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Multi-criteria evaluation of renewable and nuclear resources for electricity generation in Kazakhstan

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Abstract

Kazakhstan's electricity generation depends heavily on fossil fuels. Renewables and other non-fossil resources provide potential alternatives to diversify the electricity generation system. In this paper, various potential local non-fossil fuel resources, hydro, solar, wind, biomass and uranium are reviewed and an assessment framework for prioritizing these resources is established. A multi-criteria decision making approach, analytic hierarchy process (AHP) based on expert opinion, is utilized for developing the assessment model, using four main criteria of technical, economic, social and environmental aspects and thirteen sub-criteria. The review reveal that Kazakhstan has ample potential to develop a non-fossil fuel based electricity system. Furthermore, the model shows hydro to be the most favorable resource followed by solar; wind and nuclear are ranked third and fourth, respectively while biomass is found to be the least attractive option. It is also found that each resource is inclined towards a particular criterion; hydro towards social, solar towards economic, nuclear towards technical, with biomass and wind directed towards environmental. Besides reporting the use of the AHP model for the first time in the Kazakhstan context, the assessment carried out in this paper can assist decision-makers to articulate long-term energy policy for any country.

Keywords

Kazakhstan, Analytic Hierarchy Process, Multi-criteria decision making, Electricity

1. Introduction

Fossil fuels dominate electricity generation around the world, with 67% of the approximately 23,000TWh of electrical energy produced in 2013 coming from fossil fuels [1]. Amongst the various fossil fuels used, coal dominates at 41.3% of the share followed by natural gas at 27.1% [1]. However, there are several drawbacks to using fossil fuels for electricity generation. First, economically exploitable global fossil fuel reserves are limited [2][3]. Second, burning fossil fuels for electricity generation results in harmful emissions [4]. These emission include carbon dioxide, methane, nitrous oxides, fluorinated and other gases [5]. Along with aforementioned drawbacks, there is a security of supply risk for procuring fossil fuel for electricity production, both in the short and long run [6]. These challenges are compelling reasons countries to diversify their fuel-mix for electricity generation. Kazakhstan, a central Asian republic, is no exception in this predicament and aspires to diversify its fuel-mix for electricity generation despite having significant domestic fossil fuel reserves [7].

Kazakhstan developed into an upper-middle income country primarily due to wealth generated from oil exports [8]. Affluence resulted in socio-economic development and as a consequence, the population has adopted electricity as their primary source of energy. This dependence led to a steady increase in electricity production as depicted in Fig.1. In 2003, electricity production was around 64 TWh which rose to 94 TWh in 2014,an annual increase of 3.57%. This annual growth in electricity production falls within the range of 3%-5% annually as predicted by Atakhanova and Howie in 2007 for Kazakhstan [9]. In a long run, Kazakhstan is expected to

produce 120 TWh and consume 116 TWh of electricity by 2020 [10]. The government estimated that the electricity production will be around 150 TWh/yr by 2030 [11].
Kazakhstan is endowed with significant fossil fuel resources (oil, natural gas and coal), fissile material (uranium), and minerals (copper, lead, zinc, iron ore, chromium). At the end of 2014, there was an estimated 0.8 trillion cubic meters of natural gas, 33600 million tons of coal and 20 billion barrels of oil reserves [8,9]. Due to its abundant fossil fuel reserves, the country is locked-in to use to fossil fuel, and this has proved an obstacle to diversifying the fuel-mix for electricity generation [14]. In 2015, around 90% of the total 90.7 TWh of electricity production in Kazakhstan was from fossil fuels. Coal is the major fuel used followed by gas. The only significant renewable resource, hydro, contributed around 10% of the total power production while other renewable sources like, small hydro, biomass, wind and solar contributed less than 1% of the total fuel-mix [15].

Fig. 2 depicts the fuel-mix for electricity production. Analyzing Figs. 1 and 2 together reveal two key issues: a considerable increase electricity demand and a reliance on fossil fuels over non-fossil ones. These two issues provide a major impetus for Kazakhstan to diversify its fuel-mix for electricity production. The Kazak government targets renewable power capacity will increase to 1040MW by 2020 in the country [16].
Diversifying the fuel-mix for electricity production is vital for sustainable development [17], and its planning a complex task [18], requiring a thorough process to evaluate various resources for electricity generation. In response to this, the objective of this paper is to use multi-criteria decision support approach to evaluate various renewable resources in Kazakhstan for electricity generation along with a nuclear resource. This multi-criteria evaluation is devised to take into account technical, economic, social and environmental criteria. To achieve the stated objective, the main tasks involved are: (i) to review various renewable resources for electricity generation including non-renewable but also non-fossil, nuclear resource; (ii) to identify sub-criteria pertinent to the problem; (iii) to develop an analytic hierarchy model based on expert elicitation, and finally, (iv) to rank non-fossil resources for diversifying fuel-mix for electricity generation in Kazakhstan including nuclear.

This is the very first attempt to use a multi-criteria approach for ranking various domestic resource options for a sustainable electricity generation portfolio in Kazakhstan. This research seeks to extend country specific energy related research literature in the Eurasia region. It is also pertinent to mention that the developed model and its results would be of value to a variety of stakeholders who are responsible for making policy and investment decisions.

The rest of this paper is organized as follows: Section 2 reviews renewable energy alternatives for Kazakhstan. Section 3 discusses prior studies using multi-criteria decision making approach Section 4 presents a real case application to rank renewable energy alternatives for Kazakhstan. Section 5 presents obtained results and discussion. Sensitivity analysis of the developed model is presented in section 6 while section 7 summarizes and concludes the study.

2. Renewable resources potential

The following sub-sections discuss renewable resource potential for electricity generation in Kazakhstan. To make this review more comprehensive, a fissile resource, i.e. uranium, is also discussed.

2.1. Hydro

Kazakhstan hydro resources can broadly be divided into three major regions: the Irtysh River basin, the South-Eastern zone and the Southern zone. Table 1 summarizes the regions with major rivers.

Total large hydro power potential is 170TWh/year [19] of which only 13-15% is effectively utilized [20]. At present the country has large hydro (defined as > 50MW) installed capacity of around 2.2GW while medium (10-50MW) and small hydro (<10MW) installed capacity is around 78MW [16]. There is around another 2707MW capacity of small hydropower at various stages of project completion [15].

2.2. Solar

Kazakhstan is generously endowed with solar resource; country's annual solar radiance varies from 2,200 to 3,000 hours of sunlight per year giving it an annual solar potential of between 1,300 kWh/m^2 and 1,800 kWh/m^2 [19]. It can be seen from the solar irradiation map (**Fig. 3.** Solar irradiation map of KazakhstanFig. 3.) that the maximum solar radiation of 1750 kWh/m^2 occurs for southern Kazakhstan while there is a small region in the north of the country, where it is less than 1150 kWh/m^2 per year (Ibid).

