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Original article

Sustainable electricity generation mix for Iran: A fuzzy analytic network process approach

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ABSTRACT

Electricity supply in Iran has been heavily dependent on fossil fuels. In light of the government's emphasis on reducing the consumption of conventional energy sources, combined with the worldwide attention to environmental issues, it is necessary for Iran to revise its current energy mix policy in power sector and move towards a more diversified energy portfolio. This paper aims to contribute to energy management studies through developing a new framework for assessing the mix of energy sources for producing electricity in Iran from the perspective of sustainable development. Multiple qualitative and quantitative criteria with conflicting nature need to be taken into consideration for evaluating competing energy options for electricity production in Iran. In order to address this issue and also to consider the complex interdependence among criteria and alternatives, this paper adopts a fuzzy analytic network process (FANP) method. Seven criteria and nineteen sub-criteria are defined and structured in the form of benefits, opportunities, costs and risks (BOCR) to evaluate the share of six energy resources. The results indicate that the best energy mix for the power sector in Iran is as follows: renewable energies (31.6%), natural gas (25%), coal (12.3%), fuel oil (12.6%), nuclear (8.7%) and gas oil (9.7%).

Introduction

During the last 60 years, the global population has grown by the factor of 2.5, whereas the global primary energy consumption has increased by a factor of 4.5 [9]. Also, the worldwide demand for energy is expected to increase even more over the next 30 years [23]. A short glance at the world's energy architecture reveals that fossil fuels have remained as the dominant sources of electricity generation. The extensive consumption of fossil fuels has had negative global consequences such as climate change, depletion of fossil energy resources, and environmental pollution. In this sense, electricity sector has been the focal point in mitigating these issues mainly for two reasons [105]: first, electricity sector, especially in developing countries, is often highly carbon-intensive and is considered as a major source of greenhouse gas emissions. Therefore, moving towards generating electricity in lower carbon intensity units is a highly effective emission reduction strategy. Second, electricity sector is a relatively easy target for mitigating environmental effects because it is a large and concentrated sector.

In order to achieve long-term sustainable development and energy security, it is imperative for all the countries to diversify their energy portfolio and seek for exploiting a combination of various energy sources for generating electricity [53]; [109]. In fact, each source of energy has its own advantages and disadvantages and, as expressed by Li [53, p. 2240], "the dominance of a single energy source and system, no matter how "perfect" it might be at a time, would be unsustainable in the long run."

In this context, due to the large population and rapid economic growth of developing countries, their patterns of energy production and consumption might considerably affect the overall global energy consumption and environmental concerns. As a rapidly-growing developing country, Iran's energy demand is continuously increasing. The consumption of primary energy in Iran has grown by almost 50% since 2004 and it is expected that in the coming decades this figure would continue to grow at a rate of approximately 6% per year [22]. According to the latest Iran energy balance sheet in 2013, about 92% of electricity has been generated in fossil fuel based power plants [36]. It is estimated that by maintaining the current trend of electricity generation, the demand of power sector for fuel would be more than doubled over a 30 years period [7]. In order to address twine challenges of long-term energy security and environmental sustainability in the next decades, it is of crucial importance for Iran to revise its energy

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policy and ensure its energy security by reducing the dependence on fossil fuels. In this line, Iranian government is planning to gradually decarbonize the country's electricity generation mix and shift to a more diverse portfolio of clean, reliable and renewable sources of energy [58].

In view of the above discussion, the purpose of current research is to propose a comprehensive decision-making framework for evaluating alternative energy sources for supplying electricity in Iran and determining the best energy mix according to different aspects of sustainable development. A sustainable approach to energy planning requires a solution that simultaneously addresses multiple and potentially conflicting objectives such as economic viability, social acceptability and environmental protection [48]. The necessity of incorporating multiple inter-related goals and criteria from different perspectives in energy planning of Iran makes multi-criteria decision making (MCDM) approach as the preferred assessment method for this study. This approach is suitable for analyzing complex problems that involve high degrees of uncertainty, conflicting goals and criteria, as well as multiple actors with diverse interests. This study proposes a fuzzy group analytic network process (ANP) framework to assess the potential benefits, opportunities, costs and risks associated with exploiting different sources of energy for generating electricity in Iran.

The remainder of this paper is organized as follow: in Section "Energy status of Iran", energy status of Iran and the challenges in energy supply are described. Section "Electricity generation in Iran", outlines the electricity production and consumption in Iran. Following this, ANP and its fuzzy extension are briefly explained in Section "Literature review". In section "Methodology", the steps of the proposed BOCR–fuzzy ANP model are explained. Finally, conclusions and avenues for future research are presented in Section "Proposed fuzzy ANP model".

Energy status of Iran

Iran is the second-largest economy in the Middle East and North Africa, and also is ranked as the second most populous country in this region [101]. Compared with other oil producers in Middle East, the economy of Iran is more diversified; however, oil and gas still remain the major source of government revenues [93]. Iran has the third largest crude oil (approximately 10% of the global crude oil reserves), and second largest proved gas reserves in the world (17% of the world's reserves) [22,74]. With this huge hydrocarbon reserves, the current oil and gas production levels of Iran are well below its maximum potential. Therefore, Iran has a huge potential to increase its outputs massively [67].

The consumption of primary energy in Iran has grown by almost 50% since 2004 and is continuing to increase each year [102]. It is estimated that the energy demand in Iran continue to grow for the coming decades [22]. Iran has the highest primary energy consumption in Middle East. With the energy intensity about 2.5 times the Middle East's average, Iran is considered as the most energy intensive country in this region, and one of the world's most energy inefficient countries [67,100]. In 2013, about 244 million tons oil equivalent of primary energy was consumed in Iran, of which more than 98% came from natural gas and oil [22]. The highest energy consumption sectors in Iran are residential and power plant, which together consumes half of total country's energy [59].

Iran's energy sector has been profoundly affected by the broad range of international sanctions, which have led to a substantial decline in oil and gas production over the past few years. In the energy sector, not only sanctions slowed the progress of projects, but also it affected the investment in upstream in oil and gas projects [21]. International sanctions and inappropriate investment terms are among the important barriers to developments in the energy sector of Iran.

Electricity generation in Iran

Along with its fast-growing population and economy, production and consumption of electricity in Iran have rapidly grown recent years. By producing 239.2 billion kWh, and consuming 195.3 billion kWh, Iran is ranked 17th in the world in terms of electricity production, and 21st with regards to electricity consumption [19]. Studies on forecasting future electricity demand have shown that Iran's electricity consumption will continue to increase in the coming years [10,58]. Findings of recent studies suggest that Iran has the potential to add about 15,000–20,000 MW to its current electricity production capacity [57,66].

According to the latest energy balance sheet in 2013, more than 92% of electricity is generated in thermal power plants (consisting of steam turbine, combined cycle, gas turbine and diesel engine). The majority of electricity generated in thermal power plants, is produced by natural gas and oil (69% and 25% respectively). Only 8% of electricity is generated by renewable sources which are mainly produced from hydropower. Non-hydro renewables (e.g. wind, geothermal or solar) comprise less than 2% of produced electricity.

The extensive fossil fuels consumption in power plants has led to major challenges. Among other issues, Iran is now facing increasingly serious environmental problems. The CO_2 emissions from power plants have grown sixfold over the last three decades and currently, power plants account for almost one-third of the total CO_2 emissions [36,98]. These issues highlight the need to revisit the current carbon based electricity generation in Iran and to use more sustainable and clean sources of energy.

Although the contribution of nuclear and non-hydroelectric power is marginal for the time being, they are parts of the Iran's fourth development program and 20-year development outlook for meeting future electricity demand [67]. Iran aims to further develop its nuclear capabilities to produce 7000 MW of nuclear electricity over the next 20 years [102]. Also, by 2025, the Iranian government aims to increase the proportion of non-hydro renewable energy sources in its electricity generation mix to 10% [20].

