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Navigating the Water – Energy – Food (WEF) Nexus in Rural Development: A Case Study of the Cintamekar Micro-Hydro Power Project in Indonesia

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ABSTRACT

This study analyzes the interactions, synergies, and trade-offs within the Water–Energy–Food (WEF) Nexus at the Cintamekar Micro-Hydro Power Plant (PLTMh) in Subang, Indonesia. Using interviews, observations, and document analysis, the research identifies how water flows simultaneously sustain hydropower generation and agricultural irrigation, generating Water–Energy and Water–Food linkages. A critical finding is the emergence of a WEF trade-off after the PLTMh shutdown in 2022, when water previously allocated to energy generation was redirected entirely to irrigation, prioritizing food security while eliminating renewable energy production. This condition shows how nexus interactions are shaped not only by technical flows but also by institutional capacity, governance vulnerabilities, and dependencies on single-resource infrastructure. The study contributes by explaining how WEF trade-offs materialize during system disruptions, demonstrating the decisive role of local institutional capacity in maintaining nexus synergies, and identifying the absence of an Energy–Food linkage as a significant empirical gap in rural run-of-river hydropower systems. These findings enhance framework understanding of WEF dynamics in rural contexts and offer practical insights for designing resilient, community-based renewable energy strategies.

Keywords: Water–Energy–Food Nexus, Micro-Hydropower, & Rural Development

1. Introduction

The global transition to clean, renewable energy is essential to mitigating climate change and achieving sustainable development (International Renewable Energy Agency, 2020; UN DESA, 2023). While this transition is a universal goal, it takes on unique dynamics in rural landscapes that distinguish it from urban contexts. Rural areas, often characterized by lower population densities, geographical isolation, and limited infrastructure, face disproportionately high energy costs and unreliable supplies, which exacerbate energy poverty and hinder socio-economic progress (Baker et al., 2014; International Energy Agency, 2022). Conversely, these same landscapes often hold untapped renewable energy resources, such as solar, wind, and hydropower, positioning them to become not merely passive energy consumers but active producers of clean power (Gulagi et al., 2018; International Renewable Energy Agency, 2020). The challenge, therefore, lies in navigating the intricate socio-economic and infrastructural hurdles of these unique contexts to harness their inherent potential (Setyowati, 2021; Todd & McCauley, 2021). This analysis argues that a successful rural

energy transition (RET) requires moving beyond traditional, single-sector interventions and shifting toward an integrated, holistic approach that considers the fundamental interdependencies of vital resources.

For this reason, the Water-Energy-Food (WEF) Nexus has emerged as a crucial analytical and planning framework for understanding the complex interconnections between these three essential sectors (Rasul & Sharma, 2016; Simpson & Jewitt, 2019). As the global population grows and climate change intensifies, demand for water, energy, and food rises rapidly, creating intricate synergies and trade-offs that can no longer be ignored (Liu et al., 2017; Nhamo et al., 2018). Historically, development planning has often relied on a "siloed" or single-sector approach, which has frequently led to unintended negative consequences, such as over-pumping water resources when a new, free energy source is introduced (Mutanga et al., 2024; Srigiri & Dombrowsky, 2022). By moving beyond this fragmented model, the nexus approach provides a structured decision-support tool that identifies potential trade-offs and exploits existing synergies (DeLaurentis & Callaway, 2004; Keskinen et al., 2016). This integrated perspective improves resource efficiency, reduces negative externalities, and builds long-term resilience, directly contributing to several Sustainable Development Goals (SDGs) (Rasul & Sharma, 2016; UN DESA, 2023).

To provide a tangible example of this integrated framework in practice, this paper examines the Cintamekar Micro-Hydro Power Project (MHPP) in a rural area of West Java, Indonesia. As a 120-kilowatt run-of-the-river plant, the project provides a reliable source of electricity to a village where many households previously lacked access (Setyowati, 2021). However, its significance extends far beyond its technical output. The project's dual purpose- providing electricity to the local community while also generating income through the sale of power to the national grid has created a sustainable revenue stream that is systematically reinvested into community development, making it a unique and powerful example of integrated socio-economic advancement (Baker et al., 2014; Setyowati, 2021). By adopting the WEF nexus framework, this paper explores the dynamics, synergies, and challenges of the Cintamekar project as a valuable lesson in community-based rural development. The following sections will first review the theoretical underpinnings of rural energy transition and the WEF nexus as an integrated planning approach. Next, this report presents a detailed profile of the Cintamekar project, highlighting its unique governance, technical characteristics, and socio-economic context. The core analysis will then detail the specific synergies and trade-offs observed within the WEF nexus, followed by a discussion of broader policy implications and a conclusion summarizing key lessons for integrated, community-based rural development.

