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Title: Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell

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Corresponding Author: Dr. Ali Sohani, Ph.D.

Corresponding Author's Institution: K.N. Toosi. University of Technology

First Author: Ali Sohani, Ph.D.

Order of Authors: Ali Sohani, Ph.D.; Shayan Naderi, M.Sc.; Farschad Torabi, Ph.D.; Hoseyn Sayyaadi, Ph.D.; Yousef Golizadeh Akhlaghi, PhD. Candidate; Xudong Zhao, Ph.D.; Krishan Talukdar, Ph.D.; Zafar Said, Ph.D.

Abstract: An application-based multi-objective optimization approach is presented to acquire the best operation condition for a proton-exchange membrane fuel cell. The optimization is done for propulsion, power station, and portable applications, in which the recommended range for decision variables and importance level of the objective functions are taken into consideration for more accurate and practical results. In the multi-objective optimization, from each important aspect of the performance, i.e., technical, economic, dimensional, and environmental aspects, one objective is selected. The effect of threshold current density on both optimum decision variables and objective functions are also investigated to find the best value for that. The results reveal that increasing the maximum allowable current density leads to improvements in optimized values of all the objective functions. Moreover, the conducted sensitivity analyses determine that the threshold current density for the propulsion and power station applications is 1.3 A.cm-2 and for the portable application is 1.5 A.cm-2. Furthermore, it is found that values of the temperature, pressure and voltage in power station are not affected by optimization, whereas substantial decrease in both propulsion and portable applications brings more level of safety. Similarly, objective functions, i.e., efficiency, levelized cost, size, and greenhouse emission are averagely improved by 9.93, 16.95, 37.13, and 7.77%, respectively. The proposed procedure helps to design and manufacture the high-performance proton-exchange membrane fuel cells based on the employed application and users' preference.

Dear Editor of Journal of Cleaner Production,

This is Ali Sohani, the corresponding author of the manuscript entitled " **Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell**". We are pleased to submit our original research manuscript for consideration of possible publication in Journal of Cleaner Production. Since 17 out of 69 references from our paper were published in the journal, we believed that Journal of Cleaner Production is the best venue for submitting our manuscript.

We emphasize that the authors have complied with Elsevier's ethical requirements. It implies that this work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. Further, it implies that, if accepted, it will not be published elsewhere in the same form, in English or any other language, without the written consent of the Publisher.

Should we do anything else please do not hesitate to reflect the matter(s) to me.

Best Regards,
Ali Sohani
The corresponding author

Highlights

- The best allowable current density for portable application is 1.5 $A.cm^{-2}$.
- Allowable current density of 1.3 $A.cm^{-2}$ is the best for other applications.
- Employing the approach leads to a higher level of safety.
- On average, efficiency and levelized cost are enhanced 9.93 and 16.95%.
- Size and greenhouse emissions are averagely improved 37.13 and 7.77%.

Black = ‘comments’ & blue = ‘answers’

The revision of the text is done in “track change” mode to be able to see the applied changes easily in the updated manuscript. In the comment section, it is mentioned that each change is due to which comment, as well.

Comments from the Editors and Reviewers:

-Editor

The reviewers have submitted a series of comments and recommendations for the improvement of the manuscript. Please, consider all reviewers' comments carefully and provide a detailed list of actions taken and revisions made to the manuscript to address these comments. In case you disagree with a comment, provide a rebuttal.

Dear Editor, we are very grateful for your positive feedback on our manuscript. The constructive comments from Reviewers are highly appreciated. We tried our best to modify the manuscript based on the valuable comments from Reviewers which we believe made the manuscript successively better. In continue, we provide a point-by-point response for each comment, explaining the applied changes. We hope that the paper was modified in a satisfactory way.

In addition, consider the following:

1. As a general editorial policy, authors are not obliged to include references recommended by reviewers in the manuscript, unless these references are absolutely necessary and enhance the clarity and completeness of the manuscript.

Thank you very much for letting us know the issue. The point was considered in the revision process.

-Reviewer 1:

The following comments are presented for the primary evolution. The paper and results will be investigated more precise in the next version. Please consider all of comments for the next revision.

Dear Reviewer, we are very grateful for your valuable comments, which helped us to increase the quality of the paper. We appreciate them a lot. The manuscript was updated carefully considering all the points that you made, as it was completely in the following.

1.The title is not proper, please change it, if possible.

The title was changed based on your comment and a new proper title was chosen. The modified title is:

Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell

2. Please clarify this sentence "In multi-objective optimization, from each important aspect in the performance, one objective is selected". What is the main propose?

The sentence was modified based on your comment:

In the multi-objective optimization, from each important aspect of the performance, i.e., technical, economic, dimensional, and environmental aspects, one objective is selected.

The objective selected from each aspect was also introduced after that, in the last sentence of the abstract:

Similarly, objective functions i.e., efficiency, levelized cost, size, and greenhouse emission are averagely improved by 9.93, 16.95, 37.13 and 7.77%, respectively.

3. There is a lot of language mistakes in the paper such as in the abstract: The results reveal that increasing the maximum allowable current density leads to improve optimized values of all objective functions or ...

As you recommended, we modified the language of the paper and in it was checked by a native person as well as Grammarly software. Some examples of the corrections were indicated in the paper. The mentioned sentence has been also modified as well:

The results reveal that increasing the maximum allowable current density leads to improvements in optimized values of all the objective functions.

4. In the nomenclature, several abbreviations are not demanded such as MOO, fuel, levelized and so on. Please modify and correct the nomenclature.

Your comment was noticed. The unnecessary items were removed from the nomenclature.

5. The previous studies about the multi-objective problems and solving methodology have not been investigated sufficiently. The researcher should investigate the previous researches with more details. Hence, more paper should be investigated such as:

https://doi.org/10.1016/j.energy.2016.10.113

https://doi.org/10.1016/j.ijepes.2017.06.010

https://doi.org/10.1016/j.energy.2019.01.136

https://doi.org/10.1016/j.jclepro.2018.05.059

Thank you for suggesting appropriate references. We modified the introduction part using them and some other papers from the literature:

Such optimization procedure has been implemented in many applications, from fuel cells (Sohani et al., 2019a), to thermal power plants (Sohani et al., 2017a), photovoltaic solar systems (Saedpanah et al., 2020), electrochemical systems (Pourmirzaagha et al., 2016), and management of micro grid (Jirdehi et al., 2017; Tabar et al., 2017). For instance, Sohrabi Tabar et al. (Tabar et al., 2017) solved the problem of micro grid management by the multi-objective optimization considering pollution and cost at the same time, and Ahmadi Jirdehi et al. (Jirdehi et al., 2017) found the best plan to run a micro grid system from both economic and environmental points of view by this approach. The studies (Tabar et al., 2019; Tabar et al., 2018) are some other examples of optimization in the field.

The references *(Jirdehi et al., 2017; Tabar et al., 2017)* and *(Tabar et al., 2019; Tabar et al., 2018)* are the recommended ones.

6. What is 'APP' in the Table 3?

In the paper, the abbreviation 'APP' means "application". Considering your comment and as the abbreviation was only used in three places of the paper, the full name was employed in the revised version of the manuscript.

7. I think most sentences of the paper can be declared more properly. For instance, the length of the presented sentences is too much. In the other side, most of words are repeated over and over such 'objective function' in section 2.

The paper was checked carefully and modified according to your comment.

8. The language quality is not acceptable at all. Hence, the paper should be checked by the native English teacher or languages institute.

As you recommended, we modified the language of the paper and in it was checked by a native person as well as Grammarly software.

9. What are your novelties in the formulation? As it is obvious, all of them are presented previously.

The point is different papers have different novelties. The novelty of some of them is in formulation whereas some other ones, including the current paper, have other novelties. As it was completely described in Table 2 of the revised version of the manuscript, the gap of the research and the novelties of the paper are:

Table (2): Gap of the research and the items taken into account as the novelties of the present investigation

The gap of the research	The novelty of the current investigation
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application,	For each investigated application, namely, propulsion,

for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	power station, and portable applications, a separate range, based on the recommended range of [51] is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

10. There are a lot of structural mistakes in the text that should be corrected such as extra or low spaces, lower/upper case in the section 2.2, first line.

Thank you for your detailed comments. The manuscript was double checked and such mistakes are not seen anymore.

11. As mentioned in the constraint part, only one constraint is considered in the problem? Is it possible? Other variables have no limit?

In almost all the optimization problems in the reality, like here, the decision variables have their limits. However, in this study, following the same fashion as the Rao's book and the optimization toolbox in MATLAB software, they are called as "bounds", which are introduced in Table (3):

Table (3): The recommended range of decision variables for different applications (the considered bounds for the decision variables)

Parameter	Symbol	Application			Unit
		Application #1 (Propulsion)	**Application #2 (Power Station)**	**Application #3 (Portable)**	

Temperature	T	283.15- 363.15	283.15- 363.15	283.15- 363.15	K
pressure	P	105000- 300000	105000- 200000	105000- 200000	Pa
voltage	V	Based on PEMFC's specifications	Based on PEMFC's specifications	Based on PEMFC's specifications	V
actual to stoichiometric molar ratio of air	λ_{air}	1.3- 2.0	1.1- 2.0	1.1- 2.0	-
actual to stoichiometric molar ratio of hydrogen	λ_{H_2}	1.1- 2.0	1.1- 2.0	1.1- 2.0	-
humidity of the anode (hydrogen)	ω_{air}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{air}^{-1}$
humidity of the cathode (air)	ω_{H_2}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{H_2}^{-1}$

On the other hand, the limitations which are not the bounds are called the constraints. Based on this definition, there is only one imposed constraint, which is the one you mentioned, i.e., the maximum current density limit (The current density is a dependent parameter whose value is obtained based on the values of the decision variables, as Eq. (13) shows).

The discussed points were also added to the revised version of the manuscript:

Part 2.1.1 (Decision variables)

It should be noted that in almost all the optimization problems in the reality, like here, the decision variables have their limits, as it is seen. However, in this study, following the same fashion as (Rao, 2019) and the optimization toolbox in MATLAB software (Higham and Higham, 2016; Moore, 2017), they are called as "bounds", and not "constraints". On the other hand, the limitations which are not the bounds are called the constraints. The constraints considered in this study are introduced in the section 2.1.3.

Part 2.1.3 (Constraints)

It is worth mentioning that as it was explained in the section 2.1.1, the limitation for the decision variables are called "bounds" and the constraints cover other limitations.

12. Some of the sentences are repeated, please modify them.

Based on your comment, we double-checked the whole paper and tried to avoid repetition in the updated version of the manuscript.

13. As explained, for selecting the best results among the Pareto set, a judgment-weighted method is used. What is your justification for the accuracy of the method? Is it possible to compare the results with other methods?

In order to respond this comment, we divide it into two parts. For the first part of the comment, it should be mentioned that all the employed methods as well as the used equations are the verified ones which have been widely applied in the previous studies. As a result, the combination of them has also enough accuracy and is justified. Some sentences to describe the point were added to the part 3.2 of the manuscript. For the second part of the comment, it should be indicated that it was noticed, and based on that, in Fig. (3), the results were compared with TOPSIS, in which the same weight for all the objective functions are considered. In addition, the explanations about the comparison were also presented in the paper.

14. In the section 4.1, the impacts of current density on the optimal pressure, temperature and … are not well justified. Please propose more details. In the other words, answers to the 'why and how questions' are not acceptable (i.e., the paper only show the results without any justifications).

Thank you for the detailed review. We considered you comment and added justifications for the changes in the decision variables. Four examples of the added justifications are mentioned here; other ones can be found in the marked-up version of the manuscript.

Part 4.1.1.1 (Temperature)

As it is seen in Fig. (1a), for all the three applications, increasing $i_{threshold}$ leads to decrease in the optimum temperature. The reason in when $i_{threshold}$ grows, the movement of the ions in the electrolyte membrane as well as the movement of the electrons in the solid phase and current collectors becomes easier. In other words, the internal resistance drops by increasing $i_{threshold}$. which leads to lower operating temperatures.

Part 4.1.1.2 (Pressure)

According to Fig. (1b), by an increase in $i_{threshold}$, the optimum pressure decreases in all the three applications. It is because the operating pressure directly affects the transport of the reactants to the reaction area (catalyst layer). When $i_{threshold}$ is low, the rate of reactions falls significantly, and the density of reactants becomes higher at the interface between the gas diffusion layer and the catalyst layer. As a result, in such conditions, i.e., low values for $i_{threshold}$, the optimum value for pressure has to increase to move the reactants to the reaction area in a proper way.

Part 4.1.2.1 (Efficiency)

Based on the points discussed in part 4.1.1, when $i_{threshold}$ gets higher, the reaction happens in a better way and a higher fraction of the available reactants at the interface between gas diffusion layer and catalyst layer is consumed. Therefore, the efficiency is improved. As it is depicted in Fig. (2a), a moderate change in the optimum efficiency takes place when the maximum allowable current density goes up.

Part 4.1.2.2 (Levelized cost)

According to the points which have been discussed so far, by an increase in the value of $i_{threshold}$, the reaction takes place more properly, and consequently, the efficiency is enhanced.

Enhancing the efficiency means that the generated electricity from a constant amount of fuel increases, and as a result, the price of the produced electricity and consequently, the levelized cost is improved as per Fig. (2b).

15. As mentioned in the previous comment, the results in the next sections such as 4.2 are not well presented. I suggest to modify and improve the results section more precisely.

Your comment was considered and the paper was modified based on that. As it can be seen in the marked-up version of the manuscript, we did our best to modify and improve the results section as far as possible. For instance, in the following, one of the parts added to modify the results section is given:

Part 4.3 (Evaluation of the potential of improvement)

On average, the efficiency, levelized cost, size, and GHG are improved 9.93, 16.95, 37.13, and 7.77%, respectively. Additionally, the power generation application has the highest potential of enhancement in the efficiency and levelized cost whilst the most significant decrease in size and GHG are seen for portable and propulsion applications, respectively. In power generation application, the efficiency reaches from 59.71 to 69.71% while the levelized cost drops from 0.8024 to 0.6280 $\$.(kWh)^{-1}$. Moreover, the size in the portable application falls from 10.840 to 4.487 m^2, and GHG of propulsion application diminishes from 6488.8 to 5962.2 $g.h^{-1}$.

-Reviewer 2:

Dear Reviewer, thank you very much for taking your valuable time and sharing us your constructive comments to enhance the quality of the manuscript. We appreciate them a lot. We did our best to modify paper by considering all your mentioned points and we hope that it was done in a satisfactory way.

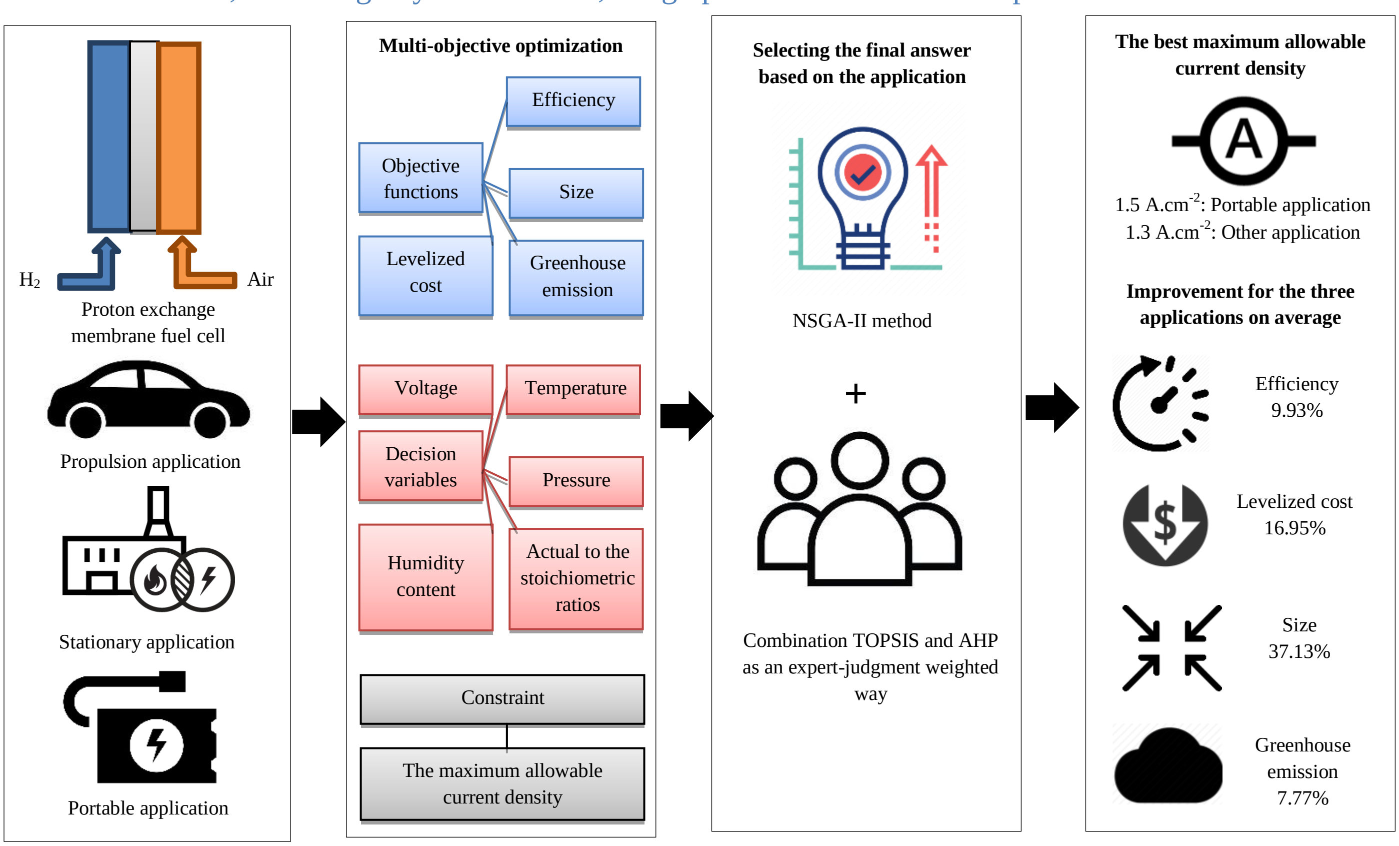
1. Originality: Does the paper contain new and significant information adequate to justify publication?
The abstract and highlight sections set the tone of the paper and is often after reading the abstract and highlight sections when readers decide whether or not to read the paper at all. Besides this, the introduction is another major important part of the paper as it positions the paper's importance and why is there a need for such study. Another point to note is that similar titles have not only been published in JCLEPRO previously, but have also been published in other reputable journals such as SSRN Electronic Journal, Science of The Total Environment, Journal of Membrane Science, Fuel, Cell Reports, International Journal of Hydrogen Energy, International Journal of Radiation Oncology*Biology*Physics, et cetera. The authors have put forth a research problem that requires the world's attention because every entity has the social responsibility to promote clean water and sanitation, sustainable cities and communities, responsible consumption and production, life on land, as well as promoting good health and well-being, as advocated in the 17 Sustainable Development Goals developed by the United Nations. However, the authors didn't mention the specific statistical analysis tool/technique employed to analyze the data and the significant findings in the 'Highlights' section. It will be more value-added if the authors documented the statistical analysis tool/technique employed to perform this analysis. Furthermore, when reading the abstract, the reviewer has been wondering what the research problem and significance of study are. Please reinforce your research problem and significance of study to make your case even stronger. In addition, the research framework/model and the graphical abstract seem to be missing from the manuscript. Please include the research framework/model and the graphical abstract to boost clarity and provide some incentives to attract reader's attention to read on. An eye-catching and attractive graphical abstract will enable the readers to grasp the overall picture at one glance (or in other words, provides a bird eye's view of the research study). In addition, it is important that the authors provide a thorough description of the underlying rationale (e.g., why?) this research should be studied. What are your research objectives? What is your significance of study? The motivation of this paper is not clearly laid out and is not convincing even though the reviewer could see the point from the authors, but the evidence that the authors try to lay out would need to be enhanced and clearly demonstrated. It would be great to see a stronger connection between your findings and the theme of the journal. How does this understanding help organizations and the industries to be more sustainable? How are your results/findings going to benefit the industries and

societies at large? Much clearer and stronger justifications need to be put forth in order to convince the readers.

We thank the reviewer for highlighting all the important points that should be addressed in the paper. We also thank the reviewer for appreciating the abstract that we have presented here. First of all, it should be mentioned that in the revised version of the manuscript, the highlights describe the main findings of the research, as shown in the following:

- *The best allowable current density for portable application is 1.5 A.cm^{-2}.*
- *Allowable current density of 1.3 A.cm^{-2} is the best for other applications.*
- *Employing the approach leads to a higher level of safety.*
- *On average, efficiency and levelized cost are enhanced 9.93 and 16.95%.*
- *Size and greenhouse emissions are averagely improved 37.13 and 7.77%.*

In addition, according to your comment, the graphical abstract was also provided:



Moreover, the employed methodology was discussed in the parts 2 and 3 of the revised version of the manuscript, where a brief but comprehensive explanation about the employed methodology and equations were given. It should be noted that since the techniques like NSGA-II, AHP, and TOPSIS were completely introduced in the previous cited studies of the research team, and in order not to make the paper lengthy, they were referred for further information. The gap of the research, the novelties and objectives of the study as well as the significance of that were also introduced in the last part of the introduction of the revised version of the manuscript:

In order to find the best operating condition, the values of performance criteria are improved by adjusting the effective parameters (Marefati and Mehrpooya, 2019; Nagapurkar and Smith, 2019). However, in PEMFCs, there is a trade-off among performance criteria (Ayodele et al., 2018; Bukar and Tan, 2019). For example, increasing efficiency as a favorable change is accompanied by an increase in the levelized cost of electricity (LCOE), which is unfavorable (Becherif et al., 2018; Chen et al., 2019). Therefore, performing single-objective optimizations like the study of Kanani et al. (Kanani et al., 2015) leads to partial results, and in order to acquire the best operating conditions, same as other energy systems (Sohani et al., 2019a; Sohani et al., 2018), multi-objective optimization (MOO) approach should be employed. A set of solutions, all of which has the potential of being the optimal answer, is obtained by running each MOO algorithm. The set is called Pareto optimal frontier (POF). Such optimization procedure has been implemented in many applications, from fuel cells (Sohani et al., 2019a), to thermal power plants (Sohani et al., 2017a), photovoltaic solar systems (Saedpanah et al., 2020), electrochemical systems (Pourmirzaagha et al., 2016), and management of micro grid (Jirdehi et al., 2017; Tabar et al., 2017). For instance, Sohrabi Tabar et al. (Tabar et al., 2017) solved the problem of micro grid management by the multi-objective optimization considering pollution and cost at the same time, and Ahmadi Jirdehi et al. (Jirdehi et al., 2017) found the best plan to run a micro grid system from both economic and environmental points of view by this approach. The studies (Tabar et al., 2019; Tabar et al., 2018) are some other examples of optimization in the field.

…

Review of the literature shows that despite valuable investigations have conducted so far; there have been some gaps that should be addressed by conducting a new study. As a result, the current study is conducted. The gap of the research and the items taken into account as the novelties of the present investigation are introduced in Table (2).

Table (2): Gap of the research and the items taken into account as the novelties of the present investigation

The gap of the research	The novelty of the current investigation
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application, for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	For each investigated application, namely, propulsion, power station, and portable applications, a separate range, based on the recommended range of [51] is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

One sentence was also added in the abstract now regarding the importance of this study to the industry or domestic sector, which is:

The proposed procedure helps to design and manufacture the high-performance proton-exchange membrane fuel cells based on the employed application and users' preference.

