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MULTI-CRITERIA DECISION MAKING-BASED COMPARISON OF FUEL CELL TYPES FOR DISTRIBUTED GENERATION APPLICATIONS

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ABSTRACT

Five major types of fuel cells were compared for distributed generation applications by using a multi-criteria decision-making method shortly named TOPSIS. The evaluation criteria were the average power output, efficiency, cost and environmental impact. The weights of each of the above-mentioned criteria were determined via an online survey, conducted on a total of 40 people all of whom are experienced stakeholders (academics, private sector or government employees) in the field of energy. Solid Oxide Fuel Cells (SOFC) turned out to be the most suitable type, followed by Molten Carbonate Fuel Cells (MCFC) whereas Alkaline Fuel Cells emerged as the least suitable option. The way the fuel cell types were ranked was attributed to the high power output and high efficiency of SOFCs and MCFCs. This analysis will help decision makers in both regulated and deregulated electricity sectors. Energy serving entities will have a new option for emission-free electricity generation.

Keywords:
distributed power generation, energy policy, fuel cell, multi-criteria decision making, TOPSIS

1. INTRODUCTION

Stationary power generation initially began as distributed generation (DG) with the main concern being proximity to the end-use. At first, there was a very open market, where customers could choose between a lot of small competing companies or entities which were offering electricity to them. Nonetheless, later it evolved into a monopolistic business due to technical factors. Installation of very large power plants made it possible to increase the distance between the source and the customer, and the transmission losses were minimized by using high voltage transmission lines. Therefore, in order to be able to promote the economic development, the ruling bodies tried to limit the power of the monopolies. According to Dufour [1] a more competitive and effective electricity supply system can only be achieved if the utilities are forced to compare how much it costs to produce energy in a centralized manner to the price of the available energy that would be obtained through distributed generation, leading to a partial competition in the energy market.

Fuel cells, in general, are a recently-emerged technology in the field of distributed electricity generation. Fuel cells offer features such as full automation possibility, very low noise and emissions release, high efficiency both directly as a fuel cell and in integrated cycles, high power density and reliability, which are all desired for an effective distributed generation system. The main contributions that fuel cells could make to the electrical grid management and control are their voltage support, active filtering capabilities, high response speed and quick load connection capabilities [1].

In this study, we performed a technical and economic evaluation of fuel cell types and compared different fuel cell types in terms of their availability as high quality power sources for distributed generation applications by using a common multi-criteria decision-making (MCDM) method named Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

1.1. Fuel cells

Fuel cells are electrochemical devices in which the energy output of a chemical reaction is directly converted into electricity and heat. Like commercial batteries, fuel cells have anode and cathode electrodes in which catalytic oxidation and reduction reactions take place, respectively. Unlike commercially available batteries, e.g. Li-ion battery, that show decreasing performance in the long term as the metal inside undergoes an irreversible electrochemical reaction; in theory fuel cells can operate with consistent performance for extended periods when compared to conventional batteries as long as they are supplied with fuel and maintained [2, 3]. Another main advantage of fuel cells over other power sources such as internal combustion engines is the higher efficiency, as the theoretical efficiency of a fuel cell can approach 80%. Fuel cells also are environmentally friendly systems, most of the time only by-product of fuel cell operation is pure water. Other advantages of fuel cells include simplicity of design, installation and maintenance; silence and high energy density per unit area or volume, and diversity of fuels that can be used [4, 5]. It is possible to connect fuel cells in series to obtain stacks so that power can be supplied to a variety of loads, thus the power output can vary in a range between few kilowatts to multi megawatts [6, 7].

