Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 11 Issue 6, June - 2024

Optimal Design Solution Selection for a Photovoltaic Pumped Hydroelectric Storage (PHES) System

Emmanuel Michael[1]

Department of Mechanical and Aerospace Engineering
University of Uyo, Nigeria
Email: enmichael234@gmail.com

Okon Aniekan Akpan[2]

Department of Mechanical and Aerospace Engineering
University of Uyo, Nigeria
Email: enmichael234@gmail.com

Anyanime Tim Umoette[2]
Department of Electrical and Electronic Engineering,
Akwa Ibom State University, Ikot Akpaden, Nigeria
libertycoast@yahoo.com

***Abstract*— In this study, design alternative considerations and optimal design solution selection for photovoltaic pumped hydroelectric storage (PHES) system is presented. Specifically, in this work, various designs of the PHES system are developed, and the best alternative is selected based on key factors such as: power transmission, material selection for manufacturing, ease of turbine maintenance and other critical parameters that contribute to achieving an optimal solution. To ensure the optimal design of the Pumped Hydro Energy Storage (PHES) system, the following factors are considered to enhance performance: safety, ergonomics, operational efficiency, manufacturing cost, maintainability, availability and reliability, ease of handling, working environment and noise reduction. By using the pairwise matrix method and Screening Pugh matrix method different design options were derived and analyzed and then scaled down to two options A and C which were subject to further assessment and weighted factor rating and ranking to identify the optimal solution with rank of 1 and the second best option with rank of 2. Generally, the results show that the alternative C has the highest overall score of 0.3657 which makes it the best option for the project and it is therefore given the rank of 1. On the other hand, alternative A has a lower overall score of 0.3391 than that of C which makes it the second best option for the project and it is therefore given the rank of 2. The ideas presented in this work are essential for selection of optimal design option for Pumped Hydro Energy Storage (PHES) system or related projects.**

Keywords*— Optimal Design Option Selection, Photovoltaic, Screening Pugh Matrix, Design Alternatives, Pairwise Matrix Method, Pumped Hydroelectric Storage

1. Introduction

Pumped water storage solar hydro power system is a system that can use solar power to pump water from a given source, store the water in a well-designed storage facility which upon release from the storage facility, the stored water drives a hydro turbine that generates the electrical energy that is fed to the load [1,2,3]. Essentially, the energy from the solar power segment is stored as pumped water in an upper reservoir which when released is converted to electrical energy by the hydro turbine [4,5]. In order to the achieve sequence of energy conversions entailed in the solar hydro power plant a number of design options are available and each option has it merits and demerits [6,7,8].

Accordingly, in this work, a number of different design options are considered for the pumped hydro energy storage (PHES) system and the optimal option that has good combination of energy efficiency and cost efficiency is determined using a number of design decision making models [9,10,11]. The study considered the different design stages and the components required at each of the stages. Careful selection of the design options ate each stage is key to the optimal design. As such, the study presents the details of the details of the optimal design selection procedure and the results when applied to the case study pumped water storage solar hydropower system.

2. Methodology

In this work the design alternative for photovoltaic pumped hydroelectric storage (PHES) **System** are considered and the best option is selected based on multi-criteria consideration and decision making. The design process of PHES **system** consists of several stages, beginning with conceptual development, where multiple design alternatives are explored to identify the optimal solution. Specifically, in this work, various designs of the PHES system are developed, and the best alternative is selected based on key factors such as: power transmission, material selection for manufacturing, ease of turbine maintenance and other critical parameters that contribute to achieving an optimal solution. To ensure the optimal design of the Pumped Hydro Energy Storage (PHES) system, the following factors are considered to enhance performance: safety, ergonomics, operational efficiency, manufacturing cost, maintainability, availability and reliability, ease of handling, working environment and noise reduction.

2.1 The Selection of Optimal Alternative for the Pumped Hydro Energy Storage (PHES) system

To determine the optimal design for the Pumped Hydro Energy Storage (PHES) system, the following key factors are prioritized during the selection process [12,13,14]:

A. **Production Cost:** The total cost is influenced by the nature of the turbine's mechanical components, material selection, size, shape, complexity, and the manufacturing processes involved. Cost-effectiveness remains a primary consideration, while still ensuring quality and functionality.

B. **Durability:** The turbine must reliably serve its intended purpose over an extended operational lifespan. The design should minimize the need for frequent maintenance.

C. **Capacity:** This considers the turbine's water discharge rate, operational efficiency, and the time required for effective power generation. The power output should be sufficient to meet consumer energy demands, significantly surpassing the capacity typically provided by battery-based photovoltaic systems.

D. **Maintainability:** The design should allow for easy access during inspection and repairs, and prioritize the use of standardized components to simplify part replacement. This ensures maintenance tasks can be performed efficiently and cost-effectively.

