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Bioethanol facility location selection using best-worst method

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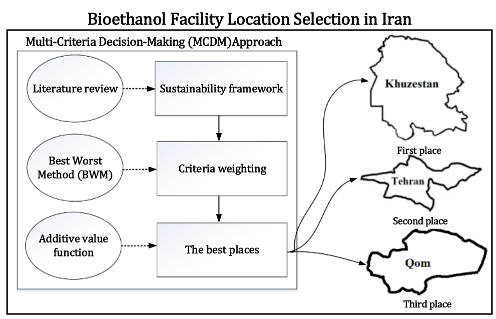
HIGHLIGHTS

- A multi-criteria framework is proposed for bioethanol facility location.
- The best worst method is used to calculate the weights of the criteria.
- The provinces of Iran are evaluated as alternatives in this study.
- A questionnaire answered by 41 experts from Iran is used for the BWM.
- Province of Khuzestan (followed by Tehran) is selected for bioethanol production.

GRAPHICAL ABSTRACT



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ABSTRACT

One of the major factors in the success of renewable energy is finding a proper location for production facilities. At a national level, different parts of a country (e.g. provinces) can be seen as alternatives that can be assessed based on a set of criteria, and ranking them to identify the best location. The focus in this paper is on identifying the best location for the production of bioethanol. After a comprehensive literature review, an evaluation framework is proposed based on the three dimensions of sustainability (economic, environmental and social). Using data provided by a sample of experts in a developing country – Iran – and applying the best-worst method (BWM), a number of decision-making criteria are evaluated. Performance data involving the various provinces of Iran are collected from different sources. The performance data and the weights identified through BWM are used to calculate an overall score for each province, which is then used to rank the provinces, with the province of Khuzestan (closely followed by Tehran) being identified as the most suitable province for bioethanol production in Iran.

1. Introduction

Increasing energy demand around the world has created challenges associated with fossil fuels, including significant weather problems and a diminishing supply of fossil fuel resources. According to forecasts, global oil and gas reserves will run out around 2042, and coal will be the only available fossil resource until 2112 [1]. At the same time, global energy and fuel consumption, especially in developing countries, is growing rapidly, if we look at criteria like population growth and economic structure [1,2].

It is crucial for countries to tap into alternative fuel sources to solve these problems, as well as address the ever-increasing demand for energy [3]. Renewable energy sources provide a valuable alternative to fossil fuel that not only addresses the growing demand for energy and improves economic and social aspects [4], but also reduces greenhouse gas emissions and improves fuel security [5]. Among the renewable

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energy sources, biomass has an extraordinary potential when it comes to the sustainable production of energy. Biomass is a renewable energy source derived from biodegradable components of agricultural waste, including herbal and animal materials, forests and industrial, and urban waste. One of the renewable fuels is ethanol, which can be obtained via biomass conversion. Bioethanol has many uses in the world today. The energy yield of bioethanol is relatively high, which means it can be used as fuel for transport [6], healthcare and manufacturing.

Different criteria play different roles in bioethanol production, in direct connection to where the facility is located. These criteria are closely related to the Triple Bottom Line (TBL) of sustainability – the economic, environmental and social dimensions of the desired location [4,7]. As a result, in bioethanol production, it is necessary not only to determine the criteria, but also to divide them into economic, environmental and social categories. Because choosing the wrong location, in addition to increasing production costs and creating problems in supplying and transporting the raw materials, also creates environmental problems and prevents the development of the industry [8,9]. Existing literature offers no unified framework that includes all the economic, environmental and social criteria involved in determining the best location for a bioethanol facility. The proposal of such a comprehensive framework, based on an extensive literature review, covering all the criteria in three dimensions of sustainability, is the first contribution of this paper. The framework is used as a basis for formulating the bioethanol facility location selection problem as a multi-criteria decision-making problem (MCDM), where different alternatives should be evaluated based on a number of criteria. This study is one the few studies to examine the problem on a large scale. That is to say, in this paper, the best location of bioethanol facility location in a given country (Iran) is studied, which can be seen as the second contribution of this study, while the proposed framework can also be useful to determine the ideal location for bioethanol facilities in other countries.

The remainder of the paper is organized as follows. In Section 2, relevant studies are reviewed and a framework is presented containing the criteria that are relevant to the location of bioethanol facilities, while the methodology is discussed in Section 3. In Section 4, the results of the study are analyzed and the best location for bioethanol production in Iran is identified and some concluding remarks are presented in Section 5.

2. Related works

To identify the relevant criteria for choosing the best location for a renewable energy facility, we conducted a comprehensive literature review. Broadly speaking, the papers involved are divided into three groups, the first of which contains MCDM papers involving biomass facility location, while the second group includes Multi-Objective Decision-Making (MODM) papers that use mathematical models, and the third group includes other papers related to the location of renewable facilities. The latter two groups are included with the aim of identifying evaluation criteria, in particular regarding the socio-economic aspects that usually play a role in renewable energy facility location. The criteria were derived from the texts and tables in MCDM papers and from mathematical objective functions in MODM papers. Because the studies in the first group and the MODM papers on bioethanol facility location selection are closely related to this study, they are discussed in the next section. Along with the results of the papers discussed below, we summarize the findings of the other two groups in Table 1 (see Table A in the Appendix for a full bibliographical information). Reading the papers and considering the description of each criterion, we assigned the criteria we identified to the three dimensions of sustainability: economic, environmental and social.

Bai, Hwang, Kang, and Ouyang [10] proposed a MILP (Mixed Integer Linear Programming) to determine the optimal location of biofuel refinery in the USA. The proposed model addresses the interdependencies in traffic congestion, shipment routing decisions, and the location of biofuel refinery decisions in bioethanol supply chain planning. Ekşioğlu, Acharya, Leightley, Arora, and Engineering [11] presented a MILP model creating a biomass supply chain system to bioethanol production from corn stover and woody biomass in the USA. The results of the proposed model determine the optimal number, location and size of biorefineries, the amount of biomass, feedstock collection and the level of biomass inventory through a multiperiod formulation. Zhang, Johnson, and Sutherland [12] provided the optimal facility location for production of biofuels from biomass using GIS in USA. They selected the best location based on shipping costs. Dal-Mas, Giarola, Zamboni, and Bezzo [13] presented a MILP modelling framework to help decision-makers assess risk management and economic performances of a bioethanol supply chain in Italy. The model addresses costs of biomass and uncertainty of selling price.