Fuel cells can be classified according to many different criteria but the most common criterion is the type of electrolyte. Accordingly, there are five major types [8]. These are:

- Proton Exchange Membrane Fuel Cells (PEMFC)
- Alkaline Fuel Cell (AFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

In addition to the five major fuel cell types listed above, technologies such as direct methanol fuel cells (DMFC) or microbial fuel cells (MFC) also exist. However, even the state-of-the-art DMFC or MFC systems cannot match the power levels that can be attained with the five major fuel cell types. DMFCs and MFCs are more ideal for small scale applications and therefore they have not been considered as viable alternatives for distributed generation applications [5]. Detailed information about the main characteristics of each fuel cell type can be found elsewhere [9-21].

1.2. Distributed generation

Because of the recent liberalization trends in the electric markets and changes in the regulatory environment, electricity systems have been going through significant changes. Technological innovations, constraints on the construction of new transmission lines as well as the increasing power demand enhanced the importance of small-scale generation connected to the local distribution systems, which are generally referred as distributed generation (DG). Some examples of DG technologies are wind turbines, photovoltaics, biomass, small hydro turbines, small and micro gas turbines, Stirling engines, internal combustion engines, and for the last but not the least fuel cells [22-25].

The main benefits of DG systems are the utilization of local resources, greater power reliability and reduction of power losses during transmission and distribution. DG systems also favour the consumers economically [23]. It also promotes new employment opportunities in rural areas. Wee states that despite bearing the disadvantage of high operation costs, the market share of DG is growing thanks to many advantages such as high energy efficiency, relatively low CO_2 emissions, easiness of construction and built-in safety [17]. It has been suggested that utilization of fuel cells as DG is especially beneficial for developing countries [26].

2. METHODOLOGY

2.1. Multi-criteria decision making

Multi-criteria decision making (MCDM) or Multiple-criteria decision analysis (MCDA) is a sub-discipline of operations research that deals with creating mathematical and computational tools to realize the subjective evaluation of a finite number of decision alternatives with respect to a finite number of performance criteria. MCDA/MCDM combines know-how from many fields, such as mathematics, behavioural decision theory, economics, computer technology, software engineering and information systems [27].

Among various MCDA/MCDM methods developed to solve real-world decision problems, TOPSIS is a versatile method that can be successfully applied in a great number of areas. Hwang and Yoon originally proposed TOPSIS in 1981 to help select the best alternative with a finite number of criteria [28]. Since then TOPSIS has gained considerable popularity amongst researchers and practitioners from diverse backgrounds [27-30].

2.2. Principles of TOPSIS

TOPSIS, developed by Hwang and Yoon in 1981, is a simple ranking method in conception and application. The main principle of standard TOPSIS method is based on choosing alternatives that simultaneously have the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution. In the positive ideal solution, the benefit criteria are maximized and the cost criteria are minimized, whereas in the negative ideal solution the cost criteria are maximized and the benefit criteria are minimized [27]. TOPSIS method involves six steps. These steps are given below [31]:

i) To calculate the normalized decision matrix. The normalized value r_{ij}, which is the value of criterion i the j^{th} alternative, is calculated as follows:

$$r_{ij} = f_{ij} / \sqrt{\sum_{j=1}^{J} f_{ij}^2}\,,\ j = 1, 2, \ldots, J;\ i = 1, 2, \ldots, n \qquad (1)$$

where J is the number of alternatives, n is the number of criteria and f_{ij} is the evaluation value of the criterion i for alternative a_i.

ii) To calculate the weighted normalized decision matrix. The weighted normalized value υ_{ij} is calculated as follows:

$$\upsilon_{ij} = w_i\, r_{ij},\ j = 1, 2, \ldots, J;\ i = 1, 2, \ldots, n \qquad (2)$$

where w_i is the weight of the criterion i.

$$\left(\sum_{i=1}^{n} w_i = 1\right)$$

iii) To determine the ideal and negative-ideal solution:

$$A^* = \upsilon_1^*, \ldots, \upsilon_n^* = (\max_j \upsilon_{ij} \mid i \in I'), (\min_j \upsilon_{ij} \mid i \in I'')$$

$$A^- = \upsilon_1^-, \ldots, \upsilon_n^- = (\min_j \upsilon_{ij} \mid i \in I'), (\max_j \upsilon_{ij} \mid i \in I'')$$

