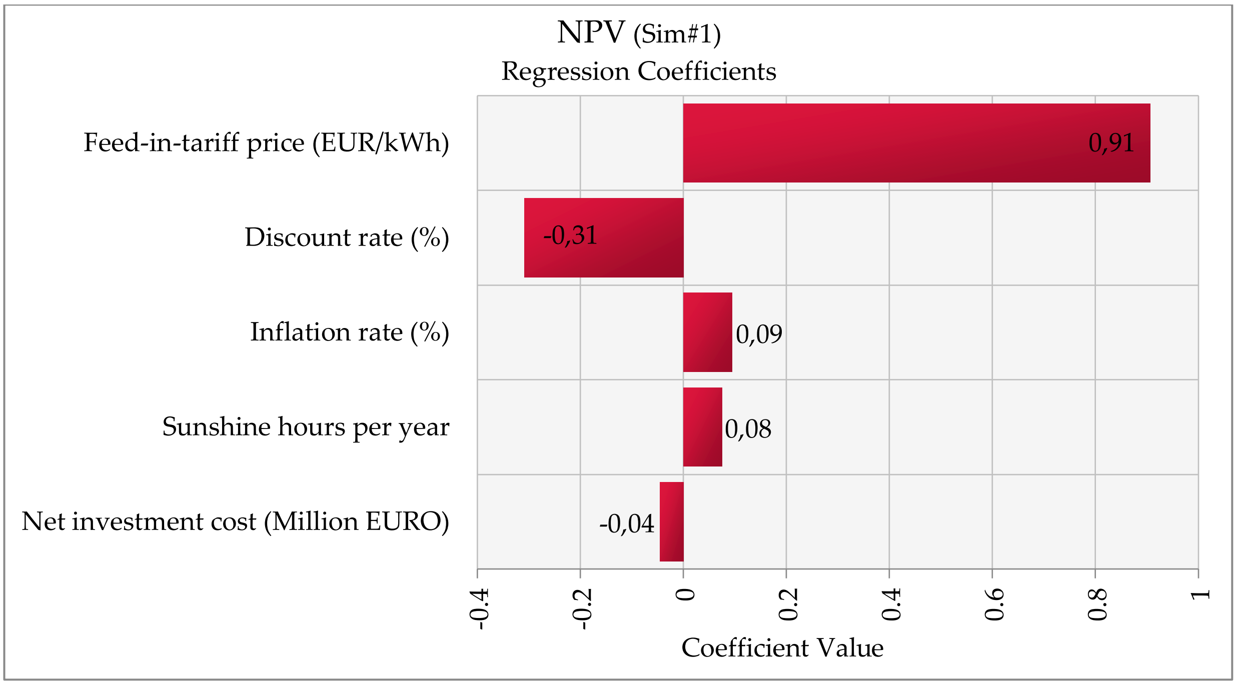

**Figure 19: Coefficients of regression analysis on the NPV based on input and output data. Source:** [30]

Figure 20 presents a statistical outcome that underscores the considerable risk at the entrepreneurial level. The low probability indicates that the economic feasibility of the enterprise, as gauged by NPV, remains relatively steady under various simulated scenarios. The fact that there is only a 25% chance of the scenario leading to a zero or negative NPV underlines the robustness of the assessed conditions, thereby offering crucial insights for decision-makers and stakeholders.

In the context of a Monte Carlo simulation, these estimated parameters exhibit resilience against unfavourable shifts that could threaten the economic sustainability of the business operation under consideration. This resilience implies that the business can withstand changes in input parameters, such as price fluctuations or operational costs, without its economic feasibility being significantly compromised.

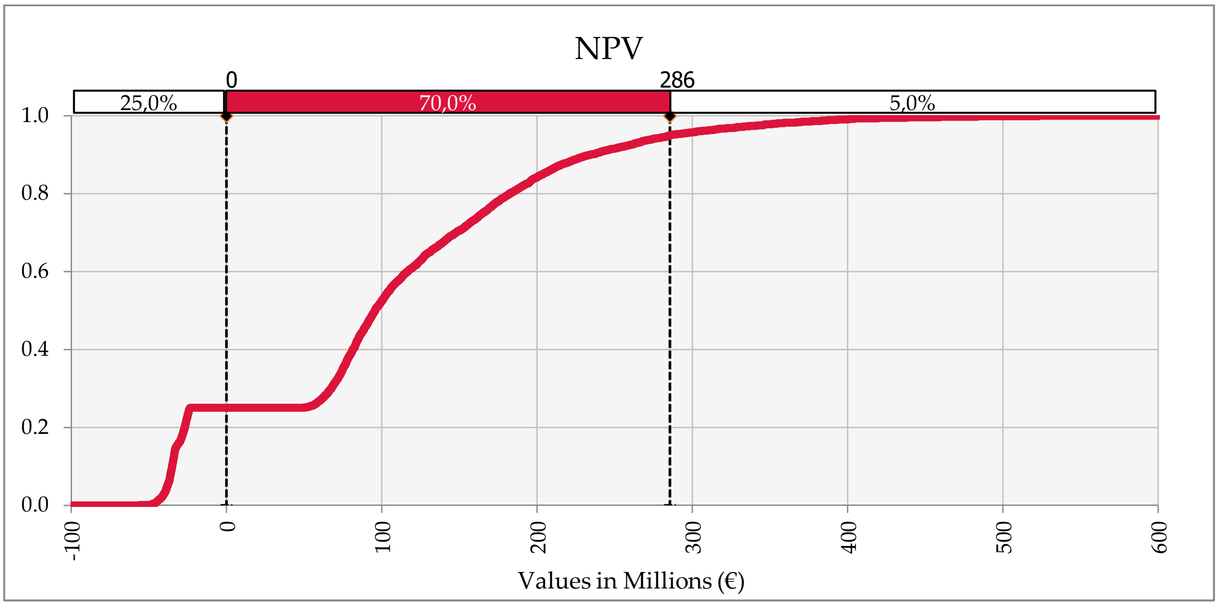

**Figure 20: Overview of Monte Carlo simulations about NPV values. Source:** [30]

In conclusion, financing, especially through public or low-cost equity and government-backed credit options, is crucial for successfully implementing agrivoltaic systems. In addition, lowering the risk premium or industry beta can improve predictability, positively affecting the economic view of agrivoltaic investments. This highlights the complex relationship between financial factors and the overall economic feasibility of agrivoltaic projects, pointing out that strategic financial adjustments can help overcome challenges and improve economic results.

By reducing the risk premium or industry beta, agrivoltaic ventures become more attractive to investors by lowering the perceived risk. Combined with favourable financing conditions such as low-cost equity and government-backed credit, this can significantly improve the economic feasibility of these projects, making them more long-term sustainable.

Therefore, while the technical and operational aspects are essential in implementing agrivoltaic systems, the role of financial factors is just as significant. This calls for a well-rounded approach that considers technical, operational, and financial factors in the planning and implementation of agrivoltaic projects.

### *4.2.3. Analysis of apple production costs on a per unit basis*

The study conducted sensitivity analyses on FIT and electricity prices, highlighting their substantial influences on PV revenues. Considering both Hungarian [134,247] and German [23] case studies, our findings show that during the mature phase (from the 4th to the 15th year), the yield of Class I and II apples is 51.75 tons/ha, with an additional 5.75 tons/ha for industrial or juice apples. The pricing dynamics are 0.29 €/kg for Class I and II apples and 0.10 €/kg for industrial apples. Financially, the revenues, excluding subsidies, amount to 15,488 €/ha, which increases to 15,671 €/ha when subsidies are included.

Table 22 compares the unit production costs of electricity and apples across three scenarios: (1) AVS, (2) GM-PV system without apple cultivation, and (3) apple cultivation without PV. The analysis covers six selected operational years - 2024, 2026, 2038, 2039, 2040, and 2053, which were chosen to represent different phases in the system's lifecycle. The total production cost includes all operating expenses associated with both electricity generation via photovoltaics and apple cultivation within the agrivoltaic system. The unit costs are calculated based on total production costs and the revenue shares of electricity and apples, allowing for the allocation of shared costs in the AVS scenario. This enables a comparative evaluation of how cost structures evolve over time for each component.

The share of electricity and apples in total revenues indicates how income is distributed between the two outputs. For years such as 2024, 2039, and 2040, the entire revenue share (1.00) is attributed solely to electricity, indicating no apple production or its negligible economic contribution during those years. Conversely, in years like 2026, 2038, and 2053, apples contribute between 9% and 15% to the total revenue. The production cost of electricity remains the dominant expense across all years, while the production cost of apples is only incurred in years when apples are cultivated (i.e., 2026, 2038, and 2053). The unit cost of electricity reflects a rising trend from 0.015€/kWh in 2024 to €0.040€/kWh in 2053, due to both inflation and system ageing effects. For apple production, the unit cost per ton rises significantly over the years, from 56€/t in 2026 to €161€/t in 2053, influenced by input costs, yield variation, and shared infrastructure expenses.

In the AVS scenario, electricity generally maintains a lower unit cost compared to the GM-PV system, especially in the early years, due to the benefit of shared infrastructure and dual land use. The unit cost of apples in the AVS is also lower than in the apple-only scenario during productive years, highlighting the economic synergy created by combining energy and food production.

All three models demonstrate unit costs that are favourable when compared to typical market prices. However, a notable difference among the three competitive technologies is that AVS significantly mitigates the fluctuations of unit costs, resulting in higher values for electricity and lower values for apple, compared to the unit costs of GM-PV and apple production. These findings are consistent with the assertions and results of [23] and [178].

**Table 22. Comparison of costs for producing electricity and apples over specific operational years**

| Years | 2024 | 2026 | 2038 | 2039 | 2040 | 2053 |
|---|---|---|---|---|---|---|
| **Total production cost (€)** | 1,120,666 | 1,452,053 | 1,822,206 | 1,271,534 | 1,375,870 | 2,631,363 |
| **Share of electricity in revenues** | 1.00 | 0.91 | 0.87 | 1.00 | 1.00 | 0.85 |
| **Share of apple in revenues** | 0.00 | 0.09 | 0.13 | 0.00 | 0.00 | 0.15 |
| **Production cost of electricity (€)** | 1,120,666 | 1,317,682 | 1,584,243 | 1,271,534 | 1,375,870 | 2,242,002 |
| **Production cost of apple (€)** | 0 | 134,371 | 237,962 | 0 | 0 | 389,361 |
| **Unit cost of electricity (€/kWh)** | 0.015 | 0.018 | 0.024 | 0.020 | 0.021 | 0.040 |
| **Unit cost of apple (€/t)** | 0 | 56 | 99 | 0 | 0 | 161 |
| **Unit cost of electricity in PV (without apple, €kWh)** | 0.013 | 0.013 | 0.017 | 0.018 | 0.018 | 0.029 |
| **Unit cost of apple (without PV, €/t)** | 0 | 196 | 285 | 0 | 0 | 399 |

*Source:* [30]

The analysis reveals that unit costs exhibited considerable variability over time, influenced by rising production expenses, fluctuating price ratios between apples and electricity, and the absence of apple yields (and associated operational costs) in the 1st, 2nd, 16th, and 17th years after planting. These variations also account for expected inflation, employing a unit cost calculation method based on revenue proportions and the 15-year lifecycle of an apple plantation. Notably, electricity unit costs rose in 2026 and 2038 due to the added operational expenses of apple cultivation compared to earlier years with no apple production. During years without apple harvests, electricity contributes 100% of the revenue, while in most other years, it accounts for approximately 90%, with apple revenue ranging between 9% and 15%. This underscores the heavy reliance on electricity as a primary income source. The revenue share from apples also fluctuates in response to changing price trends for apples and electricity. Unit costs exhibit an intriguing pattern: a temporary spike in electricity costs occurs in 2039, followed by varying apple unit costs, peaking in 2053, likely reflecting rising costs in both components of the AVS. However, anticipated higher output prices suggest that this cost increase is unlikely to impact profitability negatively.

In the years without apple harvests, the unit cost of electricity is significantly lower due to save operational expenses. A key insight is that standalone apple production would incur unit costs of 196–399 €/t, while standalone electricity generation would range between 0.013–0.029

€c/kWh. In contrast, AV systems demonstrate more balanced and closely aligned unit costs (56–161 €/t for apples and 0.015–0.040 €c/kWh for electricity), making them potentially more attractive to apple farmers. However, unit costs are subject to significant uncertainty due to weather variability, which affects both electricity and apple yields, and the shadow effect, which may differ across apple varieties. Additional location- and technology-specific factors also play a role. For instance, a hillside with a 30–35% slope is ideal for PV systems, as it allows full coverage with solar panels, though the shadow effect poses challenges for AVS. Under Hungarian conditions, a 35–40% slope optimizes electricity production and panel density per hectare but increases the risk of wind damage to AVS and PV equipment. These dynamics highlight the need for strategic planning to ensure long-term financial viability and emphasize the complex interplay of technological, operational, and market factors in AV projects.

In the analysis of agrivoltaic systems applied to apple farming, the spider diagram in Figure 21 provides a comprehensive overview of the factors influencing the unit cost of apple production. The most prominent driver, as revealed by the diagram, is the FIT rate. This policy mechanism is designed to promote the adoption of renewable energy by guaranteeing a fixed payment for the electricity generated from solar panels. Its impact is significant, as evidenced by a strong correlation with production costs in 20% of the analyzed scenarios. This suggests that variations in the FIT rate can substantially affect the economics of apple production by either enhancing or diminishing the financial returns from energy generation, thereby influencing overall production costs. Despite the prominence of FIT rates, in most scenarios, their effect on the unit cost of apple production is relatively modest, with changes leading to an adjustment of approximately 50 euros per ton. This highlights the complexity of the agrivoltaic system, where the interplay between energy policy and agricultural production is nuanced and contingent upon specific operational conditions. Interestingly, other factors such as mature apple yields, capital expenditure (CAPEX), annual sunshine hours, and the consumption purpose ratio exert minimal impact on the unit costs. Mature apple yields, which denote the productivity of fully developed apple trees, appear to be stable across the scenarios, suggesting efficient agricultural practices or consistent environmental conditions. CAPEX, representing the initial investment in solar technology and infrastructure, while significant in absolute terms, does not fluctuate dramatically enough to affect unit costs substantially once the system is operational. Furthermore, annual sunshine hours, despite their importance in solar energy generation, show negligible effects on cost variability. This finding could imply that the agrivoltaic system is designed to optimize energy capture under a range of sunlight conditions, thereby stabilizing production costs. Lastly, the consumption purpose ratio, which might reflect the market distribution of apples (e.g., fresh consumption versus processing), does not significantly alter production costs, indicating that market strategies are decoupled from production economics within the parameters of this study. The dominant role of FIT prices underscores the critical importance of renewable energy policies in shaping the financial landscape of agrivoltaic systems in agriculture. This insight aligns with previous research highlighting policy incentives' significance in adopting renewable energy [248,249]. Understanding these dynamics is essential for stakeholders aiming to optimize the dual benefits of energy generation and agricultural productivity in agrivoltaic systems.