Yu, Wang, Ileleji, Luo, Cen, and Gorec [14] proposed methods that can help determine the optimal sites for biomass power plant and satellite storages under China's specific delivery modes, using a GIS model based on ArcGIS 9.3, which enables the mapping of actual road networks to specify the location of sub-collection-regions. The results of the proposed model were compared to the mathematical model presented earlier. The combination of the proposed model and the mathematical model turns out to be useful in optimizing specific delivery and distribution modes. Van Dael, Van Passel, Pelkmans, Guisson, Swinnen, and Schreurs [15] proposed an AHP model for selecting the location in a region for biomass valorization. They identified four main criteria and 22 sub-criteria, and applied the model in Belgium to determine potentially interesting locations for establishing a biomass project, using macro screening and GIS to assess and select locations. Macro screening provided a first well-balanced scan of the probability for energy production using regional biomass.

Voets, Neven, Thewys, and Kuppens [16] selected a biomass power plant location in Belgium using GIS. Specific maintenance and operational costs, investment cost, centroid agricultural parcel to biomass plant, unloaded transport distance, diesel consumption of loaded tractor-trailer are the criteria used to assess locations by Voets et al. Zhang, Osmani, Awudu, and Gonela [17] proposed a MILP model for designing an optimal switchgrass-based bioethanol supply chain in the USA. The objective function in the proposed model minimizes the total annual cost, which includes switchgrass cultivation, different transportation costs, marginal land rental cost, storage cost, harvest, preprocessing and operational cost, and annual fixed cost of preprocessing facilities and biorefineries. The authors also evaluated the effect of changes in bioethanol demand and harvest methods, bio-refinery locations, switchgrass yield on the results by conducting a sensitivity analysis. In a survey by Perpiña, Martínez-Llario, and Pérez-Navarro [18], the most suitable location for energy generating power plant from biomass was determined in Spain. The criteria, divided into environmental, economic and social dimensions, were categorized and the most appropriate location was identified using AHP, weighted linear summation and ideal point method, using the criteria of lithology, access by road, economic development, geomorphology, potential demand, natural vegetation cover, slopes physiography, transport costs, occupation, agricultural soils, and land use.

Cheng, Li, Gao, Wang, and Mang [19] used local condition, demand of multi-duty agricultural residues and logistics to assess the agricultural biomass potential for a biomass power plant in China. They performed a sensitivity analysis by examining the competition from a nearby biomass power plant, the price of agricultural biomass, and preferential policy. Santibañez-Aguilar, González-Campos, Ponce-Ortega, Serna-González, and El-Halwagi [20] presented a multi-objective, multi-period MILP model to design biorefinery supply chains in Mexico. The proposed model minimizes the environmental impact and maximizes the profit of the supply chain, as well as the number of jobs generated by implementation of facility, using ε-constraint method to solve the proposed model. Höhn, Lehtonen, Rasi, and Rintala [2] developed a biomethane potential map by integrating the quantityof

Table 1
Bioethanol facility location criteria.

Category	Criteria	Sub-criteria		Number of references
Social	Policy and legal support			2
		• Legal and regulatory compliance		1
		• Government support degree		10
		• Obtaining of construction license		1
		• Changes in the energy policy		1
		• International relations		1
	Work force			8
		• Percentage of highly qualified people		4
		• Availability of labor (Unemployment rate)		5
		• Community language		1
		• Equal and nondiscriminatory opportunities in recruitment and during employment		3
	Acceptance			19
		• Poverty and income		3
		• Work safety		3
		• Minimum Wage		1
	Quality of life			9
		• Lifecycle cost		1
		• Health		1
		• Education		2
		• Culture		1
		• Housing		1
		• Public security		2
		• Personnel development		1
	Impact on Society			1
		• Security for food supply		2
			• Water shortage	
			• Lack of land	
		• Society benefits		
			• Cultural development	1
			• Improvement of life quality	2
			• Jobs generated	6
			• Skill development of local workers	1
			• Infrastructure and industrial development	9
		• Protection of human health (Distance to the residential area or density of the population)		24
		• Economic disadvantage		
			• Effect on agriculture	6
			• Effect on tourism (Distance to historically important areas)	12
Environmental	Ecologically sensitive areas			3
		• Tropical forest		
		• Biosphere reserve		
		• Important lake		
		• Coastal areas and rich in coral formation		
	Effect on protected areas (Distance from protected areas and wildlife designations)			11
	Ash management			3
	Effect on resources and natural reserves			7
		• Water resources		3
		• Land (Soil)		14
	Greenhouse gas emissions			27
	Energy-saving			1
	Distance from historical-tourist areas			12
	Agrological capacity			1
Economic	Investment costs			32
		• Topographical features		28
		• Installed equipment cost (Implementation cost)		2
		• Field cost		17
		• Reclamation cost		2
		• Infrastructure cost		11
		• Provincial finance subsidies		3
	Production and operation costs			29
		• Labor cost		6
		• Tax structure and tax incentives		6
		• Inventory cost		6
		• Maintenance cost		19

(continued on next page)

Table 1 (*continued*)

Category	Criteria	Sub-criteria		Number of references
			• Intensity of natural disasters	
			• Volcanic hazard	
			• Earthquake	
			• Storm	
			• Thunderbolt	
			• Access to expert	
			• Access to equipment	
		• Climate condition		24
			• Moisture	
			• Pressure	
			• Temperature	
		• Biomass price		17
		• Waste disposal		3
		• Utility costs		10
			• Fossil fuel cost	5
			• Electricity price	4
			• Water price	2
	Costs associated with logistic activity			4
		• Transportation cost		36
		• Stability in supply		
			• Resources	48
			• Variety of raw materials	7
			• Number of suppliers	2
			• Number of plants	3
			• Area potential	5
			• Land availability	5
			• Soil quality	2
		• Coordination among supply chain members		1
			• Resources /Proximity to resources (Distance)	1
			• Demand /Proximity to the demand point (Distance)	16
		• Demand		12
		• Transportation accessibility		44
			• Proximity to rail way	
			• Proximity to airport	
			• Proximity to highway) Road(	
	Safety and security cost (Risk)			2
		• Intensity of natural disasters		
			• Volcanic hazard	
			• Earthquake	
			• Storm	
			• Thunderbolt	
		• Military threats		
		• Site near to sensitive military zones		1
		• Supportive centers		1
			• Fire station	
			• Military bases	
	Possibility of capacity expansion in future			5
	NPV			5
	Payback period			4

available feedstock and spatial distribution in southern Finland and suggested site locations for biogas plants, using a road network analysis optimized in transportation effect. Duarte, Sarache, and Costa [21] applied MILP to determine the best location for a bioethanol power plant in Colombia, based on maximum profit.

