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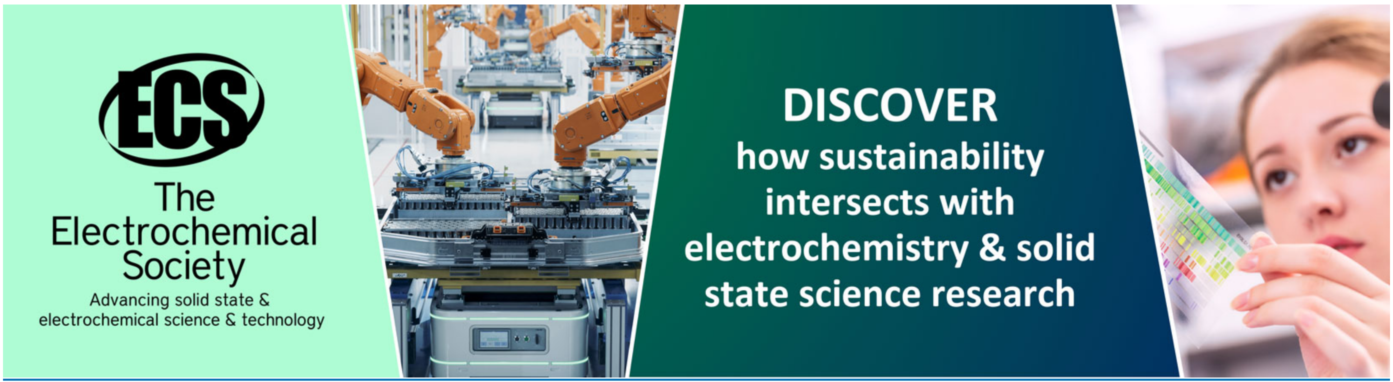

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SUSTAINABLE DESIGN OF ONSHORE WIND TURBINE FOUNDATIONS

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Abstract. In recent times, wind power has emerged as a prominent contributor to electricity production. Minimizing the costs and maximizing sustainability of wind energy is required to improve its competitiveness against other non-renewable energy sources. This communication offers a practical approach to assess the sustainability of wind turbine generator foundations from a 3-dimensional holistic point of view. Specifically, the main goal of this study is to analyse the life cycle impacts of one shallow foundation design comparing three different concrete alternatives: conventional concrete, concrete with 66-80% of blast furnace slags and concrete with 20% fly ash, and then to apply a Multi-Criteria Decision-Making model based on TOPSIS method to evaluate and compare the resulting sustainability of each alternative considered. The study results in a methodology for quantifying sustainability rather than simply qualifying it. Therefore, this methodology can be employed for design optimization, such as geometry and materials, with a sustainable perspective in mind. Specifically in this study, concrete with blast furnace slags emerges as the top-ranked sustainable alternative, followed by conventional concrete in second place, and fly ash option in third position.

1. Introduction

Wind power is a major player in electricity generation, contributing significantly to Europe's power needs with a 15% share. The EU Comission anticipates an even greater role for wind energy, targeting it to make up half of Europe's electricity supply by 2050[1]. On global scale, the World Wind Energy Association (WWEA) reported a robust 13% growth in 2022, resulting in a total installed capacity of 874 Gigawatts [2]. The majority of this capacity increase comes from onshore wind [3], favored for its ease of installation compared to offshore alternatives. To compete with non-renewable sources and sustain the rapid market growth and energy development trend, it is crucial to minimize costs and maximize sustainability.

In 1987, the Brundland Commission coined the term sustainable development, defining it as a way to satisfying the actual needs of the society without compromising the ability of future generations to meet their own needs [4]. Since then, sustainability has guided the scientific community's efforts to assess the impacts of products on society, the economy and the environment. The construction sector, encompassing both building and civil engineering, serves as a notable example of the study and application of sustainability [5-9].

Sustainability has not been consistently applied to all aspects of wind energy. Given the significant capital investment and large-scale production involved in Wind Turbine Generators (WTG) [10], the scientific community has focused its efforts on applying sustainability criteria to the design and location of wind farms [11-14], as well as the positioning and design of WTGs [15-17]. Over the past decades, sustainability has conventionally been evaluated in terms of the environmental impacts derived from human actions. However, current trends in the construction sector indicate a shift towards incorporating economic and social dimensions in sustainability assessments.[18-24]. In the context of foundations, the prioritization of sustainability implementation seems to be diminished, potentially due to their economic impact representing 5-7% of the overall investment in a wind farm [25].

In recent decades, foundation research has focused on the material reduction to save costs and reduce environmental impacts. As a result, progress has been made mainly in the development of tools for design optimization [26] and development of new materials [27]. Moreover, investigations focused on decreasing the carbon footprint [28-29] or analyzing the combined environmental impact of the WTG-foundation [30-31] have been recently conducted.