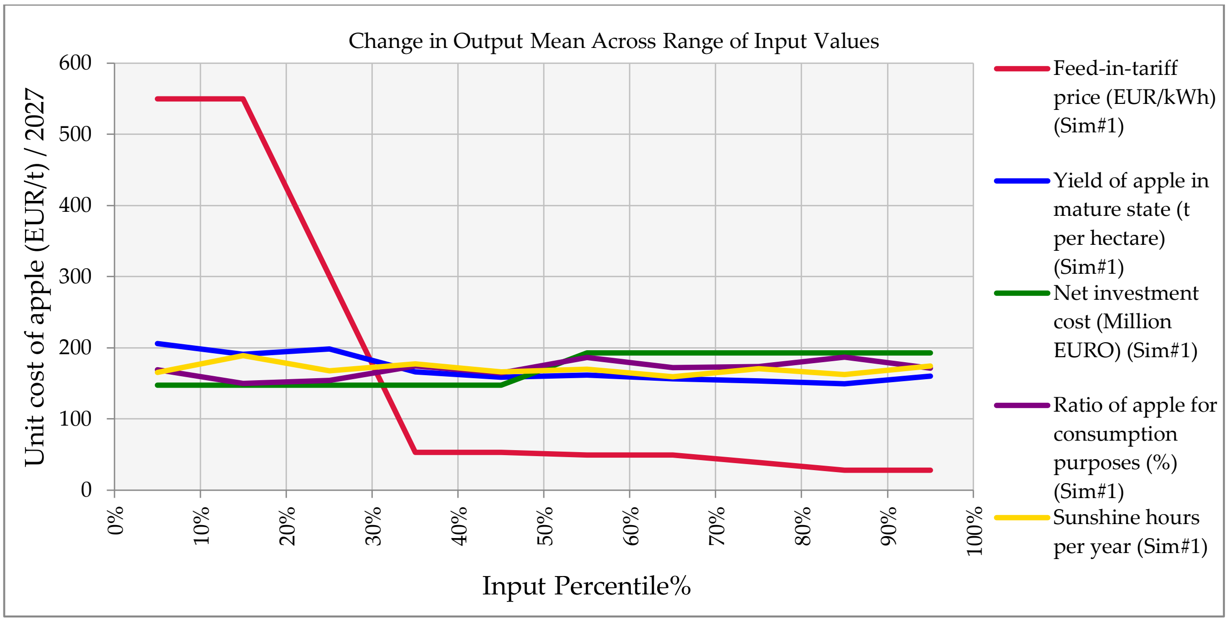

**Figure 21: Variations in the average outputs across a spectrum of input values of the unit cost of apple production. Source:** [30]

Figure 22 presents the Spearman rank correlation coefficients, illustrating the relationships between various factors and the cost of apple production. A notable finding is the strong negative correlation of −0.90 between unit costs and FIT rates. This correlation highlights the significant role of FIT rates in reducing unit costs, primarily through revenue-based cost allocation between electricity generation and apple production. The negative correlation suggests that higher FIT rates, which increase revenue from electricity, can effectively lower the overall costs of apple production by offsetting expenses. In contrast, the correlation with net investment costs is moderately positive at +0.33, indicating that higher capital expenditures are associated with increased unit costs. This relationship can be attributed to the upfront financial outlays required for implementing solar infrastructure within AVS. Other variables analyzed exhibit weaker statistical relationships, suggesting that their impact on unit costs is less pronounced within the scope of this study.

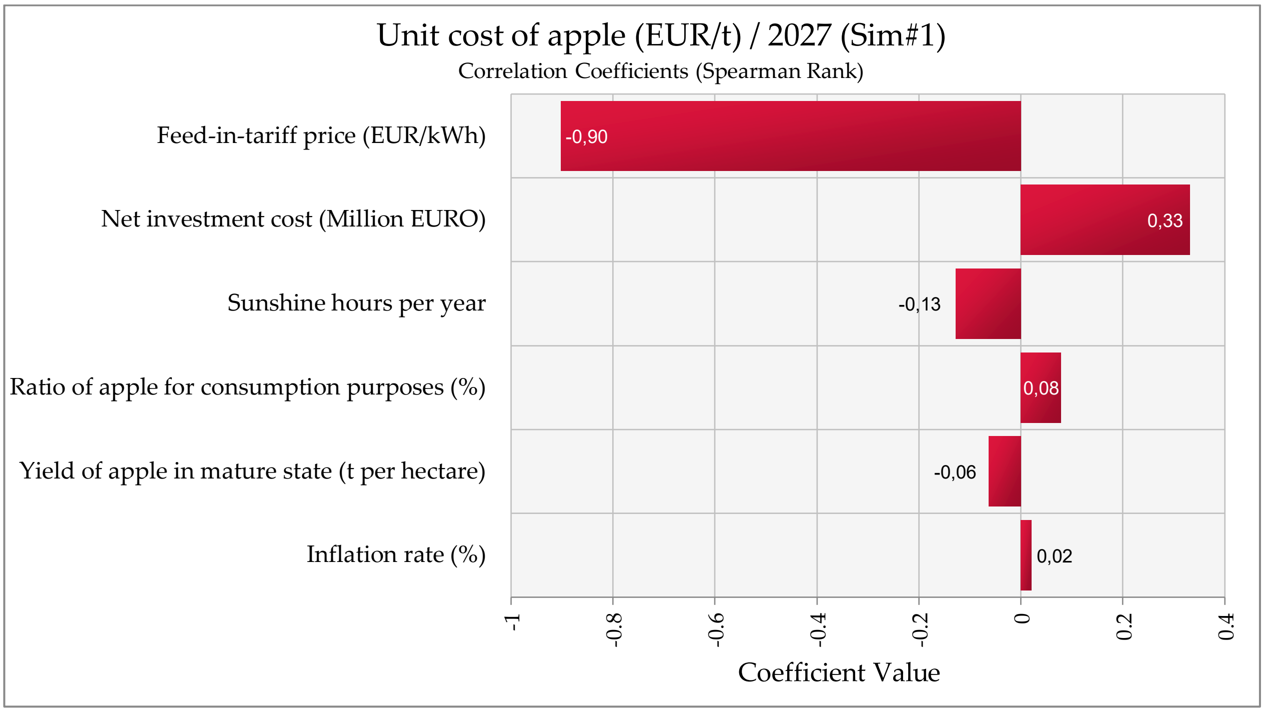

**Figure 22: Analysis of correlation coefficients (spearman rank) for input and output data related to apple production unit cost. Source:** [30]

Figure 23 complements these findings by providing a regression analysis that quantifies the impact of economic variables on unit costs. The regression results reveal a pronounced negative coefficient for FIT prices (−0.84), reaffirming their critical role in reducing costs. The regression coefficient for net investment costs is marginally positive at +0.09, aligning with the correlation analysis and indicating that while these costs contribute to higher unit costs, their effect is not as substantial as that of FIT rates. Additionally, a slight negative coefficient for mature apple yields (−0.06) suggests a minor influence of yield variations on unit costs, possibly due to consistent agricultural practices or environmental factors.

These findings collectively underscore the dominance of FIT pricing as the most critical determinant of apple production costs within AVS. The results highlight the intricate interplay between policy-driven incentives, which enhance financial viability through favorable FIT rates, and the economic burdens imposed by capital investments. Moreover, the minimal impact of mature apple yields implies that production efficiency remains stable, thus reinforcing the importance of optimizing energy-related revenues to manage costs effectively.

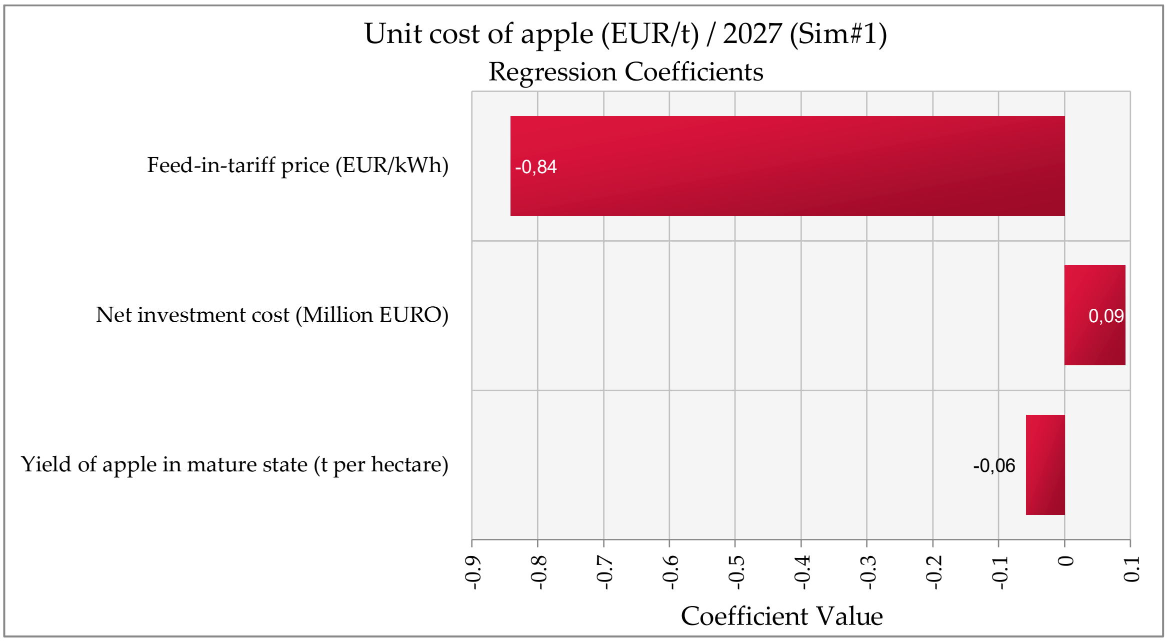

**Figure 23: Analysis of regression coefficients for input and output data of the unit cost of apple production. Source:** [30]

The Monte Carlo simulations illustrated in Figure 24 offer a robust analysis of the variability in unit costs associated with apple production within agrivoltaic systems. The simulations, which incorporate stochastic modelling techniques, highlight a significant standard deviation in unit cost values, encapsulated within a 90% confidence interval. This wide range indicates inherent uncertainties and variabilities in the economic environment affecting apple production costs. A critical insight from the simulations is the substantial impact of product prices on unit cost variability. Product prices account for approximately 25% of the observed variation in unit costs, underscoring their influential role in the economic dynamics of apple production. This finding aligns with broader economic principles where market-driven price fluctuations directly affect revenue streams and, consequently, the cost-per-unit of production. The sensitivity of unit costs to product prices suggests that market conditions, such as demand shifts and price elasticity, play a pivotal role in shaping the financial outcomes of agrivoltaic operations. Conversely, investment costs, while significant in the initial phases of project implementation, appear to exert a less pronounced influence on unit cost variability compared to product prices. This attenuated impact may be attributed to the amortization of capital expenditures over the lifespan of the agrivoltaic system, thereby diluting their effect on annual cost assessments. Furthermore, the relatively low regression coefficients between individual price points and unit costs indicate difficulties in pinpointing specific years that might disproportionately affect cost forecasts. This suggests that while price trends are influential, their effects are diffused over time, making it challenging to isolate particular temporal events as major cost determinants.

These findings have significant implications for the economic management and financial planning of agrivoltaic systems. The pronounced impact of product prices on cost variability emphasizes the necessity for adaptive pricing strategies and market risk mitigation to stabilize financial performance. Producers might consider employing financial instruments such as hedging or engaging in forward contracts to manage price risks effectively. Additionally, the results suggest that long-term financial sustainability in agrivoltaic systems may benefit from diversified revenue streams, integrating both agricultural output and renewable energy generation to buffer against market volatility.

