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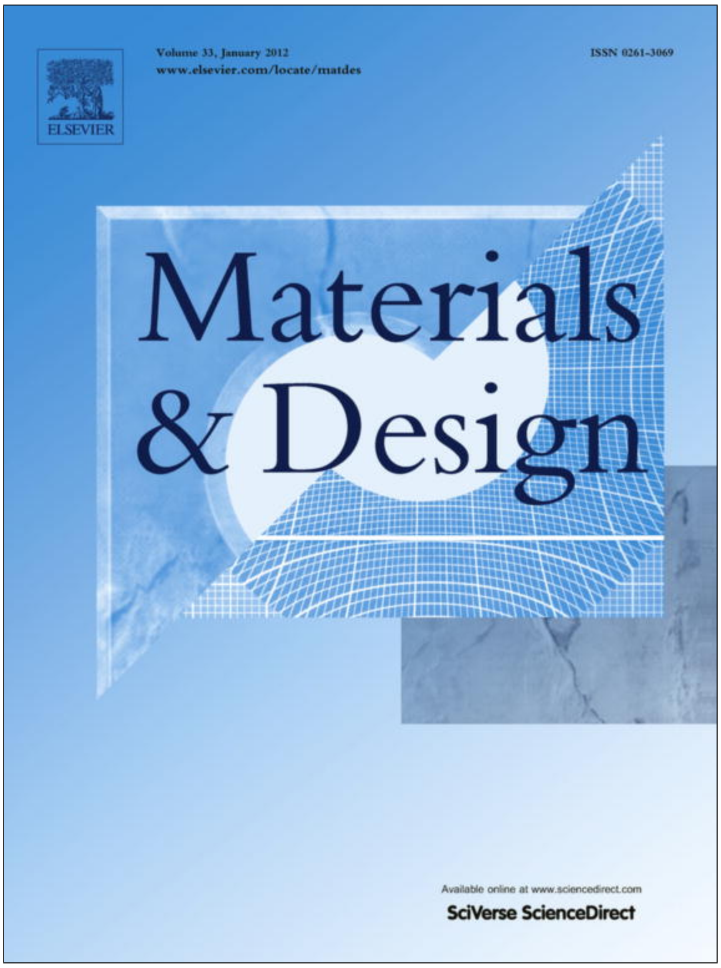
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Multi-objective material selection for wind turbine blade and tower: Ashby's approach

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ABSTRACT

The world today is continuously striving towards carbon neutral clean energy technology. Hence, renewable energy sources like wind power system is increasingly receiving the attention of mankind. Energy production is now no more the sole criterion to be considered when installing new megawatt (MW) range of turbines. Rather some important design parameters like structural rigidity, cost effectiveness, life cycle impact, and, above all, reduced mass come into the scenario from new installation point of view. Accordingly, these issues are followed up in this article from wind turbine design perspective. The study, at the outset, aims to establish blade and tower material selection indices on the basis of inherent structural constraints and potential design objectives. Next, it highlights entire blade and tower material selection aspects for small and large scale horizontal axis wind turbines, both for onshore and offshore application. Finally, it distinguishes advanced blade and tower materials in agreement with multiple constraint, compound objective based design optimization procedure. Findings from the study can be deployed to harness massive scale wind energy from structurally more promising, economically more competitive and environmentally more clean and green turbines.

1. Introduction

Wind power industry is experiencing a spectacular growth in recent days. With government thrust and deployment of latest technological know-how, new megawatt (MW) range of turbines (specially offshore ones) have eventually been evolved that are even larger than latest largest aircrafts. Extended plans have henceforth been envisaged to design 20 MW wind turbine along with extreme strength to mass ratio, high degree of reliability, and overall mass reduction [1]. Apart from mass and structural optimization, cost curtailment, embodied energy diminution and carbon footprint minimization are substantially important parameters for new generation design of such massive structures. More recently, the design space has also been expanded abundantly due to increasing number of materials. A plethora of new materials has been discovered by research community that implies further competitive design to such industries. Well-known estimates now count the number of engineering materials far more than 80,000. Many traditional materials that once ran the wheels of industrial revolution have, thus far, been thrivingly replaced with more suitable, superior quality material families. Wind turbine industry has, simultaneously, deployed better quality alloys, composite materials and sandwich structures in the past decade. Though these materials are meeting today's industry demand, there is still ample opportunity to optimize future large scale onshore and offshore wind turbine material selection process as green and recyclable composite, sandwich materials are increasingly entering the market [2] and their per unit cost is steadily declining thanks to advanced manufacturing and process technologies. Further to that, price of the traditional ones is rapidly escalating simultaneously due to inflationary onslaughts. Hence, a renewed interest in wind turbine material selection process is burgeoning in this concourse. Besides, several life cycle analysis (LCA) techniques have also been evolved lately that can evaluate cradle to grave inventory and impact assessment of an entire stand-in technology. These LCA techniques lead to environmentally more sensible design at the time when green house gas (GHG) emission, global warming and UN Intergovernmental Panel on Climate Change (IPCC) issues have notably appeared as fervent topics of the hour. Though wind power, being one of the most ubiquitous and unpolluted, in-exhaustible and sustainable energy on planet earth, contributes very little to the surrounding environment during its operation phase, the base material production processes extensively affect the environment due to enormous size. Such grim realities ultimately propel to more environmental conscious material selection for tomorrow's wind turbines with more clean and green outlook. Additionally, commercial scale wind farm development has already expanded to over 80 countries with 175 GW rated capacity while some European countries like Denmark is now planning to meet at least 50% of its electricity demand

