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# A hierarchical decision making model for the prioritization of distributed generation technologies: A case study for Iran

Ali Zangeneh [a,*], Shahram Jadid [a], Ashkan Rahimi-Kian [b]

[a] Center of Excellence for Power System Operation and Automation, Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran
[b] CIPCE, School of ECE, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

The purpose of this paper is to present an assessment and evaluation model for the prioritization of distributed generation (DG) technologies, both conventional and renewable, to meet the increasing load due to the growth rate in Iran, while considering the issue of sustainable development. The proposed hierarchical decision making strategy is presented from the viewpoint of either the distribution company (DisCo) or the independent power producer (IPP) as a private entity. Nowadays, DG is a broadly-used term that covers various technologies; however, it is difficult to find a unique DG technology that takes into account multiple considerations, such as economic, technical, and environmental attributes. For this purpose, a multi-attribute decision making (MADM) approach is used to assess the alternatives for DG technology with respect to their economic, technical and environmental attributes. In addition, a regional primary energy attribute is also included in the hierarchy to express the potential of various kinds of energy resources in the regions under study. The obtained priority of DG technologies help decision maker in each region how allocate their total investment budget to the various technologies. From the performed analysis, it is observed that gas turbines are almost the best technologies for investing in various regions of Iran. At the end of the decision making process, a sensitivity analysis is performed based on the state regulations to indicate how the variations of the attributes' weights influence the DG alternatives' priority. This proposed analytical framework is implemented in seven parts of Iran with different climatic conditions and energy resources.



## 1. Introduction

Energy has been recognized as one of the most essential and crucial inputs for social and economic development. Nowadays, the huge demand for energy to facilitate economic growth and social development is largely met with fossil fuels. However, the current energy system is not sustainable due to its significant negative effects on the well-being of humans and ecosystems (GSPM, 2002).

Sustainable development has been defined in many ways, including development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). It calls for a long-term energy policy that puts increasing emphasis on the use of renewable sources of energy, the demand as well as supply-side management, and the optimization of the efficiency of the generation, distribution and use of energy. Energy consumption is rapidly increasing in developing countries, which affects global climate change and global and regional energy management (Urban et al., 2007). Among the various kinds of energy carriers, electricity has a special role in helping to attain social and economic development. Electricity consumption in Iran, as a developing country, is intensively growing not only due to increasing social welfare, but also because of low energy prices that lead to inefficient usage. The growth rate of electricity sold to the household sector in Iran was determined to be 7.2% during the period from 1991 to 2005. Although government and legislators must apply policies such as those that actualize the price of energy by removing energy subsidies or institute demand-side management activities (e.g., peak shaving, peak shifting, etc.) to reduce energy consumption patterns (Karbassi et al., 2007), they also have to consider plans for increasing the capacity of energy production for the country. However, it is important to note that the government sector may not be able to expand electricity generation for all sectors and regions efficiently. A greater scope for the participation of private entities in electricity generation and more competition should be encouraged in this field. One of the favorable grounds for the privatization of electrical generation from the viewpoint of investors is to invest in distributed generation (DG) due to its low investment cost and financial risk. In recent years, the regulatory part of the ministry of energy (MOE) has encouraged investors and companies to invest in distributed generation units

* Corresponding author. Tel.: +98 21 77491223; fax: +98 21 77491242.
*E-mail addresses:* zangeneh@iust.ac.ir (A. Zangeneh), jadid@iust.ac.ir (S. Jadid).

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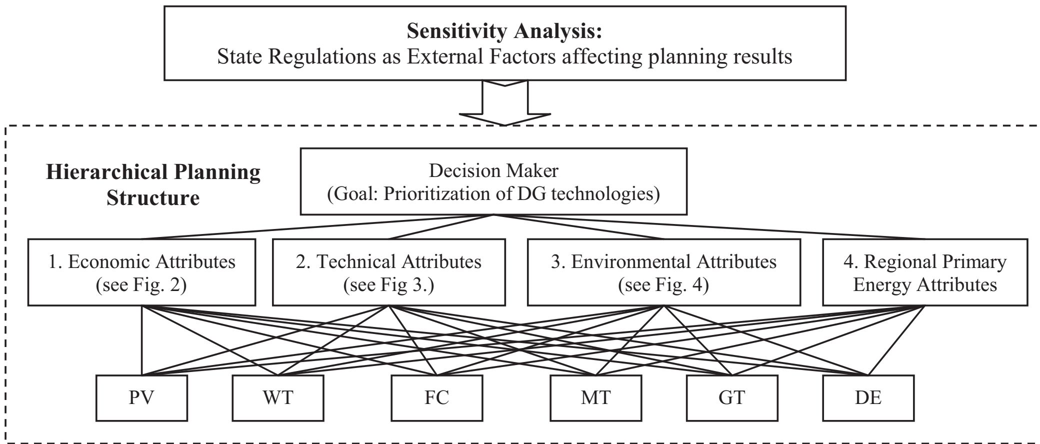


**Fig. 1.** Proposed hierarchical decision making structure to prioritize DG technologies.

to harness this increasing demand. It is one of the new strategies of the MOE for restructuring and moving toward privatization.

The importance of DG is now being increasingly accepted and realized by power system engineers (El-Khattam et al., 2004). Nowadays, DG is a feasible alternative for developing new capacity, especially in competitive electricity markets, from an economic, technical and environmental point of view. The IEA (2002) lists five major factors that contribute to this new interest in DG, i.e., developments in distributed generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the liberalization of the electricity market, and concerns about climate change.

DG is a broad concept that includes various technologies. Although diesel/gas reciprocating engines and gas turbines encompass most of the DG capacity being installed, there is not a unique DG technology that considers its different attributes such as economic, operational, environmental, etc. The aim of this work is to present a comparative assessment aimed at determining the interest for various distributed generation technologies based on their various characteristics and also to assess the opportunity and potential for domestic energy sources. In this paper, a hierarchical decision making framework based on multi-criteria decision making (MCDM) methods is presented to prioritize the distributed generation technologies according to criteria such as their economic, operational and environmental attributes. Each criterion is divided into several sub-criteria, and the decision making process is applied using an analytical hierarchy process (AHP) to help decision makers and private investors in the development of DGs. A sensitivity process is performed to assess the importance of state regulations on final decisions. This study is performed in seven regions of Iran with various potentials of primary energy resources.

This paper is set out as follows: Section 2 describes the outline of the proposed decision making structure. In Section 3, the evaluation attributes of the hierarchial structure are introduced. The AHP approach is briefly explained in Section 4 and finally, the simulation results for some specific regions of Iran are presented in Section 5.

## 2. Proposed strategic framework

Strategic planning and management of natural resources has been identified as an important factor in the economic and social development of the countries in Asia and the Pacific (GSPM, 2002). The relationships between energy, the environment and sustainable development present a difficult paradox to the governments of the Asian and Pacific region due to the huge demand of energy for facilitating economic growth and social development that is largely met with fossil fuels.

Strategic planning is a multi-criteria decision making process which considers several issues. The proposed strategy is a hierarchical decision making structure that uses AHP to prioritize preferences for DG technologies according to various criteria. The hierarchical structure is shown in three levels in Fig. 1. After introducing the goal in the first level, the attributes are divided into four main categories in the second level, namely: economic attributes, technical attributes, environmental attributes and regional primary energy resources. The first three attributes of this level consist of some sub-attributes that are concealed in Fig. 1 to avoid complexity in the diagram. These attributes and their sub-attributes are explained in detail in Section 3. The strategy is designed in such a manner so that it deals with probable challenges, both current and future, in an integrated approach. The DG technologies that are considered as alternatives in this comparative assessment are: photovoltaics (PV), wind turbines (WT), fuel cells (FC), micro turbines (MT), gas turbines (GT) and diesel reciprocal engines (DE). This analysis is performed in several regions of Iran according to their potential of conventional and renewable energy resources. The comparative assessment of all the individual technologies with all of the possible options can provide an executive summary to the decision maker how allocate their total investment budget to various technologies.

