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Sustainable Water-Energy-Food Nexus Modeling to Anticipate Land Use Changes in Magelang Regency

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Abstract

This paper aims to analyze the integrated management of water, energy, and food resources within the context of the Water-Energy-Food (WEF) Nexus in Magelang Regency, Central Java, Indonesia. The focus is on the projections for electricity demand, water needs, and potential electricity production from microhydro power plants (PLTMH) by 2030. The methodology involved simulation models using the LEAP and WEAP software to create a conceptual management model that promotes sustainable resource use. Our findings project electricity needs in Magelang Regency to increase significantly, estimated at 79,626.3 MWh under the baseline business-as-usual scenario, 90,281.53 MWh for a moderate scenario, and 92,201.78 MWh under an optimistic scenario, with the moderate and optimistic scenarios representing increases of 13.38% and 15.79%, respectively, over the baseline by the end of the projection period. Concurrently, water demand is projected at 349,953,115 m³ under the baseline scenario and slightly less at 339,542,991 m³ considering the impact of the new Yogyakarta-Bawen toll road, with a variance of 3.07% between the scenarios by 2030. Additionally, the potential electricity production from the proposed PLTMH is projected at 590.67 MWh by 2030. These projections underscore the critical contributions of sustainable infrastructural developments such as PLTMH, which, despite regulatory support, have not yet been constructed in the regency. This research illustrates the need for robust planning and integration of sustainable practices within local governance to achieve the objectives outlined in the Sustainable Development Goals (SDGs), emphasizing the importance of sustainable and innovative solutions to meet future demand for these interconnected resources effectively.
Keywords: WEF; Nexus; LEAP; WEAP; SDGs

Introduction

The intricate relationship between water, energy, and food—collectively referred to as the Water-Energy-Food (WEF) Nexus—has become increasingly crucial under the pressures of global climate change, population growth, and escalating energy demands. Initiated by the Food and Agriculture Organization in 2011, the WEF Nexus approach has aimed to highlight and manage the interdependencies of these fundamental resources, striving for a balance that supports sustainable development goals.

Magelang Regency in Central Java, Indonesia, exemplifies a region where the dynamics of the WEF Nexus are particularly pronounced. As a region experiencing rapid population growth, with a projected increase from 1,305,512 in 2021 to higher numbers by 2030, Magelang faces significant challenges in sustainable resource management (BPS, 2021b). The development pressures are evident in the large-scale infrastructural projects such as the Yogyakarta-Bawen toll road, which is set to transform 579 km² of land, much of which currently serves agricultural purposes (Tengah, 2022). This infrastructural expansion not only threatens the agricultural base but also imposes new demands on the energy and water sectors.

Electricity demand in the region has surged, with consumption in Magelang increasing twelvefold from 2019 to 2021, highlighting the urgent need for sustainable energy solutions (BPS, 2021a). In response, local authorities are exploring renewable energy projects, including microhydro power initiatives, which align with global renewable energy targets and the regional energy policy aiming to reduce dependence on fossil fuels (Magelang, 2021), (Siregar & others, 2019), (Sanatra et al., 2022).

This research is aimed at carrying out a simulation of the Progo watershed system which passes through the Magelang Regency area to get an idea of the relationship between water, energy and food needs in Magelang Regency. The description of the WEF Nexus will be used as points for water resource management planning in Magelang Regency in realizing sustainable use of water resources in accordance with the goals of the WEF Nexus which are sustainable with sustainable development goals.

This study employs the LEAP (Low Emissions Analysis Platform) and WEAP (Water Evaluation and Planning) software tools to simulate the current and future states of the WEF Nexus in Magelang. These tools are instrumental in developing a conceptual model of sustainable resource management that integrates the supply and demand dynamics of water, energy, and food within the region's socio-economic and environmental framework (Dioha, 2017), (Heaps, 2020). By doing so, the research seeks to provide a schematic blueprint for policy-makers to ensure that the growth of Magelang is sustainable, resilient, and equitable, addressing both the immediate and long-term needs of its population.