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Nomenclature

ρ_a	density of air (kg/m^3)	M_{edge}	blade edgewise bending moment (N m)
ρ	density of material (kg/m^3)	M_{bend}	bending moment at tower base (N m)
Ω	blade rotational speed (rpm)	MI	material index
σ_f	fatigue strength of material (MPa)	P	buckling load on tower (N)
σ_{flap}	flapwise bending stress (MPa)	R	blade radius (m)
σ_{shell}	edgewise bending stress (MPa)	T	rotor thrust (N)
A_2	rotor swept area (m^2)	V_1	free stream wind velocity (m/s)
C	distance between top and neutral surface (m)	V_2	wind velocity through rotor (m/s)
C_C	coupling constant	c	average chord length (m)
C_{CO}	cost per unit weight (USD/kg)	d	average chord width (m)
C_{CO_2}	carbon footprint per unit weight (carbon footprint/kg)	m_{blade}	blade mass (kg)
C_{EE}	embodied energy per unit weight (embodied energy/kg)	m_{spar}	spar mass (kg)
D	tower mean outer diameter (m)	m_{shell}	shell mass (kg)
D_{bottom}	tower bottom outer diameter (m)	m_{tower}	tower mass (kg)
D_{top}	tower top outer diameter (m)	$\dot{m}$	wind mass flow rate (kg/s)
$\dot{E}_{extracted}$	extracted power from rotor (W/s)	r	radial distance from rotor axis to blade element (m)
F	aerodynamic force on rotor (N)	$t/2$	blade shell thickness (m)
I	area moment of inertia (m^4)	t	tower mean wall thickness (m)
K_{IC}	fracture toughness (MPa $\sqrt{m}$)	w_i	weight factor percentage
L	tower length (m)		
M_{flap}	blade flapwise bending moment (N m)		

from wind power by 2025 [3]. As worldwide electricity demand is doubling itself in every 10 years, the contribution of wind power will also continue to surge simultaneously. Hence, a through exercise on wind turbine material selection process is sine-qua-non that will help explore new materials that can withstand wind turbine structural demands with even competitive mass, price and environmental impact than the currently used ones.

2. Material selection principle for horizontal axis wind turbine

Over a design life of 20 years, wind turbine endures highly turbulent aerodynamic load and numerous fatigue producing stress cycles. A large turbine in its 30–70 rpm revolution usually experiences 10^8–10^9 cycles over its lifetime with an annual 4000 h operation [4]. This may be compared to many other manufactured items that would be unlikely to experience more than 10^6 cycles over their entire lifecycle. On top of the aerodynamic loading, there is significant gravitational, centrifugal, gyroscopic, inertia, and brake loads. Interaction of these loadings together with blade aerodynamic profile makes the real-time load scenario very complex. Designing such an aerodynamic structure simultaneously for decreased mass, cost, environmental impact and embodied energy obviously leads to a multiple constraint and compound objective based optimization problem.

Within the last decades, different material selection and optimization procedures have been explored in design community. Out of these, Zhu et al. [5] proposed a knowledge-based design support system (KDSS) for optimal material selection of energy absorbers based on axiomatic design principle [6], embodying three functional requirements (so called ‘what we want to achieve’ factors) with corresponding, relevant design solutions (‘how to achieve’ factors). A purpose-built software, Swinburne Energy Absorber Design Supporter (SEADS), is used in this confluence to demonstrate the procedural material selection aspects. The functional requirements include knowledge based optimal design search destined for searching and ranking the materials, knowledge-based optimal design calculation that influences the selection if appropriate data are unavailable and concurrent ‘supporting knowledge demonstration’ process in the form of user guide, video and/or failure analysis which guides the entire decision compromise paradigm.

