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Article

Determination of the Most Suitable Technology Transfer Strategy for Wind Turbines Using an Integrated AHP-TOPSIS Decision Model

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Abstract: The high-speed development of industrial products and goods in the world has caused "technology" to be considered as a crucial competitive advantage for most large organizations. In recent years, developing countries have considerably tended to promote their technological and innovative capabilities through importing high-tech equipment owned and operated by developed countries. There are currently a variety of solutions to transfer a particular technology from a developed country. The selection of the most profitable technology transfer strategy is a very complex decision-making problem for technology importers as it involves different technical, environmental, social, and economic aspects. In this study, a hybrid multiple-criteria decision making (MCDM) model based on the analytic hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS) is proposed to evaluate and prioritise various technology transfer strategies for wind turbine systems. For this purpose, a number of criteria and sub-criteria are defined from the viewpoint of wind energy investors, wind turbine manufacturers, and wind farm operators. The relative importance of criteria and sub-criteria with respect to the ultimate goal are computed using the eigenvalue method and then, the technology transfer alternatives are ranked based on their relative closeness to the ideal solution. The model is finally applied to determine the most suitable wind turbine technology transfer strategy among four options of reverse engineering, technology skills training, turn-key contracts, and technology licensing for the renewable energy sector of Iran, and the results are compared with those obtained by classical decision-making models.

Keywords: technology transfer; wind turbine; design and manufacture; multiple-criteria decision making (MCDM); analytic hierarchy process (AHP); technique for order of preference by similarity to ideal solution (TOPSIS)

1. Introduction

The high-speed development of industrial products and goods in the world has caused "technology" to be considered as a crucial competitive advantage for most large organizations. In general, there are two ways to acquire technology assets by a firm. These are: import (technology transfer) and production (technology commercialization by in-house research and development (R&D)) [1]. Though in-house R&D is a good strategy for organizations with sufficient technological capabilities and finances, it is often time-consuming, expensive, and risky as it is impossible to take back the efforts in case of failure [2]. In recent years, developing countries have considerably tended to promote their technological and innovative capabilities, labour efficacy, and economic growth rate through importing high-tech equipment owned and operated by developed countries. This increasing attempt to transfer modern production facilities and instruments from technology owners has offered a number of challenges to organizations. For instance, not all available technology transfer solutions are applicable in high-tech industries; cost or benefit implications of technology transfer solutions are not well captured in markets; technology developers/manufacturers might tend to export their technologies only to organizations with common economic and political interests; no systematic approach is present to assess and prioritize technology transfer solutions and related needs; etc.

The identification, evaluation, and prioritization process of technology transfer strategies for technology importers is very complex due to the presence of numerous decision makers, the qualitative nature of the evaluation process, and the existence of imprecision and uncertainty in the decision making process. For these types of decision-making problems, the technology importer must decide on the most appropriate technology transfer strategy for each piece of equipment or the entire equipment among a set of possible alternatives such as reverse engineering, foreign licensing, turn-key, etc. Moreover, many different goals or comparing criteria (e.g., the investment required to transfer a technology vs. cost of technology R&D, reliability of the technology, political relations between organizations, user-friendliness of the technology for the recipient) must be taken into account for the assessment of the alternatives' performance. Therefore, technology transfer strategy selection is considered to be a complex decision-making problem.

To solve the technology transfer strategy selection problem, several methods have been introduced by researchers, e.g., benefit cost analysis (BCA) and strengths, weaknesses, opportunities, and threats (SWOT) analysis [3]. In recent years, the multiple-criteria decision making (MCDM) approach has been quite extensively used to establish the metrics and prioritize the technology acquisition strategies for high-tech products and equipment. In this analysis approach, each alternative is evaluated with respect to all criteria and their associated sub-criteria using a suitable measure. Then, the evaluation ratings are aggregated to obtain a global evaluation for each alternative. Finally, the alternatives are prioritized [4]. In order to find out the optimum solution, several techniques, e.g., analytic hierarchy process (AHP), analytic network process (ANP), technique for order of preference by similarity to ideal solution (TOPSIS), VIšekriterijumsko KOmpromisno Rangiranje (VIKOR), etc., can be applied (for more, see [5,6]). These techniques in practice may use either deterministic, stochastic, fuzzy, or combined models.

AHP is one of the most popular and widely employed MCDM analysis methodologies which was first developed by Professor Saaty in the 1970s [7] to improve the decision-making process through prioritizing items pair-wise rather than prioritizing all items at once. AHP helps the decision makers to organize the critical aspects of a complex problem into a hierarchical structure through breaking down the problem into its constituent parts. The decision-making process using the AHP technique comprises three steps: (i) developing a hierarchical structure of the problem in terms of the overall goal, criteria, and alternatives; (ii) establishing priorities through pairwise comparisons; and (iii) performing a consistency check to ensure that the judgment is sufficiently consistent. TOPSIS is another practical and useful MCDM technique which was developed by Hwang and Yoon in 1981 [8] with further developments by Yoon [9] and Hwang et al. [10]. This technique is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). The relative closeness of each alternative to the PIS is defined as the distance to the NIS divided by the sum of the distance to the negative and the distance to the PIS. The alternatives are ranked in decreasing order by the closeness index. The TOPSIS procedure consists of the following steps: (i) construction of the normalized decision matrix; (ii) determination of the positive ideal and NIS; (iii) calculation of the separation measures using the n dimensional Euclidean distance; (iv) calculation of the relative closeness to the ideal solution; and (v) ranking the preference order.

Table 1 presents the distribution of various MCDM models used for selecting the most appropriate technology transfer strategy for various applications, such as biotechnology, petrochemical, ship manufacturing, etc.

