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COMPARATIVE ANALYSIS OF FLOATING OFFSHORE WIND TURBINE FOUNDATION FOR RENEWABLE ENERGY GENERATION

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ABSTRACT: *The offshore energy industry concerning wind energy is moving its focus towards deeper water locations, which are more fitting to floating rather than bottom fixed support structures. The selection of the appropriate support structure type is an important factor in making the offshore energy industry reliable and efficient for product delivery. The study aims to develop a methodology for the evaluation and selection of an optimum structure to support offshore wind power with emphasis on three different selected support structures for wind turbines offshore based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method with modification using the pairwise comparison for obtaining the weighted vector and also using the Analytic Hierarchy Process (AHP) method for verification of approach. These methods were able to check for consistency of the weights employed in the analysis and provide a means for validating the weight of attributes. The scores obtained from the three methods used to carry out the multi-criteria decision-making analysis (TOPSIS, modified TOPSIS and AHP) and this shows how all the alternatives rank concerning each other. The Spar buoy option scores 41.00% (TOPSIS), 42.45% (Modified TOPSIS) and 29.15% (AHP) while the Semi-sub option scores 32.75% (TOPSIS), 20.90% (Modified TOPSIS) and 37.32% (AHP) and the TLP options scores 26.25% (TOPSIS), 36.64% (Modified TOPSIS) and 33.53% (AHP). The option with the best performance across all decision-making approaches is the Spar buoy platform with the TLP being the next preferred and the Semi-sub being the least preferred.*

KEYWORDS: Floating platform, Wind Turbine, weight analysis, offshore renewable energy, offshore structures

INTRODUCTION

The Nigerian system has been plagued with epileptic power generation over the years with erratic power supply due to over-dependence on the hydropower plants and gas-powered turbines as forms of energy generation. The renewable energy industry with particular emphasis on wind-generated power is a fast-growing area of interest worldwide with great potential for solving Nigeria's power problem if ventured adequately into it. The Africa – EU Corporation Programme (AERECP, 2018) in a report stated that the wind energy potential in Nigeria is very modest, with annual average speeds of about 2.0 m/s at the coastal region and 4.0 m/s at heights of 30m in the far northern region of the country. Concerning the Ministry of Science and Technology's wind energy resource mapping:

In the most suitable locations, wind speeds of up to 5 m/s were recorded, which reveals that only a local and moderate potential for wind energy exists. Offshore Wind Turbines provide a clean and efficient form of renewable energy which, if properly harnessed, can reduce the dependence of Nigeria on other significant sources of energy (hydro and thermal). The major problem plaguing the industry is the issue of selecting the optimum support structure that performs favourably for the multiple factors influencing the concept selection at offshore locations where there is the enormous potential of wind speeds that make wind power generation lucrative. This paper aims to select an optimum support structure that can be used to harness the potential that the Gulf of Guinea Offshore waters holds for renewable energy generation (wind power) using the Floating Offshore Wind Foundation (FOWF). The objectives of this study are;

i) Study of offshore wind resources and characteristics and its impact in the area of interest.
ii) Comparative analysis of Floating Offshore Wind Foundation systems with case studies being the Spar buoy, Semi-submersible and Tension Leg Platform (TLP), and their application in the Gulf of Guinea considering prevailing environmental conditions and multiple selection criteria.

iii) Comparing each proposed method using a modified approach to the Technique for Order Preference of Similarity to Ideal Solution (TOPSIS); a Multi-Criteria Decision Method to arrive at a workable optimum solution.Wind energy generated from Offshore Wind Turbines (OWT) is a promising source of energy for the Nigerian system due to the prevalent high wind speeds that exist in offshore waters and harnessing this source of renewable energy will significantly boost the Nation's power industry and reduce ours over dependence on hydro and thermal sources of energy generation — leveraging on the existing knowledge and success of the offshore oil and gas exploration and production industry in Nigerian waters. It is expedient that this knowledge and experience of floating foundations can be effectively utilised towards wind energy generation.

This paper hopes to provide an optimum support structure capable of aiding the extraction of wind power in the Gulf of Guinea through the use of floating offshore wind turbines; particular emphasis will be placed on the offshore waters off the coast of the Nigerian Delta with depths above 200m. The study will be limited to the use of Three (3) floating offshore wind turbine options, namely; a) Spar Buoy b) Semi-submersible and c) Tension Leg Platform.

System Description

For this study, a representative utility-scale multi-megawatt turbine called the 'NREL offshore 5 MW baseline wind turbine' was used for all support structure alternatives. The support systems used were modelled after the MIT/NREL TLP, the OC3-Hywind Spar buoy and the OC4-DeepCWind Semi-Sub. The floating support structure used was the NREL 5 MW wind turbines system was modelled after the MIT/NREL TLP, the OC3-Hywind spar buoy and the OC4DeepCWind Semi-Sub, which represent the floating platform alternatives. Each floating platform type is briefly described in the preceding sub-sections.

MIT/NREL TLP

This is a floating platform support structure is a product of the modification to a Tension Leg Platform (TLP) designed initially at the Massachusetts Institute of Technology (MIT). This platform is a platform of the cylindrical cross-section, which is concrete ballasted and adequately moored to the seabed by four (4) pairs of vertically connected tendons in tension (Jonkman and Martha, 2011).

OC3 – Hywind Spar

This platform concept is made up of a Spar buoy and was developed as a product of the Offshore Code Comparison Collaboration (OC3). The platform imitates the spar buoy concept called ‘Hywind,’ developed by Statoil ‘Hydro’ of Norway. The OC3- Hywind floating wind turbine system comprises of an intensely drafted, slender spar buoy attached to three (3) catenary mooring lines. These mooring lines are linked/joined to the platform via a crowfoot or delta connection to increase the yaw stiffness of the selected mooring lines (Jonkman and Martha, 2011).

OC4-DeepCWind Semi-Submersible

The OC4 project involved the modelling of a semisubmersible floating offshore wind system developed for the DeepCwind project. This concept was chosen for its increased hydrodynamic complexity compared to the only other floating system. The Semi Sub concept is the tri-floater concept effectively ballasted with seawater to arrive at a reasonable draft of 20m. It is adequately moored by a combined system of three slack catenary lines to ensure the structure does not drift (Jonkman and Martha, 2011).

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The MCDA method has enjoyed extensive use and has been well-established and used for ranking solutions to problems involving several performance criteria. It was initially introduced and developed in 1981 (Hwang and Yoon 1981) and has been improved further since then (Hsu-Shih and Hsuan-Shih 2006). TOPSIS has seen its application in several problems of diverse operational fields such as product design, HR Management, manufacturing, water management, transportation, quality control and location analysis. TOPSIS method lies in the fact that the best alternative solution should have the shortest distance from the Positive Ideal Solution (PIS) and the farthest distance from the Negative Ideal Solution (NIS), and through this provides a system of ranking the considered solutions.

TOPSIS method possesses the advantage of the simplicity of the computation involved and also utilises direct participation of human judgment in arriving at the solution model. This method ensures that the objective benchmarking is realised among the available options, taking into consideration the quantitative and qualitative attributes; the analytical procedure of this method’s application can be seen in Figure 1.

Data input

Careful consideration of the TOPSIS flowchart presented in Figure1 shows that all the data to be input aij are organised in a $m \times n$ matrix called matrix A. The matrix denotes that m solutions refer to the design alternatives of the support structure, and n refers to the design criteria/attributes. The attributes are termed and separated into two sets J^+ and J^-, with J^+ being those whose values are optimised/increased if minimised such as cost of construction, and J^- being those whose values are optimised/increased if maximised such as durability.

Thus,

$$J^+ \cup J^- = \{1,2,3,\ldots,n\} \ and \ J^+ \cap J^- = \emptyset \quad (1)$$

A decision matrix is then obtained from the above-selected input data aij where i = 1,…,m and j = 1,…,n

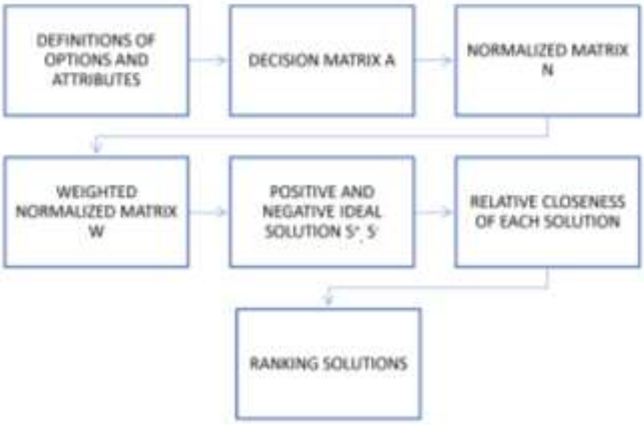


Figure 1 TOPSIS method flowchart (Lozano-Minguez et al., 2011)

The MCDM problem with m numbers of alternatives and n numbers of criteria can then be expressed in matrix notation as follows:

$$G = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{bmatrix} C_1 & C_2 & \cdots & C_n \\ a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{2}$$

In the $m \times n$ Decision Matrix (A) above, each element is representative of the mark/numerical assessment assigned to the $j - th$ option $-C$ vector for the $i - th$ marking criterion/attribute $-S$ vector, as it will be referred to in this work.