2. Methods

2.1 Water, Energy, and Food (WEF)

2.1.1 Water

Water underpins the other two sectors, energy and food, and is critical to the WEF system's sustainability. In agriculture, water is essential for irrigation and directly determines food production levels. Water also serves as a primary input in energy generation, whether for hydropower, cooling in thermal power plants, or fossil fuel extraction (de Fraiture et al., 2008; Hoff et al., 2019). Hoff (2011) notes that unintegrated water management often leads to inter-sectoral conflicts. For instance, conflicts arise when water allocation prioritizes industrial or energy demands over domestic and agricultural needs. Moreover, climate change exacerbates pressure on water availability, particularly in arid and semi-arid regions such as the MENA (Middle East and North Africa) area, where competition for water resources is exceptionally high (Waha et al., 2017).

2.1.2 Energy

Energy drives economic growth and infrastructure development, providing basic services such as electricity access, water pumping, and agricultural mechanization. Modern energy, especially from renewable sources, can boost agricultural productivity through precision irrigation technologies, improved post-harvest processes, and more efficient crop distribution (IRENA, 2016; Jobbins et al., 2015). However, energy production also necessitates significant water consumption for hydropower, thermal cooling, and fuel extraction and processing. This creates a trade-off between the water required for energy production and that needed for food

and domestic use. Consequently, integrating the energy sector with water management is crucial for maintaining the overall system's resilience.

2.1.3 Food

The food sector depends heavily on the availability of both water and energy. Global food production accounts for approximately 70% of the world's total water consumption, while energy is utilized in various forms, including chemical fertilizers, agricultural machinery, transportation, and crop storage (Godfray et al., 2010; Lundqvist, J. & Molden, 2008). This reliance makes the food sector vulnerable to energy price fluctuations and water-supply uncertainties. According to Hoff (2011), agricultural policies that overlook water and energy often hinder efforts to strengthen food security. A study in Ethiopia by Wolde et al. (2020) showed that household livelihood resilience is significantly influenced by the distribution of nexus resources, including community access to irrigation water, electricity, and food markets. Integrating a WEF approach into agricultural planning can help mitigate these challenges by improving resource use efficiency and fostering community participation.

2.2 Water, Energy and Food Nexus Interactions

The Water, Food, Energy (WEF) Nexus concept emerged as a multidisciplinary approach to understand the interconnections and interdependencies among these three vital sectors: food, water, and energy. These sectors have complex relationships, and increased demand in one invariably affects the others, directly and indirectly (Hoff, 2011). The WEF Nexus concept originated from global challenges such as climate change, population growth, urbanization, and increasing pressure on natural resources. This concept provides a framework for understanding complexity and avoiding fragmented sectoral approaches, which often lead to inefficiencies and intersectoral conflicts (Ringler et al., 2013). Given these considerations, the nexus approach is used not only to identify interlinkages but also to manage trade-offs and maximize synergies among these three sectors. This means that an intervention in one sector will inevitably have either positive or negative consequences for the others (Bazilian et al., 2011; Mohtar & Daher, 2016).

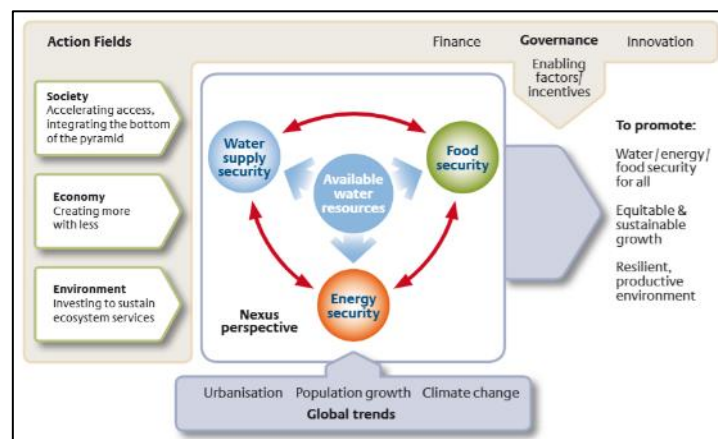


Figure 1. Nexus Water, Energy, and Food Security
Source: Hoff (2011)

