CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294167

Ranking Fuel Cell Technologies for Distributed Microgrid Stationary Power Application Using VIKOR

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There are multiple types of energy technologies that are being developed to focus on the issue of energy security and sustainability. Among these different technologies, the fuel cell microgrid system is a suitable solution for isolated and island communities that suffer from energy poverty, especially in archipelagic countries like the Philippines. There is a variety in the selection of fuel cell technologies with conflicting weaknesses, strengths, and characteristics, which make choosing a difficult task. The multiple-criteria method for decision-making called the VIKOR (Vise Kriterijumska Optimizacija Kompromisno Resenje) is applied in this study as a systematic approach in the ranking of the different fuel cell technologies for stationary power application in microgrid distributed systems. Operational characteristics of the competing technologies are evaluated based on technical and economic metrics – energy efficiency (%), lifespan (hours), power density (kW/m^3), specific power (W/kg), and cost ($/kW). Data for the different metrics are obtained from available studies in the literature and are evaluated utilizing the algorithm of VIKOR. Results show that polymer electrolyte membrane fuel cell (PEMFC) is the most suitable fuel cell technology with an assessment index Q = 0. The ranking of the different fuel cell technologies is as follows: PEMFC > PAFC > SOFC > MCFC > AFC > DMFC. PEMFC has several advantages such as high specific power, high power density, and compact design. The result of this research demonstrates that VIKOR can be utilized to assess the various technical and economic metrics. This approach can guide decision-makers to select the best fuel cell technology for microgrid power systems for isolated communities.

1. Introduction

Electricity consumption in developing countries is growing rapidly and is expected to further grow until 2050 (Asian Development Bank, 2019). In the Philippines, access to electricity is already at 95.6 % with rural areas at 93.5 % (World Bank 2019). The percentage of the population without access to electricity represents about 2.3 M homes with the bulk of it being in the rural and island communities (National Electrification Administration, 2019). A big chunk of this electricity comes from oil, gas, and coal, representing 74.36 % of all the electricity produced from various sources. Renewable energy (RE) sources represent 14.9 % of electricity production. Though the RE capacity is increasing with the installation in recent years of wind and solar farms in various parts of the country, the overall contribution to the electricity production has decreased with the peaks being in 1986 (26.6 %) and 2000 (25.6 %) (World Bank, 2019).

To solve the problem of energy poverty in isolated communities which are difficult to connect to the power grid, variable RE could be deployed in these areas. This would allow the country to meet its target of 35 % RE by 2030 and 50 % RE share by 2040 (National Renewal Energy Program, 2021) in the power generation mix while electrifying the hard to reach and isolated communities. However, technical and operational problems associated with an increase in RE share might emerge if not properly coordinated. These problems are the reduction of frequency reserves, congestion in transmission lines, and deteriorated voltage profiles (Li et al., 2019).

A smart microgrid system provides a promising solution through the integration of the various RE sources (e.g., solar photovoltaic, wind turbines, fuel cell sources), energy storage devices (e.g., battery energy storage (BES), compressed air energy storage (CAES), flywheel energy storage (FWES)), and interconnected loads (Li et al, 2019). A smart microgrid system consists of RE sources and interconnected loads that act as an integrated

Paper Received: 15 April 2022; Revised: 11 May 2022; Accepted: 23 May 2022
Please cite this article as: Ortenero J.R., Choi A.E.S., Tan R.R., 2022, Ranking Fuel Cell Technologies for Distributed Microgrid Stationary Power Application Using VIKOR, Chemical Engineering Transactions, 94, 1003-1008 DOI:10.3303/CET2294167

entity which could be connected and disconnected from the grid which enables it to operate in grid-connected and island mode. It is an efficient and reliable solution that could be adapted to remote and island communities to solve the problems of energy poverty and reliance on fossil fuel sources. If properly designed, it could provide stable and reliable electricity to the countryside while promoting and achieving the goal of a 50 % RE share in the power generation mix by 2040.