Normalisation

From the initial decision matrix obtained, a normalised matrix N will be created/developed in order to scale the results to [0,1]. The attributes have their values normalised, which enables the creation of the matrix N. The individual elements of the normalised matrix are derived as follows:

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \quad \text{where } a_{ij} \in A \text{ and } n_{ij} \in N \tag{3}$$

3.3 Weight vectors

After the construction of matrix N, a Matrix (X) of dimension $m \times n$ will be defined for every value of the Weight Vector that is considered are called the Weighted Normalized matrix.

The attributes are weighted by a vector W, which is a vector of size n with the elements of the weighted matrix being of proportional value to the relative significance of the attributes being considered. The weight vector represents the 'assessment or personalised judgment' of the different experts contacted in the area of interest relative to the research. For this paper, the weight vectors will be computed using the pairwise comparison method applied to the alternatives and obtained results verified using the method of expressing weights as linguistics variables (Jadidi et al., 2008).

Linguistic variable method of expressing weights vector

The criteria are judged with the linguistic variable and appropriate weights applied for use in creating the weighted matrix, and the linguistic variable scale used is as shown in Table 1.

Table 1 The Scale of Criterion Weights from Linguistic Variables (Jadidi et al., 2008)

Scale	**weight**
Very very Low (VVL)	0.005
Very Low (VL)	0.125
Low (L)	0.175
Medium Low (ML)	0.225
Medium	0.275
Medium High (MH)	0.325
High (H)	0.375
Very High (VH)	0.425
Very Very High (VVH)	0.475

Positive and negative ideal solutions

The positive (PIS) and negative ideal solutions (NIS), in theory, are the extremely best and worst solutions available for the support structures being considered. The positive ideal solution S^{+}, and the negative ideal solution, S^{-} regarding J^{+} *and* J^{-} are defined as follows:

$$S^{+} = \{s_1^{+}, s_2^{+}, s_3^{+}, \dots, s_n^{+}\}$$
$$s_i^{+} = max_{i=1}, \dots, m\left(x_{ij}\right)\ if\ j \epsilon J^{+} \tag{4}$$

and

$$s_i^{-} = min_{i=1}, \dots, m\left(x_{ij}\right)\ if\ j \epsilon J^{-} \tag{5}$$

$$S^{-} = \{s_1^{-}, s_2^{-}, s_3^{-}, \dots, s_n^{-}\}$$
$$s_i^{-} = min_{i=1}, \dots, m\left(x_{ij}\right)\ if\ j \epsilon J^{+} \tag{6}$$

$$s_i^{-} = max_{i=1}, \dots, m\left(x_{ij}\right)\ if\ j \epsilon J^{-} \tag{7}$$

Distance to PIS ($\boldsymbol{S}^{+}$) and NIS ($\boldsymbol{S}-$)

A calculation of the relative distances apart of each of the solutions under consideration from the PIS and NIS is calculated using the n-dimensional equivalent of Pythagoras' theorem.

This procedure now leads to a ranking scale of the estimated candidate solutions arrived at through a calculation of the relative distance of each considered

$$C_i^+ = \sqrt{\sum_{j=1}^{n} (x_{ij} - s_j^+)^2} \text{ and } C_i^- = \sqrt{\sum_{j=1}^{n} (x_{ij} - s_j^-)^2} \quad (8)$$

Comparison
The final scores obtained from above are then used to rank the support structures with regards to their overall performance, which distinctively distinguishes the most favourable and suitable concept to be selected. The Index $Scorei$is used to ascertain the relative closeness of each calculated solution to the optimum/ideal one using the equation below:

$$Score_i = \frac{C_i^-}{C_i^- + C_i^+} \quad (9)$$

Consequently, the structure that is simultaneously farthest from the NIS and closest to the PIS is considered the best structure while also obtaining the highest score. Therefore, the solution with an index Score closest to 1 is considered the most favourable.

Analytic Hierarchy Process (AHP)

The AHP was developed by T. L. Saatay in 1980 while in charge of research projects in the US. The method was developed as a response to an unavailability of easy to understand and implement a methodology that could handle complex decisions. Since its inception, the simplicity and level of impact of the AHP have made it experience vast application across multiple fields. The AHP has found application in business, defence, research and development, social studies and other fields that require decision making and are dependent on choice, prioritisation or forecasting (Saaty (1980). The AHP is a method that decomposes the given problem into a hierarchy of lower-level problems or sub-problems, which makes it easier to understand and evaluate subjectively. The subjectively evaluated problems are transformed into fundamental numerical values. These numerical values are carefully processed and used to rank each alternative or option being analysed on an outlined numerical scale. The AHP is performed in the following steps:

Step 1: The initial step of the AHP method is breaking the problem down into a hierarchy of goals, criteria, sub-criteria and alternatives. The hierarchy shows the existence of a relationship between elements of one level with those of the level immediately below. This relationship flows down to all the lowest levels of the hierarchy, and through this process, every single element is linked to each other.

Figure 2. AHP hierarchy structure (Sataay, 1980)

Step 2: In this step, data are obtained from experts or decision-makers about the hierarchic structure in the pairwise comparison of alternatives on a qualitative scale, as described below. Experts can rate the comparison as equal, marginally strong, strong, very strong, and extremely strong. The comparisons are made for each criterion and converted into quantitative numbers as per Table 2.

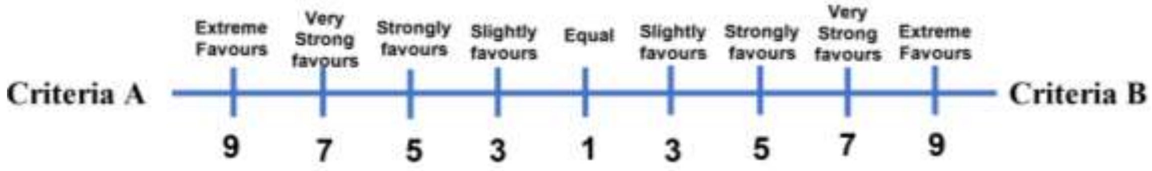


Figure 3. Likert scale for Pairwise comparison

Table 2. AHP Scale of Importance for Pairwise comparison (Taherdoost, 2017)

Importance Scale	Definition of Importance scale	Reciprocal (decimal)
9	Extreme importance	1/9(0.111)
7	Very strong importance	1/7(0.143)
5	Strong importance	1/5(0.200)
3	Moderate importance	1/3(0.333)
1	Equal Importance	1(1.000)
2,4,6,8	Intermediate values	

Step 3: The pairwise comparisons of various criteria generated at step 2 are organised into a square matrix. The diagonal elements of the matrix are 1. The criterion in the ith row is better than criterion in the jth column if the value of the element (i, j) is more than 1; otherwise, the criterion in the jth column is better than that in the ith row. The (j, i) element of the matrix is the reciprocal of the (i, j) element. The pairwise matrix is created from the criteria and the weight vector, w is computed as follows;

$$AW = \lambda_{max} \times w, \lambda_{max} \geq n \tag{10}$$

$$\lambda_{max} = \frac{\sum a_j w^{-n}}{w_1} \tag{11}$$

$$A = \{a_{ij}\}\ with\ a_{ij} = \frac{1}{a_{ij}} \tag{12}$$

Where A is the pairwise comparison, w is normalised vector λmax is the eigenvalue of matrix A, a_{ij} is the numerical comparison between the values i and j.

Step 4: The principal eigenvalue and the corresponding normalised right eigenvector of the comparison matrix give the relative level of importance of the various criteria being analysed. The obtained elements of the normalised eigenvector are termed weights and are evaluated concerning the criteria and ratings are assigned for the alternatives.

Step 5: In this step, the consistency of the pairwise matrix of order n is carried out, and the comparisons made through this method are subjective. The AHP accommodates the inconsistency of this approach through its amount of redundancy. If this consistency index does not achieve a prerequisite level, the outcome and answers of the similar process may need to be re-examined.
The consistency ratio (CR) is computed with the aid of the formula;

$$CR = \frac{CI}{RI} \qquad (13)$$

Where CI is the consistency index and it is measured through the formula;

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (14)$$

The Random Index (RI) values are obtained from Table 3, and it is a function of the dimension of the matrix. A consistency ratio (CR) with a value lower than 0.10 certifies the result of the comparison is acceptable.

