THESISES OF THE DOCTORAL (PhD) DISSERTATION

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

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1. INTRODUCTION OF THE TOPICS AND THE OBJECTIVES

According to a recent study, approximately 1.18 billion people are energy-poor, 60% more than the 733 million without electricity in 2020 [1]. 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].

Hungary's advantageous geographical position is conducive to fruit cultivation [6]. To maximize yield, alongside geographical features, the technological conditions of fruit cultivation and the genetic traits of the cultivated varieties are crucial factors [7]. 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 [8]. 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 predominance of non-irrigated crops such as maize, sunflower, lucerne, and soybean significantly influenced the temporal distribution of drought damage [9].

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 [10]. 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 [11]. Modular technologies, such as wind and photovoltaic systems, are encompassed within distributed energy resources that users can install and manage on-site [12], [13]. A holistic understanding of sustainability extends beyond economic considerations to include social and environmental dimensions [14]. 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 [15]. Key benefits include reduced desertification, improved water-use efficiency, microclimate stabilization, enhanced heat stress tolerance, and mitigation of excessive solar radiation [16]–[18]. Additionally, agrivoltaics can diversify farmers' income streams, ensure local electricity supply in rural areas, and enhance land productivity by as much as 70% [19], [20]. Over the last decade, photovoltaic systems and energy efficiency measures have often been seen as economic rivals [21]. 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 due to several compelling reasons.

Apples are economically significant in Hungary, with a well-established market and high demand both domestically and internationally [22]–[24]. This economic value provides a strong incentive to optimize apple production through advanced agricultural techniques [17]. Additionally, apples are perennial crops, which means that 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 [25]. 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 [17].

Apples offer distinct advantages compared to other land uses, such as arable crops or grass. Arable crops often require full sunlight [26] and may not benefit from the shading effect of solar panels, whereas grass typically yields a lower economic return [27]–[29]. Thus, focusing on apples maximizes both agricultural output and energy generation, making it a more economically viable option.

This study evaluates 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.

The scope of this research encompasses the exploration of AVS in the context of Hungary, focusing on evaluating the economic competitiveness of solar technical adaptions 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, emphasizing 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 tariffs rate 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 systems under the METÁR mechanism

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

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.

The evaluation of agrivoltaic systems in apple orchards is based on a sustainability framework that integrates economic, environmental, and social dimensions [30]–[32]. 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 [33].

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 both renewable energy generation and agricultural production can 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.,

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

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

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.

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.

2. MATERIAL AND METHODS

This material and methods section of the dissertation provides a comprehensive overview of the methodological framework developed to assess the integration of agrivoltaic systems within agricultural practices, with a particular focus on apple farming and the operations from the ground-mounted photovoltaic (GM-PV) systems. The study leverages data from the Mezőcsát Solar Park and the Kaposvár Solar Photovoltaic Park to compare GM-PV and conventional agricultural apple systems (ConAPS). The study is structured around a dual approach: a systematic literature review that establishes the theoretical foundations and identifies research gaps and a detailed empirical analysis that evaluates the financial viability and economic performance of agrivoltaic systems in real-world contexts.

2.1. Bibliometric review methodology

The initial research phase involved an extensive systematic review of existing literature from high-impact databases such as Scopus. The review employed a well-defined search strategy incorporating keywords like "agrivoltaics," "photovoltaic systems in agriculture," "financial viability," and "cost-benefit analysis." This strategy included only high-quality, peer-reviewed studies and reputable conference proceedings, providing a robust theoretical background. Rigorous inclusion and exclusion criteria were applied to filter out studies that did not offer empirical data or focused solely on technical aspects without addressing the economic implications. 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 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. Furthermore, each relevant study systematically extracted key information from research objectives and methodological approaches to outcomes and identified limitations. This process highlighted seminal works in the field and mapped emerging trends and critical gaps through bibliometric analysis. The insights gained from this comprehensive review laid the groundwork for developing a conceptual framework that supports the subsequent empirical investigation.