To simulate a real decision making framework, a block named external factors is included in Fig. 1 in order to assess how these factors can influence the results of final decisions. The block consists of state or government regulations. Government regulations include policy legislations such as the promotion of renewable technologies by giving subsidies or the enactment of severe power quality conditions. This block is used to perform a sensitivity analysis and to determine how the weights of attributes and sub-attributes influence the alternative hierarchies with respect to uncertainties and state regulations.

## 3. Evaluation attributes

As shown in Fig. 1, the hierarchical decision making structure consists of four attributes. These attributes along with their sub-attributes are explained in detail in the following section.

### 3.1. Economic attributes

The economic attributes (shown in Fig. 2) are divided into two main categories: cost and market. Cost attributes include both fixed and variable costs, i.e., investment and operating costs. The investment cost is a critical evaluation parameter for electricity projects under construction (Pepermans et al., 2005). The rate of investment in DG technologies varies widely depending on the technology. Conventional and fossil fuel generators have low investment rates, while renewable technologies currently have high investment rates. Another economic attribute is a variable term that is called the operating cost. This parameter is related to the cost of the primary energy and the electricity generation technology. On the other hand, market attributes denote the potential for DG technologies to earn money through their ability to participate in the electricity market or to supply ancillary services. These economic attributes can influence the rate of return of a project. This is an important factor that is necessary to persuade investors to invest in electricity generation projects. Undoubtedly, subsidies improve the economic return from DG units (Strachan and Dowlatabadi, 2002).

### 3.2. Technical attributes

The technical attributes shown in Fig. 3 are clustered into three categories, namely, the issues associated with the operational, structural and technical requirements that are based on expert opinions. Since the advent of privatization, a number of operational standards have been developed by successive regulatory authorities, which safeguard supply quality (Strbac and Mutale, 2005). The operational characteristics of DG technologies are important attributes that can affect both customers and the grid. The adequacy of the grid network is usually examined so that the network can normally absorb the full output of distributed generation under all loading conditions. Six sub-attributes are included in this category. Among these attributes, power quality and reliability are considered as two distinct categories in this paper, although they are related characteristics. Power quality is assumed to denote the voltage and harmonic characteristics of DG technologies. On the other hand, reliability is typically defined as the expected hours of power outage over a period of time; this is called the forced outage rate (FOR). The third sub-attribute is efficiency, which is considered as an important factor for demonstrating the potential of the technology for energy conservation. The startup time of DG technologies can be a valuable feature for determining their ability to provide a spinning reserve for the grid. One of the abilities of a DG unit is the ability to regulate its frequency and to chase load fluctuations. To meet this aim, the response speed of DG technologies is included in the analysis. The last sub-attribute is the capacity factor, which expresses the ratio of the total energy produced over a period of time to what its output would have been if it had operated at full capacity for that time period (Pokharel and Ponnambalam, 1997).

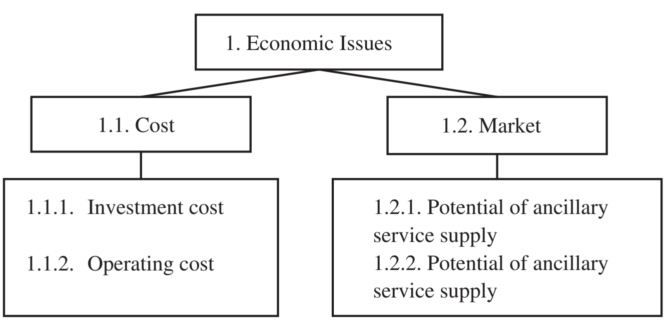


**Fig. 2.** Attributes and sub-attributes of economic issues.

Structural and constructional attributes are the other technical attributes that separate DG technologies. This attribute is divided into four parts: the footprint (required space), the lifetime, the modularity, and the installation lead time. The footprint is defined as the unit of area ($m^2$) needed for the generation capacity (kW). This parameter plays an important role in crowded regions where there is little free space. For example, renewable energy sources are generally located in areas with low populations and load densities. The nature of a distribution network is characterized by having large physical assets with long operational life times (Collinson et al., 2003). This means that any fundamental physical changes to the network necessarily take place over extended periods of time. The lifetime of DG technologies is another sub-attribute. It almost always varies between 20 and 30 years. Another sub-attribute, modularity, is one of the inherent and unique characteristics of DG units. Modularity lets owners and users of DG units connect stacks of generators in series to increase the capacity. The installation lead time is also an important factor for investors. Generally, DG units can be installed with shorter lead times in comparison to centralized generation units due to their small size. However, this parameter differs for various DG technologies.

The technical requirements are another aspect of DG units that must be considered by the DG owners. Three sub-attributes are defined in this category. First, maintenance is a necessary activity for equipment in order to increase their performance and life time; however, it can impose additional costs to DG owners. The next sub-attribute of this category is domestic technical knowledge. To reach the goal of sustainable development and to protect national interests, governments must persuade investors to invest in such DG technologies so that it is possible to build and construct them inside the country. The last sub-attribute is related to the complementary interconnection between equipment, which depends on the DG technology and its generator.

