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Ranking of energy sources for sustainable electricity generation in Indonesia: A participatory multi-criteria analysis

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ABSTRACT

An evaluation of energy sources for electricity generation should consider manifold aspects of the sustainable development concept. The evaluation also needs active participation from all involved stakeholders. The objective of this paper is to rank energy sources for sustainable electricity generation in Indonesia. A multi-criteria decision analysis using the analytic hierarchy process method was applied to deal with multiple aspects of the sustainable development in the ranking of selected energy sources. Four criteria, twelve sub-criteria and nine energy source alternatives (three fossil fuels and six renewables) were defined. Relevant Indonesian energy stakeholders from government institutions, universities, think tanks, the energy industry, civil society and international organisations participated in this research. They gave judgements on pair-wise comparisons of the criteria and sub-criteria and a performance evaluation of the alternatives against four sub-criteria. The performance of the alternatives against the other eight sub-criteria was evaluated using data from relevant literature. This paper indicates that solar is the top ranked alternative for sustainable electricity generation in Indonesia, followed by hydro and oil as the top three. To fulfil the solar energy potential, the Indonesian government should consider policies that focus on the strengths of solar in the economic and social criteria.

Keywords

Sustainable energy systems;
Sustainable energy planning;
Sustainable electricity generation;
Analytic hierarchy process;
Energy stakeholder participation;

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1. Introduction

The sustainable development concept has emerged over the past three decades and now plays a vital role in our daily life. Introduced in 1987 by the World Commission on Environment and Development, sustainable development is defined as “a development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” [1]. In 2015, the United Nations adopted 17 Sustainable Development Goals (SDGs) as a global plan of action for people, the environment, and economy. SDG 7, a goal for the energy sector, aims to ensure access to affordable, reliable, sustainable, and modern energy for all [2]. This can only be achieved by promoting energy efficiency, reducing the use of fossil fuels that produce harmful emissions to people and the environment, and at the same time by increasing renewable energy penetration into energy systems. Renewable energy is not only better for people and the environment than fossil fuels but also good for the global economy. The International Renewable Energy Agency concludes that a renewables-based energy system will, on average, increase global GDP growth until 2050 [3].

Formulating energy plans that consider the sustainable development concept has become a main concern for all governments in the world. Negative impacts of energy projects, such as health problems and land-use change, are becoming increasingly important in energy planning. Maulidia et al. [4] believe that Indonesian energy planning is short-sighted and does not consider long-term benefits to people and the environment, such as

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*Corresponding author – e-mail: yudha-irmansyah.siregar@studierende.uni-flensburg.de energy security and environmental sustainability. Moreover, energy planning in Indonesia lacks transparency and inclusiveness. The Indonesian government needs to apply a thorough analysis and participatory process in energy planning. Against this background, the present research selected Indonesia as the case study focusing on energy planning in the electricity sector.

Since the early 2000s, electricity generation has increased substantially in Indonesia. Between 2010 and 2020, it almost doubled from 156 TWh to 291 TWh [5], as shown in Figure 1. The rise corresponds to an average GDP growth of 4.74 % over that period. Nevertheless, the electricity consumption per capita was still only 1,090 kWh in 2020 [6], significantly below the national target of 2,500 kWh by 2025 [7]. Current official Indonesian documents [8–10] predict an accelerating trend of electricity generation and consumption. Several international institutions have made similar projections [11,12]. The Asia-Pacific Economic Cooperation estimates that Indonesian electricity generation will be approximately 1,050 TWh in 2050 [13].

Fossil fuel–based sources have dominated Indonesia's electricity generation over the past two decades, as shown in Figure 1, and they are expected to remain the main sources. Coal, oil and natural gas–fired power plants accounted for almost 85.5% of the total installed capacity in 2020 [5]. The latest Indonesian electricity supply business plan [10] sets the share of coal, natural gas and oil in the total installed capacity by 2030 at 45%, 23% and 4%, respectively. Coal-fired power plants will continue to dominate electricity generation in Indonesia.

Renewables development in the electricity sector has experienced slow progress in Indonesia. From 2000 to 2020, the share of renewables in the country's total electricity generation increased by just 2% [5,14]. In 2020, the installed capacity from renewables was approximately 10.5 GW or 14.5% of the total installed capacity [5]. Hydro, geothermal and biomass contributed 6.1 GW, 2.1 GW and 1.8 GW, respectively. Other renewables solar, wind and biogas only accounted for around 0.5 GW [5]. The current increase seems contradictory, considering that Indonesia has abundant renewable energy potential in various forms [14–21], and numerous Indonesian studies [23–26] conclude that renewables can compete technically and economically with fossil-based sources.