Table 1. Review of the MCDM methods used for technology transfer strategy selection (AHP: analytic hierarchy process; ANP: analytic network process; TOPSIS: technique for order of preference by similarity to ideal solution; UAV: unmanned aerial vehicle).

Ref.	Year	Type of Model		MCDM Technique				Application
		Fuzzy	Classical	AHP	ANP	TOPSIS	Others	
[11]	1994	√	-	√	-	-	-	biotechnology
[12]	2004	√	-	-	-	-	√	biotechnology
[13]	2005	√	-	√	-	-	-	not applicable
[14]	2009	-	√	-	√	-	-	software
[15]	2011	-	√	-	-	-	√	UAV
[16]	2012	√		√	-	-	-	gas
[17]	2012	-	√	√	-	-	-	petrochemical
[18]	2012	√	-	-	-	√	-	ship manufacturing
[19]	2014	√	-	-	-	-	√	aero-engine turbine
[20]	2015	√	-	-	-	√	-	wastewater

Chang and Chen [11] proposed a fuzzy MCDM algorithm based on the AHP method for technology transfer strategy selection in the area of biotechnology management. The linguistic variables and fuzzy numbers were used to aggregate the decision makers' subjective assessments about criteria weightings and appropriateness of alternatives. Tsao [12] developed an interval arithmetic-based fuzzy MCDM approach to choose the most appropriate technology transfer strategy in biotechnology. The authors used fuzzy numbers to represent the ratings of various strategies versus different criteria and the importance weights of different criteria. Albayrak and Erensal [13] presented a fuzzy AHP method to determine the most appropriate technology transfer option based on macro ergonomics criteria. Lee et al. [14] used the ANP technique to select the most appropriate acquisition mode for a required technology on the basis of five criteria: capability, strategy, technology, market, and environment. The model obtained priorities of alternatives with consideration of interrelationships among criteria. Hamzei [15] presented a "decision support system" based on statistical methods and MCDM models for determining an appropriate provider of technology. A case study of a jet unmanned air vehicle (UAV) was provided to illustrate the results. Chehrehpak et al. [16] proposed a fuzzy AHP method to select the most suitable solution for technology transfer in the gas industry by collecting the opinions of a large number of experts. Mohaghar et al. [17] used the AHP method to evaluate various technology transfer strategies in the petrochemical industry, including foreign direct investment (FDI), licensing, joint venture, turn-key, and reverse engineering. Radfar [18] presented a fuzzy TOPSIS approach to identify and prioritize various foreign investment methods for technology transfer in the ship-making industry. Wang et al. [19] proposed an optimal selection method of process patents for technology transfer, using fuzzy MCDM techniques and a 2-tuple fuzzy linguistic representation model. A case study of aero-engine turbine manufacturing was presented to demonstrate the applicability of the proposed method. Wibowo and Grandhi [20] evaluated and selected the most suitable wastewater treatment technology using a fuzzy MCDM approach based on the TOPSIS technique.

In order to improve the strengths and eliminate the drawbacks of classical MCDM techniques, some hybrid decision models have been recently developed. Hybrid MCDM approaches represent a powerful group of decision-making techniques which can assist decision-makers in handling miscellaneous information, involving stakeholders' preferences, interconnected or contradicting criteria, and uncertain environments [21]. However, as Table 1 shows, no earlier study has utilized hybrid MCDM techniques for solving technology transfer decision-making problems. Furthermore, as the above review has revealed, so far no application of the MCDM methods to wind turbine technology selection has been reported. In order to respond to these research gaps, in the current paper, a combined AHP and TOPSIS decision model is developed to select the most suitable technology transfer strategy for the design and manufacture of wind turbine systems and their associated structures. The proposed model consists of four sets of criteria, namely, economic, social, technical, and environmental, with a total of nine sub-criteria determined from the viewpoint of wind energy investors, wind turbine manufacturers, and wind farm operators. The weights of criteria and sub-criteria are computed using the eigenvalue method and then, the technology transfer alternatives are ranked based on their distance to the ideal or anti-ideal solutions. The model is finally applied to determine a suitable wind turbine technology transfer strategy in the renewable energy sector of Iran and the results are compared with those obtained by classical MCDM methods. The proposed approach can assist technology managers in selecting a profitable strategy for importing high-tech equipment and instruments, through which they can reduce the costs corresponding to the technology acquisition process.

The rest of the paper is organized as follows. In Section 2, an overview of the wind turbine technologies developed and deployed to date is presented. Section 3 provides a step-by-step procedure of the proposed decision model to determine the most suitable technology transfer strategy for wind turbines. Section 4 illustrates the applicability of the proposed approach, and finally Section 5 concludes the paper.

2. Wind Turbine Technology

A wind turbine is a device that converts kinetic energy from the wind into electricity. The wind turbine technology is one of the most emerging renewable energy technologies. In recent years, significant progress has been made in building various-scale wind turbines for electricity generation [22,23]. The small-scale wind turbines are used for charging batteries or to power traffic warning signs. Medium-scale wind turbines can be used to generate electricity for large buildings or groups of residential properties. Large-scale wind turbines are an important source of renewable energy and are used by many countries as part of their strategy to reduce reliance on fossil fuels.

2.1. Types of Wind Turbine Technology

The technology of the design, manufacture, and operation of wind turbines and associated structures can be classified in different ways:

- *Bottom fixed and floating wind turbines*

Renewable wind energy options are divided to on-shore (on-land) and off-shore (at sea). On-shore wind turbines have numerous advantages compared to off-shore wind turbines, including lower installation costs, construction (in terms of quality and quantity), cost of operation and maintenance (O&M), as well as easier access. Nevertheless, in recent years, a large number of wind turbines have been built in off-shore locations due to high wind resources and the availability of large areas for installation. The technologies involved in both the onshore and offshore wind turbines are almost similar. One of the main differences between onshore and offshore wind turbine designs is their foundation structures. Onshore wind turbines are fixed to the ground with a concrete foundation, whereas offshore wind turbines have their foundations on the sea bed (fixed-bottom) or in the water (floating). Several types of fixed-bottom foundations are currently used in the offshore wind sector, depending on the depth of water where the turbines are to be installed, such as monopoles, tripods, and jacket structures [24]. Offshore floating wind turbine concepts, e.g., HyWind (Statoil, Noway) use designs borrowed from the oil and gas industry [25].

