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Research Article

Optimising Agrivoltaic Systems: Identifying Suitable Solar Development Sites for Integrated Food and Energy Production

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Abstract: This study explores the integration of food and energy systems as a solution to address agricultural challenges in the dryland region of Gunungkidul Regency. Facing water scarcity issues, the region's abundant solar irradiation potential presents an opportunity for co-locating food and energy production, specifically through the implementation of an agrivoltaic system. Seven sub-districts had been designated in the local government regulations for solar energy development sites, including Gedangsari, Nglipar, Ngawen, Purwosari, Saptosari, Tanjungsari, and Tepus. Ten criteria and five constraints were established to assess their suitability for agrivoltaic systems. Utilising map overlay analysis and integrating GIS-MCDA with Fuzzy and AHP methodologies, three sub-districts—Semanu, Wonosari, and Tepus—emerged as the most suitable locations. Each sub-district boasts substantial total areas of 1,779.9 Ha, 1,325.5 Ha, and 1,147.21 Ha, respectively, with Tepus aligning with the local government's solar energy development plan. This comprehensive approach ensures that the selected locations meet both energy development goals and the potential for successful agrivoltaic implementation. In conclusion, this study demonstrates the feasibility of implementing food and energy combinations through an agrivoltaic system in Gunungkidul Regency, providing insights into suitable sub-districts and emphasising the importance of aligning regional energy plans with sustainable agricultural practices on arid land.

Keywords: agrivoltaic, integrated food and energy production, GIS, MCDA, fuzzy logic, land use

1. Introduction

The convergence of food and energy systems represents a crucial trend in the pursuit of sustainable development, acknowledging the complex link between agricultural practices and energy production [1], [2], [3]. This paper delves into the domain of food and energy combination site planning, centring its exploration on the dynamic landscape of Gunungkidul Regency within the Special Region of Yogyakarta, Indonesia. The region's unique characteristics and challenges serve as a background for innovative strategies aimed at harmonising agricultural activities and energy production.

In response to global challenges, the integration of photovoltaic technology with agriculture has emerged as a compelling model within the broader framework of food and energy integration [4], [5]. This intersection envisions a synergistic coexistence where agricultural activities not only fulfil the crucial role of yielding essential food supplies but also actively contribute to the generation of renewable energy [6]. However, achieving this system's success requires meticulous planning to ensure sustainability and diversity, considering the intricacies involved [7], [8], [9].

The successful implementation of food and energy combination systems necessitates careful consideration of various criteria [10]. This approach is rooted in aligning with the United Nations' Sustainable Development Goals (SDGs) [9], [11]. Recognising the need to address interconnected issues comprehensively, the study identifies the Climate, Land, Energy, and Water (CLEW) nexus as a central concern derived from various SDGs. This integrative approach becomes the cornerstone for designing and executing sustainable development initiatives, ensuring a holistic response to global challenges [7].

The CLEW nexus, widely employed to assess the feasibility of implementing a system, undergoes testing through the evaluation and comparison of interconnected criteria. Feasibility is achieved when efforts minimise trade-offs and maximise co-benefits within specific parameters [7]. This relationship between CLEW and its derivatives finds extensive use in energy planning assessments, evaluating the WEF (Water, Energy, Food) nexus for sustainable resource planning [12], [13], [14], [15]. The WEFE (Water, Energy, Food, Environment) relationship assesses the impact of food and energy production on water and the environment [16], [17]. In the realm of CLEW relationships, it has been extensively used to test the consequences of land exploitation for energy production on climate and water [8], [9], [18], [19], [20]. Several studies underscore the necessity of the CLEW paradigm in formulating sustainable planning and policies.

Navigating the complex interplay of food and energy systems demands a sophisticated approach to site planning. Leveraging Geographic Information Systems (GIS) in conjunction with Multi-Criteria Decision Analysis (MCDA), the study employs the GIS-MCDA framework as a robust tool for identifying optimal locations for food and energy combination sites. GIS-MCDA combination has been frequently used in food or energy site determination [21]. The criteria used were generally derived from the CLEW-nexus, ensuring a holistic and data-driven decision-making approach.