2.3. Biomass

To be able to estimate biomass potential for electricity production it is pertinent to describe the country's geography. Kazakhstan occupies a central position on the Asian continental land mass. In the north, are the steppe grassland and pastureland. Spanning from the central to the western catchments of the Caspian and Aral Seas are desert and semi-desert areas while the Tien Shan and Pamir ranges lie in the south. The total agricultural land is around 76.5 million hectares of which 61% is permanent pastures and 32% arable land [16]. A total of 12-14 Mt of biomass waste can obtained from agriculture and steppe grassland [15] thus giving a total potential of around 35 TWh per year [21].

2.4. Wind

Wind power potential is principally in the Dzhungar and Chilik regions of the country. The average annual wind speeds in these two regions have been recorded up to 7-9 and 5-9m/s, respectively [19]. A country-wide study, conducted by United Nations Development Program and Global Environemental Fund (UNDP-GEF), estimated a total wind potential for electricity generation to be around 929 TWh per annum [22]. This electricity generation corresponds to a capacity potential of 354 GW [22].

2.5. Nuclear

There are significant uranium reserves in Kazakhstan and was the leading producer of uranium globally in 2014 with nearly 23,000 tons of uranium [23].This amount accounted around 41% of the total world's production. . Around 80% of the reserves are located in the south of the country, 14% in the north and remaining 6% in central and west Kazakhstan [19]. The total uranium reserves (in tons of U) are summarized in Fig. 4. . According to the World Nuclear Association [24], the country has 12% of global uranium resources but only one nuclear plant that produced electricity in the period 1979-1999. The current state of uranium mining industry and its structure has been summarized by Conway [25].

3. Multi-criteria analysis in energy sector

3.1. Methods for Multi-criteria analysis

Energy sector decision-makers are faced with high levels of uncertainty while selecting a particular technology. These uncertainties are not only technical or financial but also environmental and social [26]. Decision about generation investment are critical as they define the future composition of the electricity generation system. Traditional evaluation methods such as cost-benefit analysis (CBA), cost-effectiveness analysis (CEA) and environmental impact assessment (EIA) are limited in scope [27][28][29]. It is therefore necessary to consider the use of multi-criteria decision analysis (MCDA) to complex decision problems. The strenghts of MCDA over traditional approaches, to name a few are: consolidating conflicting interest; being able to incorporate both qualtative and quantitaive information; stakeholder particpation; inclusion of criteira difficult to monetise [28][30].

MCDA comprises of a number of methods and tools. These include: Data Envelopement Analysis (DEA) [31]; the Analytic Hierarchy Process (AHP) [32]; TOPSIS [33], Multi-Attribute Utility Theory (MAUT) [34] and its sub methodology Multi- Attribute Value Theory (MAVT)[35], Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)[36] , Elimination Et Choix Traduisant la Realité (ELECTRE) [37], Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) [38] and several others. Each method has its own strengths, weaknesses and detailed comparisons of their qualities and application to energy sector have been made by Riberio et al., [39], Wang et al., [40], and Pohekar and Ramachandran [41]. Amongst all the MCDA methods, AHP has been extensively used [40][41][42][43][44]. AHP's widespread application is due to its capability of converting a complex problems into a simple hierarchy, its intuitive appeal and its ability to accommodate both qualitative and quantitative data into a single decision framework [28][41]. Once the AHP model has been developed, sensitivity analysis can be accomplished by adjusting the weights of the criteria, making the model to be particularly useful for policy analysis [30]. AHP is the most widely applied MCDA method, this paper focuses only on its application to Kazakhstan's energy sector. However, like any other tool, AHP has its weaknesses. These weaknesses being: structure of hierarchy; inconsistency in experts' opinion and choice of judgment scales [45] [46]. These limitations have been considered while developing this study's model in Section 4.1.

3.2. Use of AHP in energy sector

There are multiple examples of research relating to multi-criteria assessment and selection of energy sources for electricity generation [47]. Amer and Daim [43] analysed the sustainable electricity supply chain for Pakistan while Al Garni et al., [46] using a survey approach for developing an AHP, evaluated renewable technology options for fossil-fuel rich, Saudi Arabia. Turkey's electricity generation choices were evaluated by Bas [48] using a combined AHP

TOPSIS approach. Kahraman et al. [49], on the other hand, used a fuzzy-AHP approach for selecting renewable energy alternatives for Turkey. Tasri and Susilawati [50] also proposed a selection methodology based on fuzzy AHP approach to determine the most appropriate renewable energy sources for electricity generation for Indonesia. A total of 15 criteria were used classified in 5 categories. Contrary to norm, this study used 'requirement for waste disposal' as one of the environmental criteria for selection. To meet the policy goals for energy, enviroment and economy Shen et al. [51] evaluated six renewable technologies for electricty production in Taiwan. Keeping with the country level geographic focus, Štreimikienė et al. [52] tried to assess sustainable electricity generation option for Lithuania. In each of the five scenarios, pivoting on only one of institutional, economic, technological, environmental and social aspects at a time, Štreimikienė et al. evaluated a total of two non-renewable (nuclear and natural gas) and four renewable (biomass, geothermal, wind and hydropower) technologies. Using two distinct groups of decision-makers (one from technical and the other from political), Yi et al. [53] used AHP for sustainable electricity production options for North Korea. Their model comprised of 10 criteria grouped in three categories, being benefit, cost and risk. A similar approach was adopted by Chen and Chen [54] for China.

Moving focus from country to a region level, Rojas-Zerpa and Yusta [55] combined AHP and VIKOR (a Compromise Ranking method) for planning electricity generation for a small rural community in Venezuela. Likewise Hernández-Torres et al. [56], having the same geographical focus, used AHP for designing a small scalable renewable energy system for a rural island. Chatzimouratidis and Pilavachi [57] examined the relative benefits of both non-renewable production technologies including nuclear and renewable technologies, whereas Daim et al. [58] focused on wind and clean coal technologies for a utility company in USA.

Some very specific applications to energy conservation have also been carried out using AHP [59][60][61]. Selection of space heating teachnologies was performed by Jaber et al. [60] and by Chinese et al. [59] while in a comparison of conseravation policy, Kablan [61] found government regulation and legislation to be most favoured by experts. In a unique study by Chatzimouratidis and Pilavachi [62], AHP was used to find the impact of various power generation technologies on human living standards.

Relatively little literature can be found relating to the financial aspects of energy planning and AHP, possibly reflecting the fact that financial and economic issues are often incorporated into the holistic AHP models that have been developed. However, AHP along with PROMETHEE and ELECTRE was employed to evaluate various funding schemes for renewable projects in Cyprus by Theodorou et al. [63].

Another line of AHP literature, within energy sector, looks at the modelling of decision issues with a specific technology [42] [64][65][66][67][68][69][70][71][72].