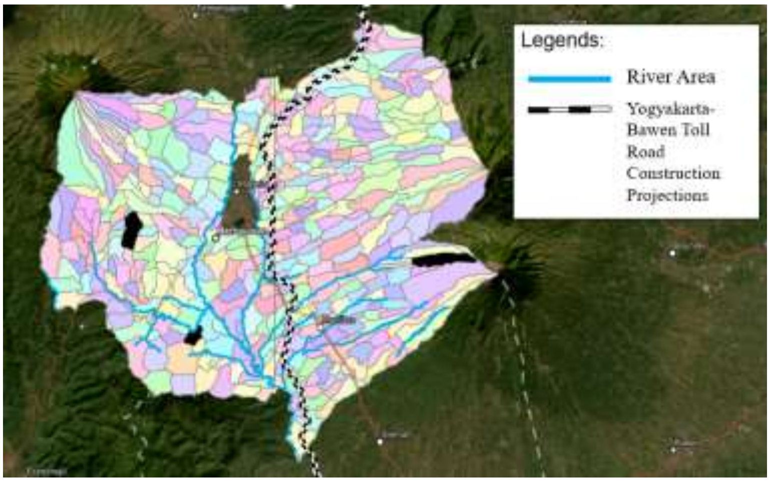

Figure 1. River Area Map of Magelang Regency

Literature Review

This extensive literature on the Water-Energy-Food (WEF) Nexus illustrates a comprehensive exploration into the interconnectedness of essential resources, emphasizing the nuanced interplay and potential trade-offs among water, energy, and food security across diverse geographical and socio-economic contexts. (Anika et al., 2022) focused on the degradation of water sources in Lampung Province, Indonesia, caused by land use changes in water catchment areas, highlighting the environmental impact of agricultural expansion on water sustainability. Similarly, (Wijayanti et al., 2020) reviewed the unsustainable water management practices in Yogyakarta, where excessive groundwater extraction has jeopardized future water security, reflecting a global concern about the overutilization of aquifers.

(Purwanto et al., 2021) provided a quantitative assessment of the WEF Nexus within local planning frameworks in Indonesia, revealing how artificial aquaculture development can increase water self-sufficiency levels without significantly affecting food and energy sectors. This points to the potential of localized interventions in enhancing water availability while maintaining balance across the Nexus. (Anugrah, 2016) projected a future water shortage by 2050 in remote areas, despite current adequacy, due to integrated WEF Nexus approaches using LEAP-WEAP software, underscoring the critical need for sustainable planning in energy and water-intensive industries.

(Nugroho et al., 2022) advocated for agroforestry as a sustainable land management practice that conserves water, prevents erosion, and restores degraded lands, effectively linking ecological health with food and energy security through microhydro power developments. This study illustrates the potential of integrated land use strategies in reinforcing the WEF Nexus. In contrast, (Novitasari et al., 2020) explored the challenges of integrating climate considerations into Indonesia's power generation sector, emphasizing the inherent dependencies and the impact of climate change on resource availability, which is crucial for disaster prevention and mitigation.

(Nasrollahi et al., 2021) utilized WEAP and LEAP models to simulate the WEF-Environment Nexus over two decades in Iran's Urmia Lake Basin, demonstrating how population growth and economic development amplify resource demands, thus stressing the importance of adaptive management strategies. (Afshar et al., 2022) called for a holistic framework to understand the WEF Nexus fully, suggesting the development of comprehensive models to explore all interrelations and interactions among resources, which is vital for crafting effective policies.

(Taniguchi et al., 2020) analyzed the WEF Nexus in the Asia-Pacific region, identifying a negative correlation between urbanization levels and the proportion of energy consumption for water and food production, which illuminates the urban-rural dichotomy in resource utilization. (Lubis et al., 2018) proposed a three-stage policy framework for optimizing water-food linkages in Indonesia's Citarum Watershed, advocating for an integrated and interconnected system approach. (Wicaksono & Kang, 2019) implemented system dynamics in their WEFSiM model to simulate the WEF Nexus in South Korea and Indonesia, providing a comparative analysis that enhances understanding of regional resource management.

(Bahri, 2020) analyzed the interconnections between water, energy, food, and land in the context of human health and migration, underscoring how environmental changes affect human well-being. Lastly, (Terrapon-Pfaff et al., 2018) emphasized the importance of energizing the WEF Nexus to bolster sustainable development at the local level, highlighting the fundamental challenges that households, small businesses, and local institutions face in simultaneously securing water, energy, and food.