In another article, Waterman et al. [7] evaluated various existing computerized material data and information systems in pursuit of further rationalizing and streamlining the concomitant objectives and requirements of the materials and design engineers. Accordingly, Sapuan [8] highlighted the genuine importance of computer aided material selection systems with added emphasis on diverse knowledge base material selection procedures with their individual voluntary selection spaces (e.g. composite, plastic or entire material genre like cambridge engineering selector (CES) database). Distinct knowledge sharing patterns are explained in addition to a concurrent analysis on how knowledge based system (KBS) contributes towards advanced material selection methods, product design and its subsequent modification, development. Apart from a commentary on companion software packages, composite material based KBS systems drew enhanced attention due to their ever-increasing usage in today’s design realm. In turn, Sirisalee et al. [9] focused on multi-objective optimization which is hinged on utility function approach with trade-off surfaces and its attributive Pareto front, dominated solution and no-dominated solutions. The trade-off surfaces and their tangential material contours offer the best compromising solutions between different conflicting objectives, a recurrent manifestation in design problems. The study demonstrated one disk brake caliper and another mini disk player casing material selection strategy based on conflicting objectives which provide sound representation of the trade-off surfaces only for maximum three objectives though the same utility function approach can be addressed for any number of objectives analytically.

However, a list of these different material screening tools can be categorized in five major sub-classes, viz., artificial intelligence based method, cost per unit property method, questionnaire based method, materials in products selection (MiPS) tools and index and chart based methods [10,11]. Out of these, index and chart based method and, more specifically, the Ashby material selection approach is applied in this discourse to explore optimal wind turbine blade and tower material selection. Ashby approach, in essence, first translates the design necessities into some performance objectives. Then, it screens out the unsuitable materials; surviving materials are, henceforward, ranked out to get the best materials according to the desired objective [12,13]. Objectives are basically aims or targets that are achieved throughout the design exercise. The minimum or maximum levels of property values, to which these objectives are achieved, are dictated by constraints. The objective function ultimately takes a form of $P = P(F, G, M)$; where F, G, M indicate functional, geometric and material parameters. For specific values of F and G, performance function, P can be improved by optimizing the appropriate material parameter, M.

Earlier, another research group applied this approach for horizontal axis wind turbine material selection [14]. The study, however, only considered rotor and did not envisage any flapwise or edgewise bending load upon the blade structure. It was, additionally, only a mass based optimization study and an analysis on tower did not get proper attention which is the heaviest component of wind turbine. Hence, a multi objective material selection study is pursued in this article on both blade and tower structure based on four conflicting objectives, viz., minimization of mass, carbon footprint, material cost and embodied energy.

3. Blade material selection methodology, results and discussion

3.1. Compound objective based material indexing

The most important loads experienced by onshore or offshore wind turbine blades are those associated with flapwise and edgewise bending [4]. During a normal operation cycle, the blades are oriented in such a way that their leading edge encounters the wind. Thus, the effective wind direction experienced by the blades is in the rotational plane of the rotor though the real-wind direction is orthogonal to it. Accordingly, flapwise bending load tends to provide rotor out-of-plane deformation in the direction parallel to the axis of rotation while edgewise bending occurs in the plane of rotation. These flapwise loads are mostly carried by blade spar while edgewise ones are carried by outer shell structure.

A schematic of a horizontal axis wind turbine blade is as shown in Fig. 1. A three bladed horizontal axis wind turbine (HAWT) with blade length, R, average chord length, c, average chord width, d, and shell thickness, $t/2$ is considered herewith an optimal aerodynamic shape to determine design material index. Density of air and blade material is denoted by ρ_a and ρ, respectively. Some structural assumptions are made in this concourse according to industry guidelines that are as follows [15,16]:

- Average chord width, d, is one-fifth of average chord length, c.
- A spar with a square cross-section is used to increase the bending rigidity. Each side of the spar equals to one-third of the average chord length, c.
- Thickness of the spar equals to 10% of each spar side, $c/3$.
- Thickness of the shell is equivalent to 10% of average chord width, d.

Consequently, the spar mass, m_{spar} can be estimated as such:

$$m_{spar} = \left\{ \left(\frac{c}{3}\right)^2 - \left(\frac{0.8c}{3}\right)^2 \right\} R\rho = 0.04c^2 R\rho \quad (1)$$

whereas shell mass, m_{shell} is symbolized as:

$$m_{shell} = \rho ctR = 0.0464c^2 R\rho \quad (2)$$

Eqs. (1) and (2) are the objective functions for spar and shell mass minimization.