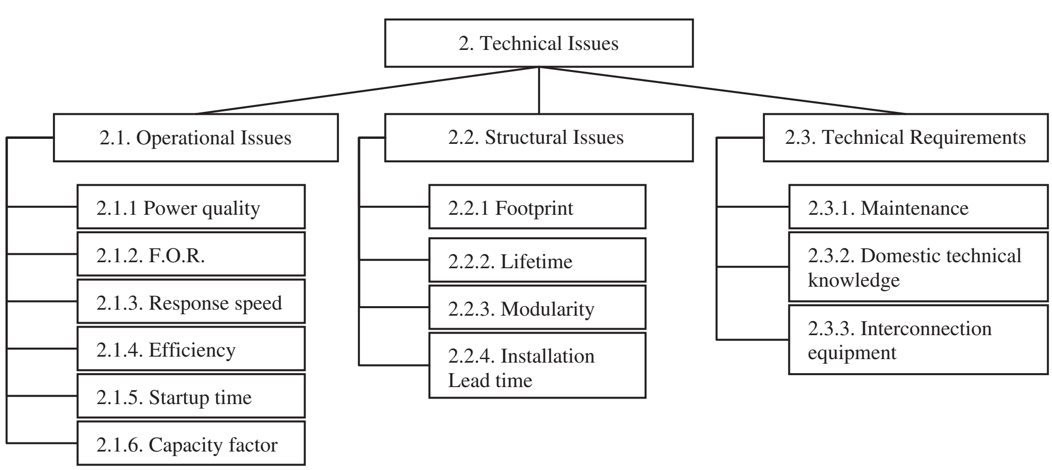


**Fig. 3.** Attributes and sub-attributes of technical issues.

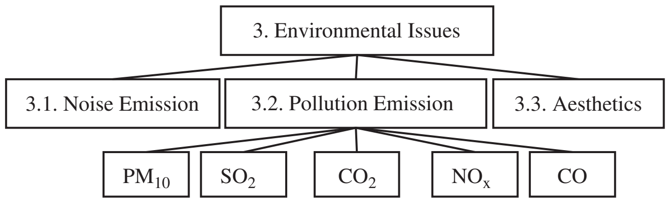


**Fig. 4.** Attributes and sub-attributes of environmental issues.

### 3.3. *Environmental attributes*

Fig. 4 shows the hierarchical levels of environmental attributes by considering three sub-attributes: noise pollution, air pollution and aesthetics. From the standpoint of air pollution, DG technologies are assessed with respect to their emissions of six green house gases (GHG). These gases are $CO_2$, $NO_x$, $SO_2$, CO and $PM_{10}$. The issue of global climate change due to GHG emissions poses a challenge to both current and future generations (Dvoracek et al., 2004), and it has had a polarizing effect both domestically and internationally since the ratification of the Kyoto Protocol. Air pollution is one of the most significant environmental issues facing Iran, especially in its capital city, Tehran. Iran emitted about 382 million tons of $CO_2$ in 2005, with the power generation sector contributing 25.1% of those emissions (Iran Energy Balance Yearbook, 2005). In addition, in order to establish an emission allowance program that determines annual caps for power plants, the government encourages industries for energy conservation and the construction of renewable and clean technologies as long-term strategies to protect the environment.

Electricity generation can also be noisy. The proximity of a DG unit to people makes this a potential disadvantage. In some cases, the noise pollution will be a deal breaker for DG projects. The noise from DG technologies may well affect the customers of a business, lower the productivity of employees, and irritate neighbors. Occupational health requirements and local noise ordinances will limit the deployment of DG technologies. For example, a micro-turbine produces noise at about 60 dB (at a distance of 3 m), while natural gas and diesel reciprocating engines make noise between 70 and 75 dB at a distance of 3 m (Gumerman et al., 2003). The aesthetics of DG installments is one of the other environmental concerns. Although it has less importance in the decision making process than the two previous sub-attributes, it can be a rather significant feature in urban regions.

### 3.4. *Regional primary energy attribute*

Primary energy availability is a very important parameter for DG owners in order to retain their available capacity for electricity generation. This parameter is affected by domestic sources and also by the potential of regional energy sources like the wind speed and solar radiation.

## 4. Analytic hierarchy process (AHP)

The inclusion of different issues in the strategic planning process necessitates an approach that deals with multiple criteria. The multi-attribute decision making (MADM) approach is one of the most suitable technical aids for strategic planning, and it selects the best resource strategy with regard to the chosen attributes (Pan et al., 2000). The AHP is widely used as one of the major MADM methods for solving a wide variety of problems that involve complex criteria across different levels in which the interaction of criteria is common (Saaty, 1977, 1980). The AHP is a powerful and flexible decision making process to help people set priorities and make the best decision when both the qualitative and quantitative aspects of a decision need to be considered (Malik and Sumaoy, 2003). It breaks down a complex multi-criteria decision problem into smaller constituents and forms a multi-level hierarchical structure. An AHP generally consists of four stages as follows (Lee et al., 2007):

*Stage (1)* the attributes that influence the decision making process are identified and then sorted into different classes to form a decision-making hierarchy. The first level of the hierarchical structure is the goal and the final level involves alternatives while the middle hierarchical levels appraise attributes and sub-attributes. In this study, through the scientist's and expert's opinions a hierarchical tree of the problem (shown in Fig. 1) is developed which selects economic, technical, environmental and regional primary energy issues as four strategic attributes in the middle level of the hierarchy for the prioritization of DG technologies.

*Stage (2)* pairwise comparisons are performed based on quantitative data and qualitative judgments. A pairwise comparison is a numerical representation of the relationship between two elements that determines which element is more important, according to its higher criterion. The pairwise comparison at each level can be performed on the basis of a questionnaire (Appendix A). Decision makers may be the consultants from the industry and academic institutions. The questionnaire responses are then

**Table 1**
The Saaty nine-point comparison scale.

| Intensity of relative importance | Definition |
|---|---|
| 1 | Equal important |
| 3 | Moderately preferred |
| 5 | Essentially preferred |
| 7 | Very strongly preferred |
| 9 | Extremely preferred |
| 2, 4, 6, 8 | Intermediate importance between two adjacent judgments |

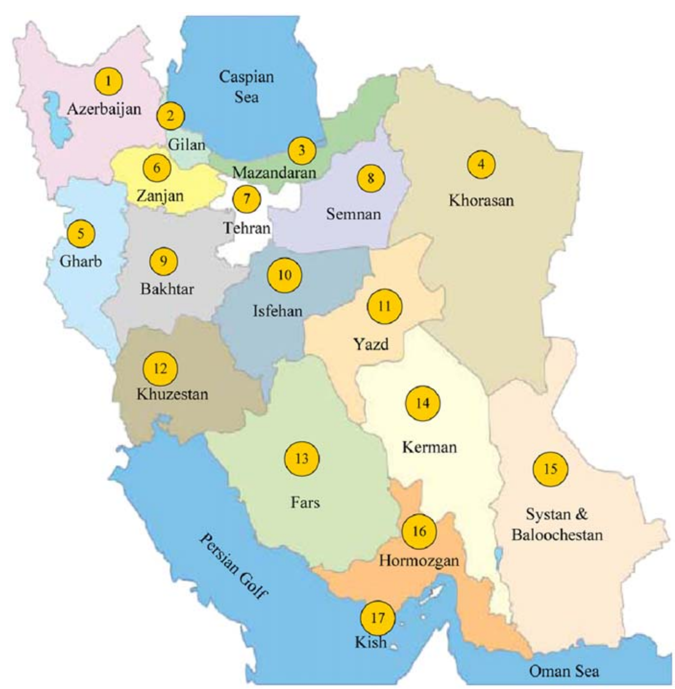


**Fig. 5.** Geographic map of regional electricity companies (RECs) in Iran.

quantified and translated into scores. This is done by adopting the pairwise comparison matrices method and the comparisons are carried out using the Saaty's nine-point scale as shown in Table 1 (Sharma and Agrawal, 2009).

*Stage (3)* aggregation of different expert assessments: Two main reasons for discrepancies may be due to differences in the aspect and opinion and different complementary information. The geometric mean method (GMM) as the most widely applied method in AHP is used for the aggregation, as recommended by Saaty (Saaty, 1980). Suppose there are $N$ expert respondents. The individual judgments of them are combined using (1).

$$a_{ij} = (\prod_{k=1}^{N} a_{ij}^{k})^{1/N} \quad (1)$$

where ${a_{ij}}^k$ is the judgment of the $k$th voter when comparing item $i$ with item $j$.

It is important to note that the efficiency of an AHP greatly depends on the accuracy of the pairwise weights. If there are $n$ attributes in a level, then the squared matrix of attributes with respect to a higher attribute or goal will be presented as (1).

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (2)$$

where $a_{ij}$ denotes the importance of $i$th attribute with respect to $j$th attribute. Also, it is assumed that $a_{ji} = 1/a_{ij}$.

*Stage (4)* in this stage, the weights to be assigned to the decision-making attributes are calculated via eigenvectors. The eigenvector calculation is widely used to determine the relative weights of attributes from the results of pairwise comparison. Briefly, in this approach, the eigenvalue from the comparison matrix is calculated and then the eigenvector that corresponds to the maximum eigenvalue is determined via (3) to normalize the weights so that their sum equals 1 (Saaty, 1980). Normally, in MADM problems, the information available to the decision maker is often imprecise due to erroneous attribute measurements and imperfect priority judgments (Agalgaonkar et al., 2006). To indicate whether the ordinal ranking of the pairwise comparisons obtained from expert evaluations are reliable, a measure called the consistency ratio (CR) is defined. If this measure is less than 0.1, the results are acceptable.

$$(A - \lambda_{max} I)w = 0 \quad (3)$$

where $\lambda_{max}$ is the maximum eigenvalue and $w$ is its corresponding eigenvector.

