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Research Note

Multi-Criteria Analysis of Biogas Feed Fuel Cell-Based Electricity Generation: Economic and Environmental Factors

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ABSTRACT

Penetration of renewable energy in the energy generation mix must be viewed from different angles. This issue shall not only cover the technological part, but also economic, environmental, and social criteria. The fuel cell provides huge potential with less reliance on fossil fuel-based electricity generation. This paper aims to model the optimum design of fuel cell-based electricity generation in Malaysia. Economic and environmental aspects are indicators that contribute to designing an optimum model. Both Multi-Criteria Analysis and Analytic Hierarchy Process were employed in order to decide on the optimum site for the system. Truck transportation, biogas storage, and fuel cell system are among the most important criteria that provide final weighted criteria. Considering both criteria for the economic and environment concerns, the best optimum location is in Sarawak State. The findings of this study influence the decision-making and help researchers and decision-makers develop proper strategies in the renewable energy roadmap.

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1. INTRODUCTION

Currently, sustainable energy becomes the main concern in power production. Climate change issues, energy security, social awareness, and fossil fuel dominance are the factors that contribute to renewable energy development. Fuel cell consumption in electricity production is one technique feed gas as input and gets the electricity and water as the output. The most applicable fuel cell is the Solid Oxide Fuel Cell (SOFC) due to its great efficiency, minimal emissions, low level of noise, and fuel flexibility [1]. Malaysia, as a tropical country, provides huge potential for producing biogas, especially from oil palm residue [2]. A combination of biogas and solid oxide fuel cell systems has been identified as a very smart energy resolution for a distributed generation [3]. To increase the percentage of renewable energy consumption, economic, social, and environmental perspectives need to be considered. Integration of all perspectives into one tool helps decision-makers analyze using Multi-Criteria Decision Analysis (MCDA). These techniques offer more robust results than other decision support systems based on cost-based or environmental-based perspective, because several criteria are combined in decision-making practice to finally influence a valid and steady-state balance which would be great assistance to all decision-makers [4]. The most widely applied method to MCDM is Analytic Hierarchy Process (AHP). AHP method has been used to determine the weights of the multiple criteria (techno-economic and environmental) as a more suitable tool to solve site selection problems [5]. Several studies have employed AHP to explore renewable energy using the pairwise comparison between the criteria [6]. Therefore, this study aims to (1) determine the criteria weights based on the relative importance of each one and (2) evaluate the multipe criteria for optimum site selection.

2. METHOD

2.1. Methodology

Data collection for each process in developing the optimum model considers the palm oil mills located in Kedah, northern region of Malaysia. About 6 mills registered under Malaysia Palm Oil Board are used as a case study in this study [7]. Figure 1 shows the location of each mill and its output capacity. Biogas production was calculated using Equation (1) in previous publication [2]. The data derived from economic and environmental criteria are obtained based on these mills as a case study, which were reported in the previous publication. Table 1 lists the main resources considered in this study [8]. The data from this analysis were used in this study to select the optimized site location.

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Table 1. Main resources data used in this study

Parameter	Resources	Ref.
Environmental	Biogas Fed-Fuel Cell Based Electricity Generation: A Life Cycle Assessment Approach	[8]
Economic	Life Cycle Cost of Biogas Feeding into Fuel Cell: Case of Malaysia	[13]

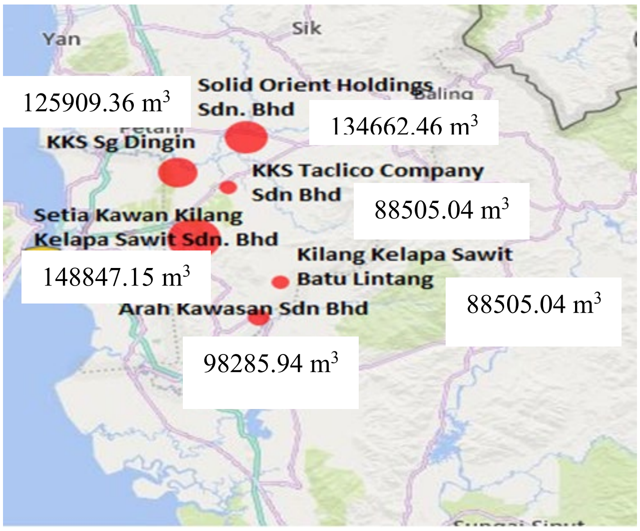


Figure 1. Kedah palm oil mill location and capacity output

Step in AHP.