- *Vertical-axis and horizontal-axis wind turbines*

Nowadays, wind turbines are manufactured in a wide range of vertical-axis and horizontal-axis types. Vertical axis wind turbines are ideal for locations where there is little space, or where the conditions are very harsh. These kinds of wind turbines are cheaper, safer, and more environmentally friendly than horizontal axis wind turbines. Vertical axis wind turbines do not need any kind of navigation system, while this system is one of the most essential components of horizontal-axis wind turbines where it constantly aligns the rotor device with wind direction. Therefore, vertical-axis wind turbines help avoid the extra cost required for installing such systems or delays in responding to sudden changes in wind direction. However, these wind turbines are still in an initial development phase and a very limited number of full-scale applications are in place.

- *Gearbox-operated and direct drive (or gearless) wind turbines*

In traditional gearbox-operated wind turbines, the blades spin a shaft that is connected through a gearbox to the generator. The gearbox converts the turning speed of the blades to one sufficient for enabling the generator to generate electricity. The gearbox is a major contributor to the cost of wind turbines in terms of initial investment and maintenance. In order to reduce the costs associated with gearbox failures, the direct drive or gearless wind turbine technology has already been developed. This kind of wind turbine technology is less complex than gearbox-operated technologies, leading to easier O&M.

2.2. Wind Turbine Technology Status in Iran

Fossil fuels account for the majority of energy production in Iran. The country's high level of dependency on fossil fuels has made its economy vulnerable to disruption in the international oil and gas markets and to price volatility. Therefore, the country seeks to considerably reduce its dependency on the hydrocarbon sector through expanding renewable energy technologies and the efficient use of energy. Over the past few years, wind energy has experienced a remarkable growth in Iran's electricity generation. In 2006, the country's wind capacity was 45 MW while the installed capacity of wind power reached over 230 MW by the end of 2016 [26]. Several wind power plants including Manjil (in Gilan province), Binaloud (in Razavi Khorasan province), and Kahak (in Qazvin province) are currently in operation and many others are under construction. SabaNiroo Company (www.sabaniroo.co.ir) and Mapna group (www.mapnagroup.com) are two well-known domestic manufacturers in this field. Germany's Siemens (www.siemens.com) and Denmark's Vestas (www.vestas.com) are also two main exporters of wind turbine technology to Iran.

Overall, the renewable energy industries in the country possess the basic knowledge required for the design and manufacture of wind turbines and structures, however a great effort is needed to acquire a wind turbine technology compatible with the country's geographical features and economic factors. Examining the studies conducted in the design and manufacture of wind turbines in the renewable energy sector of Iran as well as a survey of experts and professionals in this field revealed that the method of obtaining wind turbine technology in the country is mainly based on the reverse engineering and rapid prototyping (RE & RP) technique. This strategy is used for getting technology to the market quickly while optimizing the design of components to enhance the product's performance. Recently, the renewable energy sector of the country attained the technology of designing, constructing, installing, and operating 2.5 MW wind turbines. In addition, the country's first portable wind power station with 10 $\times$ 2.5 MW turbines is planned to be constructed using the latest technologies.

Even though RE & RP is sometimes needed due to missing technical documentation, it does pose some business risks and security problems to companies. For this reason, several other options for technology transfer are under consideration to reduce the country's technological gap. These options include:

2.2.1. Technology Skills Training

The ability to acquire technology varies from one organization to another. A firm's technology acquisition ability not only depends on the size of the importing organization, its ownership profile (whether it is foreign or locally owned), its openness to the rest of the world, etc., but also depends on the "technology training strategy". Different studies show that the training strategy has a great impact on acceptance, implementation, and adoption of technologies by the end-user. Such a strategy might include recruiting technological experts, experimenting with and adapting imported technologies, providing staff with training programs, membership in industry associations, reading of technology magazines and research on the Internet, as well as encouraging employees to feel that they are all part of the technology transfer process.

2.2.2. Technology Licensing

A licensing agreement is a contractual arrangement whereby the technology owner (licensor) allows the technology receiver (licensee) to use, modify, and/or resell patents, trademarks, service marks, copyrights, or know-how in exchange for a compensation negotiated in advance between the parties. Licensing allows the establishment of a technology in a country which is sensitive to foreign ownership.

2.2.3. Turn-Key Contracts

This is a type of contract wherein the contractor is entitled to design, construct, commission, and hand over the technology to the end-users so that they can manipulate the project by turning a key. Turn-key contacts involve not only the licensing of the technological know-how but also technical assistance and the construction of a complete plant to manufacture the wind turbines and required structures for installation.

2.3. Technology Transfer Process

Technology transfer includes the transfer of skills, knowledge, equipment, and manufacturing methods to create a product or provide a service. Technology transfer generally takes place in two ways: vertical transfer and horizontal transfer. In the vertical transfer or R&D transfer, technical information and applied research findings are transferred to the phase of engineering design and development [27]. The technology then enters into the production process through commercialization. In the horizontal transfer, a technology is transferred from one level of capability in an organization to the same level of capability in another place. The procedures and processes of technology transfer can be summarized as follows:

2.3.1. Technology Selection

The first and most important part of the technology transfer process is to select the type of technology system, assess the transferee's capability to make effective use of the technology, and compare the technology in the country of origin to that of the destination country to adapt it to the local characteristics.