Silva, Alçada-Almeida, Dias [22] examined the best location for a biogas plant in Portugal, using GIS and ELECTRE. Occupation and land use, distance to highways, regional and national roads, distance to electricity grid medium and high voltage lines, and distance to urban, industrial, and commercial infrastructure were among the criteria used to assess potential locations. Kühmaier, Kanzian, Stampfer [23] selected the most suitable locations for generating energy from wood in Italy, using infrastructure, weather and climate, construction costs and land use as the most important location assessment criteria, and using AHP, fuzzy set theory and GIS to determine the importance of criteria and the assessment of locations. Franco, Bojesen, Hougaard, and Nielsen [24] included considered planning zone suitability, distance to transport economic optimal sites, production potential, population density and distance to heating plants among the most influential factors affecting biogas plants location in Denmark, using GIS, LLSM (Logarithmic Least Squares Method)-AHP, and AHP-FWOD (Fuzzy Weighted Overlap Dominance) to identify the best alternatives. LLSM-AHP was used to calculate the attributes of the alternatives. AHP-FWOD was applied to aggregate and exploit measurements in interval form and determine the appropriate degree for each alternative.

Galvez, Rakotondranaivo, Morel, Camargo, and Fick [25] examined a reverse logistics network design problem for a biogas plant in Nancy, France, proposing a systematic approach, integrating MILP optimization, which minimizes total costs, and using AHP to select the best layout of chain components in a format of different scenarios. The global costs associated with running the network, the total distance covered to transport the waste, the quantity of CO_2 emissions and the technical feasibility of implementing the various scenarios were used as selection criteria. Delivand, Cammerino, Garofalo, and Monteleone [26] determined the optimal locations of bioenergy facilities in Italy, using an integration of AHP and GIS, followed by a logistics cost and greenhouse gas emission analysis, based on criteria such as distance from the road, slope, and distance from industrial areas to determine the optimum location of a biomass power plant. Ubando, Promentilla, Culaba, Tan [27] identified suitable locations for the cultivation of algae in the Philippines using Spatial Spray. The natural resources available, the social dimension, the number of power plants and existing demand for fuel in each region were used as the most important selection criteria. Cebi, Ilbahar, and Atasoy [28] proposed a hybrid model for a biomass power plant location in Turkey, using fuzzy sets, AHP, Opinion Aggregation method and Information Axiom method. Opinion aggregation was used to aggregate expert opinions. The information axiom approach examines the amount of information in relation to the envisaged purposes, while main and alternative biomass produced in the region, the energy potential of the region, the capacities of the energy production, and setup and operating costs are used as criteria to assess potential locations.

Existing literature reveals that there are many criteria which affect the optimal location of biofuel facility. Since, by increasing the number of criteria in each level and dimension, the decision-maker's discrimination power [29] in criteria weighting process is reduced, we have tried to limit the number of criteria using the principle of decomposition, which allows a complex problem to be structured into a hierarchy of clusters and sub-clusters. According to this principle, the components of a cluster are a set of factors that have common features and directly affect a specific goal [30]. In principle of decomposition, parent of a cluster is goal of each cluster. A cluster that has been created by the decomposition principle can improve the rate of consistency provided by human mind in the weighting process. We used references, definition and impact of each criterion for recognizing common feature (s) of each cluster created in the proposed framework (see Table 1).

In existing literature, there are some criteria (see Table 2) that have been included under two dimensions. Since including the same criteria in more than one dimension increases the complexity of the weighting process and the inconsistency rate, we decided putting them into only one dimension. To that end, we considered the characteristics of the case country, Iran, and the number of references of each criterion in each dimension for categorizing the criteria into the proposed framework.

In this study, we have decided to use a newly developed MCDM method, called Best-Worst Method (BWM). The BWM is preferred to the AHP, which has been extensively used for biofuel facility location in existing literature. Some features that justify the application of BWM in comparison to AHP are presented below:

- BWM is a vector-based method, which requires fewer comparisons compared to AHP. That is to say, BWM needs $2n - 3$ pairwise comparisons, while, for AHP, $n(n - 1)/2$ pairwise comparisons are needed [31].
- BWM provides more consistent comparisons compared to AHP. Consistency means the extent to which there is veracity between the obtained weights and the pairwise comparison data provided by the decision-maker(s). For a mathematical definition of consistency and a detailed comparison between the consistency ratio of AHP and BWM, see [31]. The higher the consistency in a comparison system, the more reliable the results.
- BWM works with integers, while AHP uses fractional numbers as well as integers, which has shown by [31,32] to be problematic.
- BWM is easy to understand and also easy to revise by the respondents [31].

Table 2
Criteria that affect more than one dimension based on literature.