2.2. Quantitative analysis of economic indicators in agrivoltaic implementations: Evidence from the Mezőcsát project in Hungary

Building upon this theoretical foundation, the empirical segment of the study focuses on the financial viability and economic assessment of integrating agrivoltaic systems into apple farming practices compared with ground-mounted photovoltaic (GM-PV) and conventional apple systems (ConAPS). The analysis is grounded in data from the GM-PV system in Mezőcsát, which serves as a practical case study to examine dual revenue streams, one deriving from solar energy production and the other from agricultural outputs on large scale farm. The model is predicated on a super-intensive orchard system characterized by substantial agricultural inputs, elevated yields and high-quality products [34]. 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 [35]. 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. A detailed financial viability model was developed to encapsulate the complex interplay between initial investment costs, ongoing operational expenses, and potential revenue generation. The model incorporates established financial assessment techniques and introduces modifications to account for the unique characteristics of agrivoltaic systems. Key performance indicators such as NPV, IRR, payback period, and unit cost of electricity and apple productions were computed to quantitatively measure the system's economic feasibility. These indicators were calculated using historical financial data and industry benchmarks and subjected to rigorous sensitivity analysis. For risk quantification, probabilistic modelling techniques such as Monte Carlo simulations are employed to reconcile deterministic system behaviours with stochastic variability [36], aligning with methodological frameworks applied in prior studies, such as those of Elkadeem et al. [37], 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 allowed for a probabilistic assessment of the system's performance by simulating various potential outcomes based on key operational and economic parameter variations. This analysis involved varying critical parameters such as energy prices, maintenance costs, and crop yield fluctuations to assess the robustness of the financial model under different market scenarios. 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. [38]. 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.

2.3. Parameter sensitivity and scenario analysis for the cost-benefit assessment of agrivoltaic integration at the Kaposvár solar photovoltaic park

In parallel, the study undertook a detailed cost-benefit analysis at the Kaposvár solar photovoltaic park to further validate the economic sustainability of agrivoltaic systems considering small scale farm. A diverse array of data sources was utilized, including primary operational records from the photovoltaic park and secondary data from regional energy databases, government publications, and previous academic studies. Furthermore, scenario analysis was performed to delineate best-case, worst-case, and base-case scenarios. This approach is extensively implemented in investment decision research and analysis of agricultural revenue [18], [39]. 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 [40]. Moreover, scholars have noted the detrimental effect of photovoltaic module degradation rates and the beneficial influence of system efficiency [41], annual operational hours, electricity pricing, and power generation subsidies [42] 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.

Overall, the methodological approach presented in this section bridges the gap between theoretical research and practical financial analysis. The systematic literature review establishes a rigorous academic framework and identifies critical research gaps. At the same time, the subsequent empirical investigations provide detailed quantitative assessments of the economic viability and cost-benefit aspects of agrivoltaic systems. By combining these complementary approaches, the study delivers a thorough evaluation of the dual-use potential of agrivoltaic systems, offering theoretical contributions and actionable insights for stakeholders involved in sustainable land use, renewable energy policy, and agricultural management. The methods employed validate the feasibility of integrating photovoltaic systems with farming practices and highlight the economic dynamics underpinning such innovations. The results derived from these analyses are poised to inform future research directions and policy development, paving the way for more efficient and economically viable strategies in deploying agrivoltaic systems.

2.4. Climatic background of the study areas

To provide a localized climatic context, Table 1 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.

Table 1. Comparative climatic parameters

Climate Parameter	Mezőcsát	Kaposvár	Data Source
GHI(kWh/m^2/year)	1281.3	1323.7	[43]
Cloud Cover (% or months)	63% (7.5 months)	64%(7.3 months)	[44], [45]
Precipitation (mm/year)	660.4	664.7	[46], [47]
Average Annual Temperature (°C)	11.76	11.2	[48], [49]
Average Relative Humidity (%)	75	71.36	[49]

3. MAIN FINDINGS OF THE DISSERTATION

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.

3.1. Systematic literature review

The subsequent section presents the findings of the agrivoltaic bibliometric analysis. The results have been categorized 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. Subsequently, instances of each application area are provided to offer a more comprehensive understanding.

Figure 1 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 recognized 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" [93]. Today, "Agrivoltaic" is the internationally accepted terminology, with "AV" as the standardized acronym.