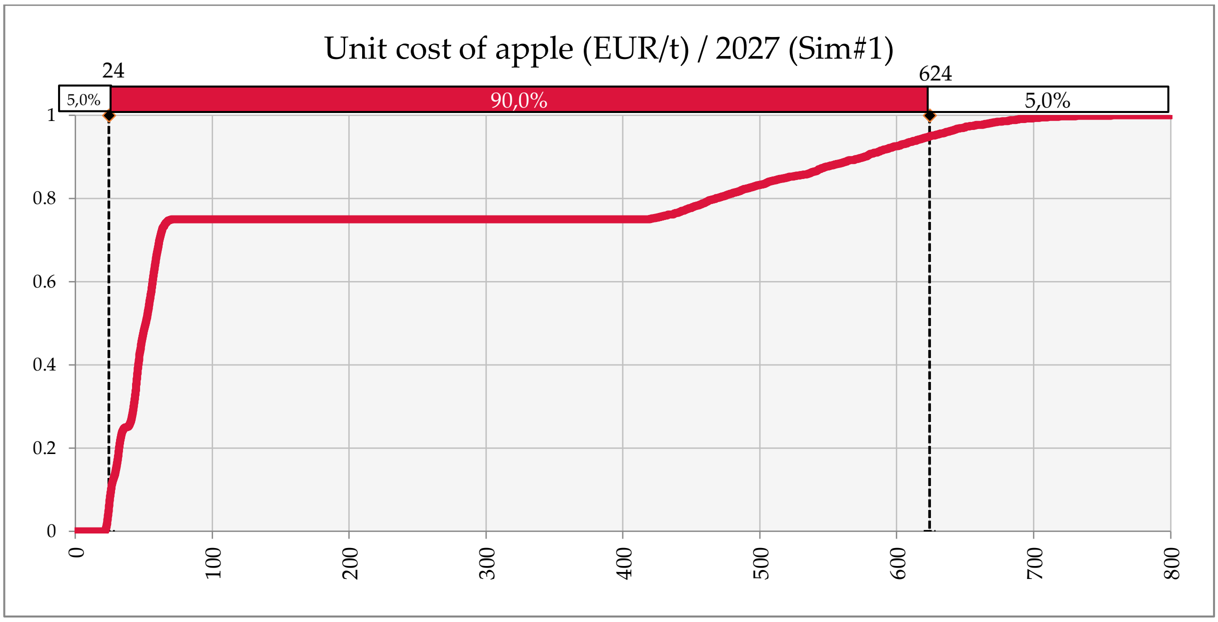

**Figure 24: Summary of Monte-Carlo simulations of the unit cost value. Source:** [30]

#### *4.2.4. Analysis of electricity costs on a per unit basis*

In analyzing the economic dynamics of apple production within agrivoltaic systems, Figure 25's spider diagram provides a nuanced depiction of the factors influencing unit costs. The unit cost was primarily swayed by two factors - CAPEX and annual sunshine hours, although in opposite directions. CAPEX, representing the upfront investment required for implementing solar infrastructure and integrating it with agricultural operations, exerts a significant upward pressure on unit costs. The prominence of CAPEX in influencing unit costs can be attributed to the substantial financial outlays necessary for purchasing and installing solar panels, inverters, and related technology. These initial costs are critical as they set the financial baseline for the operational efficiency and long-term economic sustainability of the agrivoltaic system. High CAPEX can significantly elevate fixed costs, which, in turn, translates to higher unit costs unless offset by substantial gains in productivity or energy savings. This finding underscores the importance of strategic financial planning and cost-effective procurement strategies to mitigate the impact of CAPEX on overall production costs. Conversely, annual sunshine hours emerge as a pivotal factor reducing unit costs. The positive effect of increased sunshine hours can be largely attributed to enhanced solar energy generation, which augments the system's revenue streams and reduces the dependency on external energy sources. Greater solar irradiance allows for more efficient energy capture, thereby optimizing the cost-benefit ratio of the agrivoltaic setup. This relationship highlights the critical role of geographic and climatic considerations in the economic viability of agrivoltaic systems, with regions receiving higher sunshine hours potentially offering more favorable conditions for such integrated operations.

Interestingly, the FIT price of electricity, which is often a significant driver in renewable energy economics, manifests virtually no impact on unit costs in this context. This lack of effect could be indicative of several underlying factors. It might suggest that the revenue from electricity sales is either sufficiently stable or marginal in comparison to the overall cost structure dominated by CAPEX and operational efficiencies. Alternatively, it may reflect a market context where FIT rates are not competitive enough to substantially alter the economic calculus of integrating solar power with agriculture.

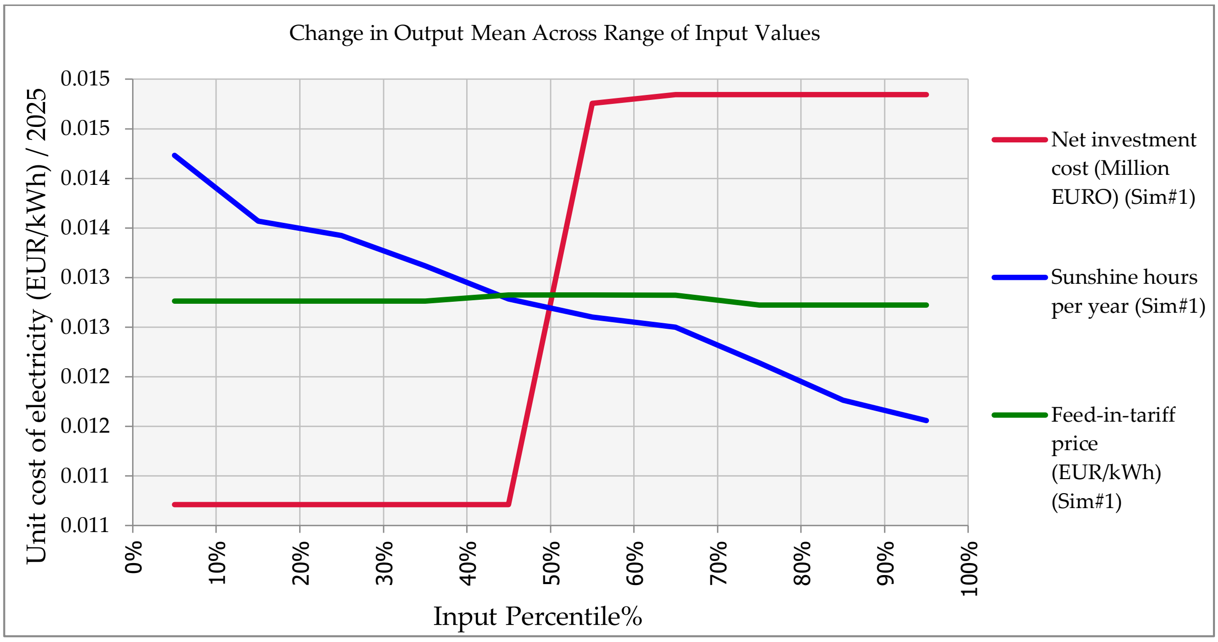

**Figure 25: Average output changes across various input values about unit cost (€/nm3) for 2024. Source:** [30]

In the detailed evaluation presented in Figure 26 and Figure 27, the Spearman rank correlation and regression coefficients offer a comprehensive understanding of the factors impacting unit costs within agrivoltaic systems. The primary influence of CAPEX on unit costs is strongly evidenced by its correlation coefficient of +0.87 and an even more pronounced regression coefficient of +0.93. These figures underscore the critical role that initial capital investments play in shaping the economic landscape of agrivoltaic operations. The high correlation and regression values suggest a direct and substantial relationship, where increases in CAPEX are closely associated with higher unit costs. This relationship can be attributed to the significant financial commitments required to acquire and install solar infrastructure, which form a substantial portion of the fixed costs in the early stages of project development. The findings indicate that the economic feasibility of agrivoltaic systems is heavily contingent on managing these initial costs effectively. Strategies to mitigate the impact of CAPEX might include pursuing cost-effective technologies, optimizing design and installation processes, and leveraging financial instruments such as loans or grants to spread the financial burden over an extended period.

In contrast, the role of annual sunshine hours, although impactful, is less pronounced than that of CAPEX. The correlation coefficient of -0.51 and regression coefficient of -0.35 indicate a moderate inverse relationship with unit costs. This suggests that increased sunshine hours, which enhance the solar energy generation capacity of the system, contribute to reducing unit costs. By providing a consistent and renewable energy source, greater sunshine hours can offset operational costs associated with energy consumption, thereby improving the overall economic efficiency of the system. The negative coefficients highlight the potential for optimizing site selection based on solar irradiance to maximize cost savings and economic returns. This underscores the importance of environmental and geographical considerations in the strategic planning of agrivoltaic systems, where selecting locations with higher solar potential can lead to significant cost reductions.

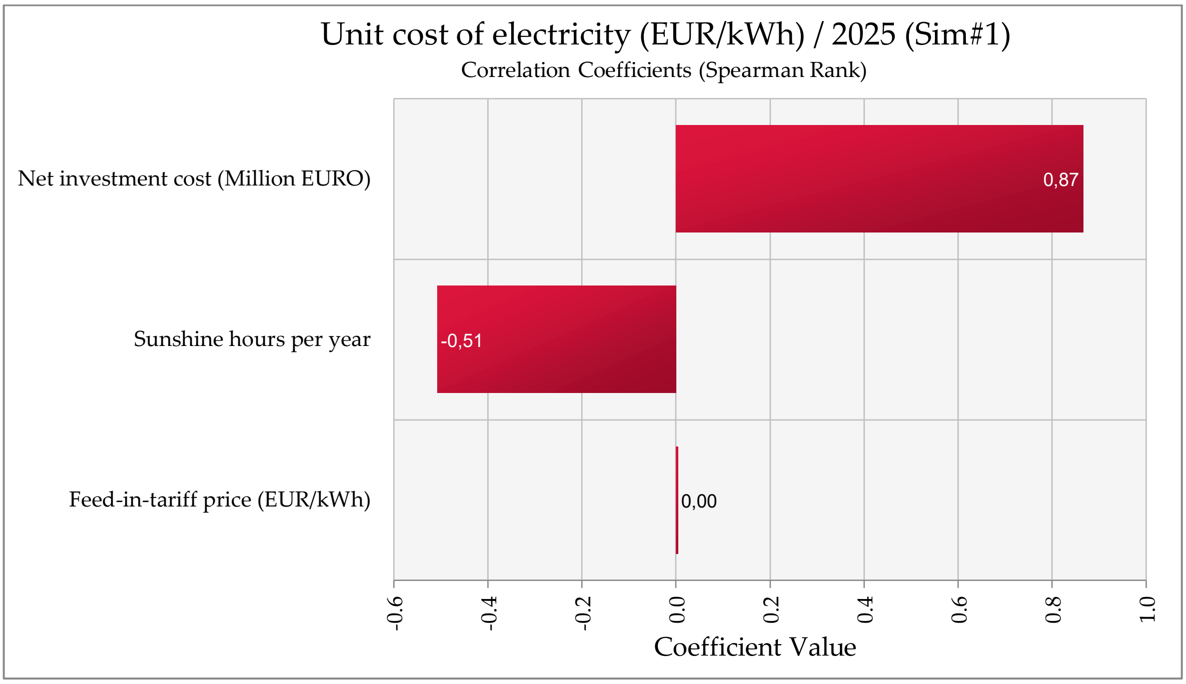

**Figure 26: Evaluation of Spearman rank correlation coefficients for input and output data impacting unit cost. Source:** [30]

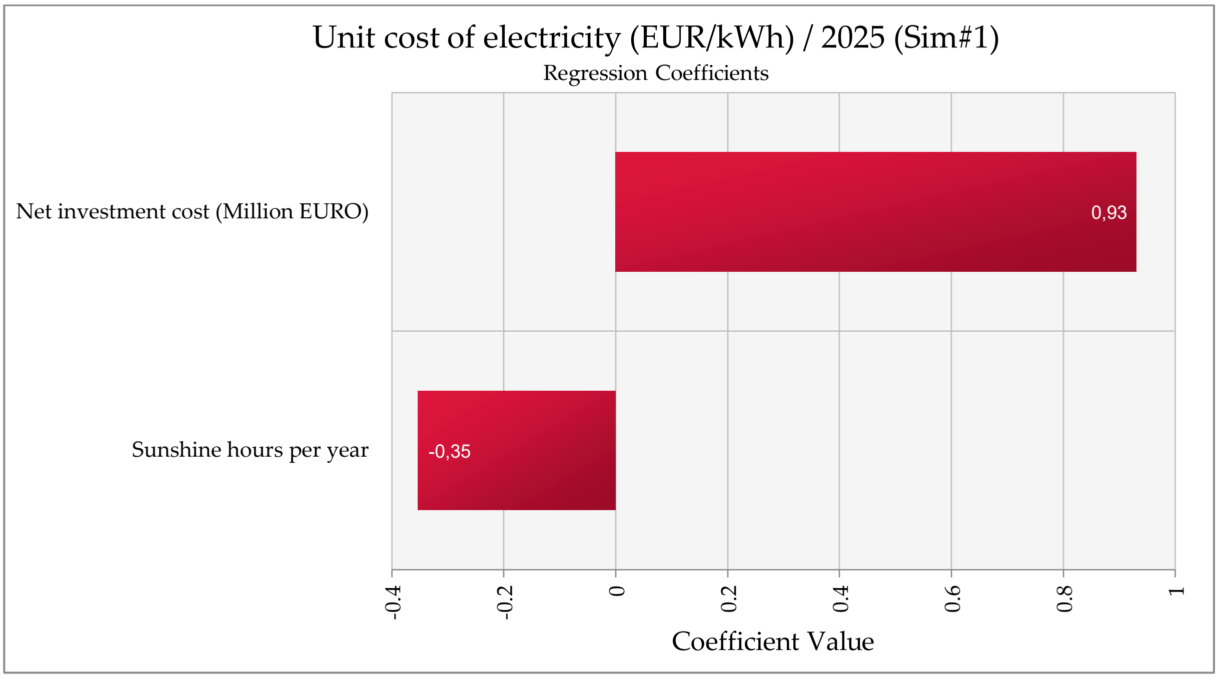

**Figure 27: Analysis of regression coefficients demonstrating the impact of input and output data on unit cost. Source:** [30]

The analysis reveals that the unit cost of electricity most likely resides within the 0.011-0.016 €/kWh interval, with the probability of observing values outside this range approaching zero (refer to Figure 28). Considering the projections concerning FIT prices as presented in [23], this particular cost interval appears to be optimally positioned to ensure profitability. This highlights the economic feasibility of the project under the given market conditions.