2.3.2. Technology Adaptation

The process of adapting the imported technology to specific local conditions, including the capital, culture, the level of knowledge and education, human resources, equipment manufacturing technology, as well as geographical conditions and national goals must be explained. The technology adaptation forms the basis for technological self-sufficiency.

2.3.3. Technology Absorption

Technology absorption is the adoption of the transferred technology across all systems so that the receiver of the technology will acquire all the necessary skills (installation, production, etc.) in order to optimize the use of the technology.

2.3.4. Application and Implementation

This includes the use of the acquired technology in the production and distribution of goods and services, after being adapted to the particular local conditions.

2.3.5. Development of the Imported Technology

This stage involves gaining experience and skills from transferring the technology, integrating the domestic knowledge with the technology providers, and developing new technologies for producing goods and providing services.

An effective transfer of technology requires the identification of industry objectives, types of technologies needed, sources of technology, transfer methods, and factors influencing its acquisition and development. As mentioned above, there are various technology transfer possibilities, from license agreements, through technical assistance and subcontracting manufacturing, to joint venture. Therefore, in the next section we propose a framework of analysis that is capable of prioritizing various wind turbine technology transfer strategies with respect to all critical features and criteria under consideration.

3. Technology Transfer Strategy Selection Model

In this study, an integrated AHP-TOPSIS decision model is developed to evaluate and prioritize the technology transfer strategies that are applicable to the design and manufacture of wind energy systems and their associated structures. To achieve the desired goal (determining the most profitable technology transfer solution) the following step-by-step process is proposed (Figure 1):

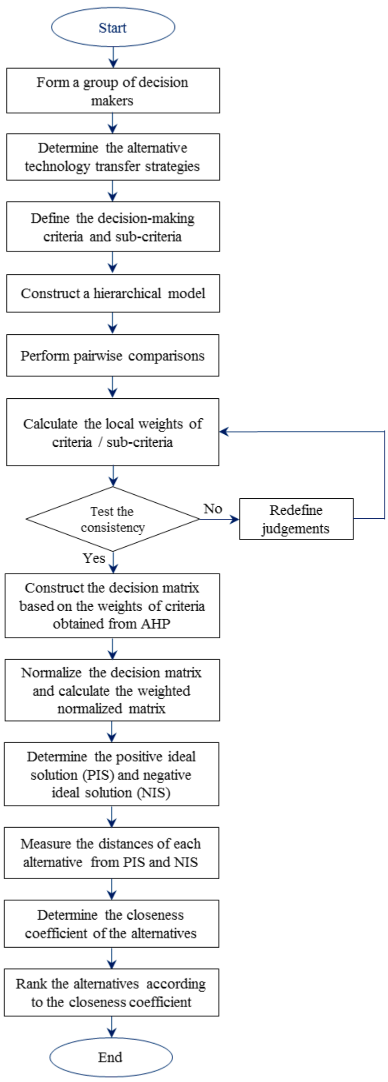

Figure 1. AHP–TOPSIS methodology applied to technology transfer strategy selection.

Step 1: Form a group of decision makers

A structured group of decision makers, including technology managers, investors, operators, and end-users is formed to analyse the data collected through literature reviews, expert elicitations, surveys, interviews, etc.

Step 2: Determine the alternative technology transfer strategies

Several strategies can be taken into account for the transfer of an advanced technology to an organization. In this study, four alternative technology transfer strategies are considered for wind turbines: reverse engineering, technology skills training, turn-key contracts, and technology licensing.

Step 3: Define the decision-making criteria and sub-criteria

In order to evaluate and prioritize the technology transfer strategies for wind turbines, the decision-making group must specify a set of criteria. Different decision-makers may have different objectives. In this paper, we first determined a list of criteria based on the review of the literature. Then, semi-structured interviews were conducted with the decision making group in order to get a better understanding of their objectives. Finally, four main criteria with nine sub-criteria were identified for consideration. All these criteria along with their relevant sub-criteria are further described in the following paragraphs.

C_1. Economic criterion

In order to determine the most appropriate alternative for technology transfer, it must be investigated how costly each strategy will be and how much added-value each of them can generate and how soon. Thus, the relevant factors describing the economic criterion are:

$C_{1.1}$. *Cost of technology transfer*

The investment required to import a particular technology is of particular importance in technology transfer strategy selection decision-making. The economic justification of each alternative must be examined according to a schedule established in cooperation with the technology transfer experts.

$C_{1.2}$. *Time to transfer a technology*

It is important to determine the length of time that each technology solution takes to be imported from a technology owner. This length of time can affect the annual economic performance of the technology transfer options and thereby their rates of investment return.

$C_{1.3}$. *Resilience against economic sanctions*

Economic sanctions are commercial and financial penalties applied by one or more countries against a targeted country, group, or individual. The sanctions may significantly impact the strategy of technology transfer from the owner to the user.

$C_{1.4}$. *Available market*

Available market is a term that is typically used to reference the revenue opportunity available for a technology, product, or service. It is defined as the number of users who are willing and capable of buying the particular technology after transfer.

C_2. Social criterion

In order to select the most suitable technology transfer strategy, the impact of each strategy on the social welfare of the destination country must be evaluated.

$C_{2.1}$. *Social acceptance*

The degree of acceptability of each technology transfer strategy in the destination country must be evaluated.

$C_{2.2}$. *Entrepreneurship*

The entrepreneurship sub-criterion represents the potential of each technology transfer alternative in job creation.

C_3. Technical criterion

The level of readiness of the importer's organization with respect to each technological option needs to examined and evaluated.

$C_{3.1}$. *Knowledge improvement*

Knowledge improvement is measured by the degree to which the knowledge, skills, and abilities in the technology importer organization can be expanded by new technologies.