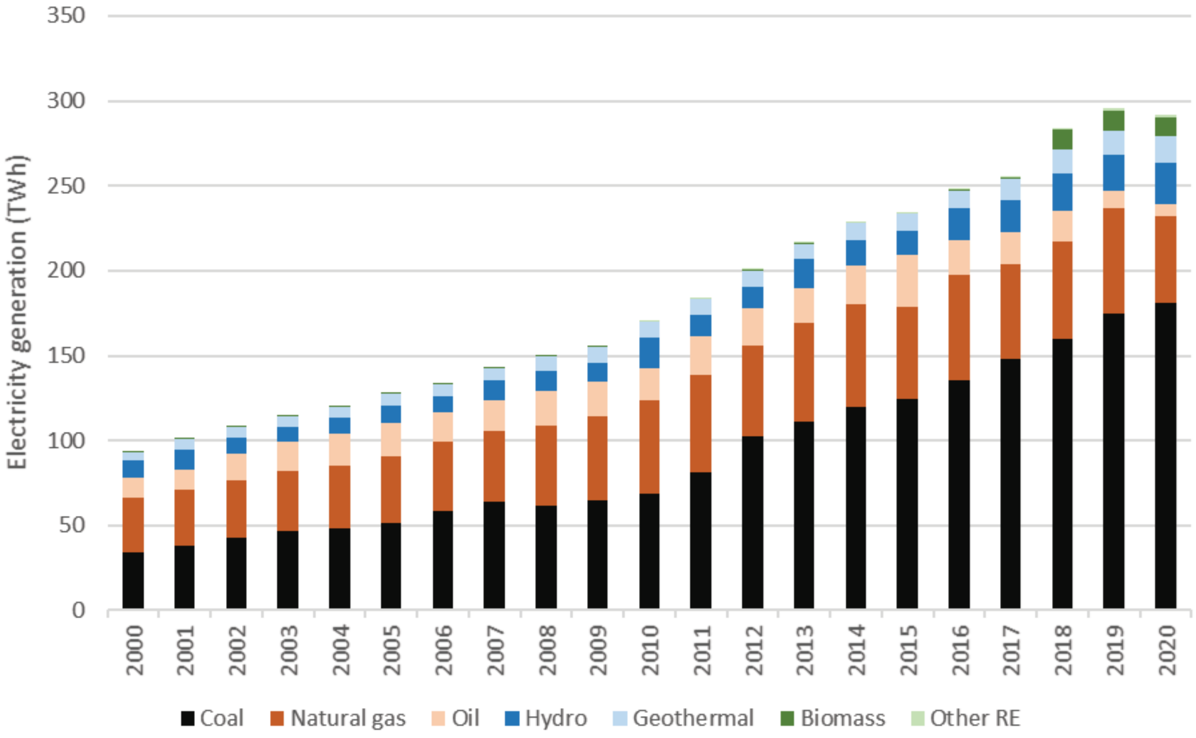

Figure 1: Total electricity generation in Indonesia from 2000 to 2020 [5,14]

An evaluation of energy sources for electricity generation in energy planning should be based on the sustainable development concept. Social, economic, and environmental aspects should be simultaneously assessed when prioritising alternative sources of energy [27]. The evaluation should also include various limitations, such as conflicting interests, economic constraints and technological challenges [28]. Multi-criteria decision analysis (MCDA) methods are suitable in dealing with these limitations and the manifold aspects of sustainable development in the energy sector. The MCDA methods can accommodate opposing interests and objectives from diverse backgrounds of stakeholders in the energy sector.

Various MCDA methods have been applied in Indonesian sustainable energy studies. Tasri and Susilawati [29] employed an MCDA method to select the most appropriate renewable energy sources for electricity generation. Miraj and Berawi [30] utilised two MCDA methods to evaluate the best solar PV alternative for electricity access on Tomia island. A combination of spatial analysis and MCDA methods was employed by Ruiz et al. [31] to select the optimal location of solar plants. However, it is believed that an evaluation using MCDA methods to rank all energy sources for electricity generation in Indonesia has not been conducted. This evaluation could be an alternative approach that is needed to consider multiple aspects of sustainable development concept in energy planning. This paper attempts to fill this literature gap by combining the use of MCDA and the active participation of relevant energy stakeholders for an evaluation of sustainable electricity generation in the country. It could benefit policymakers, planners and other relevant energy stakeholders in the development of sustainable energy plans, particularly in the electricity sector.

This paper suggests an approach for the ranking of energy sources for electricity generation in energy planning in Indonesia. The aim of the paper is to rank energy sources for sustainable electricity generation in the country. This paper applies MCDA employing the analytic hierarchy process method. A total of 23 Indonesian energy stakeholders from five different groups representing various interests and objectives participated in the present research. Four criteria and twelve sub-criteria were developed to rank the energy sources. This research evaluated a selection of all existing energy sources, both fossil fuels and renewables, which could be used in energy planning in Indonesia.

The paper lays out a research hypothesis that renewable energy sources have higher ranks than fossil fuels to generate sustainable electricity generation in Indonesia. The proposed approach that combines qualitative and quantitative data analyses could capture renewables' competitiveness in generating electricity against fossil-based power plants.

2. Methods and data

This section explains the multi-criteria decision analysis applications in energy planning, and the analytic hierarchy process method and the associated data used in this research.

2.1. Multi-criteria decision analysis in energy planning

Energy planning is a multi-dimensional process that has to deal with a broad range of qualitative and quantitative variables. A one-dimensional process that only uses quantitative variables, such as net present value or cost-benefit analysis, cannot comprehensively solve current energy planning issues. Qualitative variables, such as public acceptance and political risk, have been found to play a vital function in energy planning [32]. Competing interests and purposes amongst energy stakeholders should be captured in an analysis process that accommodates all involved variables. Multi-criteria decision analysis (MCDA) is well suited for this as it can be applied to determine trade-offs, co-benefits, and consensus results of complicated planning problems [33]. MCDA can increase the quality of decisions by creating them more explicitly, efficiently and rationally [34]. Stakeholders, such as government institutions, industry associations and civil society organisations, who actively engage in the energy planning process, need a structured framework, and this is possible with the MCDA method.

MCDA methods have been used globally as an alternative to traditional one-dimensional evaluation as they can handle many issues in energy planning, such as the ranking of energy sources or energy technologies for electricity generation. Some MCDA methods that are widely used in sustainable energy studies are Elimination and Choice Translating Reality (ELECTRE), Preference Ranking Organization Methods for Enrichment Evaluation (PROMETHEE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP). The ELECTRE method was utilised by Martínez-García et al. [35] to select the most sustainable technology for electricity generation in the United Kingdom. Seddiki et al. [36] utilised PROMETHEE to rank renewable energy technologies for electricity generation in a residential building. Alidrisi and Al-Sasi [37] employed TOPSIS to rank the G20 countries with respect to their energy selection for electricity generation. The AHP method was adopted by Shaaban et al. [38] to rank electricity generation technologies in Egypt. Al Garni et al. [39] and Ahmad and Tahar [40] utilised the AHP method for the ranking of renewables in the electricity sector in Saudi Arabia and Malaysia, respectively. Several extensive literature reviews [41–43] on MCDA applications in the sustainable energy field found that the analytic hierarchy process is the most used method.

2.2. Analytic hierarchy process for ranking alternative energy sources

The AHP method was introduced by Thomas L. Saaty in the 1970s and has been used to structure and model complex problems [44,45]. This method provides a thorough and logical framework for constructing a decision problem and solving it. The AHP method enables the ranking of different alternatives by offering a framework that can manage interests and provide solutions for conflicting aims. It transforms the decision problem into a hierarchy tree of a goal, criteria (and if needed, sub-criteria and further lower levels of sub-criteria) and alternatives. The alternatives are a group of options to be ranked based on the given criteria and sub-criteria. Figure 2 depicts the hierarchy tree for this research. The AHP method permits decision analysis processes to integrate quantitative data and qualitative judgements. This method matches a need to consider multifold aspects in the sustainable development concept. Another advantage of the AHP method is that it does not require complicated mathematical calculations [46]. Users can follow simple formulas and compute them. Figure 3 illustrates the main steps to rank energy sources for sustainable electricity generation in Indonesia using the AHP method.