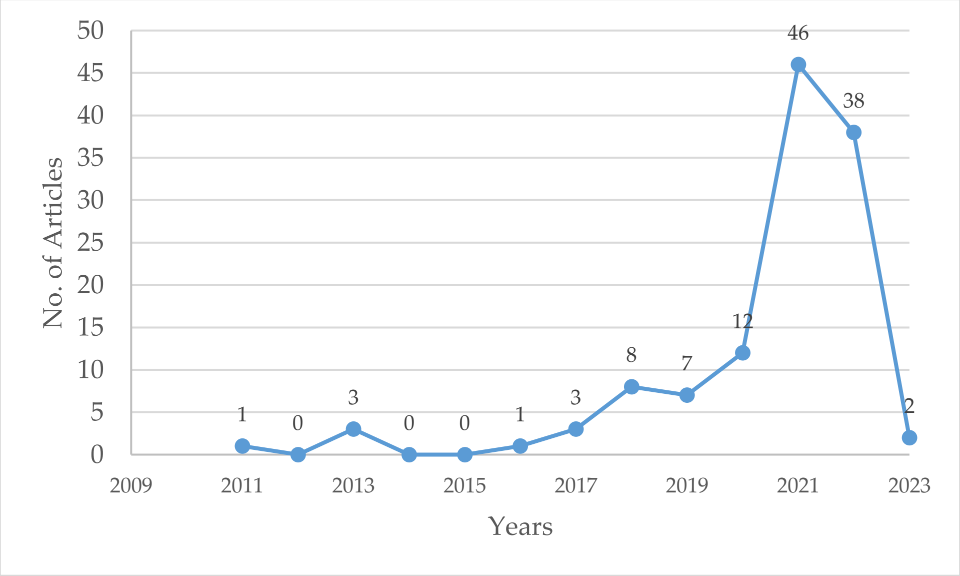

Figure 1. Yearly output of scientific works. Source*:* [50]

In this study, we have highlighted the most frequently cited papers in agrivoltaic systems. The ten most frequently cited scholarly articles presented key metadata such as author initials, publication year, publishing journal, digital object identifier (DOI), total citations, and annual citations. Table 2 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.

Table 2. Articles with the highest citation in agrivoltaic systems research

Paper	Titles	DOI	TC	TC per Year
[19], 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
[51], 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
[52], 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
[53], APPL ENERGY	Agrivoltaic systems to optimize land use for electric energy production	10.1016/j.apenergy.2018.03.081	117	23.40
[54], PLOS ONE	Remarkable agrivoltaic influence on soil moisture micrometeorology and water-use efficiency	10.1371/journal.pone.0203256	86	17.20
[55], 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
[18], 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
[56], 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
[57], SCI REP	Solar PV power potential is most significant over croplands	10.1038/s41598-019-47803-3	75	18.75
[58], 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: [50]

Table 3 details each country's scientific yield, sheds light on their contributions to agrivoltaics. The USA, a global leader in renewable energy consumption [59], 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 [54], [60]–[62]. One US study highlights the significance of incorporating solar energy applications in agriculture into broader, multi-sectoral policy frameworks [63]. With its increasing demand for clean energy like solar energy, China holds second in the number of scientific paper productions.

Table 3. 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: [50]

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) [18] 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.

