Renewable Energy Focus 56 (2026) 100751

Contents lists available at ScienceDirect

Renewable Energy Focus

journal homepage: www.elsevier.com/locate/ref

Research Paper

Assessing financial feasibility and equity prospects in agrivoltaics: a case study of Hachinohe, Japan

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ARTICLE INFO

Keywords:
Agrivoltaics
multi-criteria decision-making
economic analysis
sensitivity analysis

ABSTRACT

Agrivoltaics, which combines the use of land for both agriculture and photovoltaic energy production, is emerging as a promising solution to the land use conflicts between farming and renewable energy. By simultaneously boosting crop yields, enhancing solar panel efficiency and revitalising rural incomes, agrivoltaics is attracting farmers and solar developers, prompting innovation in technology and business models. Nevertheless, the key to scaling agrivoltaics depends on its commercial viability for different stakeholders, an area that still requires further exploration. To bridge this gap, this research examines the business model of an ongoing agrivoltaic project in the Hachinohe region of Aomori Prefecture, Japan, with a particular focus on financial feasibility and equitable distribution of benefits among stakeholders. The study applies multi-criteria decision-making method to assess the project's overall financial feasibility using NPV, IRR, and payback periods, while also exploring the equity implications through Gini coefficients. Thereafter, a sensitivity analysis is conducted to offer policy suggestions such as revenue-sharing, better lease terms, and subsidies for farmers, with the purpose of enhancing rural economic revitalization and inform equitable business model design in Japan's energy transition. Drawing on experiences from Europe and the United States, this research emphasizes the active engagement of farm owners in the development and implementation of agrivoltaic projects to enhance financial feasibility, equity and stakeholder participation.

Introduction

Climate change and sustainable development are deeply interconnected global challenges. Climate-related risks—including extreme weather, land degradation, and water scarcity—threaten the foundations of socio-environmental sustainability such as the food systems, energy security, and rural livelihoods [1]. At the same time, progress toward the Sustainable Development Goals (SDGs) remains uneven, especially in areas most vulnerable to climate impacts [2]. Numerous studies (e.g., Nerini et al., 2018) [3] emphasize that sector-specific solutions are insufficient to achieve the global targets. Instead, integrated frameworks are needed to simultaneously address environmental, social, and economic dimensions—an approach supported by policy documents such as the 2030 Agenda [4] and Japan's Sixth Basic Environment Plan [5]. Correspondingly, the localization of global goals is increasingly prioritized in policy and research. Localized strategies—designed around place-specific conditions and stakeholder engagement—can generate more inclusive and effective outcomes. Hölscher et al. [6] underscore that transformational urban and rural climate governance requires integrating SDG targets into local planning while considering cross-scale dynamics. Such approaches can enhance coherence between national climate ambitions and ground-level development needs, especially in energy and land-use systems.

At this juncture, there is a growing recognition of integrated policy approaches (like circular economy, nature-based solutions, nature positive approach, water-energy-food nexus, urban-rural linkages) to address emerging challenges linked to sustainable development. Distinctly, the Circulating and Ecological Sphere (CES) approach emerges as a multiscale and multi-dimensional approach for localization of integrated climate and sustainable development actions, as it directs localities toward effectively utilizing the locally available resources to realize a self-reliant and decentralized society, while leveraging on its co-benefits for economic revitalization, community wellbeing, localization of SDGs, and other important agendas [7,8]. Under different initiatives like the SDG Future City initiative, many regional authorities and local governments in Japan are already experimenting with ways (such as through decarbinisation efforts) to apply the CES concept for

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https://doi.org/10.1016/j.ref.2025.100751
Received 14 May 2025; Received in revised form 16 July 2025; Accepted 2 September 2025
Available online 10 September 2025

Nomenclature

Abbreviation/Symbol	Description
AGRIVOLTAIC/AV	Agrivoltaics: Dual-use land systems combining agriculture and photovoltaic power generation
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
CES	Circulating and Ecological Sphere
CSR	Corporate Social Responsibility
ESG	Environmental, Social, and Governance
FIT	Feed-in Tariff (government-fixed electricity price scheme)
Gini coefficient	A measure of statistical dispersion representing income or wealth inequality
IGES	Institute for Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
JPY (¥)	Japanese Yen
LCA	Life Cycle Assessment
MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
MCDM	Multi-Criteria Decision-Making
METI	Ministry of Economy, Trade and Industry (Japan)
NREL	National Renewable Energy Laboratory (USA)
NPV	Net Present Value
PV	Photovoltaic
ROI	Return on Investment
SDG / SDGs	Sustainable Development Goals
SMART	Solar Massachusetts Renewable Target Program
SRF	Strategic Research Fund (IGES)
SSA	Sub-Saharan Africa
UK	United Kingdom
UN	United Nations
US / USA	United States (of America)

promoting carbon and resource circulation on optimal scales according to the characteristics of the regions concerned, and the nature of resources to be recycled [9].

The notion of agrivoltaics (or dual-use solar agriculture) has been discussed since the 1980s [10]. However, it has recently gained renewed attention as a land-use innovation that simultaneously supports solar generation, crop productivity, and ecosystem services—contributing to several SDGs related to food, energy, and the environment [11]. Globally, there have been pioneering experiments in agrivoltaics in the early 2000s, but it was not until the past decade that systematic studies and large-scale demonstrations have been initiated. Dupraz et al. [12] report pioneering field experiments in Europe that show both the promise of electricity generation and the agronomic benefit of dual land use. France, Germany, United States, and Japan have also started to adopt agrivoltaic approaches, motivated by the twin demands of renewable energy and sustainable agriculture.

To simultaneously maximize solar panel output, and crop and land productivity, agrivoltaic systems need to be engineered [13]. This requires advanced panel configurations and management strategies to provide sufficient sunlight for crops while generating power [14]. Such strategies optimize the system for both electricity and agriculture [15]. In practice, agrivoltaic systems are typically designed with optimized panel height and angle. In some cases, tracking systems are used to balance agricultural productivity and solar efficiency [15]. Improvements in agricultural science and photovoltaic technology are enabling the advancement of agrivoltaic systems. Smart sensors, IoT platforms, and data analysis are all being used to optimize panel angles and irrigation in real time [16]. Barron-Gafford et al. (2019) explain how the addition of digital monitor systems to agrivoltaic configurations can achieve increased yield and energy production, addressing one of the biggest challenges to balancing these dual purposes. Usually, solar panels are mounted at adjustable angles and heights, a design ensuring sunlight is properly distributed, with enough light penetrating for the crop, while electricity is being produced. Such a design may prevent potential risks of excessive shade or overheating that may reduce crop yield [17,18]. Real-time monitoring of the situation could be integrated to achieve, for instance, seasonal or crop-specific light exposure and to adjust the technology to changing conditions. In this respect, solar panels are arranged in such a way that they protect crops from excessive evaporation by creating partial shade on the ground, which enhances their viability. In such a way, agrivoltaics can become both adaptable and sustainable for optimizing land use while achieving relevant goals related to energy transition, food security, and resource management. Nonethless, technical challenges do remain, including optimization of light distribution and microclimates under the panels. Further research is being carried out to investigate new materials to be used in panels that can optimize transmittance and reduce heat gain, thereby ensuring crop health.

Moreover, agrivoltaics also possess important environmental and social benefits. Scarano et al. [19] underline that partial shading from solar panels can reduce soil evaporation, retain moisture, and moderate microclimates—benefiting crop growth in arid regions. Weselek et al. [18] provide a comprehensive account of how agrivoltaic systems contribute to soil conservation and reduce erosion while promoting local biodiversity. Socially, agrivoltaics can contribute to rural development and social justice by diversifying farmers' income sources [20]. With rural populations facing decline and economic stagnation, the adoption of agrivoltaic projects can be a catalyst towards broader socio-economic rejuvenation. In this sense, the production of renewable electricity together with traditional farming contributes to not only the fight against climate change but also to community wellbeing and resilience, and long-term sustainability.

Since the official adoption by the Government of Japan (in 2013) towards policies in favor of agrivoltaics (also referred to as "solar sharing"), the country has experienced steady growth in the industry. Agrivoltaic installations in Japan are aimed at maintaining agricultural productivity by positioning photovoltaic panels at heights and angles that can be adjusted, thus allowing sufficient sunlight to reach crops while simultaneously generating electricity [21]. The agrivoltaic practices have specifically been regulated by the Japanese government through policy frameworks aimed at compatibility with agricultural production, resulting in the rapid growth in the industry and its adoption by farm communities [22].