Despite this partial development, high emphasis shall be put on the assessment of the social dimension of sustainability. Initiatives, such as the Social European Taxonomy, are currently under development aiming to effectively incorporate social and economic aspects in sustainability assessments. Sustainability certification systems for infrastructures, exemplified by ENVISION [32], recognize the economic and social dimensions as integral components for any infrastructure aspiring to promote sustainability. In light of these considerations, it is imperative to develop efficient methodologies that simultaneously incorporate the three dimensions of sustainability in life cycle assessments.

To cope with the actual trends and demands in sustainability assessments, the present paper proposes the application of the recognized methodology defined in ISO 14040 [33] combined with a Multi-Criteria Decision-Making model (MCDM) to quantify and compare the resulting sustainability of three different WTG foundation. Each foundation is designed with a different concrete type, specifically, conventional concrete, concrete incorporating blast furnace slags and fly ash concrete.

The paper is composed of three further sections: materials and methods, results and discussion and finally, the conclusions. The materials and methods section outlines the main objective and details, all the applied methodologies, including the definition of the functional unit, system boundaries, inventory analysis and impact assessment. The results and discussion section presents all the data obtained from the analysis along with corresponding comments. The final section emphasizes key conclusions.

2. Materials and methods

The main objective of this paper is to analyse the life cycle impacts of a WTG foundation built with different concretes from an economic, environmental and social perspective individually. Then, a Multi-Criteria Decision-Making model (MCDM) is applied to evaluate and compare the resulting sustainability of each WTG foundation alternatives considered from a holistic perspective.

For that purpose, the calculation methodology to evaluate the sustainability of civil constructions defined in UNE-EN 17472 [34] is applied. This Standard allows to use the life cycle assessment methodology developed in ISO 14040 [33] and ISO 14044 [35] for all the dimensions of the sustainability. According to ISO 14040 [33], a rigorous LCA assessment must consist of four steps 1) the definition of the objective and scope of the study, 2) an analysis of the inventory to be accounted for, 3) a description of the methods and assumptions used for the impact assessment and, 4) the presentation and discussion of the results obtained.

2.1. Goal and scope

WTG foundations contribute to huge material consumption, primarily concrete. Given that the production of cement is responsible of 8% of global CO_2 emissions [36-37], it becomes imperative to examine the influence of concrete types on the sustainability of foundation design.

For shallow foundations, the most common geometry used around the world is the circular foundation. As it is shown in Figure 1, the circular foundation presents a pedestal area in the center of the concrete mass where the anchor cage (AC) is installed. Then, the height of the slab decreases with constant slope up to the border. Usually, the main designs drivers are 0% ground gap condition or overturning, dimensioning total diameter of the foundation. Total height of the slab and pedestal are defined considering the internal bending moment. Generally three different concrete grades can appear in the concrete volume. Usually, concrete grade C35/45 is used for the slab, C45/50 for the pit (area near the bottom flange of the AC) and C50/60 for the pedestal (area near the top flange of the AC). The main reason is the excessive compression forces which appear concentrated near the anchor templates.

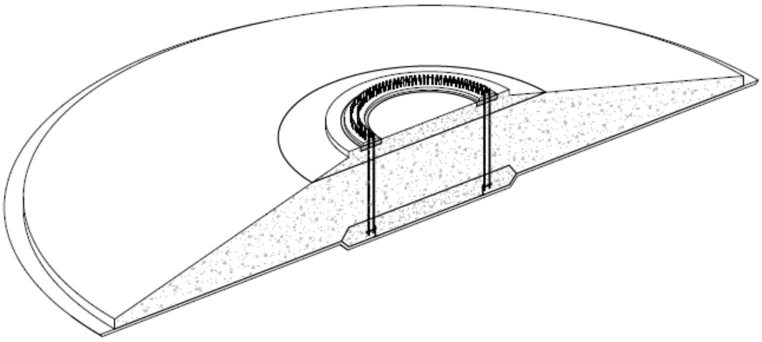

Figure 1. Isometric view of shallow circular WTG foundation

This study aims to assess the life cycle impacts of a particular shallow foundation design, specifically by comparing three alternative concrete options within the slab area (Alternative 1: conventional concrete (CONV, hereafter) Alternative 2: concrete with 66-80% of blast furnace slags (GBFS, hereafter) and Alternative 3: concrete with 20% fly ash (FA, hereafter), and then to apply a Multi-Criteria Decision-Making model for evaluating and comparing the sustainability of each considered alternative. All these three types of concretes are selected taking into consideration the recommendations and required cement type for big reinforced concrete volumes according to Spanish Standards [38-39]. For the sustainability life cycle performance, economic, environmental and social dimensions are simultaneously considered.

2.2. Functional unit

According to ISO 14040[33], a life cycle analysis must be based on the same functional unit for the results of the assessments to be comparable.