Criteria	Dimensions		
	Economic	Social	Environmental
Protection of human health (Distance to the residential area or density of the population)		*	*
Effect on agriculture		*	*
Effect on tourism (Distance to historically important areas)		*	*
Provincial finance subsidies	*	*	
Intensity of natural disasters	*		*
Climate condition	*		*
Waste disposal	*		*
Coordination among supply chain members	*	*	
Safety and security cost (Risk)	*	*	

3. Research methodology

The research method used in this study was divided into three steps. In the first step, evaluation criteria were extracted from the related articles, categorizing them according to the three dimensions of sustainability (economic, environmental, and social (see Section 2)). In the second step, relevant criteria were selected to evaluate alternatives in accordance with expert opinions regarding the characteristics of the country in question, Iran. Determining the ideal number of sub-criteria [33], improving the decision-maker's discriminatory power [29] and optimizing the reliability of comparison between criteria [31] are the reasons for the criteria screening, for which purpose experts were consulted via an online questionnaires using a five-point Likert scale. To screen the criteria, we consulted eight experts. After collecting the questionnaires, and after checking some different thresholds above 3.0 (out of 5), a minimum score of 3.6 for each criterion was used as a threshold for selecting that criterion. The reason we came up with threshold is that by using this value, the number of sub-criteria in each dimension is balanced. Fig. 1 shows the result of criteria screening. In the third step, we used BWM to assess and select the best location, for which an online questionnaire was designed based on BWM by using the criteria identified in the second step. We then, by using the optimization model of BWM, found the weights of the criteria per respondent and used arithmetic mean to calculate the aggregated weight for each criterion.

3.1. Case study

In this study, we evaluated the suitability of Iran's for a bioethanol facility location. Iran is one of the developing countries that has extreme levels of air pollution. According to a ranking based on the Environmental Performance Index (EPI), Iran ranks 83th among 138 countries [34], and thirteenth when it comes to carbon dioxide emissions. According to forecasts, the country's energy demand will increase by an average annual rate of 2.6% between 2003 and 2030 [34], while 97 percent of its energy comes from fossil fuels [35]. At the same time, the country has ample biomass resources, for example starchy and lignocellulosic material, which are suitable for the production of bioethanol [36]. The energy produced by bioethanol is relatively high, which means it has the potential to be used as a fuel for transport [6]. If Iran uses existing biomass resources to produce bio-ethanol, it can easily supply 25% of domestic gasoline demand. In fact, Iran has the potential to produce 4.91 giga-liters of bioethanol [37].

3.2. BWM

BWM is a pairwise comparison-based multi-criteria decision-making method. It has already been applied in different areas, such as green

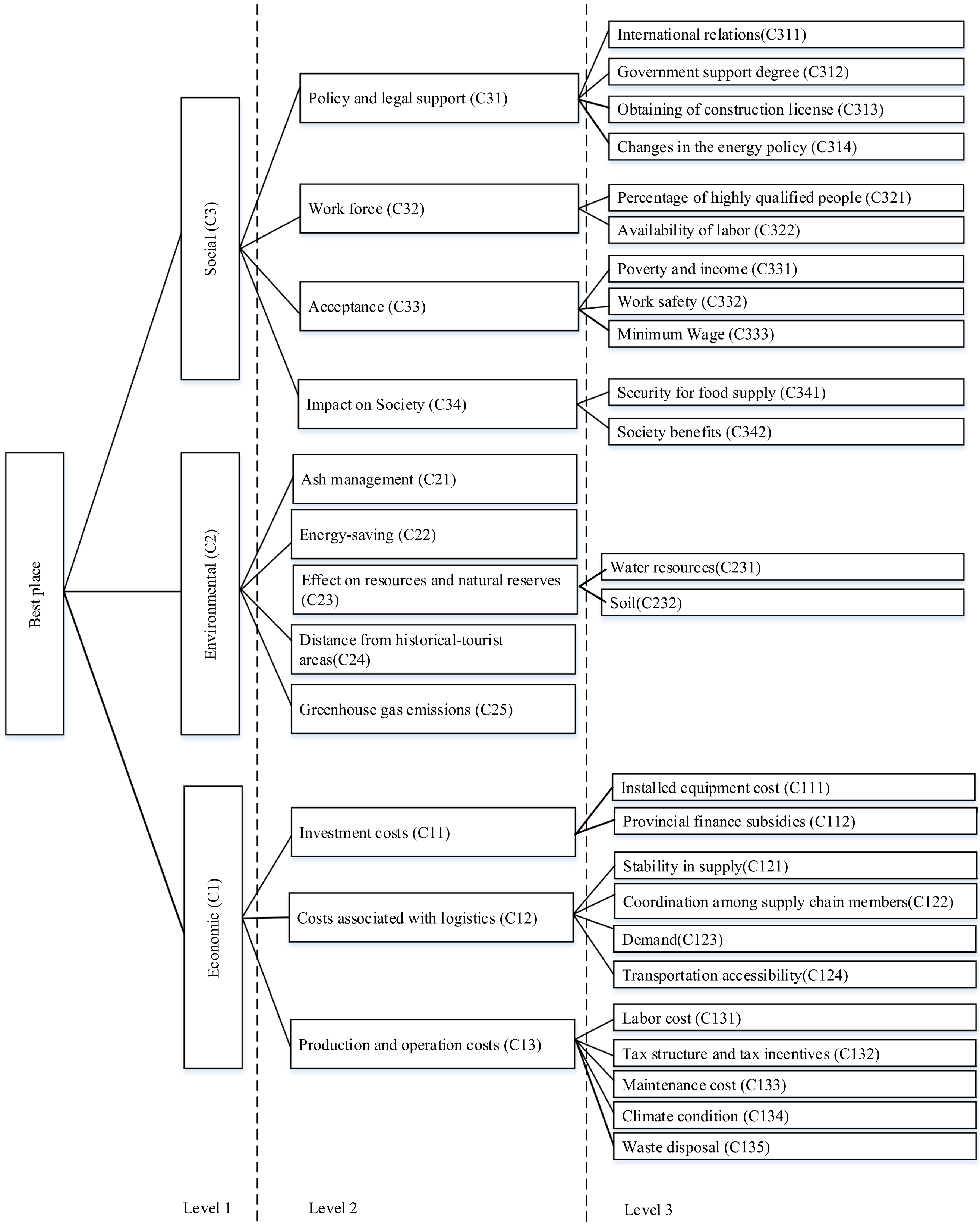

Fig. 1. Hierarchical tree for screened criteria.

innovation [38], technology evaluation and selection [32,39], logistics performance evaluation [40], and research and development performance evaluation [41]. To determine the weights of the criteria $(w_1^*, w_2^*, \cdots, w_n^*)$ using BWM, the following steps should be followed [31,42]:

Step 1. Determine a set of decision criteria $\{c_1, c_2, \cdots, c_n\}$.

Step 2. Determine the best (B) and the worst (W) criteria.

Step 3. Conduct the pairwise comparison between the best criterion and the other criteria.