With reference to blade root, flapwise bending moment amounts to the product of thrust force per blade times 2/3 of the radius. Accordingly, for a conventional three bladed horizontal axis turbine, the flapwise moment expressed as:

$$M_{flap} = \frac{2\left(\frac{4\pi\rho_a R^2 V_1^2}{9}\right)R}{9} = \left(\frac{8}{81}\right)\pi\rho_a V_1^2 R^3 \quad (3)$$

In turn, the bending moment in the edgewise direction at the root of a single blade can be derived from rotor torque:

$$M_{edge} = \frac{\dot{E}_{extracted}}{3\Omega} = \frac{0.593\left(\frac{1}{2}\dot{m}V_1^2\right)}{3\Omega} = \frac{0.067\rho_a A_2 V_1^3}{\Omega} \quad (4)$$

Next, flapwise bending load is considered as a design constraint for spar material as this load is mainly sustained by spar. Similarly, edgewise load will be considered shell material design constraint as this load is primarily carried by outer shell structure, as shown in Fig. 2. Blade length (R) is assumed fixed variable and chord length, average chord width and spar thickness are assumed free. Thus, the maximum flapwise stress due to bending at the root of blade can be expressed as:

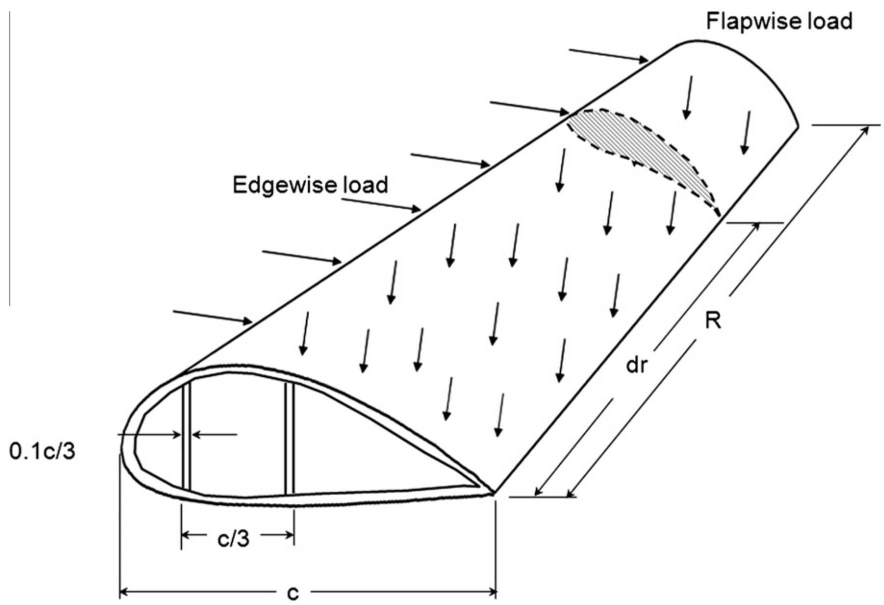

Fig. 1. Schematic diagram of a blade.

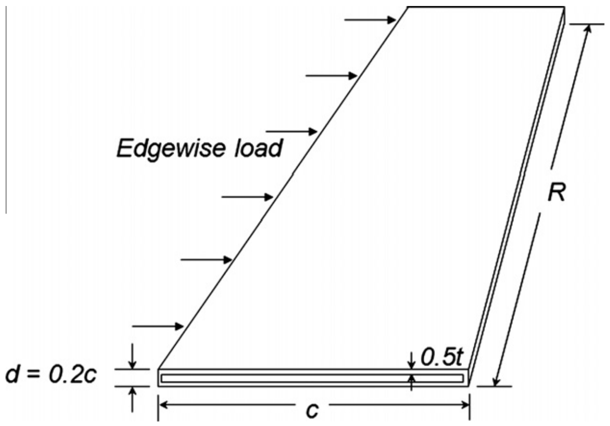

Fig. 2. Shell geometry approximation of the turbine blade.

$$\sigma_{flap} = \frac{M_{flap}C}{I} = \frac{270.5M_{flap}}{c^3} \leqslant \sigma_f$$
$$\Rightarrow c = \left(\frac{270.5M_{flap}}{\sigma_f}\right)^{\frac{1}{3}} = \left(\frac{26.72\pi\rho_a R^3 V_1^2}{\sigma_f}\right)^{\frac{1}{3}} \tag{5}$$

where C is the distance from the neutral axis, I is the second moment of area of blade cross section at root and σ_f indicates fatigue strength of the material.