In this study, the functional unit is a circular shallow foundation designed for a WTG 5.9MW located in Requena (Valencia, Spain). The design of the functional unit contemplates two different stages: stability and structural integrity. Initially, an analytical calculation is made to define the geometry of the foundation.

In these calculations, the backfill presents a specific weigh of 18.5 kN/m^3 and a soil resistance of 200 kPa. Additionally, the base of the tower presents a diameter of 4.70m connected to the foundation with an anchor cage composed 2x112 M42 10.9 bolts. The WTG loads are defined in Table 1 for 25 years of service life.

Table 1. WTG loads at tower base (Characteristic values)

Load case	**Fz [kN]**	**Fxy [kN]**	**Mz [kNm]**	**Mxy [kNm]**	**Safety Factor**
Characteristic extreme normal loads	7500.00	1200.00	1450.00	155000.00	1.35
Characteristic extreme abnormal loads	7530.00	1143.00	990.00	168500.00	1.10
Quasi-permanent loads	7550.00	900.00	3000.00	123400.00	1.00

According to IEC 64001-6[40] verifications of overturning, sliding, ground gapping, soil stresses and differential settlements are conducted. Specifically, no ground gapping condition for quasi-permanent load is the design driver for this functional unit. The results of no ground gapping verification can be checked in Table 2.

Table 2. Ground gapping verification

Parameter	Results
Eccentricity of WTG foundation	3.14 m
Limit of eccentricity for 0% ground gapping	3.19 m
% of foundation base in contact with soil	100.00 %

The geometry of the foundation is defined in Figure 2 below. The foundation exhibits a total diameter of 25.50 m (Øtot), with a pedestal of 6.5 m (Øped). The height of the foundation is variable, measuring 0.35 m at the border (Hbor) and reaching a total height of 3.10 m at the center (Hslab + Hped), with 0.20 m attributed to the pedestal (Hped). Additionally, to properly allocate the AC, a 0.30m pit is defined in the center (Hpit). The diameter of the pit is the same than pedestal diameter (Øpit).

The backfill is engineered as a structural element. Therefore, its geometry and weight (18.50 kN/m^3) shall be preserved during all the service life. The geometry of the backfill is determined based on a pedestal protrusion of 0.10m and 2% slope.

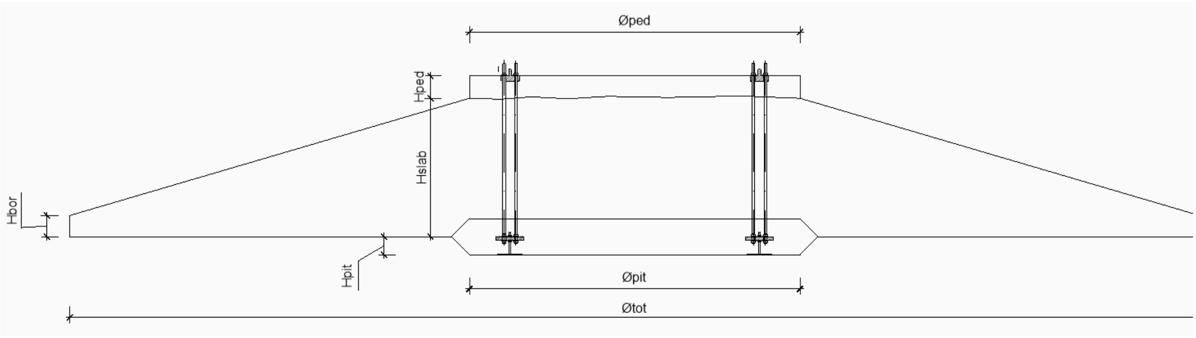

Figure 2. Geometry of the foundation

Once the geometry is established, a Finite Element Model (FEM) is implemented in SAP2000v.24 to analyse internal forces and define the reinforcement layout. Specifically, the FEM is based on shell and frame elements. The concrete material is modelled as linear elastic material type C35/45 according to Eurocode 2[41].

In the last step, boundary conditions are simulated by incorporating soil elasticity through non-linear springs. These springs only experiments force in compression according to the modulus of subgrade reaction (ks,stat=5MPa/m). The outcomes are then extracted as sectional forces and moments along a path aligned with the principal wind direction. The design exclusively accounts for dry conditions, excluding any buoyancy effects. The reinforcement bars have a characteristic yield strength of 500MPa and are arranged in a radial and circumferential layout.

Finally, local stresses calculations are implemented in the anchor cage area to define the concrete grade required in pedestal, pit and slab. The results require a C45/55 concrete grade in pit area, C50/60 in the pedestal area and a slab formed by concrete C35/45. A concise overview of the quantity of each material considered for the three alternatives can be reviewed in Table 3.