The Water-Energy-Food (WEF) Nexus approach is an analytical framework for understanding the complex interactions among the water, energy, and food sectors as an interconnected system (Figure 1). This approach aims to improve resource-use efficiency, reduce sectoral conflicts, and foster synergies for sustainable development (Hoff, 2011; Leck et al., 2015). These three sectors are inseparable, and changes in one directly or indirectly affect the others (Mohtar & Daher, 2016). Interactions among sectors within the WEF framework are not merely technical; they are also institutional and social. Hoff et al. (2019) indicate that successful implementation of the nexus approach relies heavily on cross-sectoral coordination, active stakeholder participation, and supportive national policies. Without such integration, efforts to improve resource efficiency and resilience will be challenging to achieve.

2.3 Research Location

The Cintamekar Micro-Hydro Power Plant (PLTMh) is located in Cintamekar Village, Serangpanjang District, Subang Regency, West Java. The community's need for electricity drove the construction of this PLTMh in Cintamekar Village, Subang Regency. The village was initially beyond the national electricity grid (PLN) because of its remote location. The IBEKA Foundation (Institut Bisnis dan Ekonomi Kerakyatan/Institute for People's Business and Economy) then initiated the development of a community-based PLTMh. Over time, the Mekar Sari Cooperative became the PLTMh's managing institution and also handled human resource training and community institutional strengthening. Donor organizations primarily financed the project. The Cintamekar PLTMh officially began operation in 2004 with a capacity of approximately 120 kW and is connected to the PLN grid (an on-grid system).

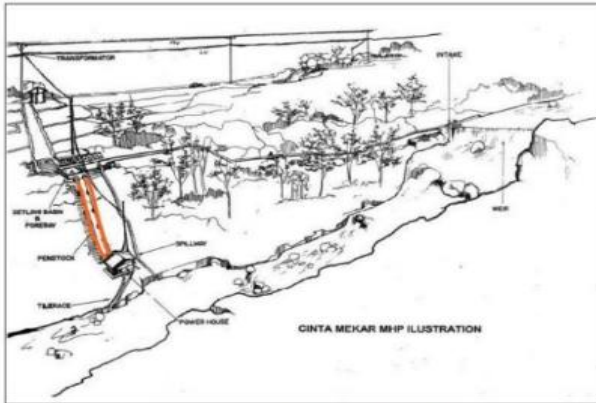


Figure 2. Illustration of the Cintamekar Micro-Hydro Power Plant (PLTMh) Plan
Source: IESR (2011)

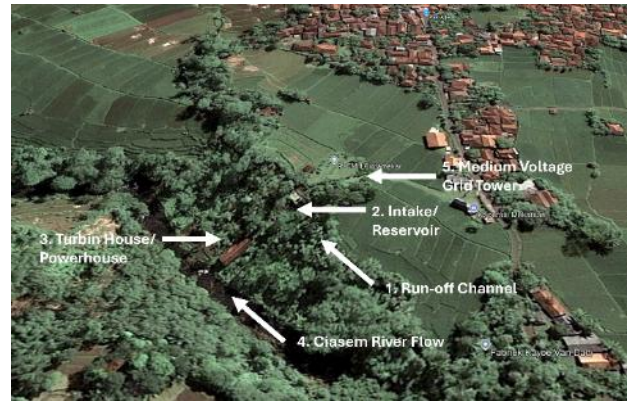


Figure 3. Infrastructure of the Cintamekar Micro-Hydro Power Plant (PLTMh)
Source: Google Earth (2025)

The Cintamekar Micro-Hydro Power Plant (PLTMh) is a system designed to harness the hydropower potential from the Ciasem River flow as a renewable resource. The PLTMh operates through several key infrastructures, including a Run-off Channel, Intake/Reservoir, Turbine House/Powerhouse, the Ciasem River flow, and a Medium Voltage Grid Tower, which work synergistically to generate electricity (Figure 3). The operational process begins by diverting water from the Ciasem River through the Run-off Channel. This channel collects discharged water and directs it to the Intake/Reservoir. Within the intake/reservoir, water is stored and regulated to ensure sufficient pressure to drive the turbines. The water is then channeled to the Turbine House, where its kinetic energy rotates the hydroelectric turbines. A generator connected to the turbines converts mechanical energy into electrical energy. The generated electricity is then transmitted via cables to the Medium Voltage Grid Tower, which serves as the integration point with the national electricity grid (an on-grid system). In this manner, the Cintamekar PLTMh not only provides local electricity but can also sell energy to PT PLN (the state electricity company), thereby generating additional income for the village community through an energy sales scheme. Furthermore, this system supports efficient use of water resources, as the run-off flow used for electricity generation can be monitored and optimized without harming the river ecosystem.