A broad range of Indonesian energy stakeholders from the Indonesian government, universities, think tanks, the fossil fuel and renewable industry, civil society and international organisations participated in this research. These groups of stakeholders were chosen to reflect diverse interests in the Indonesian energy sector. A total of 52 stakeholders (Indonesian government: 9 stakeholders; universities and think tanks: 13; fossil

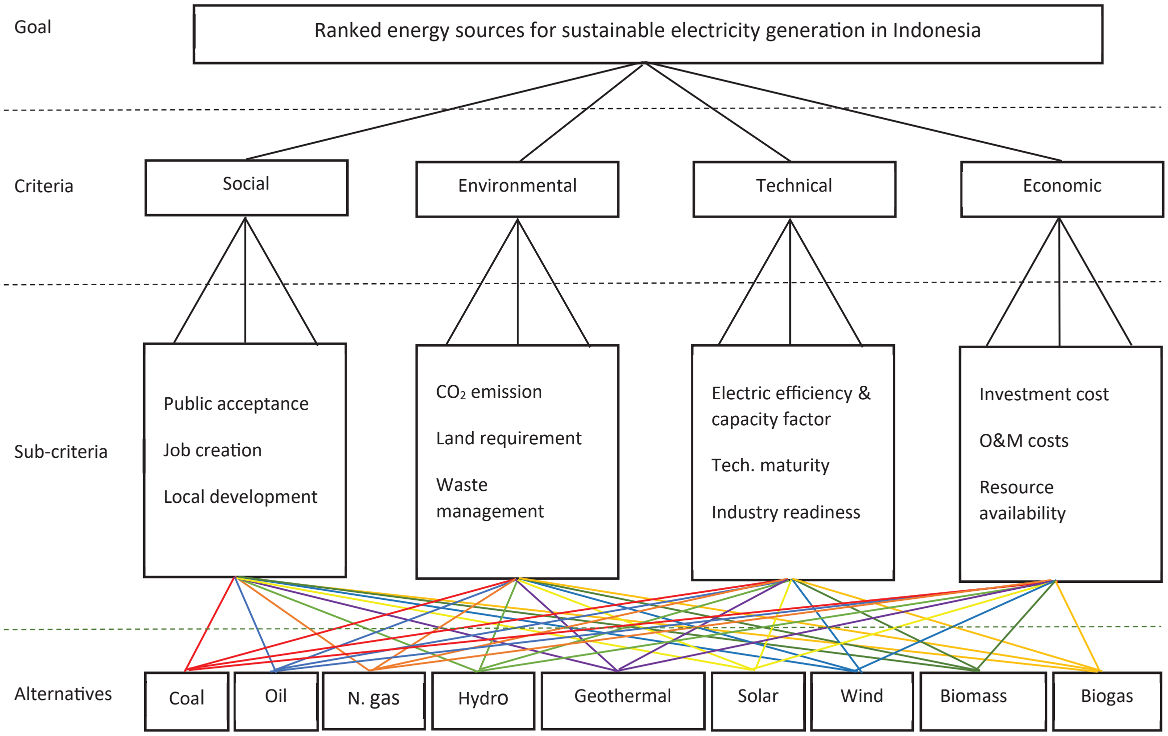

Figure 2: Hierarchy tree for ranking energy sources for sustainable electricity generation in Indonesia

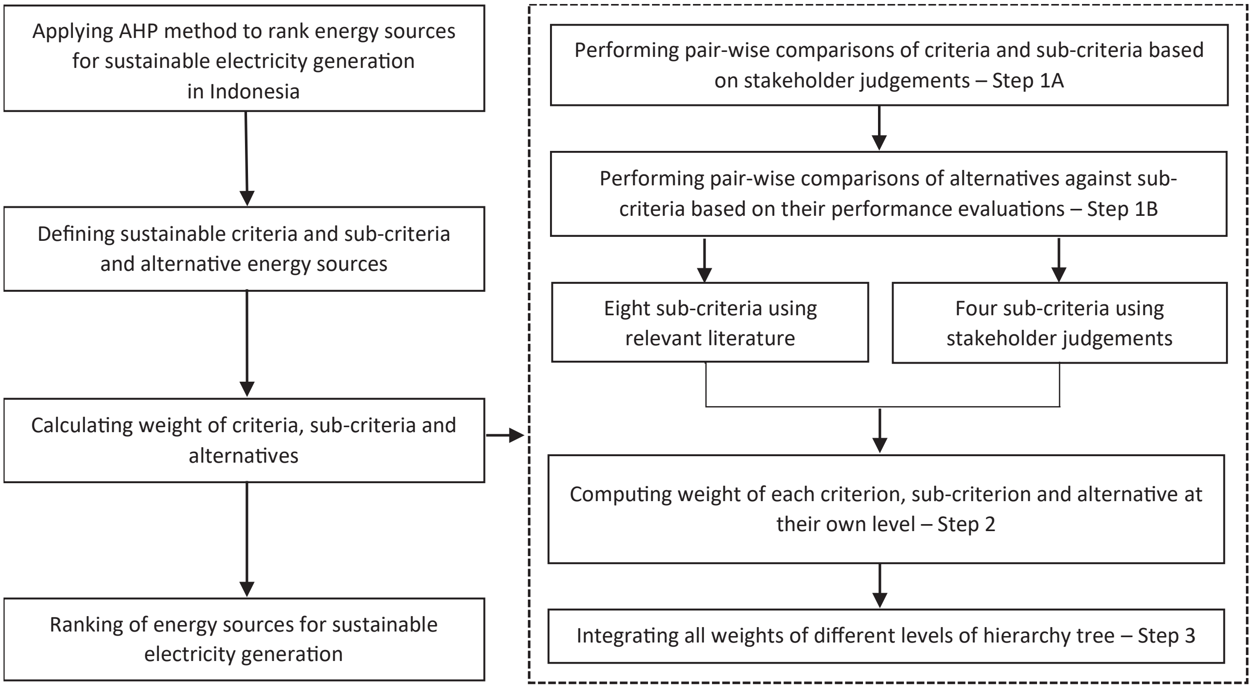

Figure 3: Main steps to rank energy sources for sustainable electricity generation in Indonesia using the AHP method

fuel industry: 7 and renewable industry: 7; civil society and international organisations: 16) were invited to participate in the research. Twenty-three stakeholders (details in Appendix 1) replied to the invitation. Data collection from the stakeholders took place between July and August 2021.

The 23 Indonesian energy stakeholders gave their judgements in two different questionnaires. The first questionnaire (Appendix 2) requested pair-wise comparisons of the criteria and sub-criteria, using Saaty's nine-integer importance scale, as shown in Table 1. The second questionnaire (Appendix 3) determined the performance of alternatives against four qualitative sub-criteria. Stakeholders evaluated the performance of each alternative on a 1-9 performance scale, as shown in Table 2. The two questionnaires in Indonesian were provided online and sent via email. The stakeholders had the opportunity to ask their own questions or clarify questions in the questionnaires.