E. **Efficiency:** This evaluates how closely the turbine's actual power output approaches its theoretical maximum under the same input conditions. A higher efficiency indicates better energy conversion and reduced operational waste.

F. **Ergonomics:** This considers the design approach that minimizes injuries and difficulties, improve work efficiency, among other benefits. It also considered ease of operation of a machine.

G. **Safety:** The design must ensure safe operation for both the system operators and the turbine equipment. It should include fail-safes and protective measures to prevent accidents and equipment damage.

2.2 Determination of the weight factors using the pairwise matrix method

The weighting factors are determined for each of the seven key factors (listed as A, B, C, D, E, F and G are used in the pairwise matrix method [15,16,17]. First the pairwise criteria are identified as listed in Table 1 with the criteria key assigned to each of them. Then, the dominance count (D_k) is assigned using the pairwise matrix as shown in Table 2.

Table 1 The Pairwise Criteria Key

A	Production Cost
B	Durability
C	Capacity
D	Maintainability
E	Efficiency
F	Ergonomics
G	Safety

Table 2: The Dominance Count **Pairwise matrix method**

K	Design Criteria	A	B	C	D	E	F	G	Dominance Count (D_k)
1	Production Cost (A)	A	A	A	A	A	A	A	6
2	Durability (B)	A	B	C	D	B	F	G	1
3	Capacity (C)	A	C	C	C	C	C	G	4
4	Maintainability (D)	A	D	C	D	E	F	G	1
5	Efficiency (E)	A	B	C	E	E	E	G	2
6	Ergonomics (F)	A	F	C	F	E	F	G	2
7	Safety (G)	A	G	G	G	G	G	G	5

The unit weight, x is defined from the Dominance Count (D_k) and the total weight. Let the total weight (X_T) be 100 units. Then,

$$X_T = 100 \quad (1)$$

$$\sum_{k=1}^{k=7}\left(D_k(x)\right) = X_T = 100 \quad (2)$$

Based on the Dominance Count (D_k) values in table 2, we have;

$$D_1(x) + D_2(x) + D_3(x) + D_4(x) + D_5(x) + D_6(x) + D_7(x) = X_T = 100$$

$$(6)(x) + (1)(x) + (4)(x) + (1)(x) + (2)(x) + (2)(x) + (5)(x) = 100$$

$$21\,x = 100$$

$$x = \frac{100}{21} = 4.762$$

Determination of weight factor, (W_k) for each of the seven factors is determined as follows;

$$W_k = D_k\left(\frac{x}{X_T}\right) \quad (3)$$

Hence, the weighting factors are computed based on the available data as shown in Table 3.

Table 3: Determination of weight factor, (W_k) for each of the seven factors

K	Criteria	Dominance Count, D_k	Weight Factor, (W_k) computation	Weight Factor , (W_k)
1	Production cost	6	$(6)\left(\frac{4.762}{100}\right)$	0.028572
2	Durability	1	$(1)\left(\frac{4.762}{100}\right)$	0.004762
3	Capacity	4	$(4)\left(\frac{4.762}{100}\right)$	0.019048
4	Maintainability	1	$(1)\left(\frac{4.762}{100}\right)$	0.004762
5	Efficiency	2	$(2)\left(\frac{4.762}{100}\right)$	0.009524
6	Ergonomics	2	$(2)\left(\frac{4.762}{100}\right)$	0.009524
7	Safety	5	$(5)\left(\frac{4.762}{100}\right)$	0.02381

2.3 Determination of the design alternative

The most important factor in the design consideration is the production cost with dominance factor of 6. As stated earlier, the total cost of the project is influenced by the nature of the turbine's mechanical components, material selection, size, shape, complexity, and the manufacturing processes involved. Cost-effectiveness remains a primary consideration, while still ensuring quality and functionality. Therefore, the key factors that may affect the performance and cost of the turbine mechanism and hence the performance and cost of the entire project are used to determine the alternative solutions available for consideration , as shown in Figure 1 and Figure 2. The set of combinations of functions (based on Figure 1) which are considered in the selection of the best alternative option is presented in Figure 2.