This research, embedded within the rich tapestry of previous studies, aims to model the WEF Nexus in Magelang

Regency, enhancing the theoretical framework with empirical data to develop resilient, sustainable strategies for managing interconnected resources effectively, especially in the face of climatic and anthropogenic changes.

Research Methods

Research Tools and Software

The primary tools utilized in this study are the LEAP (Low Emissions Analysis Platform) and WEAP (Water Evaluation and Planning) software systems. These tools are designed to simulate and analyze the relationships between water, energy, and food resources, providing a comprehensive framework to evaluate sustainable resource management strategies. LEAP is used for energy planning and policy analysis, projecting demand based on energy activities and intensity. WEAP complements this by focusing on water resources planning, integrating hydrological and policy-driven scenarios to evaluate water demands and supply under varying conditions.

Data Collection and Processing

The research involves an integrated method of data collection and processing, focusing on the complex interrelations of the Water-Energy-Food (WEF) Nexus in Magelang Regency, Indonesia. To begin, the study employs the FJ Mock method for calculating water balances and streamflow rates. This method includes an initial calculation of actual evapotranspiration using the formula:

$$\Delta ET = Kc\ x\ PET \quad (1)$$

where ΔET or Eto represents actual evapotranspiration, PET is potential evapotranspiration, and CF is the crop coefficient. Water surplus calculations follow, which consider excess rainfall and soil moisture capacity:

$$WS = ER - (SMC - SM_{n-1}) \quad (2)$$

WS is water surplus, ER is excess rainfall, SMC is soil moisture capacity, and SM_{n-1} the soil moisture from the previous month. If the calculation result is smaller than 0, then WS = 0. Then if SM_{n-1} + ER < 0, then SM = 0. If SM_{n-1} + ER ≥ SMC, then SM = SMC. Meanwhile, for calculations in the first month, SMn-1 = initial soil moisture (ISM). The direct runoff and groundwater storage are subsequently computed using:

$$DRO = WS - I \quad (3)$$

$$GWS = 0{,}5I\ x\ (1 + k) + k\ x\ GWS_{n-1} \quad (4)$$

DRO stands for direct runoff, i stands for infiltration, GWS is groundwater storage, for calculations in the first month, the value of GWS_{n-1} = IGWS (initial groundwater storage), and k is the soil percolation coefficient.

$$BF = 1 - (GWS - GWS_{n-1}) \quad (5)$$

$$TRO = DRO + BF \quad (6)$$

BF stands for base flow and TRO is total runoff. After calculating these, now Q_{cal} or calculated water discharge can be find with this formula:

$$Q_{cal} = \frac{A\ x\ TRO\ x\ 1000}{H\ x\ 24\ x\ 3600} \quad (7)$$

After calculating the water balance, the research delves into the specific equations for Crop Water Requirement (CWR), Farm Water Requirement (FWR), and Project Water Requirement (PWR). These equations are critical for understanding agricultural water needs:

$$CWR = Kc\ x\ Eto \quad (8)$$

$$FWR = CWR + Per + I \quad (9)$$

$$PWR = \left(\frac{FWR - Er}{Efp}\right) xA \quad (10)$$

Eto is evapotranspiration, per stands for percolation, er is effective rainfall, Efp is efficiency of water delivery, and A is area irrigated.