2.3. Defining criteria, sub-criteria and alternatives

The ranking of energy sources for sustainable electricity generation requires a comprehensive process of defining selected criteria and sub-criteria, which should accommodate the sustainable development aspects. An extensive literature review was undertaken to obtain a list of possible criteria and sub-criteria. The list was modified to provide the most suitable ones in the context of the Indonesian electricity sector. Literature reviews by [32,41,42,47,48] on MCDA applications in the sustainable energy field found that social, environmental, technical and economic criteria were commonly used in these applications. Sub-criteria, such as job creation, CO_2 emission, electric efficiency, and investment cost, were also found to be commonly used. Table 3 summarises the most common criteria and sub-criteria used in sustainable energy research. This present research applied a subjectivity method based on own opinion in selecting and classifying criteria and sub-criteria. This method depends on preferences of people who are responsible for conducting the research and the goals set in the research design [48].

The criteria selected in this research are social, environmental, technical, and economic. Each of these four criteria has three sub-criteria. The social criterion covers social dimensions of the development of a power plant in a specific location and contains the sub-criteria public acceptance, job creation and local development. The environmental criterion considers environmental impacts of a power plant on the environment and people and contains the sub-criteria CO_2 emission, land requirement and waste management. The technical

Table 1: Importance scale for pair-wise comparison [44]

Intensity of importance (Variable A to Variable B)	Definition
1	Variable A and Variable B are equally important
3	Variable A is weakly more important than Variable B
5	Variable A is strongly more important than Variable B
7	Variable A is very strongly more important than Variable B
9	Variable A is absolutely more important than Variable B
2, 4, 6, 8	Intermediate intensities

Table 2: Performance scale for an alternative against qualitative sub-criteria

Performance score	Definition
1	Worst performance
3	Bad performance
5	Adequate performance
7	Good performance
9	Best performance
2, 4, 6, 8	Intermediate performances

Table 3: Popular criteria and sub-criteria used in sustainable energy research

Criterion	Sub-criterion	Source
Social	Public acceptance	[29,39,40,49–51]
	Job creation	[29,40,50–54]
	Local development	[49,52,53,55,56]
	Health impact	[49,52,56]
	Political acceptance	[39,57,58]
Environmental	CO_2 emission	[29,39,49,50,52–54]
	Land requirement	[29,39,49,50,52,53]
	Waste management	[29,49,54,57,59]
	Ecological impact	[49,51,53]
	Particles emission	[60–62]
Technical	Electric efficiency	[38,39,50,53,54,63,64]
	Capacity factor	[49,50,52,53,63]
	Technology maturity	[39,40,53,64]
	Industry readiness	[29,49,53,54]
	Flexibility	[49,50,52]
Economic	Investment cost	[29,39,49,51,53,54,63]
	O&M costs	[39,49,51,53,63,64]
	Resource availability	[39,40,49,52,55]
	Fuel cost	[49,63]
	Payback period	[65,66]

criterion considers the main technical aspects of a power plant and its technological development and contains the sub-criteria electric efficiency and capacity factor, technology maturity and industry readiness. Finally, the economic criterion discusses economic factors concerning power plant construction and operation, and energy source availability for electricity generation. This criterion has investment cost, operation and maintenance (O&M) costs and resource availability as its sub-criteria.

The current research considered all of the energy sources currently being used in the Indonesian electricity sector as alternatives. These include the fossil fuels coal, natural gas, and oil, and the renewable energy sources hydro, geothermal, solar, wind, biomass (including sources from waste), and biogas. Several official energy plan documents [8–10] also use the same selection of energy sources in relation to energy planning in Indonesia. These nine energy source alternatives capture the current status of the Indonesian electricity sector and the plans for the ranking of energy sources in the future. The selection of alternatives excluded sources, such as nuclear, tidal and wave energy, as they are not used commercially in Indonesia at present.

All of the alternatives were evaluated with respect to the sub-criteria. Energy stakeholders gave their judgements on the performance of alternatives against the qualitative sub-criteria public acceptance, local development, waste management, and industry readiness. These alternative performances were ranked based on the geometric mean of all stakeholder judgements in each sub-criterion. The technology maturity sub-criterion used qualitative information from literature. The remaining sub-criteria of job creation, CO_2 emission, land requirement, electric efficiency and capacity factor, investment cost, O&M costs, and resource availability are quantitative and based on relevant literature. The source selection for these sub-criteria was carried out for their reliability and applicability, i.e., Indonesian government publications or peer-reviewed articles. It is important to note that each quantitative sub-criterion used only one source except for resource availability, which used three sources. The decision to use one source per sub-criterion provided a uniform methodology for evaluating nine different energy sources against each sub-criterion. Table 4 presents the data sources for each sub-criterion.

The following sub-sections provide detailed definitions and explain the sources used for each sub-criterion in this research.

Public acceptance. This indicates the satisfaction level of the general public for the development of a new power plant. Public acceptance directly and indirectly affects the progress of power plant development. The performance of each alternative for this sub-criterion was evaluated qualitatively by stakeholders. The best performance indicates the public's most welcomed energy source for a new power plant. Stakeholders indicated that coal is the least welcome alternative and that solar is the most welcome one. The complete evaluation for this sub-criterion can be seen in Table 5.

Table 4: Sub-criteria in this research and the sources of relevant data

Sub-criterion	Source
Public acceptance	Stakeholder judgement
Job creation	[67]
Local development	Stakeholder judgement
CO_2 emission	[68]
Land requirement	[69]
Waste management	Stakeholder judgement
Electric efficiency and capacity factor	[69]
Technology maturity	[69]
Industry readiness	Stakeholder judgement
Investment cost	[69]
Operation and maintenance (O&M) costs	[69]
Resource availability	[5,9,12]

Table 5: Performance of the alternatives for selected sub-criteria

Alternative	Public Accept-ance	Job creation		Local develop-ment	CO_2 emission (ton/GJ)	Land require-ment (1000 m^2/MW)	Waste manage-ment
		C&I stage (Job-years/MW)	O&M stage (Jobs/MW)				
Coal	1	24.64	0.31	2	0.096	0.04	1
Natural gas	3	2.86	0.31	5	0.056	0.02	3
Oil	2	2.86	0.46	1	0.074	0.05	2
Hydro	8	16.28	0.44	9	0	62	9
Geothermal	7	14.96	0.88	7	0	30	6
Solar	9	28.6	1.54	8	0	14	8
Wind	6	7.04	0.66	4	0	14	7
Biomass	5	30.8	3.30	6	0	35	4
Biogas	4	30.8	4.95	3	0	70	5