There are various RE sources, such as solar photovoltaic, biomass, geothermal, hydroelectric, and wind turbine. Fuel cell (FC) is becoming popular as energy conversion device for renewable sources of energy. Li et al. (2019) provide a review of the challenges and opportunities of FC's in microgrids. FC can provide a continuous supply of electricity and energy generation can be adjusted to suit the demand by controlling the supply of hydrogen fuel. Compared to thermal power plants, the thermodynamic efficiency of FC is not subject to the limitations of heat engine power cycles. There are various fuel cell technologies such as alkaline fuel cell (AFC), polymer electrolyte membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), direct methanol fuel cell (DMFC), direct ethanol fuel cell (DEFC), and direct carbon fuel cell (DCFC). Each type of fuel cell has its own merits, drawbacks, and level of development. Selection of the best fuel cell technology for a microgrid stationary application requires an objective assessment of the pros and cons of each FC technology available.

Multi-attribute decision-making (MADM) has been utilized in multiple aspects of ranking alternatives based on multiple criteria such as in energy storage (Ortenero and Tan, 2021) and negative emission technologies (Ng et al., 2020). It is based on a systematic approach to obtaining an aggregate score for alternatives from various environmental, technical and economic, or social attributes. Duckstein and Opricovic (1980) developed a MADM called VIKOR (Vlse Kriterijumska Optimizacija Kompromisno Resenje) which is utilized to rank alternatives to identify the nearest ideal solution. Different variations of VIKOR have been introduced such as fuzzy VIKOR (Wang and Chang, 2005), comprehensive VIKOR (Jahan et al., 2011), and interval neutrosophic numbers (Huang et al., 2017).

The VIKOR method is very popular in ranking technologies with multiple alternatives such that several variations have been proposed in the literature. To the best of our knowledge, this has not yet been utilized in the ranking of different fuel cell technologies for microgrid stationary power applications. This study applies the VIKOR method to rank the fuel cell technologies suitable for isolated and island communities to properly address the research gap. The paper is divided into the following sections: Section 2 presents the problem statement, the VIKOR methodology is elaborated in Section 3, VIKOR is applied in ranking fuel cell technology for microgrid stationary power application in Section 4, and Section 5 presents the concluding statements and possible future outlook of the study.

2. Problem Statement

The following statement summarizes the problem being addressed in this work:

- Given a set of M fuel cell technologies with a corresponding performance in different criteria, N;
- Given that the individual alternative fuel cell technologies *i* (i = 1, 2, . . ., m) has a designated value with respect to the feature of each criterion *j* (j = 1, 2, . . ., n);

There are six FC technologies that are considered in this study (PEMFC, SOFC, PAFC, AFC, MCFC, DMFC). The different criteria where the alternatives are being evaluated are energy conversion efficiency (%), lifespan (h), power density (kW/m^3), specific power (W/kg), and power cost ($/kW). This method aims to rank the alternative technologies based on the assessment index Q. The value of Q from 0 to 1 designates it as the most optimistic to the most pessimistic. This implies that the alternative with the least Q value is the closest to the ideal solution.

3. Methodology

The VIKOR methodology developed by Opricovic (1990) is used here for the ranking of various fuel cell technologies. The various fuel cell technologies have a corresponding performance value which was taken from the review article of Akinyele et al. (2020). The performance value f_{ij} of the alternative corresponding towards a designated criterion is inspected to determine the minimum$(f_{ij})_{min}$ and maximum $(f_{ij})_{max}$ values in the decision matrix. The maximum and minimum values are then utilized in the normalization and linearization of the set of scores for the individual alternative fuel cell technology according to Eq(1):

$$N_{ij} = \frac{(f_{ij})_{max} - f_{ij}}{(f_{ij})_{max} - (f_{ij})_{min}} \quad (1)$$