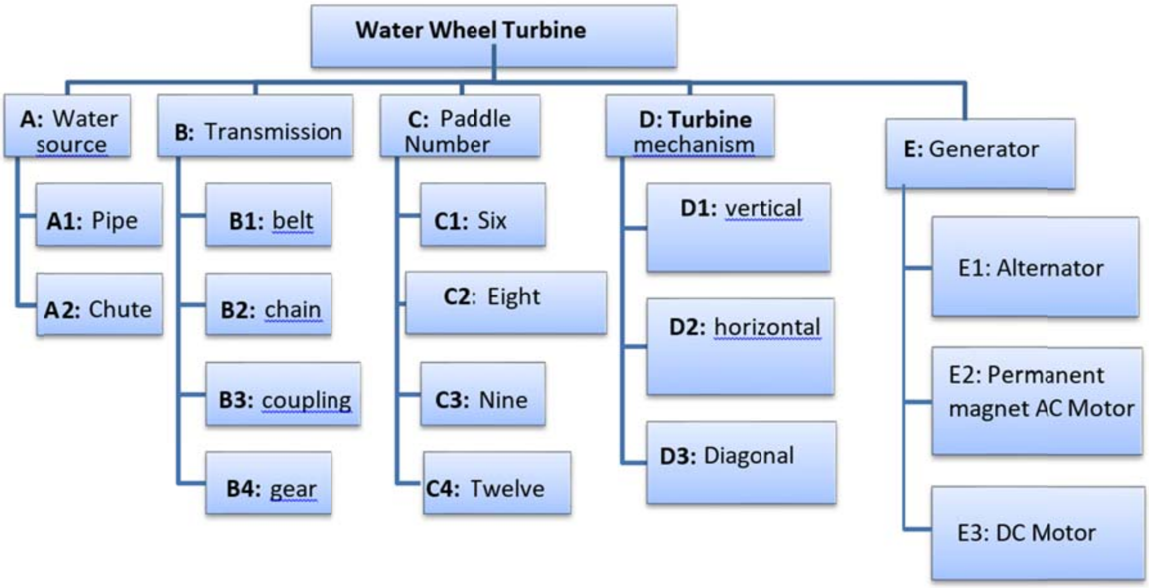

Figure 1: Criteria for the Development of Efficient Turbine Design for the PHES.