Literature review

As a result of ever increasing demand for energy along with multitude of social, environmental, economic, and technological challenges that need to be considered for energy production and planning, decision makers are forced to use more and more complicated methods for energy planning.

The formal scholarly efforts to energy planning and identifying efficient supply options started after the oil crisis in 1970s [54]. The early studies on energy planning were mainly based on single objective decision making that were primarily oriented towards identifying the best energy supply options with maximum efficiency and minimum cost [62,86]. Although such traditional single objective models may be useful for studying a small system, they prove inefficient for studying complex systems that typically involve multiple objectives, criteria, and stakeholders [48].

From 1980s, scholars started turning their attention to the necessity of incorporating environmental factors in energy planning frameworks [69]. In order to address the trade-off between environmental and economic factors in energy planning, a group of studies employed optimization models based on multi-objective linear programming to evaluate and the decision alternatives [44,45,88]. For example, [63] developed a multi-objective energy allocation model that addresses different economic and environmental objectives and employed this model in the case of Lebanon. Also, Oliveira and Antunes [72] developed a multiple objective model to evaluate sustainable energy strategies based on economic, social and environmental considerations. More recently, San Cristóbal [87] developed a goal programming model to evaluate five different renewable energy plants for electric generation and their locations and determine the optimal mix.

The raising awareness about the importance of incorporating non-economic considerations, such as environmental and social factors, in energy planning gave rise to the growing use of multi criteria decision making (MCDM) methods in this field [76].

In complex decision making problems, it is often impossible to determine alternatives that maximizes all decision criteria and therefore, decision makers need to make rational compromises among available options [41]. MCDM techniques facilitate handling complex decision making problems that involve conflicting goals, and multiple actors with diverse opinions. Also, this approach allows for incorporating both quantitative and qualitative factors in decision making model [55].

MCDM techniques have found application in various areas such as management, engineering, science, and technology (for a review of MCDM applications see [55]). Specifically, in the field of energy management, MCDM techniques have been used extensively to solve problems related to energy portfolio, sustainability assessment, renewable energies, and climate change, among others [1]. Mardani et al. [56] identified 196 published papers from 1995 to 2015 related to the application of MCDM techniques for energy management problems. The main reason for the prevalence and popularity of MCDM techniques in energy planning is that these techniques enables the decision makers to take a holistic view and account for all the objectives and criteria concurrently to make the appropriate decision [48]. In their recent review of the application of multi-criteria techniques in sustainable energy planning, Kumar et al. [56, p. 598] suggest that MCDM techniques are the "most suitable methods of solving issues related to energy".

Pohekar and Ramachandran [76] reviewed more than 90 papers that employed MCDM methods for sustainable energy planning. They found that Analytical Hierarchy Process (AHP) has been the most commonly used method in the reviewed papers. The main reason for popularity of AHP is its flexibility and simple computational process [48,106]. However, AHP can only model the problems with a hierarchical structure, and cannot incorporate the interdependence among the criteria in the model. To address these shortcommings, few studies have employed a general form of AHP called Analytical Network Process (ANP) in their energy planning analysis. ANP is a powerful technique for modeling complex decision making problems with variety of interactions and dependencies among the decision criteria and alternatives. Although, due to the complexities in the computations of ANP analysis, its application is not as common as AHP, but its usage is growing in the energy planning literature. For example, Ulutaş [104] and Atmaca and Basar [8] presented ANP models for evaluation of the alternative energy sources for Turkey from different perspectives. In another study in Turkey, Köne and Büke [46] developed an ANP model to determine the best energy mix for electricity generation. [24] employed an ANP and BOCR approach for evaluating and selecting alternative fuels for residential heating. [73] incorporated the analytic network process (ANP) to compare the alternative energy resources for the manufacturing industry in Turkey. They concluded that fossil fuels are the best source of energy for studied industry. Kabak and Dağdeviren [38] employed a hybrid MCDM approach based on BOCR and ANP to compare and evaluate five renewable energy sources based on 19 criteria. Büyüközkan and Güleryüz [13] developed a hybrid MCDM approach based on DEMATEL and ANP to evaluate and rank the renewable energies in Turkey based on different perspectives.

Despite the broad usage of the conventional MCDM techniques, they have an important limitation in that they cannot effectively address the problems that involve imprecision, vagueness, and incomplete data [40,55]. If such uncertainties are not appropriately addressed in the analysis, the final results may not be reliable [32]. To cope with the subjective and uncertain human judgments, a growing body of studies suggested the use of a fuzzy extension of MCDM methods. In comparison with conventional approaches, fuzzy-logic based MCDM methods are better able to capture the decision makers' knowledge and tackle the uncertainty and inaccuracy associated with their judgment [43,50,55,107].

In recent years, scholars have increasingly focused on the use of fuzzy based models in energy planning (for an overview see Suganthi et al. [96] and Mardani et al. [56]). However, energy planning models based on fuzzy ANP have gained scant attention. To the best of our knowledge, only two papers have adopted fuzzy ANP in this area. [75] proposed a fuzzy ANP model based on Buckley's method for assessing five green energy alternatives with respect to technological, environmental and economical perspectives. In a more recent study, Büyüközkan and Güleryüz [14] proposed a hybrid MCDM model based on linguistic interval fuzzy preferences to select the most appropriate renewable energy resources in Turkey. They adopted DEMATEL-ANP approach to calculate the priorities of evaluation criteria and used TOPSIS to rank the alternative energy sources. They concluded that geothermal sources are the best renewable energy source for Turkey.

Methodology

The aim of this paper is to provide a novel and systematic model for evaluating energy sources for generating electricity from sustainable perspective and identifying the most appropriate mix of energies. As highlighted by Prasad et al. [77, p. 696] in their comprehensive review of the energy planning techniques, a reliable and an accurate energy model "must adequately map the real world system, provide a reliable formula that translates inputs (energy policies) into outputs (impacts), handle uncertainties in the energy planning term, and respond to the needs of the model users". Consistent with this suggestion, we argue that several underlying factors make the evaluation of energy mix challenging and, therefore, an effective model needs to take them into account. First, there are multiple qualitative and quantitative factors affecting the decision making that need to be considered in the model. Second, these factors are potentially conflicting and intertwined and cannot be treated as independent. Due to these interdependencies, the factors that individually less significant, may become more important when assessed collectively [4]. Third, multiple decision makers are involved in the process of energy planning and their diverse opinion needs to be taken into account in the model. Forth, the process of decision making often involves subjective judgments and comes with a degree of uncertainty. To address the above issues, we propose the use of a group fuzzy analytic network process (FANP) approach. FANP is a powerful MCDM technique for analyzing the models with multiple and potentially conflicting decision making attributes [81]. The proposed approach can incorporate the preferences of multiple decision makers and facilitate development of a consensus among them. Also, incorporating fuzzy theory with ANP enabled us to account for the uncertainty and inaccuracy associated with the decision maker's judgment. In the following section, the ANP method, and its fuzzy extension are briefly described.

Analytic network process (ANP)

ANP was proposed by [82] as a generalization of the analytic hierarchy process (AHP) [80], which is one of the most widely implemented MCDM methods. In the AHP, problem is formulated as a hierarchy with several levels. The basic assumption in the AHP is that decision elements in the hierarchy are independent. However, in the real world problems criteria and alternatives can be interrelated, and hierarchical structure cannot fully explain these problems. In such circumstance, the ANP approach can be utilized to deal with interdependent criteria. The aim of the ANP technique is to obtain the

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[1] For recent reviews of application of MCDM techniques in energy management problems and a discussion of pros and cons of each method see Kumar et al. [48] and Mardani et al. [56].