$C_{3.2}$. *Coordination with domestic technology*

While selecting technology transfer strategies, the degree of adaptation of each option with domestic technology and the local conditions needs to be considered.

C_4. Environmental criterion

The impact of different technology transfer options on the environment should be examined [28].

$C_{4.1}$. *Environmental friendliness*

A high degree of environmental friendliness (e.g., minimum pollution impacts during production/use, potential to be recycled, safe disposal at the end of technology life) is required while selecting a technology transfer solution.

Step 4: Construct a hierarchical model

Using criteria, sub-criteria, and alternatives, a hierarchical model is constructed. Figure 2 illustrates a hierarchical model for the decision problem of selecting a suitable wind turbine technology transfer strategy. As can be seen, the proposed structure includes an ultimate goal, four criteria, nine sub-criteria, and four alternatives.

Step 5: Perform pairwise comparisons

After defining alternatives, criteria, and sub-criteria, and constructing the hierarchical model, the decision-making group will need to estimate the relative preference/importance of criteria/sub-criteria with respect to the ultimate goal. The simplest and most common method for weighing the criteria/sub-criteria is the *pairwise comparison*. Pairwise comparisons are done by comparing elements with respect to their parent element and the results are represented in a form of matrix, called a pairwise comparison matrix. A pairwise comparison matrix is a square matrix of size $n \times n$, represented by $\mathbf{A} = [a_{ij}]$, where n is the number of decision elements (criteria or alternatives) and a_{ij} denotes the comparative importance of the criterion i with respect to the criterion j, i.e.,

$$a_{ij} = w_i/w_j, \text{and } w_i, w_j > 0 \text{ for } i, j \in \{1, 2, \ldots, n\} \quad (1)$$

In the pairwise comparison matrix, a reciprocal value is assigned to the inverse comparison, that is, $a_{ji} = 1/a_{ij}$, and the diagonal values are preserved as one. Thus, the pairwise comparison matrix can be represented in the following form:

$$A = \begin{pmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \dots & w_3/w_n \\ \dots & \dots & \dots & \dots & \dots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \dots & w_n/w_n \end{pmatrix} = \begin{pmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \dots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \dots & a_{3n} \\ \dots & \dots & \dots & \dots & \dots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \dots & 1 \end{pmatrix} \quad (2)$$

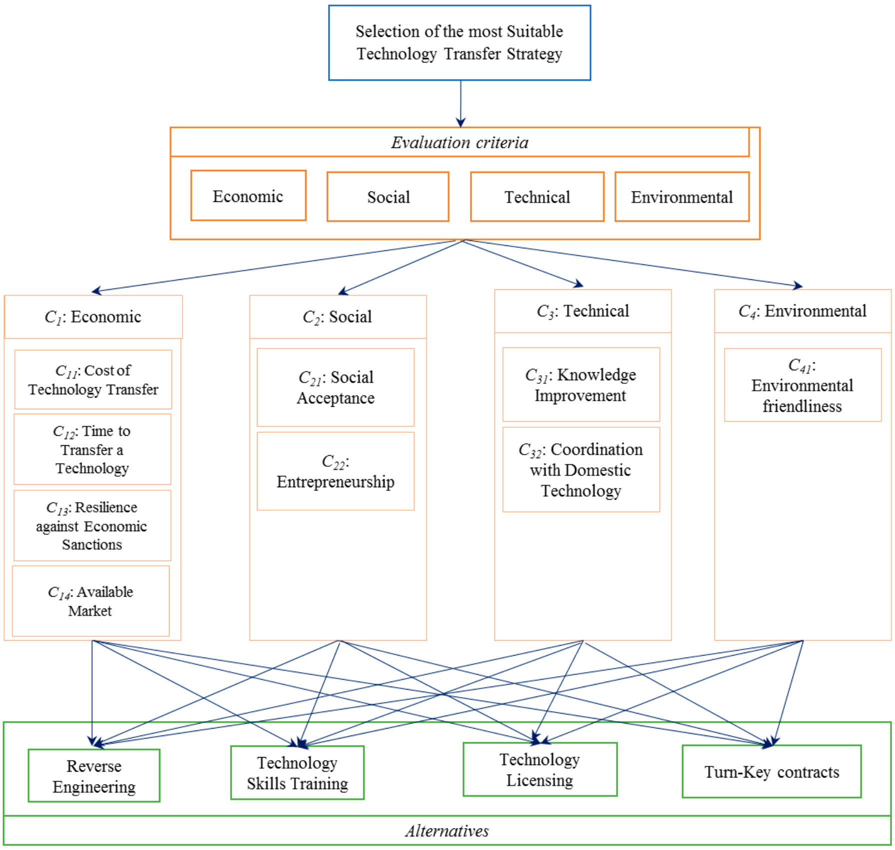

Figure 2. A hierarchical model for technology transfer strategy selection.

The criteria (sub-criteria)'s relative importance values are expressed with a scale from 1 to 9 as shown in Table 2. This scale indicates how many times more important or dominant one element is over another element with respect to the criterion or property to which they are compared [29]. A score of 1 represents equal importance between the two criteria (sub-criteria) and a score of 9 indicates the extreme importance of one element compared to the other one. To complete the pairwise comparison matrix, the decision maker is asked questions such as: "on a scale from 1 to 9, how much more important is the element *i* compared to element *j*?"

Table 2. Pairwise comparison for preferences [30].