Table 3. Value of Random Index (RI) (Gold and Wang, 1990)

Dimension	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.5799	0.8921	1.1159	1.2358	1.3322	1.3952	1.4537	1.4882

weighted normalised matrix X can, therefore, be obtained accordingly

$$If\ n_{ij} \in N\ and\ w \in W, then\ x_{ij} \in X, is\ defined\ as\ x_{ij} = n_{ij} \times w_j \qquad (15)$$

Step 6: The rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings concerning each criterion. The local ratings are then multiplied by the weights of the criteria and aggregated to get global ratings. The AHP produces weight values for each alternative based on the judged significance of one option over the others and concerning a common criterion.

Marking Criteria / Attributes

To effectively carry out the comparative analysis, ten (10) unrelated attributes (Vector S) were selected against the three (3) different options/alternatives (Vector C) of floating support structures being compared as outlined in Tables 4 and 5.

Carbon footprint (negative attribute)

Carbon footprint is a method of analysing a structure quantitatively to obtain an estimate of the total emissions produced (e.g., CO_2, etc.) in the course of manufacturing, operations and maintenance of the desired structure. This attribute makes room for the comparison of different methods of energy generation as it relates to greenhouse gas emissions. Preliminary sizing of the support structures was performed to arrive at an approximate estimate of the quantity and type of the significant materials used in its manufacture, and this constitutes how the attribute is marked. Schleisner (2010) presented an empirical formula in Equation (16) utilised in the computation of the CO_2O equivalent (CO_2e) emissions per kg of steel:

$$CO_2e = 270 \times N_2O + 24.5 \times CH_4 + 1.4 \times CO \tag{16}$$

The unit emissions per each kg of steel members produced are 0.07g, 0.04g, and 0.93g for N_2O, CH_4 and CO respectively in Table 6.

Certification (positive attribute)

Certification represents the confidence level of each support structure for use in the desired area of application (FOWTF) as against the engineering uncertainties of the structural concept. The marking of these criteria was done by considering the existing use of the selected support structure concept. The highest score was given to any structure that has been used for FOWTF. Still, the score reduces if the selected structure is used for a different application (i.e., oil & gas) or lowest mark at if the structure has seen no application at all as shown in Table 7.

Certification is a positive attribute, and therefore, the certification mark will be allotted as follows:

i) A mark of 1 was given if the structure has previously been certified for use on wind turbines,

ii) A mark of 0.5 was given if the structure has not previously been certified yet for use on wind turbines, but if certification is available for the structure for its use in the oil & gas industry offshore,

iii) A mark of 0 was given for a system that has not been certified for use before as a support structure.

Table 4. Attributes of the Support Structures used for the TOPSIS Analysis

S/n	Attributes	Attribute Effect
i	Carbon Footprint	-
ii	Certification	+
iii	compliance	-
iv	Construction Cost	-
v	Dept Compatibility	+
vi	Durability	+
vii	Dynamic Performance	+
viii	Ease of Installation	+
ix	Environmental Impact	-
x	Maintainability	

Table 5. Proposed Alternatives of Support Structures for Offshore Floating Wind Turbines

Alternatives	**Support Structure**
A	Spar platform
B	Semi-Submersible platform (Semi-Sub)
C	Tension Leg Platform (TLP)

Table 6. Carbon Footprint Result Score for the FOWT Support Structures

	Steel mass	N_20	CH_4	$C0$	$C0_20e$
Spar Bouy	7,536,110	527,527.70	301,444.40	7,008,582	159,629,881.20
Semi-Sub	13,567,704	949,739.28	542,708.20	12,617,965	287,391,104.50
TLP	8,617,597	603,231.80	344,703.90	8,014,365	182,537,943.90

Table 7. Certification Criteria Mark for the FOWT Support Structures (Kolios *et al*., 2010)

Structures	**Certification**
Spar Bouy	0.5
Semi-Sub	0.5
TLP	0.5

Compliance / maximum displacement of the rotor (negative attribute)

Compliance is described as the structure’s resistance to deflection or the displacement of the structure while exposed to the effect of forces on it. Compliance values vary and depend on the selected structural design and the application of the structure; high compliance can be seen as desirable or not. The marking is given from 1 to 5, and it is carried out in compliance with the structural application and on engineering judgment, as seen in Table 8. Compliance denotes the expected and, in most cases, predicted maximum displacement that occurs at the turbine’s hub due to a result of stiffness of its support structure.

Table 8. Compliance Criteria Mark for the FOWT Support Structures (Kolios *et al*., 2010)

Structures	**Compliance**
Spar Bouy	2
Semi-Sub	3
TLP	4

Construction cost (negative attribute)

The three most crucial cost estimate factors to consider in the preliminary design phase of any offshore floating system and are the construction costs (i.e., the manufacturing and materials cost), the cost/amount of corrosion protection and the cost/amount of mooring (lines and anchors). Offshore structures manufacturers provided typical estimated costs for European shipyards to be around US$5 per kilogram of steel. A range of ±10% on the cost being reference was included.

The mark for the construction cost criterion was derived by applying the equation:

$$C = SW \times p[USD] \tag{17}$$

Where; SW is the mass of steel used (kg), and p is cost specific to material and manufacturing (US$5/kg).

Table 9. Construction Cost Criteria Mark for the FOWT Support Structures

Structures	Steel mass	Construction Cost (US$)
Spar Bouy	7,536,110	37,680,549.81
Semi-Sub	13,567.704	67,838,519.63
TLP	8,617,597	43.087,986.00

The construction cost marking criterion gives an approximate estimate of the selected structure and assigns marks from a value for low cost (5) to another for the high cost (1). In general, the selected structure's cost is dependent on the structure's total weight, the materials quality, and the complexity in the construction of the method. The marking of this criteria is based preliminary on the design adopted based on an approximate estimate of the amount and type of primary materials that are needed and which are usually steel and concrete as shown in Table 9.

Depth compatibility (positive attribute)
Depth compatibility is a positive variable that considers the previously established confidence in design that aids the deployment of each selected concept, and it considers existing installations of similar structural composition which have been deployed in the field for any related or unrelated application about the specified reference depth (200m).

To effectively give this attribute a mark, the offshore oil and gas industry verified data are utilised for the wind turbine support foundations case. In Table10, an analytical list of the options available for use as support structures was presented against the allowable industry-standard ranges of depth. Considering each floating support structure evaluations for depth compatibility relating to the highest and lowest water depths have been evaluated carefully as follows:

i) Depth compatibility of 100% is given for a structure that has already been deployed as a support structure for offshore wind turbines and falls within the specified range of the reference water depth.
ii) Depth compatibility of 75% is given for a structure that has been deployed as a support structure for offshore wind turbines and falls within the extended range (min*0.75 < d < max*1.25) of the reference water depth.
iii) Depth compatibility of 50% is given for a structure that has been deployed as a support structure for oil & gas and falls within the specified range of the reference water depth.
iv) Depth compatibility of 25% is given for a structure that has been deployed as a structure to support the floating system for oil & gas and falls within the extended range of min*0.75 < d < max*1.25 of the reference water depth.
v) Depth compatibility of 0% for any other case.

Table 10. Wind Turbine Minimum and Maximum Water Depth and Criteria Mark per Selected Support Structures (Kolios *et al.*, 2010)

Support Structure	Min x 0.75	Min	Max	Max x 1.25	Mark (%)
Spar Bouy	90	120	700	875	100
Semi-Sub	75	100	700	875	100
TLP	45	60	300	375	100

Durability (positive attribute)

Durability is the support structure's resistance to age-related deterioration, and this can be mainly regarding corrosion and fatigue as a result of the environmental and functional loads the structure is exposed to. Structures with certain design advantages exhibit less structural redundancy or maybe inherently designed to withstand/resist higher stresses. These imply that the structures are likely to score less when marked against low stress, highly structurally redundant concepts. In this current case, marks are allotted for support structure options from 1 to 5 and are chosen depending on the exposure to corrosion and the consequences of fatigue; the higher marks signify higher durability (Kolios et al., 2010)

Table 11. Durability Criteria Mark for the FOWT Support Structures (Kolios et al., 2010)

Structures	**Durability**
Spar Bouy	4
Semi-Sub	5
TLP	5

Dynamic performance (positive attribute)

Dynamic performance is a positive variable that describes the dynamic behaviour of a foundation when exposed to the combined effect of the predominant environmental phenomena and operational loads. This attribute/variable is treated differently for fixed and floating concepts with the latter having to deal with the coupled effect of the wave load on the platform and the wind loads on the turbine (Martin et al., 2013). In this work, the dynamic performance will be scored concerning the structure's capacity to resist overturning, which is a function of its ability to create a counteracting moment. Marks are assigned ranging from 1 to 5 and are given based on the structure's capacity to generate a counteracting moment as presented in Table12 for the structures under consideration.