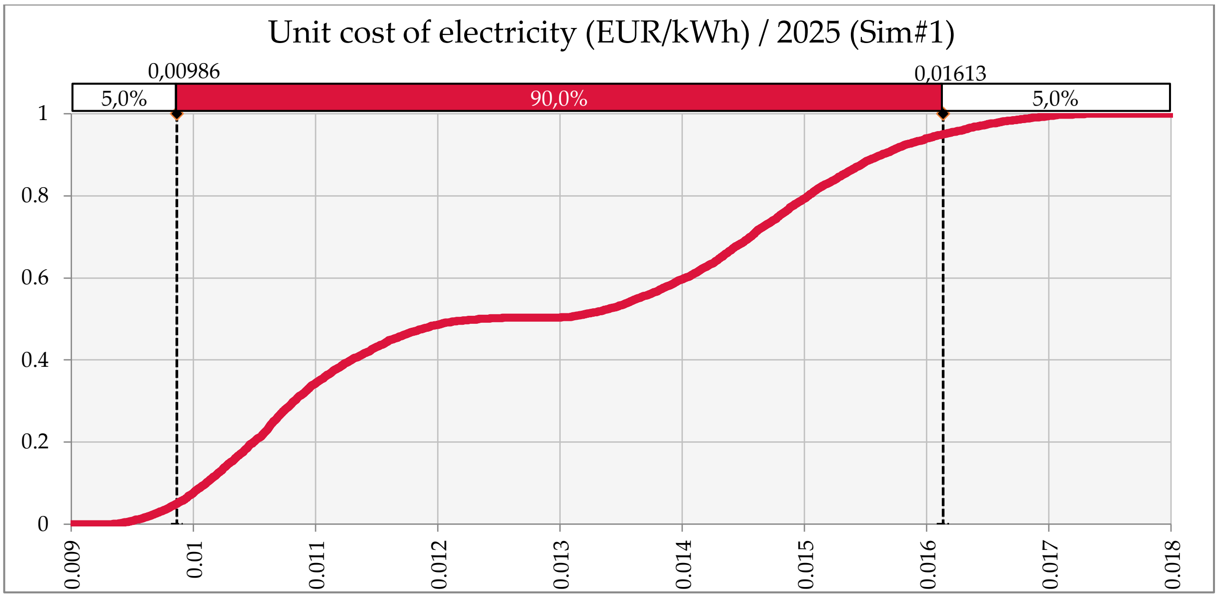

**Figure 28: Combined results of Monte Carlo simulations examining variations in unit cost. Source:** [30]

The unit costs of electricity generation within the agrivoltaic project significantly hinge on the FIT configuration. Our data shows that the electricity unit cost varies between €0.015 and €0.068 per kWh, as studies in [120,250], with the lower segment being in line with our findings. The economic viability of the agrivoltaic project in apple orchards is particularly apparent when the FIT price ascends, thus magnifying the project's financial attractiveness and potentially giving it an edge over conventional GM-PV systems. AVS' competitive standing is determined not just by its absolute profit but also by its relative advantage. For instance, it is crucial to assess whether the economic performance of AVS surpasses that of alternative activities. If investors can reap more significant financial returns from PV systems without apple production or PV systems, they might prefer these options over AVS. AVS demands an additional investment in comparison to both alternatives. As suggested by our research [184]Under standard circumstances, PV systems promise higher profits and slightly lower investment costs. In contrast, apple production has lower profit potential but is associated with significantly lower investment costs and unpredictable return on investment.

The competitiveness of agrivoltaic projects in apple plantations is intrinsically connected to FIT prices. While higher FIT prices enhance the attractiveness of the agrivoltaic project, they could simultaneously increase standalone PV systems' profitability, potentially impacting AVS's competitiveness. Another factor to consider is that agricultural integration can mitigate land use issues, especially for small farmers. Considering the pivotal role of FIT prices, policymakers and stakeholders might need to reassess tariff structures to facilitate the wider adoption of agrivoltaics in apple farming. The argument for special subsidies for AVS might be the more efficient use of land (higher profit per hectare compared to conventional farming), improving the economic conditions of small farmers, and conserving agricultural land (compared to PV systems).

The integration of apple production with the solar-agriculture-water (SAW) nexus offers a comprehensive solution for sustainable land use. This approach aligns with multiple 2030 Sustainable Development Goals (SDGs) for apple production. Specifically, AVS directly contributes to food production (SDG 2) and eco-friendly electricity production (SDG 7). It further supports SDG 5 and 8 by promoting women's involvement in social development, aligns with SDG 15 (Life on Land), and encourages responsible consumption (SDG 12) [36,251–253].

### 4.3. Scenario and sensitivity analysis results: A hypothetical comparation of agrivoltaic, photovoltaic, and conventional apple cultivation systems in Kaposvár solar park

Section 4.3 provides the findings of the baseline performance evaluation of the three distinct systems: AVS, GM-PV system, and traditional apple farming systems. The focus here is on outlining the general characteristics and potential of each system, highlighting their unique strengths and weaknesses. The subsequent sections will delve into specific data and results, providing a detailed examination of how each system performs under various conditions. These analyses will identify key performance metrics, economic viability, and potential areas for optimization. By exploring the financial impacts and operational efficiencies of each system, the following sections aim to offer actionable insights for stakeholders seeking to enhance the sustainability and profitability of their agricultural operations.

### *4.3.1. Outcomes of the baseline scenario*

This economic assessment aims to evaluate the potential economic impact of AVS compared to GM-PV systems and ConAPS. This is achieved through sensitivity analysis, which aims to quantify the economic value generated by each product—AVS, GM-PV systems, and traditional apple cultivation. The findings from this analysis will provide a foundation for subsequent technical and cost evaluations. This study defines the functional unit for economic assessment as the electricity production of a 100 MW GM-PV system with a 25-year operational lifespan. The assessment framework includes three key stages: investment costs (incorporating the additional costs specific to AVS), electricity generation, and farm revenue derived from apple production (as outlined in Table 23). The average annual electricity generation per unit is 0.11 MWh, with an average tariff rate of 0.137 kWh (expected to rise due to the ongoing energy crisis). The total investment cost is approximately €99.1 million [254], and the annual OPEX is € 4.9 million.

A comparison of the power generation costs between large-scale distributed PV systems and AVS indicates that, under current conditions, the economic competitiveness of the AV system diminishes relative to large-scale PV systems when accounting for the additional investment costs of AVS, as well as the trade-offs between apple production revenue and lost electricity generation. This conclusion aligns closely with real-world observations, highlighting the economic challenges of integrating agricultural and energy production within AVS frameworks.

When the dynamic payback period (DPP) is extended, NPV exceeds the benchmark electricity price in the absence of subsidies but remains below the grid electricity price when subsidies are applied. Consequently, the economic viability of the project is heavily influenced by the extent of subsidization. Similar conclusions have been reached in previous studies[24,255]. The following key factors were identified:

- AV systems necessitate greater financial investment for both GM-PV system and ConAPS activities.
- The additional revenue generated from agricultural activities does not compensate for the reduced revenue from electricity production caused by partial shading. As a result, the surplus investment costs cannot be fully recovered.
- Despite the substantial additional revenue from electricity generation, the extended repayment period makes the system less attractive to potential investors.
- In the absence of subsidies for AV systems, it is improbable that farmers will adopt this technology.

The distributed AV system offers several advantages, including the absence of sewage charges and fuel costs. Additionally, its impact on the power grid is minimal regarding the line-carrying capacity and voltage fluctuations, particularly in self-consumption and surplus operation modes. This allows for excluding transmission and distribution costs from the overall expense. Furthermore, the distributed AV system can be tailored to local conditions, power load requirements, and developmental contexts. This adaptability enhances the efficiency of green electricity utilization, alleviates peak shaving pressure on the power grid, and generates revenue from power sales while enabling free power consumption and gaining from agricultural production. Additionally, regarding environmental impact, completing the AVS project can reduce CO2 emissions each year.

**Table 23. Comparison of economic variances in the baseline scenario**

| **Parameters** | **Comparison** | | **Units** |
|---|---|---|---|
| | AVS vs GM-PV systems | AVS vs ConAPS | |
| Surplus CAPEX | 162 | 667 | th €/ha |
| Surplus (avg.) revenue from apple production | 2 | 0 | th €/ha |
| Value of electricity production | -17 | 53 | th €/ha |
| Static payback period | Endless | 12.6 | years |

*Source:* [184]

### *4.3.2. Scenario 1 – Kaposvár*

In the comparative analysis of AVS and GM-PV systems, several key insights emerge regarding their technical and economic dynamics. The lifespan of the large-scale GM-PV system is relatively extended, around 25 years. When observing the CAPEX of AVS and GM-PV, distinct cost structures are apparent [256]. Both AVS and GM-PV demonstrate the economic feasibility of the case project at the CAPEX level. However, the investment costs for AVS are notably higher. Under the current subsidy framework, the case project may operate at a financial loss when evaluated from an AVS perspective, indicating uncertainty regarding its long-term economic profitability. The power capacity per hectare and the corresponding capital expenditure reveals a crucial distinction between these systems. GM-PV systems, designed primarily for maximizing solar energy capture, exhibit a higher efficiency in electricity generation per unit area. This is reflected in their lower capital expenditure relative to AVS, which highlights the additional financial burden associated with integrating agricultural activities alongside energy production. The higher CAPEX in AVS may stem from the need for infrastructure that accommodates both agricultural and photovoltaic components, leading to increased complexity and cost. From an economic perspective, the analysis underscores the trade-offs involved in land use and cost efficiency. AVS, while offering the potential for dual revenue streams by combining agricultural and energy outputs, demonstrates a less efficient use of land for energy generation. This is evident in the increased land requirement per megawatt of installed capacity. Consequently, the higher unit investment costs associated with AVS reflect the economic challenges of managing dual-purpose systems effectively. The electricity production metrics further highlight the efficiency advantage of GM-PV systems in pure energy generation contexts, suggesting that these systems may be more suitable in scenarios where maximizing energy output is the primary objective. However, AVS provides a unique opportunity to leverage existing agricultural land for additional energy generation, which can be particularly beneficial in regions where land availability is limited, or agricultural activities are a priority. Despite the higher efficiency of GM-PV systems, the financial returns from agricultural activities in AVS remain consistent, indicating that while the agricultural component does not drastically alter financial outputs, it offers a stable supplementary income. The economic viability of either system thus heavily depends on site-specific factors, such as land value, energy prices, and strategic priorities related to sustainability and land optimization. Nevertheless, the AV system has the potential to generate economic benefits through dual revenue streams from electricity generation and agricultural production on the same land. In contrast, from a GM-PV perspective, the case project remains economically viable at the existing subsidy levels, as illustrated in Table 24 and Table 25.

**Table 24. Comparison between AVS and GM-PV**

| | GM-PV | AVS |
|---|---|---|
| Power capacity (kWp/ha) | 500 | 376 |
| Area (ha) | 200 | 200 |
| CAPEX (th €/MWp) | 999 | 1344 |
| Sunshine hours (h/yr) | 1075 | 1075 |

*Source:* [184]

**Table 25. Comparison of economic data between large-scale Kaposvár PV Systems and AV Systems**

| Parameter | GM-PV | AVS | Unit |
|---|---|---|---|
| Necessary area for 1 MWp capacity | 2.00 | 2.66 | ha |
| Unit investment cost for 1 MWp capacity | 999 | 1344 | th €/MWp |
| Unit investment cost for 1 ha capacity | 500 | 672 | th €/ha |
| Unit investment cost of 1 ha apple plantation | 5 | 5 | th €/ha |
| Electricity production of 1 ha capacity | 538 | 405 | MWh/yr |
| Average electricity price in Hungary | 9.5 | 9.5 | €c/kWh |
| The average income of 1 ha apple plantation | 2 | 2 | th €/ha |

*Source:* [184]

Variations in specific economic parameters can directly impact the computation of the AV system's real and opportunity costs and revenues, consequently affecting the economic profitability of the PV power project. By incorporating investment analysis, the uncertainty enveloping the project's long-term economic benefits can be more distinctly highlighted. As Hungary's PV power project continue to evolve, several factors contribute to the growing uncertainty surrounding their long-term economic viability. These include the investment costs associated with the three previously mentioned systems, fluctuations in green electricity prices, variations in PV efficiency, the extent of PV coverage in AV systems, and the impact of shading on plant species and agricultural yields within AV systems. These elements collectively amplify the complexity and unpredictability of the economic outcomes for AVS power projects over time. These outcomes are demonstrated in Table 26. The merits of agrivoltaic generation must be evaluated comprehensively, considering its adaptation to the subsidy system. This necessitates a focus on the economic advantages of AVS and the environmental benefits they provide. These benefits serve dual purposes: proving advantageous to land users and eliminating the necessity of investing in shade-growing systems and hail protection, thereby influencing the design of future subsidy frameworks. The economic profitability of AVS is primarily driven by the quantity of electricity fed into the grid and the prevailing price levels of grid-connected PV systems. However, it is crucial to consider that integrating PV system generation into the grid incurs additional costs, such as value-added and corporate income taxes. As evidenced by a pilot AV system in Germany, it is feasible to establish feed-in tariffs above traditional energy market prices for PV power projects and adapt incentive levels over time to ensure economic viability [257].

**Table 26. Comparison of economic results in baseline scenario**

| | Comparison | | Unit |
|---|---|---|---|
| | AVS vs PV systems | AVS vs ConAPS | |
| Surplus CAPEX (incl. apple) | 177 | 667 | th €/ha |
| Surplus (avg.) revenue from apple production | 2 | 0 | th €/ha |
| Value of electricity production | -12.6 | 38 | th €/ha |
| Static payback period | Endless | 17.4 | years |

*Source:* [184]

### 4.3.3. Sensitivity analysis

This research is grounded in multiple assumptions, requiring a systematic sensitivity analysis of critical financial parameters. The process begins by identifying uncertain variables and quantifying their deviations from baseline economic values. Key factors influencing the cost of AVS include CAPEX, financial costs, electricity pricing and energy generation efficiency. These variables significantly influence cost-benefit evaluations during AV system deployment considerations.

This analysis evaluates income fluctuations linked to CAPEX, agricultural outputs (e.g., apple production), system capacity, solar exposure, and electricity pricing under varying uncertainties to assess economic resilience. These calculations are performed under ceteris paribus conditions, isolating the impact of individual variables. The outcomes are visualized through sensitivity gradients, illustrating the proportional influence of each parameter. The Kaposvár Solar Power Plant Project is employed as a case study, selected due to its comprehensive cost-revenue data across AVS, GM-PV, and ConAPS. By analysing these configurations, the study quantifies the economic sensitivity of each system to market and operational variables. The results in Table 27 and Table 28 highlight comparative vulnerabilities and opportunities, offering insights into risk mitigation and subsidy optimization for hybrid energy-agricultural projects.