Weight	Definition	Description
1	Equal importance	Elements *i* and *j* are equally important
3	Moderate importance	Element *i* is weakly more important than element *j*
5	Strong importance	Element *i* is strongly more important than element *j*
7	Very strong importance	Parameter *i* is very strongly more important than parameter *j*
9	Absolute importance	Element *i* is absolutely more important than element *j*
2, 4, 6, 8	Intermediate values	Represents compromise between the priorities

Step 6: Calculate the local weights of criteria/sub-criteria and test the consistency

After performing pairwise comparisons between the elements, the eigenvalue method is used to estimate the relative weights of the decision elements. In this method, we can estimate the relative weights of the criteria (sub-criteria) (w) by the following equation:

$$\mathbf{A} \times w = \lambda_{max} \times w, \tag{3}$$

where λ_{max} represents the largest eigenvalue of the pairwise comparison matrix **A**. The consistency property of each pairwise comparison matrix needs to be examined. The consistency index (CI) and consistency ratio (CR) are used to measure the consistency of the pairwise comparison matrix. The CI and CR values are defined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \tag{4}$$

$$CR = \frac{CI}{RI}, \tag{5}$$

where RI represents the average value of CI for numerous random entries of same order reciprocal matrices. The values of RI for n = 3 to n = 11 are computed and given in Table 3. If the value of CR is smaller or equal to 10%, the inconsistency is acceptable; otherwise, the decision makers are asked to revise their judgments in order to improve the consistency level [31].

Table 3. Random Index (RI) [31].

n	3	4	5	6	7	8	9	10	11
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Step 7: Construct the decision matrix based on the weights of criteria obtained from AHP

After the weights of the criteria and sub-criteria are obtained by the AHP method, the decision matrix is constructed to represent the performance ratings of alternatives with respect to the criteria. As shown in Table 4, the decision matrix has a size of $m \times n$, where m and n represent the number of alternatives and criteria (sub-criteria), respectively.

Table 4. Decision matrix.

Alternatives	C_1	C_2	...	C_n
	w_1	w_2	...	w_n
A_1	b_{11}	b_{12}	...	b_{1n}
A_2	b_{21}	b_{22}	...	b_{2n}
...	...	...	...	...
A_m	b_{m1}	b_{m2}	...	b_{mn}

Step 8: Normalize the decision matrix and calculate the weighted normalized matrix

Given that the decision matrix consists of attributes with different units, the values within the matrix must be normalized so that all attributes can be measured in dimensionless units. We use the following formula to normalize each value b_{ij} in a decision matrix $\mathbf{B} = (b_{ij})_{m\times n}$ into a corresponding element r_{ij} in the normalized decision matrix [32]:

$$r_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{m} b_{ij}^2}}, \text{ for } i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{6}$$

After normalizing the decision matrix, the resulting matrix is multiplied by the local weights matrix obtained for criteria/sub-criteria using the eigenvalue method, which is itself a diagonal matrix whose elements on the main diagonal are equal to the weights of the criteria/sub-criteria. Thus, the weighted normalized decision matrix (**v**) is given by:

$$\mathbf{v} = [v_{ij}]_{m\times n} = [r_{ij}]_{m\times n} \times [w_{jj}]_{n\times n}, \text{ for } i = 1,2,\ldots, m; j = 1,2,\ldots, n \tag{7}$$

Step 9: Determine the positive ideal solution (PIS) and negative ideal solution (NIS)

After obtaining the weighted normalized decision matrix, the PIS and the NIS are determined. The PIS is composed of all the best criteria values attainable, whereas the NIS is composed of all the worst criteria values attainable. The maximum value of the benefit attributes and the minimum value of the cost attributes constitute the PIS (A^+), while the minimum value of the benefits attributes and the maximum value of the cost attributes constitute the NIS (A^-). The PIS (A^+) and NIS (A^-) for the benefit attributes are defined, respectively, as follows:

$$A^+ = [v_1^+, v_2^+, \ldots, v_n^+], \text{ where } v_j^+ = \max_{1\leq i\leq m}\{v_{ij}\} \tag{8}$$

$$A^- = [v_1^-, v_2^-, \ldots, v_n^-], \text{ where } v_j^- = \min_{1\leq i\leq m}\{v_{ij}\} \tag{9}$$

Step 10: Measure the distances of each alternative from PIS and NIS

To prioritize the technology transfer strategies using the TOPSIS method, their distances from the PIS and NIS must be measured. The following formulas are used to calculate these distances:

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2} \text{ for } i = 1,2,\ldots, m \tag{10}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \text{ for } i = 1,2,\ldots, m \tag{11}$$

Step 11: Determine the closeness coefficient of the alternatives

The closeness coefficient (CL) of the ith alternative strategy A_i with respect to the PIS is defined as:

$$CL_i^+ = \frac{d_i^-}{d_j^- + d_i^+} \text{ for } i = 1,2,\ldots, m \tag{12}$$

Step 12: Rank the alternatives according to the closeness coefficient

A set of alternatives can be ranked by preference according to the descending order of the closeness coefficient; in other words, a larger closeness coefficient means a better alternative. The strategy with the largest closeness coefficient will be chosen as the superior technology transfer solution.

4. Application

In this section, a case study illustrates our findings. The proposed AHP-TOPSIS decision model is applied to select a suitable strategy of technology transfer for the design and manufacture of a new wind turbine configuration in the renewable energy sector of Iran. The data used for this analysis were all gathered from face-to-face semi-structured interviews with experts who are actively involved in the management of new technologies in the renewable wind energy industry. By interviewing the wind turbine technology managers, investors, operators, and end-users, it is concluded that the criteria and sub-criteria in Section 3 can be accepted. Therefore, the hierarchy model presented in Figure 2 is used for this study.

The pairwise comparison matrix of four criteria with respect to the ultimate goal was formed to estimate their relative weights. Table 5 shows the pairwise comparison of the criteria as well as their priority weights with a consistency ratio 0.004157. As can be seen, in evaluation of the technology transfer strategies for wind turbines, the greatest weight is given to the economic criterion followed by the technical criterion.

Table 5. Pairwise comparison matrix for the criteria with respect to the ultimate goal.