Table 12. Dynamic performance Criteria Mark for FOWT Support Structures (Kolios *et al.*,)

Structures	**Dynamic Performance**
Spar Bouy	3
Semi-Sub	3
TLP	4

Ease of installation (positive attribute)

This attribute is concerned with the relative ease of installing the floating offshore support structure in their designated position on site. This focuses on the equipment needed and its availability, the necessary manpower need, the cost consideration, and the time required. TLPs have the lowest score in this because of the relatively complex nature of their installations (turbine, hulls, tendons, foundations). Attributes are assigned marks from 1 to 5 which are chosen based on a comparison of different installation procedures with the mark increasing in value according to the ease of installation (Kolios et al., 2010). Table13 presents the criteria mark for the FOWT alternatives under consideration.

Table 13. Ease of Installation Criteria Mark for the FOWT Support Structures (Kolios et al., 2010)

Structures	**Ease of Installation**
Spar Bouy	3
Semi-Sub	4
TLP	2

Environmental impact (negative attribute)

Environmental impact is a location and structure design specific attribute that considers all potential impact of the selected and installed wind turbine as it relates to the destruction of the sea bed as a result of the installation, operation and maintenance of the offshore wind turbine structure. The major factors considered are the disturbance of the seabed, shadow cast by the structure and the adverse effect of the selected structure on marine life. Environmental impact assesses the structure's impact on the surrounding environment qualitatively.

Lozano-Minguez et al. (2011) evaluated the environmental impact assessment of fixed offshore support structures for use as wind turbines support structures. Vibration, noise, Electromagnetic fields, and impact on birds are some of the aspects considered. However, in the analysed case of floating support structures, the different structural concepts will have relatively the same impact on birds, lead to the emission of the same electromagnetic fields produce the same vibration levels and noise levels since these properties mainly depend on the selected wind turbine and independent on the support structure. Consequently, the methods of mooring will have a different impact on the sea bed and its conditions. For instance, a catenary system of mooring was loaded cyclically, and this action leads to the chains scouring the seabed which has an impact on flora and fauna of the area being affected by the mooring chain.

From the above, it can be illustrated that the footprint is approximately the same for the different structures employing catenary mooring for support and station keeping. Therefore, the environmental impact assessment of offshore floating wind turbines supports structure is a factor mainly affected by the mooring system employed; Catenary or Taut mooring systems. For this reason, this attribute favours the TLP structure over the others as seen in Table14.

Table 15. Environmental Impact Scores for Different Support Structure (kolios *et al*., 2010)

Structures	**Environmental Impact**
Spar Bouy	2
Semi-Sub	1
TLP	5

Maintainability/maintenance cost (negative attribute)

Maintainability consists of two distinct elements of cost and downtime incurred by the structure in the course of maintenance. The marks attributed to maintenance are influenced by the ease of maintenance and cost incurred, structures that can be transported to nearshore or moved to dry docks score better for maintainability when compared to fixed and immovable structures that require offshore maintenance operations.

We are considering the results of a qualitative assessment performed on similar structures with an emphasis on the complex nature of the structure and its ease of maintenance to ascertain the mark for the attribute. Factors such as the selected mooring system, the length of welds, and the number of bracing are taken into consideration to evaluate/ascertain the structure's complexity. The draught also impacts on structure's inspection accessibility. This attribute is scored negatively, with lower scores being better, as seen in Table 15.

Table 15 Maintainability/Maintenance Cost Scores for Different Support Structures (Kolios *et al.*, 2010)

Structures	**Maintainability**
Spar Bouy	5
Semi-Sub	5
TLP	3

RESULTS AND DISCUSSION

The procedural results of the TOPSIS analysis are presented from Table 16 – 23

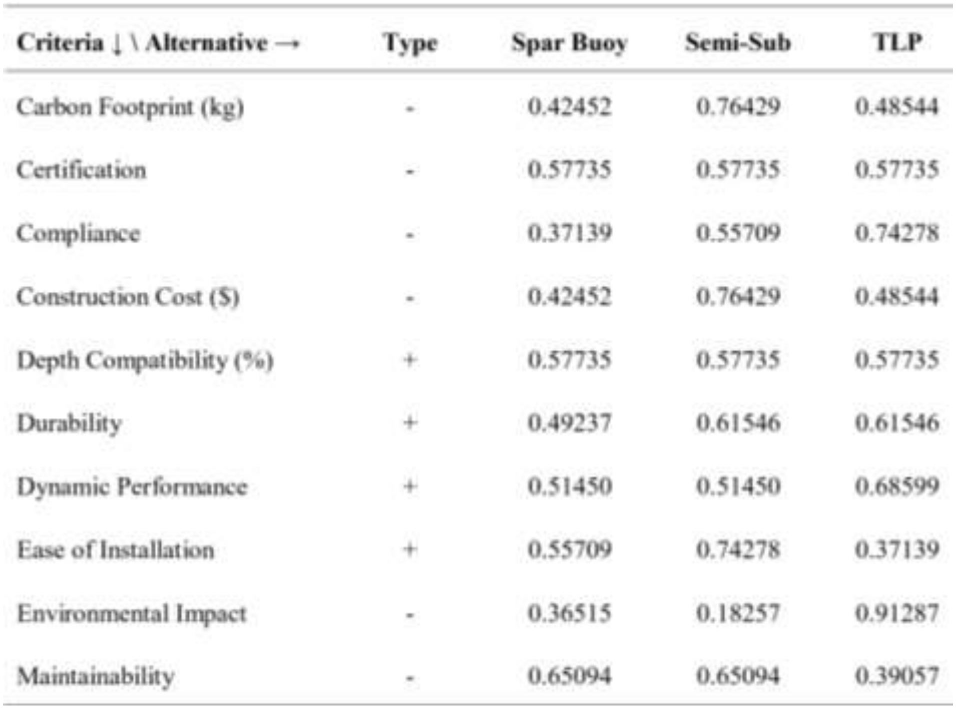
Table 16. Decision Matrix, A

Criteria↓ \Alternative →	**Type**	**Spar Bouy**	**Semi-Sub**	**TLP**
Carbon Footprint (kg)	-	159,629,881.20	287,391,104.50	182,537,943.90
Certification	-	0.5	0.5	0.5
Compliance	-	2	3	4
Construction Cost ($)	-	37,680,549.81	67,838,519.63	43,087,986.00
Dept Compatibility (%)	+	100	100	100
Durability	+	4	5	5
Dynamic Performance	+	3	3	4
Ease of Installation	+	3	4	2
Environment Impact	-	2	1	5
Maintainability	-	5	5	3

The Decision matrix was obtained by estimating the marks of the selected criteria based on expert judgment, as seen in referenced works of literature and as shown in Table 16.

The mark Carbon Footprint and Construction Cost were estimated from Equations (16) and (17) respectively and the Steel mass obtained from computations of data obtained from the table of summary of properties for the NREL 5 MW baseline wind turbine (Source: Jonkman et al., 2011)

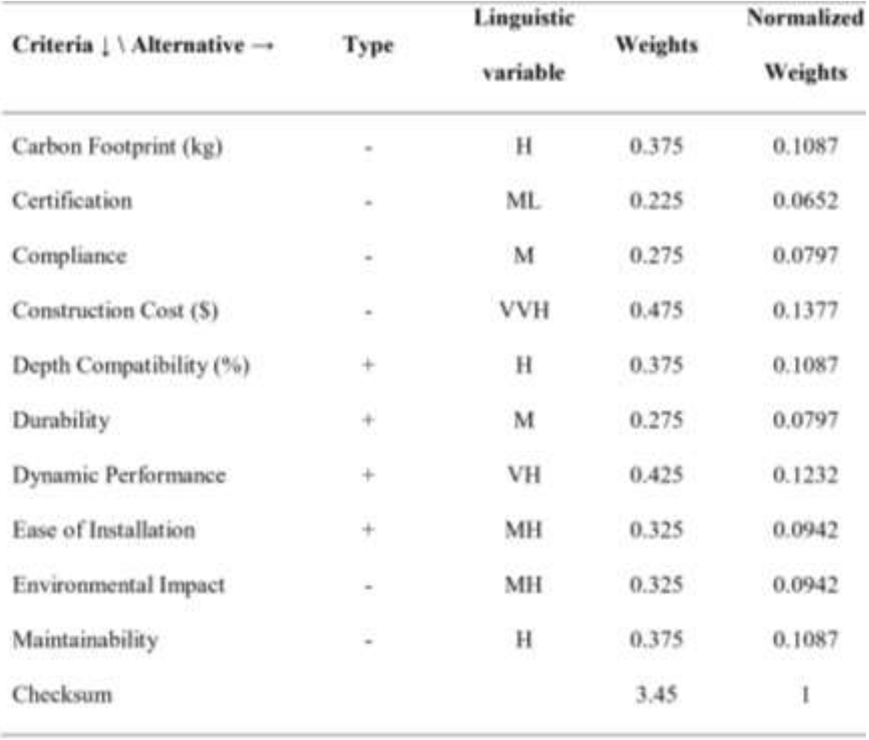
Table 17. Normalised matrix, N



Criteria ↓ \ Alternative →	Type	Spar Buoy	Semi-Sub	TLP
Carbon Footprint (kg)	-	0.42452	0.76429	0.48544
Certification	-	0.57735	0.57735	0.57735
Compliance	-	0.37139	0.55709	0.74278
Construction Cost ($)	-	0.42452	0.76429	0.48544
Depth Compatibility (%)	+	0.57735	0.57735	0.57735
Durability	+	0.49237	0.61546	0.61546
Dynamic Performance	+	0.51450	0.51450	0.68599
Ease of Installation	+	0.55709	0.74278	0.37139
Environmental Impact	-	0.36515	0.18257	0.91287
Maintainability	-	0.65094	0.65094	0.39057