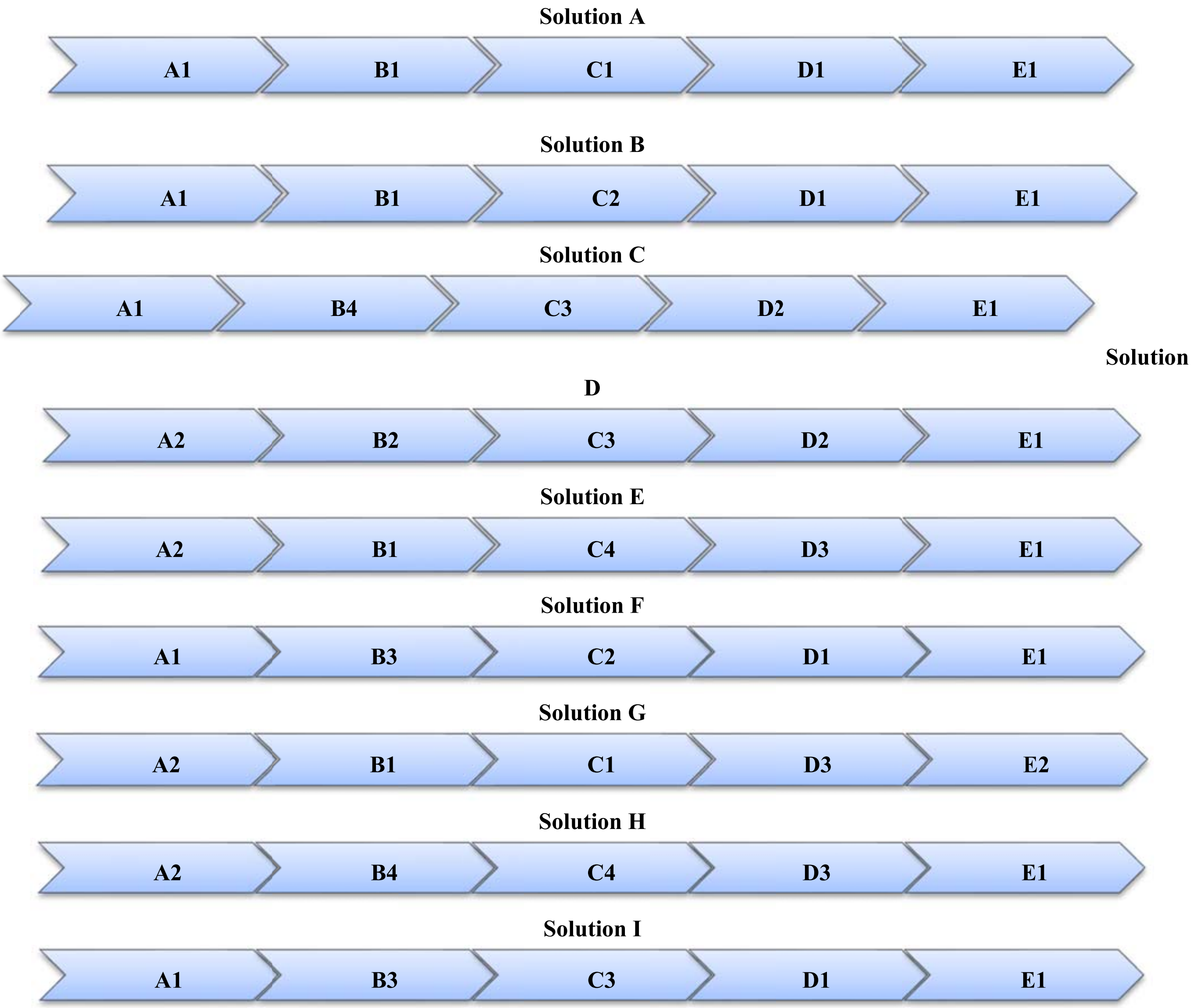

Figure 2: The Set of Combination of Functions Considered in the Selection of the Best Alternative Option

The Screening Pugh matrix is used to select the best alternative [18,19]. In this case, the Pugh matrix table is created from the ideas in Figure 1 and Figure 2 and presented in Table 4 (the Pugh matrix table for the alternatives)

Table 4: The Pugh Matrix for Determining the Most Efficient Turbine Design Option

Design criteria	Solution A	Solution B	Solution C	Solution D	Solution E	Solution F	Solution G	Solution H	Solution I
Capacity	0	0	0	+	+	0	+	0	0
Production cost	+	+	+	+	+	+	+	-	-
Efficiency	0	0	+	0	-	0	-	0	+
Safety	+	0	+	-	-	0	0	+	0
Ergonomic	+	0	+	-	-	+	-	-	0
Pugh Matrix Score	3	1	4	0	-1	2	0	-1	0

3 The results and Discussion

The Pugh matrix scores for each of the seven design alternatives as computed in Table 4 are presented in Figure 3. The results showed that the best solution is option C with 4 points followed by option A with 3 points. The worst solution include option E and H, which means they performed less than the base line case. Based on the Pugh matrix scores, the two options C and A are selected as the design alternatives (as shown in Table 5) and the two options are further examined and their details are discussed in this section.

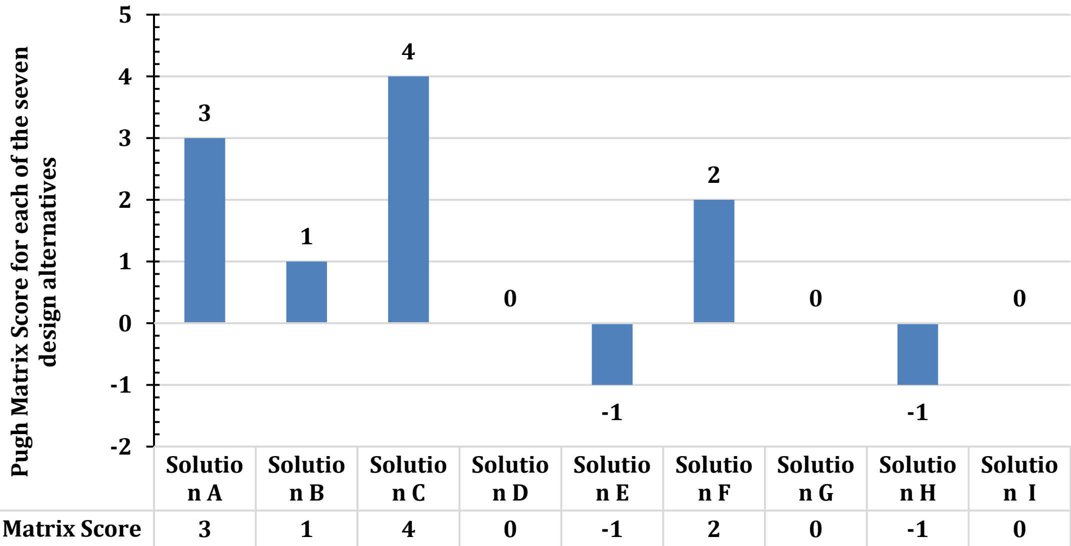

Figure 3 Pugh matrix score for each of the seven design alternatives

Table 5 The Design Alternatives

S/N	TYPE	DESIGN
1	A	A six-paddle, vertically aligned turbine driven by pipe-directed water flow, powering a belt transmission connected to an alternator.
2	C	A nine-paddle, horizontally aligned turbine driven by pipe-directed water flow, powering a gear transmission connected to an alternator.