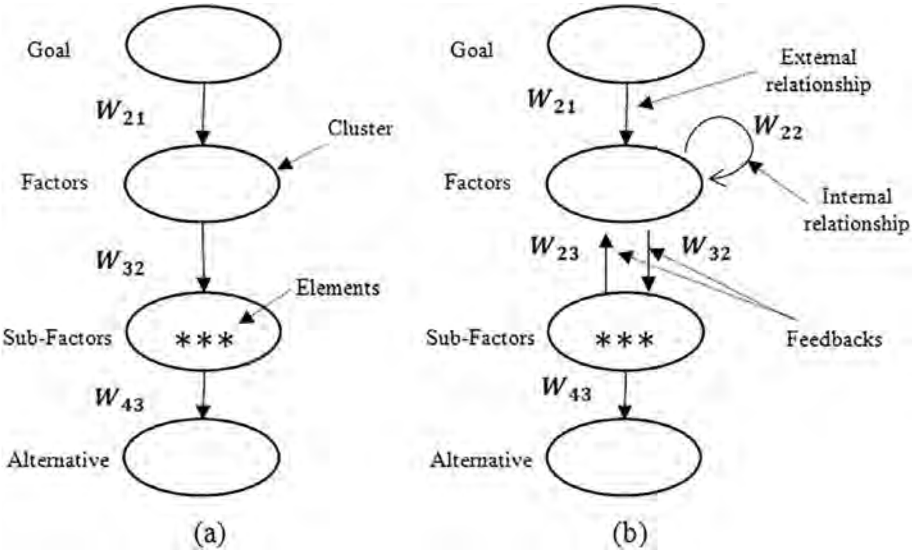

Fig. 1. ANP and AHP structure: (a) AHP; (b) ANP [89].

synthesized impact of all the decision making factors in conjunction with one another [83].

In order to address the shortcomings of hierarchal models, the ANP extends the AHP by replacing a hierarchy with a network. This allows for addressing more complex problems that involve interaction and feedback within and between clusters [61]. For example, not only the importance of the criteria may influence the weight of the alternatives, but also the importance of the alternatives determines the weight of the criteria [82]. Similar to the AHP, the weights of elements in ANP model are obtained based on decision makers’ judgments by conducting pairwise comparisons between each pair of criteria.

Fig. 1 depicts the difference between the structure of a network and a hierarchy model. Fig. 1(a) depicts an example of a hierarchical structure in which the interactions and feedback relations among clusters are ignored. Also, Fig. 1(b) shows a network model with four interdependent clusters.

Fuzzy ANP

In the conventional ANP, the decision makers’ judgments are represented by discrete numerical values of 1–9. Although this discrete scale is simple and easy to use, this approach had been criticized on the ground that it is not able to effectively cope with uncertainties and imprecisions inherent in experts' judgments [55]. In this research, we propose the use of a fuzzy based ANP to overcome these shortcomings and address the uncertainty and imprecision in the prioritization process. Utilizing fuzzy based modeling in energy planning studies has gained momentum in the past decade (for a review see Strantzali and Aravossis [94] and Suganthi et al. [96]). However, although conventional ANP has been adopted extensively in extant energy policy studies, relatively little research attention has been given to Fuzzy ANP in this domains (examples include [51,52] and Shafiee [90]).

The fuzzy set was first proposed by Zadeh [108] as a mathematical theory for modeling uncertainty in decision makings. Because of its resemblance to the way of human reasoning, fuzzy set theory is suitable for handling the inaccuracy and uncertainty associated with complex problems with multiple parameters. In this approach, instead of using exact numbers to describe the evaluations, decision makers are asked to express their opinion using natural language terms. These linguistic variables are then quantified and translated into numerical inputs using the fuzzy set theory.

In the fuzzy ANP (FANP), weights of elements in the model are obtained using linguistic variables represented by fuzzy numbers. In order to use Fuzzy ANP, one needs to adopt methods proposed for Fuzzy AHP and then extend them to networks. Different fuzzy AHP methods have been proposed in the literature (for a review see Kahraman et al. [43]). In this paper, Chang's extent analysis method is utilized to evaluate the pairwise comparisons and obtain the importance weights. For the complete details of this methodology, please refer to Chang [15,16].

Proposed fuzzy ANP model

Assessing the electricity generation mix represents a typical MCDM problem that involves multiple conflicting qualitative and quantitative criteria. In this study, a hybrid model based on BOCR (Benefits, Opportunities, Costs, and Risks) and FANP is reconstructed to select the best energy portfolio for electricity generation in Iran. For further details on the major steps of implementing fuzzy ANP, including technical information on the algorithms employed, refer to Tuzkaya and Onut [103]. The proposed model in this study is composed of eleven different steps as follows.

Step 1: Forming a group of experts and defining the problem

The proposed methodology requires expert judgments to calculate the importance of criteria and identify the share of alternative energy sources. For this research, we formed an expert panel consisting of ten highly informed experts in the field of energy management and planning. The “core experts” team comprised of six individuals who, at the time, were engaged in the energy planning and policy makings in Iran. This core expert team collaborated closely with the authors for identifying the criteria, validating the proposed model and evaluating and prioritizing the criteria and alternatives. Four of these experts were academicians whose main research area is energy and have been closely involved in national energy planning projects and research. One of the experts was chief manager of Iran organization for Management of Electric Power Generation and Transmission (Tavanir) with more than 15 years of managerial experience in energy sector. The sixth expert was the network planning manager of Tavanir with significant executive experience in this organization. In addition to this core expert team, we employed four “supporting experts” to assist us with certain parts of this research. These supporting experts were academicians in fields of Electrical engineering, Mechanical Engineering, and Political Science. Unlike the core export team who completed almost all the pairwise comparisons, these supporting experts were only asked to do the pairwise comparisons for the sections relevant to their expertise.

In order to identify the criteria and construct in the model, we conducted a series of face-to-face interviews with the experts. Interviews with experts were performed individually and they did not know each other's judgments. In addition, we organized a round of focus group meeting with the members of core expert team. Also we distributed a comprehensive pairwise comparison questionnaire among them to extract their judgments.

Step 2: Model construction and problem structuring

In this stage, based on reviewing the extant literature, as well as interviews with the experts, the main selection criteria and sub-criteria for evaluating the energy portfolio were identified. These criteria are later used in the developed fuzzy ANP model in order to assess energy resource alternatives.

The fuzzy ANP model proposed in this study is composed of two key parts. The first part includes a network of relationships among different elements of the model. In turn, this network is comprised of four sub-networks (BOCR), each representing the type of interconnections among its own elements and clusters. The second part of the proposed model consists of a control hierarchy which is used to determine the priorities of BOCR [82].

Step 3: Decomposing the energy resources portfolio problem into a BOCR network

After a thorough review of the relevant studies, and also interviewing with the experts, the criteria and sub-criteria shown in Table 1 are selected as the most important factors for energy resource mix problem in Iran. These factors can be categorized into four main aspects of economic, technical, environmental and sociopolitical.

This network consists of four sub-networks of benefits, opportunities, costs and risks (BOCR). For example, there are two criteria clusters under the benefits sub-network that contain sub-criteria associated with the attainment of benefits of the main goal. Each sub-network includes a cluster with six energy resource types, namely natural gas, fuel oil, gas oil, coal, nuclear, renewable energies in it. The selection of these different energy resources is based on either their present usage or potential availability in the country. These energy resources are selected according to either their potential availability or their present usage in the country.

The first part of our ANP model consists of the four main sub-networks of benefits, opportunities, costs and risks (BOCR). These sub-networks that represent the relationships between the criteria, the sub-criteria, and the alternative clusters are presented in Fig. 2. There are three types of connections between clusters in a sub-network, namely one way, two way and loop. One-way arrow is used to show the one-sided dependence between two clusters, and two-way dependence between the clusters is illustrated by two-sided arrow. Inner dependencies inside clusters are represented by loop connections.

Step 4: Determining the control hierarchy and strategic criteria

Interviews with the experts revealed that benefits, opportunities costs, and risks carry different weights in assessing the energy portfolio. Therefore, in this stage in order to calculate the priorities of the BOCR, a control hierarchy is formed. A control hierarchy is a hierarchal model of essential strategic criteria that need to be considered to investigate the problem, and assess the BOCR aspects. The strategic criteria can be considered as the secondary objectives (or sub-goals) in the decision making problem.