2. Relationship to literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?

A research model/framework that aptly represents the variables at play seems to be missing. Please kindly include the research model/framework to give readers a clear picture regarding what are the relevant variables and the proposed relationships between the variables at one glance. Besides this, there are several problems that minimize its overall contribution to the literature. What is your 'theory'? How has this paper contributed to existing theory? How has this paper advanced our understanding on the previous work on the existing theories? Perhaps the authors could consider the Resource-based view (RBV) theory or Natural Resource-based view (NRBV) theory. In addition, the authors did cite relevant work published by JCLEPRO, which is the most cited journal in GSCM and sustainability paradigms (de Oliveira et al., 2018). This smart move has indeed added value and enhanced the credibility of the current research paper. Thank you.

Reference:
de Oliveira, U. R., Espindola, L. S., da Silva, I. R., da Silva, I. N., & Rocha, H. M. (2018). A systematic literature review on green supply chain management: research implications and future perspectives. Journal of Cleaner Production, 187,537-561.

We thank the reviewer for the positive comments. About the research model/framework, as it was mentioned in the response to the previous comment, it was described in the sections 2 and 3 of the revised version of the manuscript. Moreover, the following sentences were added as the answer to the question: “What is your 'theory'? How has this paper contributed to existing theory? How has this paper advanced our understanding on the previous work on the existing theories?”

As the existing theory, the optimum values of the operating parameters for a PEMFC is obtained from the recommended values or the multi-objective optimization approaches which have not considered all the performance criteria at the same time and have assumed the same priority level for the optimized objective functions. However, in this study, conducting the multi-objective optimization in which all the key factors including technical, economic, dimensional, *and environmental aspects are taken into account is studied as the new theory. In addition, the new theory considers different levels of importance for the objective function based on the application. As a result, the proposed theory is a more practical and realistic one, and helps to design high-performance PEMFC more comprehensively and according to the users' preferences in different applications, in which the objective functions do not have the same level of priority.*

In addition, according to your comment, we added the following sentences to the revised version of the manuscript:

The final point which should be indicated in this part is based on the comprehensive conducted review on the green supply chain management system, journal of cleaner production is the most cited journal in this field and sustainability paradiagrams (de Oliveira et al., 2018), and based on the cited references and the topic, it is one of the best venues for publishing the paper.

3. Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed appropriate?

Again, what is the theory that is most relevant to your research framework/model? How has this paper contributed to existing theories? How has this paper advanced our understanding on the previous work on the existing theories? Besides this, please specify which software/statistical analysis tool that you used to conduct the analysis. Furthermore, is the sample size sufficient to represent the entire population? Can the subsequent results be generalized across the entire population? The generalizability of the results is questionable. In summary, the authors need to clarify and justify how the chosen samples can represent the population reasonably well. Besides this, the reviewer humbly believes that the authors must first establish the research objectives and state the RO clearly and explicitly at the beginning of the manuscript. The data analysis method (statistical method) must be able to help the authors to achieve the RO. Thank you.

In the revised version of the manuscript, the research framework/model was discussed in the sections 2 and 3. Moreover, the novelties and objectives of the paper and the contribution to the existing theories were introduced in the last part of introduction (the beginning of the manuscript):

Table (1): Gap of the research and the items taken into account as the novelties of the present investigation

The gap of the research	The novelty of the current investigation
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application, for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	For each investigated application, namely, propulsion, power station, and portable applications, a separate range, based on the recommended range of [51] is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

As the existing theory, the optimum values of the operating parameters for a PEMFC is obtained from the recommended values or the multi-objective optimization approaches which have not considered all the performance criteria at the same time and have assumed the same priority level for the optimized objective functions. However, in this study, conducting the multi-objective optimization in which all the key factors including technical, economic, dimensional, and environmental aspects are taken into account is studied as the new theory. In addition, the new theory considers different levels of importance for the objective function based on the *application. As a result, the proposed theory is a more practical and realistic one, and helps to design high-performance PEMFC more comprehensively and according to the users' preferences in different applications, in which the objective functions do not have the same level of priority.*

The employed software programs were also introduced in different parts of the revised version of the manuscript:

Part 2.2 (Step II: Performing MOO algorithm and obtaining POF)

It should be also noted that MATLAB software was used to conduct the NSGA-II and obtain POF.

Part 2.3 (Step III: Determination of the relative priority and selecting the final solution)

The codes developed in MATLAB software was employed to run the decision making method and select the final answer by the introduced method.

Part 3.3.4 (The final weights)

For obtaining the final weights from the matrix of pairwise comparison, Expert Choice software program (Choice, 1999) is used to do calculations.

About the generality, it should be noted that, like other similar cases in energy systems, such as previous published studies of the authors, a general approach was presented. Since obtaining numerical values for the investigated criteria needs to have the values of the effective parameters, a case study had to be considered and the approach employed for it. As a result, for other case studies, the approach is applicable; the only difference is the values of the effective parameters, and consequently, the investigated criteria are not the same. We added some sentence about it to the revised version of the manuscript:

In addition, it is worth mentioning that, like other similar cases in energy systems, such as previous published studies of the authors (Sohani et al., 2019b), a general approach was presented. Since obtaining numerical values for the investigated criteria needs to have the values of the effective parameters, a case study had to be considered and the approach employed for it. As a result, for other case studies, the approach is applicable; the only difference is the values of the effective parameters, and consequently, the investigated criteria are not the same.

In addition, about the data analysis and the points related to that, it should be mentioned, as described in the introduction of the revised version of the manuscript, all the necessary information was presented in the revised version of the manuscript, and in order not to make paper too lengthy, it was referred:

In addition, all the necessary information about the data analysis of the employed models were given in the previous study of the authors conducted on PEMFC (Sohani et al., 2019a), and in order not to make paper too lengthy, it is referred for more details.

4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together the other elements of the paper?

Please justify how your results are deemed accurate and reliable. Are your results any different as compared to similar studies in Iran and the United Arab Emirates? Please also elaborate if current study is consistent with findings from past and recent studies in other country settings. The discussion should include further elaborations on the previous findings in relation to the existing ones and also what are the differences and your contributions. In the reviewer's humble opinion, academics and industry practitioners will be even more interested in the effective ways to overcome any limitations in order to further improve on current practices and also increase yield. Besides this, what are the limitations of your analysis in terms of methodology and the subsequent results? Please clarify. Please also provide the corresponding recommendations/solutions to overcome the limitations. Thank you.

As it is seen, all the used methods and employed equations were adopted from the published literature and they have been utilized in several researches in different fields. Therefore, each of them, and consequently, the combination of them are accurate and reliable. Moreover, considering the fact that only economic indicators such as discount rate are not the same in the two different countries, only the levelized cost will be different and studying in another country does not have any impacts on the values of the other performance criteria in the same condition for the effective parameters. For the levelized cost, however, it should be also noted that in spite of having different values in two different countries, the variation trend is almost similar.

Additionally, although the impacts of the maximum allowable current density on the results of optimization has not been studied before the current study, in some references, it has been mentioned that this value has impacts on the optimum results, and the results of this study is found consistent with them. Moreover, in spite of the fact that all the key important performance aspects have not been considered at the same time in the multi-objective optimization, a huge improvement in the values of the objective functions is achieved compared to the base-case condition, and it is also in agreement with the points mentioned about the ability of the multi-objective optimization in the literature.

Moreover, two items can be mentioned as the limitations of the conducted analysis:

- This study investigated proton exchange membrane fuel cell. It means that other types of fuel cell were not considered.

- Like other similar studies in which an approach is presented, a case study with a specified capacity was investigated.

In order to overcome the mentioned limitations, these solutions are suggested:

- The variation impacts of the maximum allowable current density on the optimum results are studied for the other types of fuel cells in a further work.
- The impact of size on the results of optimization is investigated in another work. Here, using the objective functions which are not related to the capacity, such as specific or dimensionless performance criteria, would help to provide better insight.

All the discussed points here were also indicated in the revised version of the manuscript as well.

5. Implications for research, practice and or society. Does the paper identify clearly between any implications for research, practice and or society? Does the paper bridge the gap between theory and practice? How can the research be used in practice, in teaching, to influence public policy, in research. What is the impact upon society? Are these implications consistent with the findings and conclusion of the paper?

The theoretical, methodological, practical and societal implications/contribution of this paper seemed minimal, which I believe to be its biggest flaw. It would help if the authors can use research questions (in question format) and addressed them more thoroughly in this section. In a nutshell, the theoretical, methodological, practical and societal implications/contribution of this paper should be clearly distinguished from the other sections. It would be much better if the theoretical and practical implications can be further strengthened. For example, the details on how this study is benefiting the society and mankind are clearly and explicitly presented. Without this information, it will be difficult to assess if the paper has bridged the gap between theory and practice.

The research questions as well as the theoretical, methodological, practical, and social implications/contribution of the paper were presented in the introduction of the revised version of the manuscript. According to your recommendation, the theoretical and practical implications were also further strengthened:

The following items are the implications of this paper:

- *Designing a PEMFC is done by a systematic approach in which the best operating condition is determined in way that all the important performance criteria are in the best condition at the same time. It helps to have a PEMFC with the lowest possible cost and* *the highest performance at the same time, which is the theoretical implication of the conducted research.*

- *A method to obtain the best operating condition based on the application and users' preference is obtained. It can be taken into account as the methodological contribution of this study. It should be also noted that the proposed approach can be done for different capacities, countries, and applications.*
- *Not only can the designing process be done using the presented methodology, adjusting the operating conditions and as a result, retrofitting an in-operation PEMFC can be also performed by the proposed approach. Therefore, the methodology employed in this paper have the potential of being used in a wide range of products at different stages. This item can be considered as the practical implication of the current study.*
- *When a system has the best performance from different perspectives, including the technical, economic, and environmental aspects, policy-makers and end-users are encouraged more to use it (Sohani and Sayyaadi, 2020). Since the conducted investigation covers all the mentioned criteria in addition to the size as the other key factor and find the best possible condition for them, it will help to make PEMFC more popular all around the world. It is the social implication of this paper. The more popular clean technologies like PEMFC is used in the world, the better condition to live for human beings will be provided.*

Additionally, the main research questions were also provided in the introduction part:

Considering the items indicated in Table (2), the following items are posed as the main research questions, which will be addressed in this study:

- *How much improvement compared to the recommended values of (Piela et al., 2017) is achieved when the multi-objective optimization considering all the key performance criteria is done?*

- *How different the optimized solutions are when the importance level of objective functions in different application is considered?*

- *What are the difference between the condition the same priority levels for the objectives are assumed and the time the application-based method is implemented?*

- *How do the decision variables and objective functions change when the maximum allowable current density change?*

- *Does the maximum allowable current density have a great or small impact on the optimization results?*

- *What are the best recommended values for the maximum allowable current density?*

6. Quality of communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.

Please do thorough grammatical checking to the manuscript to improve the readability of this study. Besides this, a long string of citations does not really add value to the manuscript. Perhaps the authors can consider citing the two best and most relevant references. The authors are also highly encouraged to cite the most relevant and most updated work published by highly reputable international journals because the reviewer noticed the presence of numerous non-English journals in the reference list. Furthermore, please check your spacing. Please make sure there is a spacing between two words and between the last word of a sentence and the subsequent in-text citation. Thank you.

The language of the manuscript was double-checked and modified carefully using both a native person and Grammarly software. The spacing was also checked and the manuscript was modified accordingly. Some examples of the corrections from linguistic and spacing points of view were indicated in the marked-up version of the manuscript.

In addition, such mentioned citations were removed, and instead, only one or two references, which are the most related ones, were cited. Moreover, in the revised version of the manuscript, all the references are from highly reputable international journals, and there is not reference from non-English ones.

-Reviewer 3:

From the references used in the work, it is observed that other researches were conducted on the same theme.

- There is no relevant thematic originality in relation to the chosen theme; However, the article is important to the area.

- A grammatical revision is suggested as it compromises the comprehension of the article for the reader.

Dear Reviewer, thank you very much for your positive feedback on the paper. We appreciate it a lot. It should be mentioned that although the work has the same theme as the previous studies, i.e., the multi-objective optimization of a PEMFC, it has the novelties, which were mentioned in Table (2) of the revised version of the manuscript:

Table (2): Gap of the research and the items taken into account as the novelties of the present investigation

The gap of the research	The novelty of the current investigation
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application, for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	For each investigated application, namely, propulsion, power station, and portable applications, a separate range, based on the recommended range of [51] is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

Considering the point that in this paper, a comprehensive multi-objective optimization is done by taking all the key performance criteria, including the environmental objective, and based on the references which have been published in the journal of cleaner production, we selected JCLP to submit this paper and we should be also thankful again to you for giving us the positive feedback on that and chance of revision.

Your comment was noticed and the paper was modified based on that. The manuscript was checked carefully and completely by both a native person and Grammarly software to enhance the language quality. Some examples of the corrections were indicated in the revised paper.

-Reviewer 4:

The paper presents an application-based multi-objective optimization approach for acquiring the best operation conditions of a proton-exchange membrane fuel cell. Through the study the authors are able to explain the effect of optimization on various parameters in a power station. The paper is well written and contributes to the body of knowledge and provides novel findings through application-based multi-objective optimization approach.

Dear Reviewer, we would like to express our sincere gratitude to you for taking your valuable time to read the manuscript and also your positive feedback on our paper. We appreciate it a lot.

Suggestion:

Please use abbreviations which are distinct enough.

For e.g.

d - discount rate

dj+ - distance to the ideal answer

dj- - distance to the non-ideal answer

It would be advisable if some other notation is used for the discount rate as it is clearly distinct from the discount rate and creates a confusion.

Your comment was noticed and the paper was modified based on that. As an example, for the mentioned abbreviations, 'd' was kept for the discount rate while 'dst_{j+}' and 'dst_{j-}' were used for the distance to the ideal and non-ideal answers, respectively.

Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell

~~An Application Based Approach to Find the Best Current Density and Optimum Condition for a Proton Exchange Membrane Fuel Cell~~

Comment [A1]: Related to the comment 1 from Reviewer 1

Ali Sohani [a1*], Shayan Naderi [a], Farschad Torabi [a], Hoseyn Sayyaadi [a], Yousef Golizadeh Akhlaghi [b], Xudong Zhao [b], Krishan Talukdar [c], Zafar Said [d]

[a] Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

[b] School of Engineering, University of Hull, HU6 7RX, UK

[c] German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, Stuttgart, 70569, Germany

[d] Sustainable and Renewable Energy Engineering Department, University of Sharjah, PO Box, 27272, Sharjah, United Arab Emirates

Abstract

An application-based multi-objective optimization approach is presented to acquire the best operation conditions ~~of~~ for a proton-exchange membrane fuel cell. The optimization is done for ~~three applications i.e.,~~ propulsion, power station, and portable ~~usage~~applications, in which the recommended range for decision variables and importance level of ~~various~~ the objective functions are taken into consideration for more accurate and practical results. In the multi-objective optimization, from each important aspect of ~~in~~ the performance, i.e., technical, economic, dimensional, and environmental aspects, one objective is selected. The effect of threshold current density on both optimum decision variables and objective functions are also investigated to find the best value for that. The results reveal that increasing the maximum allowable current density leads to ~~improved~~ improvements in optimized values of all the objective functions. Moreover, the conducted sensitivity analyses determine that the threshold current density for the propulsion and power station applications is 1.3 A.cm^{-2} and for the portable application is 1.5 A.cm^{-2}.

Comment [A2]: Related to the comment 3 from Reviewer 1

Comment [A3]: Related to the comment 2 from Reviewer 1

Comment [A4]: Related to the comment 2 from Reviewer 1

*Corresponding author. Tel: +98 912 270 43 02
Email addresses: alisohany@yahoo.com, asohani@mail.kntu.ac.ir (Ali Sohani)

Furthermore, it is found that values of the temperature, pressure and voltage in power station are not affected by optimization, whereas substantial decrease in both propulsion and portable applications brings more level of safety. Similarly, objective functions, i.e., efficiency, levelized cost, size, and greenhouse emission are averagely improved by 9.93, 16.95, 37.13, and 7.77%, respectively. The proposed procedure helps to design and manufacture the high-performance proton-exchange membrane fuel cells based on the employed application and users' preference.

Keywords: *Application-based ~~Surveys~~survey; Polymer ~~Electrolyte~~ electrolyte ~~Membrane~~ membrane ~~Fuel~~ fuel ~~Cell~~cell; Techno-~~Economic~~ economic ~~Investigation~~investigation; Multi-~~Objective~~ objective ~~Optimization~~optimization; Weighted ~~Decision~~ decision making*

Comment [A5]: Related to the comment 2 from Reviewer 1

Comment [A6]: Related to the comment 1 from Reviewer 2

Comment [A7]: Related to the comment 10 from Reviewer 1

Nomenclature		*W*	power (kW)
A	area (m^2)	**Abbreviations**	
C	cost ($)	AHP	analytical hierarchy process
CI	closeness index	POF	Pareto optimal frontier
d	discount rate	*MEA*	membrane electrode assembly
dst_{j+}	distance to the ideal answer	*TOPSIS*	technique for order of preference by similarity to ideal solution
dst_{j-}	distance to the non-ideal answer	***Scripts***	
i	current density ($A.m^{-2}$)	*asm*	assembly
f	dimensionless objective function	*BOP*	balance of plant
F	objective function	*ele*	electrode
ghg	specific greenhouse gas emission ($g.(MJ)^{-1}$)	*inv*	investment
GHG	greenhouse gas emission ($g.h^{-1}$)	*mem*	membrane
HHV	higher heating value ($kJ.kg^{-1}$)	*opt*	optimum condition
huf	hydrogen utilization factor	*opr*	operation
LHV	lower heating value ($kJ.kg^{-1}$)	*phm*	peripheral materials
LCOE	levelized cost of electricity ($\$.(kWh)^{-1}$)	*pt*	platinum
$\dot{m}$	mass flow rate ($mol.s^{-1}$)	*st*	stack
$\dot{n}$	molar flow rate ($mol.s^{-1}$)	***Greek symbols***	
P	pressure (Pa)	η	efficiency (%)
t	time (s)	λ	actual to stoichiometric ratio
T	temperature (K)	ω	humidity ($kg.kg_{air}$ or $kg.kg_{H_2}$)
V	voltage (V)		

Comment [A8]: Related to the comment 4 from Reviewer 1

1. Introduction

Proton-exchange –membrane type (PEMFC) is one of the most popular kinds of fuel cells. Working at a lower temperature and level of noise (Atyabi and Afshari, 2019), and producing electricity with greater power densities (Charoen et al., 2017) are taken into account as the most significant advantages of PEMFC in comparison to the other types. Moreover, this type of fuel cell is easy to handle and assemble (Haghighat Mamaghani et al., 2018; Shaygan et al., 2019). The mentioned advantages encourage a lot of researchers to conduct studies to enhance the performance of PEMFCs as a ~~very~~ promising technology as far as possible (Chatrattanawet et al., 2017; İnci and Türksoy, 2019), since its high efficiency can be higher than other kinds of renewable energy technologies, such as wind (Naderi et al., 2018; Naderi and Torabi, 2017). The enhancement has been done by changing the structure (Duclos et al., 2017), using novel materials (Mehrpooya et al., 2019) or finding the best operating condition (Marefati and Mehrpooya, 2019).

In order to find the best operating condition, the values of performance criteria are improved by adjusting the effective parameters (Marefati and Mehrpooya, 2019; Nagapurkar and Smith, 2019). However, in PEMFCs, there is a trade-off among performance criteria (Ayodele et al., 2018; Bukar and Tan, 2019). For example, increasing efficiency as a favorable change is accompanied by an increase in the levelized cost of electricity (LCOE), which is unfavorable (Becherif et al., 2018; Chen et al., 2019). Therefore, performing single-objective optimizations like the study of Kanani et al. (Kanani et al., 2015) leads to partial results, and in order to acquire the best operating conditions, same as other energy systems (Sohani et al., 2019a; Sohani et al., 2018), multi-objective optimization (MOO) approach should be employed. A set of solutions, all of which has the potential of being the optimal answer, is obtained by running each MOO

Comment [A9]: Related to the comment 3 from Reviewer 1

Comment [A10]: Related to the comment 3 from Reviewer 1

Comment [A11]: Related to the comment 6 from Reviewer 2

Comment [A12]: Related to the comment 6 from Reviewer 2

Comment [A13]: Related to the comment 6 from Reviewer 2

Comment [A14]: Related to the comment 6 from Reviewer 2

algorithm. The set is called Pareto optimal frontier (POF). Such optimization procedure has been implemented in many applications, from fuel cells (Sohani et al., 2019a), to thermal power plants (Sohani et al., 2017a), photovoltaic solar systems (Saedpanah et al., 2020), electrochemical systems (Pourmirzaagha et al., 2016), and management of micro grid (Jirdehi et al., 2017; Tabar et al., 2017). For instance, Sohrabi Tabar et al. (Tabar et al., 2017) solved the problem of micro grid management by the multi-objective optimization considering pollution and cost at the same time, and Ahmadi Jirdehi et al. (Jirdehi et al., 2017) found the best plan to run a micro grid system from both economic and environmental points of view by this approach. The studies (Tabar et al., 2019; Tabar et al., 2018) are some other examples of optimization in the field.

Comment [A15]: Related to the comment 1 from Reviewer 2

Comment [A16]: Related to the comment 5 from Reviewer 1

The model which is used to run the PEMFC is based on a single domain formulation (Sohani et al., 2019a; Um et al., 2000) that couples electrochemical governing equations with equations governing the fluid flow in the gas channels, gas diffusion layers, catalyst layers and electrolyte membrane. The positive aspect of this approach is that it solves the whole cell as a sandwich in a way that there is no need to generate new equations as boundary conditions (Esfahanian and Torabi, 2006; Esfahanian et al., 2008). It can be used for simulation of batteries as well (Torabi and Aliakbar, 2012; Torabi and Esfahanian, 2011). This model is utilized to run the simulation under different operating conditions as stated in (Sohani et al., 2019a), then stepwise regression method is used to extract an equation describing the performance of the FC. Although numerical methods have been used to solve the governing equations (Hosseinzadeh et al., 2019a; Seyedmohammad Mousavisani, 2019), analytical methods may be a good choice for future research (Hosseinzadeh et al., 2019b; Sohani et al., 2017b). In addition, all the necessary information about the data analysis of the employed models were given in the previous study of the authors conducted on PEMFC (Sohani et al., 2019a), and in order not to make paper too lengthy, it is referred for more details.

Comment [A17]: Related to the comment 3 from Reviewer 2

In order to provide a brief but clear insight, the studies have been done in the field of multi-objective optimization of PEM FCs are listed in Table (1).