Brudermann et al. [64] developed an AHP model to rank factors related to continuance of biogas power plants in Austria using expert judgment. A study by Tahri et al. [65] combined GIS with AHP to find the best location for developing solar power farms in Morocco. Likewise, Sánchez-Lozano et al. [66], integrated AHP and TOPSIS for solar farm siting. In their integration, the analysis and calculation of the weights of the criteria were found using AHP while the assessment of the alternatives was performed by employing the TOPSIS method. Similar in approach to Tahri et al. [65] of using GIS and AHP, Zubaryeva et al. [70] developed an information system for decision-makers for identifying regional clusters of biogas in Apulia Region of Italy.

Nixon et al. [67] utilized AHP to select an optimal solar thermal collection technology for the north-west of India while Aragonés-Beltrán et al. [68] proposed a combination of an AHP/ANP (analytic network process) model to support concentrated solar power (CSP) companies in Spain in project selection.

Shirgholami et al.[42] used AHP to support decision-makers in selecting wind turbines while Gumus et al. [69] combined AHP and GRA to select the best method to store hydrogen energy. Kumar and Singal [71] applied AHP as one of the methods for selecting the best material for civil works for small hydropower installations while Singh and Nachtnebel [72] used a survey to experts to bring forth the factors effecting hydropower development and subsequently ranking various future hydropower projects in Nepal.

It can be inferred from the literature that AHP applications focus on countries and regions. This focus is quite logical as each country/region has its own specific conditions. For the technologies, it can be inferred that renewable technologies are given more attention than non-renewable ones. Finally, AHP has been combined with other methods either for optimization purpose or for comparing methods. However, multi-method approaches have not been able to bring forth any significant reason for using different methods to complement AHP (for example, see the study by Theodorou [63]). Therefore, in this research, we focus on the first two inferences from the literature review.

4. AHP model development

4.1. AHP method requirements

As mentioned previously the AHP approach to MCDA is adopted for this study. The reason for following this approach is that: (i) a complex problem can be decomposed into a manageable hierarchy; (ii) pair-wise comparisons at each level ensure a thorough investigation, and, (iii) a single decision output can be obtained.

The details of AHP model development are well documented in [27][73][74]. Nevertheless the process is summarized below in four steps.

STEP 1. Structure a problem as a hierarchy with the goal of model at the top.
STEP 2. Elicit and represent judgments with meaningful numbers.
STEP 3. Synthesize results at all levels of the hierarchy
STEP 4. Analyze sensitivity to changes in judgments

4.2. Developing AHP model

The goal of the decision problem being modelled in this study is to rank the appropriateness of various renewable resources and uranium for electricity generation in Kazakhstan. The four criteria identified are technical, economic, social and environmental and are such that a multi-perspective evaluation of a particular resource can be performed. These criteria conform to the 2013 Government of Kazakhstan's 'National Concept for Transition to a Green Economy up to 2050' plan [15].The model is augmented by thirteen sub-criteria, each having a direct influence on ranking process. The multi-criteria parameters are supported by the literature. A description of assessment criteria, sub-criteria and literature sources are provided in Table 2.

The hierarchy of the model formulated is in four levels. In this current study, the top level consists of the objective of the study followed by the 4 primary criteria at level two. Each criterion is further expanded into sub-criteria at level three. The final (fourth) level consists of the alternative technologies that are to be evaluated. Fig. 5 shows the detailed structure of the AHP model used for this research. This concludes the STEP 1 of AHP model development process.

To perform STEP 2, a questionnaire was developed to obtain experts' pairwise comparison of criteria, sub-criteria and alternatives. Saaty [32] recommends a linear nine point scale for pairwise comparison. However, in this study, a constant sum approach proposed by Amer and Daim [43] is used. In this approach 100 points are distributed between pairs for comparison. The main advantage of using 100 points is that it frees expert from limiting to nine point scale thus giving a more focused comparison. This approach has been used previously by Amer and Daim [43]. Details of 13 experts/respondents participating in this study can be found in Appendix A1. Once the experts' pair-wise comparisons are collected, they are put into a formal format using MS EXCEL thereby completing STEP 2.

Since a group decision modelling approach is adopted in this research, following Basak and Saaty [73] and Malik et al. [74],a geometric mean is used for combining individual expert's pair-wise comparisons for all four hierarchy levels. In calculating the priority weights at criteria and sub-criteria level, the most widely used method of Eigenvectors is employed [81]. All the computational process involved in STEP 3 and STEP 4 are performed using an open source software package called PriEst (Priority Estimation Tool). Details of the package and its capabilities can be found in [82].

5. AHP model results and discussion

Pair-wise comparisons are made at each level of the model shown in Fig. 5. Table 3 shows the geometric mean value of the pair-wise comparison performed by the experts for the criteria with respect to the goal. The next step is to define the relative priorities of criteria (the final column of Table 3) by computing 'priority weights. Saaty's [32] 'consistency principle' is employed for calculating priority weights. According to this principle, the level of inconsistency in the comparison, measured by consistency ratio (CR), is required to be less than 0.10.

The assessment model indicates economic and technical aspects to be the most important criteria; the relative weight of each criterion is 0.344 and 0.242, respectively. The environmental aspect is found to be the third most important criteria while social aspect is treated as the least important one by the experts. The latter two criteria are having priority weights of 0.214 and 0.20, respectively. The relative weights of the criteria with respect to goal are shown in Fig. 6.

To develop a better understanding of the priorities reported in Table 3, a pair-wise comparison of the sub-criteria within each criteria, based on the consensus responses of the experts' opinion, is performed (Tables 4–7). Table 4 gives the priority listing for the three Economic (ECO) sub-criteria. The Capital Cost (ECO1) is heavily favored (0.460) over the other two; operational cost (ECO2) and financial support (ECO3) rated at 0.293 and 0.247, respectively. Similarly, within the Technical (TEC) sub-criteria resource availability (TEC4) is considered the most important having a priority of 0.273 while grid connectivity (TEC5) is considered least (Table 5). Table 6 shows that consensus among experts is to rate ENV2 being the most important sub-criteria. Finally, for the social (SOC) criterion, the experts rated (public acceptance (SOC2) at 0.654 over job creation (SOC1). Table 7 shows the priority weights of social sub-criterion comparison.
Further analysis can be performed for each sub-criteria with respect to the goal of the study. This step develops the overall priority of the 13 sub-criteria. The priority weights of the sub-criteria with respect to the goal are depicted in Fig.7.

Capital cost under the economic criterion has the highest importance of 15.8% followed by job creation at 12.9%. It is quite understandable that capital cost was awarded the highest priority because investments in the energy sector are capital intensive. However, job creation being the second most important sub-criterion is a bit unusual, particularly in comparison to previous studies carried out for other countries, e.g. Amer and Daim[43] and Ahmad and Tahar [27]. One possible explanation could be that the electricity sector in Kazakhstan is publically owned thus creating jobs through investments in power sector may be an important criterion for the government.