In this step, decision-makers determine their preference, using a number from 1 to 9 (where 1 is equally important and 9 is extremely more important). Vector $A_B = (a_{B1}, a_{B2}, \cdots, a_{Bj}, \cdots, a_{Bn})$ is the result of Best-to-Others comparisons, where a_{Bj} indicates the preference of the criterion B over criterion j.

Step 4. Conduct the pairwise comparison between the other criteria and the worst criterion.

In this step, decision-makers determine their preference using a number from 1 to 9. Vector $A_w = (a_{1W}, a_{2W}, \cdots, a_{jW}, \cdots, a_{nW})$ is the result of Others-to-Worst comparisons, where a_{jW} indicates the preference of criterion j over the criterion W.

Step 5. Compute the optimal weights $(w_1^*, w_2^*, \cdots, w_n^*)$.

For each pair of w_B/w_j and w_j/w_W the optimal weight should provide $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. For satisfying them, the maximum differences of $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j should be minimized, which is translated to the following mathematical model:

$$\begin{aligned} &\min \max_j \left\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right|\right\} \\ &\text{s. t} \\ &\sum_{j=1}^n w_j = 1 \\ &w_j \geq 0, \quad \text{for all } j \end{aligned} \tag{1}$$

Model (1) can be transferred into:

$$\begin{aligned} &\min \xi \\ &\text{s. t.} \\ &\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \quad \text{for all} j \\ &\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \quad \text{for all} j \\ &\sum_{j=1}^n w_j = 1 \\ &w_j \geq 0, \quad \text{for all} j \end{aligned} \tag{2}$$

For a problem with more than three criteria and $\xi^* \neq 0$, model (2) may result in multiple optimal solutions. The following two linear programming problems are then solved to determine the minimum and maximum optimal values of the weight of each criterion.

$$\begin{aligned} &\min \ w_j \\ &\text{such that} \\ &|w_B - a_{Bj} w_j| \leq \xi^* w_j, \\ &|w_j - a_{jW} w_W| \leq \xi^* w_W, \\ &\sum_{j=1}^n w_j = 1, \\ &w_j \geq 0, \quad \text{for all} j. \end{aligned} \tag{3}$$

$$\begin{aligned} &\max \ w_j \\ &\text{such that} \\ &|w_B - a_{Bj} w_j| \leq \xi^* w_j, \\ &|w_j - a_{jW} w_W| \leq \xi^* w_W, \\ &\sum_{j=1}^n w_j = 1, \\ &w_j \geq 0, \text{for all} j. \end{aligned} \tag{4}$$

where $\xi^*$is the optimal objective value of Model (2).

Solving (4) and (5) for each criterion, we get w_j^{min*} and w_j^{max*} respectively, and then [43]:

$$w_j^* = \frac{(w_j^{min*} + w_j^{max*})}{2} \tag{5}$$

To check the consistency of the comparisons, we use the following formula:

$$\text{Consistency Ratio} = \frac{\xi^*}{\text{Consistency index}} \tag{6}$$

The consistency index can be retrieved from Table 3.

Table 3
Consistency index (CI) [31].

a_{BW}	1	2	3	4	5	6	7	8	9
CI (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

As the consistency ratio decreases, the veracity of the comparisons increases.

If there are different levels of criteria (which there are in this study, see Fig. 1), we first determine the local weights for each level, after which we need to specify the global weight of each sub-criterion, which is done by multiplying its local weight by the weight of the category to which it belongs. Having determined the final (global) weight of criteria, we can compute the overall score of alternative i as follows:

$$V_i = \sum_{j=1}^n w_j u_{ij} \quad \text{for all} \quad i \tag{7}$$

where u_{ij} is the normalized value of alternative i in criterion j. u_{ij} is the actual score of alternative i in criterion j. To calculate the amount of u_{ij}, we used Eqs. (8) and (9). Eq. (8) is used for positive criteria, while Eq. (9) is suitable for negative criteria.

$$u_{ij} = \frac{x_{ij}}{\sum_j x_{ij}} \quad \text{for all} i \tag{8}$$

$$u_{ij} = \frac{1/x_{ij}}{\sum_j 1/x_{ij}} \quad \text{for all} i \tag{9}$$

3.3. Data recollection

Since energy production from biomass is a new industry in Iran, scientific researchers are the best candidates to answer questions about selecting locations for a bioethanol facility. To screen the criteria and then determine their weight, we surveyed 8 and 41 experts, respectively. The experts who responded to the survey were the faculty members and PhD candidates at some Iranian universities working in applied chemistry bio-systems, engineering and chemical engineering, energy engineering, as well as some practitioners in Research Institute of Petroleum Industry in Iran, Renewable Energy and Energy Efficiency Organization and Niroo Research Institute. All these experts have conducted extensive studies on biomass in Iran, as well as having extensive practical experience in producing different types of energy from biomass. We identified them by reviewing their profiles on the websites of the universities and research institutes. In Table 4, the specifications of the experts are presented. The data collection process for steps two and three took 21 and 44 days, respectively.

In study, we assessed the suitability of the various provinces of Iran as alternatives for establishing a bioethanol facility, using criteria like Provincial Finance Subsidies, Tax Structure and Tax Incentives, Climate Condition and International Relations. The value for each province with regard to the criteria was determined by experts in the final part of BWM survey using a ten-point Likert scale. The information regarding other criteria was collected from the websites of the Statistical Center of Iran, the Ministry of Science, Research and Technology, the Institute for Research and Planning in Higher Education, the Ministry of Culture and Islamic Guidance, the Ministry of Housing and Urban Development, the Law Enforcement Force of the Islamic Republic of Iran, the Ministry of Health and Medical Education, the Ministry of Petroleum and Iran Meteorological Organization. Table B in the Appendix shows the website addresses used for data recollection.

4. Result and discussion

In this section, we start by presenting the results and discussion the

Table 4
Specifications of experts.

Respondents	For screening criteria	Average years of work experience	For weighting criteria	Average years of work experience
Faculty members (Ph.D.)	4	8.5	16	13.9
Ph.D. candidates	2	2.5	13	3.5
Research Institute of Petroleum Industry	1	5	2	7.5
Renewable Energy and Energy Efficiency	–	–	3	7.7
Niroo Research Institute	1	4	7	7.6

global weights of the criteria and sub-criteria at the main level and the three dimensions (economic, environmental and social), after which the best location for establishing bioethanol facility in Iran is selected.