The Gunungkidul Regency is celebrated as the most spacious region in the Special Region of Yogyakarta, characterised by a distinctive landscape dominated by extensive dryland. With the majority of the population engaged in agriculture, understanding the challenges presented by the arid environment becomes crucial, especially considering that approximately 80% of agricultural activities take place in these dryland areas [22]. Recognising the local context is imperative for tailoring effective strategies that consider the region's unique characteristics and demands.

The primary objective of this study is to identify optimal areas for the integration of food and energy systems. Then, the area would be used to evaluate the suitability of the planned solar energy development site in the Gunungkidul Regency. This dual land use also emphasised land productivity enhancement through innovative strategies. The paper underscores the integral role of renewable energy, highlighting how the synergy between agriculture and energy production can significantly contribute to the electrification of agricultural practices. This multifaceted approach aims to address the region's evolving needs while fostering sustainable development, aligning with both local and global goals.

2. Methods

The research was conducted in the Gunungkidul Regency area, one of the regions in the Special Regency of Yogyakarta. This region has the most spacious area among the five regions in the same province, approximately 1,486.36 km^2 or equivalent to 46.63% of the total province's area. Gunungkidul faces sustainability challenges since most regions are covered by arid areas, which impacts most people's occupation as dryland farmers [22]. As electrification enables dryland agriculture to increase its productivity [14], [23], [24], this research tries to map the potential of the implementation of a food and energy combination system in Gunungkidul. The study flow diagram is shown in Figure 1.

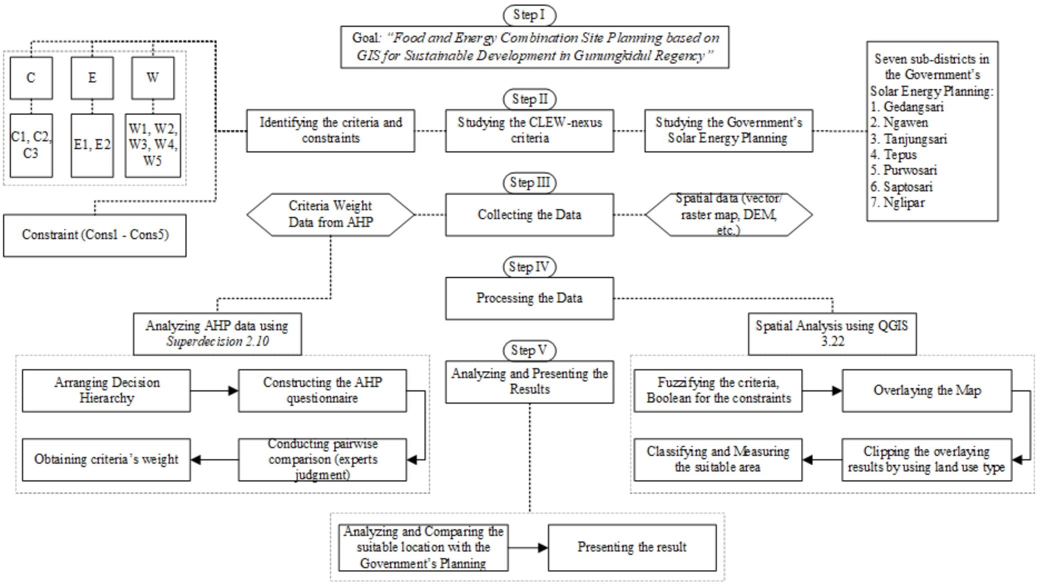


Figure 1. Flow diagram of the study.