Next, maximum edgewise stress due to bending at the root of the blade can be expressed as:

$$\sigma_{shell} = \frac{M_{edge}C}{I} = \frac{M_{edge}\left(\frac{c}{2}\right)}{0.002c^4} = \frac{250}{c^3}\,\frac{0.067\rho_a\pi R^2 V_1^3}{\Omega} \leqslant \sigma_f$$
$$\Rightarrow c = \left(\frac{16.5\pi\rho_a R^2 V_1^3}{\Omega\sigma_f}\right)^{\frac{1}{3}} \tag{6}$$

At the end, spar and shell mass are summed up to get total blade mass and associated material index. According to Eqs. (1)-(6):

$$m_{blade} = m_{spar} + m_{shell} = 0.04c^2R\rho + 0.0464c^2R\rho$$
$$= (A+B)\frac{\rho}{\sigma_f^{2/3}} \tag{7}$$

where $A = 0.04R(26.72\rho_a\pi R^3V_1^2)^{\frac{2}{3}}$; $B = \frac{0.0464R(16.5\rho_a\pi R^2V_1^3)^{\frac{2}{3}}}{\Omega^{2/3}}$.

Hence, the material index for minimizing the blade mass appears the form:

$$MI_{blade,mass} = \frac{\rho}{\sigma_f^{2/3}} \tag{8}$$

The blade mass can be decreased by minimizing the value of the material index $\rho/\sigma_f^{2/3}$. Similarly, the material index for blade carbon footprint, embodied energy and price minimization can be achieved by replacing ρ with ρC_{CO_2}, ρC_{EE} and ρC_{CO} whereas C_{CO_2} indicates total carbon dioxide produced and released into the atmosphere as a consequence of per unit material production (kg/kg), C_{EE} indicates energy content of the material (MJ/kg) and C_{CO} indicates material cost (USD/kg).

3.2. Final blade material selection by normalized surface and weight factor approach

At this setting, material optimization intrinsically turns into a conflicting objective problem as materials with higher fatigue strength can maintain higher carbon footprint, while materials with high densities often exhibit lower embodied energy, in turn, materials with high price can maintain lower carbon footprint. So the material indexing should consort with some trade-off studies where a base material will help expedite the entire material selection process depending on corresponding property comparisons. Accordingly, glass fiber reinforced epoxy, as being one of the mostly used blade materials in today's multi-megawatt wind turbine, has been used as base material. Comparatively, the blade mass made from an alternative material differs from one made of glass fiber reinforced epoxy by the factor:

$$\frac{m_{new}}{m_{\mathrm{GFRP}}} = \frac{(A+B)\rho_1}{\sigma_{f_1}^{2/3}} * \frac{\sigma_{f_2}^{2/3}}{(A+B)\rho_2} = \frac{212\rho_1}{\sigma_{f_1}^{2/3}} \tag{9}$$

Similarly, blade carbon footprint, embodied energy and total cost made from an alternative material differs from one made of glass fiber reinforced epoxy by the factor:

$$\frac{CO_{2,new}}{CO_{2,\mathrm{GFRP}}} = \frac{27.02\rho_1 C_{CO_2,1}}{\sigma_{f_1}^{2/3}} \tag{10}$$

$$\frac{EE_{new}}{EE_{\mathrm{GFRP}}} = \frac{1.89*10^{-6}\rho_1 C_{EE,1}}{\sigma_{f_1}^{2/3}} \tag{11}$$

$$\frac{CO_{new}}{CO_{\mathrm{GFRP}}} = \frac{10.50\rho_1 C_{CO,1}}{\sigma_{f_1}^{2/3}} \tag{12}$$

Material properties like density, fatigue strength, per unit carbon footprint, embodied energy and cost of glass fiber reinforced epoxy are taken from Cambridge Engineering Selector (CES) 2010 database [17]. In addition to the existing material indices, a limit based search criterion is implemented to sort out superior materials:

$$\sigma_f \geqslant 50\ \text{MPa (for small blade)};$$
$$\geqslant 150\ \text{MPa (for large blade)} \tag{13}$$

$$K_{IC} \geqslant 5\ \text{MPa}\sqrt{\text{m}}\ \text{(for small blade)};$$
$$\geqslant 15\ \text{MPa}\sqrt{\text{m}}\ \text{(for large blade)} \tag{14}$$

whereas σ_f, K_{IC} represent fatigue strength and fracture toughness, respectively. Due to variation in aerodynamic load and fluctuation in turbulence in varying height (wind shear effect), the limit based search criterion is addressed differently for small (<100 kW) and large scale turbine blades. A maximum fatigue strength value of 50 MPa at 10^7 cycles and fracture toughness value of 5 MPa $\sqrt{\text{m}}$ would be reasonably fine for small blades in less turbulent regions, while for larger ones, 150 MPa fatigue strength and 15 MPa $\sqrt{\text{m}}$ fracture toughness are considered as minimum limiting value according to certification guidelines [18]. Accordingly, a larger horizon of materials appears to be competitive for small scale turbine blades in comparison to their larger counterparts.