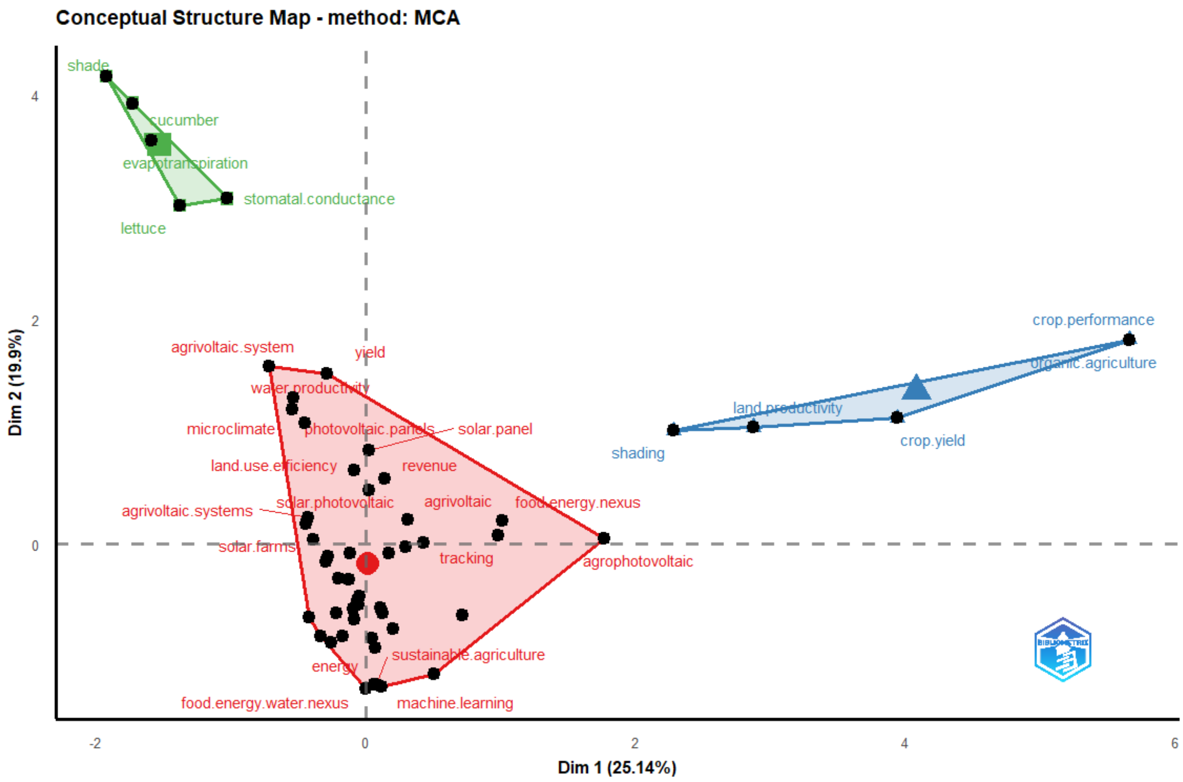

Figure 2. Analysis of high-frequency keywords through multiple correspondences. Source: [50]

Figure 2 illustrates a co-word analysis designed to visualize 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.

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.

3.2. 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 (in the full version of the dissertation) if not explained below. In the first step, the structure of the costs and the revenues are 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.

Table 4 compares unit costs for AVS, GM-PV systems without apple production, and apple cultivation without PV in 6 selected operational years. The reasons for choosing these years are the same as those in Table 4. The unit costs are presented for both electricity production and apple cultivation. The calculations are based on the total production cost, the revenue shares of electricity and apples to compute the shared production costs of electricity and apple (in the case of AVS), and the unit costs for both components. All models demonstrate lower unit costs in comparison to expected 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 [17] and [64].

Table 4. Comparison of costs for producing electricity and apples over specific operational years

Years	2024	2026	2038	2039	2040	2053
Total production cost (EUR)	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 (EUR)	1,120,666	1,317,682	1,584,243	1,271,534	1,375,870	2,242,002
Production cost of apple (EUR)	0	134,371	237,962	0	0	389,361
Unit cost of electricity (EUR/kWh)	0.015	0.018	0.024	0.020	0.021	0.040
Unit cost of apple (EUR/t)	0	56	99	0	0	161
Unit cost of electricity in PV (without apple, EUR/kWh)	0.013	0.013	0.017	0.018	0.018	0.029
Unit cost of apple (without PV, EUR/t)	0	196	285	0	0	399

Source: [25]

Figure 3, 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.