Since the study objective has been established, in the second step, several sub-criteria derived from the CLEW-nexus were determined to be analysed in the study, as seen in Table 1. Those sub-criteria are solar irradiation (C1) [25], [26], environment temperature (C2) [25], [26], [27], rain intensity (C3) [28], substation (E1) [29], distribution and transmission line (E2) [29], Surface River (W1), Underground River (W2), Spring (W3), Lake/Reservoir (Small/Medium size) (W4), and Canal/Irrigation Network (W5) [30], [31], [32]. Afterwards, six criteria were also defined to ensure that the agrivoltaic implementation will not infringe on the restricted zone and will be effectively planned. Those constraints are Slope (Cons1) [27], Forest Area (Cons2) [27], [33], Settlement Area (Cons3) [25], [27], Local Road (Cons4) [25], and Collector Road (Cons5) [25]. Seven sub-districts were also identified as solar energy implementation location planning based on regional regulation [34].

The criteria and constraints were determined based on the data collection in the third step. The data collection followed the necessity of the GIS-MCDA analysis. In this study, GIS-MCDA was combined with the analytic hierarchy process (AHP) and fuzzy logic. Thus, the collected data will be weighted based on the expert's judgment and set of map spatial data.

Table 1. Criteria and sub-criteria in the study.

Main Criteria	Sub-criteria/Code	Value	Processing	Source
(C) Climate	Solar irradiation (C1) Temperature (C2) Precipitation (C3)	4.73 – 5.34 m^2/year 22.4 – 26.7 °C 0 – 2,000 mm/year	AHP, LAFM function AHP, LDFM function AHP, LDFM function	*https://solargis.com* *http://geoportal.jogjaprov.go.id*
(L) Land use	Agriculture dryland	-	Map classification, masker/clipper	*http://geoportal.jogjaprov.go.id*
(E) Energy	Sub-station (E1) Distribution/transmission line (E2)	100 m buffer	AHP, buffer, proximity distance, LDFM function	Department of land and spatial planning (DISPERTARU) Gunungkidul Regency
(W) Water	Surface river (W1) Underground river (W2) Spring (W3) Lake/reservoir (small/medium size) (W4) Irrigation network (W5)	100 m buffer	AHP, buffer, proximity distance, LDFM function	*http://geoportal.jogjaprov.go.id*
(Cons) Constraints	Slope (Cons1) Forest area (Cons2) Settlement area (Cons3) Local road (Cons4) Collector road (Cons5)	>10% 100 m buffer 100 m buffer 10 m buffer 50 m buffer	Boolean Buffer, boolean	*http://tanahair.indonesia.go.id/portal-web*

The AHP collecting and analysing process included constructing the criteria hierarchy, setting the AHP questionnaire, conducting expert judgment and obtaining the criteria's weight. The expert's judgment later needs to be calculated its consistency ratio (*CR*) using equation (1) [35]

$$CR = \frac{CI}{RI} \tag{1}$$

where *CI* represents the consistency index and *RI* is the random index.

The *RI* can be known by referring to the random index (Table 2), and the *CI* can be obtained using equation (2):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λmax is the eigenvalue and *n* is the number of used criteria in the pairwise comparison. The judgment is considered consistent as long the *CR* is below 0.1.

Table 2. Random index.

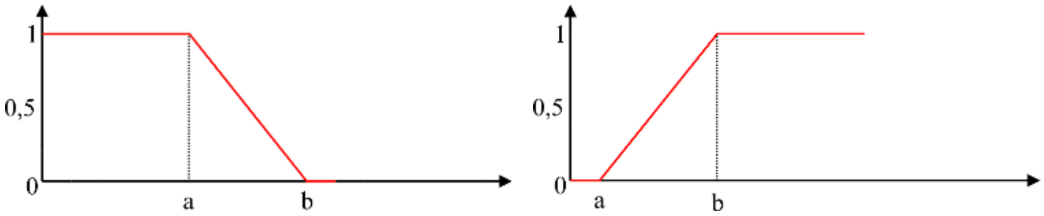
n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