Despite the many advantages of agrivoltaics, the financial feasibility issues continue to hinder the scaling of agrivoltaics model, which includes high initial costs, low farmer income and limited farmer participation because of technical barriers and unequal benefit distribution (Bhandari et al., 2021) [23]. While Japanese government policies such as the Feed-in Tariff (FIT) scheme and direct subsidy schemes (like subsidies for up to 50% of the initial investment) have triggered initial market growth and reduced the risk for investors, there is often a reduced yield for specific crops, with farmers being put under the pressure of heavy investments that hold down wider adoption of this innovative model. Even though the practice of agrivoltaics hold signficant potential, their implementation in Japan continues to grapple with technical, economic, and social challenges [24]. Despite favorable policies and technological advancements, the current business models primarily benefit large energy companies, offering limited participation and returns to farmers. These issues are particularly relevant in the context of Japan's high electricity costs and the need to maintain rural economies in an emerging market context [25]. Customizing the current business models to be economically sustainable and enacting fair profit distribution between involved members remains a challenge. This imbalance raises concerns about financial equity, as reflected in indicators such as the Gini coefficient in agrivoltaic profit distributions [21]. Furthermore, the evolving market for electricity, with a phased transition from fixed FIT tariffs to market prices, contributes to the uncertainty. The need to investigate financial feasibility from the perspectives of multiple stakeholders, from farmers to energy companies, to financing institutions, distribution companies, and government, is thus timely and significant, as Japan seeks to reconcile rural revitalization, community wellbeing, and energy policy against a backdrop of rural depopulation issues. Taylor et al. [26] emphasize that an energy justice approach can guide regulatory reforms so that agrivoltaic projects yield equitable benefits, which can help "unlock the full potential of co-locating" solar and farming.

In light of the above situation, this study investigates an ongoing agrivoltaic project in Japan, to inform policy interventions that can help make the agrivoltaic system more inclusive and sustainable, while guiding and optimizing the development of new business models in Japan and other countries. This research specifically focuses on an ongoing project in the region around Hachinohe city, Aomori Prefecture, Japan, wherein the shrinking population is leading to an increase in vacant houses, a decline in the number of agricultural sector workers, and underutilized agricultural land [27]. Drawing on the existing business model of this ongoing project, the research uncovers financial dynamics and equity implications among stakeholders, to guide future agrivoltaics policies. While this study does not directly evaluate broader aspects of social equity or community well-being, it considers how financial feasibility and profit distribution can implicitly inform such discussions. The subsequent Section 2 establishes a theoretical background based on review of recent studies and reports on agrivoltaics. Section 3 describes the overall methodology of this research. The derived results and key observations are discussed in Section 4. Finally, Section 5 paper outlines key conclusions and a way forward.

Theoretical background

The notion of integrating renewable energy technologies into agricultural operations, or agrivoltaics, is gaining strong academic interest as it offers significant benefits for enhancing agricultural production and renewable energy generation [17,12]. By strategically utilizing the same piece of land for agriculture and solar photovoltaic (PV) power generation, agrivoltaic schemes are optimizing the use of available land, while helping to overcome competing uses for the land [28]. Nevertheless, a detailed financial, environmental, and social analysis on agrivoltaics [29] is imperative, due to the fact that schemes are linked to high capital costs upon initial investment, ongoing operating costs, and stakeholder engagement complexities (Di Francia and Cupo, 2023) [30]. Despite the technological potential, studies suggest that agrivoltaic schemes in Japan have certain social equity issues [31]. Existing business models mean that the majority of benefits are gained by energy companies and large investors, with minimal economic benefits for smallholder farmers, thereby constraining rural income growth. As Koga et al. (2025a) [32] argue, the dominant academic debates of community energy governance (CEG) have used the Western European cases extensively, overlooking Japan's context-specific practices and social injustices. By exploring the pattern of distribution of financial benefits in agrivoltaic schemes, this paper presents empirical evidence of how balanced business model arrangement can address geographical inequalities and participation hurdles in Japan's decentralized energy transformations, thereby enriching the contextual theorization of CEG in Japanese academic discourse. Japanese farmers, particularly small-scale farmers, face severe challenges to participating proactively in agrivoltaic schemes due to a lack of bargaining power, limited technical knowledge, lack of finances, and minimal participation in decision-making which often limits the economic benefits [22]. Furthermore, social equity has become a core focus within agrivoltaic sustainability. Equitable sharing of the project benefits directly impacts the public acceptance of agrivoltaics, their long-term equity and project feasibility, and community support [33]. Karakaya and Sriwannawit [34] identify the paramount role that equity assumes within the success of renewable energy projects using the Gini coefficient as a numerical indicator of the level of equity within the financial results. High levels of inequality in any project may indicate potential risks for long-term sustainability and the need for inclusive financial structures. In Japan, the intersection of decentralized energy systems and social equity has gained attention in recent studies. Asuka and Jin [35] discuss energy democracy as a pathway toward more inclusive energy governance in East Asia, while Koga et al. [31] analyze how community-based energy practices in Japan reflect evolving debates on fairness and participation in energy transitions.

In terms of financial equity, revenue-sharing schemes can help enhance equitable profit-sharing, wherein farmers could have a stake beyond lease arrangements. Such schemes facilitate increased stakeholder engagement and shared accountability through the establishment of a collective stewardship and sense of ownership [18]. Government interventions through subsidies, direct financial support, and tax relief interventions enhance social fairness through the reduction of entry barriers, and encourage universal engagement of small-scale and under-resourced agricultural stakeholders [36].

Ajanovic and Haas [37] emphasize the need for adequate financial analysis to drive renewable energy investments for long-term. The financial feasibility evaluation of agrivoltaic projects typically involves the application of various financial metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period, and Profit Margin. NPV, used extensively for its capability to capture future cash flows and time-value of money, remains essential for stakeholders in determining investment viability (Bakos & Tsagas, 2002) [38]. Further, the IRR factor offers a relative measure for stakeholders to compare profitability across various renewable energy projects with clear signs of anticipated returns against other projects (Diaz et al., 2017) [39]. The investment recovery period serves as a key short-term liquidity and risk assessment indicator crucial for the smallholder agricultural enterprises. Hernandez et al. [40] also point out the value of Discounted Payback Period calculations for determining financial feasibility from the perspective of smallholder farmers who are most likely to face tighter financial constraints and risk aversion. The Profit Margin is a direct measure of operating performance and financial feasibility essential for the maintenance of stakeholder trust and future investment attraction. It helps in assessing short-term profitability, operating efficiency, factors of operating sustainability, most notably during the early stages of an agrivoltaic project. Moreover, recent literature also calls for incorporating environmental and social analysis into conventional financial appraisals. Cucchiella et al. (2016) [41] advocate for the incorporation of lifecycle assessment (LCA) methodologies into financial modeling with the reasoning that combined analysis can best capture sustainability goals through balancing economic profitability with broader ecological and social impacts.

Given the complexity of agrivoltaic projects with multiple stakeholders including farmers, investors, financial institutions, utilities, and policymakers, structured decision-making methodologies are imperative. The decision theory provides methodologies such as Multi-Criteria Decision-Making (MCDM), Analytical Hierarchy Process (AHP), and Analytical Network Process (ANP), which can help manage the complexity and conflicting interests associated with agrivoltaic projects. Triantaphyllou [42] illustrates the Benchmarking Scoring Technique, a variant of MCDM used for measuring stakeholder sustainability through the systematic assessment of the performance of each stakeholder against industry standards. The model helps with the management of the wide range of priorities and power dynamics present within agrivoltaic project stakeholders. The AHP process outlined by Saaty [43] organizes decision-making into hierarchical levels, allowing stakeholders to prioritize goals in a structured manner. AHP facilitates open and stakeholder-participatory decision-making, thus improving the legitimacy and acceptability of the project. Diaz et al. (2017) [39] further elaborate this idea through the Analytic Network Process (ANP), addressing the complicated interdependences between different financial, environmental, and social factors, thereby making the evaluation more sophisticated. Mitchell et al [44] suggest stakeholder salience theory with the areas of focus including power, legitimacy, and urgency as critical elements for determining stakeholder influence within decision-making frameworks. The theory is very useful within agrivoltaics where the varying stakeholders' resource investment and economic contribution calls for equitable strategies to maximize overall sustainability.