3. 1 The Design Alternative A

The design alternative A is solution with six-paddle, vertically aligned turbine driven by pipe-directed water flow, powering a belt transmission connected to an alternator. In this solution, water is directed through a pipe onto a vertically aligned turbine fitted with six paddles. The force of the flowing water causes the turbine to rotate continuously. This rotation is supported by ball bearings, which allow smooth and efficient motion with minimal resistance. As the turbine spins, it directly drives a belt transmission system. The belt is mounted on a pulley attached to the turbine shaft and transfers the rotational motion to another pulley mounted on the shaft of an alternator. This setup converts the mechanical energy from the rotating turbine into electrical energy through the alternator. The entire mechanism is mounted on a sturdy bracket structure that holds the turbine and the alternator in perfect alignment. The advantages and disadvantages of solution A are as follows:

The Advantages of Design Alternative A

i. It has a simple design and construction.
ii. It is semi-automatic.

The Dis-advantages of Design Alternative A

i. Energy loss due to friction
ii. The belt may have a shorter lifespan and require frequent replacement.

Experts and other selected focus group members are used as judges to rate the option A and C. The judges score for design alternative A is presented in Table 6.

Table 6: The Judges Score for Design Alternative A

Judges	Production cost	Durability	Capacity	Maintainability	Efficiency	Ergonomics	Safety
1	4	3	3	4	5	2	3
2	5	4	3	3	3	3	4
3	4	3	4	3	4	2	3
4	4	2	3	5	3	3	4
5	3	5	4	2	3	4	2
Average	4	3.4	3	3.4	3.4	2.8	3.2

3.2 The Design Alternative C

The design alternative C is solution with nine-paddle, horizontally aligned turbine driven by pipe-directed water flow, powering a gear transmission connected to an alternator. Water is directed through a pipe onto a horizontally aligned turbine fitted with nine paddles. The force of the flowing water causes the turbine to rotate continuously. This rotation is supported by ball bearings, which allow smooth and efficient motion with minimal resistance. As the turbine spins, it directly drives a gear transmission system. The turbine shaft is fitted with a gear that meshes with a larger gear mounted on the shaft of an alternator. As the turbine rotates, the gear system transmits the mechanical motion directly to the alternator shaft. This setup efficiently converts the mechanical energy generated by the rotating turbine into electrical energy. The entire mechanism is supported by a sturdy bracket structure that maintains precise alignment between the turbine and the alternator. The advantages and disadvantages of solution C are as follows:

The Advantages of Design Alternative C

i. It has allows for easy maintenance.
ii. It is fully automatic.

The Dis-advantages of Design Alternative C

i. Requires precise manufacturing techniques.

The judges score for the design alternative A is presented in Table 7.

Table 7: The Judges Score for Design Alternative C

Judges	Production cost	Durability	Capacity	Maintainability	Efficiency	Ergonomics	Safety
1	5	3	4	4	2	4	3
2	4	4	3	5	3	3	3
3	5	3	5	4	2	3	4
4	4	2	3	4	3	5	3
5	5	5	3	3	4	2	4
Average	4.6	3.4	3.6	4	2.8	3.4	3

3.3 Comparison and selection of the best solution

Comparison of the Judges Rating for A and C alternatives are presented in Figure 4 which shows that C has better production cost ranting of 4.6 whereas A has 4. Also, C has high rating than A in other factors except efficiency and safety where A has the higher ratings. Essentially, option C is a tradeoff to minimize cost at the expense of efficiency and safety. However, there are safety threshold which once satisfied, the product is good for the consumer community. This safety criteria must have been satisfied before the solution is selected a viable option for the project.

The total weighted score and rank for the alternatives A and C are presented in Table 7. The comparison of the weighted score for each factor for A and C alternatives are presented in Figure 5 while the total weighted factor for A and C alternatives is presented in Figure 6. Again, the comparison of the total score and ranking for A and C alternatives is presented in Figure 6. Generally, the results show that the alternative C has the highest overall score of 0.3657 which makes it the best option for the project and it is therefore given the rank of 1. On the other hand, alternative A has a lower overall score of 0.3391 than that of C which makes it the second best option for the project and it is therefore given the rank of 2.