Based on Eqs. (7)-(14), six normalized surfaces are plotted in CES for larger blade category, as evident in Figs. 3–8. Fig. 3 highlights some materials that exhibit more competitive mass and carbon footprint with respect to reference material (GFRP composite).

For instance, intermediate modulus (IM) carbon fiber reinforced polyether ether ketone (PEEK) composite can design same size wind turbine blade with only 25% weight and it, simultaneously, reduces carbon footprint by 50%. Low alloy steel, 0.42C, 300M, in turn, provides 50% carbon savings but increases the weight nearly 80%. Similarly, beryllium alloy grade I-250 ensures 30% mass savings but it increases the blade carbon footprint almost 13 times. Based on relative mass versus cost index log–log plot, Fig. 4 features materials from both composite and engineering alloy family perform better than prevailing glass fiber reinforced epoxy material. For example, S-glass fiber reinforced epoxy material provides 60% mass and cost savings, on average. Epoxy/high strength carbon

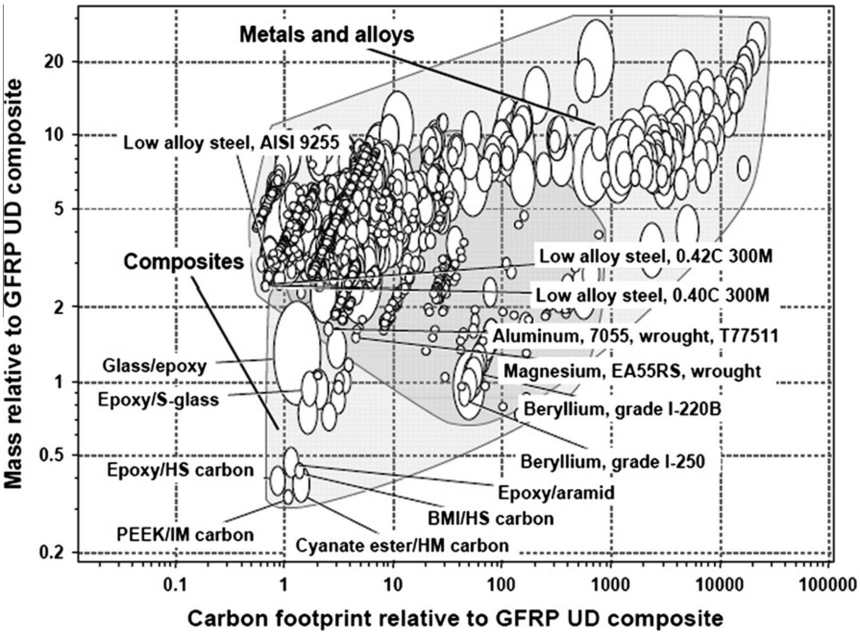

Fig. 3. Normalized mass and carbon footprint of blade material.

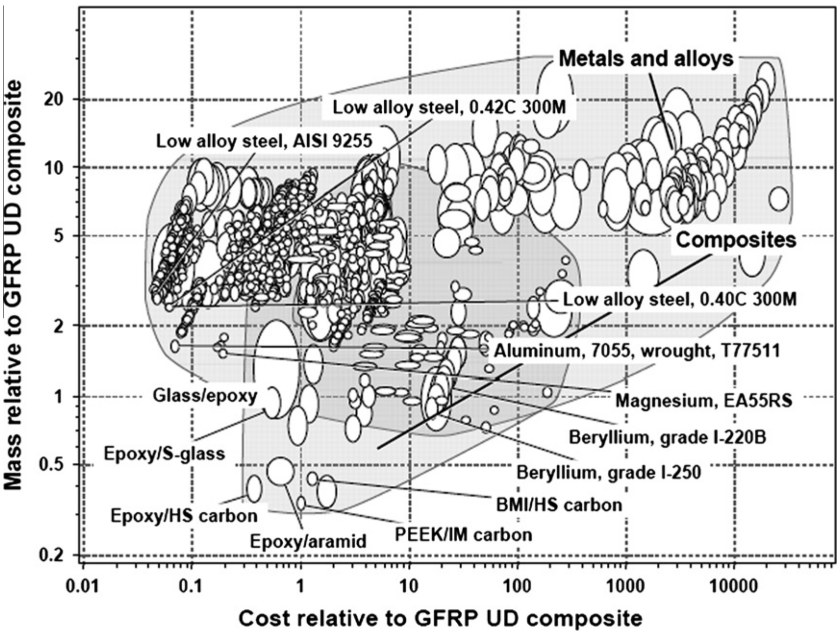

Fig. 4. Normalized mass and cost of blade material.