As the criteria's weights were obtained, the analysing process can be continued to the GIS analysis as the fourth step. The GIS analysis process included synchronising the coordinate reference system (CRS) of each spatial map data into EPSG:32749 - WGS 84 / UTM zone 49S, rasterising the spatial map data into pixel ratio in 10×10, fuzzifying the criteria's map, processing the constraints map into boolean form, and overlaying the criteria and constraints map using equation (3) [36], [37]:

$$S = \sum_{i=0}^{n} W_i X_i \prod C_j \tag{3}$$

where S is the suitability, i is the criterion, n is the number of criteria, W_i is the weight of each criterion, X_i is the attribute value of each criterion in fuzzy form (0 to 1), and C_j is the value of each constraint in boolean form (0 and 1).

The fuzzy values in this study were calculated using two different functions: linear ascending membership (LAM), and linear descending membership (LDM), as seen in Figure 2 [37].



(**a**) (**b**)

Figure 2. (**a**) Linear ascending membership (LAM) function; (**b**) Linear descending membership (LDM) function.

Equations (4) and (5) describe LAM and LDM functions, respectively:

$$\mu(x) = \begin{cases} 0, \ x \le a \\ \dfrac{x-a}{b-a}, \ a \le x \le b \\ 1, \ x \ge b \end{cases} \tag{4}$$

$$\mu(x) = \begin{cases} 1, x \le a \\ \dfrac{x-b}{a-b}, a \le x \le b \\ 0, x \ge b \end{cases} \tag{5}$$

where $\mu(x)$ is the membership function, a is the starting point of the regular value converted into the fuzzy value, and b is the ending point of the regular value. According to the implemented fuzzy membership function, either the a or b can be standing for 0 or 1 or the otherwise.

3. Results and Discussion

The AHP analysis is detailed in Table 3, where sub-criteria C1 (solar irradiation) emerged as the most crucial factor in food and energy combination site planning. At the same time, sub-criteria W2 (underground river) was deemed the least significant. Two experts contributed their judgment to this analysis. The AHP weights derived from this analysis would then be utilised in GIS analysis through overlaying.

The GIS analysis, conducted using QGIS software, incorporated a raster map fuzzifying process. This process aimed to standardise values from different maps into fuzzy values for consistency. Subsequently, the constraint map was converted into a boolean parameter to ensure suitability for restricted zones. The results of each map's fuzzy and boolean transformations are depicted in Figure 3, encompassing ten sub-criteria and five constraint maps utilised in the analysis.

Table 3. Criteria's weights.

Sub-criteria	Weights	Sub-criteria	Weights
C1	0.497	W1	0.018
C2	0.074	W2	0.009
C3	0.116	W3	0.011
E1	0.019	W4	0.017
E2	0.155	W5	0.053