(3)

where I' is associated with the benefit criteria and I'' is associated with the cost criteria.

iv) To calculate the separation measures, using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as:

$$D_j^- = \sqrt{\sum_{i=1}^{n} (\upsilon_{ij} - \upsilon_i^-)^2}\,,\ j = 1, 2, \ldots, J$$

$$D_j^* = \sqrt{\sum_{i=1}^{n} (\upsilon_{ij} - \upsilon_i^*)^2}\,,\ j = 1, 2, \ldots, J \qquad (4)$$

Then, the relative closeness to the ideal solution should be calculated. The relative closeness of the alternative a_j with respect to A^* is defined as:

$$C_j^* = D_j^- / (D_j^* + D_j^-),\ \ j = 1, 2, \ldots, J \qquad (5)$$

v) To rank the preference order

TOPSIS method has certain advantages. First of all, it is a relatively simple and fast method. It can be used for the comparison of an infinite number of alternatives by considering an infinite number of criteria (or attributes). While selecting the optimum alternative, the effect of each attribute cannot be evaluated alone and must always be seen as a trade-off with respect to other attributes. In other words, changes in one attribute can be compensated for in a direct or opposite manner by other attributes [30]. One significant advantage of TOPSIS method over other MCDM methods is that the output can be a preferential ranking of the alternatives with a numerical value that provides a clearer understanding of differences and similarities between alternatives, whereas other MCDM techniques such as the ELECTRE method only determine the rank of each alternative. Furthermore, TOPSIS does not require pair-wise comparisons as in the case of Analytical Hierarchy Processes (AHP). This is especially useful when working with a large number of alternatives and criteria [32-34]. It can also be modified to solve more specific problems, as exemplified by Aloini et. al when they made an intuitionistic peer-based modification to standard TOPSIS method to obtain the group opinion on the relevance of the single decision makers and to aggregate individual opinions of decision makers for rating the importance of criteria and alternatives [35]. Other studies that involve the use of an improved and/or modified TOPSIS methodology can also be found in the literature [36-39].

2.3. Review of previous studies

The application of MCDM methods in general (not only TOPSIS) in the fields of fuel cells or distributed generation is not very common. Chang et al. [40] developed a fuzzy MCDM method to evaluate fuel cells for several applications such as vehicular applications, combined heat and power systems, portable electronics and finally, distributed generation. While this study shows resemblance to our study, there is no comparison of various fuel cell types in Chang et al.'s paper. Zangeneh et al [41] evaluated different distributed generation technologies including fuel cells to decide on which one is most suitable for Iran by using a hierarchical decision-making process. Wang et al. [42] used a fuzzy multi-criteria decision making method to compare several trigeneration technologies (combined power, heating, and cooling), including solid oxide fuel cells. Alanne et al. [43] used the MCDM approach to compare various residential energy supply systems, one of which is solid oxide fuel cells. Jing et al. [44] developed a fuzzy MCDM model to determine the most effective energy source for combined cooling, heating and power systems (CCHP); however, they only considered molten carbonate fuel cells and not any other type of fuel cell. Finally, Papadopoulos and Karagiannidis [45] used the above-mentioned Electre method for the optimization of decentralized energy systems; however, they did not consider fuel cells as an energy source option at all.