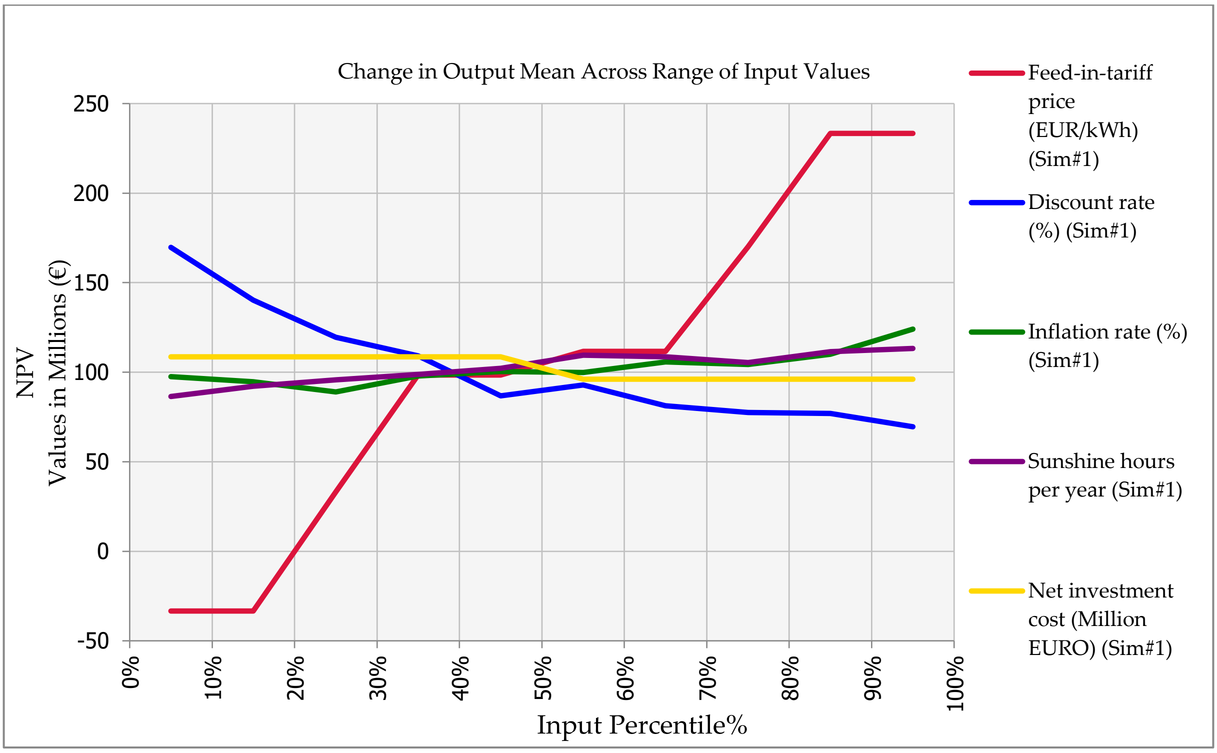

Figure 3: Variation in output averages across a range of input values with respect to NPV. Source: [25]

Figure 4 shows Spearman rank correlation coefficients between key variables and apple production costs. A strong negative correlation (−0.90) with FIT rates indicates that higher FIT revenues significantly reduce unit costs by offsetting them with income from electricity generation. In contrast, net investment costs show a moderate positive correlation (+0.33), reflecting the cost-increasing effect of higher capital outlays for AVS infrastructure. Other variables show weaker correlations, suggesting limited influence on unit costs in this context.