Criteria	Economic	Social	Technical	Environmental	Weight
Economic	1	4.2	2.1	5.3	0.5243
Social	0.24	1	0.57	1.76	0.1391
Technical	0.48	1.85	1	2.54	0.2452
Environmental	0.19	0.57	0.39	1	0.0914

Note: *CR* (consistency ratio) = 0.004157.

After constructing the pairwise comparison matrix of the four criteria with respect to the ultimate goal, the pairwise comparison matrices of sub-criteria with respect to their corresponding criterion are formed. Table 6 gives the pairwise comparison matrix of four economic sub-criteria as well as their priority weights with a *CR* = 0.013702.

Table 6. Pairwise comparison matrix of the sub-criteria with respect to the economic criterion.

Economic Criteria	Cost of Technology Transfer	Time to Transfer a Technology	Economic Sanctions	Available Market	Weight
Cost of technology transfer	1	2.2	1.31	3.41	0.3879
Time to transfer a technology	0.45	1	0.72	1.84	0.1927
Economic sanctions	0.76	1.39	1	4.3	0.3232
Available Market	0.29	0.54	0.23	1	0.0972

Note: *CR* (consistency ratio) = 0.013702.

After obtaining the local weights of the criteria and sub-criteria by the AHP method, the decision matrix is constructed. Table 7 gives the attribute values for each alternative technology transfer strategy.

Table 7. Decision matrix in the AHP-TOPSIS technique.

Alternatives	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{2.1}$	$C_{2.2}$	$C_{3.1}$	$C_{3.2}$	C_4
Weights	0.20339	0.101	0.169	0.0509	0.0368	0.1023	0.1669	0.0783	0.0914
Reverse engineering	60 M	15	9	2000 M	7	15,400	9	7	1
Technology skills training	40 M	10	5	10,000 M	9	14,000	8	9	7
Turn-key contracts	80 M	5	1	5000 M	5	11,000	6	5	5
Technology licensing	120 M	2	2	6000 M	3	500	2	2	9

After normalizing the above decision matrix, it is multiplying by the weights of the sub-criteria obtained from the AHP method to derive the weighted normalized decision matrix. Table 8 shows the weighted normalized decision matrix.

Table 8. Weighted normalized decision matrix.

Alternatives\Criteria	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{2.1}$	$C_{2.2}$	$C_{3.1}$	$C_{3.2}$	C_4
Reverse engineering	0.0757	0.0806	0.1447	0.0079	0.0201	0.0669	0.1104	0.0435	0.0073
Technology skills training	0.0505	0.0537	0.0804	0.0397	0.0259	0.0608	0.0981	0.0559	0.0512
Turn-key contracts	0.1009	0.0269	0.0161	0.0198	0.0144	0.0478	0.0736	0.0311	0.0366
Technology licensing	0.1514	0.0107	0.0322	0.0238	0.0086	0.0022	0.0245	0.0124	0.0659

The best and the worst attribute values for each sub-criterion are then obtained and the positive and NISs are calculated. Table 9 shows the PIS and NIS.

Table 9. Positive and negative ideal solutions (PISs and NISs).

PIS (NIS)\Criteria	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{2.1}$	$C_{2.2}$	$C_{3.1}$	$C_{3.2}$	C_4
A^+	0.0505	0.0107	0.1447	0.0397	0.0259	0.0669	0.1104	0.0559	0.0659
A^-	0.1514	0.0806	0.0161	0.0079	0.0086	0.0022	0.0245	0.0124	0.0073

The distances of each technology transfer solution from the PIS and NIS are measured using Equations (9) and (10). These distances are given in Table 10.

Table 10. Distances from the PISs and NISs.

d^+ (d^-)\Criteria	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$	$C_{2.1}$	$C_{2.2}$	$C_{3.1}$	$C_{3.2}$	C_4
$d_1{}^+$	0.0006	0.0049	0.0000	0.0010	0.0003	0.0000	0.0000	0.0002	0.0034
$d_1{}^-$	0.0057	0.0000	0.0166	0.0000	0.0001	0.0042	0.0074	0.0010	0.0000
$d_2{}^+$	0.0000	0.0018	0.0041	0.0000	0.0000	0.0004	0.0002	0.0000	0.0002
$d_2{}^-$	0.0102	0.0007	0.0041	0.0010	0.0003	0.0034	0.0054	0.0019	0.0019
$d_3{}^+$	0.0025	0.0003	0.0166	0.0004	0.0001	0.0004	0.0014	0.0006	0.0009
$d_3{}^-$	0.0025	0.0029	0.0000	0.0001	0.0003	0.0021	0.0024	0.0003	0.0009
$d_4{}^+$	0.0102	0.0000	0.0127	0.0003	0.0003	0.0042	0.0074	0.0019	0.0000
$d_4{}^-$	0.0000	0.0049	0.0003	0.0003	0.0000	0.0000	0.0000	0.0000	0.0034

After calculating the distances of all solutions from the best and the worst attribute values, the closeness coefficients of the alternatives are calculated and then the superior option will be selected. The relative closeness of four technology transfer strategies to the PIS are represented in Figure 3. As shown, the technology skills training with a relative closeness of 0.68 is chosen to be the most appropriate technology transfer strategy for the renewable energy sector of Iran. This technology transfer strategy is followed closely by the reverse engineering strategy with a closeness of 0.65.