The control hierarchy utilized in this study is depicted in Fig. 3. The overall objective is placed in the top level and the strategic criteria are located in the second level of the control hierarchy. This study seeks the best way to achieve sustainable development in Iran through determining the best energy portfolio for electricity generation. The three dimensions of sustainable development (namely, environmental, social and economic sustainability) are considered as strategic criteria. Finally, four merits (BOCR) are located in the third level.

Step 5: Determining the weights of strategic criteria

ANP uses pairwise comparisons to measures the relative importance of elements and their effects on each other. In this step, the importance of BOCR is assessed by the experts using the linguistic scale presented in Table 2.

The pairwise comparison matrix of strategic criteria with their calculated relative weights is presented in Table 3.

Step 6: Determine the weights of BOCR based on strategic criteria

In order to evaluate the importance of BOCR merits, the strategic criteria are compared based on the goal of "determining the best electricity generation mix for Iran". Following the procedure recommended by Saaty [83], a five-point scale (very high, 0.42; high, 0.26; medium, 0.16; low, 0.10; very low, 0.06) is used to rate the merits.

For calculating the importance weight of each merit, the weight of that merit under each strategic criterion needs to be multiplied by the weight of the corresponding strategic criterion (calculated in Step 5). Finally, the overall weights of the four merits are obtained by adding up the calculated weights for BOCR and normalizing the weights. According to these results (presented in Table 4), weights of BOCR are 0.37, 0.27, 0.31, and 0.05 respectively.

Step 7: Constructing the pairwise comparison matrix of BOCR clusters

In this step, we calculate the local weights of each cluster and its elements (sub-criteria) assuming that factors are independent of each other. Each member of the expert team responded to a series of pairwise comparison questions. In each question, they were asked to compare two elements at a time with respect to their contribution to the element on their upper level [61]. Experts completed the pairwise comparison matrices using the linguistic scale described in step 5.[2]

Afterward, for each of the pairwise comparisons, the judgments of individuals (represented by triangular fuzzy numbers) are aggregated to the group level using a fuzzy geometric mean group aggregation procedure proposed by Buckley [12]. After aggregating these pairwise comparisons and calculating the final weights of elements, these weights are arranged in an unweighted supermatrix.

Throughout this study, wherever statistics and quantitative information of energy resources for desired criteria were available, instead of employing pairwise comparisons, exact values have been used in the analysis. For this purpose, these values have been normalized using linear normalization method.[3] Summary of alternative energy sources statistics can be found in Table 5.

The environmental loads for renewable-based power plants are small because the operation of such plants does not produce any direct emissions. The environmental loads for renewable energy sources are mainly related to the construction of power plant and production of equipment and material [46].

Statistics on the amount of gaseous pollutant emissions produced in

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[2] In this study, all the pairwise comparison matrices are constructed in Microsoft Excel workspace designed for solving fuzzy ANP matrices.

[3] Under the general assumption that fuel oil and gas oil share similar characteristics, wherever the data of one of them was not available, the value of the other used is the calculation. Similarly, For the case of renewable energies, the average value of available renewable alternatives (hydropower, solar, wind, geothermal and biomass) is utilized. Also the difference between domestic and export fuel price is considered as opportunity cost. Since currently coal, nuclear energy and renewable energies are not available for export, for these energy sources the value of opportunity cost is equal to zero.

Table 1
The subnetworks, clusters and elements under BOCR merits.

Merits	Criteria	Sub-criteria	Description	References
Benefits	(B1) Economic	(B11) Efficiency	The amount of electricity that can be obtained from an energy source. It is defined as the ratio of the output energy to the input energy.	Afgan and Carvalho [1], Chatzimouratidis and Pilavachi [18], Kablan [39], Amer and Daim [6], Büyüközkan and Güleryüz [13], Büyüközkan and Güleryüz [14]
		(B12) Added value	The difference between the market value of electricity produced from an energy source and its overall costs.	
		(B13) Heat recovery	Possibility of effective capture and use of heat rejected from the power cycles.	Huang and Wu [35]
		(B14) Reliability	The capacity of the power plant to perform as designed. Reliability of an energy system is defined by its resistance to failure and is measured by probability of occurrence of failures.	Chatzimouratidis and Pilavachi [18], Amer and Daim [6], Wang et al. [106], Büyüközkan and Güleryüz [13], Wang et al. [106], Büyüközkan and Güleryüz [14,33]
		(B15) Return on investment	The ratio of energy delivered to energy costs. This criterion specifies if it worth to invest on an alternative energy source. This criterion can be measured based on payback period indicator.	Haralambopoulos and Polatidis [34]; Kontić et al. [47]; Tasri and Susilawati [97], Büyüközkan and Güleryüz [13], Büyüközkan and Güleryüz [14], Haddad et al. [33]
	(B2) Political	(B21) Independence	The degree of sufficiency of domestic electricity production for meeting domestic demand.	Farooqui [28,91]; Büyüközkan and Güleryüz [13], Erdogmus et al. [24], Büyüközkan and Güleryüz [14]
		(B22) International acceptability	The degree of acceptability of energy policy in international level. This factor takes into account the international legislations for energy policies.	
		(B23) Compatibility with the national energy policy objectives	The degree of convergence between the national energy policy and the suggested energy policy. This factor takes into account government approval and accessibility of legal and financial incentives for utilizing alternative energies.	Kahraman and Kaya [41,85]; Kablan [39], Tasri and Susilawati [97], Büyüközkan and Güleryüz [13], Büyüközkan and Güleryüz [14], Haddad et al. [33]
Opportunities	(O1) Source of energy	(O11) Domestic access	Domestic availability of energy source.	Kontić et al. [47], Farooq and Kumar [27], Amer and Daim [6,68,5]; Büyüközkan and Güleryüz [14]
		(O12) Renewability efficiency	Reuse potential of an energy source.	
	(O2) Technology	(O21) National technical knowledge	The capacity of local actors for maintenance and installation of technology for the energy alternative. This factor takes the national technological maturity into account.	Shen et al. [91], Kabak and Dağdeviren [38,42]; Amer and Daim [6], Kahraman et al. [42], Büyüközkan and Güleryüz [13]
		(O22) Access to technical equipment	The availability of equipment for maintenance and installation of technology for the energy alternative.	Shen et al. [91], Amer and Daim [6], Al Garni et al. [5]
Cost	(C1) Cost	(C11) Total cost	All costs related to investment (costs related to purchase of equipment, installations, construction, connection to the national electricity web), operation (insurance, labor costs, taxes, and cost of fuel), maintenance of power plant, and R&D costs.	Kabak and Dağdeviren [38,2]; Amer and Daim [6], Büyüközkan and Güleryüz [13], Büyüközkan and Güleryüz [14]
		(C12) Opportunity cost	The value of the next-highest-valued alternative use of that energy resource. This factor takes into account the difference between return of investment in one energy source and the return of alternative sources.	
		(C13) Duration of preparation phase	The availability of the alternative energy policy to decrease financial assets and reach the minimum cost.	Kahraman et al. [42], Amer and Daim [6], Kahraman et al. [42]
Risk	(R1) Sociopolitical	(R11) Risk of sanction	The impact of international sanctions on utilizing an energy source.	
		(R12) Social risk	Relative hazards to human health, measured by expected years-of-life lost due to electricity production from an energy source.	Strupczewski [95]
	(R2) Environmental	(R21) Greenhouse gas emission	Estimated quantity of a CO_2 emitted per unit of energy. Greenhouse gases are responsible for global warming.	Afgan and Carvalho [1], Ahn et al. [2,3]; Chatzimouratidis and Pilavachi [17], Büyüközkan and Güleryüz [13], Kahraman and Kaya [41], Büyüközkan and Güleryüz [14], Haddad et al. [33]
		(R22) Other pollutant emissions	The total estimated quantity of SO_2, NO_x, and CO emitted per unit of energy. These emissions are responsible for environmental risks such as global warming, acid rains, and air pollution.	Kontić et al. [47], Shen et al. [91], Amer and Daim [6]