2.3. System boundaries

After establishing the functional unit, the system boundaries needs to be delineated in accordance with ISO 14040[33] guidelines to ensure a comprehensive life cycle assessment. For this purpose, the boundary system is constructed using a “cradle to site” approach covering from production of the different construction materials in their respective production centers up to the end of the construction of the WTG foundation.

As a cut-off criterion and considering the comparison-oriented scope of the present assessment, identical processes and common to every alternative have been omitted from the system definition. Consequently, all processes associated with the anchor cage and its assembling, as well as those related to the grout pocket, are excluded. Furthermore, as the foundation is a buried structure inaccessible for maintenance, this particular stage is not factored into the analysis. Figure 3 shows a detail of the system boundaries considered for the analysis presented in this communication.

Finally, the end-of-life stage is not incorporated into the design. Two potential scenarios for the end-of-life stages may arise; a wind farm life-extension or dismantling it. Both situations are right now uncertain[42].

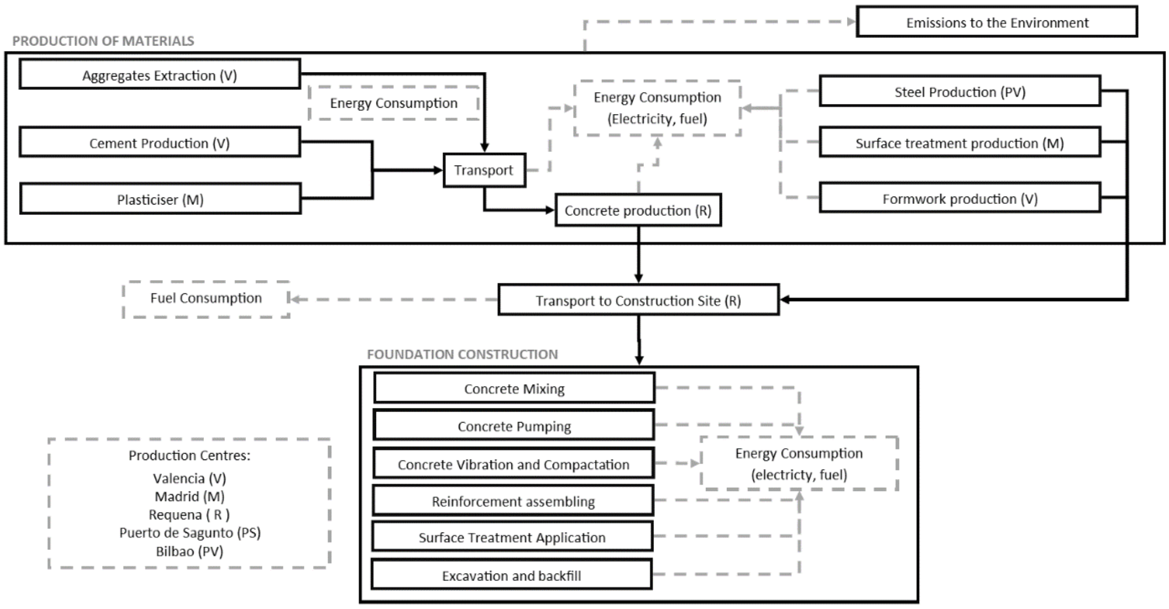

Figure 3. Boundaries of the product system considered for the functional unit

2.4. *Inventory analysis*

All the data required to properly quantify the relevant inputs and outputs of the product system under study are defined in this section. As recommended in ISO 14040 [33], all data used for this purpose have come from accepted sources.

Table 3 presents the different materials used to define the functional unit. These products are the concrete and reinforcing steel used to build the foundation, but also the formwork required for the construction, the backfill to cover the foundation and guarantee its stability and the bituminous paint required to protect the buried structure.

Table 3. Materials used to build the functional unit. Quantities and properties.

Product	Quantity	Properties [39]
Slab concrete C35/45	716.88 m^3	2500 kg/m^3
Pit concrete C45/50	25.44 m^3	2500 kg/m^3
Pedestal concrete C50/60	25.07 m^3	2500 kg/m^3
Lean concrete C20/25	55.84 m^3	2400 kg/m^3
Reinforcing steel B500SD	96696 kg	7850 kg/m^3
Formwork	32.12 m^2	3 uses

Excavation	1362.69 m^3	1850 kg/m^3
Backfill	1268.91 m^3	1850 kg/m^3
Bituminous paint	1070.44 m^2	0.8 kg/m^2

In Table 4, the concrete components used for each concrete considered in the study are defined. The different types of cement considered fulfil the requirements of Spanish Standards [38-39].

Table 4. Concrete components for 1m^3 of concrete.