**Table 27. Parameter Sensitivity for GM-PV and AVS**

| | GM-PV | AVS |
|---|---|---|
| Power capacity (kWp/ha) | 500 | 500 |
| Area (ha) | 200 | 200 |
| CAPEX (th €/MWp) | 999 | 1344 |
| Sunshine hours (h/yr) | 1075 | 1075 |

*Source:* [184]

**Table 28. Calculation of AVS and GM-PV**

| Parameter | GM-PV | AVS | Unit |
|---|---|---|---|
| Necessary area for 1 MWp capacity | 2.00 | 2.66 | ha |
| Unit investment cost for 1 MWp capacity | 999 | 1344 | th €/MWp |
| Unit investment cost for 1 ha capacity | 500 | 672 | th €/ha |
| Unit investment cost of 1 ha apple plantation | 5 | 5 | th €/ha |
| Electricity production of 1 ha capacity | 538 | 405 | MWh/yr |
| Average electricity price in Hungary | 9.5 | 9.5 | €c/kWh |
| The average income of 1 ha apple plantation | 2 | 2 | th €/ha |

*Source:* [184]

Assuming equal capacity for both AVS and GM-PV systems with 100% coverage (Table 27), as demonstrated in Table 29, surplus investment is unlikely to yield a return, rendering it unprofitable for both PV developers and farmers. The price per kilowatt-hour of power is a primary factor influencing AV enterprises' revenue. This places a stringent boundary on investment, exerting cost pressure on PV developers regarding investment income accounting and posing significant challenges to farmers. Power generation enterprises should pay close attention to the government's AVS subsidies and PV electricity price policies when establishing AVS in farms. The government is also responsible for maintaining the stability of subsidies and electricity pricing to encourage corporate investment in renewable energy generation. For instance, if a one-time capacity investment ranging from 2 kWp to 50 MWp qualifies for an investment subsidy—potentially covering up to 24% of the total investment costs, as estimated in our baseline scenario for Agricultural-Photovoltaic Systems (AVS)—this could significantly shorten the AVS investment repayment period to less than 10 years. Such measures would enhance the financial attractiveness of renewable energy projects and promote their adoption. The government might also consider offering operational and net investment costs tax rebates.

Implementing these suggestions could potentially render AVS competitive when compared to PV.

**Table 29. Comparative analysis of economic results in the scenario with equivalent capacity of AVS and PV System**

| | Comparison | | Unit |
|---|---|---|---|
| | AVS vs PV systems | AVS vs ConAPS | |
| Surplus investment cost (incl. apple) | 177 | 667 | th €/ha |
| Surplus (average) income from apple production | 2 | 0 | th €/ha |
| Value of electricity production | 0.0 | 51 | th €/ha |
| Static payback period | 88.7 | 13.1 | years |

*Source:* [184]

If the surplus investment cost for apple plantations utilizing a V-shaped system (highly intensive) increases, there is potential for adopting AVS, leveraging farmer-generated revenue. Due to their high densities, V-systems often yield more than other systems. However, the V-system has drawbacks, including expensive initial tree training, apple plantation investment costs, and potential disadvantages, such as smaller fruit size than the vertical axis planting system [258]. It is important to note that PV power generation costs vary significantly across regions, allowing for an optimized PV industry layout by considering factors such as solar irradiance, climate conditions, and land expenses. The total investment cost is critical in determining the expenses associated with PV panel installation and apple orchard establishment. A substantial reduction in overall costs would significantly lower PV power generation expenses.

This study's analysis highlights that construction investment significantly influences both PV power generation costs and apple orchard setup, while interest expenditures have a relatively minor impact. However, due to the high upfront construction costs and other contributing factors, financial institutions often hesitate to invest in AV systems. Consequently, agrivoltaic projects require government policy support during their initial production phase, as their production costs are not yet competitive enough to attract private investment (see Table 30).

**Table 30. Comparative indicators of the economic feasibility of various production systems**

| | Comparison | | Unit |
|---|---|---|---|
| | AVS vs PV systems | AVS vs ConAPS | |
| Surplus investment cost (incl. apple) | 177 | 667 | th €/ha |
| Surplus (average) income from apple production | 2 | 0 | th €/ha |
| Value of electricity production | 0.0 | 51 | th €/ha |
| Static payback period | 88.7 | 13.1 | years |

*Source:* [184]

Hungary ranks among the top ten most promising countries in South-Eastern Europe and Central Eastern Europe, as assessed by favourable conditions for investing in the expansion PV systems [259]. Furthermore, advancements in agrivoltaic technology have improved land use efficiency for PV power generation projects in Hungary. The project adheres to government regulations, demonstrates strong relevance, and aligns with national clean energy development strategies. Upon completion, it is anticipated to drive the growth of AVS, increase household incomes, and support efforts toward agricultural diversification. Furthermore, AVS plays a pivotal role in advancing the integration of the agricultural and solar energy sectors within the renewable energy industry.

## 4.4. Sunlight Availability and Solar Efficiency: Evaluating energy yield potential for agrivoltaic systems

In this section, the influence of local climatic conditions on solar energy generation is analyzed for the two selected study sites: Kaposvár (Somogy County) and Mezőcsát (Borsod-Abaúj-Zemplén County), Hungary. These regions differ in their geographical and meteorological profiles, which are essential factors in assessing the feasibility and productivity of agrivoltaic systems. This builds on the background introduced in the "Climatic Background of the Study Areas" (see Section 3.4), serving as a foundation for interpreting solar generation performance in realistic environmental settings.

This study utilizes solar power generation data provided by MAVIR [260] for two representative seasonal periods: January 1–2, 2025 (winter) and June 1–2, 2025 (summer). The data encompass a continuous 32-hour window, spanning from 6:00 AM on the first day to 2:00 PM the following day, allowing for an in-depth examination of daily solar generation patterns.

The datasets include five key variables that characterize the forecasting and measurement of solar power generation. The day-ahead forecast represents predictions generated 24 hours in advance, relying on weather models and historical trends. The intraday forecast refines these predictions using updated meteorological data during the day, improving temporal resolution and accuracy. The current estimate further updates forecasts in near real-time, incorporating the latest available information to enhance precision. These forecast layers represent the progression from long-term to short-term predictive models. Actual solar generation is quantified through two complementary measurements: the net trade settlement metering, which reflects the amount of solar energy reported for market settlements, and the net operation control measurement, indicating the real-time solar power injected into the grid and managed by system operators.

Figure 29 displays the comparison of solar power generation forecasts and actual measurements for the winter period January 1–2, 2025. During the winter period, solar generation remains relatively low, as expected due to the shorter photoperiod and lower solar elevation angle. Forecast performance is generally less accurate, with noticeable discrepancies particularly during the morning and late afternoon hours. The day-ahead forecast consistently overestimates generation, while the intraday and current forecasts exhibit improved alignment with actual measurements. This highlights the difficulty in modeling winter irradiance conditions, which are often affected by cloud cover, fog, and low solar intensity. These forecasting challenges in Hungary have also been linked to external factors such as Saharan dust intrusions, which significantly reduce solar irradiance and increase forecast errors, especially in the winter months [261]

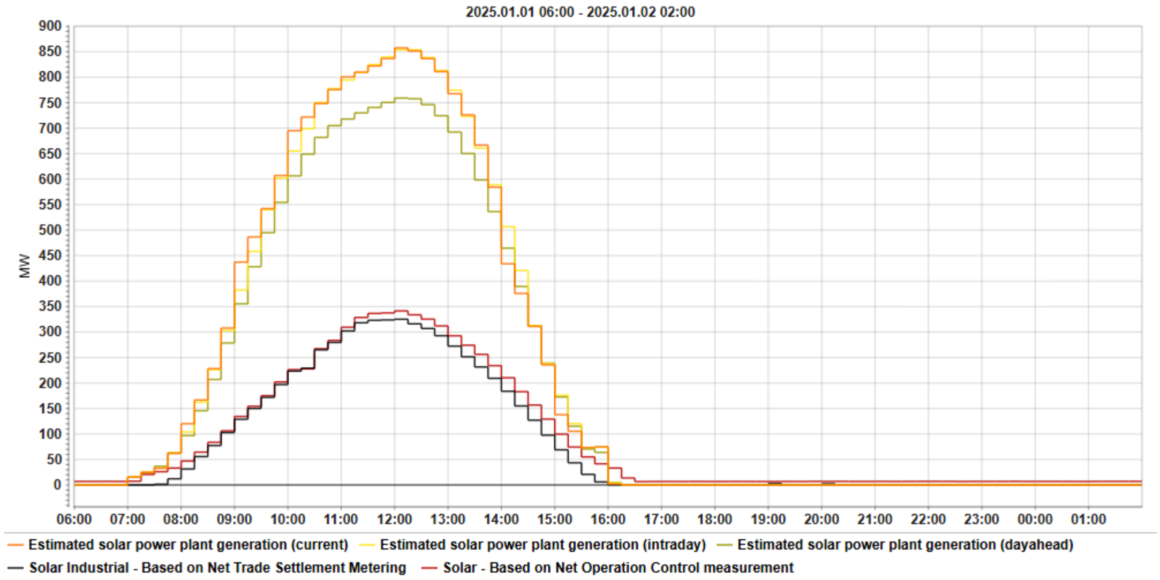

**Figure 29: Solar power generation forecasts and actual measurements for the winter period. Source:** [260]

In contrast, the summer period (see Figure 30) demonstrates significantly higher levels of solar production, reflecting extended daylight hours and stronger solar irradiance. Forecasts are considerably more accurate across all time horizons. Although slight underestimations occur around peak generation periods in the day-ahead forecast, both intraday and current forecasts closely mirror actual output. The improved alignment between forecasted and measured values during summer months corresponds with the findings of national-scale PV performance assessments in Hungary, which report enhanced reliability of solar predictions under stable atmospheric conditions [262].

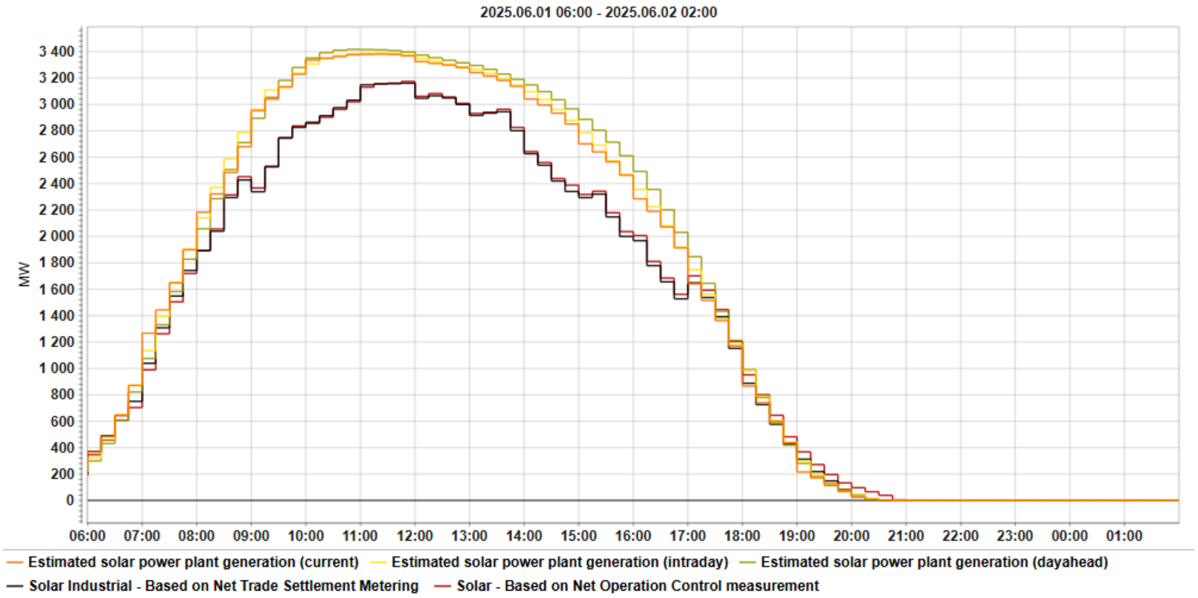

**Figure 30: Solar power generation forecasts and actual measurements for the summer period. Source:** [260]

Solar energy generation is highly dependent on geographical location, climatic conditions, and seasonal variations in solar radiation. Hungary, being a central European country, experiences a continental climate, which significantly influences solar energy generation potential. In this comparison, we use specific climatic data for Kaposvár and Mezőcsát to assess the reasons behind the differing solar energy generation potentials in these two regions of Hungary. Seasonal analysis further underscores these differences. Figure 31 illustrates the seasonal fluctuation in PV electricity generation in Kaposvár, presented as minimum, average, and maximum daily output per installed kilowatt across the four meteorological seasons. In summer, Kaposvár reaches its peak output, averaging 6.83 kWh/day/kW, ranging from 5.9 to 7.4 kWh/day/kW. Strong solar irradiance, long photoperiods, and stable atmospheric conditions drive this high yield. Despite elevated module temperatures that could reduce efficiency, the abundant radiation offsets potential thermal losses. Spring maintains robust performance, with an average of 4.75 kWh/day/kW (range: 3.8–5.5 kWh/day/kW), thanks to moderate temperatures, increased sunlight, and low thermal resistance in PV modules. Autumn, however, sees a drop to an average of 3.10 kWh/day/kW, driven by lower solar angles, shorter daylight, and increased cloud cover. In winter, output is lowest, averaging 1.74 kWh/day/kW (range: 1.2–2.3 kWh/day/kW) due to low sun angles, frequent overcast, and possible snow accumulation on panels.