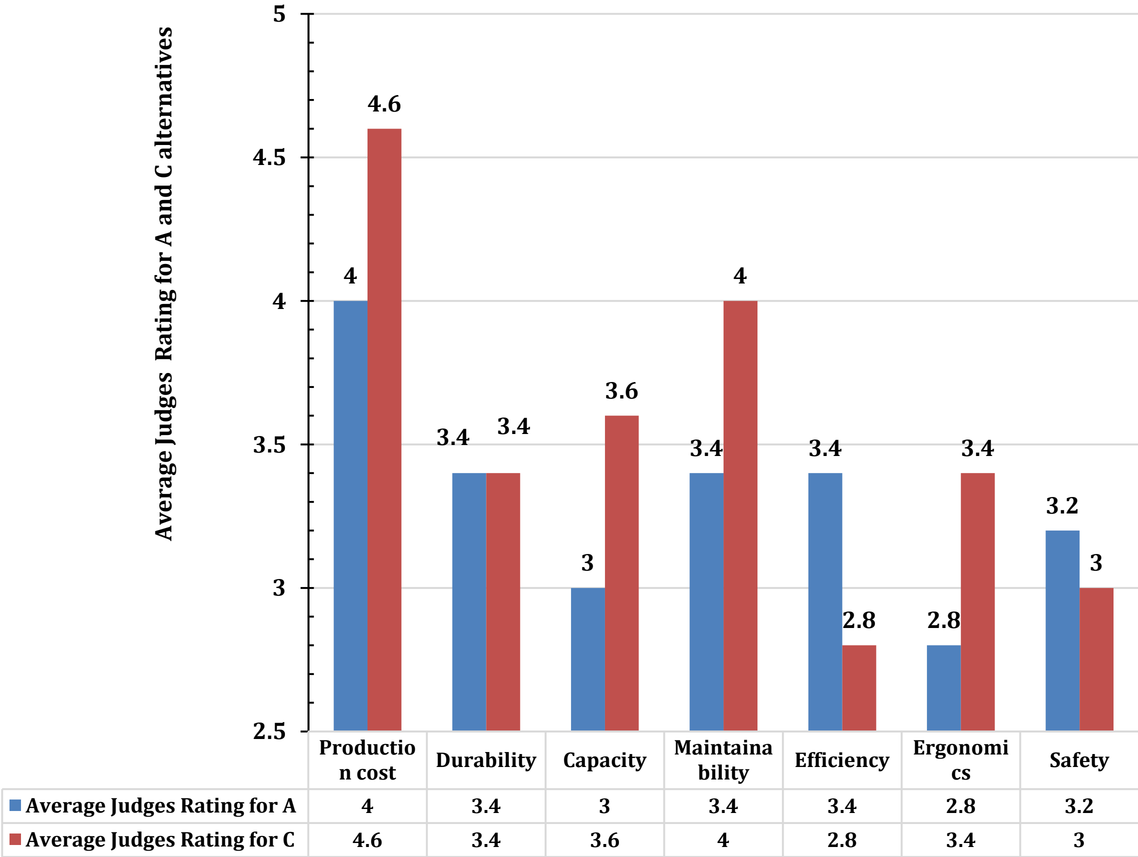

Figure 4 Comparison of the Judges Rating for A and C alternatives

Table 7 The Total weighted Score and Rank for the Alternatives

		Production cost	Durability	Capacity	Maintainability	Efficiency	Ergonomics	Safety	Total Score	Rank
	Weighted Factor	0.02857	0.00476	0.01905	0.004762	0.009524	0.009524	0.02381		
A	**Rate**	4	3.4	3	3.4	3.4	2.8	3.2		
	Score	0.114288	0.016191	0.057144	0.016191	0.032382	0.026667	0.076192	0.339054	2
C	**Rate**	4.6	3.4	3.6	4	2.8	3.4	3		
	Score	0.131431	0.016191	0.068573	0.019048	0.026667	0.032382	0.07143	0.365722	1

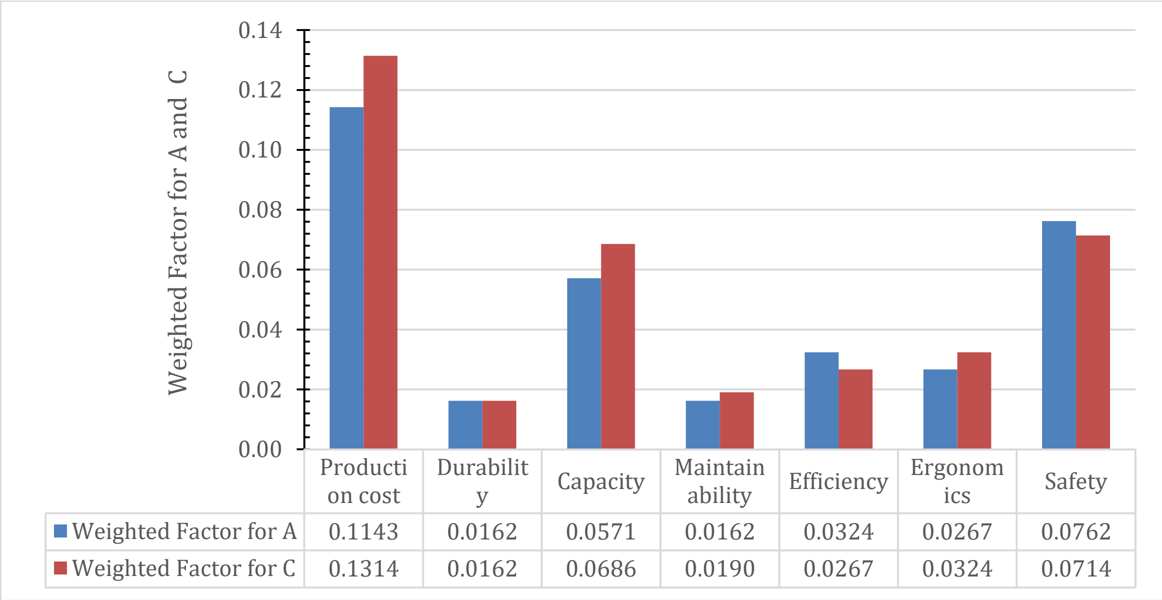

Figure 5 Comparison of the Weighted score for each factor for A and C alternatives