4.1. Main level

To determine the best location for the bioethanol facility, we evaluated each place based on three dimensions of sustainability. Table 5 shows the mean and standard deviation of the weight of those three dimensions. The column of CR in Table 5 is the consistency ratio of pairwise comparisons. According to the experts' opinion, the economic dimension is the most important, followed by social and environmental dimensions (see Table 5).

That may have to do with the economy of a developing country like Iran, where economic issues tend to be considered more important than environmental aspects [44].

4.2. Economic

The weights of the sub-criteria in levels two and three of the economic dimension are shown in Tables 6 and 7, respectively. Like the results of studies by Voets, Neven, Thewys, and Kuppens [16] and Vafaeipour, Zolfani, Varzandeh, Derakhti, and Eshkalag [45], investment costs were identified by the experts as being the most influential factor in the economic category (see Table 6).

Unsustainable economic conditions, sanctions, and the costs of the equipment used to generate energy from biomass [46] could be the reasons why investment costs were given such a high ranking, because these conditions increase the risk involved in the investment and exploitation of renewable energy sources in Iran [47]. In addition, Iran has large oil and gas reserves, and few people are interested in renewable energies that are more expensive than fossil fuel [48]. The costs associated with logistics were assigned the lowest weight, after operational and production costs, because the different transportations modes in Iran are virtually identical in terms of costs and accessibility [49].

Financial subsidies represent the most important sub-criterion of the category of investment costs (see Table 7). The importance of this particular sub-criterion in this study, compared to studies like Wu, Zhang, Yuan, Geng, and Zhang [50] stems from the high energy production facility costs and the high investment risks, due to the volatility of Iran's economic conditions [46]. Government support, for instance in the form of long-term loans and trade facilitation, not only reduces the costs, but also lowers the psychological threshold for investors wanting to enter this field. Stability in supply was identified by experts as the most important sub-criterion of costs associated with logistic activity (see Table 7), due to the fact that successive droughts have affected a major source of bio-ethanol (agriculture) in Iran [51]. The results are consistent with those reported by Voets, Neven, Thewys, and Kuppens [16] and Vafaeipour, Zolfani, Varzandeh, Derakhti, and Eshkalag [45]. Demand and coordination among supply chain members are two other important criteria in this category.

Roughly equal population density, a similar situation in the supply and demand of raw materials and manufactured products in most of the provinces of Iran and the absence of bioethanol facilities [52] are the reasons for the low weight of coordination among supply chain members. According to the experts, labor cost and maintenance cost are the main sub-criteria in the production and operational costs category (see Table 7). Complexity of the bioethanol production process [53], along with the lack of production history in Iran [54] and the demanding work involved in bioethanol production, could be the reasons for the high weights of labor and maintenance costs. Maintenance costs were also mentioned as being important in the studies by Wu, Zhang, Yuan, Geng, and Zhang [50] and Vafaeipour, Zolfani, Varzandeh, Derakhti, and Eshkalag [45]. Tax structure incentives and waste disposal are two other important sub-criteria in this category. Climate condition was considered as the least important sub-criteria of operation and production costs (see Table 7), because weather conditions are very similar in all provinces of Iran [55].

Table 5
Main criteria weight.

Criteria	Weight	Standard deviation	Rank	CR
Economic	0.462	0.156	1	0.195
Environmental	0.212	0.113	3	
Social	0.326	0.148	2	

Table 6
Sub-criteria weight for economic dimension in level 2.

Sub-criteria	Weight	Standard deviation	Rank	CR
Investment costs	0.446	0.148	1	0.145
Costs associated with logistics	0.223	0.152	3	
Production and operation costs	0.331	0.106	2	

4.3. Environmental

We present the weights of the sub-criteria in levels two and three of environmental dimension in Tables 8 and 9 respectively. Experts selected effect on resources and natural reserves as the main sub-criterion in the environmental category (see Table 8), because agricultural products and forest waste are the principal sources of bioethanol production worldwide [56], which means that forests, water resources and soil may be affected by excessive use.

According to the experts, the main source that may be affected the most in Iran is water (see Table 9), Iran being a dry and semi-arid country which, in recent years, has had to deal with droughts [57]. Energy saving, greenhouse gas emissions, ash management and distance from historical-tourist areas are other important criteria in this category (see Table 8).

4.4. Social

The weights of the sub-criteria in levels 2 and 3 for social dimension are presented in Tables 10 and 11, respectively. Political and legal support was identified as the most important sub-criterion in the social category (see Table 10). The inconsistency between law and policy in Iran could be the reason for selecting it as a significant sub-criterion [58]. It has led to social dissatisfaction and the unjust distribution of wealth for people in various provinces of Iran [59]. Work force,

Table 7
Sub-criteria weight for economic dimension in level 3.

Category	Sub-criteria	Weight	Standard deviation	Rank	CR
Investment costs	Provincial finance subsidies	0.543	0.284	1	0.00
	Installed equipment cost	0.457	0.284	2	
Costs associated with logistics	Stability in supply	0.320	0.117	1	0.225
	Coordination among supply chain members	0.190	0.081	4	
	Demand	0.266	0.140	2	
	Transportation accessibility	0.223	0.099	3	
Production and operation costs	Labor cost	0.296	0.091	1	0.229
	Tax structure and tax incentives	0.175	0.048	3	
	Maintenance cost	0.251	0.071	2	
	Climate condition	0.119	0.056	5	
	Waste disposal	0.158	0.043	4	

Table 8
Sub-criteria weight for environmental dimension in level 2.

Sub-criteria	Weight	Standard deviation	Rank	CR
Ash management	0.164	0.081	3	0.242
Effect on resources and natural reserves	0.256	0.096	1	
Energy-saving	0.222	0.080	2	
Distance from historical-tourist areas	0.146	0.058	4	

Table 10
Sub-criteria weight for social dimension in level 2.