Job creation. This sub-criterion indicates the opportunities for creating new jobs by building a new power plant. Jobs can be associated with direct employment during the stages of both construction and operation. This primarily generates development and prosperity in local communities. Job creation is the most used sub-criterion in the social criterion [32]. For this sub-criterion, the performance of the alternatives is taken from a recent study by Ram et al. [46], which investigated the number of jobs created by all types of power plants across the globe. Until now, no such comprehensive study has been carried out in Indonesia. Ram et al. [67] specify job creation factors for different regions. The current research applied the job creation factor of the Southeast Asia region. The job creation sub-criterion contains two different performances, which were evaluated for the stages of building a power plant. First, there is the construction and installation (C&I) stage with the unit job-years/MW. Second, it is the operation and maintenance (O&M) stage with the unit jobs/MW. These two performances equally evaluated alternatives and are listed in Table 5.

Local development. This expresses social progress in a region where a power plant has been built. In the Indonesian context, the power plant could affect either one or several cities and regencies, or at a broader level, provinces. Quantifying the full indirect impact of a new power plant is extremely difficult. This research used qualitative judgements of stakeholders to rank the performance of alternatives for this sub-criterion. Hydro is ranked as having the highest impact on local development, and oil is ranked as having the lowest impact. Table 5 shows the full evaluation for this sub-criterion.

CO_2 emission. This sub-criterion evaluates the direct impact of alternatives on the environment by assessing the volume of CO_2 emitted into the air in the process of generating electricity. The sub-criterion is taken from quantitative data, in the unit CO_2 ton/GJ, from the Indonesian GHG Inventory Data for Energy Sector [68]. Only fossil fuel sources are assumed to be CO_2 emitters. Renewable energy sources do not produce CO_2 in electricity generation. This assumption also applies in Indonesian energy planning documents [8–10]. Table 5 shows the performance of alternatives with regard to the CO_2 emission sub-criterion.

Land requirement. This requirement quantifies the area of land needed to build a power plant and its supporting facilities. It is a quantitative sub-criterion with data taken from the newest Technological Data Catalogue for Power Sector in Indonesia [69]. It is worth mentioning that the catalogue is predominantly based on power plant projects in Indonesia. This can ensure the country-specific nature of land requirement for each energy source. The land requirement for each alternative is shown in Table 5.

Waste management. This sub-criterion assesses all processes of waste disposal from the construction phase to the decommissioning of a power plant. The sub-criterion indicates that every energy source needs specific waste treatment, which can be harmful to people and the environment if not managed properly. Each performance of the alternatives against this sub-criterion was evaluated qualitatively by stakeholders. The best performance is associated with the alternative that requires the least effort to manage its waste. The worst performance of an alternative is associated with the greatest effort required. Stakeholders ranked hydro as the best alternative and coal as the worst in this sub-criterion. The complete ranking is shown in Table 5.

Electric efficiency and capacity factor. This sub-criterion provides data on two separate performances: electric efficiency and capacity factor and shares an equal portion in the evaluation of alternative performance. The performance of electric efficiency is the ratio between the total amount of electricity delivered to the grid and fuel consumption. The capacity factor is the ratio of the average net annual electricity generation to its theoretical annual generation if the power plant were operating at full capacity all year round. This quantitative sub-criterion used electric efficiency and capacity factor data from the Indonesian Technological Data Catalogue for Power Sector [69]. Data for this sub-criterion are shown in Table 6.

Technology maturity. This sub-criterion evaluates the maturity of the technology used for each alternative. It also reflects its commercial viability at national and international levels. The performance of each alternative for this sub-criterion was evaluated qualitatively, referring to the Technological Data Catalogue for Power Sector in Indonesia [69]. The nine energy source alternatives were grouped into two category levels: Level 3 (moderate deployment) and Level 4 (large deployment). Level 3 indicates that the maturity level of the technology is well known, and that it is likely that there will be major improvements in the technology in the future. Level 4 indicates that there is a high level of maturity and that only incremental improvements are likely. Technology maturity for each alternative is shown in Table 6.

Industry readiness. This sub-criterion assesses the readiness of Indonesian industry to actively develop the power plant technology of each alternative. The sub-criterion also indicates the availability of national and local workforce to produce and install the equipment and to operate and maintain the power plant facilities. The performance for each alternative was evaluated qualitatively using stakeholder judgements. The best performance indicates the most established industry associated with an energy source in Indonesia. Oil has the highest performance, and wind energy the lowest. Table 6 shows the full evaluation for this sub-criterion.

Investment cost. This sub-criterion consists of mechanical and plant equipment costs, and installation costs. The former expenditure covers all physical equipment costs, while the latter contains equipment installation, building construction and grid connection expenses. Investment cost is the most commonly used sub-criterion in the economic criterion [42]. This sub-criterion used data from the Indonesian Technology Catalogue for Power Sector [69]. The full list of investment costs for each alternative is provided in Table 6.

Operation and maintenance (O&M) costs. Both fixed and variable costs of operating a power plant are included in this sub-criterion. The fixed costs include payments for administration, salaries, service and network charges, property tax, and insurance. The variable costs comprise auxiliary material costs, such as lubricant and fuel additives, waste treatment costs, spare part expenses, and output-related repair and maintenance costs. These fixed and variable costs share equal weighting in the evaluation of the performance of the alternatives. The fuel cost for thermal power plants is not part of the O&M costs. This quantitative sub-criterion used data from the Indonesian Technological Data Catalogue for Power Sector [69]. The stated O&M

Table 6: Performance of the alternatives for selected sub-criteria

Alternative	Electric efficiency (%)	Capacity factor (%)	Technology maturity (Level)	Industry readiness	Investment cost (million USD/MW)	O&M costs		Resource Availability
						Fix cost (USD/ MW/ year)	Variable cost (USD/MWh)	
Coal	42	87	4	8	1.52	56,600	0.11	972 EJ
Natural gas	56	90	4	6	0.69	23,500	2.30	66 EJ
Oil	45	98	4	9	0.80	8,000	6.40	24 EJ
Hydro	95	36	4	7	2.08	37,700	0.65	94.3 GW
Geothermal	15	80	3	4	4.00	50,000	0.25	28.5 GW
Solar	100	19	3	5	0.79	14,400	0	207.8 GW
Wind	100	34	3	1	1.50	60,000	0	9.3 GW
Biomass	31	88	3	3	2.00	47,600	3.00	32.3 GW
Biogas	34	90	3	2	2.15	97,000	0.11	0.5 GW

costs in this data catalogue are the average O&M costs during the whole lifetime of a power plant. O&M costs for each alternative are shown in Table 6.