Empirical studies across diverse global environments underscore the pragmatic potential and diverse outcomes of agrivoltaic designs. Barron-Gafford et al. [17] reveal data from dryland environments with increased water use efficiency and improvement in agricultural yield, underscoring the economic and environmental feasibility of agrivoltaics, most significantly under arid environments. Empirical findings from Germany and the United States also underscore the influence of well-defined financial structures and unambiguous revenue-sharing mechanisms in facilitating stakeholder satisfaction and overall viability within the project (NREL, 2023) [45]. Dinesh and Pearce [46] reference data from new financial models with a focus on equity, which demonstrate the powerful positive influence such factors have upon the viability and acceptability of the projects. Their work explains how inclusive financial mechanisms greatly enhance the take-up and long-term viability of agrivoltaic schemes.

The identical experiences and patterns in agrivoltaic operations worldwide offer valuable lessons for agrivoltaic development in Japan. For example, in France and Germany, agrivoltaic facilities are carefully planned to prevent land-use conflict by sustaining crop yields through adaptive panel configurations and real-time management [47]. Similarly, in the United States, particularly in states like Massachusetts, some agrivoltaic schemes (e.g., the SMART program) have successfully increased farmer engagement by providing farmers with additional sources of income (Proctor et al., 2021) [48]. In addition to the developed coutries in the US, EU, and Japan, recent studies from the Global South have started to foreground the wider sustainability implications, governance, and equity impacts of agrivoltaics and decentralized models for renewable energy. For example, Pandey et al. (2024) [49] simulated comparative agrivoltaics for Australia, Iran, and Chad, demonstrating that such systems not only increase agricultural productivity in semi-arid ecosystems but also increase economic returns and energy provision in low-income contexts. Taylor et al. [26] proposed a justice framework for the evaluation of agrivoltaics in New South Wales, Massachusetts, and Japan, with a focus on the role that institutional design can play in ensuring that benefits from agrivoltaics accrue to local populations, and that inclusive decision-making is practiced. In the economic sphere, Liu et al. [50] illustrated how sustainable finance mechanisms, when nested in strong institutional frameworks, could dramatically increase the equity impacts of energy transitions in developing countries in Asia. Calcaterra et al. [51] also found that lowering the upfront costs of renewables in developing countries benefits not just the goals for climate, but also affordability and energy justice, supporting the co-benefits of just energy access. These results highlight the international significance of equity-informed finance models and the role that different forms of governance can play in scaling agrivoltaics in socially just and environmentally robust ways.

Taking account of the complexity in agrivoltaics, which involves many stakeholders with conflicting interests, structured theories of decision are imperative. Practical implementation of structured theories of decision as outlined by Mardani et al. [52] demonstrate how systematic methodologies are capable of balancing conflicting financial, environmental, and social objectives and thus maximize sustainability outcomes. By employing structured methodologies like AHP, ANP, and MCDM, stakeholders can articulate their preferences freely, resolve conflicts effectively, and make logical trade-offs between competing goals and thus ensure overall sustainability [53,54]. These methodologies facilitate enhanced stakeholder involvement with all the concerned perspectives appropriately included within the decision process. While successful implementation of agrivoltaic systems relies upon robust economic analysis coupled with sophisticated decision-theoretical strategies involving economic, environmental, and social factors considered as a whole [55], there is a lack of a comprehensive research on equity problems. Further research is needed for developing these methodologies utilizing longitudinal performance data and prioritization of equity-focused stakeholder engagement to further enhance the real-world viability and sustainable impact of agrivoltaic projects globally.

Materials and methods

About Hachinohe Region and the Agrivoltaic Project

The Hachinohe region lies in the southeast part of Aomori Prefecture, Japan. Spread across an area of 1346.85 km^2, with a total population of 306,816 persons (in 2021), the region consists of eight municipalities, with plains on the eastern side and some mountainous areas on the western edge. Hachinohe city's Pacific coastal areas are equipped with large-scale industrial, fishing, and commercial ports. Furthermore, the key industries in municipalities other than Hachinohe city are agriculture, livestock farming, and forestry. Although Hachinohe continues to be one of the major industrial cities in the northeastern part of Japan, its shrinking population is causing serious concerns in terms of maintaining basic public services such as public transport and medical care. In addition, there is an increase in vacant houses and underutilised agricultural land that brings environmental problems (e.g., biodiversity loss) and socio-economic challenges (including a shrinking agricultural sector). Sato et al. [27] reveal that there has also been a consequent decline in agricultural land, from 1997 to 2016, by 8.61%, with a proportionate decline in the number of agricultural sector workers as well. Over the recent years, a number of community-based energy co-operatives have initiated operations to enhance energy self-sufficiency, economic gains, and a carbon–neutral society in Hachinohe. Multiple agrivoltaics (solar-sharing) projects have been established, whereby solar panels are installed on agricultural lands, whilst farming activities continue underneath them. With variations in size, scale, and type of croplands (like rice and soybean), numerous projects are today fostering cooperation between local communities and private sector.

To evaluate the financial feasibility and equity prospects of the ongoing project, a certified power generation facility (49.5 kilowatts capacity) has been identified in Towada city in the Hachinohe region, based on desk-research and local stakeholder consultation. Established in Februrary 2020, the facility operates based on a cooperative business model between the farm owner and the energy company. The energy company signed a contract with the farm owner for a period of cooperation of 20-year, whereby the farmowner leases a portion of farmland for installation of solar panels, with the costs (construction, operation, and maintenance of the photovoltaic facility) covered by the energy company supported by bank loans. In return, the private company provides an annual rent-based incentive to the farm owner. The project model has been serving as a win-win scenario for all stakeholders, as the landownership remains with the farm owner and they also earn profits, while the private company benefits through surplus revenue generated through selling the produced energy. The business model of this ongoing agrivoltaic project is illustrated in Fig. 1, wherein the energy company plays a central role in construction, power generation, operation and maintenance, and contract and sales.