Sub-criteria	Weight	Standard deviation	Rank	CR
Policy and legal support	0.320	0.137	1	0.231
Work force	0.303	0.106	2	
Acceptance	0.189	0.079	3	
Impact on Society	0.188	0.076	4	

acceptance and impact on society are other important sub-criteria in the social category. The similarity of infrastructure in the different provinces of Iran could be why impact on society was indicated as being the least important factor. The degree of government support was identified as a main criterion among the sub-criteria of political and legal support (see Table 11), because, in most societies, government is responsible for monitoring and supporting businesses in terms of proper implementation [60].

Because of special economic circumstances, government support should be more important and stronger in Iran, because, without government support, it is almost impossible to invest in the type of facility under study. Changes in the country's energy policy and the need to obtain a construction license are two other important criteria, after government support. The war and lack of progress in neighboring countries in the production of biofuels [61] and Iran's need for bioethanol are the reasons why international relations are considered the least important factor among the political and legal support sub-criteria. According to the experts, the percentage of highly qualified people is more important than the availability of labor in the work force category (see Table 11). Because unemployment is high in Iran, especially among people graduating from university [62], if the facility were to be established in a place with a high percentage of educated people, they would benefit, directly and indirectly. Among the three sub-criteria of acceptance, minimum wage was identified as the primary criterion by the experts (see Table 11). This may be due to high inflation and high unemployment levels in Iran [62]. A location in a low income area may be the most suitable option for establishing a facility, because it would bring economic prosperity to the people in the area. Work safety is the second least important criterion, after poverty and income (see Table 11), perhaps due to the low probability of error in the bioethanol production process [63] in comparison with similar products, such as petrochemicals. As shown in Table 11, food supply security and societal benefits are almost equally important in the impact on society category. The growing population of Iran and the increased attention to physiological needs, including food and water [61], may be the reasons for the slightly higher importance of the sub-criterion food supply security (see Table 11).

4.5. Alternatives' rank

To rank the provinces of Iran as potential locations for a bioethanol facility, V_i in Eq. (7) was calculated. The weight (w_j) and the provinces' scores on the criteria (u_{ij}) are two of the factors used to calculate V_i. We used the global weight of criteria shown in Table 12 for w_j and the normalized data from Eq. (8) or Eq. (9) for u_{ij}(see Table C in Appendix).

According to V_i (see Table 13), Khuzestan and Tehran are the best alternatives, with little difference between the two. Fig. 2 shows the scores of the three first and the worst provinces (alternatives) compared to the average. The performance of Khuzestan, Tehran and Qom in 18, 9 and 8 criteria (out of 28) are respectively better than the average (see Fig. 2). Khuzestan is a southern province with a population of more than 4.7 million, making up 5.9% of the country's entire population. Government support for the development of the province, a cheap labor force, international relations and suitable weather conditions are important factors for selecting of Khuzestan as the best place (see Fig. 2).

Tehran, the capital of Iran, with a population of about thirteen million, covering a geographical area of about 570 km^2, ranks first in terms of population, air pollution, unemployment and the number of educated people among Iran's provinces, as a result of which (see Fig. 2), Tehran is the second-best alternative for establishing a bioethanol facility in Iran, with Qom coming in third place.

Qom is located in the central northwest of Iran. It has a population of about 1 million. The city performs besy in tax structure, tax incentives and maintenance cost, among the 28 criteria (see Fig. 2). Fig. 3 shows the location of three top alternatives. Based on the research

Table 9
Sub-criteria weight for environmental dimension in level 3.

Category	Sub-criteria	Weight	Standard deviation	Rank
Effect on resources and natural reserves	Water resources	0.770	0.075	1
	Soil	0.230	0.075	2

Table 11
Sub-criteria weight for social dimension in level 3.

Category	Sub-criteria	Weight	Standard deviation	Rank	CR
Policy and legal support	International relations	0.183	0.091	4	0.240
	Government support degree	0.301	0.133	1	
	Obtaining of construction license	0.252	0.109	3	
	Changes in the energy policy	0.264	0.126	2	
Work force	Percentage of highly qualified people	0.583	0.256	1	–
	Availability of labor	0.417	0.256	2	
Acceptance	Poverty and income	0.342	0.169	2	0.197
	Work safety	0.307	0.152	3	
	Minimum wage	0.351	0.186	1	
Impact on Society	Security for food supply	0.495	0.273	2	–
	Society benefits	0.505	0.273	1	

outcome, Alborz, Kerman and Yazd are among the least likely candidates for establishing bioethanol production facility.

5. Conclusion and further research

The aim of this study has been to determine which of the provinces of Iran would make the best candidate as a location for a bioethanol production facility. We started by identifying the important factors that would affect the location of a bioethanol facility, by reviewing related studies, after which we created a framework of criteria using the sustainability approach. The factors we identified were then assessed by experts and 28 criteria were selected to evaluate the locations. The Best-Worst Method was used to weight the criteria and determine the optimal location. We used an online survey to collect expert opinions. The fact that there is a limited number of experts operating in the area of biofuel production, and that some of them decided not to cooperate, combined with a lack of data regarding alternatives on some criteria were among the limitations of this study.

Based on the results of the weighting, the economic criteria were identified as being the most important criteria on level one. According to the experts, investment costs is the main criterion of the economic dimension. Stability in supply, provincial subsidies, and labor and maintenance cost were viewed as the most important sub-criteria on level three of the economic category, while the experts identified

Table 12
Global weight of sub-criteria.

Row	criteria	Weight	Rank
1	Installed equipment cost	0.0943	2
2	Provincial finance subsidies	0.1119	1
3	Stability in supply	0.0331	11
4	Coordination among supply chain members	0.0196	24
5	Demand	0.0275	17
6	Transportation accessibility	0.0230	21
7	Labor cost	0.0454	5
8	Tax structure and tax incentives	0.0269	18
9	Maintenance cost	0.0384	9
10	Climate condition	0.0182	27
11	Waste disposal	0.0242	20
12	Ash management	0.0348	10
13	Energy-saving	0.0471	4
14	Water	0.0418	7
15	Soil	0.0125	28
16	Distance from historical-tourist areas	0.0309	14
17	Greenhouse gas emissions	0.0448	6
18	International relations	0.0191	25
19	Government support degree	0.0314	12
20	Obtaining of construction license	0.0262	19
21	Changes in the energy policy	0.0276	16
22	Percentage of highly qualified people	0.0575	3
23	Availability of labor	0.0411	8
24	Poverty and income	0.0210	23
25	Work safety	0.0189	26
26	Minimum wage	0.0216	22
27	Security for food supply	0.0303	15
28	Society benefits	0.0309	13

Table 13
Ranking result of Iran's provinces for bioethanol production.