The evaluation and final prioritization of DG technologies was accomplished with the aid of the AHP software, Expert Choice (Expert Choice Inc.). The Expert Choice (EC) software is a multi-objective decision support tool based on the analytic hierarchy process (AHP). Expert Choice not only assists decision-makers in structuring complexity and exercising judgment, but it also incorporates both the objective and subjective factors that are used in the decision making process.

## 5. Case study: Iran

Iran is located in the Middle East. It has an area of 1,648,000 km$^2$. The population of Iran was about 70 million in 2006 and the urban population accounts for 66.3% of the total population (Iran Statistical Yearbook, 2006). The Iranian economy is still heavily dependent on oil exportation, which accounts for about 80% of total export earnings (CBI, 2006). The Iranian power industry was a monopoly of the government run on the public budget of the country and, therefore, the final price of the electricity was kept artificially low due to government subsidies. In recent years, Iran has put a great deal of effort into moving towards restructuring and privatizing the power industry by establishing 17 regional electricity companies (RECs), 28 generation management companies and 42 distribution companies.

One of the main results of this effort has been to incite the private sector to take part in power industry development. For this purpose, one of the appropriate methods is to develop DG technologies due to their low capital investment and other benefits. Since DG technologies are conceptually defined as local resources and also the prioritization of various technologies depends on the regional potential of primary energy availability (conventional or renewable), in this paper 7 RECs (out of the 17 that are indicated in Fig. 5) are considered as case studies to present a strategic policy making process for the prioritization of DG technologies in each region. As mentioned before, the main aim of this paper is to guide electricity companies and private investors how distribute their budget for various DG technologies. The potential availabilities of the primary energy sources of these regions are presented in Table 2. It should be pointed out that energy from biomass and hydropower cannot generally play a major role in the production of electricity due to the scarcity of forests and

**Table 2**
Potential of primary energy resources of specified RECs.

| REC | No. | Oil | Gas | Solar (KWh/m$^2$) | Wind |
|---|---|---|---|---|---|
| Azerbaijan | 1 | Intermediate | Intermediate | 2 | Intermediate |
| Gilan | 2 | Intermediate | Intermediate | 1 | Good |
| Khorasan | 4 | Intermediate | Good | 4 | Good |
| Tehran | 7 | Good | Good | 3 | Unfit |
| Khuzestan | 12 | Excellent | Excellent | 6 | Intermediate |
| Fars | 13 | Good | Excellent | 5.5 | Intermediate |
| Systan | 15 | Intermediate | Good | 6 | Excellent |

**Table 3**
Technical attributes of DG technologies.

| Attributes | DG technologies[a] | | | | | |
|---|---|---|---|---|---|---|
| | PV | WT | FC | MT | GT | DE |
| Maintenance (hr/yr) | 10 | 40 | 12 | 20 | 350 | 250 |
| Generation range (kW) | 100 | 1500 | 200 | 250 | 5000 | 5000 |
| Required space (m$^2$/kW) | 0.02 | 0.01 | 3 | 59 | 59 | 50 |
| Life time (yr) | 30 | 20 | 30 | 20 | 30 | 20 |
| Installation lead time (month) | 1 | 12 | 10 | 1 | 9 | 7 |
| Capacity factor (%) | 20 | 30 | 50 | 95 | 70 | 80 |
| Start-up time | – | – | $<$10 min | 30–60 s | 100–600 s | 10 s |
| Efficiency (%) | 15 | 40 | 80 | 82 | 42 | 40 |
| Forced outage rate (FOR) (%) | 0.5 | 3.2 | 1.5 | 6.7 | 4.2 | 5.7 |
| Capacity factor (%) | 20 | 25 | 30 | 35 | 40 | 30 |

[a] Photovoltaics (PV), wind turbines (WT), fuel cell (FC), micro-turbine (MT), gas turbines (GT), diesel engines (DE).

**Table 4**
Economic and environmental attributes of DG technologies.

| Attributes | DG technologies[a] | | | | | | |
|---|---|---|---|---|---|---|---|
| | PV | WT | FC | MT | GT | DE | |
| Investment cost ($/kW) | | 6500 | 5600 | 2700 | 1150 | 750 | 350 |
| Operating cost ($/kWh) | | 2.5 | 10 | 13 | 8 | 4 | 6 |
| Pollution emission (kg/MWh) | $CO_2$ | 0 | 0 | 366.1 | 328,236 | 307,670 | 294,507 |
| | $NO_x$ | 0 | 0 | 6.17 | 90.49 | 236.5 | 4483.4 |
| | $SO_2$ | 0 | 0 | 12.34 | 1.64 | 1.64 | 93.34 |
| | CO | 0 | 0 | 2.06 | 246.8 | 143.96 | 1275.1 |
| | $PM_{10}$ | 0 | 0 | 0 | 18.51 | 16.45 | 160.4 |
| Noise (dB)[b] | | 0 | 84 | 46 | 60 | 70 | 75 |

[a] Photovoltaics (PV), wind turbines (WT), fuel cell (FC), micro-turbine (MT), gas turbines (GT), diesel engines (DE).
[b] Noise emissions of DG units are measured at a distance of 3 m.

**Table 5**
Pairwise comparison of main attributes vs. main attributes with respect to the goal (results of group respondents) for REC no. 2 (Gilan).

| | Economic attributes (C1) | Technical attributes (C2) | Environ-mental attributes (C3) | Regional primary energy (C4) |
|---|---|---|---|---|
| Economic attributes (C1) | 1 | 4.6 | 7.2 | 2.1 |
| Technical attributes (C2) | 1/4.6 | 1 | 3.7 | 1/4.3 |
| Environmental attributes (C3) | 1/7.2 | 1/3.7 | 1 | 1/6.4 |
| Regional primary energy (C4) | 1/2.1 | 4.3 | 6.4 | 1 |

Inconsistency of pairwise comparison is equal to 0.06

**Table 6**
Pairwise comparison of sub sub-attributes with respect to the technical operating attribute (results of group respondents).

| | Power quality | F.O.R. | Response speed | Efficiency | Start-up time | Capacity factor |
|---|---|---|---|---|---|---|
| Power quality | 1 | 1/2.3 | 4.1 | 1/6.7 | 3.1 | 1/4.8 |
| F.O.R. | 2.3 | 1 | 4.5 | 1/5.3 | 3.9 | 1/2.15 |
| Response speed | 1/4.1 | 1/4.5 | 1 | 1/3.7 | 2.5 | 1/7.7 |
| Efficiency | 6.7 | 5.3 | 3.7 | 1 | 8.5 | 2.8 |
| Start-up time | 1/3.1 | 1/3.9 | 1/2.5 | 1/8.5 | 1 | 1/5.3 |
| Capacity factor | 4.8 | 2.15 | 7.7 | 1/2.8 | 5.3 | 1 |

Inconsistency of pairwise comparison is equal to 0.07.

surface waters, respectively. Also geothermal resources are not included in this study, since it does not exist everywhere (mostly, it only exists wherever there is a volcano, i.e., region 1).