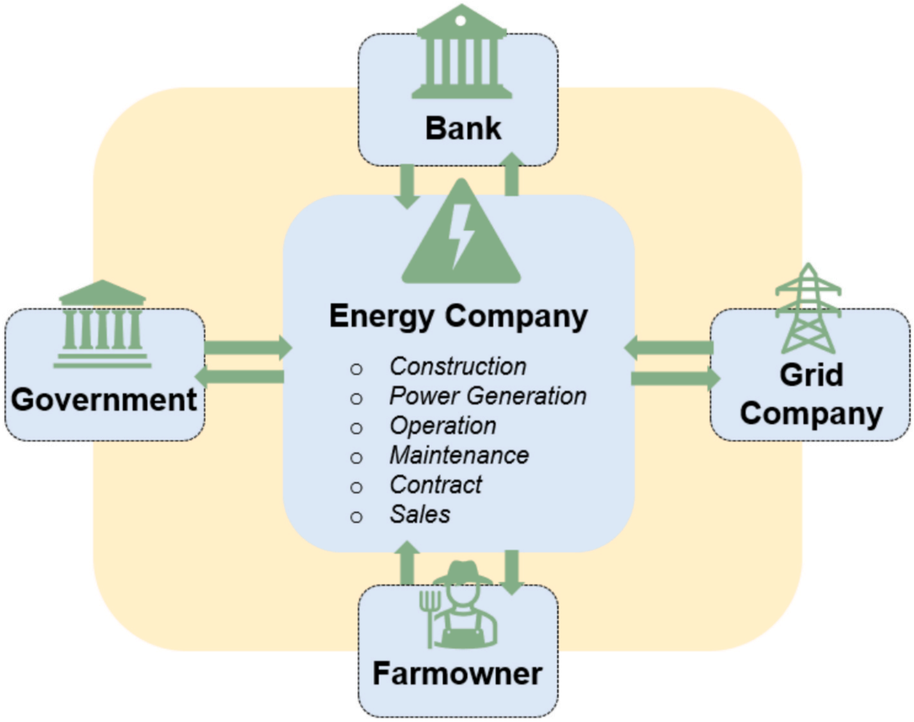

Fig. 1. Business model of the selected case (Image)
Source: Authors

Research Methods

Fig. 2 illustrates the methodical approach adopted for this research, comprising four key components: (1) Data Collection: The primary data from relevant stakeholders are gathered through key informant interviews and group discusions. The interview component involves the use of semi-structured questionnaires for local farmers and representatives of energy companies, to collect quantitative data on income generation, land lease arrangements, government subsidies received, and agricultural productivity under agrivoltaics. The questionnaire design is informed by standardized templates adopted in existing agrivoltaic studies (e.g., [18], and subsequently refined through expert consultation to align with the specific policy and institutional context of Japan. (2) Financial Analysis: Evaluating parameters such as NPV, IRR, and risk ratios; (3) Benchmark Scoring: Comparing stakeholders' finanical performance and deriving a feasibility score. In this part, the industry benchmark finanical feasibility is set as a standard and the score is obtained by comparing the feasibility in our case against the industry benchmark; (4) Policy Recommendation and Evaluation: To address identified issues, suitable policy interventions are identified, and the impact of proposed policy actions on the overall financial feasibility is assessed. Together, these interconnected steps form a comprehensive framework for evaluating the financial feasibility and equity of the business model under study. The following subsections elaborate the description for each of the methodological components.

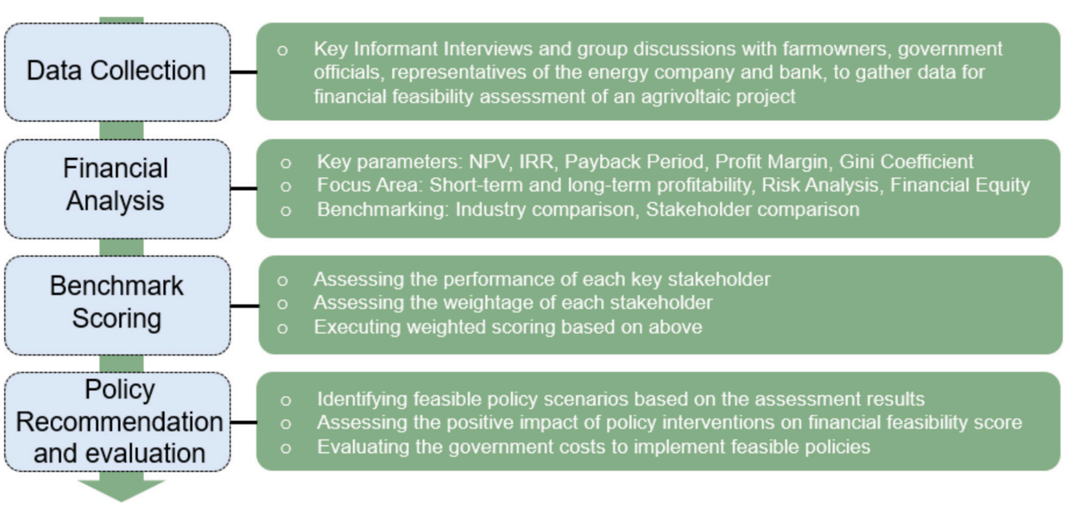

Fig. 2. Methodological framework of the study (Image)
Source: Authors

Data collection

To evaluate the financial feasibility and equity prospects of the selected agrivoltaic project, primary data is collected through key-informant interviews as focused group discussion with key stakeholders of the project (conducted from June-August 2024). A total of four group discussions are held with the: 1) Farmer cooperative, 2) Local energy company, 3) Financial organization, and 4) Officials from the city government, based on semi-structured questionnaires. For the distribution company, relevant information is derived through desk research as well as from the energy company. The questionnaires include several basic questions for all stakeholders on their experiences and information on the ongoing project, together with stakeholder-specific questions on financial feasibility prospects, as follows:

Farmer: a) In general, how much money does the farmer earn from an agrivoltaic project every year? b) What is the tenure of contract for the current agrivoltaic project? c) What is the estimated reduction in agriculture yield per year under agrivoltaics? d) How much subsidy does the farmer receive from the government for agrivoltaics? e) In general, how many hours does the farmer spend on farming in the agrivoltaic project?

Energy Company: a) How much money does the energy company earn from this project every year? b) In general, how much does the energy company pay for equipment, installation, yearly operation, and yearly maintenance, equipment and software upgrade? c) How much did the energy companies invest in the selected agrivoltaic project? How much of it is loaned from banks? For how many years is the loan awarded? What is the interest rate and repayment pattern?

Financial organization: (Is there any existing financial scheme to support clean energy or agriculture development projects? For renewable energy projects, are there any criteria for developers to meet, to receive financial assistance, such as in terms of loans? What is the bank interest rate (maximum) for loan provision to this kind of project? Also, what could be the maximum size for such projects?

Hachinohe city government: To become carbon–neutral, what are the different actions that Hachinohe city is currently taking? Is there any existing policy direction that can promote the development of agrivoltaics-based renewable energy in Hachinohe or Aomori? Under the current policy framework, are there any challenges that need to be addressed for widescale application of agrivoltaic projects

Key assumptions on electricity price fluctuation

Selling price from producer to grid

It is assumed that the Ministry of Economy, Trade and Industry (METI), Japan, has brought out a clear-cut policy to continue to reduce FIT and to further their goal toward the marketization of renewable energy, more particularly solar power. This is to take place through market-based auctions for future renewable projects that will increasingly determine electricity prices rather than FIT rates [56]. With the technology improvement and the maturation of the market, the government will continue its expectation regarding decreased costs for generation from solar power in the upcoming decade, for further facilitating a swifter marketisation process. According to IRENA [57], the world's marginal cost of solar has already dipped into 0.044USD/kWh, and may decrease further with time. Therefore, this research considers that the cost of solar power will continue to decrease until it is capped at 6 Japanese yen/kWh over the next twenty years.

Selling price from grid to users

This research assumes that the future electricity prices in Japan will have an expected trend through a linear regression model, which might indicate that the prices will steadily increase over the next two decades. This assumption is made to root the analysis into something plausible, as the thrust of the study is not on electricity price fluctuations or trends. Thus, the projected price path will give a coherent and plausible background for the research to concentrate on its more primary objectives.

Financial feasibility analysis

To evaluate the financial feasibility of the selected agrivoltaic project and profit-sharing prospects among various stakeholders, this research takes into account the perspectives of relevant stakeholders, and examines the reported financial situation, thereby establishing the data for subsequent implementation of benchmarking scoring. In the joint business model, local farmers, banks, electricity buyers and energy companies are classified as key actors who are seeking higher profits, whereas the government is considered a not-for-profit organization. For individual players, the financial conditions are measured with a balance in with a long-term, short-term aspect and a multidimensional perspective. In more detail, NPV and IRR focus on long-term profitability and project viability, and Profit Margin and Discounted Payback Period ensure that short-term risks and cash flow concerns are fully considered. The industrial discount rate for calculating the project reflects the expected risk level of the industry and cost of capital of similar projects, so the discount rates used in this research vary for stakeholders representing different sectors.

In the current business model for the ongoing agrivoltaic project in Hachinohe, the farmer has leased a portion of their land for solar energy installations over their farmland, so the farm owner will lose that asset of use, which a traditional cash flow analysis might not capture. The traditional cash outlays are certainly not made by the farmers in these scenarios, yet farmers give up the use of an asset—a bundle of property rights attached to the land. This forfeiture represents an implicit cost, often referred to as an opportunity cost, which should be considered in the financial analysis. This can be converted into a loss in the agricultural output as a cash outflow amount to revenue on account of installation of solar panels. This amount is thereby considered as implicit cash outflow while calculating the Internal Rate of Return for the farmer. The IRR results will therefore reflect the actual economic effect on the farmer. In other words, it will reflect a realistic financial analysis. The decision-making framework takes into account the opportunity cost associated with this project, and hence it shall be a more balanced view of financial implications for all stakeholders. It also brings in reliability to the financial feasibility assessment for more informed decision-making regarding agrivoltaic projects.