Table (1): List of the studies done on the optimization of PEMFCs

Study	year	The considered objective functions	Were all technical, economic, dimensional, and environmental characteristics as the main performance criteria of a PEMFC optimized together?	Was the range of variation of decision variables selected based on the recommended range for different applications?	Was a final optimal point introduced by considering the preference based on the application?	Was the effect of maximum allowable current density on the optimum results studied?
(Wishart et al., 2006)	2006	Exergetic efficiency and net power	No	No	No	No
(Na and Gou, 2007)	2007	Efficiency and cost	No	No	No	No
(Ang, Sheila Mae C et al., 2010)	2010	Size and efficiency	No	No	No	No
(Sayyaadi and Esmaeilzadeh, 2013)	2013	Exergetic efficiency, power density and power cost	No	No	No	No
(Tahmasbi et al., 2015)	2015	Power and levelized cost	No	No	No	No
(Mert et al., 2015)	2015	Energy and exergy efficiencies, cost generation and power output	No	No	No	No
(Kanani et al., 2015)	2015	Power	No	No	No	No
(Mamaghani et al., 2016)	2016	Net electrical efficiency and total capital cost	No	No	No	No
(Chen et al., 2017)	2017	Efficiency and power output	No	No	No	No
(Mamaghani et al., 2017)	2017	Net electrical efficiency and thermal generation	No	No	No	No
(Liu et al., 2017)	2017	Output power and power consumption	No	No	No	No
(Chen et al., 2018)	2018	Exergy efficiency, annual cost and green house pollutant emission	No	No	No	No
(Kwan et al., 2018)	2018	Fuel consumption and required super capacitor size	No	No	No	No
(Ahmadi et al., 2018)	2018	Fuel consumption and efficiency	No	No	No	No

(Loreti et al., 2019)	2019	Cost of fuel and revenue	No	No	No	No
(Guo et al., 2019)	2019	energetic and exergetic performance characteristic as well as power density	No	No	No	No
(Sohani et al., 2019a)	2019	Efficiency, power density, levelized cost, and size	No	No	No	No
The current study	**2019**	**Efficiency, levelized cost, size and produced green-house generation**	**Yes**	**Yes**	**Yes**	**Yes**

Table (1) shows that despite valuable investigations have conducted so far; there have been some gaps ~~which~~ that should be addressed by conducting a new study. As a result, the current study is conducted. The gap of the research and the items taken into account as the novelties of the present investigation are introduced in Table (2).

Comment [A18]: Related to the comment 3 from Reviewer 1

Table (2): Gap of the research and the items taken into account as the novelties of the present investigation

Comment [A19]: Related to the comment 9 from Reviewer 1 as well as the comments 1, 2, and 3 from Reviewer 2

The gap of the research	**The novelty of the current investigation**
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application, for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	For each investigated application, namely, propulsion, power station, and portable applications, a separate range, based on the recommended range of (Piela et al., 2017) is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

As the existing theory, the optimum values of the operating parameters for a PEMFC is obtained from the recommended values or the multi-objective optimization approaches which have not considered all the performance criteria at the same time and have assumed the same priority level for the optimized objective functions. However, in this study, conducting the multi-objective optimization in which all the key factors including technical, economic, dimensional, and environmental aspects are taken into account is studied as the new theory. In addition, the new theory considers different levels of importance for the objective function based on the application. As a result, the proposed theory is a more practical and realistic one, and helps to design high-performance PEMFC more comprehensively and according to the users' preferences in different applications, in which the objective functions do not have the same level of priority.

Comment [AS20]: Related to the comments 2 and 3 from Reviewer 2

The following items are the implications of this paper:

- Designing a PEMFC is done by a systematic approach in which the best operating condition is determined in way that all the important performance criteria are in the best condition at the same time. It helps to have a PEMFC with the lowest possible cost and the highest performance at the same time, which is the theoretical implication of the conducted research.

- A method to obtain the best operating condition based on the application and users' preference is obtained. It can be taken into account as the methodological contribution of this study. It should be also noted that the proposed approach can be done for different capacities, countries, and applications.

- Not only can the designing process be done using the presented methodology, adjusting the operating conditions and as a result, retrofitting an in-operation PEMFC can be also performed by the proposed approach. Therefore, the methodology employed in this paper have the potential of being used in a wide range of products at different stages. This item can be considered as the practical implication of the current study.

- When a system has the best performance from different perspectives, including the technical, economic, and environmental aspects, policy-makers and end-users are encouraged more to use it (Sohani and Sayyaadi, 2020). Since the conducted investigation covers all the mentioned criteria in addition to the size as the other key factor and find the best possible condition for them, it will help to make PEMFC more popular all around the world. It is the social implication of this paper. The more popular clean technologies like PEMFC is used in the world, the better condition to live for human beings will be provided.

Comment [A21]: Related to the comment 5 from Reviewer 2

Considering the items indicated in Table (2), the following items are posed as the main research questions, which will be addressed in this study:

- How much improvement compared to the recommended values of (Piela et al., 2017) is achieved when the multi-objective optimization considering all the key performance criteria is done?

- How different the optimized solutions are when the importance level of objective functions in different application is considered?

- What are the difference between the condition the same priority levels for the objectives are assumed and the time the application-based method is implemented?

- How do the decision variables and objective functions change when the maximum allowable current density change?
- Does the maximum allowable current density have a great or small impact on the optimization results?
- What are the best recommended values for the maximum allowable current density?

Comment [A22]: Related to the comment 5 from Reviewer 2

In addition to the introduction presented above, the remaining part of the paper consists of four main sections. Section 2 in which the developed algorithm comprising MOO details, objective functions, and decision variables are introduced. Section 3 where the specifications of the investigated PEMFC and economic parameters are discussed. Section 3 is followed by the fourth section that is dedicated to results and discussion, and finally, the main contributions and key results are summarized in the conclusion, which is the fifth section of this study.

The final point which should be indicated in this part is based on the comprehensive conducted review on the green supply chain management system, journal of cleaner production is the most cited journal in this field and sustainability paradiagrams (de Oliveira et al., 2018), and based on the cited references and the topic, it is one of the best venues for publishing the paper.

Comment [A23]: Related to the comment 2 from Reviewer 2 as well as comment from Reviewer 3

2. Description of the presented application-based MOO approach

Comment [A24]: Related to the comments 1, 2, and 3 from Reviewer 2

In this part, the presented approach is introduced step by step; for each step, a brief but complete explanation is given. More details about the background of the employed methods, which is beyond the scope of this study, are found in the cited references.

2.1. Step I: Definition of the multi-objective optimization problem

A multi-objective optimization problem is defined by introducing its decision variables, objective functions, and constraints.

2.1.1. Decision variables

Temperature, pressure, voltage, actual to stoichiometric molar ratios of air and hydrogen, and humidity of the cathode and anode, as seven main adjustable effective parameters of a PEMFC, are selected as the decision variables. The recommended range of decision variables for different applications is given in Table (3).

Table (3): The recommended range of decision variables for different applications (the considered bounds for the decision variables) (Piela et al., 2017)

Parameter	**Symbol**	**Application** ~~APP~~ **Application #1 (Propulsion)**	**Application**~~APP~~ **#2 (Power Station)**	**Application**~~APP~~ **#3 (Portable)**	**Unit**
Temperature	T	283.15- 363.15	283.15- 363.15	283.15- 363.15	K
pressure	P	105000- 300000	105000- 200000	105000- 200000	Pa
voltage	V	Based on PEMFC's specifications	Based on PEMFC's specifications	Based on PEMFC's specifications	V
actual to stoichiometric molar ratio of air	λ_{air}	1.3- 2.0	1.1- 2.0	1.1- 2.0	-
actual to stoichiometric molar ratio of hydrogen	λ_{H_2}	1.1- 2.0	1.1- 2.0	1.1- 2.0	-
humidity of the anode (hydrogen)	ω_{air}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{air}^{-1}$
humidity of the cathode (air)	ω_{H_2}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{H_2}^{-1}$

It should be noted that in almost all the optimization problems in the reality, like here, the decision variables have their limits, as it is seen. However, in this study, following the same fashion as (Rao, 2019) and the optimization toolbox in MATLAB software (Higham and Higham, 2016; Moore, 2017), they are called as "bounds", and not "constraints". On the other

Comment [A25]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A26]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A27]: Related to the comment 6 from Reviewer 1

Comment [A28]: Related to the comment 6 from Reviewer 1

Comment [A29]: Related to the comment 6 from Reviewer 1

hand, the limitations which are not the bounds are called the constraints. The constraints considered in this study are introduced in the section 2.1.3.

2.1.2. Objective functions

The performance criteria which are going to be improved by MOO are called objective functions. The desirable performance of a PEMFC is achieved when all the technical, economic, dimensional, and environmental performance characteristics are simultaneously at the best possible conditions, so from each of them, one objective function should be considered. Therefore, one of the most widely-used functions for each mentioned aspect is selected and optimized as the objective function, which leads to having four objective functions. ~~They~~ The considered objective functions are introduced in the following section. It should be noted that in order not to make the article so lengthy, the definitions of the symbols used in the equations are presented in the nomenclature, and they are not explained after each equation.

2.1.2.1. Technical objective function

PEMFC efficiency, which is defined as the ratio of the generated power to the enthalpy of reaction, which is the maximum available power in the ideal condition, is defined as the technical objective function (Mert et al., 2011):

$$\eta = \frac{W_{st}}{\dot{n}_{H_2} HHV_{H_2}} \tag{1}$$

2.1.2.2. Economic objective function

The levelized cost of electricity generation, briefly called the levelized cost, is considered as the economic objective function. The levelized cost is calculated as follows (Sohani et al., 2019a):

Comment [A30]: Related to the comment 11 from Reviewer 1

Comment [A31]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A32]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A33]: Related to the comments 1, 2, and 3 from Reviewer 2

$$C_{levelized} = \frac{1}{\sum_{j=1}^{year}\sum_{t=0}^{t_{opr}} \frac{W_{st}t}{(1+d)^j}} \left[C_{inv} + \sum_{j=1}^{year}\sum_{t=0}^{t_{opr}} \frac{C_{fuel}t}{(1+d)^j} \right] \tag{2}$$

In Eq. (2)~~,~~ C_{fuel} and C_{inv} denote fuel and investment costs, which are determined by Eqs. (3) (Sohani et al., 2019a) and (4) (Na and Gou, 2007), respectively:

$$C_{fuel} = \frac{\dot{m}_{H_2} C_{H_2}}{huf} \tag{3}$$

$$C_{inv} = (C_{st} + C_{BOP})A + C_{asm}W_{st} \tag{4}$$

C_{st} in Eq. (4) is also calculated from Eq. (Na and Gou, 2007):

Comment [A34]: Related to the comment 6 from Reviewer 2

$$C_{st} = C_{mem} + C_{elc} + C_{bpp} + C_{pt} + C_{phm} \tag{5}$$

2.1.2.3. Dimensional objective function

Comment [A35]: Related to the comments 1, 2, and 3 from Reviewer 2

~~Area~~ The area of the membrane electrode assembly is selected as the dimensional objective function ~~of PEMFC~~in the multi-objective optimization. It is computed by Eq. (6) (Ang, Sheila Mae C. et al., 2010):

Comment [A36]: Related to the comment 3 from Reviewer 1

$$A_{MEA} = \frac{W_{st}}{pow_{out}} \tag{6}$$

In which W_{st} is the power required in each application while pow_{out} is the multiplication of operational current density by the output voltage.

Comment [A37]: Related to the comment 3 from Reviewer 1

2.1.2.4. Environmental objective function

Comment [A38]: Related to the comments 1, 2, and 3 from Reviewer 2

The process of consuming the fuel (hydrogen) in a PEMFC is with almost no emissions. However, the hydrogen production process is accompanied by polluting the environment. One of the processes, which is assumed as the way of providing hydrogen in this study, is water electrolysis employing wind energy. By using data indicated in Table (4), in which the values of specific environmental emissions of the hydrogen generation process (ghg) are given, the produced green-house generation (GHG) is obtained for this process (Chen et al., 2018):

Comment [A39]: Related to the comment 6 from Reviewer 2

$$GHG = \dot{m}_{H_2} LHV_{H_2} ghg \tag{7}$$

Table (4): The greenhouse emission comes from the hydrogen production process by water electrolysis employing wind energy (Chen et al., 2018)

Comment [A40]: Related to the comment 3 from Reviewer 1

Process	**Specific Pollution level (g.(MJ)$^{-1}$)**
Power generation and water electrolysis	6.85
Hydrogen compression	13.7
Total (ghg)	20.55

In this study, GHG is considered as the environmental objective function.

2.1.3. **Constraints**

Comment [A41]: Related to the comments 1, 2, and 3 from Reviewer 2

In the optimization problems, usually, there are one or more limitations, which should be considered to obtain applicable results. They are called as the constraints. Here, the current density limitation is the only imposed ~~as the only~~ constraint. It states that the current density must be less than a threshold value ($i_{threshold}$), whose mathematical form is:

Comment [A42]: Related to the comment 3 from Reviewer 1

Comment [A43]: Related to the comment 6 from Reviewer 2

Comment [A44]: Related to the comment 6 from Reviewer 2

$$i \le i_{threshold} \tag{8}$$

As it will be completely discussed in the results and discussion part, MOO is done in different values of $i_{threshold}$, and having performed a comprehensive analysis among the obtained results, the best threshold current density for each application will be determined.

It is worth mentioning that as it was explained in the section 2.1.1, the limitation for the decision variables are called "bounds" and the constraints cover other limitations.

2.2. Step II: Performing MOO algorithm and obtaining POF

The optimization problem has been completely defined in the previous ~~Step~~step. Therefore, ~~in~~ at this ~~step~~stage, MOO is employed to find a set of solutions ~~which~~ that ~~have~~ has the potential of being the final answer, called Pareto optimal frontier (POF). Non-dominant sorting genetic algorithm 2 (NSGA-II), which was completely introduced and employed in the previous publications of the authors like (Sohani and Sayyaadi, 2017; Sohani et al., 2019b), is employed for this purpose. NSGA-II is one of the ~~most~~ widely-used methods to find POF. It should be also noted that MATLAB software was used to conduct the NSGA-II and obtain POF.

2.3. Step III: Determination of the relative priority and selecting the final solution

As it was previously stated, running a multi-objective algorithm leads to obtaining a set of answers, called POF. It means that employing the MOO algorithm ~~individually~~ does not give the final solution individually, and the final answer~~it~~ must be selected ~~by~~ using a decision making method. In this study, to avoid non-realistic results caused ~~from~~ by assuming the same preference for all ~~of~~ the performance criteria, AHP is used in combination ~~of~~ with TOPSIS.

In the used combined method, initially, the relative level of importance for each criterion (objective function) in the selection of the final solution is obtained by pairwise comparison of criteria to each other. It is done by forming a matrix, called the matrix of pairwise comparisons (MPC) (Sohani et al., 2017a). The comparisons are done by the suggested scale of Saaty, which is presented in Table (5).

Comment [A45]: Related to the comment 11 from Reviewer 1

Comment [A46]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A47]: Related to the comment 10 from Reviewer 1

Comment [A48]: Related to the comment 3 from Reviewer 1

Comment [A49]: Related to the comment 3 from Reviewer 2

Comment [A50]: Related to the comments 1, 2, and 3 from Reviewer 2

Comment [A51]: Related to the comment 3 from Reviewer 1

Comment [A52]: Related to the comment 3 from Reviewer 1

Comment [A53]: Related to the comment 3 from Reviewer 1

Comment [A54]: Related to the comment 3 from Reviewer 1

Table (5): the Suggested scale of Saaty used to ~~do~~ make pairwise comparisons in the AHP method (Saaty, 1977)

Value	Description
1	Equal importance
3	Fairly higher importance
5	Higher importance
7	Much higher importance
9	Extremely higher importance
Even values between two odd mentioned ones (2, 4, 6, 8)	An importance level between the corresponding importance of the two odd values

After performing the pairwise comparisons by conducting the mathematical matrix operations discussed in details in (Boukhari et al., 2018), the relative level of importance of each criterion in the selection of the final answer is determined. The output for the ist criterion is the weight ~~of~~ w_i, which is a numerical value between 0 and 1, and shows the relative importance degree of that criterion compared to the other criteria. Having determined the w_i values for the criteria involved in the decision making (which are objective functions), the closeness index (Cl) for each point on POF is calculated from Eqs. (9) to (12), and the answer with the highest Cl is selected as the final optimal solution (Karami and Sayyaadi, 2015):

$$f_{ij}^{n} = \frac{w_i\ F_{ij}}{\sqrt{\sum_{j=1}^{m}(w_i.F_{ij})^2}} \tag{9}$$

$$dst_{j+} = \sqrt{\sum_{j=1}^{num}(f_{ij} - f_i^{ideal})} \tag{10}$$

$$dst_{j-} = \sqrt{\sum_{j=1}^{num}(f_{ij} - f_i^{non-ideal})} \tag{11}$$

Comment [A55]: Related to the comment 3 from Reviewer 1

Comment [A56]: Related to the comment 3 from Reviewer 1

Comment [A57]: Related to the comment 6 from Reviewer 2

Comment [A58]: Related to the comment from Reviewer 4

Comment [A59]: Related to the comment from Reviewer 4

$$Cl = \frac{dst_{j-}}{dst_{j+} + dst_{j-}} \quad (12)$$

Comment [A60]: Related to the comment from Reviewer 4

It should be also mentioned that, as it is clear from definition, in case the relative level of importance of criteria in comparison to each other becomes the same, the introduced combined method reduces to the ordinary TOPSIS (Sohani et al., 2016). The codes developed in MATLAB software was employed to run the decision making method and select the final answer by the introduced method.

Comment [A61]: Related to the comment 3 from Reviewer 2

3. The investigated case-study

Comment [A62]: Related to the comments 1, 2, and 3 from Reviewer 2

Application of the proposed approach is shown by employing it for a PEMFC. Consequently, in this part, the specifications of the PEMFC considered as the case study are given. The PEMFC considered in this study, is the one which has been investigated in the previous studies of the authors like (Sohani et al., 2019a). In addition to the specifications, the priority level of the objective functions for the case study based on experts' judgments, which is necessary to obtain the final solution by the combination of AHP and TOPSIS, are also introduced. It should be noted that the priority level is totally dependent on the experts' points of view, and it might be different for other cases.

In addition, it is worth mentioning that, like other similar cases in energy systems, such as previous published studies of the authors (Sohani et al., 2019b), a general approach was presented. Since obtaining numerical values for the investigated criteria needs to have the values of the effective parameters, a case study had to be considered and the approach employed for it. As a result, for other case studies, the approach is applicable; the only difference is the values of the effective parameters, and consequently, the investigated criteria are not the same.

Comment [A63]: Related to the comment 3 from Reviewer 2

3.1. General specifications

Comment [A64]: Related to the comments 1 and 2 from Reviewer 2

Table (6) presents the specification of the investigated case study, which is a 50 kW PEMFC.

Table (6): The specifications of the 50 kW PEMFC considered as the case study

Parameter	Unit	Value
Thickness of air and hydrogen channels	mm	0.8
GDL thickness	mm	0.21
Catalyst layer thickness	mm	0.012
Membrane Thickness	mm	0.036
GDL porosity	-	0.5
Catalyst porosity	-	0.5
Membrane porosity	-	0.28
GDL and catalyst permeability	-	1e-12
Anode exchange coefficient	-	2
Cathode exchange coefficient	-	2

In (Sohani et al., 2019a), Eq. (13) was obtained by the stepwise regression method to predict the current density based on the values of the decision variables for the investigated PEMFC. This equation is also employed in this study.

Comment [A65]: Related to the comment 3 from Reviewer 1

$$\begin{aligned} i = & -569786.180 + 3848.163T - 0.23717P + 4194.37526\lambda_{H_2} + 20875.16491\lambda_{air} - 86756.03593\omega_{H_2} \\ & -449126.8480\omega_{air} - 37565.929V + 000808232TP - 8.81763T\lambda_{H_2} - 32.7289T\lambda_{air} \\ & +781.70708T\omega_{air} + 0.0099263P\lambda_{air} - 0.18041948P\omega_{air} + 0.00922283PV - 1438.71619215\lambda_{H_2}\omega_{air} \\ & -8649.784500005\lambda_{air}V + 43583.517723\omega_{H_2}V + 357377.647286\omega_{air}V - 5.964732329T^2 \\ & -247.4630933695\lambda_{H_2}{}^2 - 1250.538655\lambda_{air}{}^2 + 158078.948844\omega_{H_2}{}^2 - 52667.71773303V^2 \end{aligned} \tag{13}$$

3.2. Economic details

Comment [A66]: Related to the comments 1 and 2 from Reviewer 2

Table (7) gives the data required to calculate LCOE as the economic objective function. The important point for economic data is they should be up to date (Sohani and Sayyaadi, 2018), and for this reason, the data indicated in Table (7) is compared to the online prices found in the references like (Fuel Cell Store, 2019). The comparison shows that there is a good agreement between the data and online information.

Table (7): The considered values for economic analysis (Sohani et al., 2019a)

Parameter	Unit	Value
Nafion membrane 117	$ m^{-2}	2455.56
Platinum; 2–4 thickness	$ m^{-2}	176.29
Electrode; max. 0.8 mm for single cell	$ m^{-2}	177
Bi-polar plate; max. 4 mm	$ m^{-2}	1650
Peripheral parts	$ m^{-2}	15.6
Assembly	$ (kW)$^{-1}$	391
Discount rate	%	6
Cost of hydrogen	$ kg^{-1}	1.00
Cost of the balance of plant to cost of stack ratio	-	0.5
Lifetime	years	15
Annual operating hours	hours	6150

Comment [A67]: Related to the comment 3 from Reviewer 1

As it is seen, all the used methods and employed equations were adopted from the published literature and they have been utilized in several researches in different fields. Therefore, each of them, and consequently, the combination of them are accurate and reliable. Moreover, considering the fact that only economic indicators such as discount rate are not the same in the two different countries, only the levelized cost will be different and studying in another country does not have any impacts on the values of the other performance criteria in the same condition for the effective parameters. For the levelized cost, however, it should be also noted that in spite of having different values in two different countries, the variation trend is almost similar.

Comment [A68]: Related to the comment 13 from Reviewer 1

Comment [A69]: Related to the comment 4 from Reviewer 2

3.3. Relative importance of performance criteria

Comment [A70]: Related to the comments 1 and 2 from Reviewer 2

As discussed previously, in order to select the final solution among the points on POF by using the combined AHP and TOPSIS, the relative importance of performance criteria (objective functions) must be determined. Consequently, three experts involved in decision making done in (Sohani et al., 2019a) for PEMFCs were invited again, and they were asked to ~~do~~ make the pairwise comparisons for three applications. ~~Their evaluation~~The results are reported in this sub-section while the matrices of pairwise comparisons are reported in the supplementary material (Tables (S1) to (S3)). It should be noted that, as it was completely discussed in (Hasani Balyani

Comment [A71]: Related to the comment 3 from Reviewer 1

Comment [A72]: Related to the comment 3 from Reviewer 1

et al., 2015; Sohani et al., 2017a), in cases that the experts have different judgments, the geometric mean is used to obtain the final evaluation.

3.3.1. ~~APP~~ Application #1: Propulsion

Comment [A73]: Related to the comment 6 from Reviewer 1

For this application, three experts have the following judgments about the performance criteria:

Judgement #1: According to this judgment, size and GHG have the highest level of importance. Then, efficiency and LCOE are in the next places, respectively.

Judgement #2: This judgment says that size and GHG are more important than efficiency and LCOE. However, in this case, efficiency and LCOE are as important as each other.

Judgement #3: Based on judgment #3, GHG is more important than size. After that, efficiency and LCOE are in the third and fourth places, respectively, with the close level of priority.

3.3.2. Application~~APP~~ #2: Power station

Comment [A74]: Related to the comment 6 from Reviewer 1

In spite of the propulsion, for the power station application, the three experts reached an agreement to evaluate performance criteria compared to each other. They believe that LCOE is the most important criterion. Next, there are efficiency and GHG with the same level of importance while size has the lowest level of priority among the objective functions.

3.3.3. Application~~APP~~ #3: Portable

Comment [A75]: Related to the comment 6 from Reviewer 1

For this application, like the power station usage, all the three experts have the same judgments. According to this judgement, size has the highest level of priority here while GHG and efficiency are in the next places with a similar priority. LCOE has also a little bit lower importance than the two aforementioned performance criteria

3.3.4. The final weights

By using the matrices of pairwise comparison and as discussed in the previous section, the relative importance of performance criteria is obtained for the three application in form of w_i weights, which are introduced in Table (8). For obtaining the final weights from the matrix of pairwise comparison, Expert Choice software program (Choice, 1999) is used to do calculations.