From the technical perspective resource availability is found to be the most important sub-criteria. This inclination of resource availability over other technical aspects indicates the risk aversive behavior with respect to newer technologies. Within the technical criterion grid-connectivity was identified as the least important to experts. The network is currently aged and inefficient and one possible explanation for this preference could be the confidence felt by experts in the modernization of the transmission and distribution network which is currently being undertaken [10]. On the environmental side, the impact on environment is considered crucial in comparison to the CO_2 emission reduction capability and land requirement sub-criteria.

The most extensive pair-wise comparison is performed at the alternative level of the model. At this level each alternative is compared with each sub-criteria. Table 8 shows the pairwise comparison of each alternative with respect to Technical maturity.
Appendix A2 shows priority weights of each alternative with respect to sub-criterion.

All the pair-wise comparisons made at each level in this study are found to be consistent except one, the pair-wise comparison for capital-cost at alternative level of the model. The consistency of this comparison is improved by following the work carried out by Zeshui and Cuiping [83]. Appendix A3 shows the process performed in detail.

The final ranking of the resources matrix calculations performed by PriEsT is defined by Equation 1.

$$\begin{bmatrix} priority\ weight \\ of\ five\ \ alternatives \\ with\ respect\ to \\ criteria \end{bmatrix} * \begin{bmatrix} priority\ weight \\ of\ criteria \\ with\ respect\ to \\ goal \end{bmatrix} = \begin{bmatrix} priority \\ weight\ of \\ each\ alternative \end{bmatrix} \quad (1)$$

Equation 2 shows the corresponding matrix calculation.

$$\begin{bmatrix} 0.189 & 0.208 & 0.379 & 0.254 \\ 0.229 & 0.264 & 0.149 & 0.216 \\ 0.131 & 0.130 & 0.127 & 0.146 \\ 0.199 & 0.250 & 0.149 & 0.223 \\ 0.253 & 0.148 & 0.196 & 0.161 \end{bmatrix} * \begin{bmatrix} 0.242 \\ 0.344 \\ 0.200 \\ 0.214 \end{bmatrix} = \begin{bmatrix} 0.247 \\ 0.222 \\ 0.133 \\ 0.212 \\ 0.186 \end{bmatrix} \quad (2)$$

The AHP model output ranks hydro above other four alternatives considered, followed by solar power. The priority weight of hydro is 0.246 followed by 0.222 for solar, and 0.212 for wind. The least preferred resources are nuclear and biomass, with priority weights of 0.186 and 0.133, respectively. The ranking of the five resources assessed with respect to the objective of the study is shown in Fig. 8. Hydro outranks other resources on the basis of its higher public acceptance, greater job creation potential, and better emission reduction capability.

Further analysis reveals that none of five resources under evaluation perform equally on all criteria. Hydro is more inclined towards social criteria while nuclear tends towards technical ones and solar performs better on economic criteria. In comparison to all five resources considered, biomass scores the least on all four assessment criteria. This situation is depicted in Fig. 9.

Our results corroborate with earlier findings from Karatayev and Clark [16] which ranked solar and wind higher than biomass for Kazakhstan.

6. Sensitivity Analysis

Sensitivity analysis is used to highlight any minor variation in experts' preferences that might change the end result of the AHP model. In this research, the sensitivity analysis is performed on each criteria by changing its priority weight. In each scenario, only one criterion is set as important (0.5 weighting) while others are kept constant (0.1667). The priority weights used are shown in Table 9.

The output of each scenario is shown in Table 10 with priority weights for the five resources under evaluation; the resources are ranked by their priority weights accordingly. Sensitivity analysis suggests that as there is no significant change in the main findings thus it seems inconsequential to change model parameters. Hydro power is ranked highest followed by solar. Wind and nuclear are next in line, ranking third and fourth respectively, while for each scenario biomass is least favoured.

7. Summary and conclusions

Kazakhstan relies heavily on fossil fuels for meeting its electricity demand. Though hydro power technology is a major source of renewable-based electricity generation, the overall share of renewables is still relatively small. It is expected that government plans for economic development is going to raise electricity demand in future, emphasizing the need to find a sustainable electricity generation option for Kazakhstan reliant on indigenous renewable resources. Thus, in this study, first an overview of various renewable resources is presented for the country, confirming that are sufficient resources available. A multi-criteria analysis approach is then selected for ranking four renewable technologies along with a nuclear option for electricity generation. The model framework consisted of appraisal criteria and sub-criteria based on Kazakhstan's policies regarding the future composition of the country's energy sector and relevant literature.

The model results show that capital and operational cost are the most important sub-criteria under economic criteria whereas potential of job creation is the most important one under the social criterion. The emphasis on these two criteria and subsequent sub-criteria, demonstrates that financial and social concerns are more important in comparison to technological and environmental aspects in the country. Of the 5 alternatives considered, in terms of overall benefits, hydropower and solar emerged as the preferred options over wind and nuclear while caution is advised regarding biomass as a sustainable option. Although nuclear power ranks higher than wind under social scenario, at the higher level of hierarchy, environmental concerns are found to be more important than the social criteria. Thus, it is proposed that the Kazak government should emphasize the development of hydro, solar and wind technologies while nuclear and biomass should be delayed.

Hydrocarbon wealth plays a major role in Kazakhstan economy. By conserving this resource and by diversifying the fuel-mix for electricity generation, the sustainability of sovereign wealth can be ensured. This research provides planners and decision-makers with a tool to assist their decision-making in a structured and strategic way in diversifying the technology-mix for electricity production before unsustainable solution becomes locked in.

Though the results are specific to Kazakhstan and may not be applicable globally, inferences could be used for argumentation purposes for future energy policy development, especially for developing countries. Additionally this research did not differentiate between different groups of decision-makers. Future research will consider expanding the stakeholders groups (e.g., academics, general public, government officials, and utility managers), allowing them to independently assign weights to the four evaluation criteria. Finally it would be possible to augment the model with emerging technologies like solar-thermal or micro-hydro technologies.