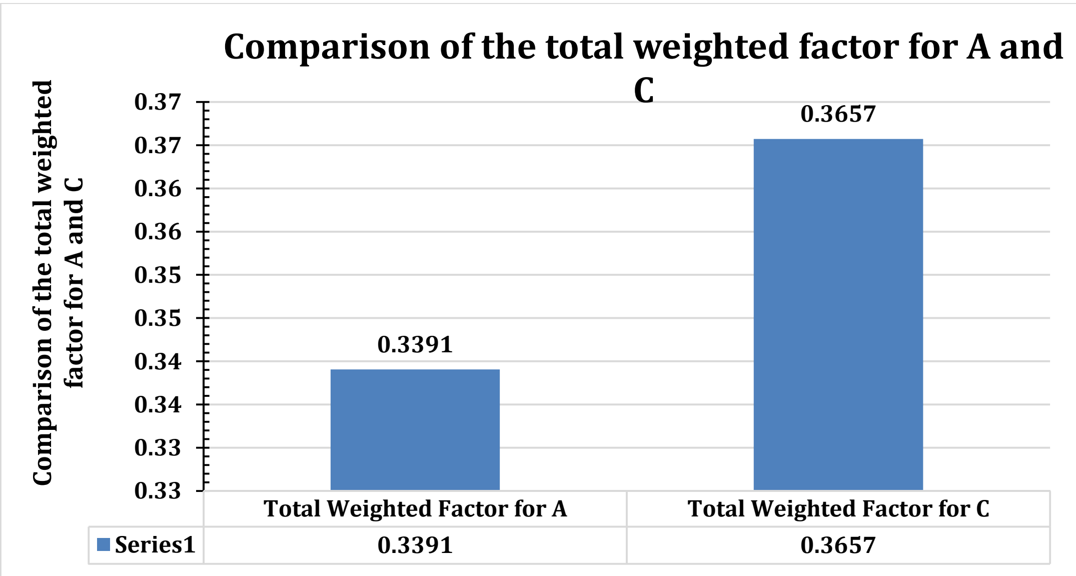

Figure 6 Comparison of the Total Weighted Factor for A and C alternatives

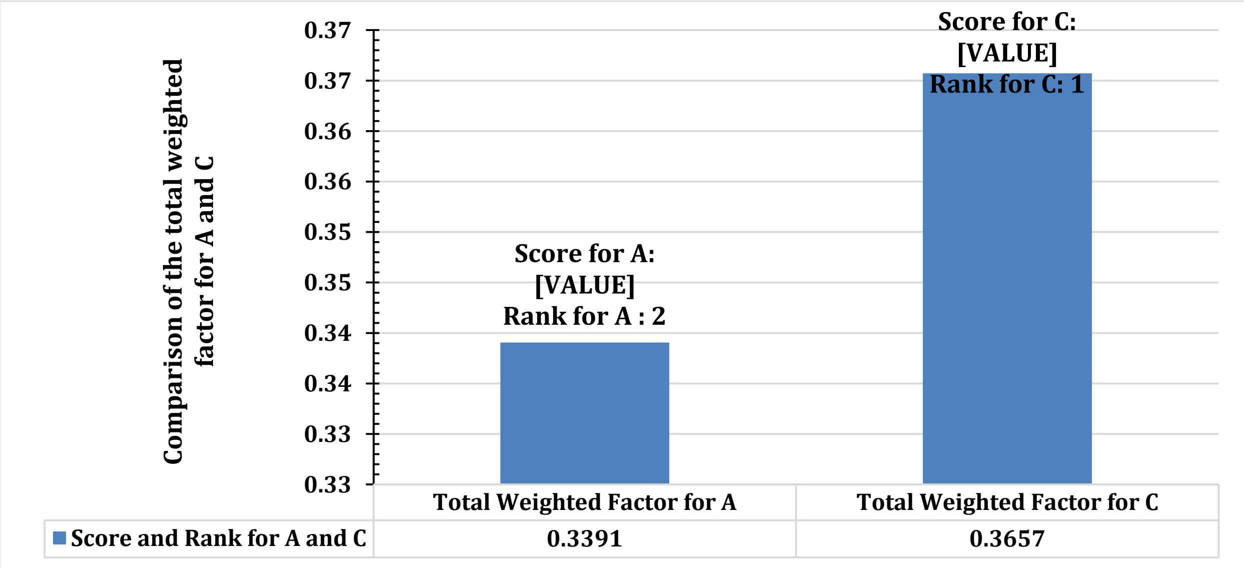

Figure 8 Comparison of the Total Score and Ranking for A and C alternatives

4 Conclusion

The design of options for photovoltaic pumped hydroelectric storage (PHES) **System** are considered with focus on determining the best option based on seven factors that are considered essential for the project. The pairwise matrix method and Screening Pugh matrix were utilizes along with some human judge ratings of the option. In all, two options were selected and ranked as the best and second best option for the project implementation. The ideas presented in this work are essential for selection of optimal design option for Pumped Hydro Energy Storage (PHES) system or related projects.

References

1. Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and sustainable energy reviews*, *61*, 421-432.
2. Petrollese, M., Seche, P., & Cocco, D. (2019). Analysis and optimization of solar-pumped hydro storage systems integrated in water supply networks. *Energy*, *189*, 116176.
3. Xu, B., Chen, D., Venkateshkumar, M., Xiao, Y., Yue, Y., Xing, Y., & Li, P. (2019). Modeling a pumped storage hydropower integrated to a hybrid power system with solar-wind power and its stability analysis. *Applied Energy*, *248*, 446-462.
4. Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy*, *3*(2), 022003.
5. Jurasz, J., Mikulik, J., Krzywda, M., Ciapała, B., & Janowski, M. (2018). Integrating a wind-and solar-powered hybrid to the power system by coupling it with a hydroelectric power station with pumping installation. *Energy*, *144*, 549-563.
6. Armaroli, N., & Balzani, V. (2016). Solar electricity and solar fuels: status and perspectives in the context of the energy transition. *Chemistry–A European Journal*, *22*(1), 32-57.
7. Kougias, I., Szabó, S., Monforti-Ferrario, F., Huld, T., & Bódis, K. (2016). A methodology for optimization of the complementarity between small-hydropower plants and solar PV systems. *Renewable Energy*, *87*, 1023-1030.
8. Mahmoudimehr, J., & Shabani, M. (2018). Optimal design of hybrid photovoltaic-hydroelectric standalone energy system for north and south of Iran. *Renewable energy*, *115*, 238-251.