Based on calculations, Iran enjoys only a moderate supply of wind power, though some regions have continuous airflows with sufficient energy to produce electricity (Fadai, 2007). The potential capacity of wind power is figured at about 6500 MW for the country, mostly in the eastern sections (Maaghooli, 1992). Iran is potentially one of the best regions for the utilization of solar energy. In Iran, the average solar radiation per square meter equals 4 kWh, and the average number of hours with sunlight is measured to exceed 2800 per year (Fadai, 2007). Although conventional fossil fuel resources like oil and gas are mostly located in the south and southwest of country, these fuels are available throughout country based on established oil and gas pipelines. Therefore, as it is shown in Table 1, the availability of these resources is significant in all RECs (Ghobadian et al., 2009). As it is observed from Table 1, the availability of oil and gas resources are illustrated by excellent, good and intermediate statements. Excellent is used for the regions that have enormous resources of oil and gas, good is denote to the regions that are adjacent to oil and gas resources. Although these fuels are available throughout country based on the pipelines and transportation, remote area which are placed on the end of pipelines, suffer shortages of fuel in some seasons of the year. Therefore the intermediate statement is used for regions far from the resources.

Table 3 presents various technical attributes related to DG technologies (CADER, 1999; Resource Dynamics Corporation, 2001). Similarly, the economic and environmental attributes of the DG technologies are presented in Table 4 (CADER, 1999). These tables help decision makers and respondents to perform pairwise comparisons and determine preferences among DG technologies. The other data required for judgments based on pairwise comparisons are obtained based on the expert's opinions. For this purpose, a questionnaire and pairwise comparison form (Appendix A) was prepared and handed out among 51 experts from universities, the Electricity Network Management Company and the New Energy Organization (SANA). The collected responses were tested for consistency, and based on the test results, 37 of them were retained to assess and make final decisions about preferences of DG technologies.

The data for the pairwise comparisons that were collected from the survey are assessed using geometric mean method (GMM) according to (1). Table 5 presents the aggregation results of pairwise comparisons by the group of experts for REC no. 2 (Gilan). It is observed that economic attribute hast the most important based on the expert's opinion and environmental attribute has the lowest important due to soft laws of environmental protection in this region. In this case, inconsistency parameter is equal to 0.06. Since the comparison values are determined using GMM of survey results, these values are not integer as mentioned in Table 1. The pairwise comparisons are performed among alternative or attributes at each level of hierarchy structure with respect to the attribute and goal in a higher level. For instance, Table 6 also illustrates the pairwise comparison between sub sub-attributes with respect to the technical operating attribute for all RECs. The comparison shows that efficiency and capacity factor are respectively the most important attributes in this category. After accumulating all pairwise comparisons, obtained values are analyzed through AHP-Expert Choice. The weights that are obtained provide a measure of the relative importance of each of the attributes, and these are presented in Table 7 for REC no. 7. This table shows the attributes' weights for each level and also the overall weights of the hierarchical decision making framework. Among the assessments for this REC, the weight was the highest for 'economic attributes' (0.443) followed by

**Table 7**
Weights of attributes and sub-attributes for REC no. 7 (Tehran).

| Attributes | Weight (1) | Sub-attributes | Weight (2) | Sub sub-attributes | Weight (3) | Overall = (1) × (2) × (3) |
|---|---|---|---|---|---|---|
| 1. Economic | 0.441 | 1.1 Cost | 0.745 | 1.1.1 Investment cost | 0.566 | 0.186 |
| | | | | 1.1.2 Operating cost | 0.434 | 0.143 |
| | | 1.2 Market | 0.255 | 1.2.1 Potential to enter electricity market | 0.750 | 0.084 |
| | | | | 1.2.2 Potential of ancillary service supply | 0.250 | 0.028 |
| 2. Technical | 0.186 | 2.1 Operating issues | 0.514 | 2.1.1 Power quality | 0.082 | 0.008 |
| | | | | 2.1.2 Forced outage rate (FOR) | 0.130 | 0.012 |
| | | | | 2.1.3 Response speed | 0.040 | 0.004 |
| | | | | 2.1.4 Efficiency | 0.470 | 0.045 |
| | | | | 2.1.5 Startup time | 0.033 | 0.003 |
| | | | | 2.1.6 Capacity factor | 0.245 | 0.023 |
| | | 2.2 Structuring issues | 0.185 | 2.2.1 Footprint (required space) | 0.273 | 0.009 |
| | | | | 2.2.2 Lifetime | 0.254 | 0.009 |
| | | | | 2.2.3. Installation lead time | 0.350 | 0.012 |
| | | | | 2.2.4 Modularity | 0.124 | 0.004 |
| | | 2.3 Technical requirements | 0.301 | 2.3.1 Maintenance | 0.256 | 0.015 |
| | | | | 2.3.2 Domestic technical knowledge | 0.665 | 0.037 |
| | | | | 2.3.3 Interconnection equipment | 0.079 | 0.004 |
| 3. Environmental | 0.118 | 3.1 Noise emission | 0.260 | | | 0.031 |
| | | 3.2 Pollution emission | 0.670 | 3.2.1 $CO_2$ | 0.362 | 0.029 |
| | | | | 3.2.2 $NO_x$ | 0.247 | 0.019 |
| | | | | 3.2.3 $SO_2$ | 0.171 | 0.014 |
| | | | | 3.2.4 CO | 0.150 | 0.012 |
| | | | | 3.2.5 $PM_{10}$ | 0.071 | 0.006 |
| | | 3.3 Aesthetic | 0.070 | | | 0.008 |
| 4. Regional primary energy resources | 0.255 | | | | | 0.255 |