The Decision Matrix A was normalised to obtain a matrix. This was carried out to makes the elements of the matrix more regular in the form of [0,1] and more representative for use in computations

Table 18. Weighted Vector, w



Criteria ↓ \ Alternative →	Type	Linguistic variable	Weights	Normalized Weights
Carbon Footprint (kg)	-	H	0.375	0.1087
Certification	-	ML	0.225	0.0652
Compliance	-	M	0.275	0.0797
Construction Cost ($)	-	VVH	0.475	0.1377
Depth Compatibility (%)	+	H	0.375	0.1087
Durability	+	M	0.275	0.0797
Dynamic Performance	+	VH	0.425	0.1232
Ease of Installation	+	MH	0.325	0.0942
Environmental Impact	-	MH	0.325	0.0942
Maintainability	-	H	0.375	0.1087
Checksum			3.45	1

Using weights expressed as linguistic variables (Jadidi et al., 2008), which is based on levels of importance of criteria concerning floating offshore wind turbine foundations, Table 19 was obtained.

Table 19. Weighted Normalized Decision Matrix W

Criteria ↓ \ Alternative →	Type	Spar Buoy	Semi-Sub	TLP
Carbon Footprint (kg)	-	0.04614	0.08307	0.05277
Certification	-	0.03765	0.03765	0.03765
Compliance	-	0.02960	0.04441	0.05921
Construction Cost ($)	-	0.05845	0.10523	0.06684
Depth Compatibility (%)	+	0.06276	0.06276	0.06276
Durability	+	0.03925	0.04906	0.04906
Dynamic Performance	+	0.06338	0.06338	0.08451
Ease of Installation	+	0.05248	0.06997	0.03499
Environmental Impact	-	0.03440	0.01720	0.08600
Maintainability	-	0.07075	0.07075	0.04245

The weighted normalised matrix, X, was obtained by applying equation (7). This procedure involved multiplying the criteria weight, w by its weighing criteria, n in the normalised matrix.

Table 20. Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)

Criteria ↓ \ Alternative →	Type	S^+	S^-
Carbon Footprint (kg)	-	0.04614	0.08307
Certification	-	0.03765	0.03765
Compliance	-	0.02960	0.05921
Construction Cost ($)	-	0.05845	0.10523
Depth Compatibility (%)	+	0.06276	0.06276
Durability	+	0.04906	0.03925
Dynamic Performance	+	0.08451	0.06338
Ease of Installation	+	0.06997	0.03499
Environmental Impact	-	0.01720	0.08600
Maintainability	-	0.04245	0.07075

The Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) were obtained by obtaining the maximum value and minimum value respectively per criteria. This provides a representative view of the range of the optimum solution. The optimum solution is the solution closest to the PIS and farthest from the NIS while considering all criteria. This was carried out by applying equation (8), (9), (10), and (11).

Table 21. Distance to PIS (S^+) and NIS (S^-)

Distance↓ /Alternative→	Spar Bouy	Semi-Sub	TLP
C^+	0.04411	0.07084	0.08335
C^-	0.08601	0.07920	0.06112

The distance between the PIS and the NIS was obtained by applying Equation 14 to evaluate the separation between the PIS and NIS. Relative closeness to the PIS (S+) using the linguistic variable method of obtaining weights.

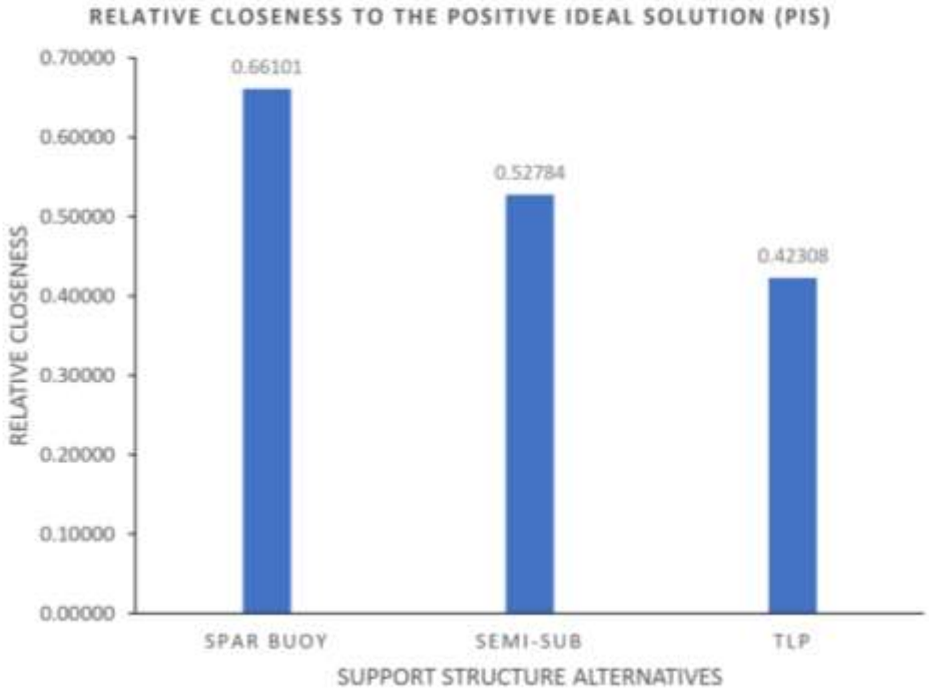


Figure 4. Relative Closeness to the PIS (Linguistic variable for weighted vector estimation)

Figure 4 shows the relative closeness of each alternative to the ideal solution. Equation (14) was used to estimate the score index.

Table 22. TOPSIS Rank

Alternative	Rank
Spar Bouy	1
Semi-Sub	2
TLP	3

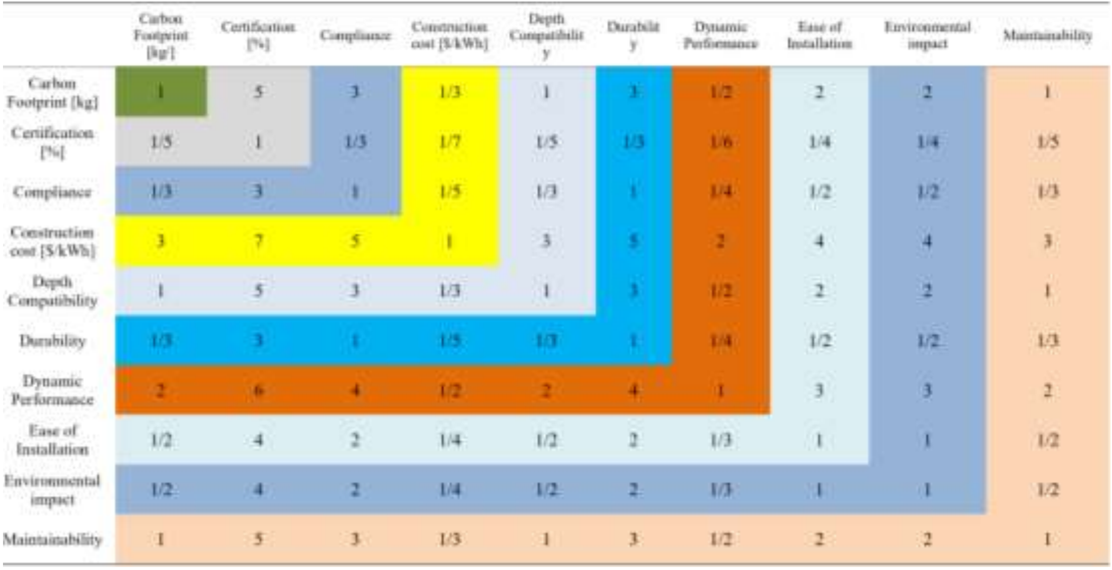
DISCUSSION OF RESULTS

Table 16 shows the decision matrix obtained. It can be inferred that the carbon footprint (CO2 emissions) and construction cost is a factor of the steel mass and materials of construction with the Semi-Submersible possessing an enormous steel mass and thus the highest cost and carbon footprint. The decision matrix shows a representative mark assignment per criteria in different units.