Concrete mix component	C50/60	C45/55	Blinding concrete	C35/45 CONV	C35/45 GBFS	C35/45 FA
Cement I (kg/m^3)	390	370	220	360	-	-
Cement II/A-V (kg/m^3)	-	-	-	-	-	500
Cement III/B (kg/m^3)	-	-	-	-	330	-
Gravel (kg/m^3)	1020	1020	990	990	990	940
Sand (kg/m^3)	860	864	1035	850	880	750
Plasticiser (kg/m^3)	4.37	4.44	1.76	3.7	3.3	4
Water (l/m^3)	97.50	74	129.80	162	158.4	185

Table 5 specifies the km required for transport of each material used in the concrete mixtures. Transport with truck is considered if distance is lower than 500 km. For higher distances, then train is selected as the main transport.

Table 5. Transport distances in km for each material considered in this study.

Production process	Transport with lorry (km)	Transport with train (km)	Total (km)
Aggregates	58.4	-	58.4
Cement	67.6	-	67.6
Plasticiser	418.5	-	418.5
Concrete	30.2	-	30.2
Steel	30	932.7	962.7

Reinforcing steel	107.5	-	107.5
Bituminous paint	448.7	-	448.7

The inventory data to perform the environmental assessment of each alternative have been collected from the Ecoinvent 3.8 environmental database [43]. Ecoinvent database is a diverse repository with over 20.000 datasets modeling human activities, covering global and regional sectors. The datasets include information on processes, resources used, emissions and resulting products, co-products and wastes.

The economic data to evaluate costs of each of the alternatives throughout the life cycle have been collected from the Spanish construction cost database [44]. The costs of each construction element include the proportional part of the machinery and labour involved in the manufacture of the material and its installation on site. The unit costs of each economic concept are indicated in Euros (€) updated to 2023. Table 6 shows the costs considered for each material.

Table 6. Unit cost of each material.

Material	Cost
Excavation	12.82 €/m^3
Blinding concrete	17.40 €/m^2
Concrete C45/55	116.45 €/m^3
Concrete C35/45 CONV	109.45 €/m^3
Concrete C35/45 GBFS	101.20 €/m^3
Concrete C35/45 FA	129.85 €/m^3
Concrete C50/60	120.45 €/m^3
Reinforcing steel (f_{yk}=500MPa)	1.70 €/kg
Backfill (18.5 kN/ m3)	9.63 €/m^3
Formwork	22.74 €/m^2
Bituminous paint	7.79 €/m^2

Finally, social dimension is focused on workers from different production sites. Special emphasis is put on the problems related to gender discrimination and high unemployment. Local economy is also important since benefits from the economic inflows due to the production and construction helps the region.

Inventory data are gathered through web research from the Spanish National Institute of Statistics [45], Spanish Tax Office database [46] and the official OECD (Organization for Economic Co-operation and Development) databases [47]. To understand the meaning of the social context of the regions involved in the present study in relation to the rest of the regions in the Spanish territory, information has been collected as well on the minima and maxima values to be found in the Spanish regions for each of the social indicators. It is noted that this information does not allow the evaluation of the social impact of a specific activity per se, but does contextualize it. Performance values regarding material production and those related to worker activities are obtained also from [48] and shown in Table 8.

Table 7. Background data on Unemployment and gender discrimination

Data	Requena	Buñol	Sagunto
Unemployment rate (%)	12.87	12.74	15.35
Maximum and minimum national unemployment (%)	7.13-17.05	7.13-17.05	7.13-17.05
Male unemployment (%)	12.30	12.00	11.50
Female unemployment (%)	14.80	14.50	14.30

Table 8. Performance values considered for production and construction activities

Activies	Performance values
Cement	0.165 h/tn
Aggregate extraction	0.1925 h/tn
Concrete production	0.18 h/tn
Concreting	0.35 h/m^3

2.5. *Impact assessment*

The assessment of the environmental life cycle impacts is based on the international ReCiPe 2016 methodology [49]. This method integrates the environmental problem-oriented and damage-oriented approaches by transforming life cycle inventory data into two sets of impact categories: 18 midpoints indicators and 3 end points indicators. In both cases, emissions and resource extractions are translated into corresponding environmental impact scores using characterization factors based on three cultural perspectives, namely individualistic, hierarchical and egalitarian. This analysis adopts hierarchical perspective as the most consensus model and the endpoint approach that considers damage to ecosystem diversity (ED), damage to resource availability (RA) and damage to human health (HH).

In evaluating the economic dimension, the economic resources used in each phase of the life cycle considered are quantified in Euros (€)[50].

Finally, regarding the social dimension, the methodology described by [48] is used which is aligned with the Guidelines for social life cycle assessment of products and organizations 2020 reported by the United Nations[51]. Local employment is the indicator selected to quantify the social dimension as indicated following equation (1):

$$x_{local\ employment} = \frac{y_{local} - Y_{min}}{Y_{max} - Y_{min}} \tag{1}$$

Where:

- $y_{local}$is the unemployment rate at the activity location.
- Y_{max} is maximum national unemployment rate.
- Y_{min} is minimum national unemployment rate.