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Appendix

A1. List of experts' affiliation

1. Zhambyl Hydro Power Station, Zhambyl Kazakhstan
2. Energy of Semirechie Almaty, Kazakhstan
3. First Wind Electrical Station, Astana, PVES
4. East Kazakhstan Regional Energy Company, EKO
5. TOO Samruk Green Energy, Almaty
6. AO Balkhash thermoelectric power station
7. AO Shulbin Hydro Power station, Ustkamenogorsk
8. AO Mangistau Regional Electrical Company
9. AO Almaty Electrical Stations
10. AO Nuclear Technologies Park
11. Institute of Nuclear PfAthysics
12. AO Shardara Hydro Power Station

A2. Priority weights of alternatives at level four

Table A2.1. Priority weights of alternatives with respect to sub-criteria

	Technical					**Economic**		
	TEC1	TEC2	TEC3	TEC4	TEC5	ECO1	ECO2	ECO3
Hydro	0.174	0.296	0.109	0.128	0.272	0.184	0.271	0.176
Solar	0.154	0.136	0.315	0.303	0.23	0.219	0.266	0.345
Biomass	0.073	0.079	0.161	0.212	0.095	0.16	0.15	0.052
Wind	0.148	0.162	0.265	0.225	0.196	0.251	0.224	0.28
Nuclear	0.451	0.328	0.151	0.133	0.208	0.186	0.089	0.148

Table A2.2. Priority weights of alternatives with respect to sub-criteria

	Environmental			**Social**	
	ENV1	ENV2	ENV3	SOC1	SOC2
Hydro	0.389	0.374	0.263	0.218	0.322
Solar	0.218	0.113	0.166	0.285	0.142
Biomass	0.075	0.154	0.167	0.139	0.124
Wind	0.202	0.121	0.238	0.256	0.12
Nuclear	0.116	0.239	0.165	0.102	0.292

A3. Improving pairwise inconsistency

Algorithm I, developed by Zeshui and Cuiping [83], is used for modifying an inconsistent comparison matrix. This algorithm is chosen due to its simplicity in comparison to one developed by [84].

Original capital-cost comparison matrix (A) for alternatives

$$A = \begin{bmatrix} 1 & 1.273 & 0.755 & 0.850 & 1.571 \\ 0.786 & 1 & 1.594 & 0.942 & 2.533 \\ 1.325 & 0.627 & 1 & 1.051 & 0.311 \\ 1.176 & 1.062 & 0.952 & 1 & 1.088 \\ 0.637 & 0.395 & 3.212 & 0.919 & 1 \end{bmatrix}$$

For this matrix, the maximum eigenvalue, $\lambda_{max}(A)$ and CR, and the principal right eigen vector $w = (w_1 \ldots w_i \ldots w_n)^T$ are:

$\lambda_{max}(A) = 5.472$; CR = 0.106>0.1, $w = (0.203\ 0.206\ 0.155\ 0.194\ 0.202)^T$

Modified capital-cost comparison matrix, $A^{(m)}$ for alternatives using the following,

$$a_{ij}^{(m)} = (a_{ij})^{\lambda} \left(\frac{w_i}{w_j}\right)^{1-\lambda}$$

with$\lambda = 0.1$ and one iteration of algorithm only.

$$A^{(m)} = \begin{bmatrix} 1 & 0.878 & 1.085 & 0.724 & 1.026 \\ 1.139 & 1 & 1.365 & 0.853 & 1.255 \\ 0.922 & 0.733 & 1 & 0.662 & 0.781 \\ 1.381 & 1.172 & 1.511 & 1 & 1.345 \\ 0.975 & 0.797 & 1.28 & 0.743 & 1 \end{bmatrix}$$

$\lambda_{max}(A^{(m)}) = 5.005$, CR = 0.001<0.1, $w^{(m)} = (0.184\ 0.219\ 0.160\ 0.251\ 0.186)^T$

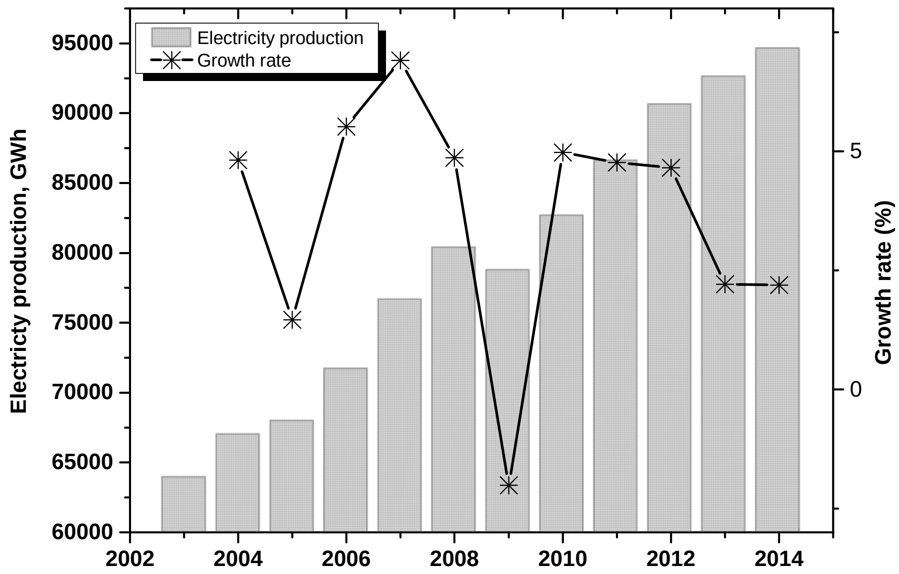

Fig. 1. Annual electricity production and growth rate of Kazakhstan
Data source. www.stat.gov.kz