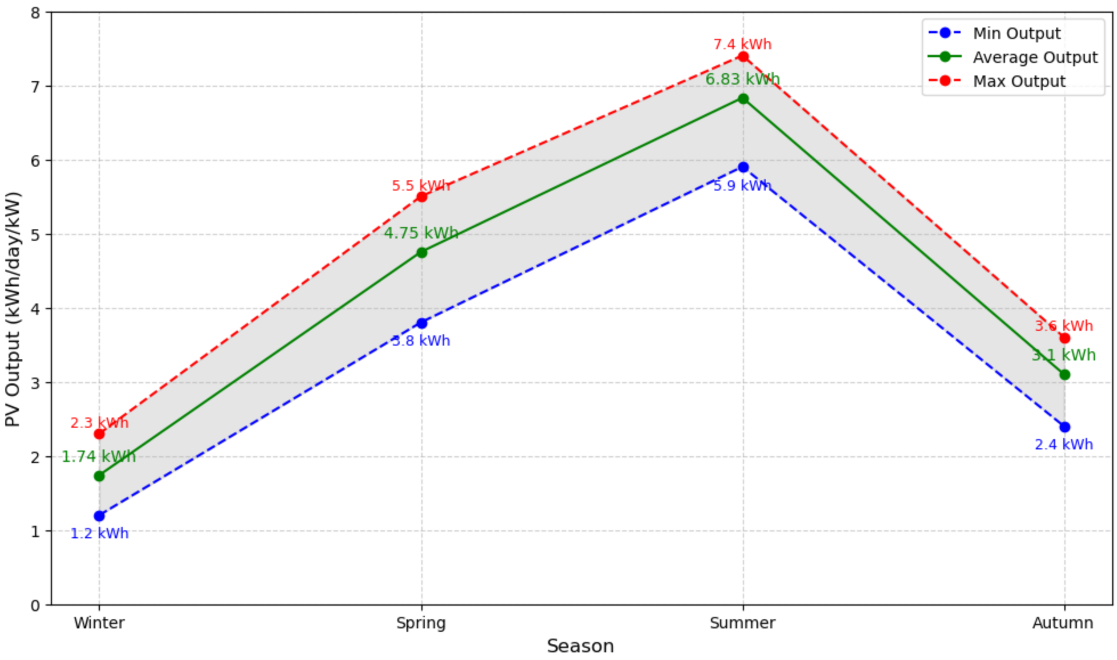

**Figure 31: Seasonal fluctuations in photovoltaic performance across minimum, mean, and peak levels in Kaposvár. Data source:** [263,264]

In contrast, Mezőcsát's PV performance is considerably lower across all seasons (Figure 32). Seasonal average daily output values, derived from its annual GHI and adjusted for seasonal distribution, indicate outputs of approximately 1.26 kWh/day/kW in summer, 0.98 kWh/day/kW in spring, 0.42 kWh/day/kW in autumn, and only 0.14 kWh/day/kW in winter. These reduced values reflect the impact of Mezőcsát's greater cloud cover, higher humidity, and slightly more variable weather patterns. Although Mezőcsát's cooler temperatures might slightly improve PV module efficiency in colder months, this advantage is more than offset by limited solar irradiance and shorter days. Additionally, Mezőcsát's terrain, which is more rural and moderately hilly compared to Kaposvár's flat and solar-optimized landscape, may constrain optimal panel placement and orientation.

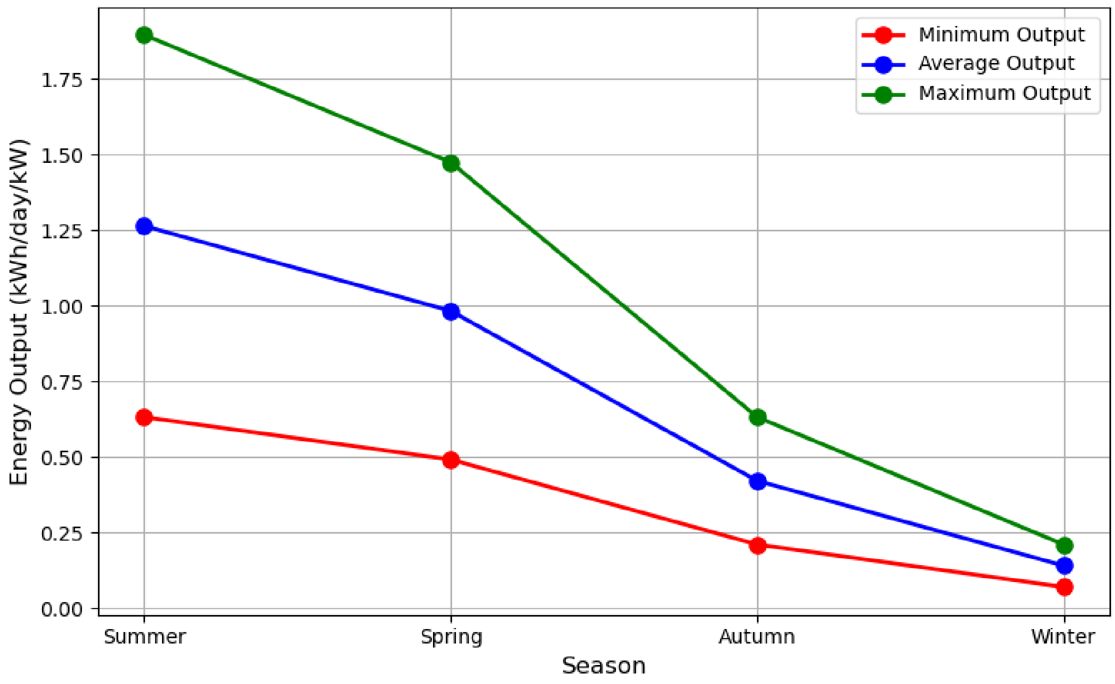

**Figure 32: Estimated Seasonal Photovoltaic Energy Output in Mezőcsát. Data sorce:** [217,265,266]

From an infrastructural perspective, Kaposvár is more developed in terms of renewable energy integration and accessibility to grid systems, which facilitates larger-scale solar deployment. This, coupled with its geographical and climatic advantages, positions Kaposvár as a superior location for solar energy development in Hungary. Mezőcsát, while still viable for localized PV installations, experiences lower overall solar potential due to less favorable environmental conditions.

The differences in solar energy generation between these two regions are therefore not merely a result of geographic positioning but are amplified by interrelated climatic and seasonal factors. Kaposvár's combination of higher GHI, favorable temperature ranges, and clearer atmospheric conditions supports a more consistent and efficient solar energy profile throughout the year. In comparison, Mezőcsát's slightly lower irradiation levels, coupled with higher humidity and reduced winter sunlight, lead to diminished seasonal and annual PV performance.

The agrivoltaic concept holds strong potential for Hungary, especially given the country’s favorable solar irradiance levels ranging from 1,200 to 1,400 kWh/m² annually in many regions [267]. While agrivoltaics is still in the early stages of development in Hungary, international implementations provide a valuable benchmark. For instance, large-scale systems in France [9], Germany [43], and Japan [268] have demonstrated that dual land use can maintain agricultural productivity while generating substantial solar energy. These systems optimize solar efficiency through elevated or semi-transparent PV modules, ensuring adequate light distribution for crops. Studies such as [22] also highlight microclimate improvements under PV panels, which can be particularly advantageous during hot summers in Hungary.

Overall, the results confirm that the energy yield potential in agrivoltaic systems is not only determined by system design and geographic location but also by the accuracy of solar irradiance and power production forecasts. Forecast accuracy is seasonally dependent and strongly influenced by meteorological variability, particularly under continental climate conditions like those in Hungary. As the forecasting horizon shortens, performance improves markedly, highlighting the essential role of high-resolution, real-time meteorological inputs. Moreover, actual production data based on operational control measurements demonstrate their importance in validating forecast precision for both grid management and energy market operations. Given the rapid growth of PV capacity in Hungary, which exceeded 5.8 GW by 2023, improved forecasting accuracy is essential for supporting system stability and market integration [269,270].

### 4.5. Discussion

This discussion synthesizes existing literature with theoretical cost estimates for implementing agrivoltaic systems in Hungarian apple orchards. The analysis compares the system's capital and operating expenditures with those of conventional photovoltaic installations and evaluates the potential impacts on agricultural practices.

The cost structure of the agricultural component is largely mirrored by what is found in the literature. Investment costs for essential infrastructure such as irrigation and frost protection systems [271,272] and planting materials [273] fall within the average ranges reported in previous studies. In contrast, expenditures related to hail protection systems [173,247] appear at the lower end of the expected spectrum. Although these initial estimates agree with the literature, further refinement is expected as actual data from project implementations becomes available.

When comparing ConAPS and GM-PV systems with an agrivoltaic configuration, the analysis reveals a nearly twofold increase in CAPEX for the integrated system. This rise is primarily attributable to the costs associated with photovoltaic modules, supporting substructures, installation, and balance-of-system components [24,36,55]. On the other hand, OPEX is reduced by almost 20% in the agrivoltaic setup. The findings for a mature "Golden Delicious" apple orchard in France align with findings from Juillion et al. [10] and Schindele et al. [24], indicating a total CAPEX of €1,343,850 for AVS installation and commissioning, compared to €1,031,035 for GM-PV systems. Additionally, the IRR for AVS is 1.6% lower than the WACC. Such trends—an increase in CAPEX coupled with a decrease in OPEX are consistent with findings in related studies, even though most of those investigations have focused on arable rather than perennial cropping systems.

A further theoretical consideration involves potential cost reductions in post-installation soil tilling. These savings hinge on the multifunctional use of machinery initially employed for installing hail protection nets, which could also serve the agrivoltaic system, provided that an adequate market for such dual-purpose equipment is developed. In apple farming, the breakdown of operating costs shows notable deviations from some literature values. For instance, compared to [274], the current theoretical framework suggests:

- A threefold increase in spending on plant protection measures.
- Only about one-third of the expenditure on crop regulation.
- Approximately a 25% reduction in harvesting costs.

From a plant protection perspective, maintaining optimal microclimatic conditions is essential for minimizing disease risks in apple orchards. The AVS creates partial containment through overhead PV panels, which can lead to increased humidity and reduced air circulation, factors that are known to favour fungal pathogens like Venturia inaequalis and Podosphaera leucotricha [148,275]. The extent of this risk depends significantly on the design of the AVS. Factors such as the height and spacing of the PV panels, system transparency, and local climatic conditions all influence the microclimate under the canopy [22,53]. Furthemore, agrivoltaic systems with more open panel designs or greater spacing may allow for better air exchange and reduced humidity, mitigating potential disease development.

From an agronomic perspective, at the early stages of development, apples in the agrivoltaic zone exhibited small fruit sizes and immature morphology, with predominantly green colouration, indicating limited maturation. In contrast, apples in the control zone began to show slight red hues, suggesting the onset of ripening. Leaf development was vigorous in both zones, and active tree growth was observed across both environments. As the season progressed, apples in both zones increased in size and reached mid-ripening stages, with apples in the agrivoltaic zone retaining predominantly green skin with slight red tinges. Field observations revealed no significant stress or disease symptoms in the agrivoltaic or control zones despite the potential risks associated with increased humidity under the agrivoltaic panels. These findings suggest that the risk of disease, including fungal pathogens that thrive in high-humidity conditions, may not be elevated in agrivoltaic systems when air circulation is effectively managed. This suggests that with proper management, such as maintaining adequate air circulation, the risk of disease in agrivoltaic systems may not be significantly higher [275].

Nevertheless, harvesting remains the most significant cost driver, typically representing nearly 50% of total operational expenses. In the agrivoltaic system evaluated here, the acquisition costs are usually up-front costs compared to GM-PV systems, as substructures are needed to place the PV modules. Agrivoltaics in apple farming contribute significantly higher substructure costs due to the spacing between two PV systems and higher vertical clearance.

In a broader context, author [276] highlights V-shaped systems' high apple yield efficiency, which balance crop production and vegetative growth, contingent on their economic performance. This study further emphasizes that the profitability of AV systems and the costs associated with establishing apple orchards are heavily influenced by financial factors, with high CAPEX posing a potential barrier compared to conventional GM-PV systems.

However, Malu et al. [47] argue that land-use cost for AV system installation is less than for GM-PV systems due to a reduced PV packing ratio in AVS compared to GM-PV farms. Authors contend that while certain combinations may lack profitability, AV systems remain advantageous by protecting against hail and sunburn damage and diversifying farmers' revenue streams. These benefits underscore the potential of AV systems to enhance agricultural resilience and economic sustainability despite initial financial challenges.

The study aimed to assess the economic feasibility of integrating agrivoltaic systems within Hungarian apple orchards, with hypotheses formulated to guide this evaluation. The findings present varying degrees of alignment with these hypotheses, providing insights into the financial dynamics of this integration.

1. Alignment with Hypothesis 1: The financial analysis confirms that larger agrivoltaic systems benefit from economies of scale, leading to better financial indicators higher NPV and IRR due to optimized CAPEX distribution and improved energy output

relative to investment costs. While agrivoltaic systems demonstrate a notable increase in revenue through dual land use, the financial viability is highly dependent on specific conditions such as energy pricing, subsidy availability, and orchard productivity. The results indicate positive economic performance but with variations across different scenarios. In this context, the IRR for AVS stands at 27%, significantly higher than the WACC. This relationship indicates that the investment is viable and favourable, as the IRR exceeds the WACC, suggesting that the project generates sufficient returns to cover the cost of capital and compensate for associated risks. For AVS, the IRR and WACC comparison highlights the financial gap that suggests reducing costs through technological innovations and operational efficiencies or enhancing revenue streams through strategic business models. The investment's attractiveness can be improved by addressing these areas, potentially realigning it with shareholder interests and ensuring a better alignment between risk and return.

2. Partially rejected with Hypothesis 2: The hypothesis proposed that the interaction of FIT, investment costs, apple yield, and sunshine variability produces significant nonlinear effects on the unit costs of electricity and apple production in agrivoltaic systems, leading to more effective cost reduction through integrated optimisation. However, the spider diagram presented in Figure 7 reveals that the unit cost of apple production is predominantly influenced by FIT prices, with significant correlation observed in only 20% of the cases. In the majority of cases, FIT prices exhibit only a marginal effect on the unit cost (approximately 50 EUR/t of unit cost of apple production). Meanwhile, the other variables, such as apple yield at maturity, net investment cost, consumption ratio, and sunshine hours per year, demonstrate minimal to negligible impact on the unit cost of apple production.

   These results suggest that, contrary to the hypothesis, the combined nonlinear interactions among the analysed variables are limited, with FIT price being the primary driver of unit cost variability. Therefore, the hypothesis is partially rejected, as the expected significant nonlinear tradeoffs and integrated optimization effects were not strongly supported by the data under the current simulation parameters.

3. Alignment with Hypothesis 3: The analysis indicates that variability in subsidies and feed-in tariffs introduces significant economic uncertainty, which, coupled with high agrivoltaic component costs, elevates the LCOE and financial risk profile of agrivoltaic installations. In contrast, GM-PV systems consistently demonstrate lower and more stable costs under current regulatory frameworks. However, sensitivity analysis shows

that aggressive cost control and targeted innovation in agrivoltaic components can mitigate these disadvantages. Thus, the hypothesis is accepted, highlighting the critical need for policy stability and technological advancement to enhance agrivoltaic competitiveness.