Row	Provinces of Iran	V_i	Rank
1	Khuzestan	0.0477	1
2	Tehran	0.0450	2
3	Qom	0.0394	3
4	Golestan	0.0368	4
5	Ilam	0.0365	5
6	Hormozgan	0.0363	6
7	Razavi Khorasan	0.0359	7
8	Kordestan	0.0357	8
9	South Khorasan	0.0344	9
10	Zanjan	0.0343	10
11	Ardabil	0.0336	11
12	East Azarbaijan	0.0331	12
13	Gilan	0.0317	13
14	Qazvin	0.0317	14
15	Fars	0.0316	15
16	Kohgeluyeh and Boyer-Ahmad	0.0312	16
17	Semnan	0.0310	17
18	Markazi	0.0306	18
19	Hamadan	0.0305	19
20	Kermanshah	0.0302	20
21	Bushehr	0.0292	21
22	Chaharmahal and Bakhtiari	0.0291	22
23	Isfahan	0.0287	23
24	Lorestan	0.0285	24
25	North Khorasan	0.0284	25
26	West Azarbaijan	0.0284	26
27	Sistan and Baluchestan	0.0281	27
28	Mazandaran	0.0276	28
29	Yazd	0.0255	29
30	Kerman	0.0255	30
31	Alborz	0.0238	31

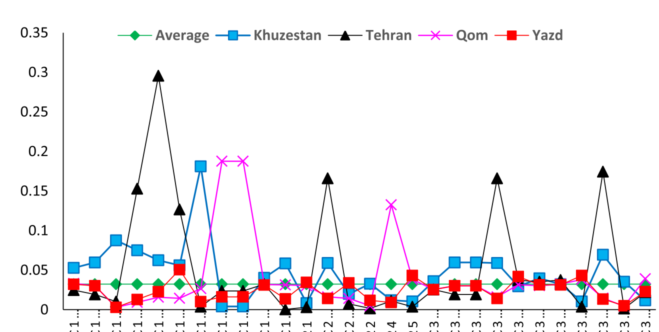

Fig. 2. The scores of four alternatives (three top provinces and the worst one) in 28 criteria.

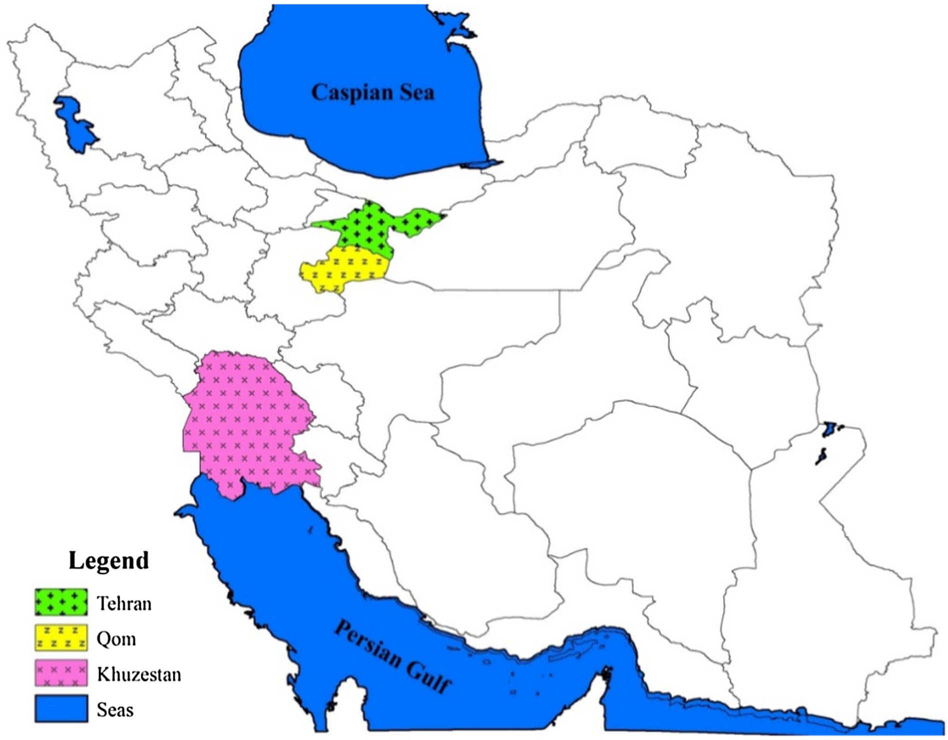

Fig. 3. Best alternatives for bioethanol facility location in Iran.

political and legal support as the most important factor in the social category. The degree of government support, minimum wage, percentage of highly qualified people and food supply security were identified as evaluation sub-criteria on level three of the social category. In the environmental dimension, the effect on resources and natural reserves, and water resources were viewed as the main sub-criteria on levels two and three. Analysis shows that provincial subsidies is the most influential criterion for selecting the best location. In developing countries, the government is responsible for developing and promoting industries. The final result of this study is that Khuzestan is the best location for establishing a bioethanol facility in Iran (closely followed by Tehran and Qom).

The proposed framework, the influential factors we identified, and their weights have the following implications for practitioners and scholars. Public policy-makers can use the information presented in this paper to support their decision about the development of renewable energy in Iran. There are many different criteria in a product's supply chain that affect the possible location of a facility. However, when the sustainability score is good, a location can have great potential. But other factors, such as dynamics in the transportation of raw materials and products, should be considered as well. As such, using the results of this paper as an objective function in a bioethanol supply chain network's model can be useful. The proposed framework can also be used for other liquid biofuels, like bio-diesel and bio-methane, which is something future research can examine. In addition, locating a bioethanol facility and considering different types of technologies is also suggested as a subject for further research, because, for each technology, raw material, knowledge and expertise, investment costs and environmental aspects may have a different effect

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.03.054.

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