Table (8): The relative importance of the performance criteria (objective functions) in the form of w_i weights

Performance criteria	Relative importance (w_i)		
	~~APP~~ Application #1 (Propulsion)	**~~APP~~ Application #2 (Power Station)**	**~~APP~~ Application #3 (Portable)**
Efficiency	0.214	0.256	0.236
LCOE	0.201	0.306	0.206
Size	0.298	0.177	0.322
GHG	0.287	0.256	0.236

4. Results and discussion

After implementing the described optimization and decision making processes on the introduced PEMFC, the effect of threshold current density on the both decision variables and objective functions are investigated in ~~the following~~this part.

4.1. The ~~impacts of~~ variation impacts of the maximum allowable current density on results of the multi-objective optimization ~~results~~

~~So far, t~~The proposed approach has been completely introduced so far. Furthermore, the improvement potential of the multi-objective optimization ~~improvement~~ for different applications has been evaluated in details. Here, to bring more extensive insight, the ~~impacts of~~ variation impacts of the maximum allowable current density ($i_{threshold}$) on the ~~values of~~ optimum values of decision variables and objective functions are investigated. For this purpose,

Comment [A76]: Related to the comments 1 and 2 from Reviewer 2

Comment [A77]: Related to the comment 6 from Reviewer 1

Comment [A78]: Related to the comment 6 from Reviewer 1

Comment [A79]: Related to the comment 6 from Reviewer 1

Comment [A80]: Related to the comment 6 from Reviewer 2

Comment [A81]: Related to the comment 6 from Reviewer 2

Comment [A82]: Related to the comment 6 from Reviewer 2

Comment [A83]: Related to the comment from Reviewer 3

Comment [A84]: Related to the comment from Reviewer 3

Comment [A85]: Related to the comment from Reviewer 3

Comment [A86]: Related to the comment from Reviewer 3

Comment [A87]: Related to the comment from Reviewer 3

the introduced approach is employed to find the best operating conditions ~~of~~ for the studied PEMFC at five different values for $i_{threshold}$, which are 1.1, 1.2, 1.3, 1.4, and 1.5 A.cm^{-2} and the results are employed to plot the graphs presented in the next subsections. The effects of variation of the maximum allowable current density ($i_{threshold}$) on the values of decision variables and objective functions ~~of~~ in the optimum condition are shown in Fig. (1a) to Fig. (1g), and Fig. (2a) to Fig. (2d), respectively.

4.1.1. **The decision variables**

First of all, ~~the~~ changes ~~of~~ in each decision variable as a result of ~~change~~ variation in the threshold current density are investigated.

4.1.1.1. Temperature

As it is seen in Fig. (1a), for all the three applications, increasing $i_{threshold}$ leads to ~~the reduction of~~decrease in the optimum temperature ~~in all of the three applications~~. The reason in when $i_{threshold}$ grows, the movement of the ions in the electrolyte membrane as well as the movement of the electrons in the solid phase and current collectors becomes easier. In other words, the internal resistance drops by increasing $i_{threshold}$~~,~~. which leads to lower operating temperatures. In propulsion and portable applications, the slope of decrement remains constant~~,~~. ~~however~~ However ~~in~~ for ~~the case of~~ power station usage, the values approach ~~to~~ the constant value of 333.5 K after the threshold current density of 1.3 A.cm^{-2}. Changing the value of $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2} is accompanied by only 1.01, 1.99, and 1.15% fall in the optimum temperature ~~of~~ for propulsion, power station, and portable applications, respectively, which shows that the sensitivity of ~~this decision variable~~ the optimum temperature to $i_{threshold}$ is low.

Comment [A88]: Related to the comment from Reviewer 3

Comment [A89]: Related to the comment from Reviewer 3

Comment [A90]: Related to the comment 3 from Reviewer 1

Comment [A91]: Related to the comment from Reviewer 3

Comment [A92]: Related to the comment 14 from Reviewer 1

Comment [A93]: Related to the comment from Reviewer 3

Comment [A94]: Related to the comment from Reviewer 3

Comment [A95]: Related to the comment 3 from Reviewer 1

4.1.1.2. Pressure

According to ~~the trend of variation shown in~~ Fig. (1b), by an increase in $i_{threshold}$~~,~~, the optimum pressure decreases in all ~~of~~ the three applications. It is because the operating pressure directly affects the transport of the reactants to the reaction area (catalyst layer). When $i_{threshold}$ is low, the rate of reactions falls significantly, and the density of reactants becomes higher at the interface between the gas diffusion layer and the catalyst layer. As a result, in such conditions, i.e., low values for $i_{threshold}$, the optimum value for pressure has to increase to move the reactants to the reaction area in a proper way.

~~However~~Nevertheless, the behaviors are not the same for ~~the~~ different applications. In the portable application, the optimum pressure decreases linearly. In power station application first, it decreases fast, then, the decrement slope becomes slow, and after that, a moderate slope is observed~~,~~. ~~and in~~In the propulsion usage~~,~~, the values approach ~~to~~ the constant value of 113 kPa after the maximum allowable current ~~density becomes greater than~~of 1.3 A.cm^{-2}. In addition to the mentioned decrementing behavior, the sensitivity of the optimum pressure to $i_{threshold}$ is different for the three applications; in the case of propulsion, power station, and portable applications, reaching $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2} leads to 11.65, 17.39, and 3.88% decrease for the investigated application, respectively.

4.1.1.3. Actual to the stoichiometric molar ratio of hydrogen

In this case, as shown in Fig. (1c), the optimum ~~actual to stoichiometric molar ratio of hydrogen~~value increases by the increase in $i_{threshold}$ in all the three applications. The reason is that, as discussed in the previous part, in lower values for $i_{threshold}$, the rate of reactions is low, and in order to make it as fast as possible, the actual to the stoichiometric molar ratio of the hydrogen increases.

Comment [A96]: Related to the comment 14 from Reviewer 1

Comment [A97]: Related to the comment from Reviewer 3

Comment [A98]: Related to the comment from Reviewer 3

Comment [A99]: Related to the comment 3 from Reviewer 1

Comment [A100]: Related to the comment from Reviewer 3

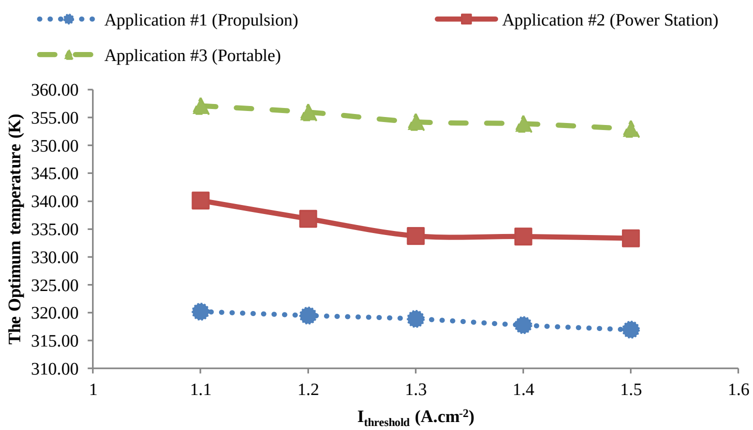
Comment [A101]: Related to the comment from Reviewer 3

Comment [A102]: Related to the comment 3 from Reviewer 1

Comment [A103]: Related to the comment 3 from Reviewer 1

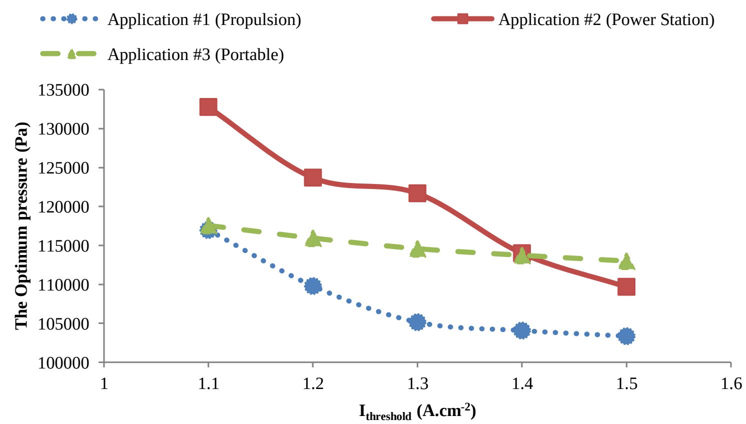
Comment [A104]: Related to the comment 3 from Reviewer 1

Comment [A105]: Related to the comment 14 from Reviewer 1



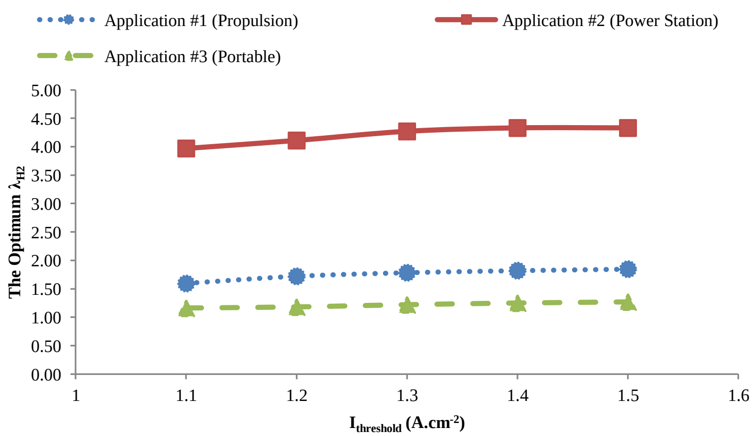
Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum temperature (K)
360.00
355.00
350.00
345.00
340.00
335.00
330.00
325.00
320.00
315.00
310.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

(a)



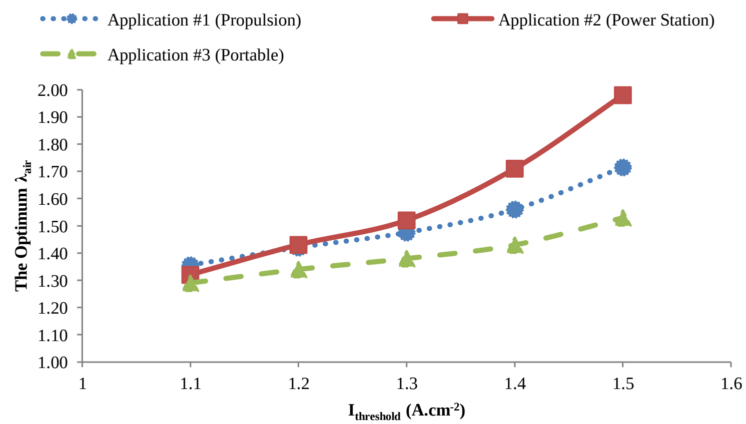
Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum pressure (Pa)
135000
130000
125000
120000
115000
110000
105000
100000
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

(b)



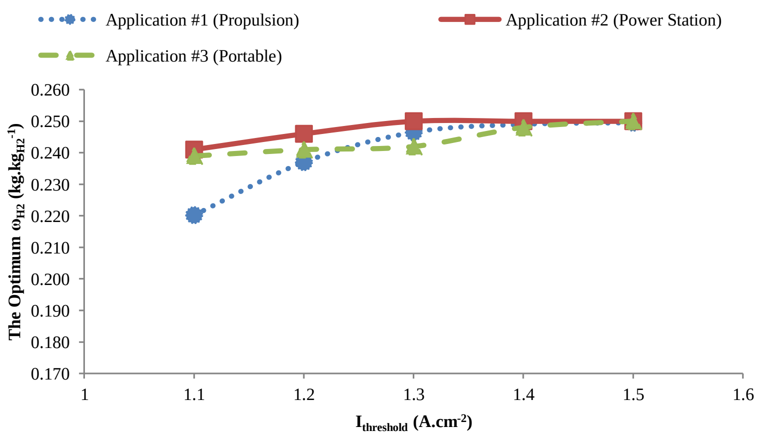
Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum λ_{H2}
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

(c)

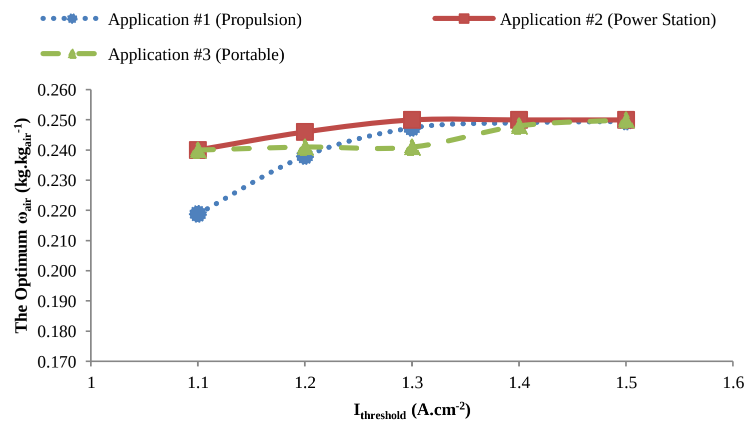


Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum λ_{air}
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

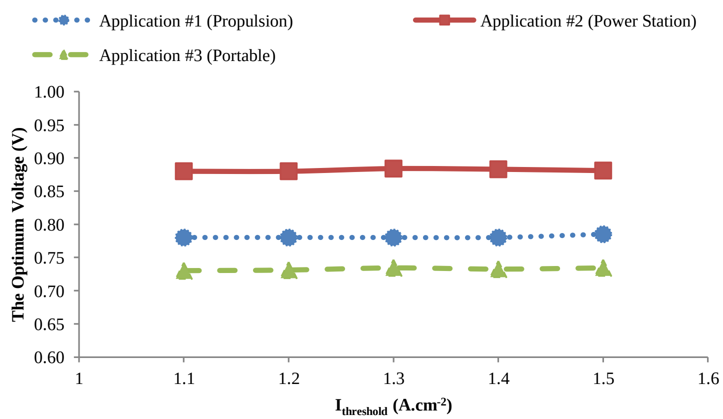
(d)



(e)



(f)



(g)

Fig. (1): The impacts of variation of the maximum allowable current density ($I_{threshold}$) on the values of decision variables in the optimum condition (a) temperature; (b) pressure; (c) actual to molar ratio of hydrogen; (d) actual to molar ratio of air; (e) humidity of anode; (f) humidity of cathode; (g) voltage

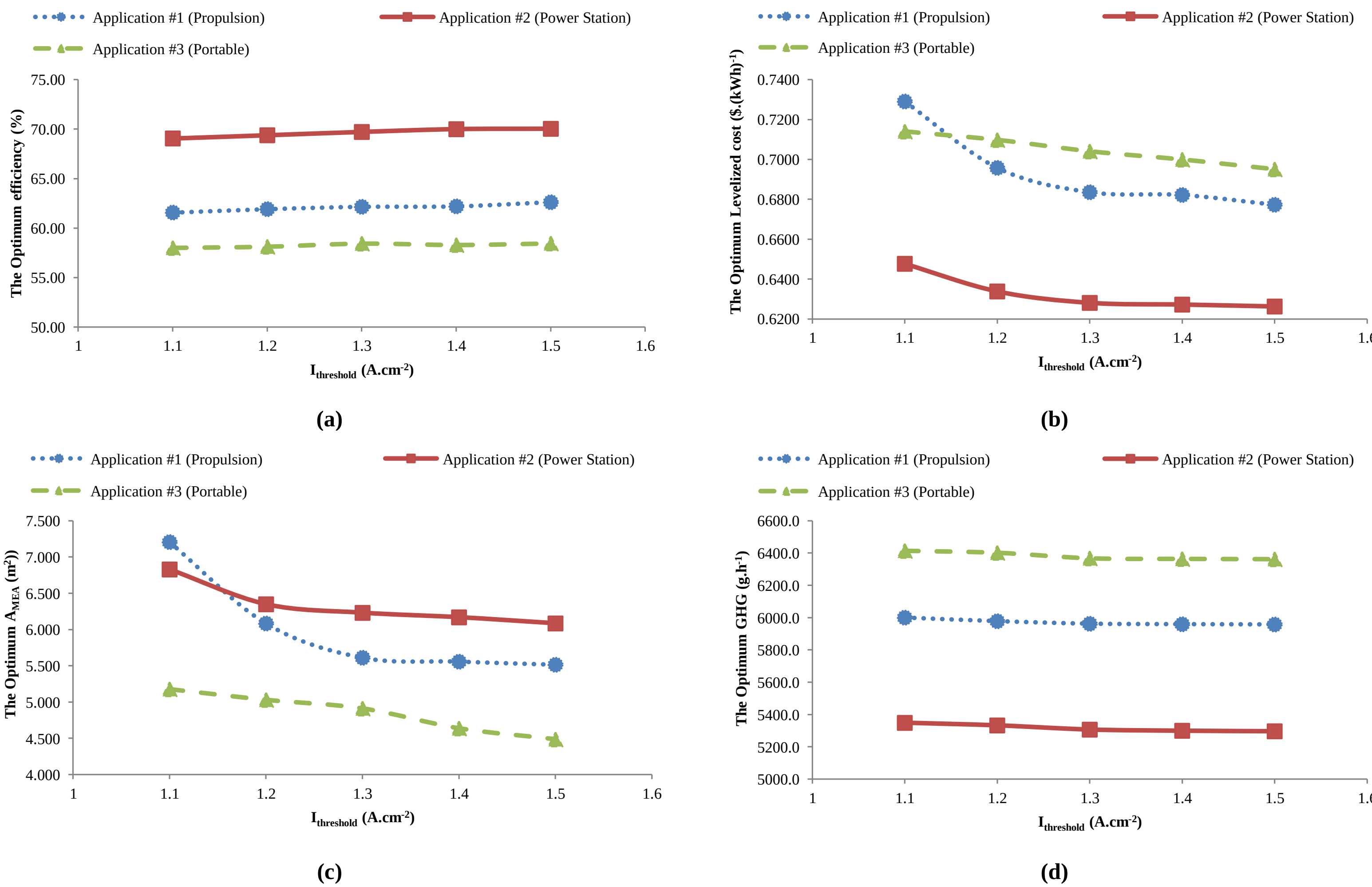


Fig. (2): The impacts of variation of the maximum allowable current density ($I_{threshold}$) on the values of objective functions in the optimum condition (a) efficiency; (b) levelized cost; (c) area of membrane electron assembly (A_{MEA}); (d) GHG

While the optimum actual to molar ratio of hydrogen approaches a constant value from 1.4 A.cm^{-2} in the power station application, for two other ones, it continuously grows. Here, like the optimum pressure, different levels of sensitivity to $i_{threshold}$ are observed for the three applications; 15.86, 9.07, and 9.48% changes in the propulsion, power station, and portable applications are observed, respectively.

4.1.1.4. Actual to the stoichiometric molar ratio of air

As Fig. (1d) shows, the optimum actual to the stoichiometric molar ratio of air ~~is~~ has almost the same value for the three applications in $i_{threshold}$ of 1.1 A.cm^{-2}. However, when $i_{threshold}$ reaches ~~to~~ 1.5 A.cm^{-2}, different values for this parameter are seen. Here, and like the stoichiometric molar ratio of hydrogen, the optimum value increases to make the rate of reactions as fast as possible.

The lowest increasing rate belongs to the portable application. Propulsion is in the middle and power station has the highest growth rate. In the case of power station application, the optimum values increases significantly in the higher levels of $i_{threshold}$ in comparison to the lower values. For this application, ~~I~~increasing $i_{threshold}$ from 1.2 to 1.3 A.cm^{-2} leads to an increase in the optimum ratio from 1.43 to 1.52 while by changing the maximum allowable current density from 1.4 to 1.5 A.cm^{-2}, the value of actual to stoichiometric molar ratio of air in the optimum condition reaches from 1.71 to 1.98. In addition to the power station application whose optimized ratio increases 50.00% from the beginning to the end of the range, propulsion and portable applications have also 26.50 and 18.60% increase between the mentioned range of $i_{threshold}$. The above-mentioned values demonstrate that the sensitivity of the optimized actual to the stoichiometric molar ratio of air to $i_{threshold}$ is more than the other studied decision variables.

Comment [A106]: Related to the comment 3 from Reviewer 1

Comment [A107]: Related to the comment 3 from Reviewer 1

Comment [A108]: Related to the comment 3 from Reviewer 1

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Comment [A110]: Related to the comment 3 from Reviewer 1

Comment [A111]: Related to the comment 14 from Reviewer 1

Comment [A112]: Related to the comment from Reviewer 3

Comment [A113]: Related to the comment 3 from Reviewer 1

Comment [A114]: Related to the comment from Reviewer 3

Comment [A115]: Related to the comment from Reviewer 3

Comment [A116]: Related to the comment from Reviewer 3

Comment [A117]: Related to the comment 3 from Reviewer 1

4.1.1.5. Humidity of the anode and cathode

Comment [A118]: Related to the comment from Reviewer 3

Based on the obtained results, it is found that the optimization algorithm prefers to select almost equal humidity values in anode and cathode parts in all of the applications and values of $i_{threshold}$. As a result, the trends of variation of for both decision variables, which are presented in Fig. (1e) and Fig. (1f), are the same. In lower values of $i_{threshold}$ the optimized humidity values of for the propulsion usage are less than the two other ones, but in higher values (more than 1.5 A.cm^{-2}), the values optimum humidity content for all the applications approaches to a constant value. From the beginning to the end of the range for propulsion, power station, and portable applications almost 13.5, 4.0, and 4.5% changes are observed, respectively. For these two decision variables, the optimum values increase since, increasing the humidity content in both cathode and anode parts means a faster reaction rate, which is accompanied by a better PEMFC performance.

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Comment [A120]: Related to the comment from Reviewer 3

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4.1.1.6. Voltage

In contrast to all of the previously studied decision variables, the optimum voltage remains constant in the whole investigated range as it is illustrated in Fig. (1g). The optimized values of voltage for propulsion, power station, and portable applications are 0.78, 0.88, and 0.73 V, respectively. Therefore, it is concluded that for all the applications, the optimum voltage does not depend on the value of the maximum current density.

Comment [A124]: Related to the comment 3 from Reviewer 1

4.1.2. **The objective functions**

After examining investigation the effect of $i_{threshold}$ on the optimum values of decision variables, the impacts of this parameter on the optimum values of the objective functions are studied in this part.it is interesting to investigate how it affects the optimum values of objective functions, which are the far more important than decision variables.

Comment [A125]: Related to the comment from Reviewer 3

Comment [A126]: Related to the comment from Reviewer 3

4.1.2.1. Efficiency

Based on the points discussed in part 4.1.1, when $i_{threshold}$ gets higher, the reaction happens in a better way and a higher fraction of the available reactants at the interface between ~~GDL~~gas diffusion layer and catalyst layer is consumed. Therefore, -the efficiency is improved. As it is depicted in Fig. (2a), a moderate change in the optimum efficiency takes place when the maximum allowable current density goes up.

In $i_{threshold}$ of 1.1 A.cm^{-2}, the optimum efficiency for propulsion, power station, and portable applications are 61.57, 69.05, and 58.00% while for $i_{threshold}$ of 1.5 A.cm^{-2} the values reach ~~to~~ 62.61, 70.03, and 58.45%, respectively. It means that 1.04, 0.97, and 0.45% improvement is achieved.

4.1.2.2. The levelized cost

According to the points which have been discussed so far, by an increase in the value of $i_{threshold}$, the reaction takes place more properly, and consequently, the efficiency is enhanced. Enhancing the efficiency means that the generated electricity from a constant amount of fuel increases, and as a result, the price of the produced electricity and consequently, the levelized cost is improved as per Fig. (2b).~~According to Fig. (2b), an increment in the value of maximum allowable current density leads to a drop in the optimum levelized cost. This may be caused by a reason similar to the one that led to the increase in efficienecy. To be more precise, more electricity will be generated if the $i_{threshold}$ increases, mainly due to the higher reactant utilization. Consequently, more power is generated by a specific amount of reactants~~.