Simulation with LEAP and WEAP

The data processed from the aforementioned methods will then be input into the Low Emissions Analysis Platform (LEAP) and the Water Evaluation and Planning (WEAP) systems. These software tools are pivotal in modeling and simulating the interactions within the WEF Nexus under various scenarios. LEAP serves as a comprehensive decision-support system for conducting integrated resource planning, climate change mitigation assessments, and energy policy analysis. Its user-friendly interface facilitates the modeling of complex energy scenarios where users can simulate and project energy demand, production, and distribution, as well as assess their impacts on greenhouse gas emissions across different scenarios. LEAP's flexibility allows it to cater to various analytical needs, ranging from local energy planning to national energy strategy development. It enables users to establish baseline conditions, explore alternative scenarios, and compare the outcomes in terms of energy security, environmental impacts, and economic viability. The platform supports a range of data types, including demographic and economic growth projections, to tailor energy models that reflect specific policy or research questions accurately. In this research, LEAP will primarily handle the energy component, modeling the demand and supply under different future scenarios, considering the variations in population growth, economic development, and land use changes. LEAP is accounting-based software that can be used to simulate the energy planning of a region. Demand (energy demand) in LEAP is calculated based on the product of the total activity (total activity) energy consumption and energy intensity (Anugrah, 2016). WEAP, on the other hand, serving as a tool for comprehensive water resource planning and analysis. Its use is geared towards simulating the water dynamics within the complex framework of the Water-Energy-Food (WEF) Nexus in Magelang Regency, Indonesia. WEAP allows for the integration of various water-related data, such as hydrology, usage patterns, and infrastructural impacts, into a unified model that reflects both current and future water demands under different scenarios (Institute, 2024). Simulation process on LEAP and WEAP software can be seen in Figure 2 and Figure 3.

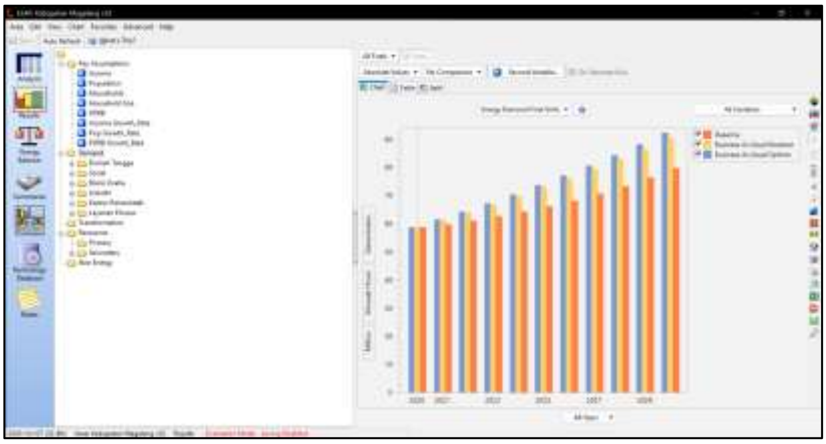

Figure 2. Simulation Process on LEAP Software

Figure 3. Simulation Process on WEAP Software

Results and Discussion

This research explores the projected impacts of demographic and economic changes on water, energy, and food demands within Magelang Regency over the period from 2020 to 2030. These projections are vital for local planning and strategic resource management. The findings were processed using the LEAP and WEAP software tools, which facilitated detailed simulations of future scenarios based on current trends and proposed development projects.

Population and Household Projections

The study predicts a steady increase in the population of Magelang Regency, from approximately 1.3 million in 2020 to about 1.4 million by 2030, aligning with the natural growth rate and regional development plans. The associated rise in household numbers, from 324,965 in 2020 to 350,524 in 2030, underscores the increasing demand for residential energy and water use, thus impacting local infrastructure and resource allocation policies. The results of population and household projections can be seen in Table 1 Below:

Table 1. Population and Household Projections

Year	Population (person)	Households

2020	1,299,859	324,965
2021	1,309,738	327,434
2022	1,329,722	329,923
2023	1,319,692	329,923
2024	1,339,827	334,957
2025	1,350,010	337,503
2026	1,360,270	340,068
2027	1,370,608	342,652
2028	1,381,025	345,256
2029	1,391,521	347,880
2030	1,402,096	350,524

Electricity Demand Scenarios

In modeling using LEAP software, three scenarios were developed to illustrate the electricity demand in Magelang Regency. The rationale for utilizing these three scenarios is to explore the trends in electricity demand. The first scenario, termed the baseline projection, considers the historical trend of rising electricity demand to predict future needs. The second scenario projects a moderate increase in electricity demand based on the business-as-usual trend, with an average annual increase of 4.42% from 2021 to 2030. This scenario assumes a slower economic growth rate, which in turn is expected to slow down the growth in electricity sales across customer sectors. The third scenario, an optimistic business-as-usual projection, anticipates an average increase in electricity demand of 4.64% annually from 2021 to 2030. This scenario assumes that electricity demand will accelerate due to stronger economic growth compared to the moderate scenario. The results of simulation on LEAP software can be seen in Table 2.