4. Support for Hypothesis 4: As agrivoltaic systems have not yet been implemented in Hungary, precise estimations remain challenging. However, according to research studies, the analysis supports Hypothesis 4 by confirming that Hungary's solar irradiance and climatic conditions are conducive to the operational efficiency of agrivoltaic systems. Although integrating agrivoltaic systems contributes to financial resilience by diversifying income streams, the extent of risk mitigation related to climate variability and market fluctuations was less than hypothesized. This suggests that while agrivoltaic systems provide a buffer against economic volatility, additional financial mechanisms may be necessary to stabilize cash flows. These conditions facilitate optimal energy production without adversely affecting apple yields, as conventional apple yield data was used for estimation. Supporting the hypothesis that environmental factors positively influence the financial viability of these systems.

Overall, these findings comprehensively assess the economic potential and financial challenges associated with agrivoltaic systems in Hungary. The results emphasize the importance of aligning economic strategies with technological advancements and policy frameworks to realize the benefits of this sustainable agricultural practice fully. Future research should focus on optimizing cost structures and exploring innovative financial models to enhance the economic feasibility of agrivoltaic systems.

# 5. CONCLUSIONS

## 5.1. Systematic literature review conclusion and implications

The SLR indicates that current research trends and technological advancements establish foundational priorities for the innovative development of agrivoltaic systems in the short and long term. These priorities encompass (1) widespread adoption of environmentally sustainable and resource-efficient agricultural practices, (2) accelerating the transition to renewable energy sources, and (3) developing multifunctional, high-productivity agrivoltaic systems with minimal ecological impact.

This study employs SLR methodology to evaluate bibliometric analyses of agrivoltaic systems. Among the 121 sources analyzed, over 50% were published within the past year, reflecting rapidly growing scholarly interest in the field. While limited studies propose practical implementations of agrivoltaic systems, significant attention is directed toward the economic and financial implications of their synergistic integration with agriculture. Key themes include implementation costs, revenue streams, cost-benefit dynamics, and metrics such as NPV and LCOE specific to AVS.

The methodological strengths of the studies included the predominant reliance on technical and infrastructural frameworks, greenhouse-based cultivation models, conventional agricultural planting, often supported by large-scale datasets. However, limitations included using primary data and frequently restricting data analysis to descriptive statistics. Despite these constraints, the academic quality of agrivoltaic research is improving, evidenced by comparative analyses of AV and GM-PV systems, innovative photovoltaic designs, and an increased focus on the socioeconomic benefits of agrivoltaics for energy and agricultural sectors.

The results from this systematic literature review have several important implications. The increasing interest in agrivoltaic systems suggests a future where agriculture and energy production can be more closely integrated, leading to more sustainable and resource-efficient practices. The identified priorities for developing agrivoltaics, such as the transition to green electricity and environmentally friendly use of agrivoltaic systems, indicate the potential for significant environmental and economic benefits. Furthermore, the need for more comprehensive research on the ecological effects, crop selection, technical and social adaptation, and long-term economic implications of AVS underscores the importance of ongoing investigation in this field. By understanding why farmers choose to implement agrivoltaic systems and developing a recommendation system to facilitate this decision-making, we can accelerate the adoption of these systems and realise their benefits.

## 5.2. Conclusion and implications of the theoretical application of agrivoltaic system in Mezőcsát solar farm

This study underscores the critical importance of reducing costs associated with key components. It also highlights the positive impact of favourable electricity pricing and lower discount rates on AVS's financial viability.

The research provides a comprehensive economic evaluation of agrivoltaic systems applied to apple cultivation, expanding beyond conventional metrics to incorporate OPEX, CAPEX and unit cost. Advanced Monte Carlo simulations are employed to address uncertainties and deliver essential insights into risk mitigation strategies. By concentrating on theoretical agrivoltaic project in Mezőcsát, Hungary, with a solar PV capacity of 38,269 kWp, the study emphasizes the significance of efficient space utilization and sustainable land management in improving the economic feasibility of such projects.

The investment analysis in Chapter 4.2.1 reveals that, under the baseline scenario, the project demonstrates financial attractiveness, with 75% of Monte Carlo simulation iterations yielding a positive NPV. Regression and correlation analyses identify the FIT price as the most influential economic factor, followed by financing conditions (discount rate). Other variables, such as sunshine hours, inflation rate, and net investment cost, have negligible impacts on the project's financial outcomes.

Chapters 4.2.2 and 4.2.3. analyze the unit costs of electricity and apple production within AVS and assess their competitiveness. A key advantage of AVS lies in its ability to mitigate financial risks by balancing the unit costs of dual outputs higher electricity generation costs are offset by lower apple production costs compared to their independent production. This analysis highlights the system's dependence on FIT prices and state subsidies to maintain competitiveness. While subsidies currently enhance the economic appeal of agrivoltaic systems in apple farming, a comprehensive assessment of their long-term sustainability is essential.

The findings in Sections 4.2.1, 4.2.2, and 4.2.3 emphasize the critical role of agricultural yield in determining the economic viability of AVS. Even marginal increases in agricultural yield can offset higher PV sector costs. Customizing PV modules to meet the specific demands of the agrivoltaic market, where there is a higher willingness to pay, could significantly improve the financial feasibility of such projects.

In light of Hungary's rapid renewable energy development, it is recommended that effective policies be integrated with market dynamics, investments in energy infrastructure be increased, and the coordinated growth of centralized and distributed energy systems tailored to local conditions be promoted. This approach will facilitate the development and utilization of cost-effective renewable energy solutions.

The findings of this research hold significant implications for advancing AVS. Key findings stress the necessity of lowering costs for critical components and the advantageous effects of optimized electricity pricing structures and reduced discount rates on financial performance. These insights can guide policymakers and industry practitioners in their decision-making processes.

The research underscores agricultural yield as a central determinant of AVS economic feasibility, demonstrating that even incremental gains in crop productivity can offset elevated PV sector expenses. This highlights the importance of prioritizing yield-enhancing practices in AVS design and management to strengthen economic viability. Furthermore, the study identifies opportunities to align PV technologies and services with the agrivoltaic market's unique demands, where stakeholders exhibit greater willingness to invest in tailored solutions.

The analysis also reveals the system's dependence on FIT mechanisms and state subsidies to maintain competitiveness, underscoring the need for stable policy frameworks and market incentives to support AVS implementation. Policymakers and regulators can leverage these insights to craft targeted subsidies, risk-sharing mechanisms, and long-term pricing guarantees that align with renewable energy goals.

A novel contribution of this work lies in its development of apple orchard management strategies designed explicitly for agrivoltaic stakeholders, including facility managers, investors, and farmers. By addressing their distinct operational and financial requirements, the study provides a pathway to harmonize agricultural productivity with renewable energy generation, fostering sustainable and economically resilient agrivoltaic practices. This dual-focused approach bridges gaps between energy infrastructure and agricultural innovation, offering a scalable, policy-driven AVS deployment model.

## 5.3. Conclusion and implications of considering agrivoltaic systems at Kaposvár solar photovoltaic park

To reconcile the ongoing "food or energy" debate, AVS must address the interplay between PV power generation and agricultural production. This involves enhancing AV benefits and land use efficiency, premised on the economic data and conclusions drawn by Schindele et al. [24]. Our research identifies and discusses various factors influencing AVS output, exemplified through the Kaposvár Solar Power Plant Project. By analyzing pertinent data from a typical day at the photovoltaic power station, we visually compare and contrast the output of AVS and PV systems and ConAPS.

A comprehensive sensitivity analysis is conducted using a statistical approach to evaluate multiple influencing factors and predict decision outcomes, offering a more rigorous and systematic framework than basic correlation analysis. This method is applied to assess the competitiveness of AVS relative to standalone PV and agricultural systems. The study establishes a foundation for identifying primary factors to serve as predictive inputs for PV power generation models by analysing key economic variables.

Farmers in Hungary face numerous challenges in developing agrivoltaic systems, given that such development requires careful consideration of investment costs and benefits in relation to government legislation geared towards agrivoltaic development. To navigate these challenges, farmers should standardize their actions, innovate scientifically and technologically, optimize their agricultural production structure, and explore various forms of collaboration with PV developers.

Modern agriculture is characterized by the integration of advanced technologies, data-driven practices, and sustainability principles to enhance productivity, resource efficiency, and resilience. Key criteria for modern agriculture involve precision farming, mechanization, sustainable input management, and digital technologies (e.g., GPS, sensors, drones), alongside climate-smart practices and high-yield systems [275,277]. In the coming years, as awareness of AVS grows and modern agricultural practices in Hungary continue to advance, the declining costs of PV power generation and the energy efficiency benefits of agrivoltaics will play a pivotal role in driving their adoption in rural regions. Several factors, such as high investment costs and low farmer income, inhibit the implementation of AV systems, necessitating government support for building AV systems in Hungary due to non-competitive production costs.

The study highlights that the successful utilization of sensitivity analysis for predicting the economic outcomes of AVS advocates for its broader adoption within the sector. This technique could help stakeholders comprehend the comparative profitability of AVS vis-à-vis conventional photovoltaic and agricultural methodologies.

The study concludes that the profitability of AVS is substantially influenced by financial considerations, particularly high capital expenditures. This observation carries implications for pricing strategies and funding models within the field. It suggests that stakeholders may need to explore innovative funding architectures and pricing structures to augment the economic appeal of these systems.

The necessity for farmers to adapt and innovate insinuates that training and support programs could play an instrumental role in promoting the adoption of AVS. Such programs may encompass technical training, financial planning assistance, and guidance on forging collaborations with photovoltaic developers.

The study's finding that governmental support is indispensable for successfully deploying AV systems in Hungary underlines the significance of policy considerations in the development of AVS. Policymakers are encouraged to ponder how they can optimally support this nascent field, potentially through subsidies, legislative measures, and public education campaigns.

### 5.4. Main findings of the study

The study found that agrivoltaic systems could effectively balance photovoltaic power generation and agricultural production, enhancing land use efficiency. It was observed that using sensitivity analysis could be beneficial in predicting the economic outcomes of agrivoltaic systems and understanding their profitability compared to conventional methods. Financial considerations and exceptionally high capital expenditures heavily influence the profitability of AV systems, indicating the need for innovative funding and pricing strategies. Furthermore, the study identified the need for farmer training and support programs to adopt agrivoltaic systems successfully. Government support was found to be crucial for the successful implementation of AV systems. Lastly, the study revealed the potential of agrivoltaics in diversifying farmers' income and promoting sustainability in the agricultural sector.

### 5.5. New scientific results

The study presented new insights into applying agrivoltaic systems in the context of the Mezőcsát solar farm and Kaposvár solar photovoltaic park. It provided a theoretical basis for implementing such systems, pointing out the potential challenges and solutions. The research also highlighted the need for a systemic approach that considers various factors like the adoption of sensitivity analysis, innovative funding and pricing strategies, the importance of training and support programs for farmers, and the role of government support. These findings contribute to the existing knowledge of agrivoltaic systems and provide a practical guide for their implementation in similar contexts. The following points encapsulate the novel contributions made by this research:

1. The financial analysis revealed that agrivoltaic systems substantially enhance key economic indicators such as NPV and IRR, leveraging dual revenue streams from both energy production and agricultural yields.

2. Sensitivity analysis pinpointed vital financial determinants, including variations in solar irradiance and agricultural commodity prices, highlighting the necessity for adaptive financial modelling to manage investment risks effectively.
3. The study identified power purchase agreements (PPAs) and bespoke feed-in tariff structures as pivotal financial instruments crucial for ensuring predictable cash flows and enhancing the investment appeal of agrivoltaic projects.
4. Emphasizing the role of farmer education, the research advocates for capacity-building initiatives that enhance financial literacy and technical skills, thus optimizing operational efficiency and economic benefits within agrivoltaic systems.
5. The analysis underscored the critical impact of government policy support, specifically through fiscal incentives and subsidies, in lowering capital expenditure barriers and facilitating the broader adoption of agrivoltaic technologies, aligning with national energy transition goals.

These findings provide a theoretical and practical foundation for agrivoltaic system implementation and offer a strategic framework for maximizing their economic viability in similar agricultural and energy settings in Hungary.

### 5.6. Future research work

Exploring agrivoltaic systems within apple orchards has opened up several avenues for future research, which will be critical to advancing this technology's understanding and practical implementation. Given the complexity and multifaceted nature of agrivoltaics, the following areas are recommended for further investigation:

1. Microclimate Analysis: Future studies should delve into the microclimatic conditions within agrivoltaic systems, particularly in apple orchards. Understanding how these conditions impact operating costs and crop yields is crucial for optimizing system design and management. AVS designed to cover apple tree canopies may limit direct rainfall contact with leaves, leading to dust accumulation. This could impair photosynthesis, leaf health, and crop yields due to reduced natural rain-washing. Dust accumulation can block sunlight, hinder photosynthetic efficiency, and potentially increase disease risk, reducing fruit quality and yields. Additionally, research should explore the accumulation of dust and pesticides on photovoltaic panels due to agricultural practices and their subsequent effects on microclimatic conditions. For future research, the following approaches should be explored to mitigate dust accumulation in agrivoltaic systems (AVS) for apple orchards:

  - Regular irrigation (sprinkler or drip) can wash dust off leaves, maintaining photosynthetic activity. Systems should be optimized to prevent waterlogging and soil erosion.
  - Adjusting solar panel angles and height can improve rainwater interception and airflow, reducing dust accumulation. While this may increase costs, it ensures long-term system efficiency.
  - Installing windbreaks or dust barriers around the orchard can reduce dust infiltration. While this is a long-term solution, it improves overall plant health and reduces dust deposition.

2. Social Acceptance: As highlighted in Section "Literature review", the social acceptance of agrivoltaic technology is pivotal for its widespread adoption. Future research should aim to gather and analyze data on social perceptions and attitudes towards agrivoltaics, identifying potential barriers and facilitators to acceptance among different stakeholders.
3. Market Flexibility: Examining agrivoltaic systems that permit flexibility in crop and cultivation methods could enhance market acceptance. This is particularly relevant in regions with variable agricultural demands or environmental constraints. Such flexibility could make agrivoltaic systems more attractive to farmers who wish to diversify their agricultural practices.
4. Water Resource Management: In areas with limited water resources, investigating the potential for rainwater collection and redistribution within agrivoltaic systems could prove beneficial. Research should focus on the cost savings and potential increases in agricultural yield that could arise from improved water management practices.
5. Integration of Robotics: The intersection of agrivoltaics and robotics presents a promising area for study. Future research should assess how integrating robotic technologies with agrivoltaic systems could affect cost structures compared to conventional farming methods. This includes examining labour savings, efficiency gains, and potential impacts on crop management.
6. Complex System Integration: The integration of AV systems introduces additional complexity, necessitating further investigation to understand the interactions between energy production and agricultural outputs fully. The PV module was used in the pilot plant in a fixed position to facilitate follow-up work. It would be interesting for future

work to investigate the extent to which a tracking system could positively affect apple yield.