-For the portable application, the variation is almost linear. However, in the two other cases the levelized cost approaches ~~to~~ a constant value around ~~the~~ $i_{threshold}$ of 1.3 A.cm^{-2}. Another point is that the improvement ~~of~~ in the optimum levelized cost in the propulsion usage is more

Comment [A127]: Related to the comment 14 from Reviewer 1

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significant than the others. By changing $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}, 7.10% decline is achieved in propulsion usage ~~while~~ whereas, the values for power station~~,~~ and portable applications are almost half ~~as high as that of propulsion~~.

4.1.2.3. Size

By the increase in the maximum allowable current density, the optimum efficiency is enhanced as discussed in the previous parts. In this way, the magnitude of the power density of the PEMFC is also improved and therefore, the optimum size has a downward trend as per Fig. (2c).

~~The more $i_{threshold}$ is, the less optimum size is obtained. It is obvious that higher power densities can be achieved if $i_{threshold}$ goes up and up. It should be mentioned that the technological constraints limits $i_{threshold}$ and more it is, the better.~~ The trend of variation shown in Fig. (2c) demonstrates that when $i_{threshold}$ is 1.1 A.cm^{-2}, the optimum size ~~of~~ in the propulsion application is more than the portable usage, but at~~in~~ the higher values of $i_{threshold}$ (i.e. 1.2 A.cm^{-2}), the ~~figure~~ curve for the portable usage overtakes that of propulsion. This behavior is the same as the changes in the levelized cost.

Moreover, in this case, the values for both propulsion and power station applications approach ~~to a~~ constant values after the $i_{threshold}$ of 1.3 A.cm^{-2}, which is another similarity of the variation trend of the optimum size to the optimum levelized cost. However, in contrast to the levelized cost, because of the priority levels discussed before, here, the values for portable application is better than the power station usage. Almost huge improvements in the size of the optimized PEMFC are obtained by changing the value of $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}. 23.47, 10.89, and 13.35% reduction~~ing~~ in the size for propulsion, power station, and portable applications

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Comment [A136]: Related to the comment 3 from Reviewer 1

Comment [A137]: Related to the comment from Reviewer 3

Comment [A138]: Related to the comment from Reviewer 3

Comment [A139]: Related to the comment from Reviewer 3

Comment [A140]: Related to the comment from Reviewer 3

Comment [A141]: Related to the comment from Reviewer 3

Comment [A142]: Related to the comment 3 from Reviewer 1

show~~s~~ that the size of PEMFC in the optimum condition is the most sensitive objective function to changes of $i_{threshold}$.

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4.1.2.4. The produced green-house generation (GHG)

As Fig. (2d) shows, increasing the maximum allowable current density is accompanied by a fall in the optimum value of GHG for all the three investigated applications. However, GHG is the least sensitive objective function to changes in $i_{threshold}$. The variation rate of GHG is so gentle that only 0.71, 0.98, and 0.81% decrease~~ment~~ is observed for propulsion, power station, and portable applications, respectively.

Comment [A144]: Related to the comment from Reviewer 3

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4.2. Selection of the best maximum allowable current density for different applications

As it was investigated in section 4.1 increasing the maximum allowable current density not only reduces the operating temperature and pressure but also improves the optimized values of all ~~of~~ the objective functions simultaneously. The conducted sensitivity analyses demonstrated that for the propulsion and power station applications, increasing $i_{threshold}$ to more than 1.3 $A.cm^{-2}$ does not change the optimized results significantly. Therefore, considering technical aspects, for these two applications, the value of 1.3 $A.cm^{-2}$ is selected for $i_{threshold}$. Moreover, based on the obtained results from the sensitivity analyses, the upper considered limit for $i_{threshold}$, i.e., 1.5 $A.cm^{-2}$ is recommended for the portable usage.

Comment [A146]: Related to the comment 15 from Reviewer 1

4.3. Evaluation of the potential of improvement

In addition to the suggested variation range for the decision variables, which was previously indicated in Table (3), in ~~the reference~~ (Piela et al., 2017), for each decision variable, a recommended value was also introduced in each application. Considering those values as the values of decision variables in the base-case conditions, the condition before optimizations, and

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Comment [A148]: Related to the comment from Reviewer 3

Comment [A149]: Related to the comment from Reviewer 3 the selected values for $i_{threshold}$ in the section 4.2, in this part, the improvement potential of the proposed approach for three different applications are evaluated. Values of the objective functions of the base-case and the optimum conditions are compared together in Fig. (3a) to Fig. (3d). In addition, in these figures, the values of the objective function when the ordinary TOPSIS (the same weight for all the objectives) was employed are also compared. As it is clear, TOPSIS gives the same optimized answer for all the three investigated applications.

Comment [A150]: Related to the comment 13 from Reviewer 1

Evaluation of the The results shows that in some cases, like temperature and pressure in power station application as well as the voltage for all of the applications, the values of decision variables of the base-case and the optimum conditions are close together. However, for other casesdecision variables, the values are different. Moreover, for both propulsion and portable applications, the values of the optimum pressures are much smallerless than the base-case (recommended) values, which means that implementation of the optimization results leads to an operation condition with more level of safety. In addition to pressure, the temperature decreases significantly in propulsion application; it reaches from 353.15 to 318.88 K. The resulted temperature reduction (34.27 K) is also a great achievement.

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Comparison of the results with the selection of TOPSIS also shows that for all the three applications, the employed judgement-weighted method offers a better optimized levelized cost, size, and GHG. However, for the efficiency and GHG, TOPSIS has only a better optimized value compared to the employed judgment-weighted approach in the portable application. Nevertheless, in general, and considering improvement in the objective functions together, it is concluded that the employed judgement-weighted method provides better optimized conditions for all the three investigated applications.

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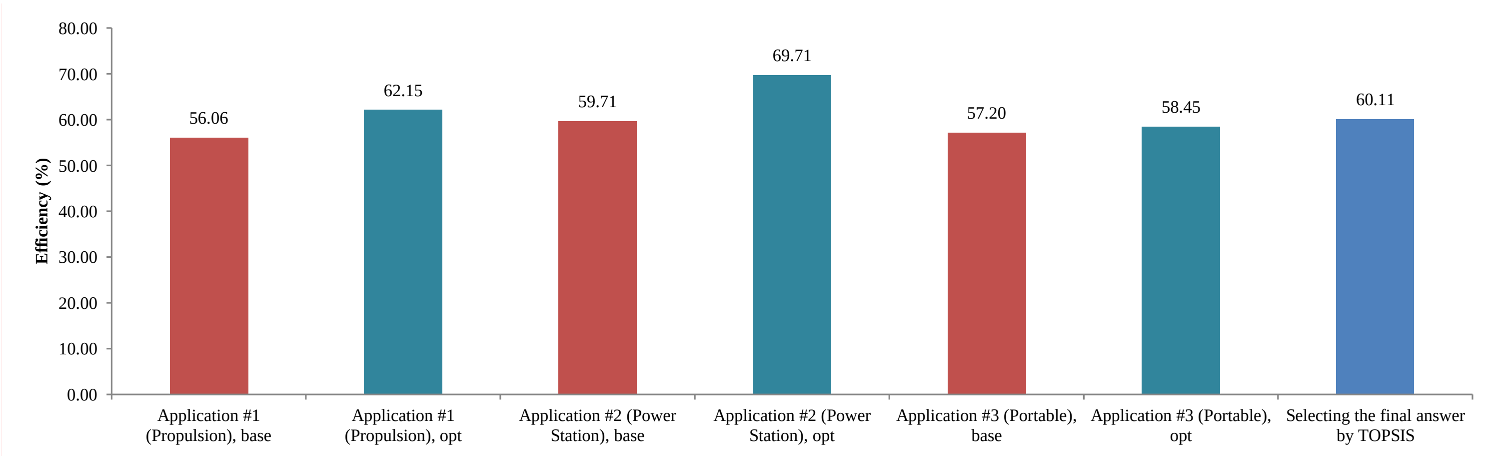
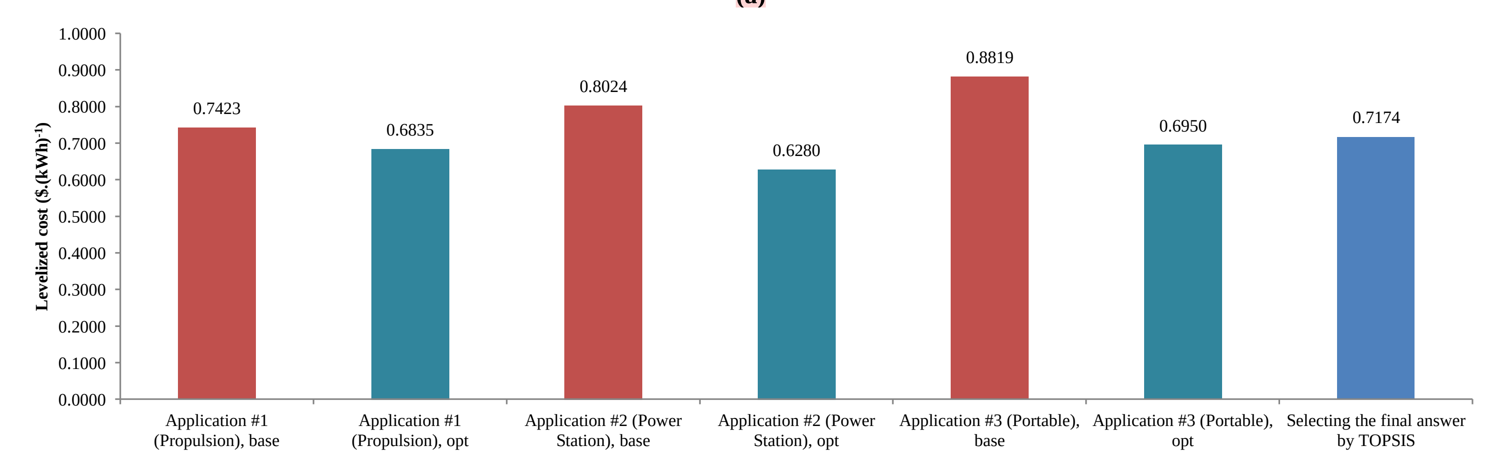


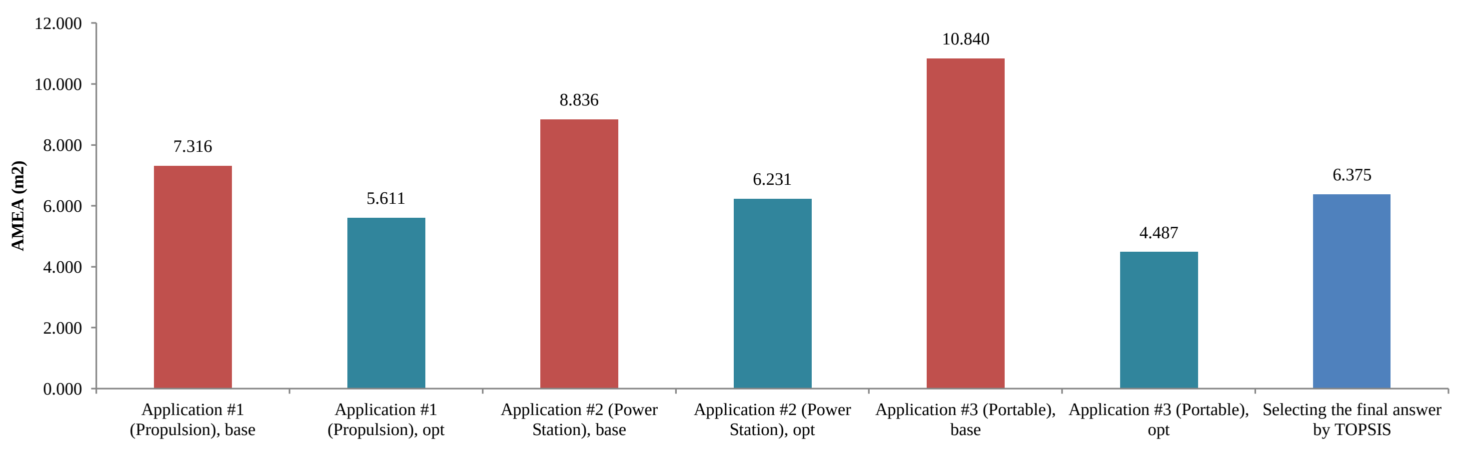
Efficiency (%)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
56.06
62.15
59.71
69.71
57.20
58.45
60.11
Application #1 (Propulsion), base
Application #1 (Propulsion), opt
Application #2 (Power Station), base
Application #2 (Power Station), opt
Application #3 (Portable), base
Application #3 (Portable), opt
Selecting the final answer by TOPSIS

(a)

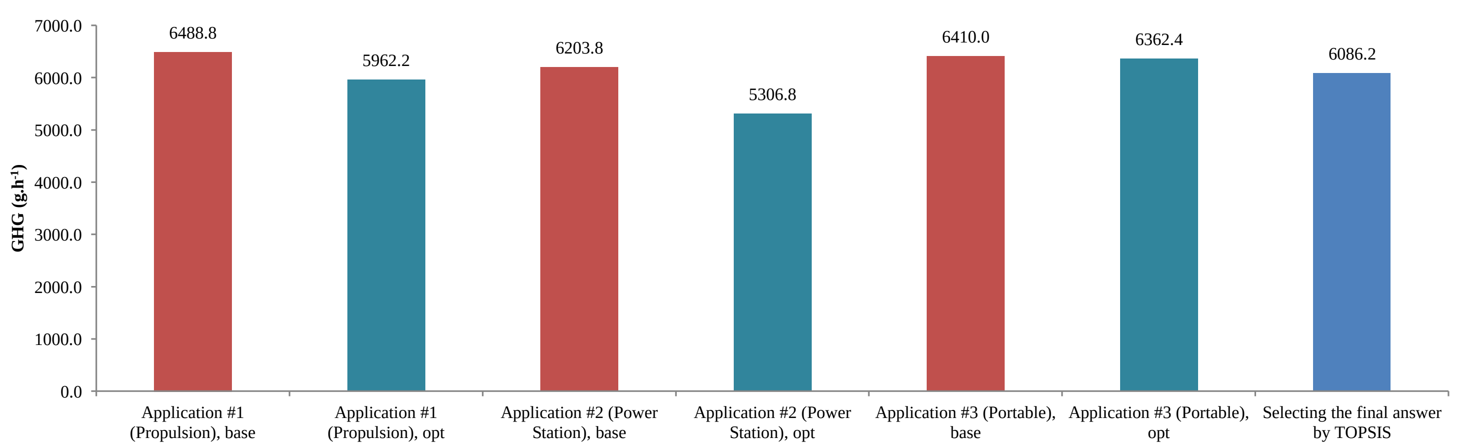


Levelized cost ($.(kWh)-1)
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
0.7423
0.6835
0.8024
0.6280
0.8819
0.6950
0.7174
Application #1 (Propulsion), base
Application #1 (Propulsion), opt
Application #2 (Power Station), base
Application #2 (Power Station), opt
Application #3 (Portable), base
Application #3 (Portable), opt
Selecting the final answer by TOPSIS

(b)



(c)



(d)

Fig. (3): Comparison of the values of objective functions of the base case and the final optimum conditions for different applications (a) efficiency; (b) levelized cost; (c) area of membrane electron assembly (A_{MEA}); (d) GHG. In these figures, the selection of TOPSIS, in which the same weight for all the objective functions are considered, is also compared.

Comment [A156]: Related to the comment 13 from Reviewer 1

According to the values reported in Figs (4a) to (4d), it is observed that big improvements in the values of objective functions are obtained through ~~implementation of~~ the proposed multi-objective optimization approach. On average, the efficiency, levelized cost, size, and GHG are improved 9.93, 16.95, 37.13, and 7.77%, respectively. Additionally, the power generation application has the highest potential of enhancement in the efficiency and levelized cost whilst the most significant decrease in size and GHG are seen for portable and propulsion applications, respectively. In power generation application, the efficiency reaches from 59.71 to 69.71% while the levelized cost drops from 0.8024 to 0.6280 $\$.(kWh)^{-1}$. Moreover, the size in the portable application falls from 10.840 to 4.487 $m^{2,}$ and GHG of propulsion application diminishes from 6488.8 to 5962.2 $g.h^{-1}$.

Comment [A157]: Related to the comment 15 from Reviewer 1

Although the impacts of the maximum allowable current density on the results of optimization has not been studied before the current study, in some references, it has been mentioned that this value changes the the optimum result, and the results of this study is found consistent with them. Moreover, in spite of the fact that all the key important performance aspects have not been considered at the same time in the multi-objective optimization before this study, a huge improvement in the values of the objective functions is achieved compared to the base-case condition, and it is also in agreement with the points mentioned about the ability of the multi-objective optimization to enhance the performance of energy systems (Sohani et al., 2019c).

Comment [A158]: Related to the comment 4 from Reviewer 2

5. Conclusions

A multi-objective optimization (MOO) approach for 50 kW PEMFC was conducted to improve the performance criteria of the technology in propulsion, stationary and portable applications. The final solution among the sets provided by POF, were determined using the combined AHP and TOPSIS, by which the relative importance was taken into account to achieve more practical solutions. Moreover, the impacts of variation of the maximum allowable current density ($i_{treshold}$) on the values of optimum decision variables and objective functions were also investigated. The main optimization achievements are outlined as follows:

- Sensitivity of the optimized actual to stoichiometric molar ratio of air to $i_{threshold}$ is more than the other studied decision variables whereas except $i_{threshold}$ of 1.1 A.cm^{-2} where the optimum actual to stoichiometric molar ratio of air is almost the same for three applications, an increment is recorded by increasing the $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}.
- In lower values of $i_{threshold}$ the optimized humidity values of propulsion usage are less than the two other ones, but in higher values (more than 1.5 A.cm^{-2}) the values for all the applications approach to a constant value. Increasing the $i_{threshold}$ has led to almost 13.5, 4.0 and 4.5% changes in for propulsion, power station and portable applications respectively.
- The optimized values of voltage for propulsion, power station and portable applications are 0.78, 0.88 and 0.73 V, respectively.
- Increasing the maximum allowable current density not only reduces the operating temperature and pressure, but also improves the optimized values of all of the objective functions simultaneously.
- Furthermore, it is found that values of the temperature, pressure and voltage in power station are not affected by optimization, whereas substantial decrease in both propulsion and portable applications have brought about more level of safety. Similarly, objective functions i.e., efficiency, levelized cost, size and GHG are averagely improved by 9.93, 16.95, 37.13, and 7.77% respectively.

Two items can be mentioned as the limitations of the conducted analysis:

- This study investigated proton exchange membrane fuel cell. It means that other types of fuel cell were not considered.
- Like other similar studies in which an approach is presented, a case study with a specified capacity was investigated.

In order to overcome the mentioned limitations, these solutions are suggested:

- The variation impacts of the maximum allowable current density on the optimum results are studied for the other types of fuel cells in a further work.
- The impact of size on the results of optimization is investigated in another work in the future. Here, using the objective functions which are not related to the capacity, such as specific or dimensionless performance criteria, would help to provide better insight.

Comment [A159]: Related to the comment 4 from Reviewer 2

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Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell

Ali Sohani [a1*], Shayan Naderi [a], Farschad Torabi [a], Hoseyn Sayyaadi [a], Yousef Golizadeh Akhlaghi [b], Xudong Zhao [b], Krishan Talukdar [c], Zafar Said [d]

[a] Faculty of Mechanical Engineering-Energy Division, K.N. Toosi University of Technology, P.O. Box: 19395-1999, No. 15-19, Pardis St., Mollasadra Ave., Vanak Sq., Tehran 1999 143344, Iran

[b] School of Engineering, University of Hull, HU6 7RX, UK

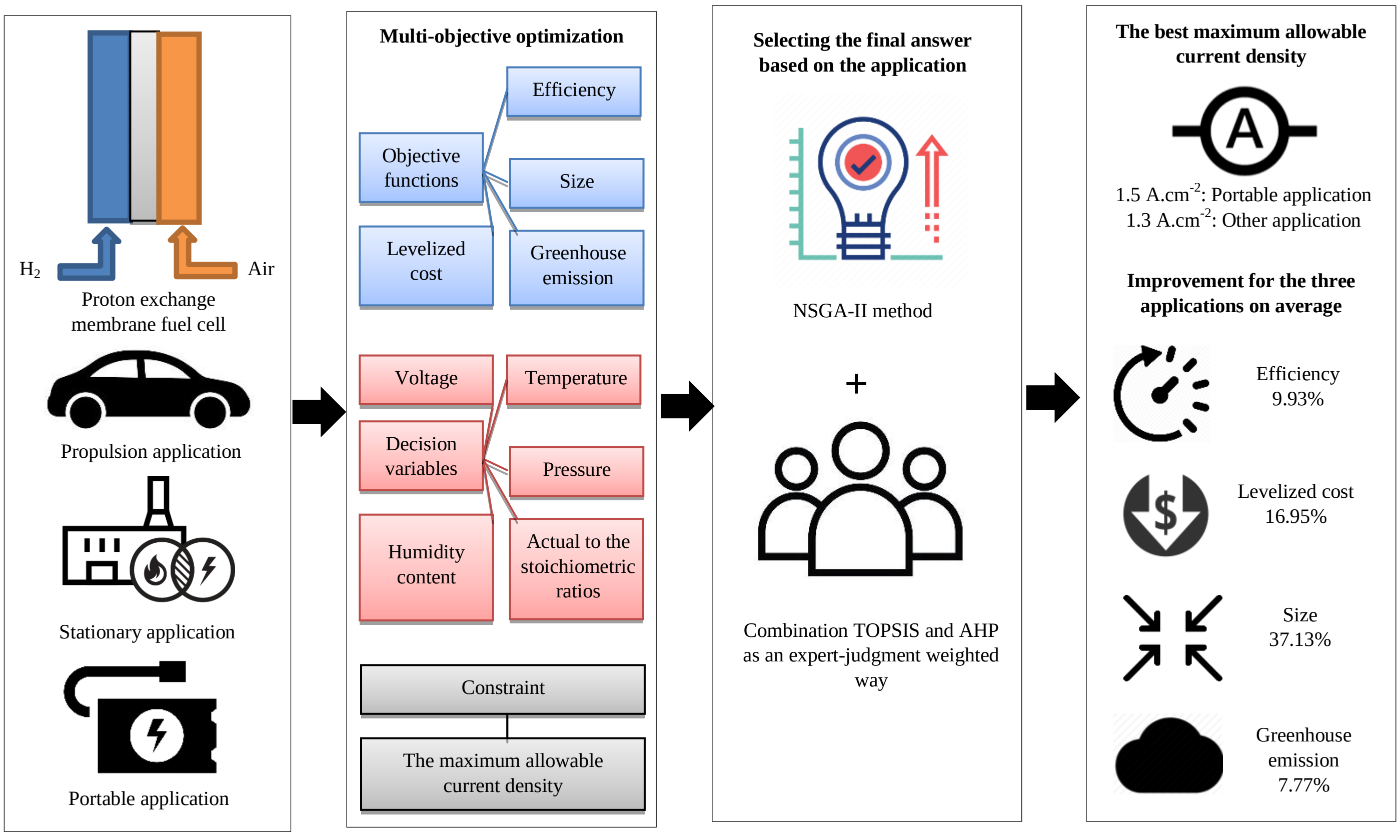
[c] German Aerospace Center (DLR), Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, Stuttgart, 70569, Germany

[d] Sustainable and Renewable Energy Engineering Department, University of Sharjah, PO Box, 27272, Sharjah, United Arab Emirates

*Corresponding author. Tel: +98 912 270 43 02
Email addresses: alisohany@yahoo.com, asohani@mail.kntu.ac.ir (Ali Sohani)

Graphical Abstract

Graphical abstract



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[b] School of Engineering, University of Hull, HU6 7RX, UK

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[d] Sustainable and Renewable Energy Engineering Department, University of Sharjah, PO Box, 27272, Sharjah, United Arab Emirates

Abstract

An application-based multi-objective optimization approach is presented to acquire the best operation condition for a proton-exchange membrane fuel cell. The optimization is done for propulsion, power station, and portable applications, in which the recommended range for decision variables and importance level of the objective functions are taken into consideration for more accurate and practical results. In the multi-objective optimization, from each important aspect of the performance, i.e., technical, economic, dimensional, and environmental aspects, one objective is selected. The effect of threshold current density on both optimum decision variables and objective functions are also investigated to find the best value for that. The results reveal that increasing the maximum allowable current density leads to improvements in optimized values of all the objective functions. Moreover, the conducted sensitivity analyses determine that the threshold current density for the propulsion and power station applications is 1.3 $A.cm^{-2}$ and for the portable application is 1.5 $A.cm^{-2}$. Furthermore, it is found that values of the temperature, pressure and voltage in power station are not affected by optimization, whereas substantial decrease in both propulsion and portable applications brings more level of safety. Similarly, objective functions, i.e., efficiency, levelized cost, size, and greenhouse emission are averagely improved by 9.93, 16.95, 37.13, and 7.77%,

*Corresponding author. Tel: +98 912 270 43 02
Email addresses: alisohany@yahoo.com, asohani@mail.kntu.ac.ir (Ali Sohani)

respectively. The proposed procedure helps to design and manufacture the high-performance proton-exchange membrane fuel cells based on the employed application and users' preference.