2.4 Methods

This study employed a qualitative descriptive method, aiming to reinforce several existing theories that serve as references for this research (Semeniuk & Cresswell, 2018). Specifically, this research used a single case study to provide an in-depth understanding of the complex interactions among water, energy, and food systems in a specific local context. This approach is appropriate because the WEF Nexus involves socio-institutional dynamics, stakeholder interactions, and local governance processes that quantitative data alone cannot fully capture. The case study design enables an in-depth examination of how these interactions occur in a specific rural development context.

Data were collected between April and June 2025 through in-depth interviews, observation, and documentation. The gathered data were then analyzed to explain the Water, Energy, and Food (WEF) Nexus phenomenon within the case study of the Cintamekar Village Micro-Hydro Power Plant (PLTMh).

development in Subang, West Java. In-depth interviews were conducted with eight respondents representing various local government officials, including those from the Regional Development Planning, Research, and Development Agency (Bappeda Litbangda), the Department of Manpower, Transmigration, and Energy (Disnakertrans Energi), Serangpanjang Sub-district Office, the Cintamekar Village Government, as well as "Abah Jak," who is an operator at the Cintamekar PLTMh. The researchers also conducted observations and documentation to obtain a comprehensive overview of the existing conditions. The team then validated the collected data through triangulation, drawing on secondary data, books, news articles, and other relevant sources. The team analyzed the collected data using thematic analysis. First, the team reviewed and coded interview transcripts, observation notes, and documents to identify key statements related to water, energy, and food interactions. The team then grouped the codes into broader themes aligned with the WEF Nexus analytical dimensions, including nexus framing, opportunities, technical solutions, stakeholder involvement, and framework conditions. The study triangulated data by comparing interview findings with observations and secondary sources to strengthen the analysis.

This research uses the Water, Energy, and Food (WEF) nexus analytical framework proposed by Hoff et al. (2019) and the principles of sustainable WEF system management outlined by Borge-Diez (2022). To understand the WEF Nexus, Hoff et al. (Hoff et al., 2019) emphasize the need to explain several key aspects, including:

1. **Nexus Framing:** This involves explaining how key issues and interlinkages among sectors (water, energy, food) are understood within a specific context, and identifying relevant synergies and trade-offs.
2. **Nexus Opportunities:** This focuses on identifying opportunities where the nexus approach can add value, such as improving resource efficiency, climate resilience, or poverty reduction.
3. **Technical and Economic Nexus Solutions:** This focuses on technical and economic solutions that can be implemented to leverage synergies and mitigate inter-sectoral conflicts, such as water-saving technologies or investments in integrated production systems.
4. **Stakeholder Involvement:** This focuses on technical and economic solutions that can be implemented to leverage synergies and mitigate inter-sectoral conflicts, such as water-saving technologies or investments in integrated production systems.
5. **Framework Conditions:** This explains the institutional, policy, regulatory, and incentive conditions that either support or hinder the implementation of the nexus approach at local to national levels.
6. **Monitoring, Evaluation, and Next Steps:** This involves establishing indicators and evaluation mechanisms to monitor the impact of nexus implementation, and designing subsequent steps, including replication and scaling up.

3. Result and Discussion

3.1 Water, Food, and Energy Nexus Framework

3.1.1 Nexus Framing

Since the construction of the Cintamekar Micro-Hydropower Plant (PLTMh), cross-sectoral interconnections have formed distinct flows within the nexus system. The Water–Energy flow is reflected in the use of water from the Ciasem River to drive the PLTMh turbines, as well as the energy flow that supports water distribution. The Water–Food flow is evident in the provision of clean water and improved irrigation systems. Joint rehabilitation of irrigation channels and the PLTMh run-off system has enhanced agricultural productivity. Meanwhile, no observable Energy–Food flow has been identified in the current system.

3.1.2 Nexus Opportunities

The potential for synergies within the Mini Hydropower Plant (PLTMh) in the context of the Water-Energy-Food (WEF) Nexus involves efficiently using resources to support multiple sectors simultaneously. By identifying these opportunities, integrative strategies can be developed to enhance resource resilience at both local and regional levels.