There are examples of MCDM techniques being applied on energy-related problems. Kabak and Dağdeviren proposed a hybrid model based on BOCR (Benefits, Opportunities, Costs and Risks) and ANP (Analytic Network Process) to determine Turkey's energy status and prioritize alternative renewable energy sources [46]. They used 19 different criteria to compare five sources which were hydro, solar, geothermal, wind, and biomass. The most important criterion was chosen as economy, followed by security, human wellbeing, technology and global effects. Hydro power was determined as the optimal energy source for Turkey. Streimikiene et al. [47] studied developing the multi-criteria decision support framework for choosing the most sustainable electricity production technologies, by using multi-criteria decision methods MULTIMOORA and TOPSIS for the analysis. As expected, the multi-criteria analysis showed that renewable energy sources-based electricity production technologies are preferable. Hydro and solar power systems emerged as the most sustainable. On the other hand, conventional energy technologies, namely oil, gas, coal, and nuclear power, were found to be the least sustainable. The combined application of two multi-criteria decision-making methods, namely, the Analytical Hierarchy Process (AHP) and Compromise Ranking method (VIKOR), to facilitate the selection of the best solution for electrical supply of remote rural locations, involving technical, economic, environmental and social criteria was proposed [48]. The weights were determined based on expert opinions. They concluded that hybrid systems composed of renewable technologies and a storage system are the most suitable option.

The results of our literature review show that the studies about the utilization of fuel cells for distributed generation or any other application do not justify why a particular type of fuel cell has been chosen for a particular type of application. From this perspective, we believe that our study fills an important gap in the field as the comparative evaluation of different fuel cell types by TOPSIS or any other MCDM method for distributed generation applications has never been realized before.

3. RESULTS AND DISCUSSION

3.1. Determination of evaluation criteria and scores

In this section, the technical and economic evaluation of five major fuel cell types will be presented. As mentioned before, DMFCs have very low power output when compared to other major types, thus DMFCs should not be considered as a viable alternative for distributed generation as far as the current technological status is concerned.

1.1.1. Average power output

Fuel cell types whose operation temperatures are higher than others like MCFC and SOFC have higher power outputs than PEMFC, AFC, or PAFC. The main reason for this fact is the high conversion of reactants because of increased chemical activity at elevated temperatures. Hence, it is more common to utilize MCFC or SOFC technology for large scale processes. However, in some resources the term power density is preferred over power output to compare fuel cells. Power density, which is defined as power output per unit volume (kW/m^3) or per unit chemically active surface area (kW/m^2) values may appear in a different order of rank, due to the fact that certain fuel cell types can be built into much smaller units. One example is PEMFC. The presence of the solid electrolyte enables the manufacturers to design and build compact and versatile PEMFC systems for a wide variety of applications. In this study, average power output is chosen over power density as a criterion because the term power density can be misleading in the sense that small-scale fuel cell systems that definitely do not have the capacity to power DG systems can have higher scores than large-scale fuel cell systems if power density values are taken into account.

1.1.2. Efficiency

Efficiency of a fuel cell can be defined in different ways; however, the most direct approach would be calculating the ratio of actual energy output to maximum theoretical energy output. For a fuel cell, the maximum theoretical energy output would be the lower heating value (LHV) of hydrogen. High temperature fuel cells like MCFC and SOFC have higher efficiencies when compared to other types [7,8,26,49]. If the heat that is released as a result of the exothermic fuel cell reactions can be utilized for heating purposes, then the overall system efficiencies can reach values as high as 75 to 80%. However, in this study the efficiency of electricity output for stationary applications is taken into account.

1.1.3. Cost

Since all the fuel cell types rely on essentially the same technology to produce power, it is the materials used in the construction that determines the cost of the systems. As indicated before, all fuel cell reactions require catalysts to proceed. One method of eliminating the need for highly active, expensive catalysts such as Pt is reaching high temperatures in the fuel cell medium. However, the materials used for construction must then be durable to such extreme conditions, and more durable the materials, more expensive they get. For example, in SOFCs ceramic materials are preferred over metals for construction purposes as ceramics are more durable to extreme temperatures, and this significantly increases the manufacturing cost.