Three scenarios were modeled to predict future electricity demand:

- Baseline Scenario: Assumes a steady increase in demand without significant changes in policy or technology, projecting a rise from 58,582 MWh in 2020 to 79,626 MWh in 2030.
- Moderate Business as Usual Scenario: Considers moderate economic and demographic growth, leading to a higher electricity demand, estimated at 90,282 MWh by 2030.
- Optimistic Business as Usual Scenario: Anticipates a more rapid economic growth, pushing demand up to 92,202 MWh by 2030.

Table 2. Projection of Electrical Energy Demand in Magelang Regency (MWh)

Year	Baseline	Business As Usual Moderate	Business As Usual Optimist
2020	58,581.71	58,581.71	58,581.71
2021	59,711.14	61,171.02	61,299.90
2022	61,003.19	63,874.78	64,144.21
2023	62,474.07	66,698.04	67,120.50
2024	64,141.94	69,646.09	70,234.90
2025	66,027.21	72,724.45	73,393.79
2026	68,152.81	75,938.87	76,903.91
2027	70,544.54	79,295.37	80,472.25
2028	73,231.48	82,800.23	84,206.16
2029	76,246.38	86,460.00	88,113.33
2030	79,626.26	90,281.53	92,201.78

Alongside the table above, the result of LEAP software can also be seen as Figure 4 below:

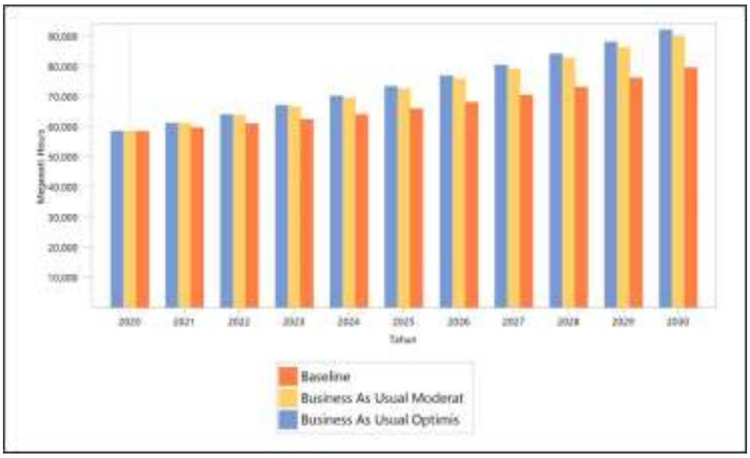

Figure 4. Graph of Electrical Energy Demand in Magelang Regency

Water Flow Projections

The projected water discharge of the Progo watershed flowing in Magelang Regency is calculated based on water balance calculations. Mock using rainfall data obtained from the nearest rainfall observation station in Magelang Regency. River flow discharge is calculated by following water balance rules. In a water balance system, the total water volume is considered constant, only circulation and distribution show variations in value. Things that influence river discharge and flow conditions are rainfall, temperature, solar radiation, relative humidity and wind speed. From the evapotranspiration input data, it can be used to find the river water discharge value using equation (7). Water flow projection for Progo watershed in Magelang Regency in year 2030 is 1,442,946,812 m^3.

Water Demand Projections in Kabupaten Magelang for 2020-2030

In forecasting the water demand projections for Kabupaten Magelang over the 2020-2030 period, this study develops two scenarios. The first scenario, termed the baseline scenario, serves as a reference scenario. It outlines the expected trends in water needs for Kabupaten Magelang should there be no new changes or interventions. This scenario anticipates increases in water demand primarily due to population growth affecting domestic water usage. The second scenario incorporates the impacts of the Yogyakarta-Bawen toll road construction, which affects parts of Kabupaten Magelang. In this scenario, agricultural land area in Kabupaten Magelang is projected to decrease, following the ongoing trend of diminishing farm land year by year, and due to the effects of the toll road construction. This reduction in agricultural land is expected to take place around 2025, following land acquisition processes scheduled for 2023-2024.