The next step is to elicit the weights to be assigned for the various criteria. This step is highly subjective and requires expert knowledge on the contribution of the different criteria on the merit of the different fuel cell technologies for application in microgrid stationary power. Systematic methodologies that include the Criteria Importance Through Inter-criteria Correlation (CRITIC) (Diakoulaki et al., 1995), Best-Worst Method (BWM) (Rezaei, 2015), and Analytic Hierarchy Process (AHP) (Saaty, 1980), could be applied to appropriately determine the weights. The best $(f_{ij})_{max} = f_i^+$ and worst $(f_{ij})_{min} = f_i^-$ value for non-beneficial and beneficial criteria from the normalization and linearization N_{ij} are utilized.
The following Eq(2) to Eq(4) are then used for the determination of the average group utility (S) and maximum regret (R):

$$S_i = \sum_{j=1}^{n} \left[w_j \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right] \quad i = 1, 2, \dots m \tag{2}$$

$$R_i = Max \left[w_j \frac{f_i^+ - f_{ij}}{f_i^+ - f_i^-} \right] \quad i = 1, 2, \dots m \tag{3}$$

$$S_i = \sum_{j=1}^{n} \left[w_j \frac{f_{ij} - f_i^-}{f_i^+ - f_i^-} \right] \quad i = 1, 2, \dots m \tag{4}$$

Where, the best and worst values of the criteria are represented by f_i^+ and f_i^-.
Eq(4) is used for non-beneficial criteria where a low value is desired such as the cost of the technology. In the evaluation of maximum regret for non-beneficial criteria, the numerator of Eq(3) is replaced by $f_{ij} - f_i^-$. The final step in the methodology is the determination of the assessment index (Q) which can be calculated using Eq(5).

$$Q_i = v \left[\frac{S_i - S_i^-}{S_i^+ - S_i^-} \right] + (1 - v) \left[\frac{R_i - R_i^-}{R_i^+ - R_i^-} \right] \tag{5}$$

The best and worst values of average group utility S_i and maximum regret R_i are considered in the determination of Q.

$$S_i^- = \min(S_i) \quad \text{and} \quad S_i^+ = \max(S_i) \tag{6}$$

$$R_i^- = \min(R_i) \quad \text{and} \quad R_i^+ = \max(R_i) \tag{7}$$

The determination of Q requires the determination of the maximum group utility, v ($0 \leq v \leq 1$), based on the optimism of the decision-maker. This parameter is usually taken as 0.5. In the second term of Eq(5), 1- v, represents the weight of individual regret. In a sensitivity analysis, the value of v can be adjusted to determine the effect on the ranking of the technologies and approximate the consistency of the solution corresponding towards the v parameter (Opricovic and Tzeng, 2007).
After the determination of the index Q , the technologies are ranked from least to highest. The technology with the least Q value is the most desirable solution while the technology which is closest to 1.0 is the worst solution. If $Q_j < Q_k$, then alternative a_j is a better solution compared to alternative a_k. For a compromised solution, the first alternative is to check for acceptable advantage compared to the second-best alternative (Opricovic and Serafim, 2004):

$$Q(a_k) - Q(a_j) \geq DQ \tag{8}$$

$$DQ = \frac{1}{J-1} \tag{9}$$

Where, a_j is the best alternative, a_k is the second-best alternative, and J is the number of alternatives.
The second condition that needs to be checked is the acceptable stability of the solution. In terms of the average group utility and maximum regret, alternative a_j must also be on top of the ranking. If one of these two conditions is not satisfied, a compromise solution for the decision-making is:

- Alternative a_j and a_k if only stability is not satisfied, or
- Alternatives a_j, a_k, . . ., a_m if acceptable advantage is not established,

where, a_m is determined by the inequality:

$$Q(a_m) - Q(a_j) < DQ \tag{10}$$

4. Case study

The Philippines needs to create a smart microgrid system that interconnects RE sources, energy storage, and loads to achieve a 100 % electrification rate in the island and rural communities and achieve the goal of 50% RE share in the power mix by 2050. Fuel cell technology is a promising solution to provide continuous and reliable electricity generated from variable RE sources. Alternatively, the fuel cell can be applied as backup/auxiliary applications, combined heat and power (CHP), and FC vehicles. In this study, there are six fuel cell technologies that are assessed as given in Table 1. The data for the performance of the six different fuel cell technologies are taken from the review of Akinyele et al. (2020) based on the following criteria: energy conversion efficiency, lifespan, power density, specific power, and power cost.