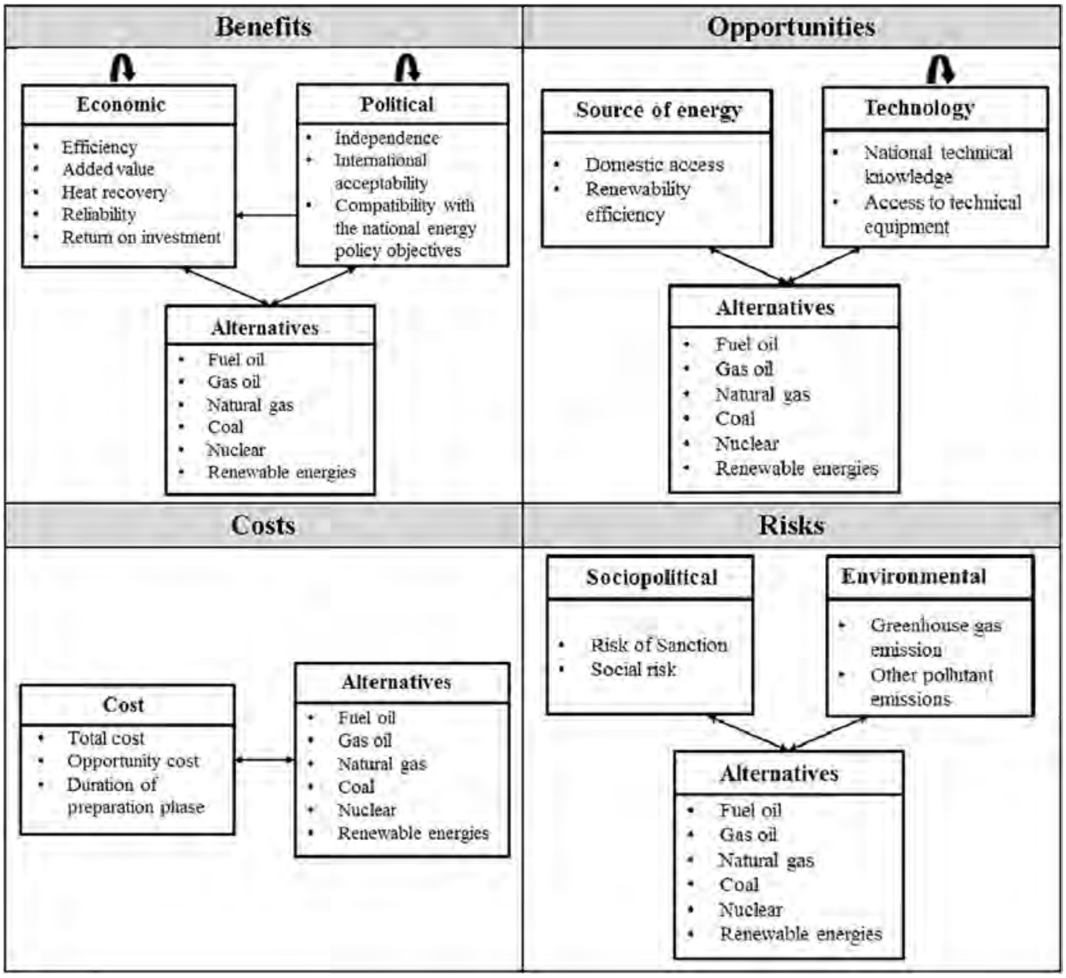


Fig. 2. The sub-networks for BOCR.

fossil fuel power stations is summarized in Table 6. In this research, we only take into account the direct emissions due to generating electricity in the fossil fuel power plants. Therefore, despite the indirect emissions, the amount of greenhouse gasses and other pollutant gasses related to nuclear and renewable energies are assumed to be zero in the analysis.

Step 8: Forming the weighted supermatrix

ANP uses supermatrix as a unifying framework to deal with the interdependence and feedback among the network of components [80]. First, an unweighted supermatrix is developed by entering the local priority matrices calculated in Step 7 in the related columns of a matrix. Second, for each cluster in each sub-network, a cluster priority matrix is calculated using pairwise comparisons. This matrix determines the impact of each cluster on other clusters in a particular sub-network. Finally, the blocks of the unweighted supermatrix are multiplied by the weights of cluster priority matrix to form a weighted supermatrix.

As an example, the matrix of priorities (or inner dependence matrix) for benefits sub-network is given in Table 7. Each column of this matrix represents the priority vector related to one of the clusters in benefits sub-network. As can be seen in Fig. 2, the political cluster is influenced by the alternatives and economical cluster and by itself. Therefore, we

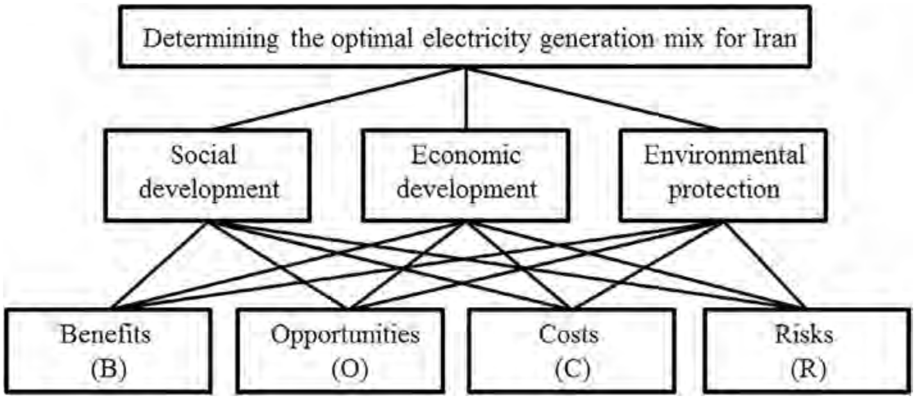


Fig. 3. Control hierarchy.

Table 2
The linguistic scale for relative dominance and their corresponding triangular fuzzy numbers [40].

Linguistic scale[a]	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equal dominance	(0.5,1,1.5)	(0.67,1,2)
Weak Dominance	(1,1.5,2)	(0.5,0.67,1)
Strong dominance	(1.5,2,2.5)	(0.4,0.5,0.67)
Very strong dominance	(2,2.5,3)	(0.33,0.67,0.5)
Absolute dominance	(2.5,3,3.5)	(0.28,0.33,0.67)

[a] For pairwise verbal comparisons, the dominance of element *i* over element *j* may be interpreted as importance, preference or influence.

Table 3
Strategic criteria pairwise comparison matrix.

Goal	Economic	Social	Environmental	Priorities
Economic	(1,1,1)	(1,1.5,2)	(0.5,0.67,1)	0.34
Social	(0.5,0.67,1)	(1,1,1)	(0.4,0.5,0.67)	0.10
Environmental	(1,1.5,2)	(1.5,2,2.5)	(1,1,1)	0.56

can calculate the priority vector for political cluster through fuzzy pairwise comparison, and obtain the relative impact of each of these three clusters on the political cluster. According to this priority vector (given in the second column of Table 7), the relative strength of influences of economic, political, and alternative clusters on political clusters are 0.23, 0.23 and 0.54 respectively. Repeating this calculation process for economical and alternatives clusters yields the matrix of priorities for benefits sub-network (Table 7).

Finally, we can obtain the weighted supermatrix by multiplying the matrix of priorities of benefits sub-network with local weights of the criteria and sub-criteria within this sub-network (determined in Step 7). The weighted supermatrix for benefits sub-network is presented in Fig. 4. This procedure is repeated for the sub-networks of costs, opportunities, and risks to calculate the weighted super matrices of these sub-networks.