The baseline scenario sets criteria based on water use projections for domestic purposes, allocating 60 liters per capita daily while accounting for annual population growth. For agricultural irrigation requirements, a linear increase is modeled based on calculated water needs from known data: 12,744.94 m^3/hectare in 2020, 14,846.24 m^3/hectare in 2021, and 14,613.43 m^3/hectare in 2022. These figures were input into the Water Evaluation and Planning (WEAP) software to generate water demand projections for Kabupaten Magelang for the years 2020 to 2030. According to these projections, the estimated water demand by the year 2030 is expected to reach approximately 349,953,115 m^3. The second scenario incorporates the impact of constructing the Yogyakarta-Bawen toll road, which traverses through the Kabupaten Magelang region. Approximately 579 hectares of the Kabupaten Magelang area are affected by this infrastructure development. Assuming that 80% of this area is agricultural land, it is estimated that about 463.2 hectares of irrigated farmland will be directly impacted by the construction of the Yogyakarta-Bawen toll road. Based on these calculations, projections have been made for the reduction in available irrigated farmland, which in turn affects the calculations for water requirements. By 2030, following the development of the Yogyakarta-Bawen toll road, the area of irrigated agricultural land in Kabupaten Magelang is projected to be approximately 13,740.5 hectares. A general comparison between these two scenarios can be seen in Table 3. and Figure 5. below:

Table 3. Water Demand Projections in Magelang Regency

Year	Baseline Scenario (m^3)	Yogyakarta-Bawen Toll Scenario (m^3)
2020	313,814,896	313,814,896
2021	343,571,856	343,571,856
2022	348,153,512	348,153,350
2023	351,542,108	351,542,522
2024	353,925,197	353,924,987
2025	355,161,117	346,914,128
2026	355,583,371	346,904,149
2027	355,197,211	346,083,721
2028	354,164,866	344,618,664
2029	352,311,290	342,333,733
2030	349,953,115	339,542,991

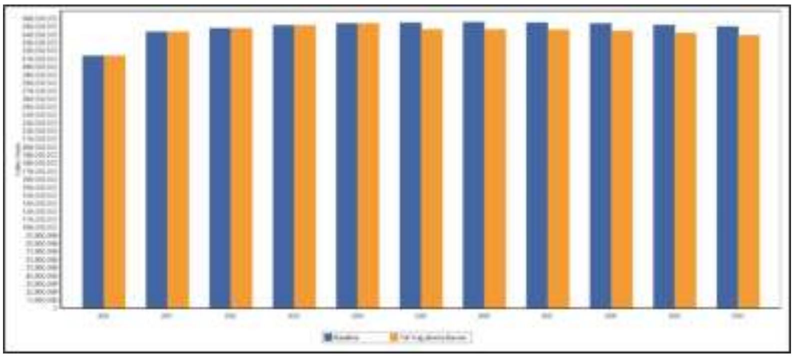

Figure 5. Water Demand Projections in Kabupaten Magelang for 2020-2030

From the results in the table and figure above, there is a total difference in water demand between the two scenarios.

In the scenario involving the construction of the Yogyakarta-Bawen toll road, there is a decrease in water demand starting from 2025 compared to the baseline scenario. The difference in water demand between the two scenarios in 2030 is approximately 55,973,540 m^3.

Conclusions

This study aimed to analyze the interconnected projections (nexus) of water, energy, and food usage in Kabupaten Magelang and to develop a conceptual model for sustainable management in the region. The conclusions drawn from the analysis and projections are as follows:

1. **Electricity Demand Projections:**
   - By 2030, the projected electricity demand in Kabupaten Magelang is estimated at 79,626.3 MWh under the baseline scenario, 90,281.53 MWh under the moderate scenario, and 92,201.78 MWh under the optimistic scenario.
   - The moderate and optimistic scenarios increasingly diverge from the baseline, showing differences of 13.38% and 15.79%, respectively, by the end of the projection period.
2. **Water Demand Projections:**
   - Water demand in Kabupaten Magelang for 2030 is projected to be 349,953,115 m^3 under the baseline scenario and 339,542,991 m^3 under the Yogyakarta-Bawen toll road development scenario.
   - The difference in water demand between the two scenarios reaches 3.07% by the end of 2030.
   - Considering the adequate water flow projected, there is potential for the development of microhydro power plants (PLTMH) in the region. The sustainable and efficient harnessing of water resources for energy production could contribute significantly to meeting the rising energy demands while promoting renewable energy initiatives in Kabupaten Magelang.

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