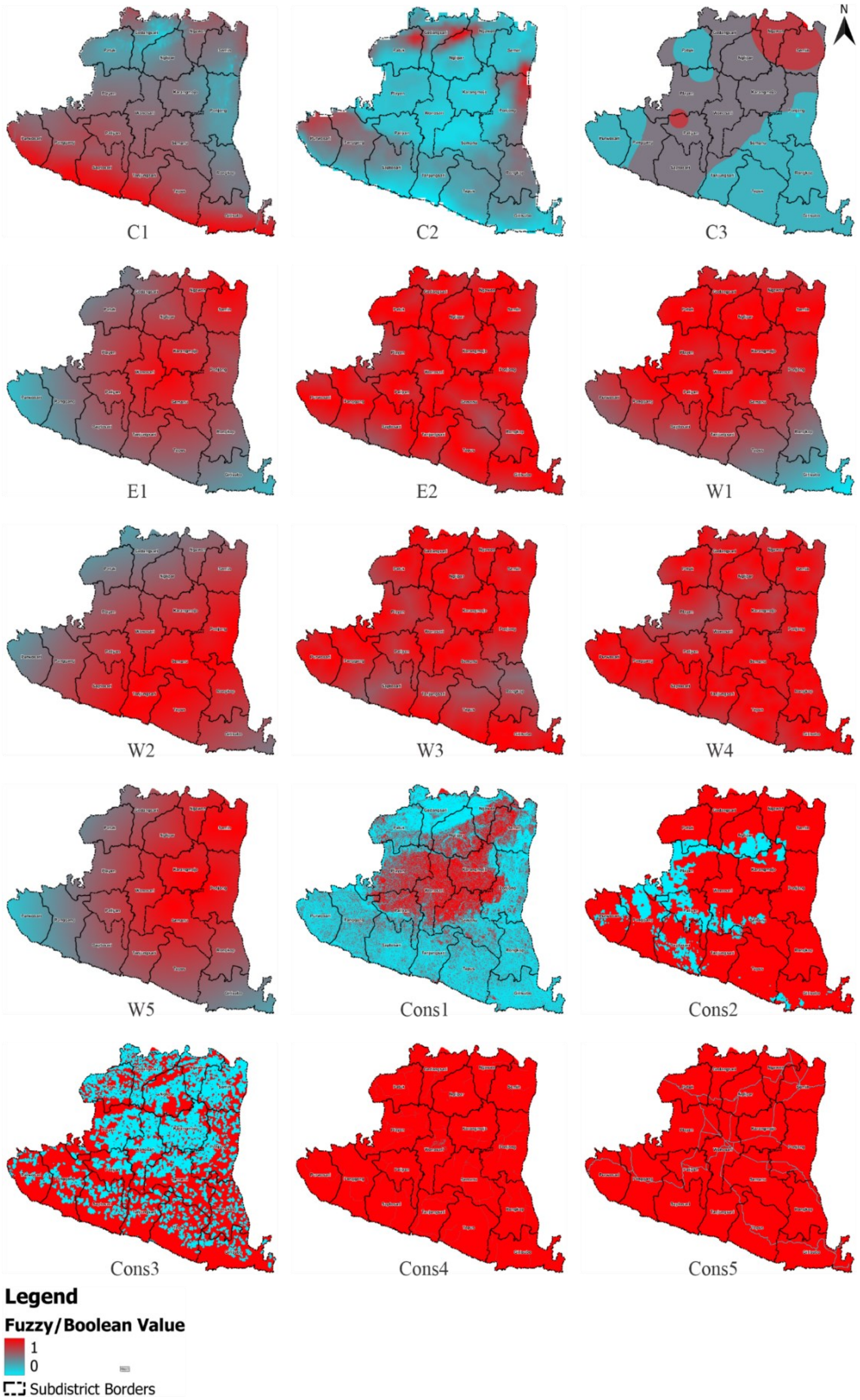
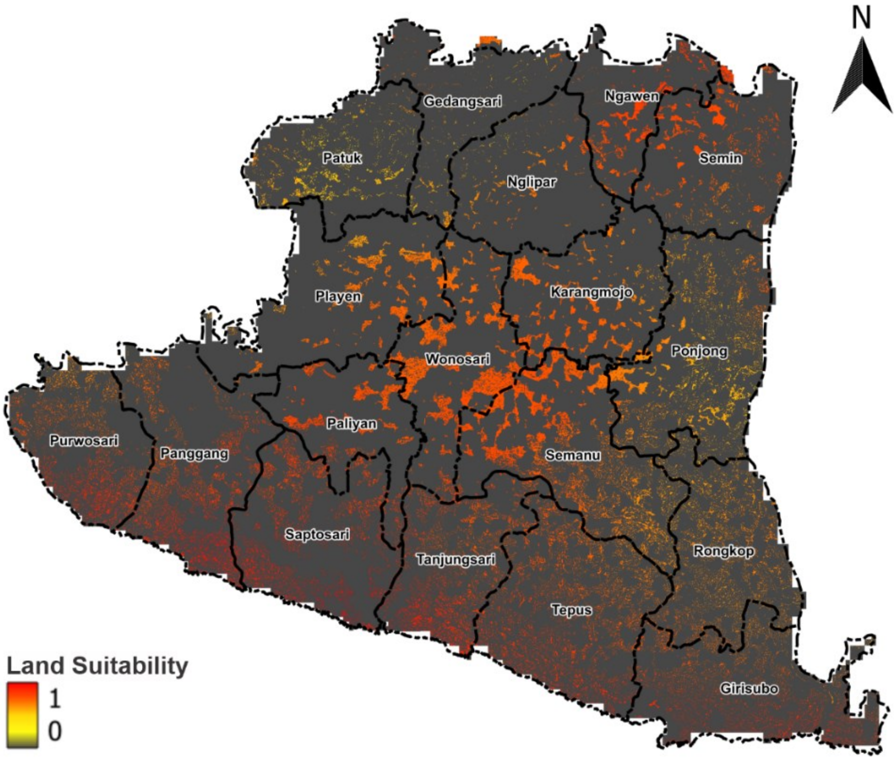