3.1.3 Technical and Economic Solutions

Technical and economic solutions form the foundation for implementing nexus management in practice. Technologies such as micro-hydro power plants (PLTMh) and precision irrigation systems offer more efficient,

environmentally friendly alternatives for resource management. Economically, investment in cross-sectoral infrastructure must be supported by sustainable business models and active stakeholder participation. Together, these solutions aim to maximize ecosystem benefits while mitigating the negative impacts of resource exploitation.

3.1.4 Stakeholders Involved

Stakeholders include the Desa Cintamekar community, the government, the Mekarsari Cooperative, investors, and private sector entities such as PT. HIBS and IBEKA, each holds a distinct role in the planning, implementation, and performance evaluation of the Cintamekar micro-hydro power plant (PLTMh). Community participation is particularly crucial to ensure local needs are met, and the program remains sustainable. Without effective coordination among these stakeholders, efforts to manage the PLTMh can lead to conflicts or inefficient resource allocation.

3.1.5 Framework Conditions and Monitoring

External factors influence the implementation of the nexus framework, namely climate change and governance and institutional structures. Changes in rainfall patterns, a direct effect of climate change, affect the operational efficiency of the Cintamekar micro-hydro power plant (PLTMh) and, consequently, Desa Cintamekar's agricultural output. Similarly, the Mekarsari Cooperative's governance and institutional framework directly influence the PLTMh's performance, particularly electricity sales and the provision of cooperative services.

3.2 Nexus: Water, Energy, and Food

This research successfully identified a Water-Energy-Food Nexus that emerged from the construction of the Cintamekar micro-hydro power plant (PLTMh) (see Figure). A more detailed analysis reveals the nexus primarily manifests as an interconnection between the water and energy sectors, as well as between water and food. The Water-Energy linkage is evident in how water from the Ciasem River is used to generate electricity. In this context, water power drives the turbine, which in turn powers the generator. The PLTMh's kinetic energy conversion depends on the water's speed and pressure. This is a run-of-river PLTMh with a run-of-discharge of 1.5 m/s, channeled through two penstock pipes, each 0.58 m in diameter, with a head of 18 m. The estimated generator output is 100.356 kW, with a maximum capacity of 120 kW. The amount of electricity the PLTMh generates for sale to PLN (Indonesia's state electricity company) depends heavily on the Ciasem River's flow rate.



Figure 4. Timeline of the Development and Operations of the Cintamekar Micro-hydro Power Plant, 2002–2025

Since 2022, the Cintamekar Micro-hydro Power Plant (PLTMh) in Desa Cintamekar has been non-operational due to technical damage and the theft of several critical components, as shown in Figure 4. As a result, the Mekarsari Cooperative, which manages the infrastructure, can no longer sell electricity to PLN. Consequently, the water flow previously used to drive the turbine has been fully redirected to meet agricultural irrigation needs. This diversion was carried out to ensure the continuity of food production in the area. This situation clearly illustrates a trade-off between the water and energy sectors within the Water-Energy-Food (WEF) Nexus framework. When water capacity is fully allocated to support agriculture, the potential to generate

renewable energy is lost. According to Hoff (2011), this trade-off shows that inter-sectoral relationships are not always synergistic; they can be competitive, depending on prevailing technical, institutional, and environmental conditions. The other nexus identified is the water-food nexus. This connection is evident in how the PLTMh project has influenced the relationship between water and food. Initially, farmers resisted the PLTMh construction, concerned that their agricultural water supply would be disrupted. In response, IBEKA, the project's initiator, engaged in discussions with the community and reached an agreement. The agreement guaranteed that the PLTMh would not affect the community's farming. If it were, IBEKA agreed to halt the PLTMh's operations.