Keywords: *Application-based survey; Polymer electrolyte membrane fuel cell; Techno-economic investigation; Multi-objective optimization; Weighted decision making*

Nomenclature		W	power (kW)
A	area (m^2)	**Abbreviations**	
C	cost ($)	AHP	analytical hierarchy process
CI	closeness index	POF	Pareto optimal frontier
d	discount rate	*MEA*	membrane electrode assembly
dst_{j+}	distance to the ideal answer	*TOPSIS*	technique for order of preference by similarity to ideal solution
dst_{j-}	distance to the non-ideal answer	***Scripts***	
i	current density ($A.m^{-2}$)	*asm*	assembly
f	dimensionless objective function	*BOP*	balance of plant
F	objective function	*ele*	electrode
ghg	specific greenhouse gas emission ($g.(MJ)^{-1}$)	*inv*	investment
GHG	greenhouse gas emission ($g.h^{-1}$)	*mem*	membrane
HHV	higher heating value ($kJ.kg^{-1}$)	*opt*	optimum condition
huf	hydrogen utilization factor	*opr*	operation
LHV	lower heating value ($kJ.kg^{-1}$)	*phm*	peripheral materials
$LCOE$	levelized cost of electricity ($\$.(kWh)^{-1}$)	*pt*	platinum
$\dot{m}$	mass flow rate ($mol.s^{-1}$)	*st*	stack
$\dot{n}$	molar flow rate ($mol.s^{-1}$)	***Greek symbols***	
P	pressure (Pa)	η	efficiency (%)
t	time (s)	λ	actual to stoichiometric ratio
T	temperature (K)	ω	humidity ($kg.kg_{air}$ or $kg.kg_{H_2}$)
V	voltage (V)		

1. Introduction

Proton-exchange membrane type (PEMFC) is one of the most popular kinds of fuel cells. Working at a lower temperature and level of noise (Atyabi and Afshari, 2019), and producing electricity with greater power densities (Charoen et al., 2017) are taken into account as the most significant advantages of PEMFC in comparison to the other types. Moreover, this type of fuel cell is easy to handle and assemble (Haghighat Mamaghani et al., 2018; Shaygan et al., 2019). The mentioned advantages encourage a lot of researchers to conduct studies to enhance the performance of PEMFCs as a promising technology as far as possible (Chatrattanawet et al., 2017; İnci and Türksoy, 2019), since its high efficiency can be higher than other kinds of renewable energy technologies, such as wind (Naderi et al., 2018; Naderi and Torabi, 2017). The enhancement has been done by changing the structure (Duclos et al., 2017), using novel materials (Mehrpooya et al., 2019) or finding the best operating condition (Marefati and Mehrpooya, 2019).

In order to find the best operating condition, the values of performance criteria are improved by adjusting the effective parameters (Marefati and Mehrpooya, 2019; Nagapurkar and Smith, 2019). However, in PEMFCs, there is a trade-off among performance criteria (Ayodele et al., 2018; Bukar and Tan, 2019). For example, increasing efficiency as a favorable change is accompanied by an increase in the levelized cost of electricity (LCOE), which is unfavorable (Becherif et al., 2018; Chen et al., 2019). Therefore, performing single-objective optimizations like the study of Kanani et al. (Kanani et al., 2015) leads to partial results, and in order to acquire the best operating conditions, same as other energy systems (Sohani et al., 2019a; Sohani et al., 2018), multi-objective optimization (MOO) approach should be employed. A set of solutions, all of which has the potential of being the optimal answer, is obtained by running each MOO algorithm. The set is called Pareto optimal frontier (POF). Such optimization procedure has been implemented in many applications, from fuel cells (Sohani et al., 2019a), to thermal power plants (Sohani et al., 2017a), photovoltaic solar systems (Saedpanah et al., 2020), electrochemical systems (Pourmirzaagha et al., 2016), and management of micro grid (Jirdehi et al., 2017; Tabar et al., 2017). For instance, Sohrabi Tabar et al. (Tabar et al., 2017) solved the problem of micro grid management by the multi-objective optimization considering pollution and cost at the same time, and Ahmadi Jirdehi et al. (Jirdehi et al., 2017) found the best plan to run a micro grid system from both economic and environmental points of view by this approach. The studies (Tabar et al., 2019; Tabar et al., 2018) are some other examples of optimization in the field.

The model which is used to run the PEMFC is based on a single domain formulation (Sohani et al., 2019a; Um et al., 2000) that couples electrochemical governing equations with equations governing the fluid flow in the gas channels, gas diffusion layers, catalyst layers and electrolyte membrane. The positive aspect of this approach is that it solves the whole cell as a sandwich in a way that there is no need to generate new equations as boundary conditions (Esfahanian and Torabi, 2006; Esfahanian et al., 2008). It can be used for simulation of batteries as well (Torabi and Aliakbar, 2012; Torabi and Esfahanian, 2011). This model is utilized to run the simulation under different operating conditions as stated in (Sohani et al., 2019a), then stepwise regression method is used to extract an equation describing the performance of the FC. Although numerical methods have been used to solve the governing equations (Hosseinzadeh et al., 2019a; Seyedmohammad Mousavisani, 2019), analytical methods may be a good choice for future research (Hosseinzadeh et al., 2019b; Sohani et al., 2017b). In addition, all the necessary information about the data analysis of the employed models were given in the previous study of the authors conducted on PEMFC (Sohani et al., 2019a), and in order not to make paper too lengthy, it is referred for more details.

In order to provide a brief but clear insight, the studies have been done in the field of multi-objective optimization of PEM FCs are listed in Table (1).

Table (1): List of the studies done on the optimization of PEMFCs

Study	year	The considered objective	Were all technical,	Was the range of	Was a final	Was the

		functions	economic, dimensional, and environmental characteristics as the main performance criteria of a PEMFC optimized together?	variation of decision variables selected based on the recommended range for different applications?	optimal point introduced by considering the preference based on the application?	effect of maximum allowable current density on the optimum results studied?
(Wishart et al., 2006)	2006	Exergetic efficiency and net power	No	No	No	No
(Na and Gou, 2007)	2007	Efficiency and cost	No	No	No	No
(Ang, Sheila Mae C et al., 2010)	2010	Size and efficiency	No	No	No	No
(Sayyaadi and Esmaeilzadeh, 2013)	2013	Exergetic efficiency, power density and power cost	No	No	No	No
(Tahmasbi et al., 2015)	2015	Power and levelized cost	No	No	No	No
(Mert et al., 2015)	2015	Energy and exergy efficiencies, cost generation and power output	No	No	No	No
(Kanani et al., 2015)	2015	Power	No	No	No	No
(Mamaghani et al., 2016)	2016	Net electrical efficiency and total capital cost	No	No	No	No
(Chen et al., 2017)	2017	Efficiency and power output	No	No	No	No
(Mamaghani et al., 2017)	2017	Net electrical efficiency and thermal generation	No	No	No	No
(Liu et al., 2017)	2017	Output power and power consumption	No	No	No	No
(Chen et al., 2018)	2018	Exergy efficiency, annual cost and green house pollutant emission	No	No	No	No
(Kwan et al., 2018)	2018	Fuel consumption and required super capacitor size	No	No	No	No
(Ahmadi et al., 2018)	2018	Fuel consumption and efficiency	No	No	No	No
(Loreti et al., 2019)	2019	Cost of fuel and revenue	No	No	No	No
(Guo et al., 2019)	2019	energetic and exergetic performance characteristic as well as power density	No	No	No	No
(Sohani et al., 2019a)	2019	Efficiency, power density, levelized cost, and size	No	No	No	No
The current study	**2019**	**Efficiency, levelized cost, size and produced green-house generation**	**Yes**	**Yes**	**Yes**	**Yes**

Table (1) shows that despite valuable investigations have conducted so far; there have been some gaps that should be addressed by conducting a new study. As a result, the current study is conducted. The gap of the research and the items taken into account as the novelties of the present investigation are introduced in Table (2).

Table (2): Gap of the research and the items taken into account as the novelties of the present investigation

The gap of the research	The novelty of the current investigation
All the important criteria in the performance of a PEMFC have not been considered and optimized together. Therefore, the desired condition for the performance of the system from all the important perspectives has not been determined.	PEMFC is optimized by considering all important performance criteria at the same time. Efficiency, levelized cost, size, and greenhouse gas pollution are optimized as the technical, economic, dimensional and environmental objective functions through multi-objective optimization.
When optimization is done for more than one application, for all the investigated applications, the same variation range for a decision variable has been considered. It might have led to not realistic results and comparisons.	For each investigated application, namely, propulsion, power station, and portable applications, a separate range, based on the recommended range of (Piela et al., 2017) is defined. Therefore, the obtained results are more realistic and practical for the investigated application, and the comparisons among the results of optimization for different applications are more accurate.
In the previous studies either the final solution has not been determined (only POF has been drawn and discussed) or the selection has been done by using methods like the technique for Order of preference by similarity to ideal solution (TOPSIS), which consider the same priority level for all the objective functions. Considering the same priority level for different applications is not correct.	The importance level of different objective functions is taken into account by using a combination of analytical hierarchy process (AHP) and TOPSIS for the three studied applications. It leads to obtaining an application-based and practical optimized solution.
For the maximum allowable current density, a constant value has been assumed, and the optimization has been conducted with that. Therefore, the impacts of the maximum allowable current density on the optimum results have not been uncovered.	The effects of the maximum allowable current density on the results of optimization, including the values of the decision variables and objective functions are studied, and after discussing results in details, the best value for each application is determined.

As the existing theory, the optimum values of the operating parameters for a PEMFC is obtained from the recommended values or the multi-objective optimization approaches which have not considered all the performance criteria at the same time and have assumed the same priority level for the optimized objective functions. However, in this study, conducting the multi-objective optimization in which all the key factors including technical, economic, dimensional, and environmental aspects are taken into account is studied as the new theory. In addition, the new theory considers different levels of importance for the objective function based on the application. As a result, the proposed theory is a more practical and realistic one, and helps to design high-performance PEMFC more comprehensively and according to the users' preferences in different applications, in which the objective functions do not have the same level of priority. The following items are the implications of this paper:

- Designing a PEMFC is done by a systematic approach in which the best operating condition is determined in way that all the important performance criteria are in the best condition at the same time. It helps to have a PEMFC with the lowest possible cost and the highest performance at the same time, which is the theoretical implication of the conducted research.

- A method to obtain the best operating condition based on the application and users' preference is obtained. It can be taken into account as the methodological contribution of this study. It should be also noted that the proposed approach can be done for different capacities, countries, and applications.

- Not only can the designing process be done using the presented methodology, adjusting the operating conditions and as a result, retrofitting an in-operation PEMFC can be also performed by the proposed approach. Therefore, the methodology employed in this paper have the potential of being used in a wide range of products at different stages. This item can be considered as the practical implication of the current study.

- When a system has the best performance from different perspectives, including the technical, economic, and environmental aspects, policy-makers and end-users are encouraged more to use it (Sohani and Sayyaadi, 2020). Since the conducted investigation covers all the mentioned criteria in addition to the size as the other key factor and find the best possible condition for them, it will help to make PEMFC more popular all around the world. It is the social implication of this paper. The more popular clean technologies like PEMFC is used in the world, the better condition to live for human beings will be provided.

Considering the items indicated in Table (2), the following items are posed as the main research questions, which will be addressed in this study:

- How much improvement compared to the recommended values of (Piela et al., 2017) is achieved when the multi-objective optimization considering all the key performance criteria is done?
- How different the optimized solutions are when the importance level of objective functions in different application is considered?
- What are the difference between the condition the same priority levels for the objectives are assumed and the time the application-based method is implemented?
- How do the decision variables and objective functions change when the maximum allowable current density change?
- Does the maximum allowable current density have a great or small impact on the optimization results?

- What are the best recommended values for the maximum allowable current density?

In addition to the introduction presented above, the remaining part of the paper consists of four main sections. Section 2 in which the developed algorithm comprising MOO details, objective functions, and decision variables are introduced. Section 3 where the specifications of the investigated PEMFC and economic parameters are discussed. Section 3 is followed by the fourth section that is dedicated to results and discussion, and finally, the main contributions and key results are summarized in the conclusion, which is the fifth section of this study.

The final point which should be indicated in this part is based on the comprehensive conducted review on the green supply chain management system, journal of cleaner production is the most cited journal in this field and sustainability paradiagrams (de Oliveira et al., 2018), and based on the cited references and the topic, it is one of the best venues for publishing the paper.

2. Description of the presented application-based MOO approach

In this part, the presented approach is introduced step by step; for each step, a brief but complete explanation is given. More details about the background of the employed methods, which is beyond the scope of this study, are found in the cited references.

2.1. Step I: Definition of the multi-objective optimization problem

A multi-objective optimization problem is defined by introducing its decision variables, objective functions, and constraints.

2.1.1. **Decision variables**

Temperature, pressure, voltage, actual to stoichiometric molar ratios of air and hydrogen, and humidity of the cathode and anode, as seven main adjustable effective parameters of a PEMFC, are selected as the decision variables. The recommended range of decision variables for different applications is given in Table (3).

Table (3): The recommended range of decision variables for different applications (the considered bounds for the decision variables) (Piela et al., 2017)

Parameter	Symbol	Application #1 (Propulsion)	Application #2 (Power Station)	Application #3 (Portable)	Unit
		Application			
Temperature	T	283.15- 363.15	283.15- 363.15	283.15- 363.15	K
pressure	P	105000- 300000	105000- 200000	105000- 200000	Pa
voltage	V	Based on PEMFC's specifications	Based on PEMFC's specifications	Based on PEMFC's specifications	V
actual to stoichiometric molar ratio of air	λ_{air}	1.3- 2.0	1.1- 2.0	1.1- 2.0	-
actual to stoichiometric molar ratio of hydrogen	λ_{H_2}	1.1- 2.0	1.1- 2.0	1.1- 2.0	-
humidity of the anode (hydrogen)	ω_{air}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{air}^{-1}$
humidity of the cathode (air)	ω_{H_2}	0.10- 0.25	0.12- 0.25	0.13- 0.25	$kg.kg_{H_2}^{-1}$

It should be noted that in almost all the optimization problems in the reality, like here, the decision variables have their limits, as it is seen. However, in this study, following the same fashion as (Rao, 2019) and the optimization toolbox in MATLAB software (Higham and Higham, 2016; Moore, 2017), they are called as "bounds", and not "constraints". On the other hand, the limitations which are not the bounds are called the constraints. The constraints considered in this study are introduced in the section 2.1.3.

2.1.2. **Objective functions**

The performance criteria which are going to be improved by MOO are called objective functions. The desirable performance of a PEMFC is achieved when all the technical, economic, dimensional, and environmental performance characteristics are simultaneously at the best possible conditions, so from each of them, one objective function should be considered.

Therefore, one of the most widely-used functions for each mentioned aspect is selected and optimized as the objective function, which leads to having four objective functions. The considered objective functions are introduced in the following section. It should be noted that in order not to make the article so lengthy, the definitions of the symbols used in the equations are presented in the nomenclature, and they are not explained after each equation.

2.1.2.1. Technical objective function

PEMFC efficiency, which is defined as the ratio of the generated power to the enthalpy of reaction, which is the maximum available power in the ideal condition, is defined as the technical objective function (Mert et al., 2011):

$$\eta = \frac{W_{st}}{\dot{n}_{H_2} HHV_{H_2}} \tag{1}$$

2.1.2.2. Economic objective function

The levelized cost of electricity generation, briefly called the levelized cost, is considered as the economic objective function. The levelized cost is calculated as follows (Sohani et al., 2019a):

$$C_{levelized} = \frac{1}{\sum_{j=1}^{year} \sum_{t=0}^{t_{opr}} \frac{W_{st} t}{(1+d)^j}} \left[C_{inv} + \sum_{j=1}^{year} \sum_{t=0}^{t_{opr}} \frac{C_{fuel} t}{(1+d)^j} \right] \tag{2}$$

In Eq. (2), C_{fuel} and C_{inv} denote fuel and investment costs, which are determined by Eqs. (3) (Sohani et al., 2019a) and (4) (Na and Gou, 2007), respectively:

$$C_{fuel} = \frac{\dot{m}_{H_2} C_{H_2}}{huf} \tag{3}$$

$$C_{inv} = (C_{st} + C_{BOP})A + C_{asm}W_{st} \quad (4)$$

C_{st} in Eq. (4) is also calculated from Eq. (Na and Gou, 2007):

$$C_{st} = C_{mem} + C_{elc} + C_{bpp} + C_{pt} + C_{phm} \quad (5)$$

2.1.2.3. Dimensional objective function

The area of the membrane electrode assembly is selected as the dimensional objective function in the multi-objective optimization. It is computed by Eq. (6) (Ang, Sheila Mae C. et al., 2010):

$$A_{MEA} = \frac{W_{st}}{pow_{out}} \quad (6)$$

In which W_{st} is the power required in each application while pow_{out} is the multiplication of operational current density by the output voltage.

2.1.2.4. Environmental objective function

The process of consuming the fuel (hydrogen) in a PEMFC is with almost no emissions. However, the hydrogen production process is accompanied by polluting the environment. One of the processes, which is assumed as the way of providing hydrogen in this study, is water electrolysis employing wind energy. By using data indicated in Table (4), in which the values of specific environmental emissions of the hydrogen generation process (ghg) are given, the produced green-house generation (GHG) is obtained for this process (Chen et al., 2018):

$$GHG = \dot{m}_{H_2} \, LHV_{H_2} \, ghg \quad (7)$$

Table (4): The greenhouse emission comes from the hydrogen production process by water electrolysis employing wind energy (Chen et al., 2018)

Process	Specific Pollution level $(g.(MJ)^{-1})$
Power generation and water electrolysis	6.85
Hydrogen compression	13.7
Total (ghg)	20.55

197 In this study, GHG is considered as the environmental objective function.

198 2.1.3. **Constraints**

199 In the optimization problems, usually, there are one or more limitations, which should be
200 considered to obtain applicable results. They are called as the constraints. Here, the current
201 density limitation is the only imposed constraint. It states that the current density must be less
202 than a threshold value ($i_{threshold}$), whose mathematical form is:

$$i \leq i_{threshold} \quad (8)$$

203 As it will be completely discussed in the results and discussion part, MOO is done in different
204 values of $i_{threshold}$, and having performed a comprehensive analysis among the obtained results,
205 the best threshold current density for each application will be determined.

206 It is worth mentioning that as it was explained in the section 2.1.1, the limitation for the decision
207 variables are called "bounds" and the constraints cover other limitations.

208 **2.2. Step II: Performing MOO algorithm and obtaining POF**

209 The optimization problem has been completely defined in the previous step. Therefore, at this
210 stage, MOO is employed to find a set of solutions that has the potential of being the final answer,
211 called Pareto optimal frontier (POF). Non-dominant sorting genetic algorithm 2 (NSGA-II),
212 which was completely introduced and employed in the previous publications of the authors like
213 (Sohani and Sayyaadi, 2017; Sohani et al., 2019b), is employed for this purpose. NSGA-II is one

of the widely-used methods to find POF. It should be also noted that MATLAB software was used to conduct the NSGA-II and obtain POF.

2.3. Step III: Determination of the relative priority and selecting the final solution

As it was previously stated, running a multi-objective algorithm leads to obtaining a set of answers, called POF. It means that employing the MOO algorithm does not give the final solution individually, and the final answer must be selected using a decision making method. In this study, to avoid non-realistic results caused by assuming the same preference for all the performance criteria, AHP is used in combination with TOPSIS.

In the used combined method, initially, the relative level of importance for each criterion (objective function) in the selection of the final solution is obtained by pairwise comparison of criteria to each other. It is done by forming a matrix, called the matrix of pairwise comparisons (MPC) (Sohani et al., 2017a). The comparisons are done by the suggested scale of Saaty, which is presented in Table (5).

Table (5): the Suggested scale of Saaty used to make pairwise comparisons in the AHP method (Saaty, 1977)

Value	Description
1	Equal importance
3	Fairly higher importance
5	Higher importance
7	Much higher importance
9	Extremely higher importance
Even values between two odd mentioned ones (2, 4, 6, 8)	An importance level between the corresponding importance of the two odd values

After performing the pairwise comparisons by conducting the mathematical matrix operations discussed in details in (Boukhari et al., 2018), the relative level of importance of each criterion in the selection of the final answer is determined. The output for the i^{st} criterion is the weight w_i, 232 which is a numerical value between 0 and 1, and shows the relative importance degree of that criterion compared to the other criteria. Having determined the w_i values for the criteria involved in the decision making (which are objective functions), the closeness index (Cl) for each point on POF is calculated from Eqs. (9) to (12), and the answer with the highest Cl is selected as the final optimal solution (Karami and Sayyaadi, 2015):

$$f_{ij}^{n} = \frac{w_i \; F_{ij}}{\sqrt{\sum_{j=1}^{m} (w_i . F_{ij})^2}} \quad (9)$$

$$dst_{j+} = \sqrt{\sum_{j=1}^{num} (f_{ij} - f_i^{ideal})} \quad (10)$$

$$dst_{j-} = \sqrt{\sum_{j=1}^{num} (f_{ij} - f_i^{non-ideal})} \quad (11)$$

$$Cl = \frac{dst_{j-}}{dst_{j+} + dst_{j-}} \quad (12)$$

It should be also mentioned that, as it is clear from definition, in case the relative level of importance of criteria in comparison to each other becomes the same, the introduced combined method reduces to the ordinary TOPSIS (Sohani et al., 2016). The codes developed in MATLAB software was employed to run the decision making method and select the final answer by the introduced method.