When considering the overall cost of a fuel cell system, auxiliary equipment such as fuel processor, humidifier, inverter, etc. should also be taken into account [50]. Amongst these equipment, humidifier is necessary for PEMFC as polymer membranes used in PEMFC must be hydrated at all times to remain proton-conductive. As fuel cells produce direct current, all systems require an inverter to convert direct current into alternating current. Hydrogen storage is also one of the most expensive items that contribute to the overall cost of fuel cell systems. Hydrogen can be stored by several methods, such as conversion to a cryogenic liquid [51], high pressure storage [52], methane reforming [53], and metal hydrides. While each of these methods has its own advantages and disadvantages, metal hydrides are usually favored due to the increased safety and storage volume efficiency.

1.1.4. Environmental impact

Fuel cell systems are relatively clean, in other words, they do not generate any direct emissions of hazardous chemicals such as CO, CO_2, NO_X, SO_2 as many conventional energy sources. However, manufacturing the fuel cell system and producing the H2 fuel have their indirect emission scores. In the literature, CO_2 emission is generally accepted as the most popular means of expressing the environmental impact [54] therefore the unit for environmental impact criterion has been decided as kg CO_2 emitted per MWh electricity output. A more detailed approach could have involved performing a life cycle assessment of all the processes associated with energy supply from fuel cells, and such a methodology would have included the investigation of all possible environmental impacts like carbon footprint, acidification, ozone layer depletion, photochemical smog formation, etc. However, that approach would not fit the scope of this particular study. For this reason, net CO_2 emission was selected as the most relevant environmental impact.

1.1.5. Summary of fuel cell evaluation

As mentioned above, four criteria have been selected for the comparison of fuel cell types. Durability or useful lifespan of the fuel cell system was also considered as a possible criterion at one point, but research revealed that all five major fuel cell types have quite similar durability scores [55], and therefore it was concluded that the effect of durability on the end results would be negligible. The overview of the evaluation criteria can be found in Table 1. While some of the values in Table 1 are exact values, some are approximations. Detailed information regarding these scores can be found elsewhere [15, 49, 56-58]. It must be mentioned that the data belong to stationary applications only and mobile applications, especially for PEMFC systems, are not taken into consideration.

Table 1. Program costs and avoided costs in assessing the savings of promoting cogeneration.

	PEMFC	AFC	PAFC	MCFC	SOFC
Average power output (kW)	50	55	250	1650	5000
Electrical efficiency (%)	50	50	40	60	70
Cost (Euro / kW)	4000	700	5000	6000	4000
Environmental impact (kg CO_2 per MWh)	514	258	477	445	334

In Table 2 below, the normalized evaluation value of each fuel cell type for each criterion is presented, as calculated according to the methodology described in section 2.2.

Table 2. Normalized evaluation scores

	PEMFC	AFC	PAFC	MCFC	SOFC
Average power output	0.002	0.003	0.012	0.077	0.233
Electrical efficiency	0.107	0.107	0.086	0.129	0.150
Cost	0.104	0.018	0.130	0.156	0.104
Environmental impact	0.131	0.066	0.122	0.114	0.085

3.2. Determination of the weights

The weights were determined via a survey which was conducted on people who are proficient in the field of power systems, especially power generation, transmission, and distribution. In other words, the weights reflect the stakeholder opinion. The questionnaire was prepared in a very simple manner to make sure that all the participants would understand the question. They were asked to rank the four criteria in the order of importance, with the most important criterion receiving a ranking of 4 and the least important criterion receiving a ranking of 1. After all the results were collected, the scores for each criterion were summed up, as formulated below:

$$TS_z = \sum_{k=1}^{n} PR_{z,k} \tag{6}$$

In the equation above, *TS* stands for the total score of an individual criterion, *z* is the criterion index, *PR* is the individual rankings given by participants to criterion *z*, *k* is the participant index, and finally *n* is the number of participants. Afterwards, the weights for each criterion were determined as follows:

$$W_z = \frac{TS_z}{\sum_{z=1}^{4} TS_z} \tag{7}$$

The questionnaire was conducted on a total of 40 people. Out of these 40 participants, 15 were academics, 17 were private sector employees (or employers), and the remaining 8 were government sector officials, with average experiences of 20.1, 6.6, and 8.9 years in the field, respectively. The fact that the average experiences of private sector or government people were lower than that of academics can be attributed to the recent changes in Turkish energy market. Before the year 2001, the entire electricity sector in Turkey (generation, transmission, and distribution) was controlled by the state – and there were only three directorates in charge of basically everything. Hence, it is impossible to find someone in Turkey with private sector experience more than 15 years in the field of energy. As far as government officials are concerned, the most likely explanation is as follows: New directorates and state departments have been created since 2001, such as The Directorate for Renewable Energy or Energy Market Regulatory Authority. These newly created institutions attracted several bright young graduates in the field of energy, but as a result the average experience of our government officials also turned out to be relatively low. In Table 3 below, the weights determined according the stakeholder opinions can be found.

Table 3. Weights for evaluation criteria

	Weight value
Average power output	0.245
Electrical efficiency	0.264
Cost	0.251
Environmental impact	0.238

Table 3 shows that the criteria are evenly matched, with an absolute standard deviation of only 0.011 and a relative standard deviation of 4.4%. Although electrical efficiency turned out to be the most important and environmental impact turned out to be the least important criteria, respectively; the difference is not significant enough.

3.3. Results of the TOPSIS analysis

The individual steps of the execution of TOPSIS have been omitted for the sake of simplicity. In Table 4 below, the relative closeness (C^*) values (please see Eq.(5)) of each fuel cell type for both cases are presented, in the order of preference.

Table 4. Ranking of fuel cell types for DG applications

Fuel cell type	C^*	**Overall ranking (1: best & 5: worst)**
SOFC	0.786	1
MCFC	0.516	2
PAFC	0.350	3
PEMFC	0.314	4
AFC	0.071	5

SOFC has the highest ranking as expected, followed by MCFC. In other words, high temperature fuel cells with high system capacities turned out to be more suitable for distributed generation applications. These systems also have high efficiencies, which is another factor that contributes to their selection. The only drawback of high temperature fuel cells is the relatively high initial costs, but since all criteria received more or less the same weight values, the benefits coming from system capacity and efficiency criteria were not compensated by the disadvantage of having high costs. AFCs were found to be the least suitable type for DG applications. As far as literature is concerned several authors concluded that, albeit without any systematic approach like the one in this paper, SOFCs are the most ideal fuel cell type for distributed generation applications [59-62].

4. CONCLUSIONS

In this study, five major fuel cell types (PEMFC, AFC, PAFC, MCFC, SOFC) were compared for distributed generation applications by using a multi-criteria decision making method named TOPSIS. After a detailed overview of fuel cells in general and fuel cell types, the comparison data was presented. Fuel cell types were compared in terms of average power output, electrical efficiency, cost and environmental impact. All the evaluation value data were obtained from the literature. The weights were determined by conducting a survey amongst power systems experts. A total of 40 experts participated in the survey. The overall weight distribution was quite uniform, with a relative standard deviation of merely 4.4%. SOFC turned out to be the most desirable fuel cell type, followed by MCFC whereas AFC was found to be the least desirable fuel cell type. The fuel cell types with highest overall rankings were all medium-high temperature fuel cells, which have relative high system outputs and efficiencies, but also high initial costs. Although the weight distribution does not favour any of the criteria, we believe the results are very meaningful because for distributed generation systems, the system output should also be the most important criterion. Let us depict a scenario in which there is no distributed but centralized generation. When the cost of installing long-distance power transmission lines from a central power generation system, and also the consequent losses of energy during transmission are taken into account, distributed generation itself (regardless of what technology is used) automatically results in economic savings. Therefore, the high costs of SOFC and MCFC should not matter as long as they can provide high ratings of power with high efficiencies. This tool helps all the stakeholders in the electricity sector use fuel cells as an effective distributed generation tool.

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