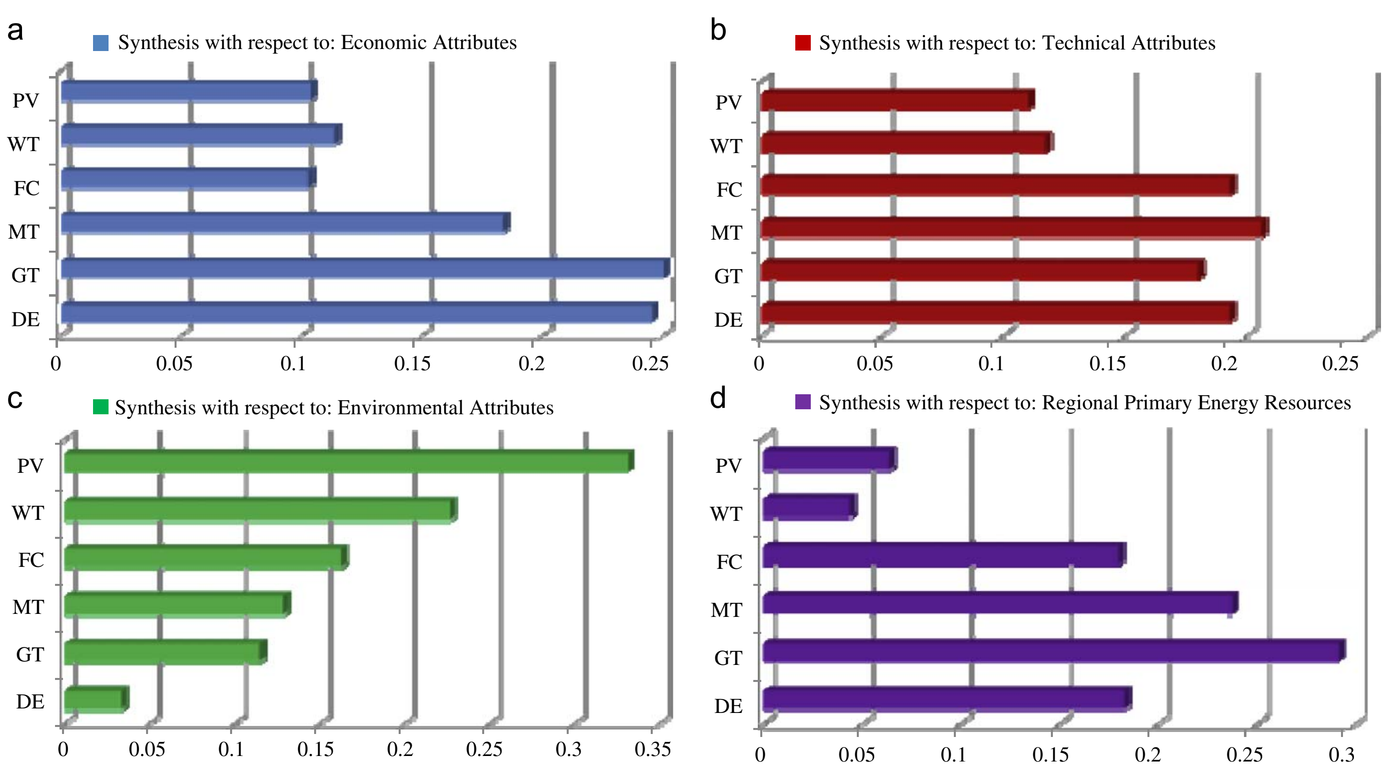


**Fig. 6.** Synthesis weight of alternatives with respect to the main attributes.

'regional primary energy' (0.254), 'technical attribute' (0.186) and 'environmental attribute' (0.117). Finally the overall weights of attributes in the lowest level of hierarchy are presented in the last column of Table 7. The overall weight, providing the global and final measure of each of the attributes, proved to be the highest for 'regional primary energy attributes' (0.255), followed by 'investment cost' (0.186) and 'operating cost' (0.143). The preference of DG technologies is determined based on the obtained overall weights. Fig. 6 depicts the relative weights of DG technologies with respect to the main attributes for REC no. 7. It is observed that gas turbines and diesel engines have the most preference in view point of the economic attributes while photovoltaics and wind turbines are considered as the best technologies with respect to the environmental issues. The final prioritization and overall weights of DG technologies are presented in Table 8 for all RECs specified in Table 1. The values of Table 8 are normalized values that show the preference of each technology in comparison with the other technologies of that region. These values can be used by regional electricity companies as a directive indicator to allocate investment budget for various DG technologies properly. This preference, especially about renewable technologies, may be differed in various regions due to the potential of primary energy, climate conditions and also the expert's opinions. For example, gas turbines are almost determined as the best technology in all RECs except in Systan (REC no. 15). This preference is due to the various advantages of gas turbine technology in Iran such as: great amount of gas resources, domestic knowledge (Iran is the greatest producer of gas turbines in the Middle East), moderate investment and operating cost and numerous other advantages. Similarly photovoltaics and fuel cells are the least preferred technologies in almost all of the RECs due to the regional climate conditions, soft environmental laws, high cost and complicated technology. However, in REC no. 13 (Fars) and REC no. 15 (Systan), PV is preferred over FC and WT and FC and MT, respectively, due to the high amount of solar radiation in those regions. It is important that in Systan, wind turbine has been chosen as the best technology to invest.

A sensitivity analysis can be performed to assess the attributes weight with respect to how it influences preferences for an alternative hierarchy. For this purpose, attributes that have the most standard deviation among the performed comparisons by respondents are chosen for sensitivity analysis. The effects of external factors such as Clean Air Act on the planning results are also assessed through a sensitivity analysis. A survey is made of how the weights of attributes and sub-attributes influence preference for the various DG technologies for REC no. 2 (Gilan). According to the results, the preference of alternatives is of the following order (Fig. 7): GT (24.3%), WT (19%), MT (17.8%), DE (16%), FC (13.9%) and PV (8.9%). It is observed that environmental attribute has the low importance (4.9%) in this region due to the soft environmental laws. If the weight of environmental attributes increases from 4.9% to 36.2%% based on regional state regulations, the preference for wind turbines (WT) will increase compared to that for gas turbines (GT) as shown in Fig. 8. In the performed opinion polls, the most discrepancy among responses is related to the pairwise comparisons among the main attributes. Therefore a sensitivity analysis is accomplished to assess the contribution range of each attribute in the priority ranking of alternatives.

**Table 8**
Economic and environmental attributes of DG technologies.

| REC | DG technologies | | | | | |
|---|---|---|---|---|---|---|
| | PV | WT | FC | MT | GT | DE |
| Azerbaijan | 0.113 | 0.127 | 0.132 | 0.179 | 0.238 | 0.212 |
| Gilan | 0.089 | 0.190 | 0.139 | 0.178 | 0.243 | 0.160 |
| Khorasan | 0.118 | 0.198 | 0.124 | 0.156 | 0.219 | 0.184 |
| Tehran | 0.122 | 0.110 | 0.146 | 0.195 | 0.231 | 0.195 |
| Khuzestan | 0.147 | 0.126 | 0.146 | 0.176 | 0.226 | 0.178 |
| Fars | 0.157 | 0.115 | 0.134 | 0.170 | 0.225 | 0.199 |
| Systan | 0.171 | 0.207 | 0.101 | 0.143 | 0.196 | 0.182 |

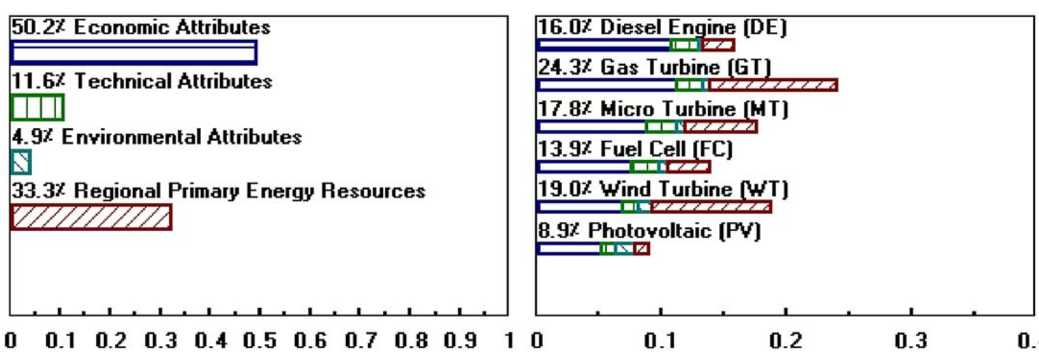


**Fig. 7.** Dynamic sensitivity for attributes below the goal.

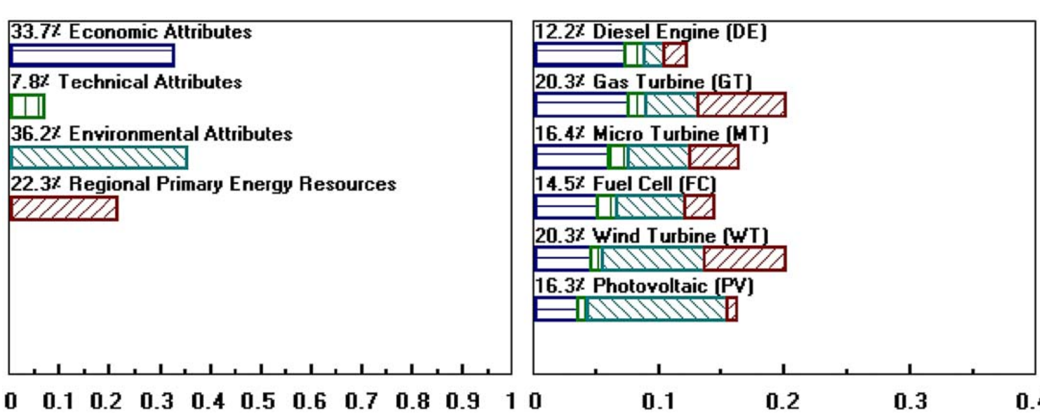


**Fig. 8.** Dynamic sensitivity for attributes below the goal when the weight of environmental attributes increases from 11.5% to 24.8%.