Resource availability. This indicates how much of each energy source is available to generate electricity in Indonesia. Because of their infinite characteristics, all six renewable energy sources were prioritised first before fossil fuels. Resource availability for renewables represents their theoretical potential for producing electricity in a GW unit. The renewables data were drawn from two sources: [9] and [12]. For fossil fuels, resource availability refers to the total energy reserves in a unit exa joule (EJ) based on the Indonesian annual statistics of energy and economic data [5]. Table 6 provides the performance of the alternatives for the resource availability sub-criterion.

2.4. Calculating criteria, sub-criteria and alternative weights

To calculate the weights of the criteria, sub-criteria and alternatives, the current research used the AHP method in three steps (see Figure 3). In the first step, pair-wise comparisons for all variables in each level of the hierarchy tree were made using Saaty's nine-integer value of importance scale, as shown in Table 1. At the criteria and sub-criteria level, the pair-wise comparisons were performed by stakeholders, who gave their judgements on the importance intensity of one variable to another. At the alternatives level, pair-wise comparisons were made based on the performance of alternatives against each sub-criterion, using rank number of alternatives as suggested by Garni et al. [39].

In the second step, the maximum eigenvalue, consistency index, consistency ratio and normalised eigenvector were computed to obtain the weight of each criterion, sub-criterion and alternative at their own level. A consistency check of pair-wise comparisons was performed in this step. Because the pair-wise comparisons are subjective, the AHP method utilises a consistency ratio (CR) to check for inconsistent judgements by stakeholders. The CR checking can be calculated using following equations:

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

Where, CI is the consistency index, λ_{max} is the maximum eigenvalue of a pair-wise comparison and n is the number of variables used in a pair-wise comparison.

$$CR = CI / RI \quad (2)$$

Where, RI is the random consistency index, a given value suggested by Saaty [44] depending on the size of n.

The CR attribute is considered to be an advantage of the method. Saaty [44] suggests that the CR value should be less than 0.1. All calculations in this step were performed using an online AHP calculator tool [70].

In the third step, all of the weights were integrated over different levels of the hierarchy tree. [70] was also employed in this step. This step determines the weight of each criterion, sub-criterion and alternative with respect to the goal. The ranking of the energy sources for sustainable electricity generation in Indonesia is defined by each alternative weight with respect to the goal.

3. Results and discussion

The result of the criteria weight with respect to the goal in this research is depicted in Figure 4. The economic criterion has the highest weight at this level. Technical comes the second, followed by environmental and social. As the economic criterion constitutes almost one-third of the total criteria weight, it is evident that it is the most important aspect to be considered for sustainable electricity generation in Indonesia. The ranking of the energy sources mainly depends on their performances in this criterion. The social criterion, however, with the lowest weight, receives a lower importance level from the Indonesian energy stakeholders than of the other criteria.

Figure 5 shows the weights of sub-criteria with respect to the goal. The top three sub-criteria represent the most weighted sub-criteria in the economic, technical and environmental criteria. Resource availability from the economic criterion is the highest weighted sub-criterion, indicating a primary priority to use the most readily-available energy source in Indonesia for electricity generation. From the technical criterion, industry readiness comes as the second most weighted sub-criterion, which could imply a high importance to prioritise the national industry for electricity generation. Waste management, as the third most weighted sub-criterion, is considered the most important aspect of the environmental criterion. It is notable that all social sub-criteria have similar low weightings. It could be interpreted that each sub-criterion has equal importance in the social criterion.

Based on the criteria and sub-criteria weights, alternative weights with respect to the goal were computed, and the results are shown in Table 7. The CR

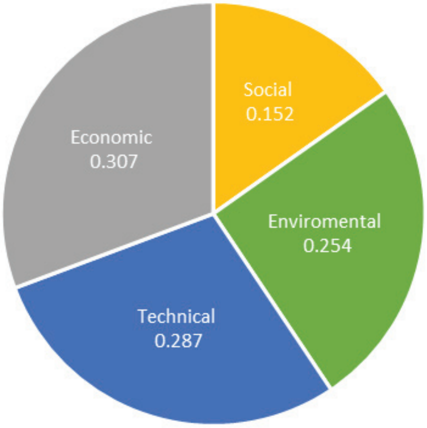

Figure 4: Weights of the criteria with respect to the goal

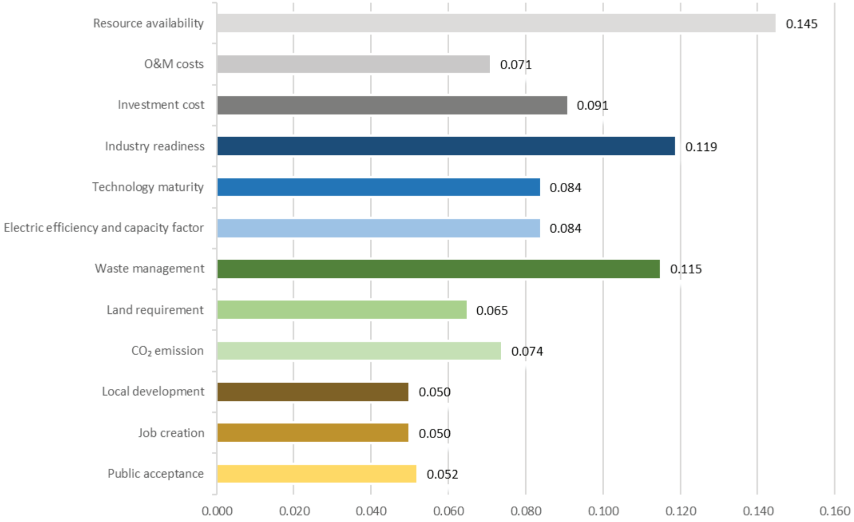

Figure 5: Weights of the sub-criteria with respect to the goal

of conducted pair-wise comparisons at all levels was less than 0.1. Detailed CR values from pair-wise comparisons made by stakeholders are in Appendix 4. This research concludes that solar is the highest ranking alternative, which should be prioritised as the energy source for sustainable electricity generation in Indonesia. Hydro is ranked second followed by oil. It should be noted that the weight for solar is much higher than other energy alternatives. Solar has a wide gap weight with hydro as the second rank (0.0475, the biggest one between two consecutive ranks, e.g. second and third rank or third and fourth rank) that emphasises a paramount priority to use this alternative for electricity generation in the country. The rankings of the remaining alternatives in high-low rank order are natural gas, wind, coal, biogas, geothermal, and biomass. This ranking result supports the stated research hypothesis that overall, renewable energy sources have higher ranks than fossil fuels. Top three and top five ranks are dominated by the renewables.