Step 9: Forming the limit supermatrix

In this step the overall weights of elements in the network is obtained by calculating the limit supermatrix. Limit supermatrix, which captures all the direct and indirect interactions among elements, can be calculated by raising the weighted supermatrix to a sufficiently large power. Raising the weighted supermatrix generates a steady state matrix in which the values in each row of the matrix is converged to the same number for each column of the matrix [30]. Limit supermatrix of benefits sub-network can be seen in Fig. 5. Repeating this procedure for all sub-networks yields the results shown in Table 8.

Step 10: Calculating overall priorities of alternatives

In the final step of the proposed framework, overall weights of alternative energy sources are identified. In order to do so, in this, step the local weights of alternatives for each of the BOCR subnetworks (calculated in Step 9) are synthesized with the corresponding normalized weights of b, o, c and r (calculated in Step 6). In the problems that involve complex network structure, the weights of the alternatives need to be synthesized through applying different aggregation formulas [84]. Five different aggregation methods have been proposed for combining the weights of each alternative under BOCR sub-networks [83]:

1- Additive

$$P_i = bB_i + oO_i + c(1/C_i)_{Normalized} + r(1/R_i)_{Normalized} \tag{1}$$

2- Probabilistic additive

$$P_i = bB_i + oO_i + c(1/C_i) + r(1/R_i) \tag{2}$$

3- Subtractive

$$P_i = bB_i + oO_i - cC_i - rR_i \tag{3}$$

4- Multiplicative priority powers

$$P_i = B_i^b O_i^o + [(1/C_i)_{Normalized}]^c + [(1/R_i)_{Normalized}] \tag{4}$$

5- Multiplicative

$$P_i = B_i O_i / C_i R_i \tag{5}$$

Table 9 presents the ultimate ranking of the alternatives derived by each of these five combining methods. Although by employing different synthesizing methods the weights of alternatives slightly change, interestingly, their rankings remain unchanged. Ultimately, the final share of alternative energy sources is calculated based on the average weights obtained by these five methods (last column of Table 9). The final share of alternative sources in the recommended energy mix for generating electricity in Iran is shown in Fig. 6. According to the findings, renewable energy sources, with the share of 31.6% have the highest priority in the energy mix of Iran, and coal, with the share of 12.3%, received the lowest priority.

Step 11: Validity analysis

In the absence of historical data, validating a not-yet-developed system is always a challenging task [29]. In this study, we have taken two approaches to ensure the validity of the model and results. The first validity check was through measuring the consistency of experts' judgments. Saaty [83] proposed a method for verifying the consistency of pairwise comparison matrices by calculating a consistency ratio (CR) index. In this study, we adopted a revised consistency test proposed by Kwong and Bai [49] for calculating CR index for fuzzy-based pairwise matrices. The consistency was checked for all the pairwise judgments and only the ones that fulfilled consistency requirement (i.e. the ones with CR below 0.1) were used for the analysis. For inconsistent judgment, the experts were asked to retake the pairwise comparison until the acceptable consistency was reached.

Moreover, following the recommendation of Prasad et al. [77] and [78], we adopted face validity to test the credibility of the model. An overall of 12 experts in energy planning and management (different

Table 4
Priorities of merits.

	Economic sustainability (0.34)	Social sustainability (0.10)	Environmental sustainability (0.56)	Average	Weight (normalized average)
Benefits	0.14	0.04	0.24	0.14	0.37
Opportunities	0.14	0.02	0.15	0.10	0.27
Costs	0.09	0.03	0.24	0.12	0.31
Risks	0.02	0.01	0.03	0.02	0.05

Table 5
Alternative energy sources statistics.

	Loss of expected life due to electricity production[a] (YoLL/TWh)	Normal	Efficiency (%)[b]	Normal	Construction period (years)[c]	Normal	Total cost ($/MWh)[d]	Normal	Opportunity cost (Rial/lit)[e]	Normal
Fuel oil	165.5	0.281	26.5	0.122	2	0.119	128	0.214	97	0.292
Gas oil	165.5	0.281	28	0.129	2	0.119	150	0.252	178	0.536
Natural gas	46.1	0.078	50	0.231	1.5	0.089	38	0.064	57	0.172
Coal	165.5	0.281	42	0.194	4	0.238	82	0.138	0	0
Nuclear	11.9	0.020	30	0.138	5	0.298	91	0.153	0	0
Renewable energies	34.42	0.058	40	0.185	2.3	0.137	107	0.179	0	0

[a] Adapted from Strupczewski [95] – loss of life expectancy in Years of Life Lost (YOLL) per terawatt hours (TWh).
[b,c] Adapted from The [99].
[d] Adapted from OECD/IEA. [70,71].
[e] Calculated according to the procedure recommended by [64] based on the exporting value of the energy source.

Table 6
Gaseous pollutants emissions due to generating electricity in fossil fuel power plants.

	Greenhouse gasses		Other pollutant gasses			Total (g/Gj)	Normalized
	CO_2 (g/Gj)	Normalized	SO_2 (g/Gj)	NO_x (g/Gj)	CO (g/Gj)		
Fuel oil	77,400	0.256	1350	195	15.7	1560.7	0.489
Gas oil	74,100	0.245	228	129	15.7	372.7	0.116
Natural gas	56,100	0.185	0.68	93.3	14.5	108.48	0.034
Coal	94,600	0.313	765	292	89.1	1146.1	0.359

Source: Adapted from European Environment Agency [25], European Environment Agency [26].

Table 7
Cluster priorities for benefits sub-network.

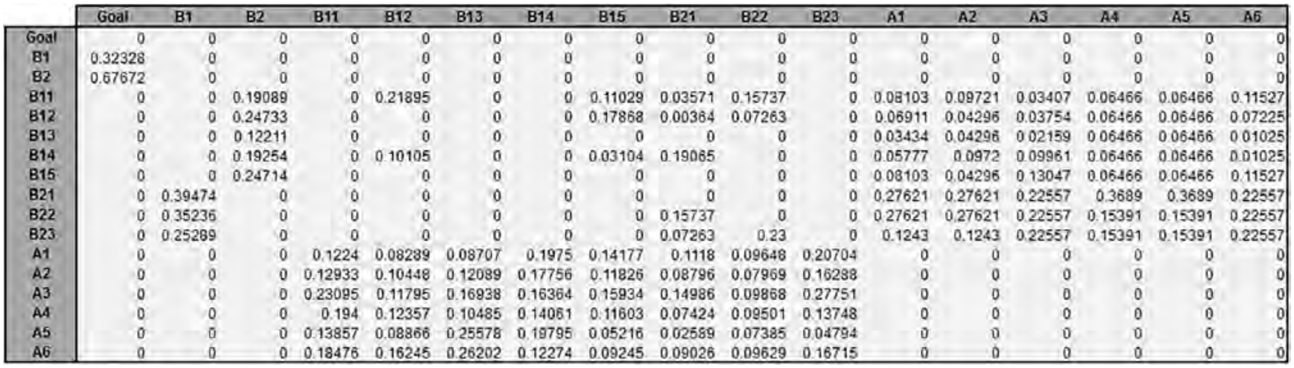
	Economical	Political	Alternatives
Economical	0.32	0.23	0.32
Political	0	0.23	0.68
Alternatives	0.68	0.54	0

from the ones that were engaged in the model building and analysis) accepted to assist us with evaluating the results. A summary of the proposed model and results, along with a set of questions about the reasonableness of the output were presented to these experts. Overall, experts agreed that the model is sufficiently exhaustive and is an accurate representation of the real problem and they were reasonably satisfied about the robustness of outputs.