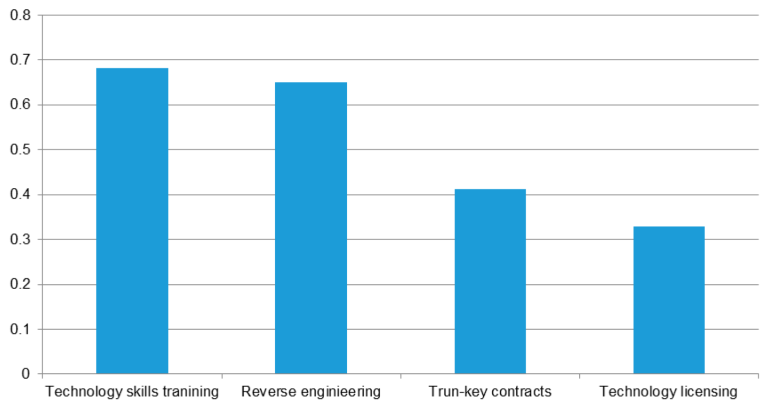

Figure 3. The relative closeness and priorities of technology transfer strategies based on AHP-TOPSIS.

To explore the efficiency of the proposed hybrid MCDM model, the results of this study are compared with the results obtained from the classical techniques of AHP and TOPSIS. These two techniques were implemented by, respectively, 'Expert Choice, Version 11' (http://Expertchoice.com) and 'Topsis Version 3.1' (http://topsis.software.informer.com/3.1/) software. The final priorities obtained from the AHP method and the relative closeness obtained from the TOPSIS method for the four technology transfer strategies are represented in Figure 4. While comparing the proposed decision model with the AHP and TOPSIS methods, it is found that the results are well-consistent and in general agreement with each other. All three techniques have ranked the two alternatives of technology skills training and reverse engineering as the two superior technology transfer solutions for the design and manufacture of wind turbines. However, the TOPSIS and AHP-TOPSIS models determined the technology skills training as the most appropriate strategy of technology transfer, but reverse engineering was chosen as the first option and the technology skills training as the second option by the AHP technique. On the other side, the rankings of alternatives based on the TOPSIS and AHP-TOPSIS models have the same preference of the first two alternatives, namely technology skills training and reverse engineering for decision makers, and are recognized to be closer to each other based on the AHP-TOPSIS model than the TOPSIS technique.

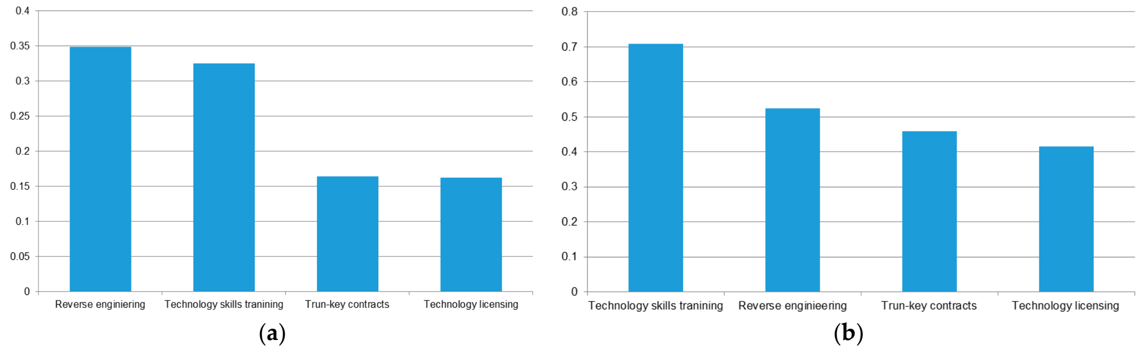

Figure 4. (**a**) Priority weights obtained from the AHP; (**b**) Relative closeness obtained from the TOPSIS.

5. Conclusions and Future Work

With the rapid development of modern wind turbine technologies [33], there is increasing interest by developing countries to promote their technological and innovative capabilities through importing high-tech equipment from developed countries. The identification, evaluation, and prioritization of technology transfer strategies for wind turbine systems and their associated structures is a very complex task due to the presence of numerous decision makers (investors, manufacturers, operators), the qualitative nature of the evaluation process, and the existence of imprecision and uncertainty in the decision making process. The technology managers must choose the most profitable transfer strategy for each component of the wind turbine (e.g., gearbox, blade) or the entire system among a set of possible alternatives (such as reverse engineering, licensing, turn-key) with respect to a set of goals or by comparing criteria.

In the current study, to evaluate various technology transfer solutions for the design and manufacture of wind turbines, four main criteria and nine sub-criteria were determined from the viewpoint of wind energy investors, wind turbine manufacturers, and wind farm operators. These were: economic (cost of technology transfer, time to transfer a technology, resilience against economic sanctions, available market), social (social acceptance, entrepreneurship), technical (knowledge improvement, coordination with domestic technology), and environmental (environmental friendliness). Then, in order to find the superior option for the transfer, a combined AHP and TOPSIS decision model was developed. The AHP method was used to calculate the weights of the criteria and sub-criteria, and the TOPSIS technique, which is based on the relative distance of alternatives from the positive and negative ideal solutions simultaneously, was employed to prioritize the technology transfer strategies.

For the purpose of clearly illustrating the proposed decision model, it is applied to determine a suitable wind turbine technology transfer strategy for the renewable energy sector of Iran and the results are compared with those obtained by the AHP and TOPSIS techniques. It was found that the results were well consistent and in general agreed with each other. Based on these results, technology skills training was chosen as the most appropriate transfer strategy followed by the reverse engineering strategy.

There is substantial scope for future research in the area of technology management for wind energy systems. The following are some possible extensions:

(1) We confined our analysis to four types of technology transfer strategies. Some other solutions such as FDI and joint venture will be considered in our future study.
(2) In addition to the proposed methodology, some other hybrid MCDM models (such as ANP-TOPSIS) can be developed to find the most profitable technology transfer solution.
(3) The proposed methodology will be extended in the near future to determine the most appropriate type of wind turbine technology systems (with respect to investment cost, power output, durability, etc.) in the renewable energy sector.

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