9. Laconi, N., Licheri, F., Cambuli, F., Cocco, D., & Petrollese, M. (2024, November). Optimized design procedure for small-scale Pumped Hydro Energy Storage systems based on the use of pumps as turbines. In *Journal of Physics: Conference Series* (Vol. 2893, No. 1, p. 012011). IOP Publishing.
10. Haas, J., Prieto-Miranda, L., Ghorbani, N., & Breyer, C. (2022). Revisiting the potential of pumped-hydro energy storage: A method to detect economically attractive sites. *Renewable Energy*, *181*, 182-193.
11. Fernandez, D. (2019). *Modular Pumped Hydro Energy Storage (MPHES): Relevance, concept design, economics and future prospect* (Doctoral dissertation, Murdoch University).

12. Saedi, A. M. (2013). *Hazards identification for safety and risk evaluation of hydroelectric dam power generation plant* (Doctoral dissertation, University of Malaya).
13. Waweru, E., & Rambo, C. (2017). Factors influencing effective hydroelectric power supply generation in Kenya; a case of Kindaruma power station project in Machakos County. *Unpublished research report*.
14. Sen, A., Mohankar, A. S., Khamaj, A., & Karmakar, S. (2021). Emerging OSH issues in installation and maintenance of floating solar photovoltaic projects and their link with sustainable development goals. *Risk management and healthcare policy*, 1939-1957.
15. Çoban, V. (2020). Solar energy plant project selection with AHP decision-making method based on hesitant fuzzy linguistic evaluation. *Complex & Intelligent Systems*, *6*(3), 507-529.
16. Kou, G., Ergu, D., Lin, C., & Chen, Y. (2016). Pairwise comparison matrix in multiple criteria decision making. *Technological and economic development of economy*, *22*(5), 738-765.
17. San Cristóbal, J. R. (2011). Multi-criteria decision-making in the selection of a renewable energy project in spain: The Vikor method. *Renewable energy*, *36*(2), 498-502.
18. Guler, K., & Petrisor, D. M. (2021). A Pugh Matrix based product development model for increased small design team efficiency. *Cogent Engineering*, *8*(1), 1923383.
19. Raudberget, D. (2010). The decision process in Set-based Concurrent Engineering-An industrial case study. In *DS 60: Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia* (pp. 937-946).