For the local government, it is difficult to comprehensively analyse financial feasibility , as their key aim is to achieve higher welfare of society overall. For example, one key interest of the local government when supporting this project includes the cost reduction in carbon management. However, this research only analyzes the financial factors that are directly related to the project. For example, taxes, investment and profit-sharing related to this project are analyzed, but the indirect costs reduced for carbon management are not considered in this research. Table 1 shows the financial indicators of the corresponsive stakeholders and their relative weight measurement method.

Key financial indicators of financial feasibility

Table 1 also highlights the key financial indicators for assessing the short-term and long-term feasibility of the agrivoltaic project in this research. In this research, short term refers to 1-2 years, and long term refers to period longer than that. However, it is not an absolute definition, and the term sometimes depends on the characteristics of the industry. For example, one year is short term for the farmers involved in agrivoltaics, but 10 years may be also be considered short term for the banking industry since the payback period tends to be more than 10 years when a contract term is for 20 years.

Net present value (NPV). This measures the difference between the present values of a project's cash inflows and outflows, indicating its

Table 1
Key indicators selected for evaluation of financial feasibility and equity prospects

Classification	Stakeholder	Financial Measurement	Weight Measurement	
			Support to Project	Influence from Project
Key Actors	Farmer	NPV, IRR, Profit Margin Payback Period	Time and Investment	Profit Margin
Key Actors	Energy Company	NPV, IRR, Profit Margin Payback Period	Time and Investment	Profit Margin
Key Actors	Financial Organization	NPV, IRR, Profit Margin Payback Period	Time and Investment	Profit Margin
Key Actors	Distribution Company	NPV, IRR, Profit Margin Payback Period	Time and Investment	Profit Margin
Not-for-profit Organization	Government	Tax, Investment, Profit-sharing	Time and Investment	Profit Margin

long-term viability. Cash flows are discounted using the discount rate chosen to reflect the time value of money. A positive NPV means that an investment is expected to be profitable.

$$NPV = Totalpresentvalueofinflows - Initialcashoutflow$$

$$Presentvalueofcashflowofyear_n = \frac{cashflow_n}{(1 + discountrate)^n}$$

Discount rate. This is the interest rate used to discount a project's whole-life future cash flows to their present value. The discount rate is thus related to the time value of money and the risk associated with the investment. The discount rate varies depending on the industry, region or country. It is either calculated by companies and industries, or it is determined by the sovereign government. The discount rate is key to the present value of future cash flows. A higher discount rate reduces present value, as it represents the risk or its opportunity cost.

Internal rate of return (IRR). This is the discount rate that sets the net present value of both positive and negative cash flows from a certain project or investment to zero, and thus it focuses on the project's long-term profitability. IRR is essentially derived by finding the discount rate which yields an NPV equal to zero.

$$NPV = 0 = \sum_{1}^{n} \frac{cashinflowofyear_n}{IRR} - cashoutflowofyear_0$$

Since the IRR represents expected annual return on investment, the higher the IRR, the more profitable the project. As such, it is an important metric to compare different investment opportunities.

Discounted payback period. This is the time required for cumulative discounted cash inflows to equal the initial investment, and indicates exactly how many years it takes for the total cash in-flows to recover the initial outlay, given the time value of money. This technique is useful for assessing the risk and liquidity of a project.

Return on investment (ROI). This measures the gain or loss generated on an investment relative to its cost, and is a simple way to measure an investment's profitability. The higher the ROI, the more the investment is likely to gain.

$$ROI = \frac{Netgainoftheinvestment}{Investmentcosts} \times 100\%$$

$$Netgainfrominvestment = Totalrevenuefrominvestment - Relevantcosts$$

Profit margin. This measures short-term profitability and reveals a company's financial health.

$$ProfitMargin = \frac{NetIncome}{Revenue} \times 100\%$$

$$Netprofit = Totalrevenues - Totalcosts$$

Overall evaluation of the financial feasibility

This research applies multi-criteria decision analysis method [42], which appropriately weights the stakeholders involved in certain scenarios and assesses the comprehensive decision-making result by comparing the actual performance of each stakeholder with industry benchmark. The overall financial feasibility analysis in this research takes all stakeholders into consideration, assigns weightage to each of them, marks the financial performance of each stakeholder, and calculates the overall sustainable financial score to derive a targeted policy recommendation.

Weight assignment for stakeholders

The importance of each stakeholder in decision-making is divided into the support for and influence of the project on stakeholders [44]. In this research, support is measured by the time and money costs spent on the project with a scope of between 1-100 points, which has been derived through stakeholder interviews. Furthermore, the influence of the project on stakeholders in this research is derived from the effect of the project on the stakeholder's financial interests, whereby profit margin is opted because it measures how much stakeholders earn related to their costs. ROI and NPV are experimentedwith to measure the influence of the project. However, the former cannot be applied to stakeholders without any initial investment and the latter is not chosen because NPV is calculated based on absolute values, so larger companies typically have higher investments, which leads to higher NPV, which could potentially overshadow the interests of weaker groups like farmers.

Benchmarks

In this research, the photovoltaics-related data from the American market is used as benchmark to compare with the data of farmers, energy companies, and distribution companies. The reason for this choice is the strong maturity of US's photovoltaics market [17] and its rich publicly-available data from the National Renewable Energy Laboratory and the U.S. Bureau of Labor Statistics. Moreover, the data for banks and government is derived from Japan, as they are largely influenced largely by domestic policies. Recent huge fluctuations in the Japanese yen exchange rate may also influence the calculation. Accordingly, domestic data are obtained from Statistics of Japan, Bank of Japan, Financial Services Agency and World Bank.

Strategic recommendations and sensitivity analysis

Based on the financial analysis results, targeted recommendations are proposed to address the identified key challenges. To evaluate the effectiveness and efficiency of the suggested recommendations, sensitivity analysis is carried out by adjusting key input variables including land lease subsidy, and tax incentives to energy companies and farmers.

The analysis measures how changes in these variables affect financial feasibility across stakeholder groups and whether these recommendations could deal with the identified challenges by assessing the long-term financial equity and feasibility of the proposed recommendations in policy adjustments.

Results and discussion

Table 2 presents the key financial feasibility results based on the data obtained from the case study in Hachinohe. Table 3 showcases the key benchmarks of best practices from Japan and the United States. Some specific observations about the financial feasibility results are discussed in following subsections.

Financial feasibility analysis

Farmers

Net present value (NPV). In the current business model of Hachinohe's agrivoltaic project, farm owners perform a minimal role by leasing a part of their farmland. Thus, the industry data for NPV is derived from farmland lease income and relevant costs occurring on similar farmland in Japan. According to the Ministry of Agriculture, Forestry and Fisheries (MAFF, 2023) [58], the rental price of farmland for business use range from JPY 100,000 to 500,000 per year per hectare, NPV is simulated to range from JPY 1,071,909 to 6,788,757.

An NPV of JPY 3,930,333 is comparatively generous for small operations in agriculture. One of the primary reasons for higher NPV is the favourable lease terms and lease rate in comparison to the market. Furthermore, the Japanese government has been very proactive in supporting renewable projects through subsidies and feed-in tariffs. While these policies are not directed at the farmers engaged in joint business models, they do provide support to the energy companies so they can pay a higher lease rate to the farmers. Going forward, the Japanese renewable energy market is likely to be much more conducive for this type of agrivoltaic project due to the fact that electricity prices are high and current policies support renewables. In such cases, a higher lease rate would be generated, providing a higher NPV for farmers participating in agrivoltaics.

Internal rate of return (IRR). An IRR of 67.17% is extremely high in the industry where the average for solar land lease generally has IRRs of between 10% and 25% for farmers (Carsey School of Public Policy, 2023) [59]. This implies that the return rate for farmers is high because of very good lease conditions, extremely low investment and costs, with relevant crop decrease costs as the only costs borne by farmers. However, despite the high IRR, the absolute profit for farmers remains constrained, as their low investment only leads to limited gains from such projects.