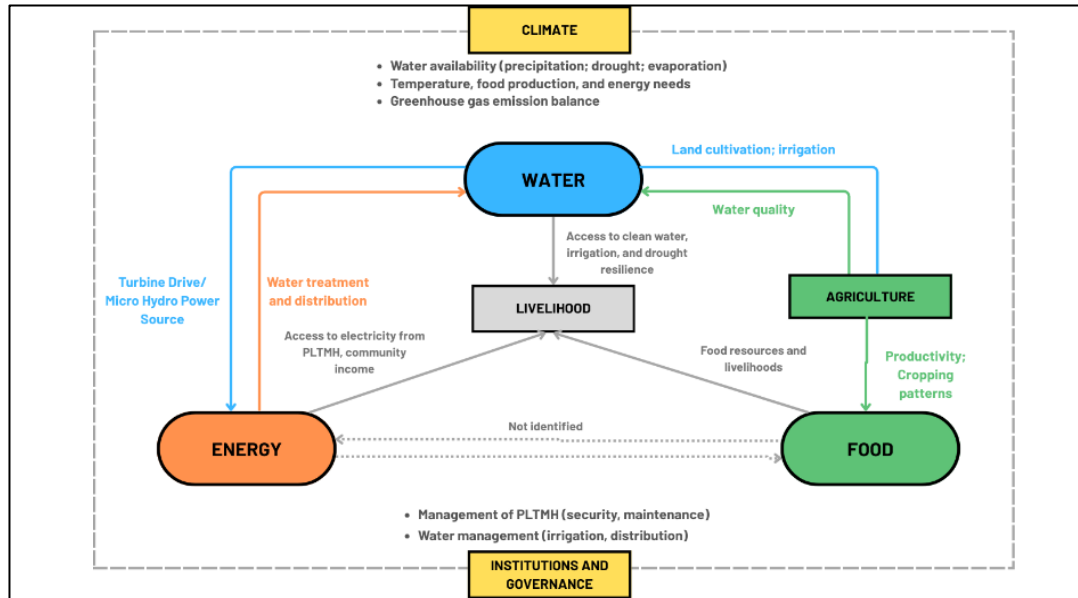


Figure 5. Nexus Water, Energy, and Food of PLTMh Framework

With the PLTMh in operation and the construction of water run-off channels, the water supply to farmlands did not decrease; instead, it expanded the irrigated area. The PLTMh ensures a consistent water supply to agricultural fields through an appropriate discharge rate, even during dry and rainy seasons, contributing to increased agricultural production in Desa Cintamekar. One interviewee, Abah Jak, emphasized this point, explaining that water diverted to the power plant also flows into the irrigation channels serving farmers' fields. As he stated:

“Masuk air ke pembangkit serentak ke saluran, (bisa dialirkan) saluran petani juga”

(“The water diverted to the power plant is simultaneously channeled into the irrigation system, allowing it to be distributed to farmers' fields”).

“Ga akan kering, malah makin ini (air mengalir ke pertanian) terus”

(The water supply does not diminish; rather, it continues to flow steadily to agricultural land).

This improved condition has also raised community awareness about environmental protection and the importance of preserving their farmlands, indirectly helping to maintain water catchment areas and environmental quality. Additionally, PLTMh managers plan to use the water flow around the plant to develop a fish-farming area.

Table 1. Identification of Synergy and Trade-off Nexus

Synergy	Trade-off
1. The PLTMh provides electricity to the community while also supporting water distribution through the run-off channel's gates.	1. If the water flow is insufficient to drive the turbine, the Mekarsari Cooperative will not be able to sell electricity.
2. An efficient irrigation system enhances agricultural productivity.	2. If the water flow is fully utilized for the PLTMh, the amount of water available for irrigation and community consumption may be reduced.

3.3 Sustainable Management of WEF System

The development of the Cintamekar micro-hydro power plant (PLTMh) demonstrates a clear synergy within the Water–Energy–Food (WEF) nexus. The PLTMh not only supplies electricity to the local community but also supports water distribution through runoff channels, enabling both domestic water use and irrigation. This aligns with findings by McNabola et al. (2022), who emphasize that micro-hydropower can generate multi-sectoral benefits and strengthen WEF interactions in rural contexts. This integrated system improves agricultural productivity by ensuring a more reliable, efficient irrigation supply, while also generating renewable energy that supports local economic activities through electricity sales managed by the community cooperative. In this context, water serves as a shared resource that supports both energy generation and food production, creating mutual reinforcement between sectors.

However, this synergy comes with inherent trade-offs. During periods of insufficient water flow, the PLTMh turbines cannot operate optimally, limiting electricity generation and reducing the cooperative's ability to sell power. Conversely, when water flow is prioritized entirely for electricity production, the volume of water available for irrigation and community consumption may decrease, potentially undermining agricultural output and water security. These dynamics echo broader observations in recent WEF literature, where climate variability and hydrological instability intensify cross-sectoral tensions and undermine nexus coherence (Canamary et al., 2025). These trade-offs highlight the system's vulnerability to seasonal variability and competing water demands, emphasizing the need for adaptive, integrated management.