Table 1: Performance of various fuel cell technologies (Akinyele et al., 2020).

Fuel Cell Technology	Energy Conversion Efficiency (%)	Lifespan (h)	Power density (kW/m^3)	Specific Power (W/kg)	Power cost ($/kW)
PEMFC	39	9,200	16.28	402.4	6,720
SOFC	58	4,600	10.22	1.298	5,400
PAFC	40.2	54,000	1.24	120	2,340
AFC	47	8,000	1	86	1,160
MCFC	49.8	7,400	1.67	21.88	3,320
DMFC	22	2,400	0.6	38	81,000

To apply Eq(1), the maximum and minimum values for each fuel cell technology are determined for each criterion. High value is desired for energy conversion efficiency, lifespan, power density, and specific power because efficient, long shelf-life, and compact installation are desirable characteristics of a fuel cell. The capital and operational cost of running fuel cells are preferably low to reduce expenditures associated with the power installation. The normalization of the values in Table 1 using Eq(1) is presented in Table 2.

Table 2: Normalized value of fuel cell technology for each criterion

Fuel Cell Technology	Energy Conversion Efficiency (%)	Lifespan (h)	Power density (kW/m^3)	Specific Power (W/kg)	Power cost ($/kW)
PEMFC	0.53	0.87	0	0	0.07
SOFC	0	0.96	0.39	1	0.05
PAFC	0.49	0	0.96	0.70	0.01
AFC	0.31	0.89	0.97	0.79	0
MCFC	0.23	0.90	0.93	0.95	0.03
DMFC	1	1	1	0.91	1

A favourable performance indicator for the individual criterion has a value of the fuel cell technology near 0. Conversely, an unfavourable indicator in the fuel cell technology is observed when the value is near 1. The results in Table 2 indicate that a greater number of fuel cell technologies have values relatively near to 1 toward the microgrid stationary power application. Notable results in Table 2 shows that PEMFC has a promising performance in the aspect of power density and specific power. The advantage of this technology can display a consistent efficiency irrespective of its fabricated size, and it is compact, light, and robust (Fraser et al., 2009). However, PEMFC is lagging from a low lifespan. Additional research is essential to further enhance this performance criterion of PEMFC. In the criteria for energy conversion efficiency, Table 2 also show that the SOFC shows promise based on the results of the normalized values. SOFC is recognized for its stability that attributes with high power efficiency (Sammes et al., 2005). For the lifespan criteria of the fuel cell technology, the PAFC has the longest lifespan as indicated in Table 1. This technology is also appropriate for the combined pressure and heat due to elevated temperature setting. It can be observed that all other FC technologies lag behind PAFC in terms of lifetime. AFC is the best technology in terms of the power cost criteria. This type of technology has its edge for having a quick start-up and operates at low temperature settings (McLean et al., 2002). Both MCFC and DMFC did not display a good performance on the normalized value for the different criteria. This may be attributed to the major shortcoming of MCFC and DMFC for incurring breakdown of cell components and having an extremely low efficiency (Akinyele et al., 2020).

For the normalized values listed in Table 2, average group utility S is subsequently identified by obtaining the contribution of the attributes to the specified fuel cell technology. The corresponding values for the R refer to the poorest performance for the individual fuel cell technology throughout its different incurring attributes. The assumption includes equal weights designated to each of the criteria, w_j = 0.20. Table 3 lists the results for the values for S and R for the specified fuel cell technology. Table 4 shows the normalized values of S and R denoted by the primes and of Q values computed by Eq(5) using a maximum group utility value (v) of 0.85.