fiber, on the other hand, presents nearly 80% mass and 75% cost savings. A variety of steel alloys, in turn, offers very high weight, sometimes up to 800%, with substantial cost reduction. Fig. 5 shows mass versus embodied energy correlation with respect to glass fiber reinforced epoxy. It is evident that though there are many materials available that can optimize either mass or embodied energy, only a few simultaneously appear to be preferable in both objectives. Beryllium, grade I-220B alloy provides 50% weight savings. In the same time it increases per unit mass embodied energy consumption by 1200%. Steel alloys, comparatively, consume less embodied energy (J/kg) during material production cycle.

Fig. 6 compares the blade materials based on carbon footprint and cost. Cast iron based alloys appear to function best in this category. Aluminum alloys, conversely, provide lower cost and higher carbon footprint while a few cast iron based alloys like cast iron, nodular graphite, BS 900/2 material provides up to 85% carbon footprint and 95% cost savings, on average. Fig. 7, consecutively, provides a linear relationship between carbon footprint and embodied energy. As like previous, steel and cast iron based alloys perform best. PEEK/IM carbon fiber which was previously exhibiting 80% mass savings, now demonstrates five times carbon dioxide extraction and embodied energy consumption, on average. It displays profound conflict between the chosen objectives. Accordingly, Fig. 8 represents the log–log plot between cost and embodied energy objectives. Very few composite materials emerge as competitive in this setting. Aluminum alloys, as well, do not perform well due to high embodied energy, though they offer nearly 90% cost saving, on average, with respect to base material. Some tool

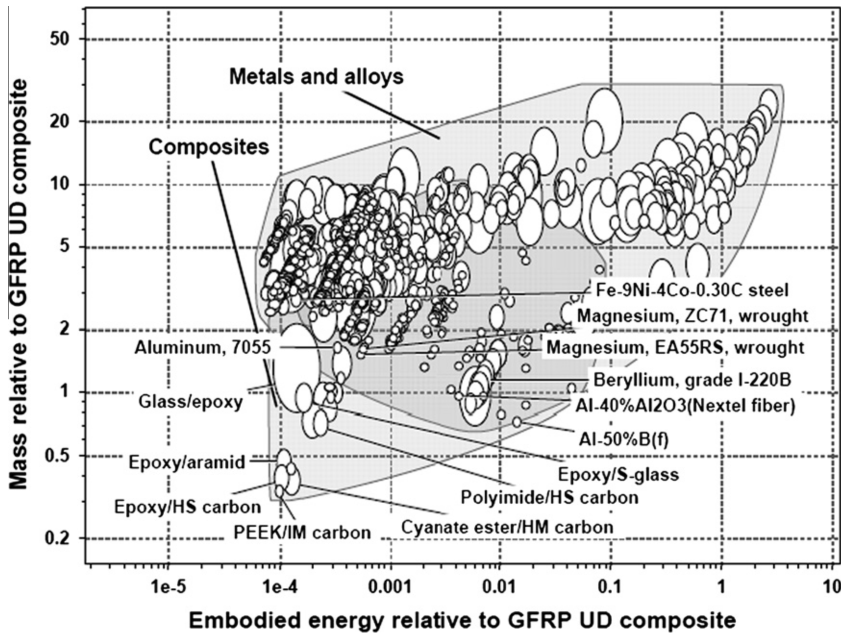

Fig. 5. Normalized mass and embodied energy of blade material.