Table 18 shows the normalised decision matrix expressed in [0,1], which is useful for computations and analysis. The criteria were weighted concerning importance using the linguistic variable method (Jadidi et al., 2008). The weights assigned were representative of the level of priority of each criterion to the alternatives and obtained for the corresponding numerical constants assigned to the linguistic variable, as seen in Table 1 and used in calculating the weighted normalised matrix in Table 19.

The weights show that the construction cost, dynamic performance, carbon footprint, and durability possessed similar weights and therefore, levels of importance to the alternatives. The relative closeness of the options/alternatives to the ideal solution were obtained and ranks apportioned. The Spar Buoy was closest to the ideal solution with 0.6610 and hence, was considered the optimum solution. The TLP and Semi-Sub alternative had 0.5278 and 0.4231, respectively.
The Procedural result if the AHP analysis is presented from Table 23-28

Table 23. Pairwise Comparision Matrix



	Carbon Footprint [kg']	Certification [%]	Compliance	Construction cost [$/kWh]	Depth Compatibility	Durability	Dynamic Performance	Ease of Installation	Environmental impact	Maintainability
Carbon Footprint [kg]	1	5	3	1/3	1	3	1/2	2	2	1
Certification [%]	1/5	1	1/3	1/7	1/5	1/3	1/6	1/4	1/4	1/5
Compliance	1/3	3	1	1/5	1/3	1	1/4	1/2	1/2	1/3
Construction cost [$/kWh]	3	7	5	1	3	5	2	4	4	3
Depth Compatibility	1	5	3	1/3	1	3	1/2	2	2	1
Durability	1/3	3	1	1/5	1/3	1	1/4	1/2	1/2	1/3
Dynamic Performance	2	6	4	1/2	2	4	1	3	3	2
Ease of Installation	1/2	4	2	1/4	1/2	2	1/3	1	1	1/2
Environmental impact	1/2	4	2	1/4	1/2	2	1/3	1	1	1/2
Maintainability	1	5	3	1/3	1	3	1/2	2	2	1

Table 24. Normalized Pairwise Comparison Matrix

	Carbon Footprint [kg]	Certification [%]	Compliance	Construction cost [$/kWh]	Depth Compatibility	Durability	Dynamic Performance	Ease of Installation	Environmental impact	Maintainability	**Weights**
Carbon Footprint [kg/year]	0.1014	0.1163	0.1233	0.0941	0.1014	0.1233	0.0857	0.1231	0.1231	0.1014	**0.1093**
Certification [%]	0.0203	0.0233	0.0137	0.0403	0.0203	0.0137	0.0286	0.0154	0.0154	0.0203	**0.0211**
Compliance	0.0338	0.0698	0.0411	0.0565	0.0338	0.0411	0.0429	0.0308	0.0308	0.0338	**0.0414**
Construction cost [$/kWh]	0.3041	0.1628	0.2055	0.2823	0.3041	0.2055	0.3429	0.2462	0.2462	0.3041	**0.2603**
Depth Compatibility	0.1014	0.1163	0.1233	0.0941	0.1014	0.1233	0.0857	0.1231	0.1231	0.1014	**0.1093**
Durability	0.0338	0.0698	0.0411	0.0565	0.0338	0.0411	0.0429	0.0308	0.0308	0.0338	**0.0414**
Dynamic Performance	0.2027	0.1395	0.1644	0.1411	0.2027	0.1644	0.1714	0.1846	0.1846	0.2027	**0.1758**
Ease of Installation	0.0507	0.0930	0.0822	0.0706	0.0507	0.0822	0.0571	0.0615	0.0615	0.0507	**0.0660**
Environmental impact	0.0507	0.0930	0.0822	0.0706	0.0507	0.0822	0.0571	0.0615	0.0615	0.0507	**0.0660**
Maintainability	0.1014	0.1163	0.1233	0.0941	0.1014	0.1233	0.0857	0.1231	0.1231	0.1014	**0.1093**
Checksum	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	1.0000

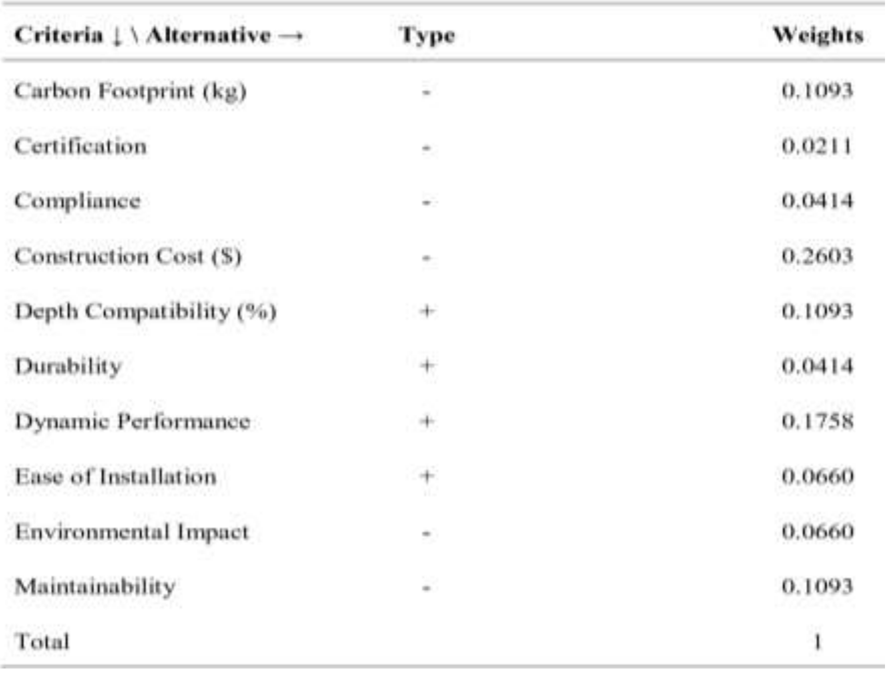
Table 25. Consistency Index (CI) from the Normalised Pairwise Matrix

	Carbon Footprint [kg]	Certification [%]	Compliance	Construction cost [$/kWh]	Depth Compatibility	Durability	Dynamic Performance	Ease of Installation	Environmental impact	Maintainability	**weights**
Carbon Footprint [kg]	1	5	3	1/3	1	3	1/2	2	2	1	**0.1093**
Certification [%]	1/5	1	1/3	1/7	1/5	1/3	1/6	1/4	1/4	1/5	**0.0211**
Compliance	1/3	3	1	1/5	1/3	1	1/4	1/2	1/2	1/3	**0.0414**
Construction cost [$/kWh]	3	7	5	1	3	5	2	4	4	3	**0.2603**
Depth Compatibility	1	5	3	1/3	1	3	1/2	2	2	1	**0.1093**
Durability	1/3	3	1	1/5	1/3	1	1/4	1/2	1/2	1/3	**0.0414**
Dynamic Performance	2	6	4	1/2	2	4	1	3	3	2	**0.1758**
Ease of Installation	1/2	4	2	1/4	1/2	2	1/3	1	1	1/2	**0.0660**
Environmental impact	1/2	4	2	1/4	1/2	2	1/3	1	1	1/2	**0.0660**
Maintainability	1	5	3	1/3	1	3	1/2	2	2	1	**0.1093**
	9 7/8	43	24 1/3	3 1/2	9 7/8	24 1/3	5 5/6	16 1/4	16 1/4	9 7/8	
	1.0783	**0.9078**	**1.0078**	**0.9223**	**1.0783**	**1.0078**	**1.0256**	**1.0729**	**1.0729**	**1.0783**	**10.2519**

Consistency Index (CI) and Consistency Ratio (CR) of the pairwise matrix were calculated using the Equation (7) and (8), respectively. The CI and CR obtained were 0.02799 and 0.01879, respectively using 1.49 as the value of RI obtained from Table 4 for the 10 x 10-dimension matrix. The CR obtained was < 10%, and therefore, the pairwise comparison is consistent and acceptable.