A summary of the indicators considered for each sustainability dimension considered is exposed in Table 9.

Table 9. Sustainability indicators considered in this study.

Sustainability Field	Criterion Id.	Criterion description	Impact assessment
Environment	1	Damage to human health	ReCiPe methodology.
	2	Damage to ecosystem	ReCiPe methodology.
	3	Damage to resource availability	ReCiPe methodology.
Economy	4	Construction costs	BoQ – Spanish construction data base.
Social	5	Local employment	[48]

3. Results and discussion

The results obtained in this study are exposed in this section. Section 3.1, 3.2 and 3.3 present the results of the analysis for each considered dimension, including the outcomes for each indicator. Finally, section 3.4 shows the result of the multicriteria analysis that provides a quantitative assessment of the sustainability for each studied foundation alternative.

3.1. LCA results

The environmental impact resulting from each design analysed in this study are shown in Figure 4. The higher the score obtained, the greater the impact. Based on the indicators, there is a noticeable disparity between the impact on the ecosystem and resources. Almost all the alternatives affect the ecosystem twice as much as they do resources. As for human health, all the alternatives impact it to a third compared to their impact on the ecosystem.

Regarding the comparison among the analysed alternatives, the results exhibit a similar trend the different concrete types analyzed. GBFS emerges as the optimal choice, displaying the lowest score in each impact category. The second alternative, CONV, ranks as the second-best in terms of environmental impacts, while FA option is considered the least favourable.

Nevertheless, it is worth noting that the difference between alternatives for each indicator is very small. When comparing the results of both GBFS and FA with CONV, it is observed that, in regard to ecosystem quality, they show a 2.46% decrease and a 1% increase in impact, respectively. For the resources, the percentages are 0.2% decrease and 1.4% increase, respectively. Finally, the impact on human health for GBFS compared to CONV is 6% lower, whereas for FA compared to CONV, it is 1.4% higher.

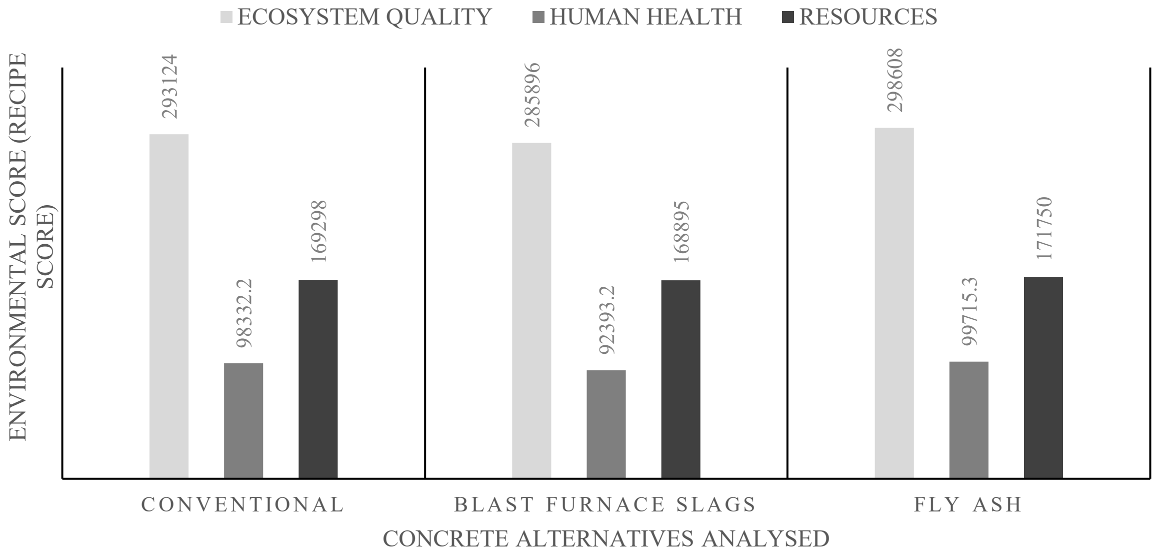

Figure 4. Environmental results obtained for each alternative and indicator.

3.2. Economic results

Figure 5 exposes the economic results obtained for each alternative analysed. These results clearly show that the alternatives to conventional concrete incur higher costs. The economic comparison reveals CONV is the most cost-effective solution, with a total budget of approximately 283.000€. Following this, GBFS proves to be 2.09% more expensive than CONV. Finally, FA emerges as the last economically favorable option, exhibiting a higher cost difference of 7.26% compared to CONV.