Table 3: Average group utility (S) and maximum regret (R) value for the FC technologies.

Fuel Cell Technology	S	R
PEMFC	0.29	0.17
SOFC	0.48	0.20
PAFC	0.43	0.19
AFC	0.59	0.19
MCFC	0.61	0.19
DMFC	0.98	0.20

The fuel cell technologies are ranked with values of 0 and 1 for the most optimistic and pessimistic, respectively. It is observed that the PEMFC is the clear winner for having the lowest Q values of 0. The benefits of the PEMFC are attributed to high power density and specific power, a relatively high lifespan, and its cost effectiveness. Its high energy density and specific power is the reason for its compact size and light weight compared to other FC technologies. This is advantageous for locations with scarce space. It is also flexible and easy to install. PEMFC is also able to operate in low temperature, flexible in input fuel, and has a solid electrolyte membrane. Other FC technologies employ liquid electrolyte which is susceptible to leakage. This clearly ensures its high reliability with less complexity in terms of its system construction. It has great potential for small portable application and transportation where weight is an important parameter. The main drawbacks of PEMFC are the need for expensive platinum catalyst and high purity hydrogen fuel. High platinum catalyst loading is necessary to improve electrocatalytic activity of the electrodes while high purity hydrogen is needed to avoid catalyst poisoning especially in the presence of CO (Behling, 2013).

Table 3: Normalized S' and R' values and the Q value for each fuel cell technology

Fuel Cell Technology	S'	R'	Q	Rank
PEMFC	0.0	0.0	0.0	1
SOFC	0.27	1.00	0.38	3
PAFC	0.21	0.69	0.28	2
AFC	0.43	0.81	0.49	5
MCFC	0.46	0.61	0.48	4
DMFC	1.00	1.00	1.00	6

PEMFC has clear acceptable advantage over the second-best alternative which is PAFC. Eq(8) and Eq(9) show that $[Q(a_k) - Q(a_j) = 0.28] \geq [DQ = 0.20]$. In addition, the technology has acceptable stability, wherein it has the best overall performance in the average group utility $S(a_j) = 0.29$ and maximum regret $R(a_j) = 0.17$. The DMFC is identified as the worst technology. This is attributed to having the highest Q values of 1.00. This is also due to being the worse in terms of its energy conversion efficiency, lifespan, power density, and power cost as compared to the other fuel cell technologies. DMFC is currently in its early stages of research and development along with direct ethanol fuel cell (DEFC) and direct carbon fuel cell (DCFC).

5. Conclusions

In this study, the VIKOR methodology was applied in the aspect of ranking six fuel cell technologies (PEMFC, SOFC, PAFC, AFC, MCFC, and DMFC) for the microgrid stationary power application. PEMFC emerged as the best fuel cell technology option for this application through the lowest assessment index value Q = 0. It has advantages such as high specific power and energy density which is the reason for its compact design and light weight. Conversely, DMFC is ranked the worst technology due to having the lowest energy conversion efficiency, lifespan, power density, and the most expensive among the fuel cell technologies. Future work includes analysis of the environmental criteria, extension of the methodology to account for uncertainties in the data, and adjustment of the method to account for the weights of the different attributes using CRITIC, BWM, or AHP. The result of this study can be used as a guide for decision-makers in selecting the fuel cell technology for the design of smart distributed microgrid systems that will interconnect with RE sources and storage technologies for remote and off-grid communities.

Nomenclature

a_j – the best alternative technology, a_k is the second-best alternative, and a_m are other alternative technologies
f_{ij} – performance value of each alternative i on criterion j
i, j – indices for alternative technology and criterion
Q_i – assessment index for alternative technology i
R_i – maximum regret for alternative technology i, R_i^- is min(R_i), and R_i^+ is max(R_i)
S_i – average group utility for alternative technology i, S_i^- is min(S_i), and S_i^+ is max(S_i)
v – maximum group utility
w_i – weight of each criterion j

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