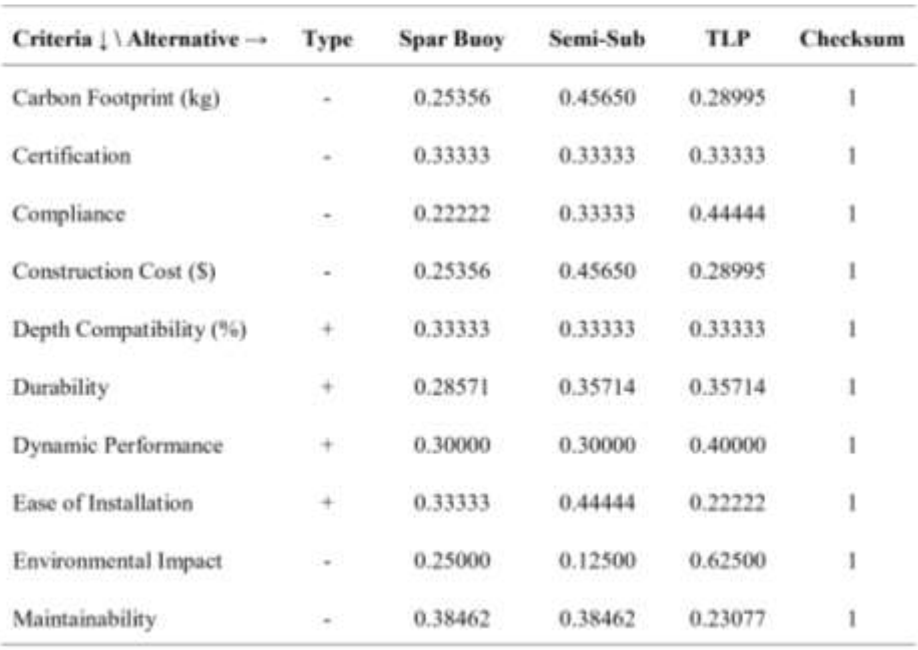
The Result of the AHP Weighted vector obtained from pairwise Comparison

Table 26. Weighted Vector w, from Pairwise Comparison for AHP



Criteria ↓ \ Alternative →	Type	Weights
Carbon Footprint (kg)	-	0.1093
Certification	-	0.0211
Compliance	-	0.0414
Construction Cost ($)	-	0.2603
Depth Compatibility (%)	+	0.1093
Durability	+	0.0414
Dynamic Performance	+	0.1758
Ease of Installation	+	0.0660
Environmental Impact	-	0.0660
Maintainability	-	0.1093
Total		1

Table 27. AHP Normalised Matrix, N



Criteria ↓ \ Alternative →	Type	Spar Buoy	Semi-Sub	TLP	Checksum
Carbon Footprint (kg)	-	0.25356	0.45650	0.28995	1
Certification	-	0.33333	0.33333	0.33333	1
Compliance	-	0.22222	0.33333	0.44444	1
Construction Cost ($)	-	0.25356	0.45650	0.28995	1
Depth Compatibility (%)	+	0.33333	0.33333	0.33333	1
Durability	+	0.28571	0.35714	0.35714	1
Dynamic Performance	+	0.30000	0.30000	0.40000	1
Ease of Installation	+	0.33333	0.44444	0.22222	1
Environmental Impact	-	0.25000	0.12500	0.62500	1
Maintainability	-	0.38462	0.38462	0.23077	1

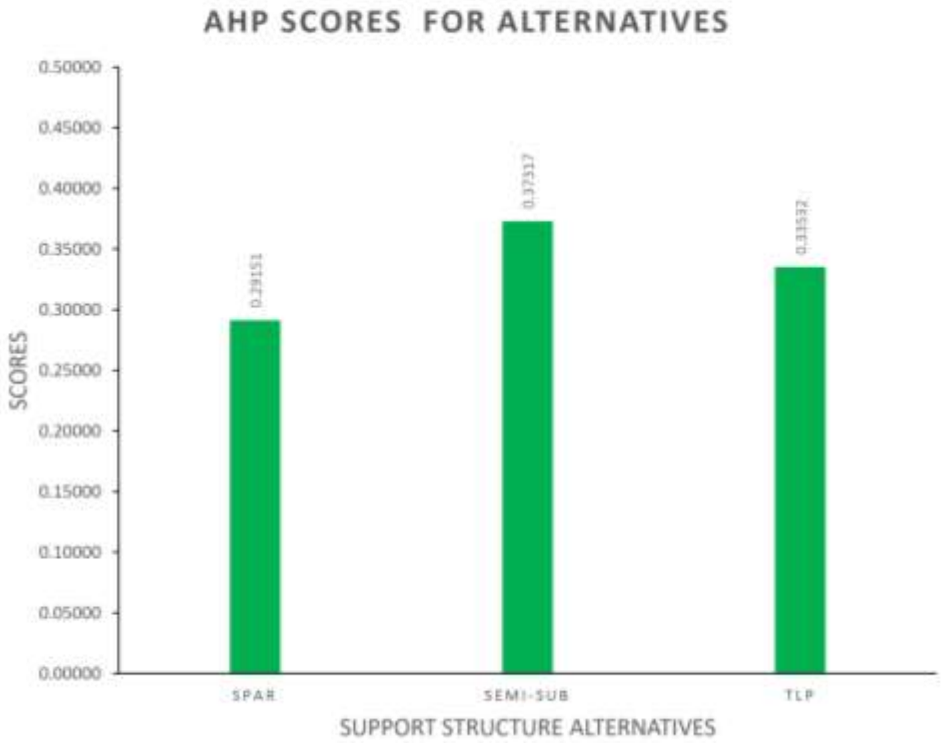


Figure 5. AHP Scores for the alternatives

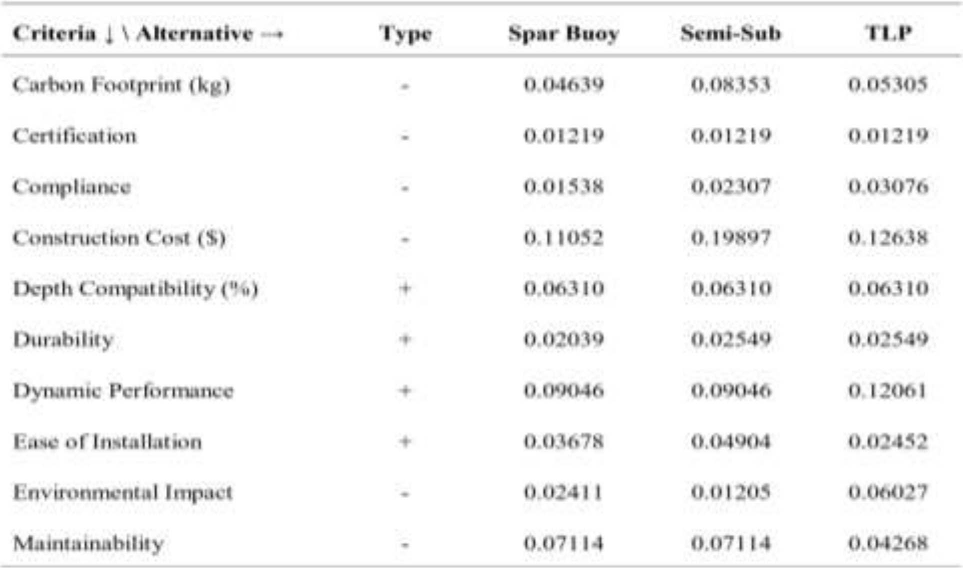
Table 28. AHP Rank

Alternative	**Rank**
Spar Bouy	3
Semi-Sub	1
TLP	2

Discussion

Table 23 Using the pairwise comparison method, the pairwise comparison matrix above was developed. The pairwise matrix provides a comparison of selected criteria in pairs showing how individual criterion performs against each other. This property enables a consistent means of obtaining the criteria weights. Table 24 The pairwise matrix was normalised to create a matrix with values that can be used in computations by making the matrix dimensionless and able to interact with the weight vector. The sum of the normalised matrix of each criterion is 1. The consistency ratio (CR) of 1.88% was obtained for the paired criteria to ascertain that the evaluation and relationship of the criteria being compared were executed logically. Since the pairwise matric was consistent, the calculated weight vector is acceptable and therefore used in obtaining the weighted matrix. It can be observed from the weights that the construction cost is the most important criteria with a 26.03% score relative to the other criteria, as shown in Table 25. The weights obtained from the pairwise comparison are presented in Table 26 and used in computing the AHP scores by multiplying it with the AHP normalised decision matrix in Table 27. The normalisation was verified by checking the sum of the individual normalised elements, which equals 1. Figure 5 shows the plot of the alternatives using the AHP method provides an additional comparison of the alternatives are being compared and aids in decision making. Table 29 gives the optimum solution as the Semi-sub with a score of 37.32% while the TLP and Spar buoy followed respectively with scores of 33.53% and 29.15%.