Table 9 shows these effects on the first three priority ranking of alternatives. For instance, when the contribution of economic attributes change from 0 to 0.65, the priority ranking in Gilan (REC no. 2) is GT–WT–MT. Similarly for the range 0.61–0.63, 0.63–0.65 and 0.65–1, the corresponding rankings are presented in Table 9. Fig. 9a and b shows the change in the preferences for DG technologies due to a decrease in the relative weight of domestic technical knowledge from 66.5% to 49.8%. It is concluded that the preference of new technologies like micro turbines and photovoltaics increase by decreasing the importance of this attribute. In Fig. 10a–c, the sensitivity of the preferences for alternative technologies are also shown with respect to the changing operational sub-attributes.

**Table 9**
Sensitivity analysis: change in the first three priority ranking of alternatives as importance of main attributes change.

| | Contribution range | First three priority ranking |
|---|---|---|
| Economic attributes | (0–0.61), (0.61–0.63) (0.63–0.65), (0.65–1) | (GT–WT–MT), (GT–MT–WT) (GT–MT–DE), (GT–DE–MT) |
| Technical attributes | (0–0.22), (0.22–0.36) (0.36–0.74), (0.74–0.87) (0.74–1) | (GT–WT–MT), (GT–MT–WT) (GT–MT–DE), (MT–GT–DE) (MT–DE–GT) |
| Environmental attributes | (0–0.0.36), (0.36–0.38) (0.38–0.47), (0.47–0.56) (0.56–0.75), (0.75–1) | (GT–WT–MT), (WT–GT–MT), (WT–GT–PV), (WT–PV–GT), (PV–WT–GT), (PV–WT–FC) |
| Regional primary energy resources | (0–0.18), (0.18–0.23) (0.23–0.26), (0.26–1) | (GT–DE–MT), (GT–MT–DE) (GT–MT–WT), (GT–WT–MT) |

## 6. Conclusions

Electricity demand in Iran is growing at a rate of almost eight percent each year and this rate is expected to be maintained for the next 10 years. In order to keep pace with this rate, the MOE is planning to provide the high electricity demand of consumers by promoting DG technologies among private investors. Private investment in DG has the potential to meet the increasing demand of Iran for electricity with a competitive economic environment that assures the lowest-cost for electricity. Additionally, clean DG technologies will play a role in reducing local, regional and even global air pollution. Since Iranian consumers suffered through huge numbers of electricity outages in summer of 2008 due to several factors such as power plant depreciation, the failure to erect new power plants to meet the increase in power demands, the lack of precipitation and international sanctions, this strategy helps the MOE to meet the excessive electricity demand of customers in the short and mid-term. However, the best strategy for this purpose, and the most sustainable, is to promote demand-side management activities and to actualize electricity prices.

In this study, an AHP based assessment model was developed for the prioritization of DG technologies with respect to the economic, technical, and environmental attributes and the potential of regional primary energy resources. The choice of attributes and their relative weights were determined according

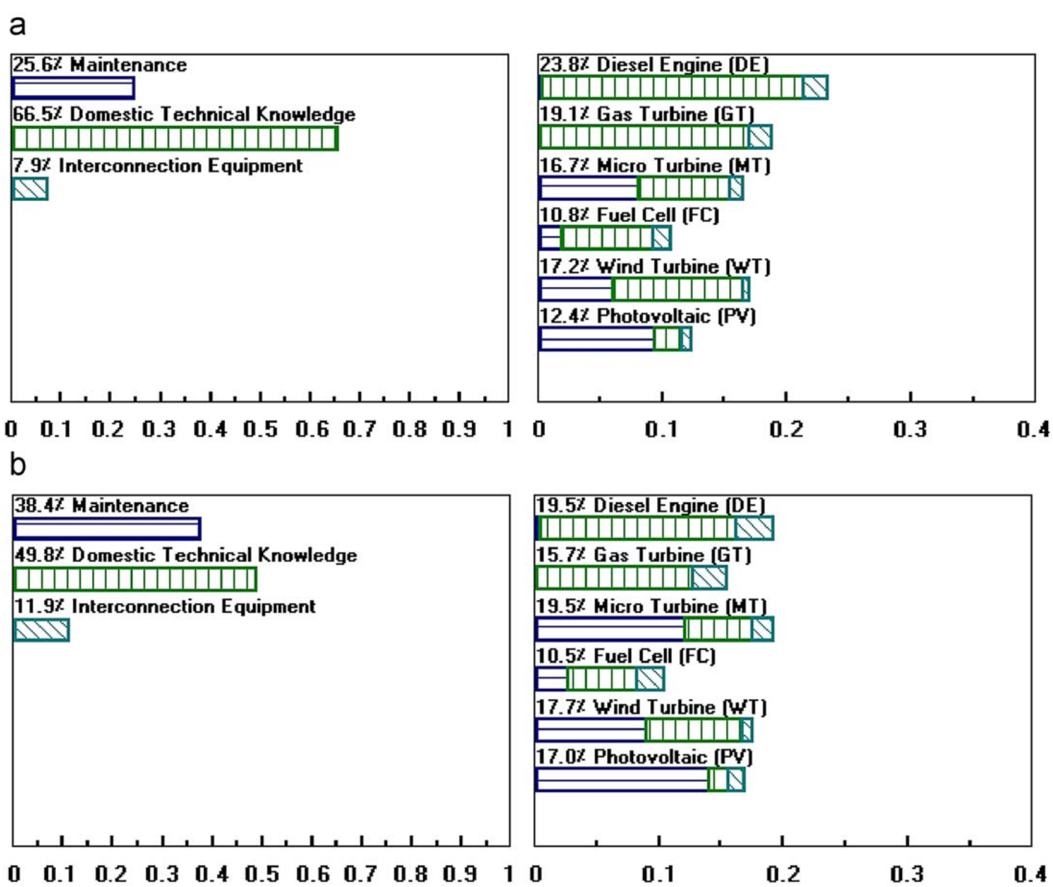


**Fig. 9.** Dynamic sensitivity of domestic technical knowledge: (a) preferences for alternatives in the base case; and (b) preferences for alternatives when domestic technical knowledge decreases from 66.5% to 49.8%.