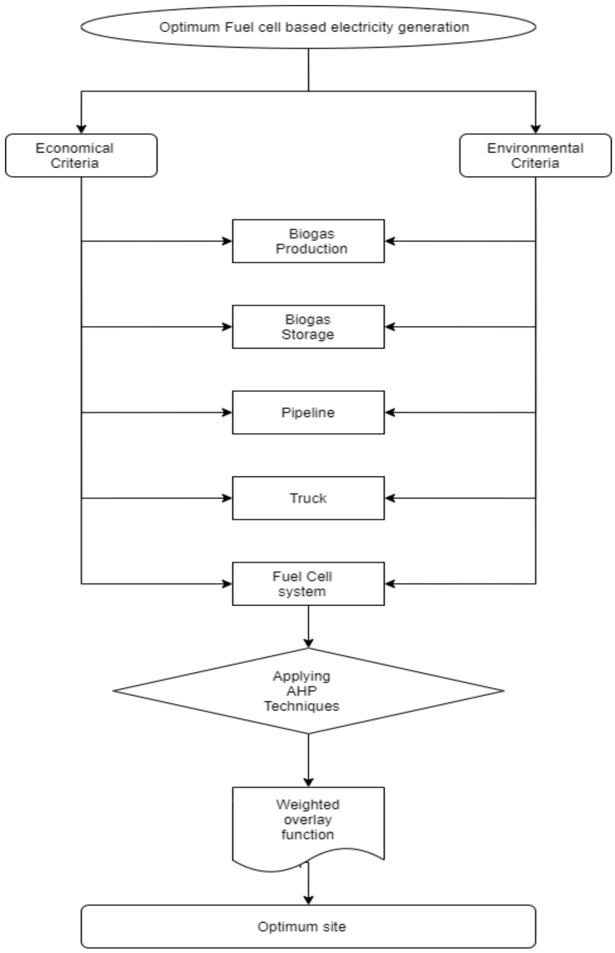


Figure 2. Approach to formation of the optimum model

Initially, the aim of the AHP process is set, as shown in Figure 2. Both economic and environmental aspects consider the following criteria or process mentioned in Figure 2: biogas production_BP, pipeline_P, biogas storage_BS, truck transportation_T, and fuel cell system_FC). The pairwise comparison is estimated on a 1-to-9 scale for each process, as developed by [9].

Then, build a pairwise comparison matrix M (n X n), where n is the number of process or criteria. Table 2 and Table 3 show the comparison matrix for economic and environmental aspects, respetively.

Table 2. Pairwise comparison matrix for the economic process

Process	BP	P	BS	FC	T
BP	1	9	0.14	0.14	7
P	0.11	1	0.11	0.11	0.33
BS	7	9	1	3	5
FC	7	9	0.33	1	5
T	0.14	3	0.2	0.2	1
Total	**15.25**	**31**	**1.79**	**4.45**	**18.33**

Table 3. Pairwise comparison matrix for the environmental process

Process	BP	P	BS	FC	T
BP	1	0.33	3	3	0.11
P	3	1	7	0.33	0.2
BS	0.33	0.14	1	0.2	0.11
FC	0.33	3	5	1	0.11
T	9	5	9	9	1
Total	**13.67**	**9.48**	**25**	**13.53**	**1.53**

From the comparison matrix table, the normalized comparison matrix (a̅jk) is obtained. Equation (1) is used to calculate each cell for matrix, as presented in Table 4 and Table 5.

$$\bar{a}_{jk} = a_{jk}/\sum_{1}^{n} a_{lk} \quad (1)$$

Table 4. Normalized economic pairwise comparison matrix

Process	BP	P	BS	FC	T	Normalized priority	Weight %
BP	0.07	0.29	0.08	0.03	0.38	0.17	16.99
P	0.01	0.03	0.06	0.02	0.02	0.03	2.90
BS	0.46	0.29	0.56	0.67	0.27	0.45	45.10
FC	0.46	0.29	0.19	0.22	0.27	0.29	28.66
T	0.01	0.10	0.11	0.04	0.05	0.06	6.35

Table 5. Normalized economic pairwise comparison matrix

Process	BP	P	BS	FC	T	Normalized priority	Weight %
BP	0.07	0.04	0.12	0.22	0.07	0.10	11.08
P	0.22	0.11	0.28	0.02	0.13	0.15	13.85
BS	0.02	0.02	0.04	0.01	0.07	0.03	3.51
FC	0.02	0.32	0.20	0.07	0.07	0.14	16.01
T	0.66	0.53	0.36	0.67	0.65	0.57	55.55

The overall weight vector is computed using Equation (2). Finally, the consistency of the comparison matrix is checked. The value of the random consistency index, RI, was pursued in [9]. **Equation 3** is used to calculate the consistency ratio, CR. The obtained value of CR determines the acceptable ratio of the study with < 10 %; if CR > 10 %, it requires to revise the analysis and decision made [9].

$$W_j = \sum_{l=1}^{n} a_{jl}/m \quad (2)$$

$$CR = CI/RI \quad (3)$$

Then, the final weight is used in **Equation 4** for determining the optimum site location for Malaysia. The optimum site location index is estimated using Equation (4) [10]. The obtained results are applied to estimate the optimum site for Malaysia based on the availability of palm oil mills for the whole country [7].

$$SI = \sum_{1}^{i=n} W_i \mu_i \quad (4)$$

where n denotes the total number of preference process; i is the final weight of preference process for both economic and environmental aspects; W stands for the weight reflecting the relative importance of preference process; μ is the spatial percentage of preference process for the state.