Figure 3. Results of each map's fuzzy and Boolean transformations.

The generation of a suitability map involved an overlaying process using equation (3). Each weight from Table 3 was incorporated into the map in Figure 3 based on its specific criteria. The overlaying results are depicted in Figure 4, which were clipped using two agricultural dryland maps. Those agricultural land maps were classified from several individual maps by referring to the local government policy, including non-technical irrigation land, dry farmland, bushland, and wasteland [34].

Figure 4. Overlaying result.



The result of the cropping is the suitability map for the food and energy combination site on Gunungkidul's arid land. Those maps, subsequently, were divided into eighteen sub-districts within Gunungkidul Regency. Afterwards, the suitable land will be measured to determine the total area precisely. The results of the measurement of each sub-district's suitable area are presented in Table 4.

Table 4. Suitable area for each sub-district in Gunungkidul Regency.

Sub-district	Suitable area (Ha)
Gedangsari	102.21
Patuk	34.06
Nglipar	172.85
Ngawen	432.78
Semin	512.12
Playen	602.17
Wonosari	1,325.54
Karangmojo	842.58
Ponjong	832.16
Purwosari	615.85
Panggang	851.96
Paliyan	491.56
Saptosari	752.82
Tanjungsari	786.33
Semanu	1,779.90
Tepus	1,157.21
Rongkop	696.17
Girisubo	680.93

As detailed in Table 4, the areas of eighteen sub-districts have been meticulously measured. The measurement results indicate that Semanu, Wonosari, and Tepus stand out as promising locations, boasting total areas of 1,779.90 Ha, 1,325.5 Ha, and 1,147.21 Ha, respectively. The suitability profile of those three sub-districts is visually presented in Figure 5. Semanu and Wonosari exhibit concentrated suitable areas, while Tepus demonstrates a more distributed suitability profile.

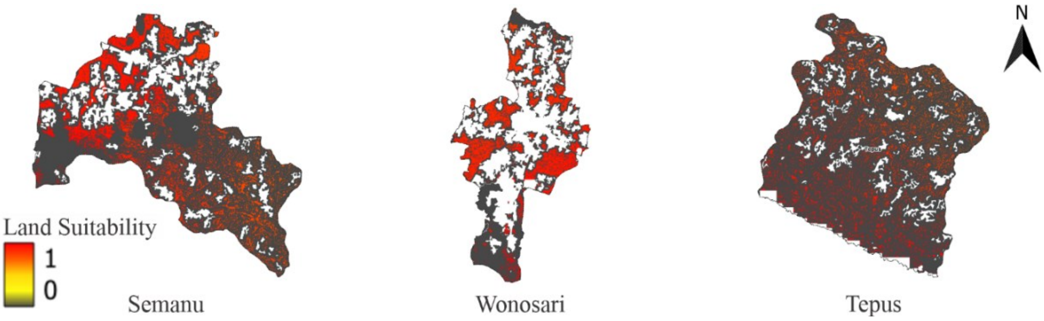


Figure 5. Land suitability for Semanu, Wonosari, and Tepus sub-districts.