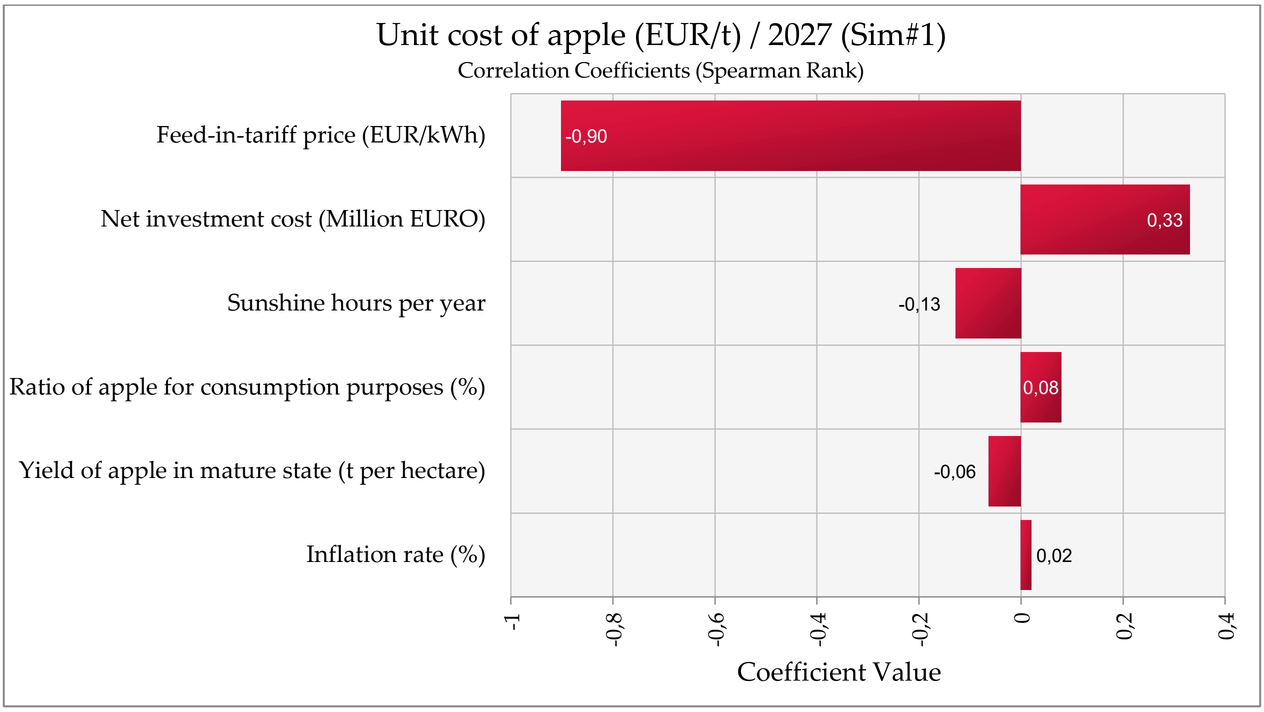

Figure 4: Analysis of correlation coefficients (spearman rank) for input and output data related to apple production unit cost. Source: [25]

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 5). Considering the projections concerning FIT prices as presented in [17], 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.

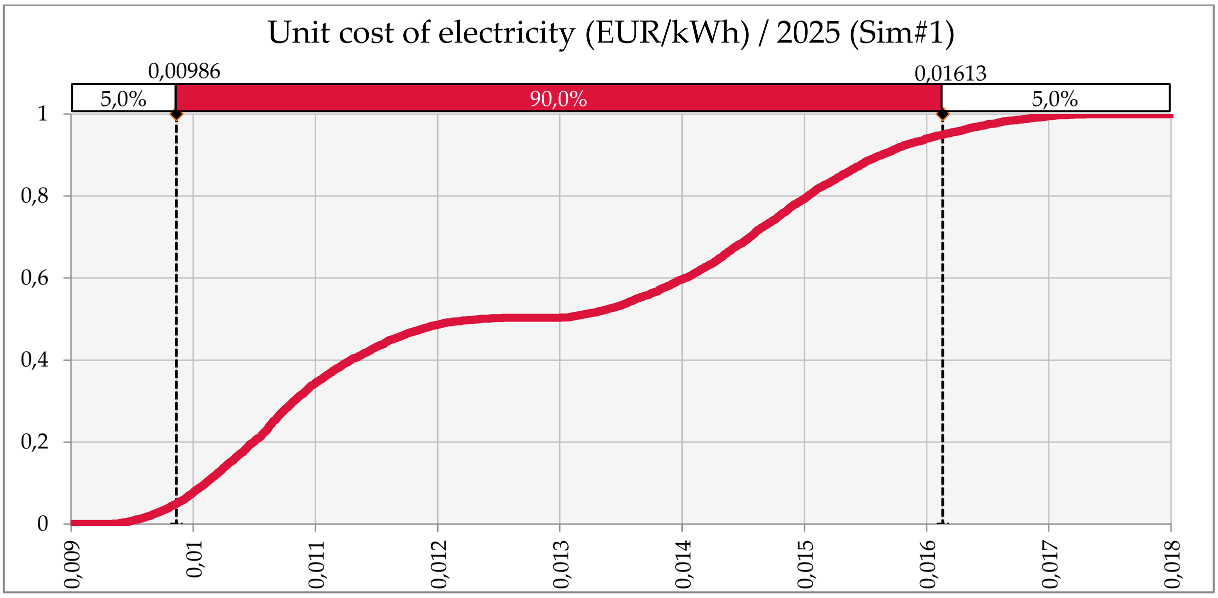

Figure 5: Combined results of Monte Carlo simulations examining variations in unit cost. Source: [25]