Conclusion and policy implications

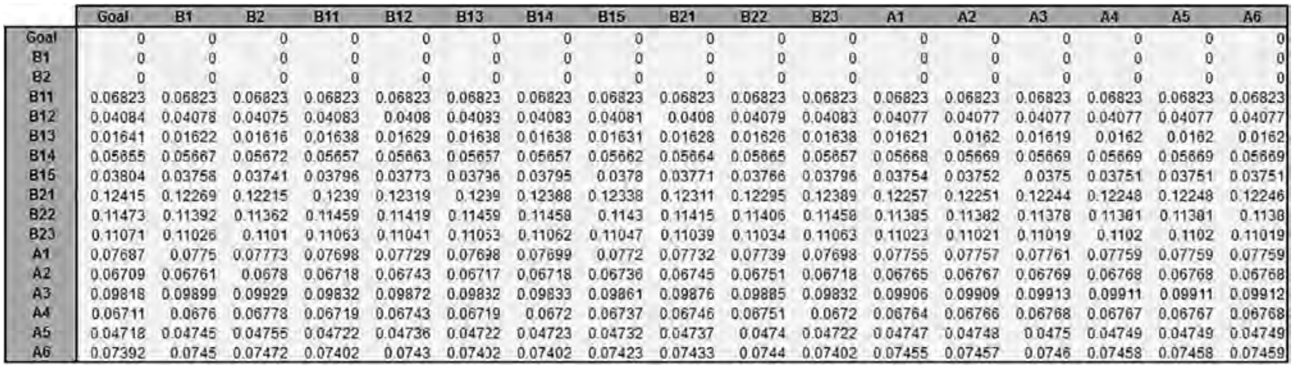
This paper proposes a new framework for assessing the mix of energy sources for generating electricity in Iran from the perspective of sustainable development. A group fuzzy ANP model is used to assess and compare six different competing energy options against various economic, technical, social and environmental criteria. In order to address the uncertainties and imprecisions inherent in this complex decision making problem, fuzzy linguistic assessment variables are utilized in the pairwise comparison process.

Compared to the traditional approaches for assessing electricity generation mix, the proposed framework has several advantages: First, this framework provides a more comprehensive picture of influencing factors in energy mix assessment by simultaneously accounting for multiple evaluation criteria from different perspectives. This study brings together a broad range of factors that have been scattered across many studies, along with some factors that are idiosyncratic for the context of Iran. Second, this framework enables to taking the complex interrelationships among criteria into account. Third, adopting fuzzy logic in evaluations by employing linguistic variables enables handling uncertainties in the process of decision-making. Fourth, the proposed framework allows for incorporating the judgments of multiple decision makers and to systematically integrate them to come up with an assessment that represents the group's preferences.



	Goal	B1	B2	B11	B12	B13	B14	B15	B21	B22	B23	A1	A2	A3	A4	A5	A6
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B1	0.32328	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B2	0.67672	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B11	0	0	0.19089	0	0.21895	0	0	0.11029	0.03571	0.15737	0	0.08103	0.09721	0.03407	0.06466	0.06466	0.11527
B12	0	0	0.24733	0	0	0	0	0.17868	0.00364	0.07263	0	0.06911	0.04296	0.03754	0.06466	0.06466	0.07225
B13	0	0	0.12211	0	0	0	0	0	0	0	0	0.03434	0.04296	0.02159	0.06466	0.06466	0.01025
B14	0	0	0.19254	0	0.10105	0	0	0.03104	0.19065	0	0	0.05777	0.0972	0.09961	0.06466	0.06466	0.01025
B15	0	0	0.24714	0	0	0	0	0	0	0	0	0.08103	0.04296	0.13047	0.06466	0.06466	0.11527
B21	0	0.39474	0	0	0	0	0	0	0	0	0	0.27621	0.27621	0.22557	0.3689	0.3689	0.22557
B22	0	0.35236	0	0	0	0	0	0	0.15737	0	0	0.27621	0.27621	0.22557	0.15391	0.15391	0.22557
B23	0	0.25289	0	0	0	0	0	0	0.07263	0.23	0	0.1243	0.1243	0.22557	0.15391	0.15391	0.22557
A1	0	0	0	0.1224	0.08289	0.08707	0.1975	0.14177	0.1118	0.09648	0.20704	0	0	0	0	0	0
A2	0	0	0	0.12933	0.10448	0.12089	0.17756	0.11826	0.08796	0.07969	0.16288	0	0	0	0	0	0
A3	0	0	0	0.23095	0.11795	0.16938	0.16364	0.15934	0.14986	0.09868	0.27751	0	0	0	0	0	0
A4	0	0	0	0.194	0.12357	0.10485	0.14061	0.11603	0.07424	0.09501	0.13748	0	0	0	0	0	0
A5	0	0	0	0.13857	0.08866	0.25578	0.19795	0.05216	0.02589	0.07385	0.04794	0	0	0	0	0	0
A6	0	0	0	0.18476	0.16245	0.26202	0.12274	0.09245	0.09026	0.09629	0.16715	0	0	0	0	0	0

Fig. 4. Weighted supermatrix of benefits sub-network.



	Goal	B1	B2	B11	B12	B13	B14	B15	B21	B22	B23	A1	A2	A3	A4	A5	A6
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B11	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823	0.06823
B12	0.04084	0.04078	0.04075	0.04083	0.0408	0.04083	0.04083	0.04081	0.0408	0.04079	0.04083	0.04077	0.04077	0.04077	0.04077	0.04077	0.04077
B13	0.01641	0.01622	0.01616	0.01638	0.01629	0.01638	0.01638	0.01631	0.01628	0.01626	0.01638	0.01621	0.0162	0.01619	0.0162	0.0162	0.0162
B14	0.05655	0.05667	0.05672	0.05657	0.05663	0.05657	0.05657	0.05662	0.05664	0.05665	0.05657	0.05668	0.05669	0.05669	0.05669	0.05669	0.05669
B15	0.03804	0.03758	0.03741	0.03796	0.03773	0.03796	0.03795	0.0378	0.03771	0.03766	0.03796	0.03754	0.03752	0.0375	0.03751	0.03751	0.03751
B21	0.12415	0.12269	0.12215	0.1239	0.12319	0.1239	0.12388	0.12338	0.12311	0.12295	0.12389	0.12257	0.12251	0.12244	0.12248	0.12248	0.12246
B22	0.11473	0.11392	0.11362	0.11459	0.11419	0.11459	0.11458	0.1143	0.11415	0.11406	0.11458	0.11385	0.11382	0.11378	0.11381	0.11381	0.1138
B23	0.11071	0.11026	0.1101	0.11063	0.11041	0.11063	0.11062	0.11047	0.11039	0.11034	0.11063	0.11023	0.11021	0.11019	0.1102	0.1102	0.11019
A1	0.07687	0.0775	0.07773	0.07698	0.07729	0.07698	0.07699	0.0772	0.07732	0.07739	0.07698	0.07755	0.07757	0.07761	0.07759	0.07759	0.07759
A2	0.06709	0.06761	0.0678	0.06718	0.06743	0.06717	0.06718	0.06736	0.06745	0.06751	0.06718	0.06765	0.06767	0.06769	0.06768	0.06768	0.06768
A3	0.09818	0.09899	0.09929	0.09832	0.09872	0.09832	0.09833	0.09861	0.09876	0.09885	0.09832	0.09906	0.09909	0.09913	0.09911	0.09911	0.09912
A4	0.06711	0.0676	0.06778	0.06719	0.06743	0.06719	0.0672	0.06737	0.06746	0.06751	0.0672	0.06764	0.06766	0.06768	0.06767	0.06767	0.06768
A5	0.04718	0.04745	0.04755	0.04722	0.04736	0.04722	0.04723	0.04732	0.04737	0.0474	0.04722	0.04747	0.04748	0.0475	0.04749	0.04749	0.04749
A6	0.07392	0.0745	0.07472	0.07402	0.0743	0.07402	0.07402	0.07423	0.07433	0.0744	0.07402	0.07455	0.07457	0.0746	0.07458	0.07458	0.07459

Fig. 5. Limit supermatrix of benefit sub-network.

Results indicate that renewable energies, with the average share of 33.5%, have the largest share in the proposed energy portfolio of Iranian power plants. The share of other energy resources is determined as follows (in descending order): natural gas (25%), coal (12.3%), fuel oil (12.6%), nuclear (8.7%) and gas oil (9.7%).