3. The investigated case-study

Application of the proposed approach is shown by employing it for a PEMFC. Consequently, in this part, the specifications of the PEMFC considered as the case study are given. The PEMFC considered in this study, is the one which has been investigated in the previous studies of the authors like (Sohani et al., 2019a). In addition to the specifications, the priority level of the objective functions for the case study based on experts' judgments, which is necessary to obtain the final solution by the combination of AHP and TOPSIS, are also introduced. It should be noted that the priority level is totally dependent on the experts' points of view, and it might be different for other cases.

In addition, it is worth mentioning that, like other similar cases in energy systems, such as previous published studies of the authors (Sohani et al., 2019b), a general approach was presented. Since obtaining numerical values for the investigated criteria needs to have the values of the effective parameters, a case study had to be considered and the approach employed for it. As a result, for other case studies, the approach is applicable; the only difference is the values of the effective parameters, and consequently, the investigated criteria are not the same.

3.1. General specifications

Table (6) presents the specification of the investigated case study, which is a 50 kW PEMFC.

Table (6): The specifications of the 50 kW PEMFC considered as the case study

Parameter	Unit	Value
Thickness of air and hydrogen channels	mm	0.8
GDL thickness	mm	0.21
Catalyst layer thickness	mm	0.012
Membrane Thickness	mm	0.036
GDL porosity	-	0.5
Catalyst porosity	-	0.5
Membrane porosity	-	0.28
GDL and catalyst permeability	-	1e-12
Anode exchange coefficient	-	2
Cathode exchange coefficient	-	2

In (Sohani et al., 2019a), Eq. (13) was obtained by the stepwise regression method to predict the current density based on the values of the decision variables for the investigated PEMFC. This equation is also employed in this study.

$$
\begin{aligned}
i = & -569786.180 + 3848.163T - 0.23717P + 4194.37526\lambda_{H_2} + 20875.16491\lambda_{air} - 86756.03593\omega_{H_2} \\
& -449126.8480\omega_{air} - 37565.929V + 000808232TP - 8.81763T\lambda_{H_2} - 32.7289T\lambda_{air} \\
& +781.70708T\omega_{air} + 0.0099263P\lambda_{air} - 0.18041948P\omega_{air} + 0.00922283PV - 1438.71619215\lambda_{H_2}\omega_{air} \\
& -8649.784500005\lambda_{air}V + 43583.517723\omega_{H_2}V + 357377.647286\omega_{air}V - 5.964732329T^2 \\
& -247.4630933695\lambda_{H_2}{}^2 - 1250.538655\lambda_{air}{}^2 + 158078.948844\omega_{H_2}{}^2 - 52667.71773303V^2
\end{aligned}
\qquad (13)
$$

3.2. Economic details

Table (7) gives the data required to calculate LCOE as the economic objective function. The important point for economic data is they should be up to date (Sohani and Sayyaadi, 2018), and for this reason, the data indicated in Table (7) is compared to the online prices found in the references like (Fuel Cell Store, 2019). The comparison shows that there is a good agreement between the data and online information.

Table (7): The considered values for economic analysis (Sohani et al., 2019a)

Parameter	Unit	Value
Nafion membrane 117	$ m^{-2}	2455.56
Platinum; 2–4 thickness	$ m^{-2}	176.29
Electrode; max. 0.8 mm for single cell	$ m^{-2}	177
Bi-polar plate; max. 4 mm	$ m^{-2}	1650
Peripheral parts	$ m^{-2}	15.6
Assembly	$ (kW)$^{-1}$	391
Discount rate	%	6
Cost of hydrogen	$ kg^{-1}	1.00
Cost of the balance of plant to cost of stack ratio	-	0.5
Lifetime	years	15
Annual operating hours	hours	6150

As it is seen, all the used methods and employed equations were adopted from the published literature and they have been utilized in several researches in different fields. Therefore, each of them, and consequently, the combination of them are accurate and reliable. Moreover, considering the fact that only economic indicators such as discount rate are not the same in the two different countries, only the levelized cost will be different and studying in another country does not have any impacts on the values of the other performance criteria in the same condition for the effective parameters. For the levelized cost, however, it should be also noted that in spite of having different values in two different countries, the variation trend is almost similar.

3.3. Relative importance of performance criteria

As discussed previously, in order to select the final solution among the points on POF by using the combined AHP and TOPSIS, the relative importance of performance criteria (objective functions) must be determined. Consequently, three experts involved in decision making done in (Sohani et al., 2019a) for PEMFCs were invited again, and they were asked to make the pairwise comparisons for three applications. The results are reported in this sub-section while the matrices of pairwise comparisons are reported in the supplementary material (Tables (S1) to (S3)). It should be noted that, as it was completely discussed in (Hasani Balyani et al., 2015; Sohani et al., 2017a), in cases that the experts have different judgments, the geometric mean is used to obtain the final evaluation.

3.3.1. **Application #1: Propulsion**

For this application, three experts have the following judgments about the performance criteria:

Judgement #1: According to this judgment, size and GHG have the highest level of importance. Then, efficiency and LCOE are in the next places, respectively.

Judgement #2: This judgment says that size and GHG are more important than efficiency and LCOE. However, in this case, efficiency and LCOE are as important as each other.

Judgement #3: Based on judgment #3, GHG is more important than size. After that, efficiency and LCOE are in the third and fourth places, respectively, with the close level of priority.

3.3.2. Application #2: Power station

In spite of the propulsion, for the power station application, the three experts reached an agreement to evaluate performance criteria compared to each other. They believe that LCOE is the most important criterion. Next, there are efficiency and GHG with the same level of importance while size has the lowest level of priority among the objective functions.

3.3.3. Application #3: Portable

For this application, like the power station usage, all the three experts have the same judgments. According to this judgement, size has the highest level of priority here while GHG and efficiency are in the next places with a similar priority. LCOE has also a little bit lower importance than the two aforementioned performance criteria

3.3.4. The final weights

By using the matrices of pairwise comparison and as discussed in the previous section, the relative importance of performance criteria is obtained for the three application in form of w_i weights, which are introduced in Table (8). For obtaining the final weights from the matrix of pairwise comparison, Expert Choice software program (Choice, 1999) is used to do calculations.

Table (8): The relative importance of the performance criteria (objective functions) in the form of w_i weights

Performance criteria	Relative importance (w_i)		
	Application #1 (Propulsion)	**Application #2 (Power Station)**	**Application #3 (Portable)**
Efficiency	0.214	0.256	0.236
LCOE	0.201	0.306	0.206

Size	0.298	0.177	0.322
GHG	0.287	0.256	0.236

4. Results and discussion

After implementing the described optimization and decision making processes on the introduced PEMFC, the effect of threshold current density on the both decision variables and objective functions are investigated in this part.

4.1. The variation impactsof the maximum allowable current density on results of the multi-objective optimization

The proposed approach has been completely introduced so far. Furthermore, the improvement potential of the multi-objective optimization for different applications has been evaluated in details. Here, to bring more extensive insight, the variation impacts of the maximum allowable current density ($i_{threshold}$) on the optimum values of decision variables and objective functions are investigated. For this purpose, the introduced approach is employed to find the best operating conditions for the studied PEMFC at five different values for $i_{threshold}$, which are 1.1, 1.2, 1.3, 1.4, and 1.5 A.cm^{-2} and the results are employed to plot the graphs presented in the next subsections. The effects of variation of the maximum allowable current density ($i_{threshold}$) on the values of decision variables and objective functions in the optimum condition are shown in Fig. (1a) to Fig. (1g), and Fig. (2a) to Fig. (2d), respectively.

4.1.1. **The decision variables**

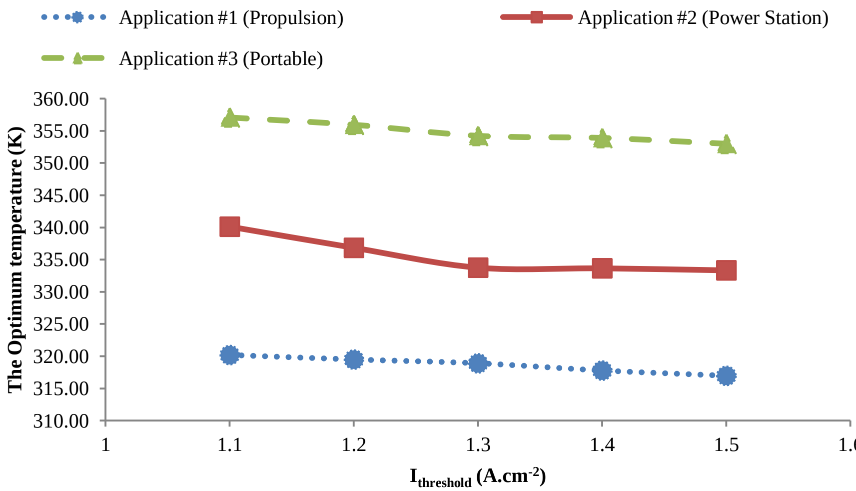
First of all, changes in each decision variable as a result of variation in the threshold current density are investigated.

4.1.1.1. Temperature

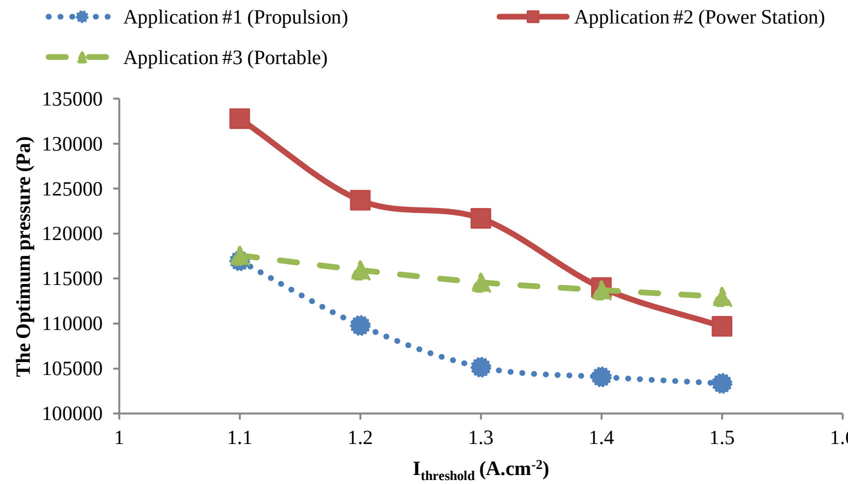
As it is seen in Fig. (1a), for all the three applications, increasing $i_{threshold}$ leads to decrease in the optimum temperature. The reason in when $i_{threshold}$ grows, the movement of the ions in the electrolyte membrane as well as the movement of the electrons in the solid phase and current collectors becomes easier. In other words, the internal resistance drops by increasing $i_{threshold}$. which leads to lower operating temperatures. In propulsion and portable applications, the slope of decrement remains constant. However for power station usage, the values approach the constant value of 333.5 K after the threshold current density of 1.3 $A.cm^{-2}$. Changing the value of $i_{threshold}$ from 1.1 to 1.5 $A.cm^{-2}$ is accompanied by only 1.01, 1.99, and 1.15% fall in the optimum temperature for propulsion, power station, and portable applications, respectively, which shows that the sensitivity of the optimum temperature to $i_{threshold}$ is low.

4.1.1.2. Pressure

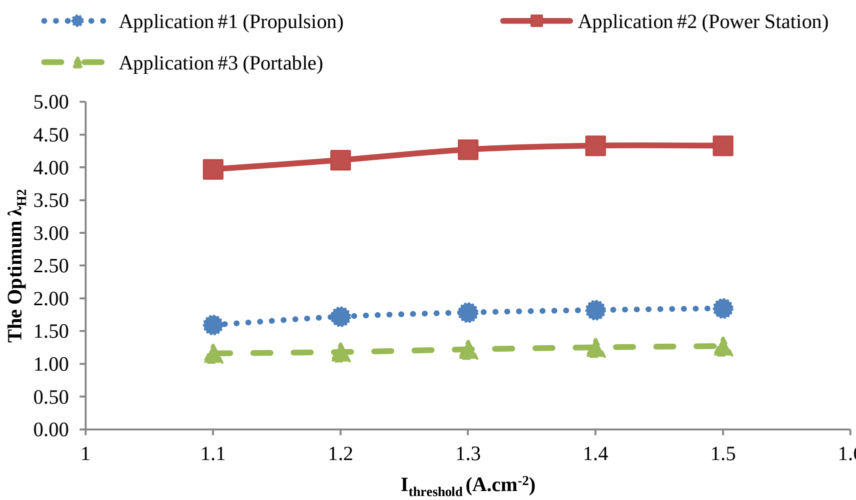
According to Fig. (1b), by an increase in $i_{threshold}$, the optimum pressure decreases in all the three applications. It is because the operating pressure directly affects the transport of the reactants to the reaction area (catalyst layer). When $i_{threshold}$ is low, the rate of reactions falls significantly, and the density of reactants becomes higher at the interface between the gas diffusion layer and the catalyst layer. As a result, in such conditions, i.e., low values for $i_{threshold}$, the optimum value for pressure has to increase to move the reactants to the reaction area in a proper way.


Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum temperature (K)
360.00
355.00
350.00
345.00
340.00
335.00
330.00
325.00
320.00
315.00
310.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

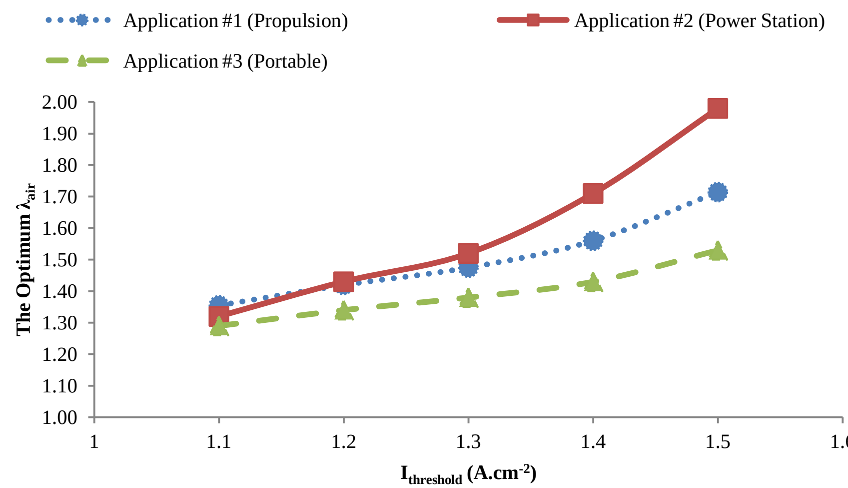
(a)


Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum pressure (Pa)
135000
130000
125000
120000
115000
110000
105000
100000
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

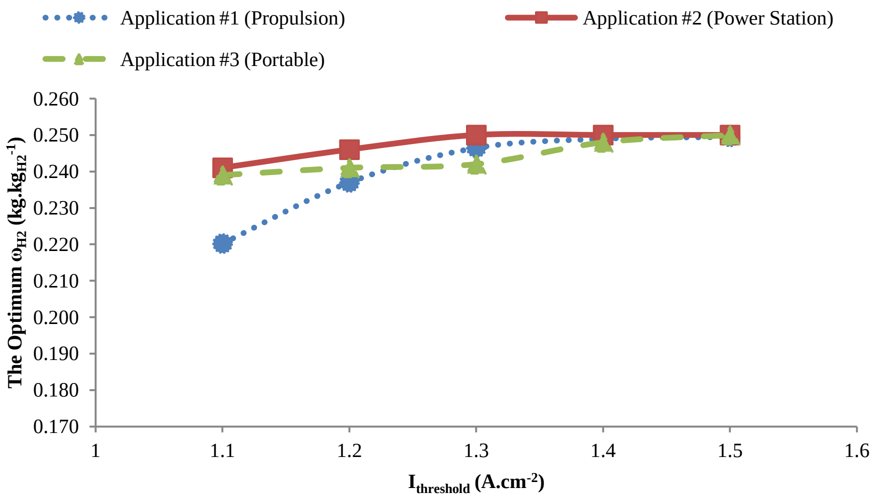
(b)


Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum λ_{H2}
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

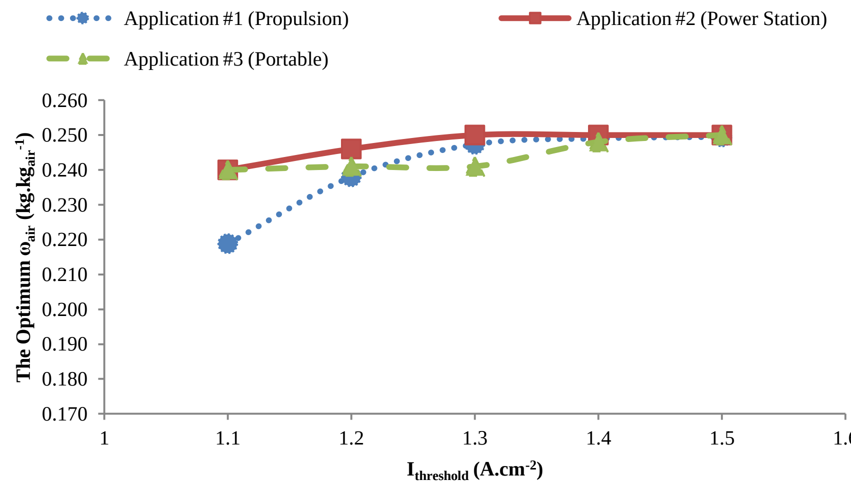
(c)


Application #1 (Propulsion)
Application #2 (Power Station)
Application #3 (Portable)
The Optimum λ_{air}
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
1
1.1
1.2
1.3
1.4
1.5
1.6
$I_{threshold}$ (A.cm^{-2})

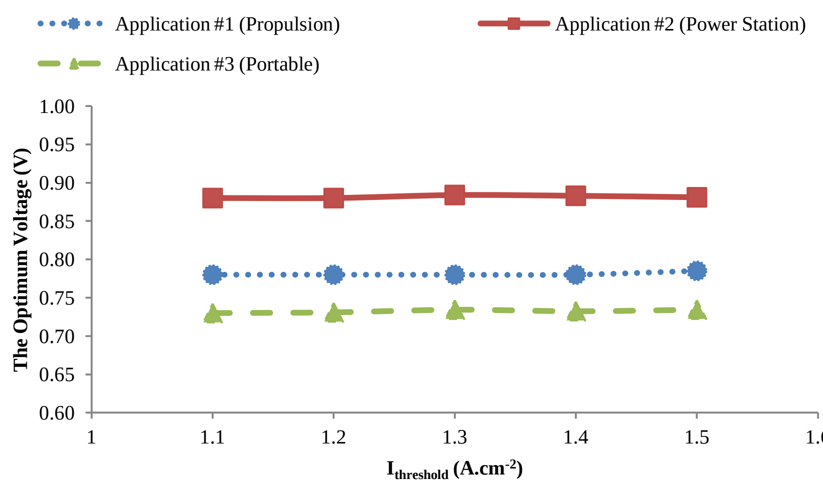
(d)



(e)



(f)



(g)

Fig. (1): The impacts of variation of the maximum allowable current density ($I_{threshold}$) on the values of decision variables in the optimum condition (a) temperature; (b) pressure; (c) actual to molar ratio of hydrogen; (d) actual to molar ratio of air; (e) humidity of anode; (f) humidity of cathode; (g) voltage

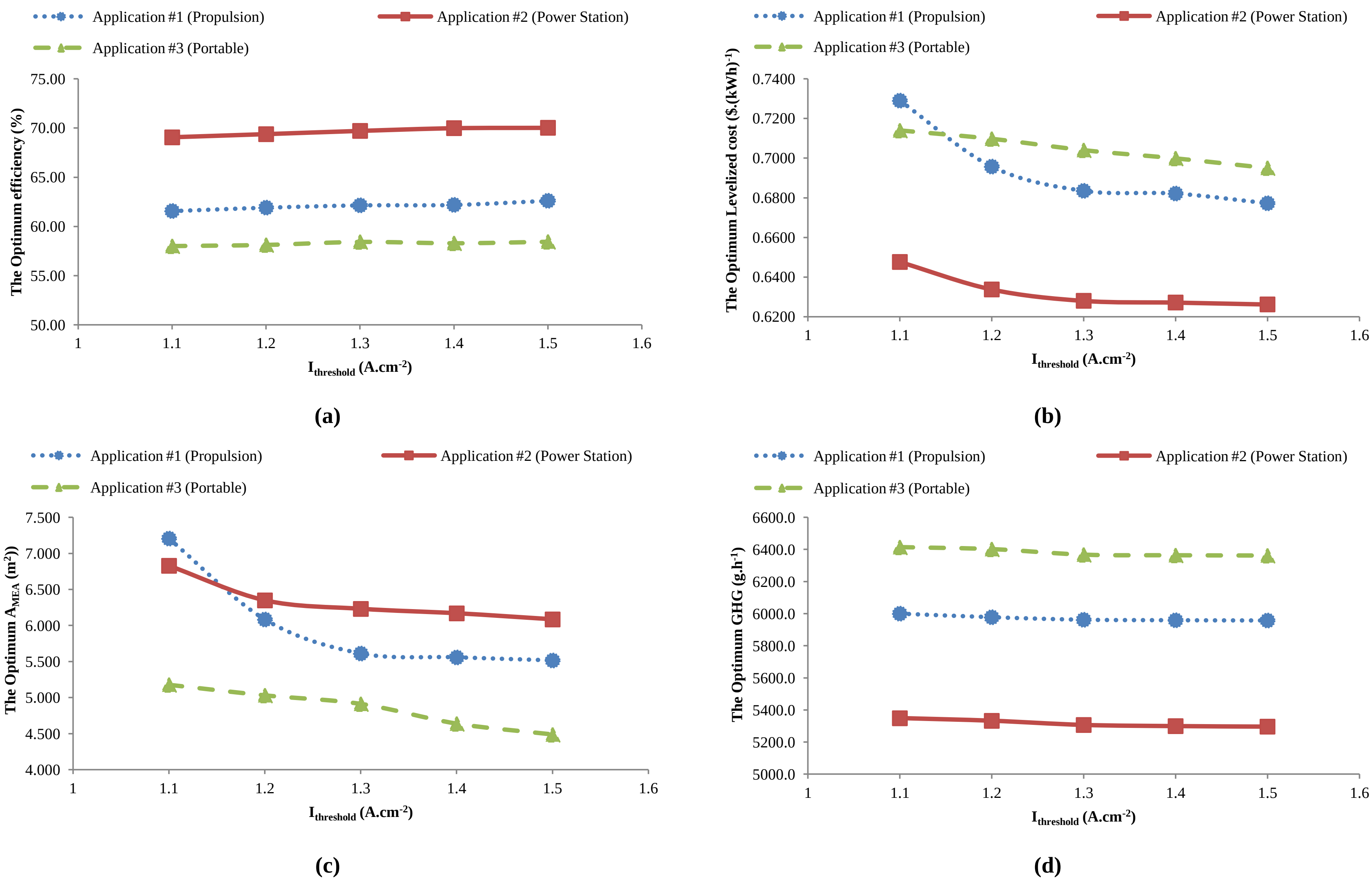


Fig. (2): The impacts of variation of the maximum allowable current density ($I_{threshold}$) on the values of objective functions in the optimum condition (a) efficiency; (b) levelized cost; (c) area of membrane electron assembly (A_{MEA}); (d) GHG

Nevertheless, the behaviors are not the same for different applications. In the portable application, the optimum pressure decreases linearly. In power station application first, it decreases fast, then, the decrement slope becomes slow, and after that, a moderate slope is observed. In the propulsion usage, the values approach the constant value of 113 kPa after the maximum allowable current of 1.3 A.cm^{-2}. In addition to the mentioned decrementing behavior, the sensitivity of the optimum pressure to $i_{threshold}$ is different for the three applications; in the case of propulsion, power station, and portable applications, reaching $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2} leads to 11.65, 17.39, and 3.88% decrease for the investigated application, respectively.