Despite the favourable conditions in Semanu and Wonosari, it's worth noting that these sub-districts are not included in the government's plans for solar energy development. On the contrary, Tepus emerges as the lone suitable sub-district among the seven designated for solar energy development according to government planning, as seen in Figure 6. This underscores Tepus as the most appropriate location for implementing a food and energy combination system, aligning with the government's strategic goals for sustainable development.

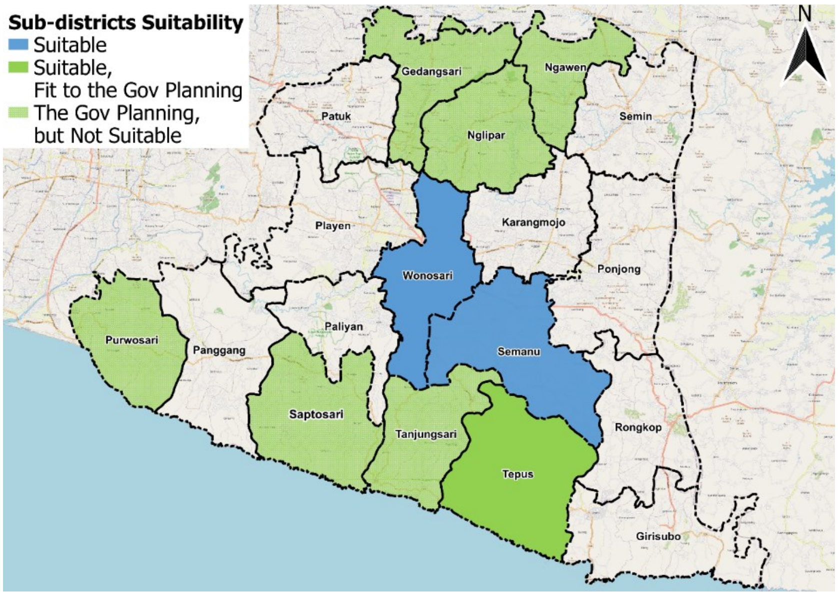


Figure 6. Suitable and not suitable sub-districts.

4. Conclusions

In the pursuit of achieving Sustainable Development Goals (SDGs), it is imperative for stakeholders, including governments, academics, and companies, to engage in discussions regarding the direction of SDGs. The food and energy sectors, integral components of the SDGs, have presented challenges in various regions. While efforts to ensure sufficient food and energy supply are ongoing, specific regions, such as Gunungkidul, face additional hurdles, such as water shortages hindering local food production. To address this, electrification has emerged as a solution for water supply in agricultural activities. Moreover, energy is now viewed not only as a supportive factor in agricultural production but also as a means to increase land productivity by co-locating food and energy production.

The study conducted in Gunungkidul Regency offers the possibility of implementing a combined food and solar energy system known as the agrivoltaic system. Considering the government's solar energy development plans, Tepus has been identified as the most suitable location among seven sub-districts, including Gedangsari, Nglipar, Ngawen, Purwosari, Saptosari, and Tanjungsari. However, the study faced challenges due to the steep land surface in Gunungkidul, which has a hilly terrain with a slope exceeding 10%. On the contrary, the agrivoltaic system requires a flat surface to maximise solar irradiation reception. Consequently, Sub-districts Wonosari and Semanu, characterised by relatively flat lands, emerged as the most suitable locations, offering spacious areas of approximately 1779.9 Ha and 1325.5 Ha, respectively. The stakeholders should consider these two sub-districts agrivoltaic system sites.

The implementation of the agrivoltaic system holds promise as a solution to address SDGs in the food and energy sectors. Beyond its environmental benefits, the system has economic advantages, as the electricity generated by photovoltaic panels can be utilised to electrify dryland agriculture activities. This creates opportunities for farmers to enhance their productivity through increased farming cycles and the sale of electricity.

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