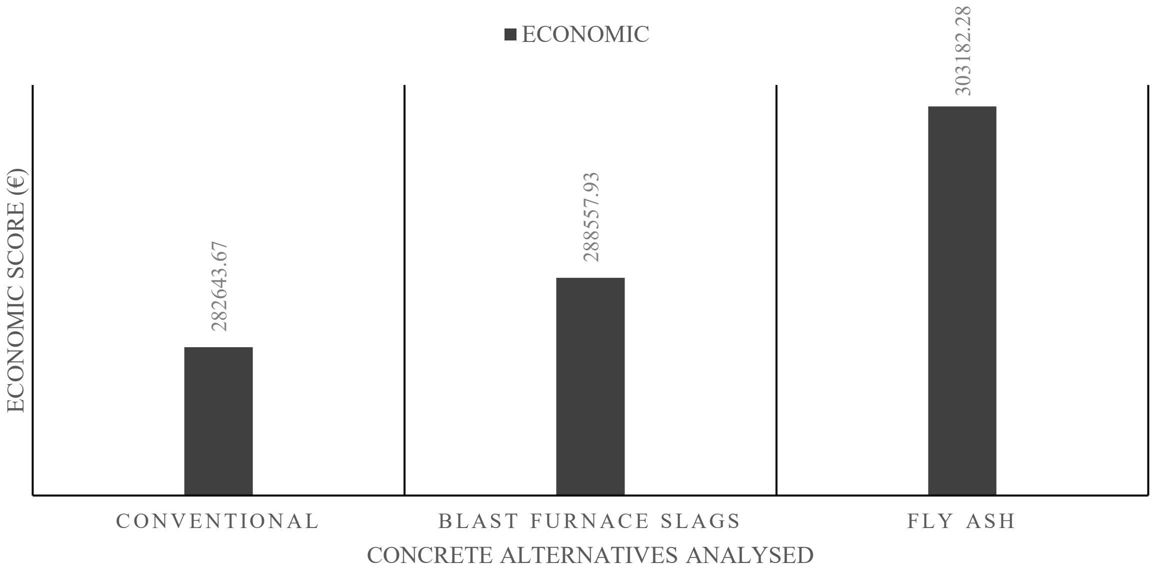

Figure 5. Results obtained for economic indicator per functional unit.

3.3. *Social results*

The employment generated through building a foundation with each of the concrete types considered in this study is shown in Figure 6. The social impact of each alternative is comparable between CONV and FA. However, it is more pronounced for GBFS. Despite these differences, the results indicate that using a concrete different from the conventional generates more employment.

Comparing the results shown in Figure 6, FA shows a 0.595% higher employment generation than CONV, whereas GBFS demonstrates significantly higher results of 43.19%. It is important to consider that these results are strongly dependent on the production centre as they rely on regional unemployment rates.

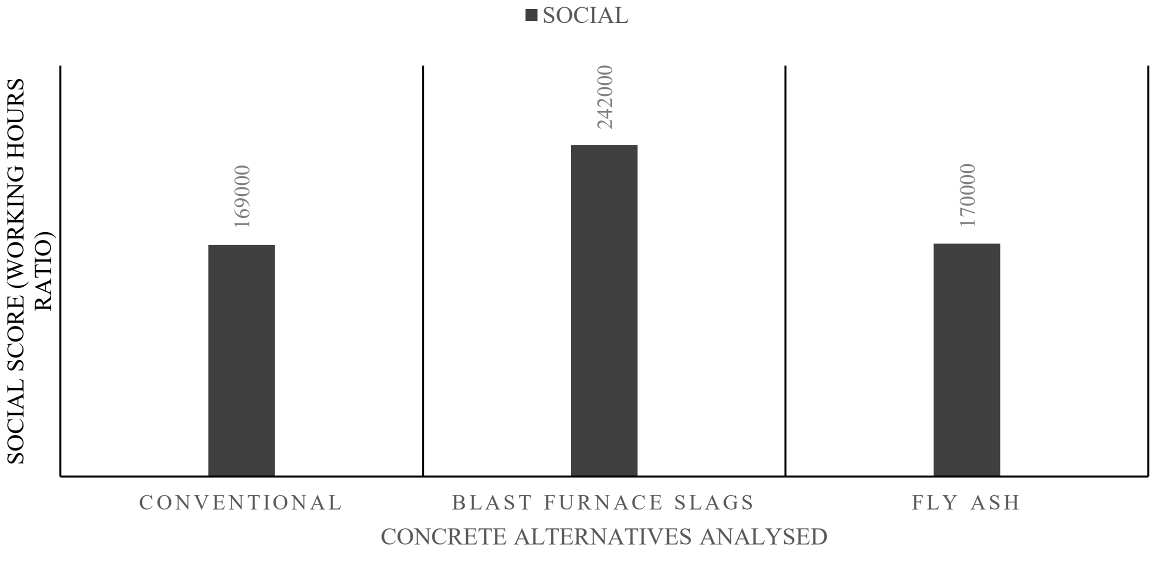

Figure 6. Results obtained for social indicator in each alternative analysed in this study.