To address these challenges, sustainable WEF management strategies must be implemented across short-, medium-, and long-term horizons, reflecting the need for phased and systemic transitions within complex resource systems, as emphasized in recent WEF governance literature (Borge-Diez et al., 2022; Canamary et al., 2025; Shah, 2023). In the short term, strengthening community participation in the PLTMh cooperative, optimizing turbine performance, and managing precision irrigation channels are essential operational measures to stabilize water–energy flows and prevent the amplification of cross-sectoral vulnerabilities. Using biomass or biogas as complementary energy sources can further reduce dependence on water-driven electricity generation. In the medium term, diversifying resource inputs through solar integration, strengthening PLTMh governance, conserving upland watersheds, and enhancing irrigation infrastructure capacity build system redundancy and adaptive resilience (Nhamo et al., 2025). Over the long term, fostering community self-reliance, promoting food–water–energy security, and advancing a local circular economy represent transformative strategies that strengthen socio-technical–ecological resilience under evolving environmental and socio-economic uncertainties. Global WEF analyses increasingly highlight that such adaptive, cross-sector, and systems-oriented strategies are indispensable for navigating future resource pressures (World Economic Forum, 2025).

3.4 Discussion

3.4.1 Contextual Background of the Cintamekar WEF System

From a WEF Nexus perspective, Cintamekar highlights how water operates as a pivotal resource that mediates both synergy and competition across sectors. Rather than functioning solely as an input for energy generation, water in this system acts as a flexible asset whose allocation reflects shifting development priorities. The shift toward irrigation reflects adaptive decision-making to safeguard food production; however, it also exposes the structural fragility of energy provision when it relies on a single water-dependent technology. This condition reinforces the argument that WEF synergies depend heavily on system reliability and institutional capacity, and that disruptions in one sector can quickly propagate trade-offs in others.

Moreover, the Cintamekar case illustrates that trade-offs within the WEF Nexus are not merely technical outcomes but are deeply shaped by governance and organizational arrangements. The Mekarsari Cooperative's dependence on uninterrupted electricity sales as its primary revenue source limits its ability to absorb shocks and finance maintenance independently. As a result, lost energy-generation capacity constrains institutional functionality, even as water and food systems continue to operate. This asymmetry suggests that, without diversified revenue streams and energy sources, local institutions remain vulnerable to cascading failures across the nexus, reducing overall system resilience.

At the same time, the continued use of the Cintamekar PLTMh as a pilot project and training site for micro-hydro technologies indicates latent nexus opportunities. Knowledge transfer and capacity-building activities represent a non-material benefit that persists despite interruptions in electricity production. From a discussion standpoint, this underscores the importance of viewing WEF systems not only in terms of physical resource flows but also through institutional learning and human capital development. Strengthening these dimensions, alongside investments in system redundancy and energy diversification, could enable future reconfiguration of the nexus in Cintamekar, transforming current trade-offs into more balanced and resilient multi-sectoral outcomes.

3.4.2 WEF Nexus Synergies and Trade-offs in Cintamekar

The Cintamekar Micro-Hydro Power Plant illustrates how the Water-Energy-Food (WEF) Nexus framework can capture both synergies and trade-offs across essential sectors. The most visible linkage is between water and energy, where the Ciasem River's flow was harnessed to generate electricity while also supporting agricultural irrigation. This dual use reflects the potential of “hidden hydropower” in water infrastructure, which McNabola et al. (2022) describe as an underutilized resource that can reduce production costs and carbon emissions without compromising water's primary function. Moreover, Hoff (2011) has long emphasized that interventions designed in one sector often create unintended cross-sectoral impacts, so an integrated perspective is crucial. The case of Cintamekar demonstrates this clearly: after technical damage and theft rendered the MHPP inoperative, water flows were redirected entirely to irrigation. This ensured food production but simultaneously eliminated electricity generation and income from energy sales. This outcome illustrates a water–energy trade-off, where one sector's gain comes at another's expense. Similar patterns have been noted in global hydropower projects, which can undermine water and food security when planned in isolation (Dombrowsky & Hensengerth, 2018).

On the other hand, the project demonstrates significant nexus opportunities. Once operational, the Micro-Hydro Power Plant supplied electricity to households and the wider area, generating revenue that the Mekarsari Cooperative reinvested in community development. At the same time, runoff channels designed for the Micro-Hydro Power Plant strengthened irrigation systems and improved agricultural productivity. These outcomes support Rasul & Sharma's (2016) argument, and others', that small-scale renewable energy, when designed with a nexus perspective, can deliver multi-sectoral benefits and enhance community resilience.