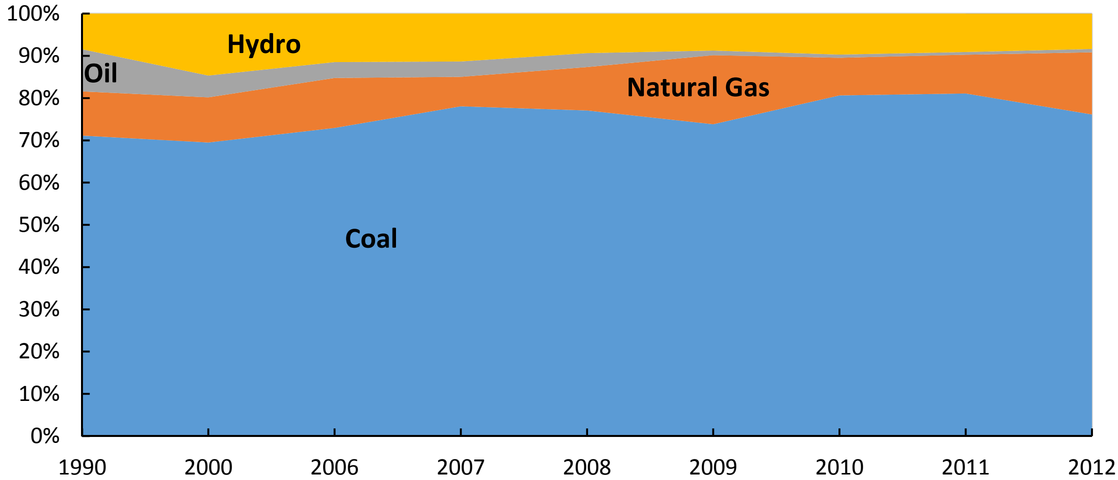

Fig. 2. Fuel-mix for electricity generation for Kazakhstan

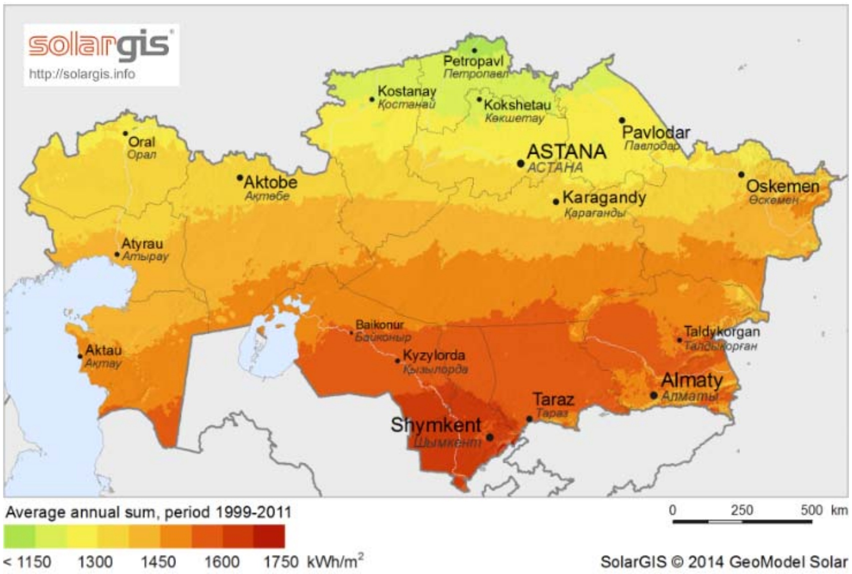

Fig. 3. Solar irradiation map of Kazakhstan

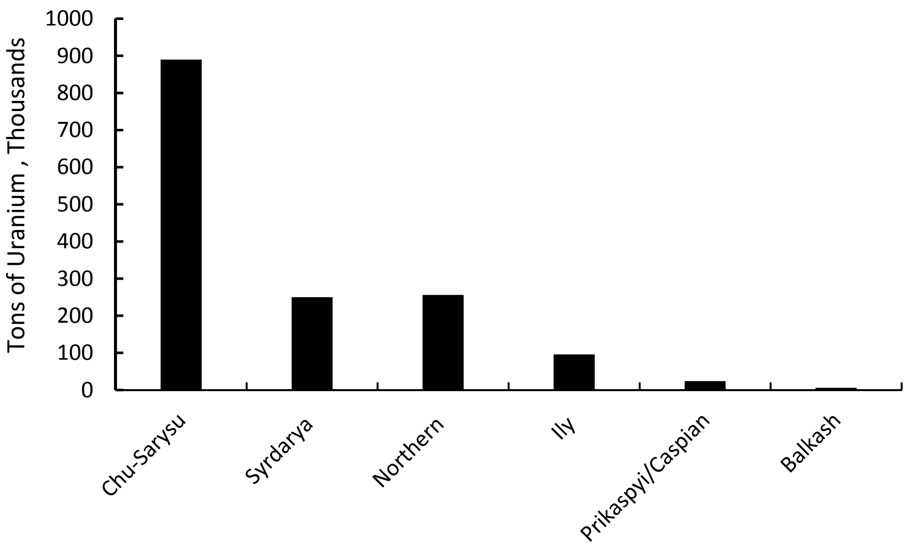

Fig. 4. Region-wise Uranium reserves.
Data Source World Nuclear Association[24]

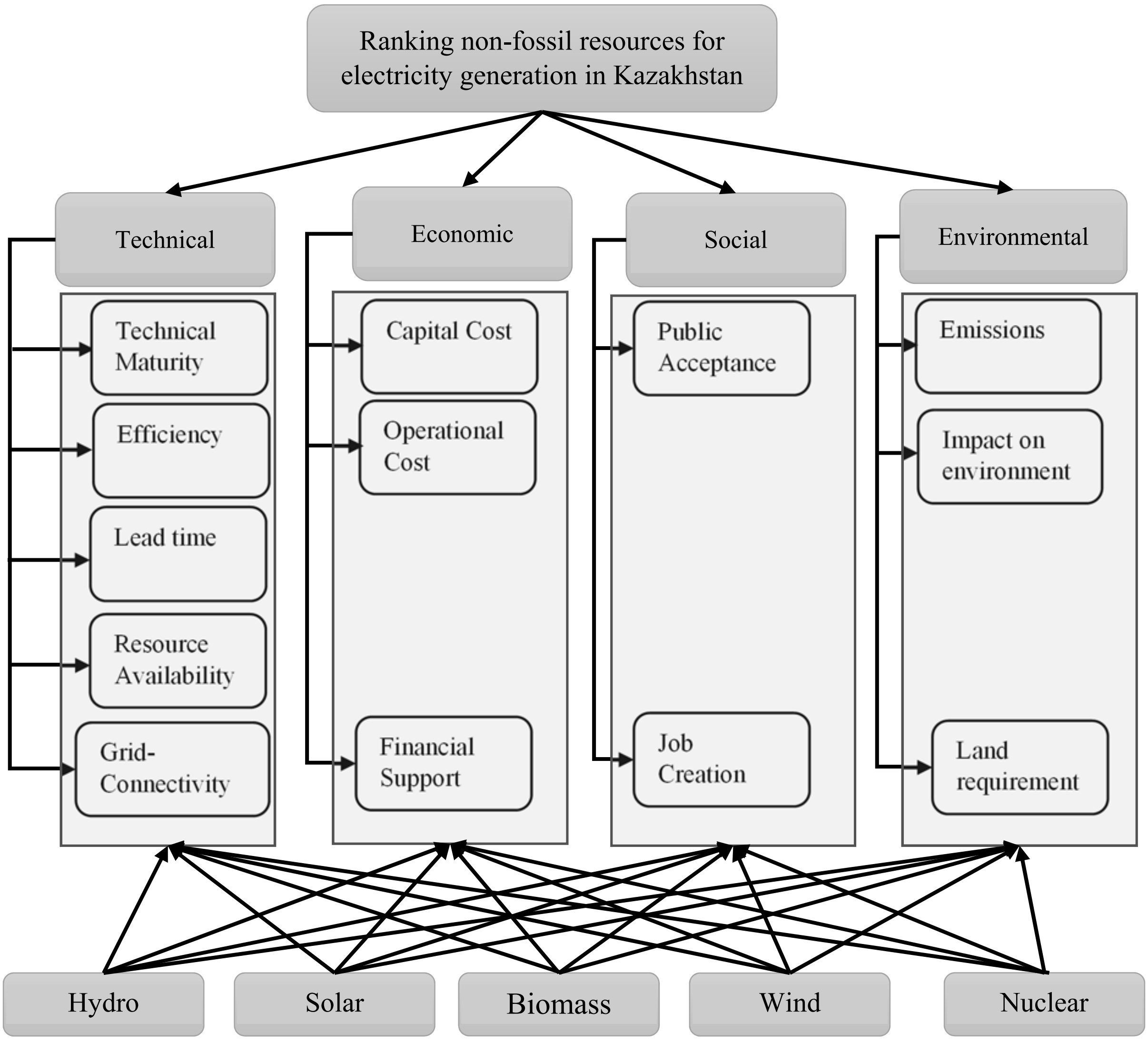

Fig. 5. The AHP model for ranking resources.