3.4. Multicriteria Decision-Making Procedure

The last stage of the sustainability assessment consists of aggregating the life cycle performance results, for each sustainability dimension and each alternative, into a single three-dimensional index that allows ranking preferences. Therefore, the results obtained for the economic, environmental and social dimension are aggregated using a distance-based method called TOPSIS, which is the second most popular technique used to deal with MCDM problems [52].

The weightings of each criterion are determined through the application of the Analytical Hierarchy Process (AHP) [53], which has been widely used to derive the relative relevance of each criterion involved in MCDM assessments related to infrastructure projects based on induvial preferences of decision-makers [54][55]. In this study, three experts in wind energy and civil engineering have been involved in the AHP. These experts have 5, 10 and 20 years of experience in the respective fields. The voting power coefficient for each expert is calculated based on the years of experience, reflecting their expertise in the field. The weights considered for the analysis are exposed in Table 10 and the results for the sustainability analysis in Figure 7.

Table 10. Weights considered for each indicator.

Indicator	Weight
Ecosystem quality	0.11
Human health	0.25
Resources	0.22
Economy	0.17
Social	0.25

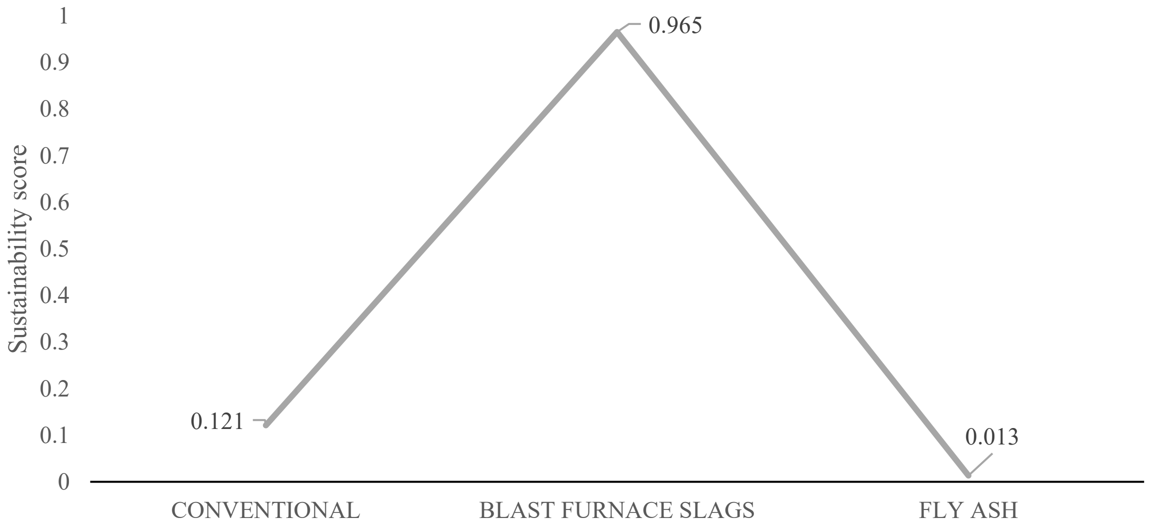

Figure 7. TOPSIS results.

In view of the results, it can be affirmed GBFS is the option that has proven to be the most sustainable of the three analysed for this particularly study, followed by CONV and FA. According to TOPSIS, Positive Ideal Solution (PIS) is defined as the sum of all the best value that can be achieved for each indicator. It can be observed that GBFS is positioned very close to the Positive Ideal Solution, as the obtained result is nearly unity.

4. Conclusion

The present communication proposes a methodology to assess the sustainability of WTG foundation designs according to the recognized international guidelines and ISO 14040[33]. In view of the results, the main conclusion is that GBFS material presents higher sustainability ratios than CONV and FA for this specific case.

- The GBFS alternative outperforms both FA and CONV in terms of environmental impacts regarding the three primary indicators (Human health, ecosystem quality and resources).
- Regarding costs, CONV proves to be 2.09% more economical than GBFS and 7.26% more cost-effective than FA.
- Considering social indicators based on workers indicator, the GBFS is more prominent than CONV and FA. Both, CONV and FA exhibit comparable social impact. These results are strongly related to the location of the concrete production centres.
- Regarding TOPSIS outcomes, GBFS emerges as the top-ranked sustainable alternative, followed by CONV in second place, and FA in third position.

To sum up, this communication offers a practical approach to assess the sustainability of WTG foundations from a 3-dimensional holistic point of view. In particular, following objectives may be drawn:

- The communication presents a methodology for quantifying sustainability rather than simply qualifying it. Therefore, this methodology can be employed for design optimization, such as geometry and materials, etc, with a sustainable perspective in mind.
- The presented methodology can be easily automated.
- As results shown, the ideal economic design point may not align with the optimal environmental design point. Both dimensions need to be considered simultaneously.
- The social dimension is essential and has the potential to influence the design when it is integrated with both the environmental and economic dimensions.

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