Our results reveal a gap between goals of sustainable energy planning and current electricity generation mix in Iran. Currently, production of electricity in Iran is heavily dependent on fossil fuels, with renewables having only marginal contribution in the installed capacity. It is estimated that by maintaining the current trend, in 20 years, only 5% of electricity demand will be supplied by renewable energies [11]. In sharp contrast to the present situation, renewable energies account for about a third of the proposed energy mix in our model. It is interesting to note that our findings are in line with the global momentum for renewable electricity generation. The raising awareness about dwindling fossil fuel supplies and their adverse environmental effects has made renewable energies as key solution for sustainable energy planning. Renewable energies are growing faster than any other source of energy and are expected to make a great contribution in the word's future energy [37]. From the end of 2004, the capacity for renewable energies in the world has continuously grown by 10–60% per year [79]. According to [60], renewable power constituted about half of the worldwide added net power capacity in 2014.

In order to achieve long-term sustainable development in Iran, it is of crucial importance to revisit the country's energy policy and transit to a more sustainable electricity production. Also, there is an urgent need for Iranian power industry to diversify its energy mix through non-fossil fuels and systematically raise the proportion of renewables in its energy portfolio. It is acknowledged that greenhouse gasses, particularly carbon dioxide (CO_2) emissions, resulting from high carbon intensity electricity generation units is a major source of environmental pollution which, in turn, has significant economic consequences [105,79]. Iran has increasingly recognized the importance of non-fossil energy resources for its longer term energy plans. Particularly, the government aims to increase the share of indigenous energy sources and enhance the proportion of renewable energies in its energy portfolio [11]. This ambitious decarburization agenda would require a strong policy commitment that supports utilizing emerging low-carbon technologies and transforming the electricity supply infrastructure.

If renewable energies are to be used to a large extent and be adequately integrated into the power supply system during the next decade, detailed feasibility studies for harnessing renewable energies needs to be carried out. Several previous studies have shown that Iran has a substantial potential for utilizing various renewable sources of energy such as wind, hydro power, solar, and geothermal [7,11,31,85,92]. Renewable energies can play a significant role in overcoming the energy shortages in the country while reducing the dependence on conventional energy sources. Besides providing electricity, there is evidence that deploying renewable energies can have an important contribution in national economic growth and improve the standards of living standards specially in remote areas [6,65]. With an enormous potential to provide cost-effective energy, renewable electricity technologies can enhance the security of energy supply in a long-term perspective, and reduce greenhouse gas emissions and other air

Table 8
Weights of merits, criteria, sub-criteria and alternatives under each sub-criteria.

Merits	Criteria	Sub-Criteria	Local weight	Global weight	(A1)	(A2)	(A3)	(A4)	(A5)	(A6)
Benefits (0.37)	Economic (0.323)	Efficiency	0.191	0.044	0.12	0.13	0.23	0.19	0.14	0.18
		Added Value	0.247	0.027	0.12	0.15	0.17	0.18	0.13	0.24
		Heat Recovery	0.122	0.011	0.09	0.12	0.17	0.1	0.26	0.26
		Reliability	0.193	0.037	0.2	0.18	0.16	0.14	0.2	0.12
		Return on investment	0.247	0.025	0.21	0.17	0.23	0.17	0.08	0.14
	Political (0.677)	Independence	0.395	0.081	0.21	0.16	0.28	0.14	0.05	0.17
		International acceptability	0.352	0.075	0.18	0.15	0.18	0.18	0.14	0.18
		Compatibility with the national energy policy	0.253	0.072	0.21	0.16	0.28	0.14	0.05	0.17
Opportunities (0.27)	Source of energy (0.696)	Domestic access	0.664	0.084	0.23	0.18	0.23	0.1	0.06	0.19
		Renewability efficiency	0.336	0.039	0	0	0	0.09	0.25	0.66
	Technology (0.304)	National technical knowledge	0.68	0.128	0.21	0.21	0.22	0.12	0.09	0.15
		Access to technical equipment	0.32	0.019	0.21	0.2	0.22	0.15	0.08	0.14
Cost (0.31)	Cost (1)	Total cost	0.545	0.145	0.21	0.25	0.06	0.14	0.15	0.18
		Opportunity cost	0.227	0.093	0.29	0.54	0.17	0	0	0
		Duration of preparation phase	0.227	0.072	0.12	0.12	0.09	0.24	0.3	0.14
Risk (0.05)	Sociopolitical (0.548)	Risk of sanction	0.5	0.012	0	0	0	0	0.8	0.2
		Social risk	0.5	0.015	0.28	0.28	0.08	0.28	0.02	0.06
	Environmental (0.452)	Greenhouse gas emissions	0.5	0.008	0.49	0.12	0.03	0.36	0	0
		Other gaseous pollutants	0.5	0.014	0.26	0.25	0.19	0.31	0	0

Table 9
Final synthesis of priorities of alternatives.

					Subtractive		Probabilistic additive		Additive		Multiple active		Multiplicative priority powers		Average weight
	B	O	C	R	priority	rank	priority	rank	priority	rank	priority	rank	priority	rank	
Fuel oil	0.179	0.155	0.203	0.239	0.112	3	0.161	3	0.150	3	0.042	3	0.163	3	0.126
Gas oil	0.156	0.134	0.289	0.174	0.034	5	0.146	5	0.126	5	0.030	5	0.151	5	0.097
Natural gas	0.228	0.158	0.095	0.083	0.318	2	0.186	2	0.220	2	0.335	2	0.193	2	0.250
Coal	0.156	0.100	0.130	0.234	0.111	4	0.161	4	0.148	4	0.037	4	0.159	4	0.123
Nuclear	0.110	0.075	0.152	0.203	0.011	6	0.149	6	0.116	6	0.019	6	0.140	6	0.087
Renewable energies	0.172	0.378	0.130	0.068	0.414	1	0.198	1	0.240	1	0.537	1	0.193	1	0.316

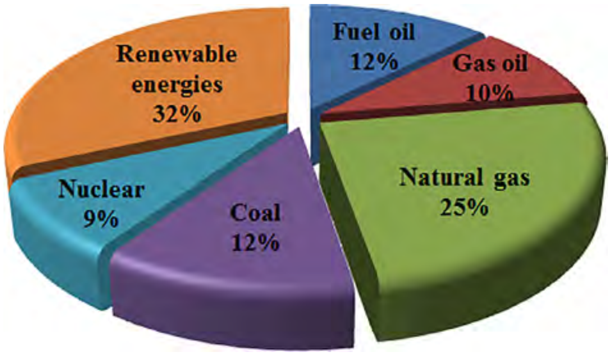


Fig. 6. Recommended energy portfolio for Iranian power sector.

pollutants.

The appropriate energy mix is idiosyncratic to each country and, therefore, the results of this study are not directly applicable to other countries. However, the proposed model in this study can be used as a guideline for assessing electricity generation mix in other countries. However, it should be noted that the assessment criteria in this model are country-specific and need to be modified for each country according to their specific needs, policies, and perspectives. Also, the choose of alternative sources of energies may need to be revised based on the options available to each country. It is also important to mention that the process of assessing energy sources for identifying an appropriate energy mix is a dynamic process. Not only the importance of different criteria and alternative energy sources may vary from one country to another, but even in each country, the priorities may change over time.

A number of avenues exist for enhancing this research. First, due to the technical limitations regarding the number of alternatives in the ANP procedure, in this study different types of renewable energies are categorized as one alternative. Given the importance of these sources of energy in the suitable electricity generation mix of Iran, it may prove fruitful to extend the current framework by distinguishing between various renewable energy types and determining the share of each source in the energy portfolio. This would be complementary to the current study and may lead to interesting and applicable results. Finally, future studies can improve the model proposed in this study by integrating ANP with other MCDM techniques such as TOPSIS, in order to enable assessing higher number of alternatives in the model.

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