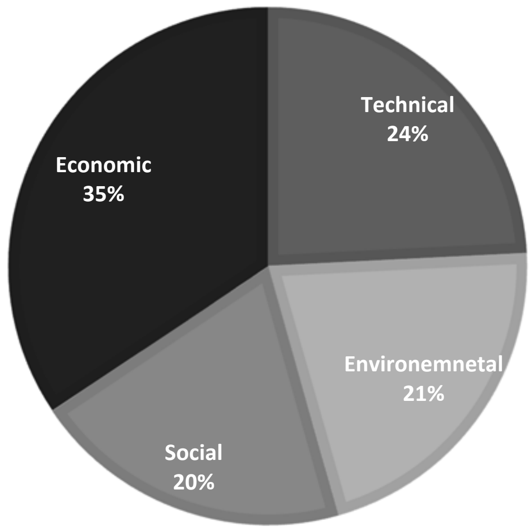

Fig. 6. Relative priority of criteria with respect to goal.

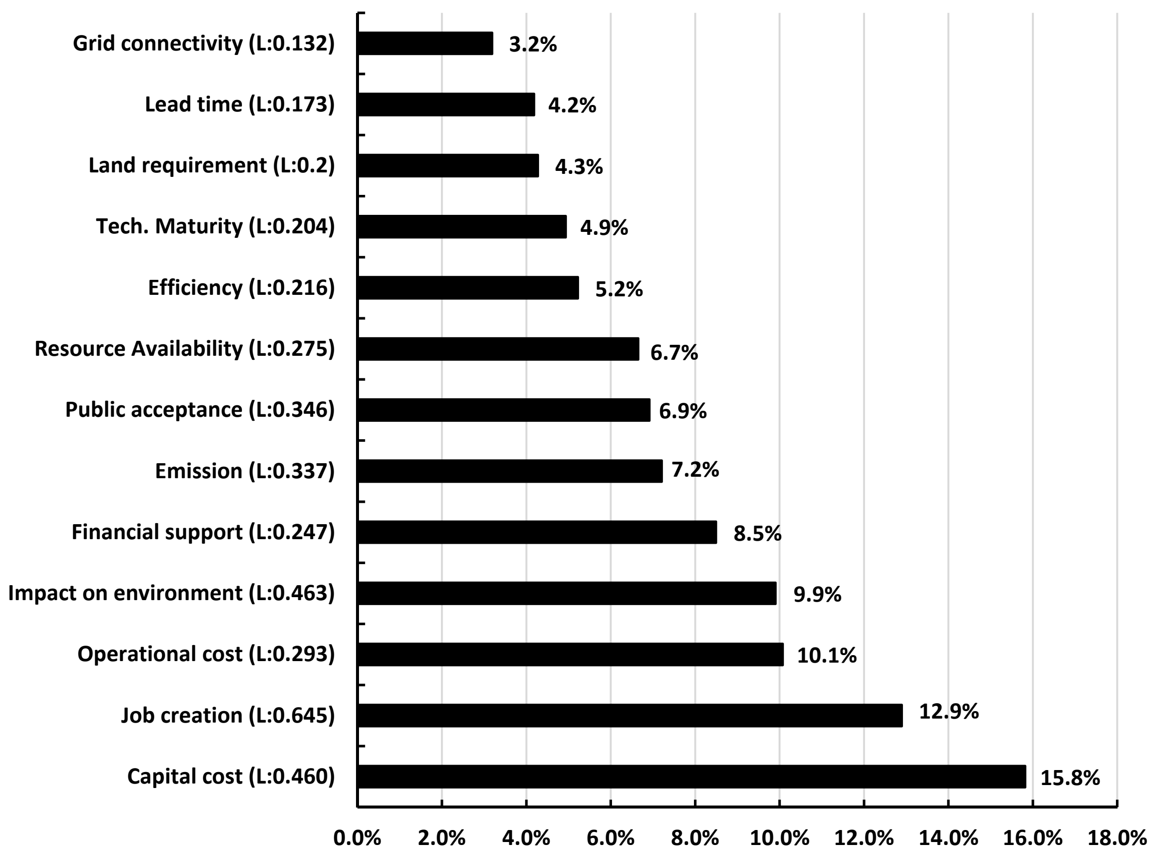

Fig. 7. Priority of sub-criteria with respect to goal.

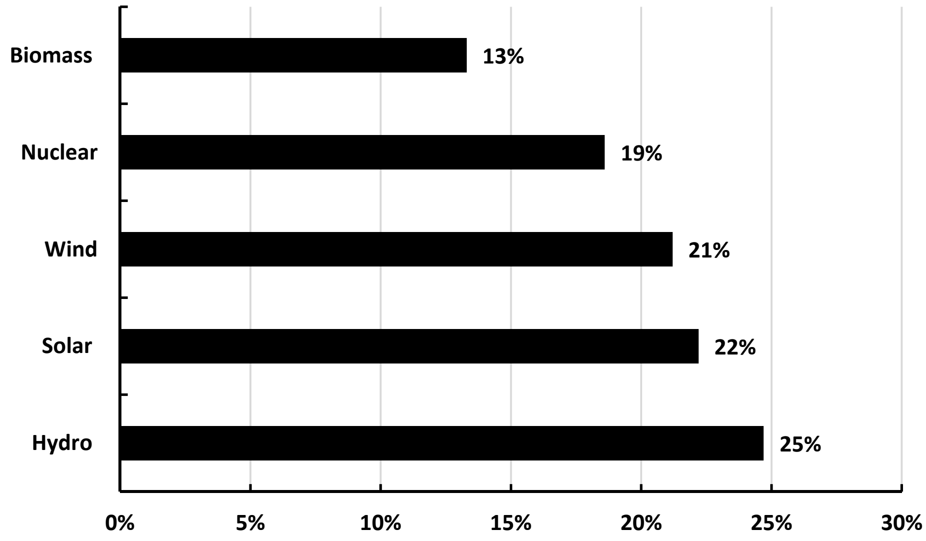

Fig. 8. Ranking based on priority weight with respect to goal.