3. RESULTS AND DISCUSSION

The obtained result is discussed in this section. Table 6 shows the final weights of the sub-criteria obtained using the AHP method. In the case of economic criterion, the greatest contribution came from biogas storage (22.55 %), while for the environmental perspective, truck transportation made the greatest contribution with 27.78 %. The significance of biogas storage is for later on-site consumption and storage before or after transportation to the next process of fuel cell systems. Location of palm oil mill proportionally affects the sub-criteria associated with truck transporation, mainly due to diesel usage.

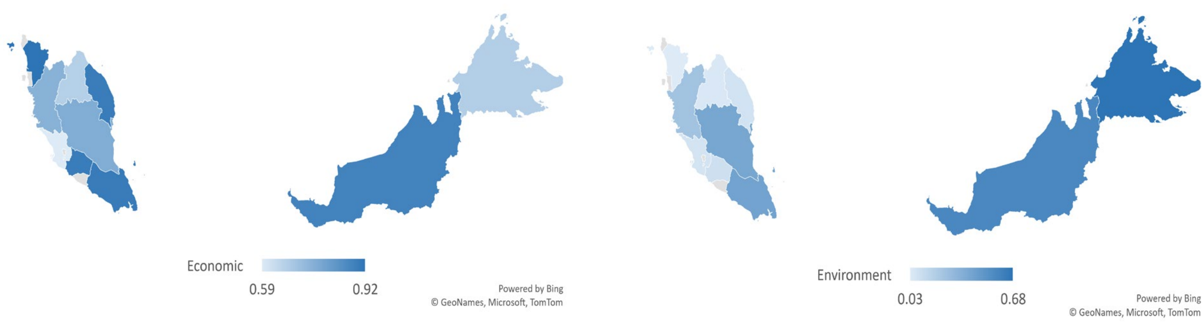
Table 6. The final weights of the sub-criteria by AHP method

Goal	Criteria	Weight %	Sub criteria	CR %	Weight %	Final weight%
Selecting optimum site	Economical	50 %	Biogas production	2.5	16.99	8.5
			Pipeline		2.9	1.45
			Biogas storage		45.10	22.55
			Fuel cell system		28.66	14.33
			Truck transportation		6.35	3.18
	Environment	50 %	Biogas production	2.7	11.08	5.54
			Pipeline		13.85	6.93
			Biogas storage		3.51	1.76
			Fuel cell system		16.01	8.01
			Truck transportation		55.55	27.78

According to Table 6, truck transportation made the highest percentage of contribution to the system (30.96 %), followed by biogas storage (24.31 %), fuel cell system (22.34 %), biogas production (14.04 %), and pipeline (8.34 %). Transportation also becomes the preferred factor in modeling biogas plant in Turkey [10]. The pairwise comparisons of economic and environmental aspects are acceptable and consistent since CR 2.5 % and 2.7 %. As a result, the AHP technique is an excellent method for measuring the different weights of multiple criteria. These can avoid the conflict between the varieties of layer application.

Biogas storage is also a relatively simple construction in the form of a large metal canister with a large piston inside, ensuring proper pressure through gravity [11].

Figure 3 shows the optimum model for both economic and environment perspectives. Sarawak is the optimum state from both economic and environmental perspectives. This means that developing the model in Sarawak will provide both advantages with minimum economic and environmental impacts. With strong support from the government, it is possible to introduce this new type of energy resource in Sarawak. Moreover, this state is also the initial state in Malaysia starting with a feasibility study on hydrogen and fuel cell applications there [12]. Meanwhile, in Peninsular Malaysia, Johor is the best selection for modeling power generation. However, this system design is generalized to the whole state. To increase the efficiency of the system design, more specific details of the on-site location need to be investigated for future research.



(a) (b)

Figure 3. The model based on (a) Economic and (b) Environmental perspectives

4. CONCLUSIONS

The most important criterion or process in AHP final weight is the truck transportation system (30.96 %), followed by biogas storage (24.31 %) and fuel cell system (22.34 %). Thus, these processes are the key to increase the suitability index for the selected site in this study. The most optimum design from both economic and environmental criteria was Sarawak State. Modeling this system in that state obtain minimum economic and environmental impacts compared to other states in Malaysia.

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