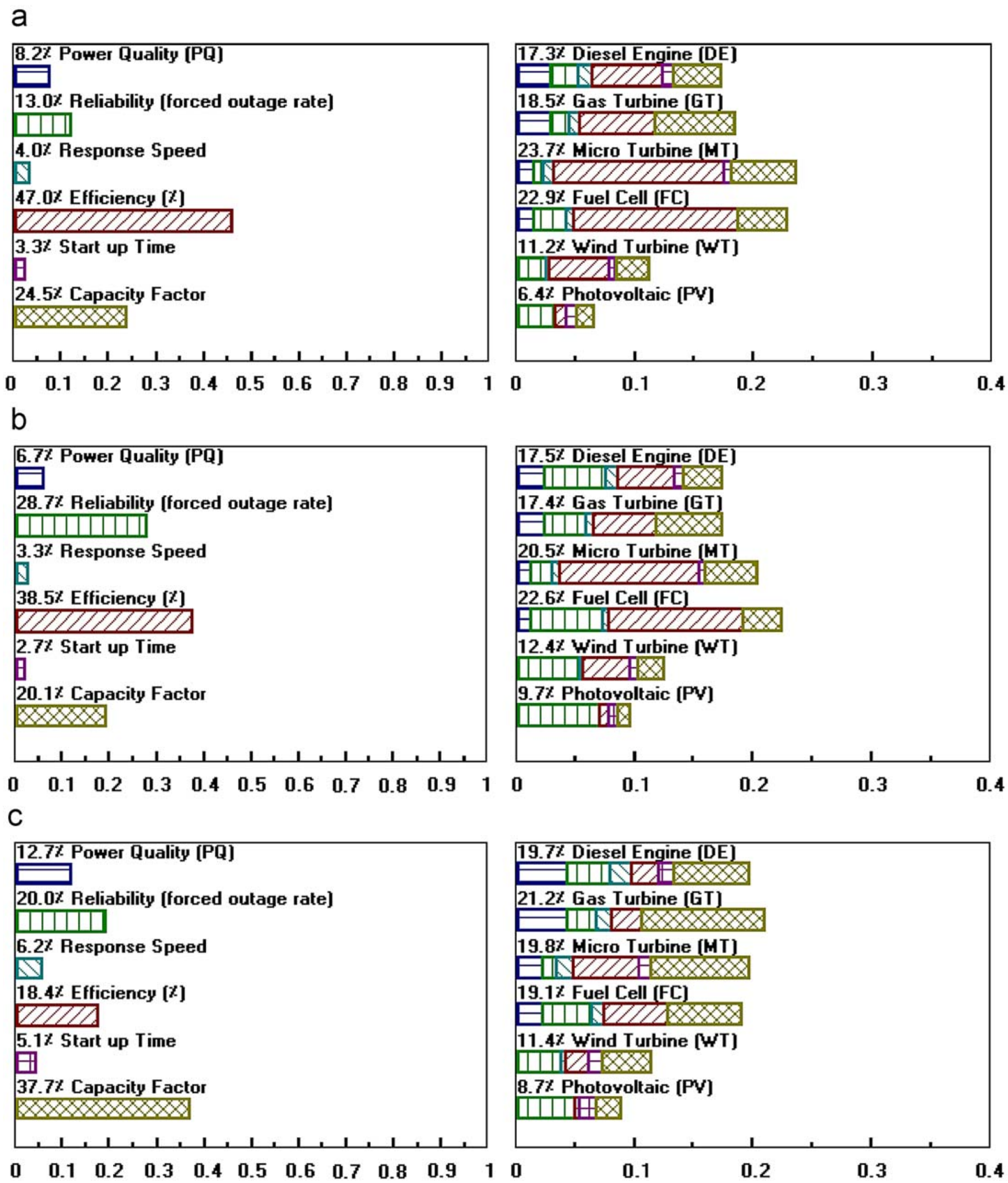


**Fig. 10.** Dynamic sensitivity of operational sub-attributes: (a) preferences for alternatives in the base case; (b) preferences for alternatives when the reliability increases from 13% to 28.7%; and (c) preferences for alternatives when the capacity factor increases from 24.5% to 37.7%.

to decision makers' expert judgments. Six common technologies considered in this paper were: photovoltaic (PV), wind turbine (WT), fuel cell (FC), micro-turbine (MT), gas turbine (GT) and reciprocating engine (RE). This study was performed in seven regions of Iran with different climatic conditions and energy resources. The proposed strategy can help governments to gain information about the preferred DG technologies for each region of Iran in order to keep moving towards sustainable development. Also this study helps electricity companies for optimal and proper allocating of their budget in DG investments according to the various attributes. For instance, the best DG technology for investing in Systan was wind turbine, while in other RECs gas turbine was chosen as the proper technology.

As a further study of this research, we are planning to analyze DG prioritization in each region using the Fuzzy AHP approach, which defines the values of pairwise comparisons as range values instead of crisp values used in this paper.

## Acknowledgements

The authors would like to thank the experts from the Electricity Network Management Company and the SANA organization who participated in the AHP survey.

## Appendix A. Questionnaire

(a) For prioritizing of DG technologies in the strategic planning, the following alternatives are considered:
1. Photovoltaic (PV)
2. Wind turbine (WT)
3. Fuel cell (FC)
4. Micro-turbine (MT)
5. Gas turbine (GT)
6. Diesel engine (DE)

(b) For prioritizing of DG technologies, the following main attributes are considered:
1. Economic (C1)
2. Technical (C2)
3. Environmental (C3)
4. Regional primary energy resource (C4)
These attributes and their sub-attributes are explained in detail in Section 3.

(c) For the weighting of the proposed alternatives or attributes, the Saaty's nine-point scale presented in Table 1 must be used. For convenience, respondents can use numerical (left column) or statement (right column) to fill pairwise comparison tables.

(d) Pairwise comparison tables:
These tables which are similar to the squared matrix (1) compare alternatives or attributes with respect to a higher attribute or goal. To fill tables, experts and scientists from the industry and academic institutions are asked to response to the prepared questionnaires. For this purpose and to obtain proper results, the information of Tables (2–4) are given to the respondents.

In the following some of the tables and questions are presented:

(Q1) Which attribute is more important in your opinion to chose the best DG technologies? (Table A1)
(Q2) Which sub-attribute is more important to you with respect to environmental issues (main attributes)? (Table A2)
(Q3) Which sub sub-attribute is more important to you with respect to structuring issues (technical sub-attribute)? (Table A3)
(Q4) Which sub sub-attribute is more important to you with respect to the pollution emission (environmental sub-attribute)? (Table A4)

**Table A1**
Pairwise comparison among main attributes with respect to the goal.

| | Economic attributes (C1) | Technical attributes (C2) | Environmental attributes (C3) | Regional primary energy (C4) |
|---|---|---|---|---|
| Economic attributes (C1) | 1 | | | |
| Technical attributes (C2) | | 1 | | |
| Environmental attributes (C3) | | | 1 | |
| Regional primary energy (C4) | | | | 1 |

**Table A2**
Pairwise comparison of environmental sub-attributes with respect to environmental attribute.

| | Noise emission (C3.1) | Pollution emission (C3.2) | Aesthetic (C3.3) |
|---|---|---|---|
| Noise emission (C3.1) | 1 | | |
| Pollution emission (C3.2) | | 1 | |
| Aesthetic (C3.3) | | | 1 |

**Table A3**
Pairwise comparison of technical sub sub-attributes with respect to structuring issue.

| | Footprint (C2.2.1) | Lifetime (C2.2.2) | Installation lead time (C2.2.3) | Modularity (C2.2.4) |
|---|---|---|---|---|
| Footprint (C2.2.1) | 1 | | | |
| Lifetime (C2.2.2) | | 1 | | |
| Installation lead time (C2.2.3) | | | 1 | |
| Modularity (C2.2.4) | | | | 1 |

**Table A4**
Pairwise comparison of various pollutants with respect to pollution emission sub-attribute.

| | $CO_2$ (C3.2.1) | $NO_x$ (C3.2.2) | $SO_2$ (C3.2.3) | CO (C3.2.4) | $PM_{10}$ (C3.2.5) |
|---|---|---|---|---|---|
| $CO_2$ (C3.2.1) | 1 | | | | |
| $NO_x$ (C3.2.2) | | 1 | | | |
| $SO_2$ (C3.2.3) | | | 1 | | |
| CO (C3.2.4) | | | | 1 | |
| $PM_{10}$ (C3.2.5) | | | | | 1 |

Similar tables are used for weighting of alternatives and attributes.

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