Profit margin and discounted payback period. Since farmers under the current business model do not invest cash in the agrivoltaic project, the initial investment in this study is defined as the discounted cost of potential crop loss due to solar panel installation—estimated at JPY 357,000. This can be recovered within two years via annual lease income of JPY 300,000. At 53.3% profit margin, there is considerable income through the lease of farmland for farmers, and the 2-year payback period is extremely swift. A major advantage of this business model is that farmers do not invest large amount in the project. However, at the same time, the biggest shortcoming about this model is also that the farmers do not participate in production of solar energy. While this system releases farmers from the stress of solar panel management and provides them with more time to manage conventional agriculture, this also results in low profit-sharing. This effect could be manifested in the results obtained by the Gini coefficient. The Gini coefficient reflection of this inequality indicates the project is economically profitable, though profits are not well distributed, with a few prominent stakeholders benefitting the most.

Table 2
Financial feasibility results from Hachinohe.

	NPV(JPY)	NPV%	IRR	Payback Period (Year)
Farmer	3,930,333	15.05%	67.17%	2
Energy Co.	9,444,896	36.18%	17.95%	6
Financial ins.	799,728	3.06%	2.99%	15
Distribution Co.	11,933,244	45.71%	NA	0

Table 3
Benchmark of the financial indicators

	NPV (JPY)	IRR	Profit Margin	Payback Period (Year)
Farm owner (the United States)	4,644,939	25.00%	56.00%	1.00
Energy Company (the United States)	1,622,449	13.58%	23.16%	7.00
Financial institution (Japan)	12,043,237	1.18%	40.00%	7.00
Distribution Company (the United Statets)	9,406,638	NA	14.23%	0.00

Although the suggested policy proposals aim to make agrivoltaics development more inclusive, structural factors that favor large energy companies over individual farmers need to be acknowledged. Large companies tend to be well-capitalized, technically capable, and institutionally experienced, allowing them to undertake technically challenging renewable energy projects. Small-scale farmers, on the other hand, often lack access to initial investment and technical assistance, or do not have a clear understanding of project finance and how to navigate regulations. These asymmetries constrain farmers from joining agrivoltaic projects meaningfully or negotiating fair lease conditions. In the absence of targeted support, such as favorable finance, cooperative arrangements, or inclusive institutions, policy incentives can end up reinforcing power asymmetries.

In addition, various risks and barriers can compromise the desired impacts of policy actions. Subsidies meant to assist rural constituents, for example, can be appropriated by corporate entities in the absence of controls. Complexity in the administrative system, and a lack of adequate outreach, can also discourage smallholder engagement. Thus, any transformation toward a farmer-focused model must not just be financed, but must also be supported by institutional changes that reduce barriers to entry and increase procedural fairness. These must be addressed to make agrivoltaics not just economically viable, but also distributive and participatory just.

Energy company

Net present value (NPV). For similar scale oriented solar power stations, the benchmark on NPVs is JPY 1.6 million (NREL, 2023) [45]. An NPV of JPY 9.44 million would obviously be a high return on their investment for a energy company. The high NPVs are driven by three factors: stable revenue guarantees throughout the project's lifespan, government subsidies for equipment investment, and a low perceived financial risk supported by a favorable discount rate and economic stability. The value would further be inflated by consistent support from the government through subsidies, making the project fiscally attractive compared to projects of the same kind in other regions with less favorable conditions. In comparison, the farmer's NPV is much lower, which is only restricted to JPY 3.9 million. This is, of course, expected, with the energy company undertaking all of these business activities, which are capital-intensive, and therefore capturing the bulk of financial benefits. The company has a more significant or huge NPV reliant economy of scale and operational specialization within the project, while the farmer cherishes a low-risk and steady income.

Internal rate of return (IRR). Typical IRRs for similar projects would be around 13.58% (NREL, 2023) [45]—far below the result indicated in this study at 17.95%. This could be explained by the Japanese market's high price of electricity led by the FIT system and huge government subsidies on initial investment. In comparison, the 67.17% IRR for farmers is also high but reflective of their minimal financial outlay. With such high IRR for both stakeholders, the project seems to be running under ideal conditions.

Profit margin. Typical industry margins in the solar industry are normally around 23.16%, (NREL, 2023) [45], and the profit margin of projects is 15.66%. This gap is likely due to the negative factor of Japan's higher land leasing rate and also due to a positive cause, which is Japan's government's FIT system and higher electricity price in the market. The value of the project to the farmer is relatively high when compared to the potential project risks and costs, with a 53.3% profit margin. While this is beneficial to the farmer, it underlines the risk-return trade-off where the ambitious investment of the energy company enjoys a lower, yet favorable, margin.

Payback period. Payback periods of around seven years are common for solar projects (NREL, 2023) [45]. In this case, six years is a normal payback period, which is supported by a fixed electricity price introduced by the FIT system and low initial investment cost. The payback period for the farmer is two years, as is shown, meaning that the engagement is over a shorter period with less risk. The result of the comparison is expected because the energy company will invest huge capital in the even longer years of operation, so that capital gets back to them slowly.

Financial institution

Net present value (NPV). The NPV of JPY 799,728 million shows that the project will have positive cash inflows throughout its life and will always be above the financial institution's cost of capital. This indicates that the loan structure is proper and that there is bound to be profit in the investment. However, the NPV is very weak against that of the other stakeholders, and this is related to the nature of the conservative return for the financial institution. Modesty in the NPV reflects low-risks and stable return from the project which is because of the favorable FIT scheme in Japan and low risk market conditions.

Internal rate of return (IRR). In Japan's context, the average loan interest rate is 1.18% in 2023 (Bank of Japan, 2023) [60]. Not only are interest rates low but inflation rates are similarly low. In that context, an IRR of 2.99% may be acceptable, especially when the rate is for long-term investments that can be back-up by government guarantees. However, this figure also indicates that not too much is expected on the upside, so financial entities must weigh this against other investment prospects.

Profit margin. The net profit margins for similar institutions in comparable infrastructure projects are usually within the range of 20% to 40% (Financial Services Agency, 2023) [61]. Therefore, a 16.4% margin falls out of the range, and indicates that the institution offers a lower interest rate for this project and perceives lower risks attached to this project because of the support from government policies.

Payback period. Payback periods of loans for infrastructure are similar and range from 7-15 years (World Bank, 1986) [62]. The payback lifetime of 15 years is within the industry average. It is not surprising that most capital investment in large future renewable energy projects would have an extended period. To a financial institution, this represents long-term durability, and it is particularly important in markets such as Japan, where levels of economic circumstances remain quite steady and where there is a very low risk of falling into default.

Distribution company

Net present value (NPV). Similar small-scale energy transmission projects in the US is simulated (with raw data from US EIA and 50KW scale) to carry a net present value of 9.4 million JPY. The NPV in this study, 11.9 million JPY, is much higher than than the industry benchmark, which is likely due to the FIT system.These differences in the result indicate variable profits made in each country. Further, the distribution company leverage from the high prices for electricity in Japan. Although this price fluctuation in the coming time may be quite large due to technology changes in the Japanese environment, this price fluctuation reflects the accepted price model in the industry. Technology changes will further diminish the operational costs and, hence, add to the profits.

Profit margin. The profit margins for energy distribution firm (Tohoku Electric, in this case) may vary around -0.4% in the past three years (Consolidated Annual Report 2023 for Tohoku Electric, 2023) [63]. The 10.33% profit margin would show this energy distribution company is efficient, and the margin also appears to be competitive in the industry, which shows that the firm has performed as per expectations.

Economies of Scale: Since the installation required for electricity distribution is highly fixed in nature, there are strong chances of enjoying economies of scale in the distribution company. As more electricity moves in the network, the per-unit cost of distribution should reduce, which acts like a booster for the margin of profit.
Regulatory Support: The regulatory environment in Japan is supportive of renewable energy and provides enabling policies that instill a stable revenue policy for distribution companies. Regulatory support keeps risks low and sustains a healthy profit margin.
Monopoly Power: Since Tohoku Power is not under any compulsion to develop the infrastructure, it involves almost no operation costs related to this.

Payback period. The reported 0-year payback is so short in comparison to what one typically sees in such projects that it suggests the distribution company more or less gets its money back up front. A few possible reasons could be the pre-existing infrastructure connecting with customers. In this line, the company might have been already using existing distribution infrastructure with minimum additional spending. This can ensure immediate returns; since the infrastructure is already in place.