There is not an alternative which completely dominates each criterion. Solar performs as the best alternative in the social and economic criteria but not in the environmental and technical criteria, as can be seen in Figure 6. Hydro has the highest weight in the environmental criterion but not in the other three criteria. Oil has the lowest weight in the social criterion but the highest weight in the technical criterion. The remaining

Table 7: Weight and rank of alternative energy sources

Alternative	Weight	Rank
Coal	0.0912	6
Natural gas	0.1013	4
Oil	0.1184	3
Hydro	0.1519	2
Geothermal	0.0815	8
Solar	0.1994	1
Wind	0.0949	5
Biomass	0.0775	9
Biogas	0.0840	7

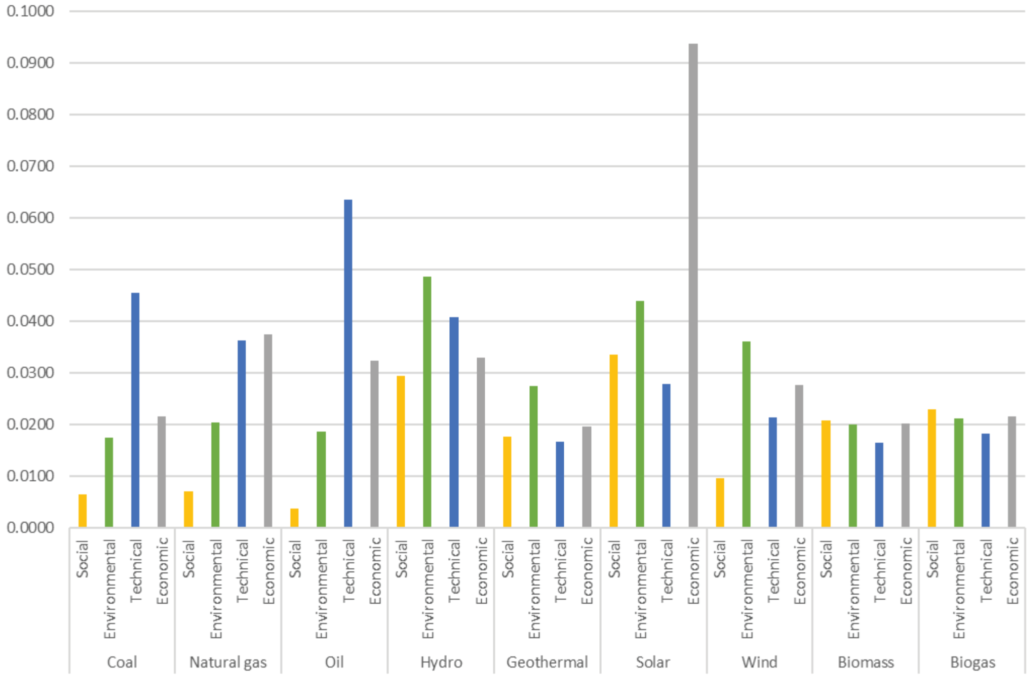

Figure 6: Alternative weights for each criterion with respect to the goal

six alternatives have a range of relatively low and high weights in one or more criteria. This could be explained by the fact that each alternative has its own strong and weak criteria. A combination of solar, hydro and oil as the top three alternatives for all four criteria appears to be the optimal mix for sustainable electricity generation in Indonesia. However, more work needs to be done, particularly with respect to technical and economic aspects of integrating different energy sources into the grid before finally concluding the optimal mix.

Another significant result is that coal is only ranked sixth as an energy source for sustainable electricity generation in Indonesia (see Table 7), although the current electricity generation is mainly from this alternative and this will continue to remain the case in the future. The present research raises the possibility of revisiting the existing planning process in the Indonesian electricity sector that puts coal as the primary energy source for electricity generation. Even though coal has a high weight (the second highest) for the technical criterion, its weights for the social and environmental criteria are low, the second lowest and lowest, respectively (see Figure 6). Sourcing coal as the primary source for electricity generation would not be sustainable. Indonesia needs a transition in its sustainable electricity generation planning, which reduces its dependency on coal. If Indonesia's dependence on coal continues for years to come, it would put its sustainable development at risk.

Stakeholder judgements make subjective evaluations based on their interests and objectives. These subjective evaluations could change the criteria and sub-criteria weights and subsequently alter the ranking of alternatives. Performing various sensitivity analyses could help to better understand the ranking results. This research conducted a sensitivity analysis based on the groups of stakeholders that they represent. The results of the criteria weight in this sensitivity analysis are shown in Table 8, and their rankings are provided in Table 9. Solar is ranked the highest by the five groups of stakeholders. The results confirm this alternative as the top ranked energy source across the different backgrounds of the stakeholders. Overall, these sensitivity analysis results indicate a similar order for the different groups with solar, hydro and oil as the top alternatives.

One interesting result in Table 9 is that oil is ranked in second place by the government stakeholder group. At the criteria level, government stakeholders give a much higher importance to the technical criterion (see Table 8). As a result, fossil-based alternatives generally have a higher weight than renewables in the technical criterion (see Figure 6) and are ranked higher by the government group than others. This might be explained by the fact that all government stakeholders are from technical institutions. It makes sense that their institutions' interest is reflected in their preference for the technical criterion. Furthermore, as they have strong technical expertise, they put the technical criterion at a higher level of importance than other criteria.

Another interesting result from Table 9 is that fossil fuels are ranked low (oil is ranked fifth; natural gas, eighth; and coal, ninth) in the fossil fuel industry group. A possible explanation for this is that the stakeholder in this group prefers to give a proportional weight for all criteria (see Table 8). As a result, fossil fuel alternatives that have lower weights for the social and environmental criteria (see Figure 6) have lower total weights when these two criteria have a bigger portion. The fossil fuel industry stakeholder might believe that the same weight for the four criteria could reflect the fossil fuel industry's interests.