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

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 [65]. 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. 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 5 and Table 6.

Table 5. 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: [66]

Table 6. 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: [66]

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 7.

Table 7. Comparison of economic results in the baseline scenario

	Comparison		Unit
	AVS vs GM-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: [66]

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 [67].

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

Figure 6 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.

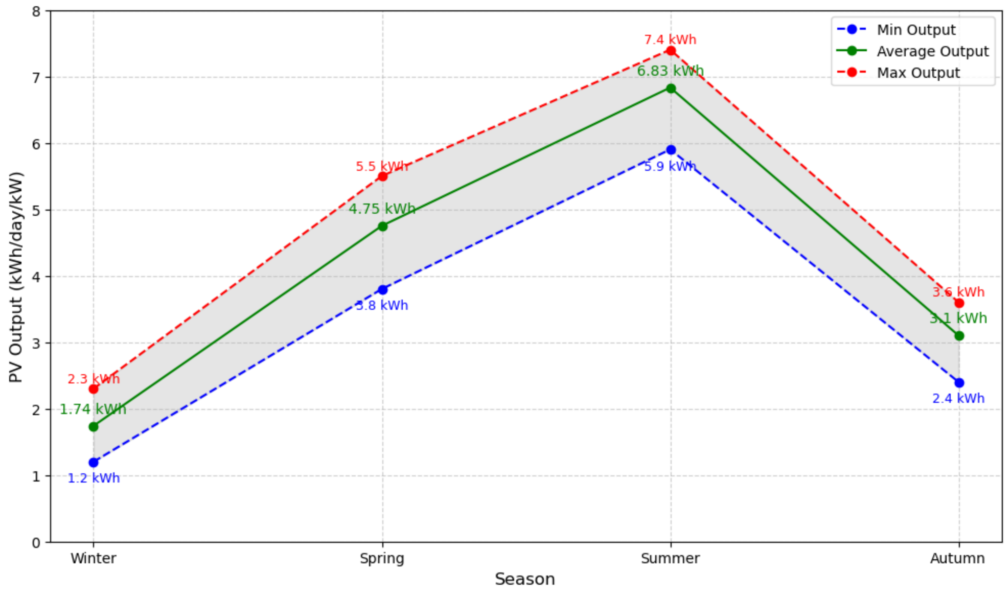

Figure 6: Seasonal fluctuations in photovoltaic performance across minimum, mean, and peak levels in Kaposvár. Data source: [68], [69]

In contrast, Mezőcsát's PV performance is considerably lower across all seasons (Figure 7). 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.