Government

Profit sharing and social equity (gini coefficient). The Gini coefficient is a measure of income inequality within a population. A lower Gini coefficient indicates that the income distribution is more equal. In such renewable energy projects, sharing by the government defines economic equality. This comes with a very high value of 79.77%, which reflects high inequality , indicating that while the projects may be earning substantial economic benefits, they are not equitably distributed among the key stakeholders. The Gini coefficient is calculated using stakeholder-level profit sharing data derived from the financial analysis in Section 4.1. Specifically, the estimated net income distributions across farmers, energy companies, financial institutions, and distribution companies are used to simulate a Lorenz curve, from which the Gini coefficient is computed. The calculation follows standard economic methodology:

$$Gini = 1 - \sum_{i=1}^{n} (Y_i + Y_{i-1})(X_i - X_{i-1})$$

Y represents the cumulative share of income and X represents population.

The typical Gini coefficient for manufacturing industry in Japan is 47.3% (Ministry of Land, Infrastructure, Transport and Tourism, 2015) [64] . In that context, 79.77% is significantly higher, and it implies the disproportionate sharing of profits made, which is associated to income disparity within the communty.

Strategic recommendations

Farmer and energy companies

To enhance long-term financial feasibility and equity of agrivoltaic projects, the energy company can establish profit-sharing models with farmers, which will increase financial stake between them and the project, and enhance the overall potential for scaling up agrivoltaic projects on a sustainable level. This will also enhance alignment among stakeholders and potentially improve the project financial feasibility. Increasing financial involvement of the farmowners can help attaining better overall project outcomes in the end. A potential alternative could be to allocate a percentage of the revenue generated from the electricity sales directly to the farmers, in addition to their fixed lease payments. For instance, the energy firm may consider that around 2% after the coverage of its operation cost from the net generated electricity sales revenue be shared. As the calculation estimates from the current project imply that the net income gained by the project per year is JPY 3.5 million and if 2% is shared with farmers; they would gain an additional sum of JPY 70,000 that is 35% of the proaction rice income. This model will multiply the farmer's financial stake in the project and also encourage them to take more interest in the efficiency of the project, with a long-term vision. While the current project under consideration is at small scale, involving 0.25 hectares of farmland, the income seems small, but if more incentives are given, farmers may choose to lease more lands for the project and decrease the overall costs for energy companies. Most of the maintenance costs occur because of staff travelling expenses, but with this responsibility, if taken by the farmers to maintain the equipment, the costs could reduce significantly.

Enhanced Farmer Engagement: Profit-sharing can enhance the relationship between the energy company and the local community, helping build goodwill and fostering long-term cooperation, which is vital for the sustainability of the project. If the farmers share part of the revenue from the project, they are likely to develop heightened engagement for further investment in the project, consequently enhancing working together, and enhance efficiency in the process. For example, as a step toward the realisation of more benefits, farmers could be engaged in leading routine maintenance works like cleaning the panels and visually inspecting equipment performance, which helps reduce operational costs and ensures efficient energy generation.

Attractiveness of the project to Investors and Improved ESG Scores: By adhering to CSR goals, profit-sharing will improve the nature of the project from Socially Responsible Investors. Strong ESG projects often gain better financing conditions or attract investment at a lower cost of capital, which would put the energy company in an improved financial position.

Financial institution

Programs that certify green electricity—operating in most of the United States and in Europe — would certify the source of electricity supply derived from eligible renewable resources. Differential certification, in fact, allows consumers to purchase electricity to serve loads that are deserving of a "green" certification and may be available at a premium. The implementation of such green certification could be facilitated by the Tohoku Electric Power company itself under a wider CSR initiative to demonstrate an alignment of support with Japan's drive to take a stringent policy on carbon emission reduction. The company may adopt a system of tiered pricing under which electric power generated from clean sources may be sold at a higher price compared to its fuel-based counterpart, thereby reflecting the environmental attributes in the price. By integrating more renewables into the grid, coupled with real-time pricing, Tohoku Electric Power can pull in a premium for its electricity. This would also enable smart grid-level demand response programs, where consumers would essentially be incentivised to reduce usage at peak times, and this could be quite profitable for the utility.

Green electricity and smart grid services will help environmentally-conscious customers and businesses become involved in the demonstrations, particularly with the carbon-neutral pathway that Japan is following to achieve net-zero by 2050. Besides, in line with government regulations, smart grid development with green certification may also lead the utility eventually to be categorised under certain subsidies or incentives of governments.

However, the realisation of such initiatives would require a signficant infrastructure investment and consumer awareness. There are also certain regulatory barrieries, as the energy market of Japan is highly regulated, and it is mandatory for new innovational pricing model or certification to meet up with such complex regulatory mechanisms.

Government

Currently, government subsidies are awarded to energy companies, which utilize them to acquire solar panels and related equipment. Though this guarantees the infrastructure for the project, it does not directly benefit the farmers whose land is being utilized. Instead, a strategic recommendation could be to redirect some of the government subsidies towards compensation of farmers in the form of improved lease agreements. As an alternative approach to funding only the hardware, an alternative government subsidy route could be through enhanced lease payments directly to farmers for using their land for the installation of solar availed from them. In this way, higher dividends to the farmers will increase farmers' motivation for more participation in the project. This will also lead to greater acceptance and more expansion of agrivoltaics over remote rural areas. Futhermore, the subsidy redirection to farmers can help balance out the income distribution, thereby reducing the Gini coefficient and promoting social equity.

Currently, agrivoltaic projects do not provide substantial tax benefits to farmers, which limits their financial attractiveness. Offering exclusive tax credits for farmers involved in agrivoltaic projects can increase their net income. Making a reduction or exemption of property tax for farmlands used in projects of agrivoltaics will reduce the overall tax load to the farmer and ensure increase of their revenues. Likewise, the allowance for an income tax deduction or credits for leasing out space for agrivoltaics or allowances for a tax credit for the investment that farmers make would invariably 'integrate' agrivoltaics into their traditional farming practices. Through these actions, the tax incentives would directly increase the net incomes for the farmers, making agrivoltaics a more rewarding option. In addition, tax relief could lower the financial barriers towards market penetration for widespread technological adoption in agrivoltaics.

Sensitivity analysis

To assess how the proposed policy recommendations will affect the operations of selected agrivoltaic project, sensitivity analysis is conducted to evaluate the effects on stakeholder participation in agrivoltaics, financial performance and social equity. In doing so, the key objective is to derive strategic measures of overall financial feasibility for various policy scenarios through variation of key parameters, hence identifying the ways in which farmers could be supported efficiently while ensuring a fair distribution of benefits. To be specific, the influence of proposed policy interventions on balanced feasibility score is measured in the following subsections.

In the sensitivity analysis, the choice of using $\pm10\%$ increments is guided by both analytical clarity and operational convenience. Saltelli et al. [65] recommends parameter variations of 5–20%, with $\pm10\%$ being the accepted standard in many applied contexts. Additionally, this convention has been consistently adopted in investment evaluation and infrastructure finance studies, particularly in energy systems modelling and public-private partnership assessments. For example, Ahmed and Rezaei-Gomari (2019) [66] applied ±10% variations to production and cost parameters in evaluating the economic feasibility of shale gas extraction. Similarly, Díaz and Guedes Soares [67] used ±10% perturbations when analyzing NPV and IRR outcomes in floating wind farm project assessments. Guindon and Wright [68] further confirmed that ±10% parameter changes are frequently employed as a standard variation for input cost sensitivity in risk evaluation practices in solar project finance.

Incentives to lease land

Such a policy intervention includes giving more subsidy to farmers based on the income generated from leasing their land. In this way, the participation of farmers will be incentivized as leasing their land for agrivoltaics would now be more attractive. Table 4 shows the influence of land lease subsidy on the overall feasibility score which measures the feasibility of the business model as a whole with a combination of all the financial indicators. The efficiency is calculated by dividing increasing feasibility score based on government's increasing investment cost in terms of increased subsidies.

- Scenario: Percentage rise in the earnings of farmers from land lease through government subsidy.
- Key Metrics changed: This shows government investment matched with the overall financial feasibility score for a variety of incentive levels.
- Results: For a 10% increase in leasing income to be reached, an increase in government investment of JPY 0.48 million will be required, correspondingly entailing a 0.97 point increase in feasibility scoring. It also represents the highest efficiency of the policy, measured as increase in feasibility score per unit of investment, beyond which the law of diminishing returns takes hold. This also means that the 10% increase in leasing income represents the most efficient equilibrium point that balances government investment with increased farmer participation, making the project attractive to farmers, yet not overly burdensome on the government financially.