4.1.1.3. Actual to the stoichiometric molar ratio of hydrogen

In this case, as shown in Fig. (1c), the optimum value increases by the increase in $i_{threshold}$ in all the three applications. The reason is that, as discussed in the previous part, in lower values for $i_{threshold}$, the rate of reactions is low, and in order to make it as fast as possible, the actual to the stoichiometric molar ratio of the hydrogen increases. While the optimum actual to molar ratio of hydrogen approaches a constant value from 1.4 A.cm^{-2} in the power station application, for two other ones, it continuously grows. Here, like the optimum pressure, different levels of sensitivity to $i_{threshold}$ are observed for the three applications; 15.86, 9.07, and 9.48% changes in the propulsion, power station, and portable applications are observed, respectively.

4.1.1.4. Actual to the stoichiometric molar ratio of air

As Fig. (1d) shows, the optimum actual to the stoichiometric molar ratio of air has almost the same value for the three applications in $i_{threshold}$ of 1.1 A.cm^{-2}. However, when $i_{threshold}$ reaches 1.5 A.cm^{-2}, different values for this parameter are seen. Here, and like the stoichiometric molar ratio of hydrogen, the optimum value increases to make the rate of reactions as fast as possible.

The lowest increasing rate belongs to the portable application. Propulsion is in the middle and power station has the highest growth rate. In the case of power station application, the optimum values increase significantly in the higher levels of $i_{threshold}$ in comparison to the lower values. For this application, increasing $i_{threshold}$ from 1.2 to 1.3 A.cm^{-2} leads to an increase in the optimum ratio from 1.43 to 1.52 while by changing the maximum allowable current density from 1.4 to 1.5 A.cm^{-2}, the value of actual to stoichiometric molar ratio of air in the optimum condition reaches from 1.71 to 1.98. In addition to the power station application whose optimized ratio increases 50.00% from the beginning to the end of the range, propulsion and portable applications have also 26.50 and 18.60% increase between the mentioned range of $i_{threshold}$. The above-mentioned values demonstrate that the sensitivity of the optimized actual to the stoichiometric molar ratio of air to $i_{threshold}$ is more than the other studied decision variables.

4.1.1.5. Humidity of the anode and cathode

Based on the obtained results, it is found that the optimization algorithm prefers to select almost equal humidity values in anode and cathode parts in all the applications and values of $i_{threshold}$. As a result, the trends of variation for both decision variables, which are presented in Fig. (1e) and Fig. (1f), are the same. In lower values of $i_{threshold}$ the optimized humidity values for the propulsion usage are less than the two other ones, but in higher values (more than 1.5 A.cm^{-2}), the optimum humidity content for all the applications approaches a constant value. From the beginning to the end of the range for propulsion, power station, and portable applications almost 13.5, 4.0, and 4.5% changes are observed, respectively. For these two decision variables, the optimum values increase since, increasing the humidity content in both cathode and anode parts means a faster reaction rate, which is accompanied by a better PEMFC performance.

4.1.1.6. Voltage

In contrast to all the previously studied decision variables, the optimum voltage remains constant in the whole investigated range as it is illustrated in Fig. (1g). The optimized values of voltage for propulsion, power station, and portable applications are 0.78, 0.88, and 0.73 V, respectively. Therefore, it is concluded that for all the applications, the optimum voltage does not depend on the value of the maximum current density.

4.1.2. **The objective functions**

After investigation the effect of $i_{threshold}$ on the optimum values of decision variables, the impacts of this parameter on the optimum values of the objective functions are studied in this part.

4.1.2.1. Efficiency

Based on the points discussed in part 4.1.1, when $i_{threshold}$ gets higher, the reaction happens in a better way and a higher fraction of the available reactants at the interface between gas diffusion layer and catalyst layer is consumed. Therefore, the efficiency is improved. As it is depicted in Fig. (2a), a moderate change in the optimum efficiency takes place when the maximum allowable current density goes up.

In $i_{threshold}$ of 1.1 A.cm^{-2}, the optimum efficiency for propulsion, power station, and portable applications are 61.57, 69.05, and 58.00% while for $i_{threshold}$ of 1.5 A.cm^{-2} the values reach 62.61, 70.03, and 58.45%, respectively. It means that 1.04, 0.97, and 0.45% improvement is achieved.

4.1.2.2. The levelized cost

According to the points which have been discussed so far, by an increase in the value of $i_{threshold}$, the reaction takes place more properly, and consequently, the efficiency is enhanced. Enhancing the efficiency means that the generated electricity from a constant amount of fuel increases, and as a result, the price of the produced electricity and consequently, the levelized cost is improved as per Fig. (2b)..

For the portable application, the variation is almost linear. However, in the two other cases the levelized cost approaches a constant value around $i_{threshold}$ of 1.3 A.cm^{-2}. Another point is that the improvement in the optimum levelized cost in the propulsion usage is more significant than the others. By changing $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}, 7.10% decline is achieved in propulsion usage whereas, the values for power station and portable applications are almost half.

4.1.2.3. Size

By the increase in the maximum allowable current density, the optimum efficiency is enhanced as discussed in the previous parts. In this way, the magnitude of the power density of the PEMFC is also improved and therefore, the optimum size has a downward trend as per Fig. (2c).

The trend of variation shown in Fig. (2c) demonstrates that when $i_{threshold}$ is 1.1 A.cm^{-2}, the optimum size in the propulsion application is more than the portable usage, but at the higher values of $i_{threshold}$ (i.e. 1.2 A.cm^{-2}), the curve for the portable usage overtakes that of propulsion. This behavior is the same as the changes in the levelized cost.

Moreover, in this case, the values for both propulsion and power station applications approach constant values after the $i_{threshold}$ of 1.3 A.cm^{-2}, which is another similarity of the variation trend of the optimum size to the optimum levelized cost. However, in contrast to the levelized cost, because of the priority levels discussed before, here, the values for portable application is better than the power station usage. Almost huge improvements in the size of the optimized PEMFC are obtained by changing the value of $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}. 23.47, 10.89, and 13.35% reduction in the size for propulsion, power station, and portable applications show that the size of PEMFC in the optimum condition is the most sensitive objective function to changes of $i_{threshold}$.

4.1.2.4. The produced green-house generation (GHG)

As Fig. (2d) shows, increasing the maximum allowable current density is accompanied by a fall in the optimum value of GHG for all the three investigated applications. However, GHG is the least sensitive objective function to changes in $i_{threshold}$. The variation rate of GHG is so gentle that only 0.71, 0.98, and 0.81% decrease is observed for propulsion, power station, and portable applications, respectively.

4.2. Selection of the best maximum allowable current density for different applications

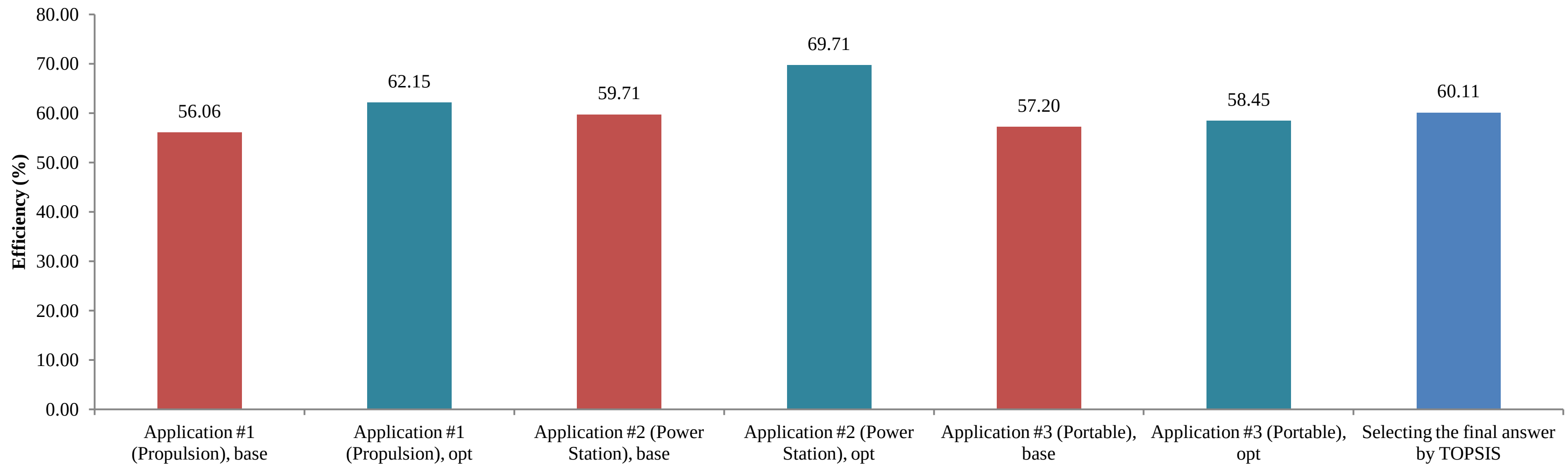
As it was investigated in section 4.1 increasing the maximum allowable current density not only reduces the operating temperature and pressure but also improves the optimized values of all the objective functions simultaneously. The conducted sensitivity analyses demonstrated that for the propulsion and power station applications, increasing $i_{threshold}$ to more than 1.3 A.cm^{-2} does not change the optimized results significantly. Therefore, considering technical aspects, for these two applications, the value of 1.3 A.cm^{-2} is selected for $i_{threshold}$. Moreover, based on the obtained results from the sensitivity analyses, the upper considered limit for $i_{threshold}$, i.e., 1.5 A.cm^{-2} is recommended for the portable usage.

4.3. Evaluation of the potential of improvement

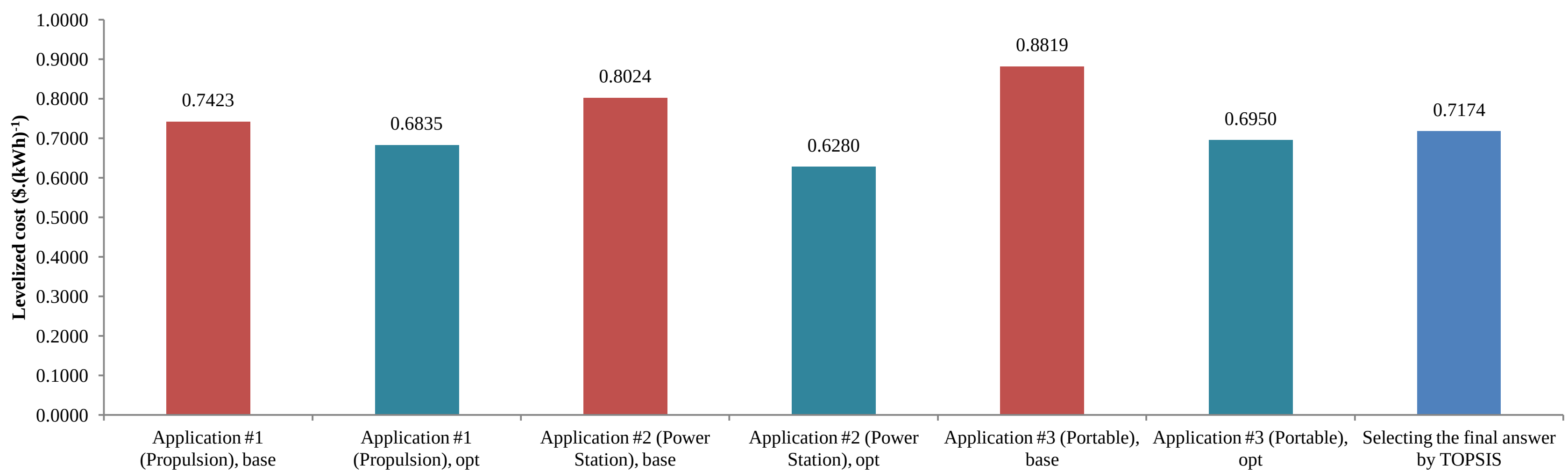
In addition to the suggested variation range for the decision variables, which was previously indicated in Table (3), in (Piela et al., 2017), for each decision variable, a recommended value was also introduced in each application. Considering those values as the values of decision variables in the base-case conditions, the condition before optimizations, and the selected values for $i_{threshold}$ in the section 4.2, in this part, the improvement potential of the proposed approach for three different applications are evaluated. Values of the objective functions of the base-case and the optimum conditions are compared together in Fig. (3a) to Fig. (3d). In addition, in these figures, the values of the objective function when the ordinary TOPSIS (the same weight for all the objectives) was employed are also compared. As it is clear, TOPSIS gives the same optimized answer for all the three investigated applications.

The results shows that in some cases, like temperature and pressure in power station application as well as the voltage for all the applications, the values of decision variables of the base-case and the optimum conditions are close together. However, for other decision variables, the values are different. Moreover, for both propulsion and portable applications, the values of the optimum pressure are much smaller than the base-case (recommended) values, which means that implementation of the optimization results leads to an operation condition with more level of safety. In addition to pressure, the temperature decreases significantly in propulsion application; it reaches from 353.15 to 318.88 K. The resulted temperature reduction (34.27 K) is also a great achievement.

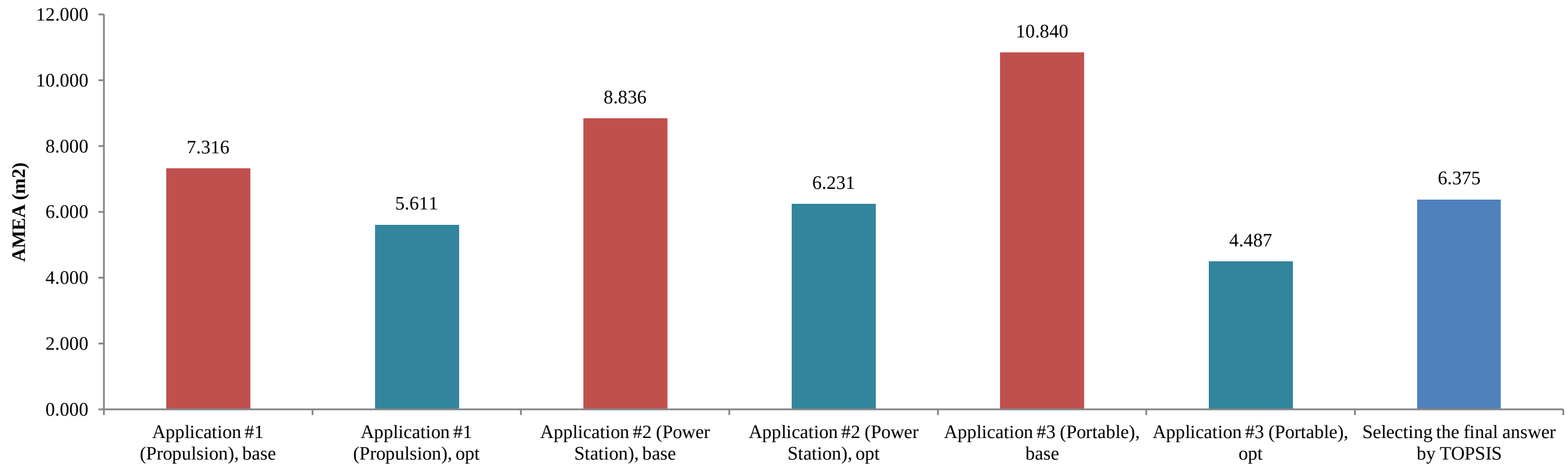
Comparison of the results with the selection of TOPSIS also shows that for all the three applications, the employed judgement-weighted method offers a better optimized levelized cost, size, and GHG. However, for the efficiency and GHG, TOPSIS has only a better optimized value compared to the employed judgment-weighted approach in the portable application. Nevertheless, in general, and considering improvement in the objective functions together, it is concluded that the employed judgement-weighted method provides better optimized conditions for all the three investigated applications.


Efficiency (%)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
56.06
62.15
59.71
69.71
57.20
58.45
60.11
Application #1 (Propulsion), base
Application #1 (Propulsion), opt
Application #2 (Power Station), base
Application #2 (Power Station), opt
Application #3 (Portable), base
Application #3 (Portable), opt
Selecting the final answer by TOPSIS

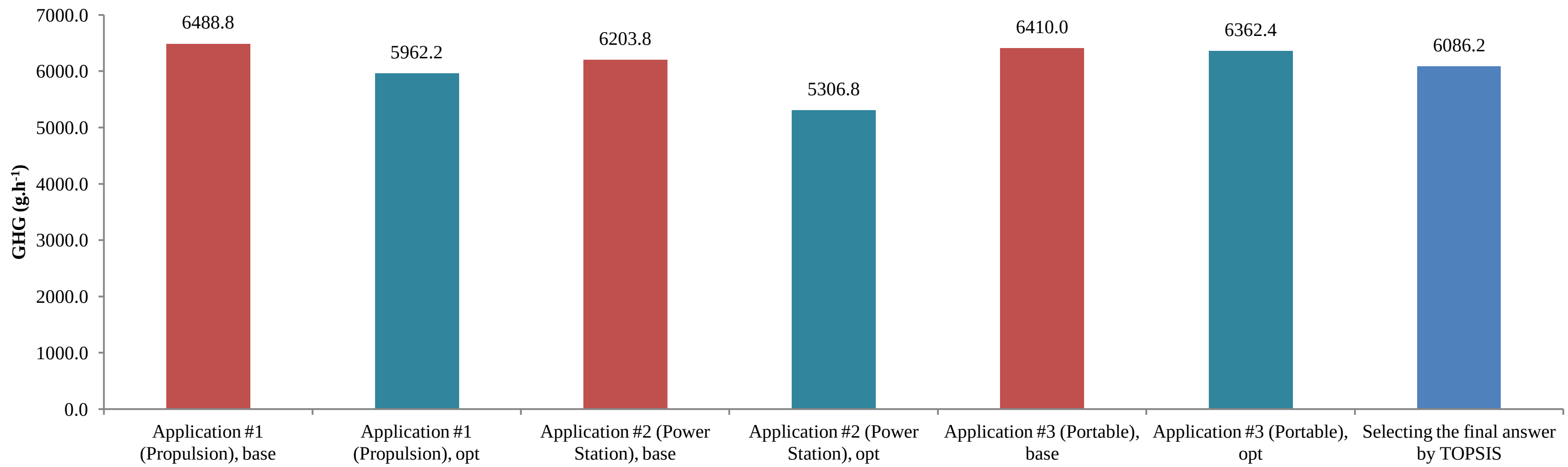
(a)


Levelized cost ($.(kWh)-1)
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
0.7423
0.6835
0.8024
0.6280
0.8819
0.6950
0.7174
Application #1 (Propulsion), base
Application #1 (Propulsion), opt
Application #2 (Power Station), base
Application #2 (Power Station), opt
Application #3 (Portable), base
Application #3 (Portable), opt
Selecting the final answer by TOPSIS

(b)



(c)



(d)

Fig. (3): Comparison of the values of objective functions of the base case and the final optimum conditions for different applications (a) efficiency; (b) levelized cost; (c) area of membrane electron assembly (A_{MEA}); (d) GHG. In these figures, the selection of TOPSIS, in which the same weight for all the objective functions are considered, is also compared.

According to the values reported in Figs (4a) to (4d), it is observed that big improvements in the values of objective functions are obtained through the proposed multi-objective optimization approach. On average, the efficiency, levelized cost, size, and GHG are improved 9.93, 16.95, 37.13, and 7.77%, respectively. Additionally, the power generation application has the highest potential of enhancement in the efficiency and levelized cost whilst the most significant decrease in size and GHG are seen for portable and propulsion applications, respectively. In power generation application, the efficiency reaches from 59.71 to 69.71% while the levelized cost drops from 0.8024 to 0.6280 $\$.(kWh)^{-1}$. Moreover, the size in the portable application falls from 10.840 to 4.487 $m^{2,}$ and GHG of propulsion application diminishes from 6488.8 to 5962.2 $g.h^{-1}$.

Although the impacts of the maximum allowable current density on the results of optimization has not been studied before the current study, in some references, it has been mentioned that this value changes the the optimum result, and the results of this study is found consistent with them. Moreover, in spite of the fact that all the key important performance aspects have not been considered at the same time in the multi-objective optimization before this study, a huge improvement in the values of the objective functions is achieved compared to the base-case condition, and it is also in agreement with the points mentioned about the ability of the multi-objective optimization to enhance the performance of energy systems (Sohani et al., 2019c).

5. Conclusions

A multi-objective optimization (MOO) approach for 50 kW PEMFC was conducted to improve the performance criteria of the technology in propulsion, stationary and portable applications. The final solution among the sets provided by POF, were determined using the combined AHP and TOPSIS, by which the relative importance was taken into account to achieve more practical solutions. Moreover, the impacts of variation of the maximum allowable current density ($i_{treshold}$) on the values of optimum decision variables and objective functions were also investigated. The main optimization achievements are outlined as follows:

- Sensitivity of the optimized actual to stoichiometric molar ratio of air to $i_{threshold}$ is more than the other studied decision variables whereas except $i_{threshold}$ of 1.1 A.cm^{-2} where the optimum actual to stoichiometric molar ratio of air is almost the same for three applications, an increment is recorded by increasing the $i_{threshold}$ from 1.1 to 1.5 A.cm^{-2}.
- In lower values of $i_{threshold}$ the optimized humidity values of propulsion usage are less than the two other ones, but in higher values (more than 1.5 A.cm^{-2}) the values for all the applications approach to a constant value. Increasing the $i_{threshold}$ has led to almost 13.5, 4.0 and 4.5% changes in for propulsion, power station and portable applications respectively.
- The optimized values of voltage for propulsion, power station and portable applications are 0.78, 0.88 and 0.73 V, respectively.
- Increasing the maximum allowable current density not only reduces the operating temperature and pressure, but also improves the optimized values of all of the objective functions simultaneously.
- Furthermore, it is found that values of the temperature, pressure and voltage in power station are not affected by optimization, whereas substantial decrease in both propulsion and portable applications have brought about more level of safety. Similarly, objective functions i.e., efficiency, levelized cost, size and GHG are averagely improved by 9.93, 16.95, 37.13, and 7.77% respectively.

Two items can be mentioned as the limitations of the conducted analysis:

- This study investigated proton exchange membrane fuel cell. It means that other types of fuel cell were not considered.
- Like other similar studies in which an approach is presented, a case study with a specified capacity was investigated.

In order to overcome the mentioned limitations, these solutions are suggested:

- The variation impacts of the maximum allowable current density on the optimum results are studied for the other types of fuel cells in a further work.
- The impact of size on the results of optimization is investigated in another work in the future. Here, using the objective functions which are not related to the capacity, such as specific or dimensionless performance criteria, would help to provide better insight.

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*Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

***Author Contributions Section**

In the following, the contribution of each author to the manuscript **JCLEPRO-D-19-13566R1** entitled **"Application Based Multi-Objective Performance Optimization of a Proton Exchange Membrane Fuel Cell"** is introduced:

Ali Sohani: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, and Project administration

Shayan Naderi: Methodology, Software, Investigation, and Writing - Review & Editing

Farschad Torabi: Conceptualization, Methodology, Writing - Review & Editing as well as Supervision

Hoesyn Sayyaadi: Conceptualization, Methodology, Writing - Review & Editing as well as Supervision

Yousef Golizadeh Akhlaghi: Conceptualization, Investigation, and Writing - Review & Editing

Xudong Zhao: Conceptualization and Writing - Review & Editing

Krishan Talukdar: Writing - Review & Editing

Zafar Said: Writing - Review & Editing

Please feel free and let me know in case you have any questions or queries.

Best Regards,

Ali Sohani

The corresponding author

Supplementary File

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