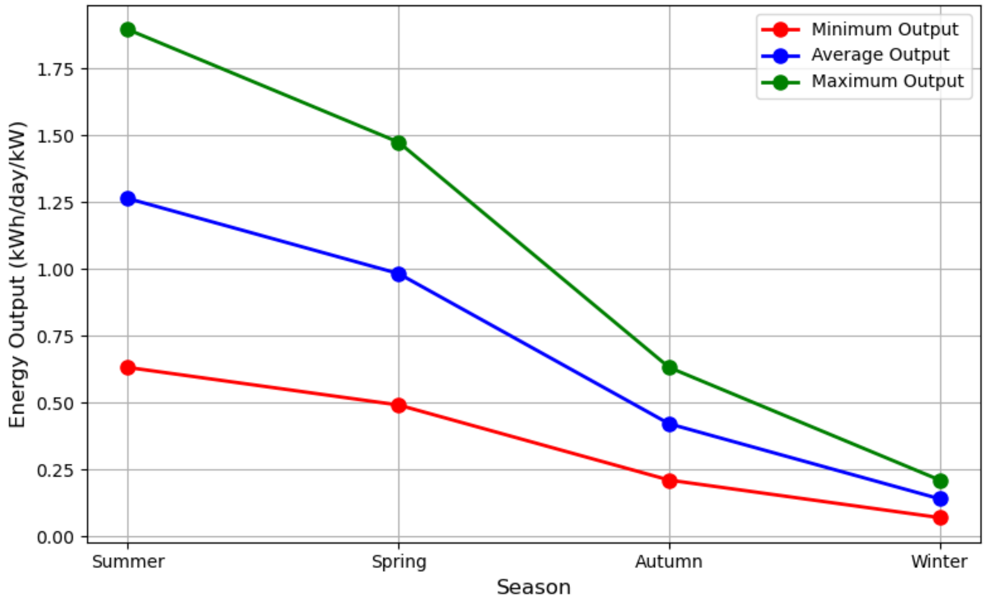

Figure 7: Estimated Seasonal Photovoltaic Energy Output in Mezőcsát. Data sorce: [43], [70], [71]

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.

4. CONCLUSION AND NOVEL FINDING

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 address uncertainties and deliver essential insights into risk mitigation strategies.

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 findings for a mature "Golden Delicious" apple orchard in France align with findings from Juillion et al. [72] and Schindele et al. [18], 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.

In a broader context, Robinson [73] highlight the high apple yield efficiency of V-shaped systems, 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.

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.
2. Partial Alignment with Hypothesis 2: While reduced OPEX improves financial returns, the extent of its impact varies significantly based on operational efficiency, maintenance costs, and local energy market conditions. The correlation exists but is not uniformly strong across all scenarios.
3. Partial Alignment with Hypothesis 3: While the study corroborates the importance of government subsidies and favourable feed-in tariffs in ensuring the economic feasibility of agrivoltaic systems, it also highlights a key financial challenge: the cost of subcomponents. These components are significantly more expensive than those used in GM-PV systems, thus impacting the financial

calculus. This partial support underscores the necessity for strategic cost management and potential technological innovations to mitigate these expenses and enhance economic outcomes.

4. Support for Hypothesis 3: As agrivoltaic systems have not yet been implemented in Hungary, precise estimations remain challenging. However, according to references, the analysis supports Hypothesis 3 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 income fully. 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.

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.

Exploring agrivoltaic systems within apple orchards offers several promising avenues for future study:

1 Microclimate Analysis: Investigate the local microclimatic conditions in apple orchards under agrivoltaic setups, including how dust and pesticide residues on photovoltaic panels affect crop yields and operating costs.

2 Social Acceptance: Examine stakeholder perceptions and social barriers to the adoption of agrivoltaic technology, identifying key factors that facilitate or hinder widespread acceptance.

3 Market Flexibility: Research agrivoltaic systems that allow for flexibility in crop choices and cultivation methods, making these systems more adaptable to varying regional agricultural demands.

4 Water Resource Management: Study the potential benefits of integrating rainwater collection and redistribution within agrivoltaic systems, focusing on cost savings and yield improvements in water-limited regions.

5 Integration of Robotics: Assess the role of robotics in enhancing agrivoltaic operations, particularly in reducing labor costs and increasing efficiency in crop management.

6 Complex System Integration: Explore the impact of dynamic PV tracking systems on apple yields and overall system performance, to better understand the interplay between energy production and agricultural outputs.

5. 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.

6. LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

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.
   DOI: http://dx.doi.org/10.3390/su16062325
   IF: 3.3 (2023)
   Quartiles: Q1
   Citations: 18
2. **Chalgynbayeva, A.,** Gabnai, Z., Lengyel, P., Pestisha, A., Bai, A.: Worldwide research trends in agrivoltaic systems: a bibliometric review.
   Energies. 16 (2), 1-25, 2023. ISSN: 1996-1073.
   DOI: http://dx.doi.org/10.3390/en16020611
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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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   DOI: http://dx.doi.org/10.3390/cleantechnol4040064
   IF: 3.8
   Citations: 13
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%)

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