Revenue sharing model

An alternate approach involves the revenue sharing models, wherein farmers could invest in the project and benefit from the sale of the electricity apart from lease income. This would help them to acquire more direct involvement with energy production and greater financial engagement. Table 5 represents the impacts of tax relief on the overall feasibility score which measures the feasibility of business model as a whole with a combination of all the financial indicators. The efficiency is calculated by dividing the increasing feasibility score by the government's increasing investment cost caused by tax allowance.

- Scenario: Farmers invest an increased share of initial investment and energy companies share part of (assumed half of Return on Investment) the revenue created from the generated electricity with farmers. With this model, government could relief energy company's tax rate from 38% to 31.2%.
- Key Metrics changed: Government investing more, further; improvement in the feasibility score; efficiency of the revenue-sharing model.
- Results: It is observed that 2.5% farmer investment, with fixed government investment at JPY 4.43 million, increases the overall financial feasibility score by 14.46 points. This indicates that efficiency increases with the 2.5% investment level and subsequently tapers off gradually. It follows that a small initial investment by farmers, subsidized through revenue sharing, can substantially raise financial feasibility and farmer participation. At the same time, such a policy could reconcile the interests of energy companies with the interests of farmers to establish long-term cooperation that would increase the viability of the agrivoltaic model.

Tax incentives given to farmers

Another approach is to give further incentives to farmers with tax relief on the income derived from agrivoltaics. This would reduce farming barriers and increase the adoption of the agrivoltaic business model. Table 6 represents the impacts of tax incentives to farmer on the overall feasibility score which measures the feasibility of business model as a whole with a combination of all the financial indicators. The efficiency is calculated by dividing increasing feasibility score with government's increasing investment cost caused by tax allowance.

- Scenario: Farmers get tax reductions on the income accrued from renting the land for agrivoltaics.
- Key Metrics Changed: More investment to be provided by the government; higher scores on feasibility; efficiency relating to tax incentives.
- Results: This would mean that the government would have to incur an expenditure of JPY 0.24 million in providing a 20% tax relief for farming, on average, for there to be an increase in the financial feasibility scores by 1.15 points. This policy exhibits steady efficiency with increased levels up to 100% tax relief. It proves that tax incentives serve as a good method to enhane the financial feasibility and social equity of the assisted housing projects without affecting the well-being of others who are stakeholders in the same.

Conclusion

By evaluating the financial feasibility of an ongoing agrivoltaic business model in the Hachinohe region of Japan, this research attempts to explore optimal pathways for enhancing the financial equity and community wellbeing prospects of agrivoltaic projects in Japan and beyond. Based on the derived results, it is inferred that there are certain variations in profit distribution through agrivoltaics, due to which the wider scope of benefits for the farm owners remains constrained, mainly due to their limited engagement, only as a beneficiary. Even though farmers have positive financial indicators like IRR and profit margins, the absolute financial benefit they gain is limited, thus reflecting the disparities in financial benefit distribution. While not a direct measure of broader social inequity, the observed imbalance in profit distribution among stakeholders raises relevant concerns. This observation is further substantiated by the Gini coefficient, which reflects that a few prominent stakeholders gain control of most of the profit. The main reason for such imbalanced profit-sharing is that farmers engagement in energy production processes is very limited, and can only share the profit through leasing the land, which provides regular income but does not fully allow a farmer to benefit from the project. The current business model is thus dominated by the energy company, due to their high investments, technical expertise, and resources. For the long-term growth

Table 4
Expected effects of lease subsidies on overall financial feasibility

Incentive on land leasing %	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Government additional investment(JPY Million)	0.48	0.96	1.44	1.92	2.40	2.88	3.36	3.84	4.31	4.80
Increase in overal scores	0.97	1.92	2.88	3.83	4.77	5.72	6.66	7.59	8.53	9.46
Efficiency(%)	2.02	2.00	2.00	1.995	1.988	1.986	1.982	1.977	1.975	1.971

Table 5
Expected effects of revenue-sharing and farmer investment on overall financial feasibility

Farmer increasing investment%	2.5%	5%	7.5%	10%	12.5%	15%	17.5%	20%	22.5%	25%
Government additional investment (JPY Million)	4.43	4.73	5.03	5.34	5.64	5.94	6.24	6.54	6.85	7.15
Increase in overal scores	14.46	14.72	15.06	15.48	15.97	16.51	17.1	17.73	18.42	19.15
Efficiency(%)	3.26	3.11	2.99	2.9	2.83	2.78	2.73	2.7	2.69	2.68

Table 6
Expected impact of tax exemptions to farmers on overall financial feasibility

Tax relief for farmers %	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Government additional investment (tax exemption for land)(JPY Million)	0.12	0.24	0.36	0.48	0.60	0.72	0.84	0.96	1.08	1.20
Increase in overal scores	0.57	1.15	1.76	2.38	3.02	3.68	4.36	5.05	5.77	6.5
Efficiency (%)	4.75	4.79	4.89	4.96	5.03	5.11	5.19	5.26	5.34	5.42

and sustainability of agrivoltaics, it is vital that farmers are engaged significantly with relative ownership and contributions in the project. Without appropriate policy interventions at the point of sharing energy benefits or including more farmers in the process of energy production, the social benefits from agrivoltaics may remain limited. This may likely lead to lower willingness of farmers to lease more farmlands to support such projects and limit the development of this business model.

To tackle the current challenges, governments could redirect a part of the energy company subsidies to farmers, which will enhance the lease agreements' viability and result in fair profit-sharing. Based on the sensitivity analysis, even a 10% increment in the land leasing incentive can yield promising results as more farmers can participate without straining government resources. In addition, the current business model could be modified by increasing farmers' investments in the project as revenue-sharing creates a high level of financial involvement by the farmers in the project. In context of the selected agrivoltaic projects, around 2.5% farmer investment is the best solution to satisfy all stakeholder interests by achieving maximum financial feasibility. Lastly, the establishment of tax relief to farmers engaging in agrivoltaics would further enhance economic viability and social justice. Tax incentives are an effective, less expensive means of enhancing farmer involvement and yet ensure the well-being of third-party stakeholders. Further policy adjustments will be needed to ensure that the profits are distributed better among all the stakeholders involved, as shown by social inequality through the Gini coefficient. This will include further government support through grants and tax reliefs, as well as more incentives for farmer participation. Future research may further explore how financial equity in agrivoltaics interacts with broader concepts of social equity and rural resilience, particularly in Japan's context of local energy transitions.

In conclusion, it is important to acknowledge the limitations of this research. The current research only assesses the financial feasibility of a specific agrivoltaic project in a specific area of Hachinohe. However, there are many different business models of agrivoltaics which are operational in different parts of the world. To develop a comprehensive understanding of actionable pathways to enhance socio-economic viability of agrivoltaics, further studies can consider the assessment of other business models as well. Future research in this area can also consider the comparison of different business models for agrivoltaics, in respect of environmental and social impacts besides financial feasibility. In other words, agrivoltaics can work as a genuine model of renewable energy development, but it is important to pay close attention to stakeholder participation and profit distribution aspects for long-term fiscal viability and social equity. It is hoped that the proposed interventions can provide a roadmap toward improvement in farmers' participation and equality, as wel as strengthening the existing business models for agrivoltaics.

CRediT authorship contribution statement

Xiao Chen: Writing – original draft, Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vibhas Sukhwani:** Conceptualization, Visualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Data curation, Resources. **Bijon Kumer Mitra:** Conceptualization, Visualization, Methodology, Investigation, Writing – review & editing, Supervision, Resources, Project administration. **Anudari Batsaikhan:** Conceptualization, Visualization, Methodology, Investigation, Writing – review & editing, Data curation. **Rajib Shaw:** Writing – review & editing, Supervision, Resources.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

All the authors sincerely acknowledge the support received from the Institute for Global Environmental Strategies (IGES) Strategic Research Fund (SRF), Japan, in conducting this study. The authors gratefully acknowledge Emma Fushimi (IGES) for reviewing and editing the manuscript for language and clarity.

Data availability

Data will be made available on request.

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