The Cintamekar case also underscores the decisive role of institutions and governance in sustaining WEF synergies. The Mekarsari Cooperative ensured local ownership and community participation, consistent with Keskinen et al. (2016), who found that cross-sectoral coordination and stakeholder engagement are critical to nexus success. This situation diverges sharply from empirical findings on the Banyubiru Micro-Hydro Power (MHP) project in Central Java. That case is framed as a condition of (un)closure, in which the initiative failed to deliver the anticipated economic dividends. This failure stemmed from the local organization's inability to meet the Commissioning Certificate (SLO) regulatory requirements, a prerequisite mandated by the state electricity utility (PLN) in its role as a strategic business partner (Kurniawan et al., 2024). Moreover, institutional fragility is a critical impediment within the nexus of institutional roles and governance.

In the Cinta Mekar context, systemic issues arose from the local entity's incapacity, specifically the Mekarsari Cooperative's, to mitigate technical degradation and illicit asset misappropriation. However, its inability to prevent technical breakdowns and theft highlights institutional vulnerabilities in long-term maintenance, reinvestment, and security. As Dombrowsky & Hensengerth (2018) note, fragmented governance often limits local institutions' capacity to manage nexus complexities effectively, undermining sustainability. Butchers et al. (2021) further emphasize that clear delineation of responsibilities within institutional governance is essential to strengthen collective accountability and enhance stakeholder participation, reducing systemic risks such as internal conflicts, neglect of technical maintenance, and financial irregularities.

In the Banyubiru case, conversely, contractual risks led to complications, as the local entity faced potential financial penalties for failing to maintain electricity supply during the dry season. This was compounded by the competing demand for water resources, which required prioritization for agricultural irrigation (Kurniawan et al., 2024). These findings suggest that without comprehensive technical and social interventions from

diverse stakeholders, community-based renewable energy initiatives struggle to achieve the long-term sustainability envisioned by the nexus model in rural contexts. Furthermore, the energy–food linkage in Cintamekar remains underdeveloped. While water has been successfully leveraged to provide both energy and agricultural benefits, renewable energy pathways such as biogas from agricultural residues or hybrid micro-hydro–solar systems remain unexplored. Borge-Diez (Borge-Diez et al., 2022) stresses that diversifying energy sources within WEF systems is critical to enhancing resilience to technical disruptions and climate variability. Integrating biogas and solar technologies, alongside watershed conservation, could thus enhance long-term sustainability in Cintamekar.

In conclusion, the Cintamekar Micro-Hydro Power Plant demonstrates that small-scale renewable energy can generate synergies across water, energy, and food systems, reinforcing the value of the WEF Nexus as an analytical and planning tool. At the same time, it highlights the risks of trade-offs when disruptions occur and the importance of diversified energy strategies, participatory governance, and alignment between national and local policies. Embedding these principles in rural development planning will be crucial to balance synergies and trade-offs within the WEF Nexus and contribute directly to progress toward the Sustainable Development Goals (SDGs).

4. Conclusion

This research demonstrates that the Cintamekar Micro-Hydro Power Plant (PLTMh) generated distinct Water–Energy and Water–Food interactions that supported rural development through electricity provision and enhanced agricultural irrigation. At the same time, the PLTMh shutdown in 2022 revealed a critical WEF trade-off: water was fully redirected to irrigation, eliminating renewable energy production but safeguarding food needs. These dynamics show that nexus interactions in rural hydropower systems are shaped not only by hydrological flows but also by technological reliability, environmental variability, and evolving community priorities. The study's scientific contribution lies in its empirical explanation of how WEF trade-offs materialize during system disruptions, showing that institutional capacity, particularly the Mekarsari Cooperative's governance role, determines nexus resilience and influences whether multi-sectoral benefits can be sustained. The absence of an Energy–Food linkage further highlights a structural limitation of run-of-river systems and underscores the importance of diversified energy pathways to strengthen cross-sectoral integration. From a policy perspective, these findings emphasize the need for adaptive management strategies, energy diversification, and robust local governance frameworks to enhance the resilience of rural WEF systems facing technical, environmental, and socio-economic uncertainties, offering practical insights for community-based renewable energy initiatives seeking to align resource efficiency, rural livelihood enhancement, and long-term sustainability.

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6. Conflict of Interest

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

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