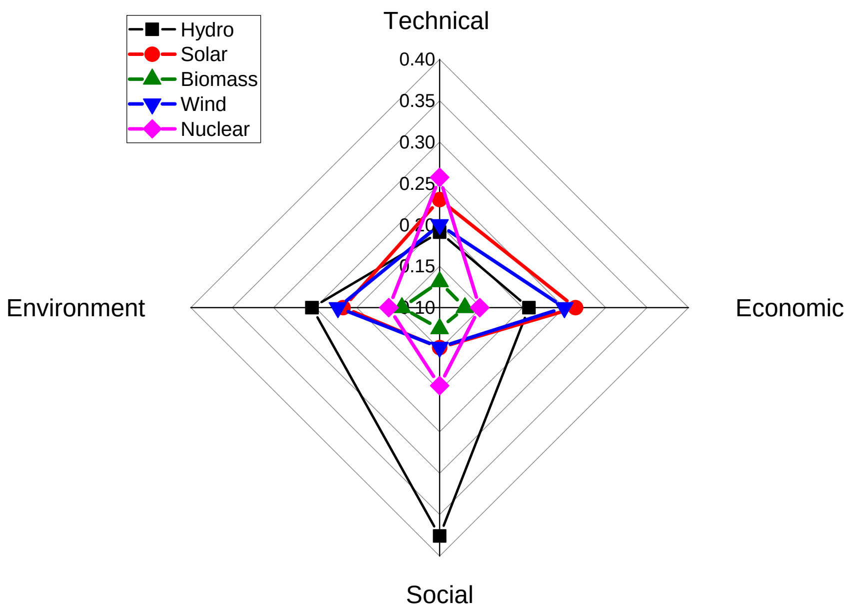

Fig. 9. Performance of resources with respect to criteria.

Table. 1. Major hydro resources and corresponding regions

Regions	Main Rivers
Irtysh River basin	Bukhtarma, Uba, Ulba, Kurchum, Kardzhil
South-Eastern zone	Ili River
Southern zone	Syrdaria, Talas, Chu

Table 2. Criteria and sub-criteria used in evaluating resources for electricity generation.

Criteria	Sub-criteria		Description	Reference
Technical **(TEC)**	Technology maturity	**TEC1**	Technology that is commercially available	[26][27][40][43] [51] [53] [58] [63][75]
	Efficiency	**TEC2**	Alternative with better technical efficiency is considered	[26][27][30][40]
	Lead time	**TEC3**	Time elapsed between planning decision to commissioning of power plant	[26][27][76]
	Resource availability	**TEC4**	Availability of locally procured fuel	[27][55] [76][77]
	Grid connectivity	**TEC5**	Ease of access to transmission grid	Own
Economic **(ECO)**	Capital cost	**ECO1**	Cost of power plant and ancillary equipment	[26] [30][40] [50] [55] [78]
	Operation cost	**ECO2**	Cost incurred in production of electricity and maintenance	[26] [27][30][40] [55][78]
	Financial support	**ECO3**	Financial subsidies to producers	[27]

Social **(SOC)**	Public acceptance	**SOC1**	Public attitude towards each technology	[26] [27] [40] [43] [50] [55][78] [79]
	Job creation	**SOC2**	Potential of each technology for creating new jobs	[26] [27] [30][40] [43] [55][78] [79][80]
Environmental **(ENV)**	Emissions	**ENV1**	capability of each technology to reduce GHG emissions	[27][40][50][75][78]
	Impact on environment	**ENV2**	Extent of impact of each technology on the visual and biodiversity of the area	[27][43][51][78]
	Land requirement	**ENV3**	Area of land required	[27][40] [55][75][78] [79]

Table 3. Pair-wise comparison matrix of criteria with respect to goal along with priority weight.

	Technical (TEC)	**Economic (ECO)**	**Social (SOC)**	**Environmental (ENV)**	**Priority weight**
Technical (TEC)	1	0.61	1.44	1.1	0.242
Economic (ECO)	1.639	1	1.79	1.35	0.344
Social (SOC)	0.694	0.559	1	1.14	0.200
Environmental (ENV)	0.909	0.741	0.877	1	0.214
				CR = 0.011	<**0.10**(Acceptable)

Table 4. Pair-wise comparison matrix of Economic sub-criteria.

	ECO1	**ECO2**	**ECO2**	**Priority weight**
ECO1	1	2.06	1.42	0.460
ECO2	0.485	1	1.55	0.293
ECO3	0.704	0.645	1	0.247
			CR = 0.063	<**0.10**(Acceptable)

Table 5. Pair-wise comparison matrix of Technical sub-criteria.

	TEC1	TEC2	TEC3	TEC4	TEC5	Priority weight
TEC1	1	0.91	1.34	0.77	1.44	0.204
TEC2	1.099	1	1.61	0.73	1.35	0.216
TEC3	0.746	0.621	1	0.91	1.26	0.173
TEC4	1.299	1.37	1.099	1	2.79	0.275
TEC5	0.694	0.741	0.794	0.358	1	0.132
					CR = 0.016	**<0.10**(Acceptable)

Table 6. Pair-wise comparison matrix of Environmental sub-criteria.

	ENV1	ENV2	ENV3	Priority weight
ENV1	1	0.83	1.48	0.337
ENV2	1.205	1	2.65	0.463
ENV3	0.676	0.377	1	0.200
			CR = 0.015	**<0.10**(Acceptable)

Table 7. Pair-wise comparison matrix of Social sub-criteria

	SOC1	SOC2	Priority weight
SOC1	1	0.53	0.346
SOC2	1.887	1	0.654
		CR = 0.000	**<0.10**(Acceptable)

Table 8. Pair-wise comparison matrix of alternative with respect to Technical maturity.

	Hydro	Solar	Biomass	Wind	Nuclear	Priority weight
Hydro	1	0.133	1.54	1.2	0.48	0.172
Solar	0.752	1	2.49	1.18	0.31	0.154
Biomass	0.649	0.402	1	0.38	0.15	0.072
Wind	0.833	0.847	2.632	1	0.30	0.148
Nuclear	2.083	3.226	6.667	3.33	1	0.453
					CR = 0.018	**<0.10**(Acceptable)

Table 9. Criteria weights used for sensitivity analysis.

	Technical	Economic	Social	Environmental
I Scenario Technical	0.500	0.1667	0.1667	0.1667
II Scenario Economic	0.1667	0.500	0.1667	0.1667
III Scenario Social	0.1667	0.1667	0.500	0.1667
IV Scenario Environmental	0.1667	0.1667	0.1667	0.500

Table 10. Various resources priority weights with corresponding rankings

		Hydro	Solar	Biomass	Wind	Nuclear
I Scenario	Priority weight	0.235	0.220	0.133	.2014	0.213
Technical	**Rank**	**1**	**2**	**5**	**3**	**4**
II Scenario	Priority weight	0.241	0.231	0.132	0.220	0.176
Economic	**Rank**	**1**	**2**	**5**	**3**	**4**
III Scenario	Priority weight	0.297	0.193	0.131	0.186	0.192
Social	**Rank**	**1**	**2**	**5**	**4**	**3**
IV Scenario	Priority weight	0.256	0.215	0.137	0.211	0.181
Environmental	**Rank**	**1**	**2**	**5**	**3**	**4**