Table 8: Criteria weight with respect to the goal based on stakeholder group

Criterion	Stakeholder group					
	All groups	Government	Fossil fuel industry	Renewable industry	University-Think tank	Civil society-International organisation
Social	0.152	0.092	0.250	0.145	0.182	0.186
Environmental	0.254	0.162	0.250	0.244	0.297	0.314
Technical	0.287	0.500	0.250	0.210	0.260	0.172
Economic	0.307	0.246	0.250	0.402	0.260	0.329

Table 9: Ranking of alternatives based on stakeholder group

Alternative	Stakeholder group					
	All groups	Government	Fossil fuel industry	Renewable industry	University-Think tank	Civil society-International Organisation
Coal	6	4	9	6	6	7
Natural gas	4	5	8	4	5	4
Oil	3	2	5	3	3	3
Hydro	2	3	2	2	2	2
Geothermal	8	8	6	8	8	6
Solar	1	1	1	1	1	1
Wind	5	6	4	5	4	5
Biomass	9	9	7	9	9	9
Biogas	7	7	3	7	7	8

4. Conclusion

The MCDA method enables a thorough analysis that considers multiple aspects and is a participatory process that involves various stakeholders. The method is ideal for use in energy planning in Indonesia. First, it can consider multifold aspects simultaneously in the design of energy plans. Second, by involving different groups of stakeholders in the energy sector, the credibility and acceptability of the planning results can be increased.

The use of the analytic hierarchy process in the MCDA method has been used here for the first time to rank nine energy sources for sustainable electricity generation in Indonesia. Solar is found to be highest ranked alternative. The sensitivity analysis results show solar to be the highest ranked alternative for all groups of stakeholders. This analysis also shows that different groups of stakeholders put different level of importance to the four criteria and in doing so represent their group's interests.

It is suggested that the Indonesian government should consider policies that can optimise the strength of solar in the economic and social criteria. For example, policies to maximise its resource availability can be implemented by promoting roof-top solar panels in big cities or by utilising reservoir dams as locations for solar farms. The latest ministerial regulation on roof-top solar utilisation [71] is a good starting point in accelerating solar use in the Indonesian electricity sector. To obtain a significant deployment of new roof-top solar users, the implementation of the regulation should be supported by the promotion of benefits to all electricity end-users [72].

Future work in the ranking of energy sources for sustainable electricity generation in Indonesia can be conducted in different ways, based on spatial and temporal research. Considering that Indonesia has a vast land area, specifying research locations and tailoring their criteria and sub-criteria accordingly could be one approach in future spatially-orientated research. Conducting a number of sensitivity analyses based on the forecasted performance of alternatives against sub-criteria could be a temporally-orientated future study.

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Appendix 1 Details of participated stakeholders

Table A1: List of participated stakeholders

Stakeholder	Job title	Age (years)
Government 01	Electricity programme analyst	34
Government 02	Policy analyst	43
Government 03	Policy analyst	42
Government 04	Renewable energy cooperation analyst	36
Government 05	Renewable energy programme analyst	33
Government 06	Director	51
Government 07	Senior researcher	61
Fossil fuel industry 01	-NA-	53
Renewables industry 01	Vice chairman - Independent consultant	58
Renewables industry 02	Technical manager	59
Renewables industry 03	Executive director	55
Renewables industry 04	Group head corporate affair	46
University – Think tank 01	Executive director	42
University – Think tank 02	Professor - Senior lecturer	69

Stakeholder	Job title	Age (years)
University – Think tank 03	Chairperson	41
University – Think tank 04	Deputy programme director	-NA-
University – Think tank 05	Professor - Senior lecturer	61
Civil society – International organisation 01	Executive director	48
Civil society – International organisation 02	Team eader	34
Civil society – International organisation 03	Manager	38
Civil society – International organisation 04	Researcher	30
Civil society – International organisation 05	Programme manager	36
Civil society – International organisation 06	Executive board member	52

Appendix 2 First questionnaire example

Please rate the importance intensity of the below four criteria with respect to the goal of ranking energy sources for sustainable electricity generation in Indonesia.

Table A2: Pair-wise comparison amongst criteria

Criterion	Importance scale of 1-9	Criterion
Social		Environmental
Social		Technical
Social		Economic
Environmental		Technical
Environmental		Economic
Technical		Economic

Please rate the importance intensity of the below three sub-criteria with respect to the social criterion.

Table A3: Pair-wise comparison amongst social criterion

Sub-criterion	Importance scale of 1-9	Sub-criterion
Public acceptance		Job creation
Public acceptance		Local development
Job creation		Local development

Appendix 3 Second questionnaire example

Please rate the performance score of the below alternatives against the qualitative sub-criteria.

Table A4: Alternative performance scoring against qualitative sub-criteria

Alternative	Public acceptance	Local development	Waste management	Industry readiness
	Performance score of 1-9			
Coal				
Natural gas				
Oil				
Hydro				
Geothermal				
Solar				
Wind				
Biomass				
Biogas				

Appendix 4 CR values of pair-wise comparisons made by all stakeholders

Table A5: CR values from pair-wise comparisons by stakeholders

Stakeholder	Amongst four criteria	Amongst social criterion	Amongst environmental criterion	Amongst technical criterion	Amongst economic criterion
Stakeholder 01	0.086	0.080	0.098	0.098	0.080
Stakeholder 02	0.073	0.080	0.080	0.090	0.090
Stakeholder 03	0.090	0.080	0.000	0.098	0.000
Stakeholder 04	0.000	0.030	0.000	0.000	0.000
Stakeholder 05	0.087	0.056	0.077	0.090	0.090
Stakeholder 06	0.076	0.077	0.000	0.000	0.000
Stakeholder 07	0.089	0.090	0.080	0.000	0.056
Stakeholder 08	0.043	0.056	0.040	0.056	0.000
Stakeholder 09	0.064	0.098	0.098	0.056	0.098
Stakeholder 10	0.000	0.098	0.000	0.074	0.056
Stakeholder 11	0.023	0.098	0.026	0.034	0.090
Stakeholder 12	0.066	0.098	0.010	0.000	0.004
Stakeholder 13	0.000	0.000	0.084	0.000	0.019
Stakeholder 14	0.099	0.019	0.019	0.056	0.056
Stakeholder 15	0.057	0.056	0.000	0.000	0.000
Stakeholder 16	0.057	0.000	0.000	0.000	0.056
Stakeholder 17	0.098	0.084	0.039	0.000	0.084
Stakeholder 18	0.000	0.056	0.089	0.000	0.056
Stakeholder 19	0.099	0.080	0.074	0.098	0.000
Stakeholder 20	0.000	0.056	0.000	0.056	0.098
Stakeholder 21	0.093	0.098	0.098	0.098	0.000
Stakeholder 22	0.057	0.019	0.056	0.000	0.000
Stakeholder 23	0.002	0.000	0.056	0.000	0.068

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