These research directions aim to enhance the technical and economic efficiency of agrivoltaic systems but also strive to ensure their sustainable integration into existing agricultural and societal frameworks. Future investigations should prioritize systematically collecting multi-regional apple yield data and its statistical correlation with annual wholesale market trends to quantify agroeconomic relationships in orchard systems. In addition, further information could be used to make a fluctuation in future apple prices separated by prices for the mainly ancient and local apple varieties such as Sóvári, Batul to refine further the forecasts, which did not possible to accurately assess how much yield may be produced and the potential economic outcomes within AVS framework in Hungary. Such further development could make well-founded statements about income stabilization. By addressing these key areas, future studies can contribute significantly to developing agrivoltaics as a viable and widely accepted component of sustainable agriculture and renewable energy production.

# 6. SUMMARY

This dissertation provides a comprehensive analysis of the economic feasibility of agrivoltaic systems, with a specific focus on their implementation in Hungary. By examining CAPEX and OPEX across various system designs, the study identifies key financial drivers and trends impacting the cost dynamics of these systems. The analysis highlights that module costs dominate CAPEX for most agrivoltaic configurations, especially agrivoltaic systems in apple orchard farming, where substructure costs are more pronounced. The study finds limited potential for cost reduction through scaling for modules and inverters, indicating their reliance on broader market factors rather than project-specific efficiencies. Nonetheless, reducing module costs could significantly influence overall CAPEX, given their substantial share in total expenses. Substructure costs, particularly in smaller systems, present opportunities for reduction through standardization and material-efficient design, offering a pathway to enhanced cost efficiency.

OPEX trends align with those observed in CAPEX, indicating interdependencies between the two. The study reveals that GM-PV systems have lower OPEX than elevated systems up to a certain scale. Notably, the percentage change in OPEX across smaller areas is less pronounced than the corresponding change in CAPEX for all system types. Among them, ConAPS exhibit the most significant decrease in OPEX, eventually becoming more cost-effective than AV systems.

The unit cost of electricity for elevated systems declines significantly, highlighting the benefits of economies of scale. The feed-in tariff is a benefit and compared with the cost of PV power generation on the same time scale, it helps to judge the long-term sustainability of PV power projects' economic benefits and identify the main factors affecting the economic benefits of PV power projects. However, even at larger scales, the cost of electricity production with elevated systems remains substantially higher than with GM-PV systems. This reinforces the existing literature's position that GM-PV systems are the most cost-effective configuration.

The marketability of agrivoltaic systems as an investment in renewable energy is complex and multifaceted, influenced by numerous factors within a dynamic market. The study concludes that the scalability of systems enhances their marketability, particularly for conventional apple systems and ground-mounted photovoltaic system configurations, which benefit from specific subsidies under the common agricultural policy (CAP) framework. However, GM-PV systems emerge as the most economically viable option, even without additional subsidies, although their attractiveness diminishes for smaller installations.

According to theoretical case studies of AVS projects in Hungary in the papers, the economic benefits of the case project depend on the discount rate. They cannot be realized stably, indicating that there is still uncertainty in the long-term economic benefits, which is further strengthened by the CAP and/or local government subsidies.

The sensitivity analysis shows that the first factor affecting the economic efficiency of the case project is the technical factor (annual utilization hours), followed by the policy factor (feed-in tariff, PV subsidy), and the economic factor (unit cost). The relatively small impact of the unit cost factor reflects the importance of reducing PV power generation and apple orchard operation and maintenance costs. In terms of technological improvement, in addition to increasing the R&D investment in basic research on AVS and the development of AV technologies with higher conversion rates, it is also necessary to pay attention to the popularization, application and expansion of the industrial scale of AVS technologies, to increase the construction of infrastructures such as transmission grids and to formulate relevant policies to stimulate demand. Considering the high discount and utilisation rates, it is important to consider the following factors. In the face of the technical and economic challenges that may arise at high discount rates, the focus of PV subsidies should be on improving subsidy efficiency, combining subsidy with improvements in power generation efficiency to sustainably realize the economic benefits of PV power projects.

In conclusion, agrivoltaics can be a viable investment in renewable energy from a system size of large-scale farms, with government subsidies playing a pivotal role in supporting the economic feasibility of such investments. This study provides a foundational financial blueprint for stakeholders considering the deployment of agrivoltaic systems, emphasizing the importance of strategic planning and policy alignment to optimize cost-effectiveness and market success.

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**Отбасыма шексіз алғыс! Отбасым бар байлығым!**

Translation: My endless gratitude to my family – my greatest treasure!

# List of Abbreviations

| | |
|---|---|
| **APV** | Agrophotovoltaic |
| **Agri-PV** | Agrivoltaics |
| **AV** | Agrivoltaic |
| **AVS** | Agrivoltaic system |
| **AVS-1** | Single row PV array |
| **CAP** | Common Agricultural Policy |
| **CAPEX** | Capital expenditure |
| **CDCF** | Cumulative Discounted Cash Flow (DCF) |
| **ConAPS** | Conventional apple production system |
| **c-Si** | Crystalline Silicon |
| **DF** | Discount factor |
| **DPP** | Discounted payback period |
| **DSSC** | Dye-sensitised solar cell |
| **FF55** | Fit for 55 package |
| **FIT** | Feed-in-tariff price |
| **GCR** | Ground-coverage ratio |
| **GDP** | Gross domestic product |
| **GHG** | Greenhouse gas |
| **GM-PV** | Ground-mounted photovoltaic |
| **GWp** | Gigawatt-peak |
| **HN** | Hail net |
| **IoT** | Internet of Things |
| **INRA** | Institut National de la Recherche Agronomique (National Institute for Agricultural Research) |
| **IRR** | Internal rate of return |
| **JPY** | Japanese Yen |
| **KRW** | South Korean Won |
| **kW** | Kilowatt |
| **kWac** | Kilowatt alternating current |
| **kWh** | Kilowatt-hour |
| **kWh/a** | Kilowatt-hours per annum (per year) |
| **kWp** | Kilowatt-peak |
| **LCOE** | Levelized cost of electricity |
| **MNB** | Hungarian National Bank (“Magyar Nemzeti Bank” in Hungarian) |
| **MW** | Megawatt |
| **MWp** | Megawatt peak |
| **NPV** | Net present value |
| **NREL** | National Renewable Energy Laboratory |
| **OPEX** | Operating expenditure |
| **OPV** | Organic Photovoltaic |
| **PI** | Profitability index |
| **PV** | Photovoltaic |
| **REPowerEU** | Renewable Energy Power EU initiative |
| **SLR** | Systematic literature review |
| **SPP** | Solar power plant |
| **SPV** | Solar photovoltaic |
| **TC** | Total citations |
| **UCe2025** | Unit cost of electricity in 2025 (first year of operation) |
| **UCa2027** | Unit cost of apple in 2027 (first harvest year) |
| **UMR** | Unité Mixte de Recherche (Joint Research Unit) |
| **WACC** | Weighted average cost of capital |

# List of Tables

## List of Figures

# List of Publications

## 1. Related to the PhD research

### Articles, studies (4)

1. **Chalgynbayeva, A.,** Balogh, P., Szőllősi, L., Gabnai, Z., Apáti, F., Sipos, M., Bai, A.: The Economic Potential of Agrivoltaic Systems in Apple Cultivation – A Hungarian Case Study.
   *Sustainability.* 16 (6), 1-34, 2024. ISSN: 2071-1050.
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2. **Chalgynbayeva, A.,** Gabnai, Z., Lengyel, P., Pestisha, A., Bai, A.: Worldwide research trends in agrivoltaic systems: a bibliometric review.
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3. **Chalgynbayeva, A.,** Mizik, T., Bai, A.: Cost-Benefit Analysis of Kaposvár Solar Photovoltaic Park Considering Agrivoltaic Systems.
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4. **Chalgynbayeva, A.,** Bai, A.: The most relevant factors and trends in energy cooperation between Kazakhstan and China, focused on renewable energy sources (RES).
   Apstract. 15 (3-4), 5-16, 2021. ISSN: 1789-221X.
   DOI: http://dx.doi.org/10.19041/APSTRACT/2021/3-4/8
   Citations: 1

### Conference papers (7)

5. World Sustainable Energy Days 2025 Conference – "Unit cost of energy and agricultural production – agrivoltaics in an apple orchard", **Chalgynbayeva, A.;** Balogh, P.; Szőllősi, L.; Gabnai, Z.; Apáti, F.; Sipos, M.; Bai, A.

6. “INTERNATIONAL SCIENTIFIC DAYS”, PhD Conference 2025 – "Financial analysis of agrivoltaic systems for enhancing energy efficiency", **Chalgynbayeva, A.,** & Bai, A.
7. Conference for PhD Students 2024 – "Comparative Analysis of Agrivoltaic System, Photovoltaic System, and Conventional Apple Farming", **Chalgynbayeva, A.,** & Bai, A.
8. “SUSTAINABLE ECONOMY –SUSTAINABLE SOCIETY", International Scientific Conference 2024 – "Initial feasibility assessment of the economic viability of agrivoltaics in apple farming", **Chalgynbayeva, A.;** Balogh, P.; Szőllősi, L.; Gabnai, Z.; Apáti, F.; Sipos, M.; Bai, A.
9. World Sustainable Energy Days 2024 Conference – "Financial Viability of Agrivoltaic Systems Supporting Energy Efficiency", **Chalgynbayeva, A.,** & Bai, A.
10. Conference for PhD Students 2023 – "Economic potential of agrivoltaic systems for horticulture cultivation in Hungary", **Chalgynbayeva, A.,** & Bai, A.
11. Agrivoltaics2022 Conference – presented two papers on "Analyzing Potential and Economic Effects of Agrivoltaics with the Key Influencing Factors", **Chalgynbayeva, A.,** & Bai, A.
12. Agrivoltaics2022 Conference – "The Potential of the Agrivoltaic Systems in Hungary", **Chalgynbayeva, A.,** & Bai, A.

## 2. List of other publications (1)

**Articles, studies**

13. Pestisha, A., Gabnai, Z., **Chalgynbayeva, A.,** Lengyel, P., Bai, A.: On-Farm renewable energy systems: A systematic review.
    Energies. 16 (2), 1-25, 2023. ISSN: 1996-1073.
    DOI: http://dx.doi.org/10.3390/en16020862
    IF: 3
    Quartiles: Q1
    Citations: 29

**Total IF of journals (all publications): 13,1**

**Total IF of journals (publications related to the dissertation): 10,1**

**Scopus/WoS ranking: 4 (80%)**

# Annexes

## Appendix A

## Academic Literature Search

A SCOPUS search was conducted to determine the required academic literature. The keywords selected for the search are those shown in Table A1. The results were refined using filters by agrivoltaic of economics, technical, infrastructure, environment, energy and agriculture-related areas and articles in English, as well as using articles all over the World.

**Table A1. Selection Parameters used for peer-reviewed literature**

| No. of Keywords | Keywords Selected |
|---|---|
| **KW1** | (TITLE-ABS-KEY (agrivoltaic) OR TITLE-ABS-KEY (agrovoltaic) OR TITLE-ABS-KEY (agrophotovoltaic) OR TITLE-ABS-KEY (agriphotovoltaic) OR TITLE-ABS-KEY ("agro-PV") OR TITLE-ABS-KEY ("agri-PV") OR TITLE-ABS-KEY ("Photovoltaic farming") OR TITLE-ABS-KEY ("Photovoltaic agriculture") OR TITLE-ABS-KEY ("Solar farming")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch")) AND (EXCLUDE (DOCTYPE, "re") OR EXCLUDE (DOCTYPE, "ch")) |
| **KW2** | (TITLE-ABS-KEY (agrivoltaic) OR TITLE-ABS-KEY (agrovoltaic) OR TITLE-ABS-KEY (agrophotovoltaic) OR TITLE-ABS-KEY (agriphotovoltaic) AND ALL (technical) OR ALL (infrastructural) OR ALL (environmental)) AND (EXCLUDE (DOCTYPE, "re") OR EXCLUDE (DOCTYPE, "cr") OR EXCLUDE (DOCTYPE , "bk")) |
| **KW3** | (TITLE-ABS-KEY (agrivoltaic) OR TITLE-ABS-KEY (agrovoltaic) OR TITLE-ABS-KEY (agrophotovoltaic) OR TITLE-ABS-KEY (agriphotovoltaic) AND ALL (agriculture) OR ALL ("agriculture activity") OR ALL ( "agriculture practice")) AND (EXCLUDE (DOCTYPE, "re") OR EXCLUDE (DOCTYPE, "bk") OR EXCLUDE (DOCTYPE, "ch")) |
| **KW4** | (TITLE-ABS-KEY (agrivoltaic) OR TITLE-ABS-KEY (agrovoltaic) OR TITLE-ABS-KEY (agrophotovoltaic) OR TITLE-ABS-KEY (agriphotovoltaic) AND ALL ("high mounted") OR ALL ("Dual-Axis Tracking") OR ALL ("Single-Axis Tracking") OR ALL ("Vertical PV")) AND (EXCLUDE (DOCTYPE, "re")) |
| **KW5** | (TITLE-ABS-KEY (agrivoltaic) OR TITLE-ABS-KEY (agrovoltaic) OR TITLE-ABS-KEY (agrophotovoltaic) OR TITLE-ABS-KEY (agriphotovoltaic) AND TITLE-ABS-KEY ("economic viability") OR TITLE-ABS-KEY (economic) OR ALL ("economic feasibility") OR ALL ("economic benefit") OR ALL (cost) OR ALL (investment)) AN (EXCLUDE (DOCTYPE, "cr") OR EXCLUDE ( DOCTYPE, "bk") OR EXCLUDE (DOCTYPE, "ch") OR EXCLUDE (DOCTYPE, "sh")) |
| **Filters** | Language: English<br>Sectors: agrivoltaic of economics, technical, infrastructure, environment, energy, and agriculture<br>Country: All countries in the World<br>Type: journal articles and conference papers |