Table 29. Weighted Normalised Decision Matrix W



Criteria ↓ \ Alternative →	Type	Spar Buoy	Semi-Sub	TLP
Carbon Footprint (kg)	-	0.04639	0.08353	0.05305
Certification	-	0.01219	0.01219	0.01219
Compliance	-	0.01538	0.02307	0.03076
Construction Cost ($)	-	0.11052	0.19897	0.12638
Depth Compatibility (%)	+	0.06310	0.06310	0.06310
Durability	+	0.02039	0.02549	0.02549
Dynamic Performance	+	0.09046	0.09046	0.12061
Ease of Installation	+	0.03678	0.04904	0.02452
Environmental Impact	-	0.02411	0.01205	0.06027
Maintainability	-	0.07114	0.07114	0.04268

Table 31. Distance to PIS (S^+) and NIS (S^-)

Distance↓ /Alternative→	Spar Bouy	Semi-Sub	TLP
C^+	0.04517	0.10479	0.05881
C^-	0.10439	0.05487	0.08913

Table 32. TOPSIS Rank

Structures	Rank
Spar Bouy	1
Semi-Sub	3
TLP	2

Table 33. Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)

Criteria ↓ \ Alternative →	Type	S^+	S^-
Carbon Footprint (kg)	-	0.04639	0.08353
Certification	-	0.01219	0.01219
Compliance	-	0.01538	0.03076
Construction Cost ($)	-	0.11052	0.19897
Depth Compatibility (%)	+	0.06310	0.06310
Durability	+	0.02549	0.02039
Dynamic Performance	+	0.12061	0.09046
Ease of Installation	+	0.04904	0.02452
Environmental Impact	-	0.01205	0.06027
Maintainability	-	0.04268	0.07114

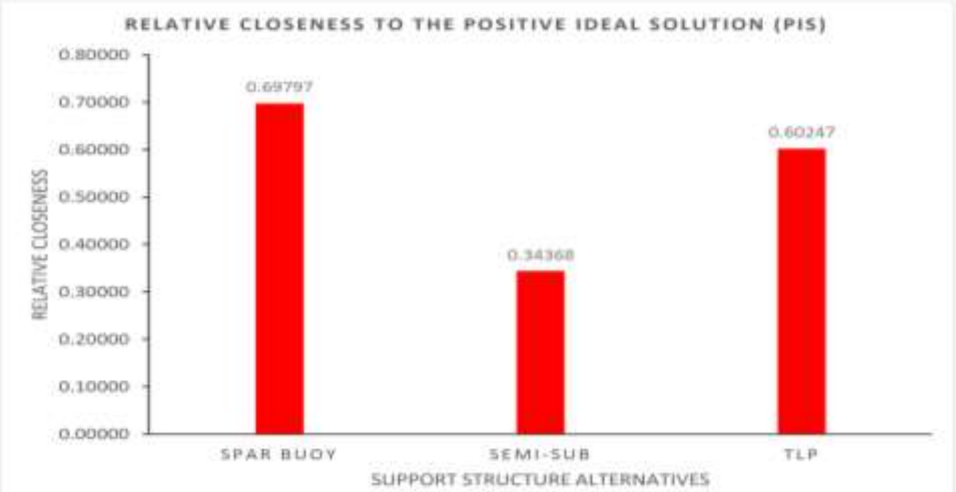


Figure 6. Relative Closeness to PIS (Modified TOPSIS Method)

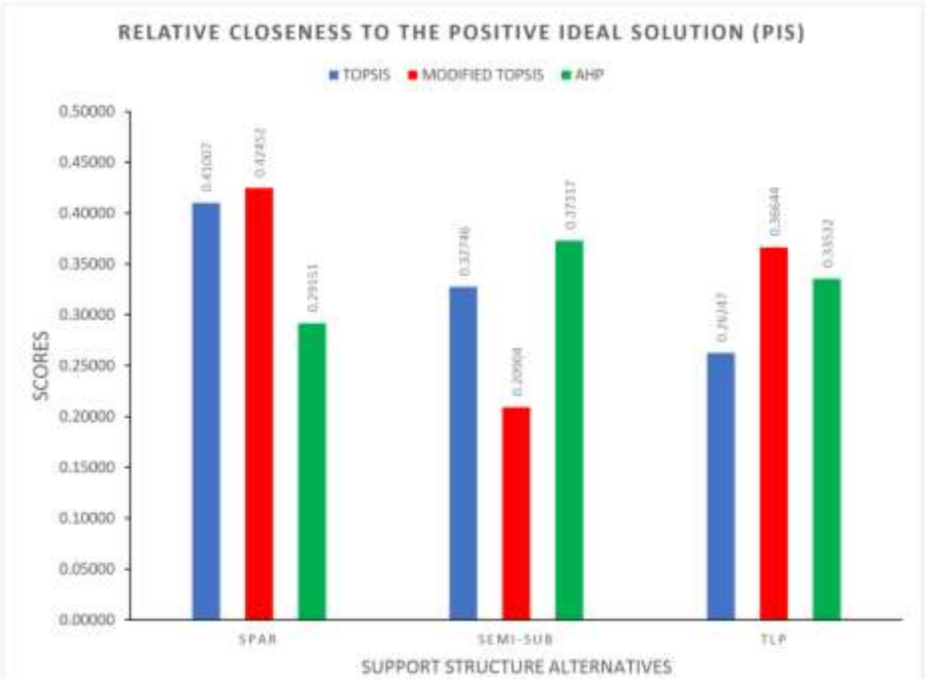


Figure 7. The score for Support Structure alternatives using TOPSIS and AHP Methods

The modified TOPSIS approach employed made use of the weights vector obtained from the pairwise comparison and presented in Table 26. The weights were multiplied by the normalised decision matrix in Table 19 to obtain the weighted normalised decision matrix using the modified TOPSIS approach.

Table 31 shows the calculated positive ideal solution (PIS) and the negative ideal solution (NIS), which shows a range of best-case and worst-case parameters of values per criteria. Table 31 shows the distance to the PIS and NIS of each analyzed alternative; these values were used in calculating the relative closeness of the alternatives to the ideal solution, as presented in Figure 6. The ranks of the alternatives using the modified TOPSIS methodology are shown in Table 32. The modified TOPSIS uses the strengths of both MCDA methodologies (TOPSIS and AHP) to arrive at an optimum solution for the floating offshore wind turbine foundation. This method employs the use of the weighted matrix obtained from the pairwise comparison between the criteria under consideration (AHP) and gives a solution that is farthest from the negative ideal solution (NIS) and closest to the positive ideal solution (PIS) (TOPSIS).

Figure 7 shows the scores obtained from the three methods used to carry out the multi-criteria decision-making analysis (TOPSIS, modified TOPSIS, and AHP), and this shows how all the alternatives rank concerning each other. The Spar buoy option scores 41.00% (TOPSIS), 42.45% (Modified TOPSIS) and 29.15% (AHP) while the Semi-sub option scores 32.75% (TOPSIS), 20.90% (Modified TOPSIS) and 37.32% (AHP) and the TLP options scores 26.25% (TOPSIS), 36.64% (Modified TOPSIS) and 33.53% (AHP). It can be inferred from the results above that the option with the best performance across all decision making approaches is the Spar buoy platform with the TLP being the next preferred and the Semi-sub being the least preferred.

CONCLUSIONS

This paper has presented a new approach to the application of multi-criteria decision making by utilising the pairwise comparison method to obtain the weighted vectors for the TOPSIS MCDM method. The methodology has been applied in the reference case of the decision-making of the selection of an offshore wind support structure deployed in a specific environment that relates to the Nigerian Offshore Oil and Gas environment with abundant wind energy potential, and three support structure alternatives were compared against a set of selection criteria.

Using the TOPSIS methodology, a list of the main requirements against which the different floating support structure configurations are marked has been proposed as follows: carbon footprint, certification, compliance, construction costs, depth compatibility, durability, dynamic performance, ease of installation, environmental impact, maintainability. Based on the relevant literature, an estimate of the mark of each structure against each criterion was carried out.

The method proposed provides valuable outcomes assigning a confidence index (CI) and confidence ratio (CR) on the result of the weight vectors, thereby presenting a weight that is the representative of the paired comparison of each selected criterion. Based on the analysis, it was observed that the Spar buoy floating foundation option performed best and ranked highest in comparison to the TLP and SEMI-sub alternatives that ranked respectively in that other.

Recommendations

A systematic methodology for evaluation and selection of an optimum support structure for offshore wind power with emphasis on three different selected offshore wind turbine support structure options based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method with modification using the pairwise comparison for obtaining the weighted vector and also using the Analytic Hierarchy Process (AHP) method for verification of approach was carried out. A total of ten (10) criteria were selected namely: carbon footprint, certification, compliance, construction costs, depth compatibility, durability, dynamic performance, ease of installation, environmental impact, maintainability and analysed across the three (3) selected floating structural support configurations namely: Spar buoy, Semi-sub and TLP. These methods were able to check for consistency of the weights employed in the analysis and provide a means for validating the weight of attributes using the Consistency Ratio (CR). The following recommendations are list below:

i. Dynamic analysis is carried out on the selected platform types concerning the coupled behaviour of the turbine and support structure for the prevalent environmental loads in Offshore Nigeria using appropriate modelling tools.

ii. Expert judgment is obtained for future MCDM analysis and the modified TOPSIS with the pairwise comparison method used in this dissertation be compared with other MCDM methods.

iii. The Levelized Cost of Energy (LCOE) is to be used in estimating the typical cost of alternatives as against using Construction Cost, which is limited.

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