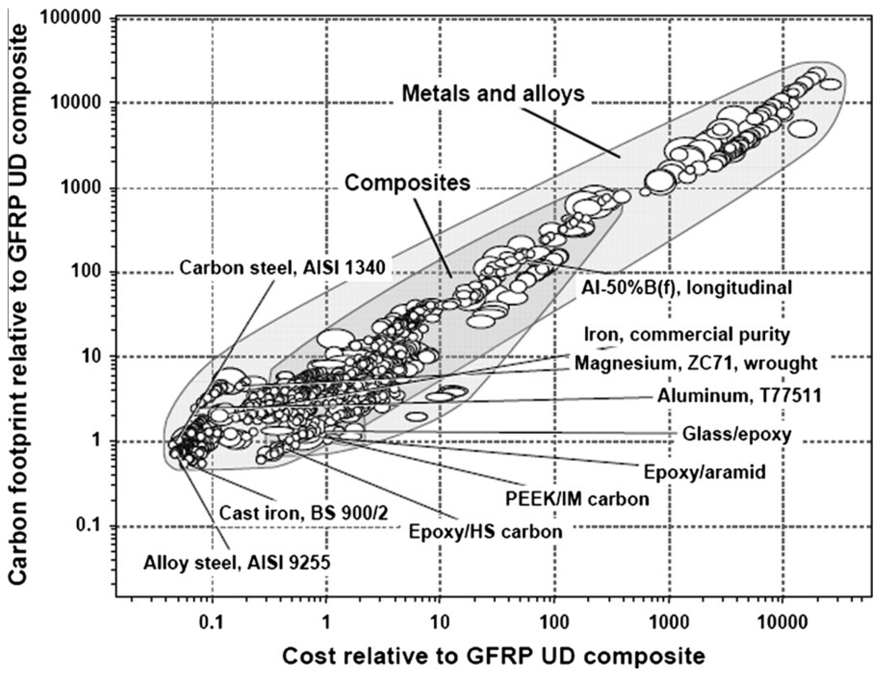

Fig. 6. Normalized carbon footprint and cost of blade material.

steel materials perform equivalent to the base material. Another competitive material group comprises of glass fiber based polyamide materials which offers equivalent embodied energy with a massive 85% cost saving.

One thing is evident from these normalized graphs that materials are exhibiting multi-faceted performance based on different objectives. The materials which offer lower mass, are not performing equally well in other objectives and vice versa. This holds applicable for all cases. In consequence to this, the materials with highest competitiveness upon the normalized surfaces have been investigated with weight factor based approach.

In this approach, competitive objectives are initially assigned some weight (w_i) depending on their relative importance in the design. Next, the absolute values of material indices (MI_i) are scaled by either maximum or minimum property value to calculate W_i:

$$W_i = w_i \frac{MI_i}{MI_{i\max}}; \quad \text{if maximization of material index is design goal},$$

or

$$W_i = w_i \frac{MI_{i\min}}{MI_i}; \quad \text{if minimization of material index is design goal}$$

Finally, all W_is are summed up to get $\sum_{i=1}^{n} W_i$. The best material appears to be the one with highest $\sum_{i=1}^{n} W_i$. Here, mass, carbon footprint, cost and embodied energy consumption minimization have been assigned 50%, 20%, 20% and 10% weight percentage,

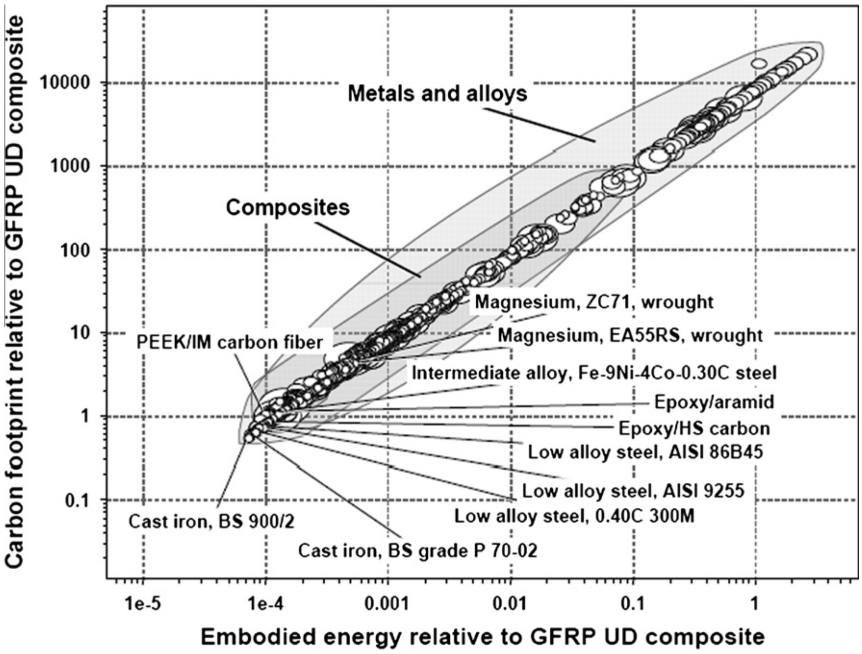

Fig. 7. Normalized carbon footprint and embodied energy of blade material.

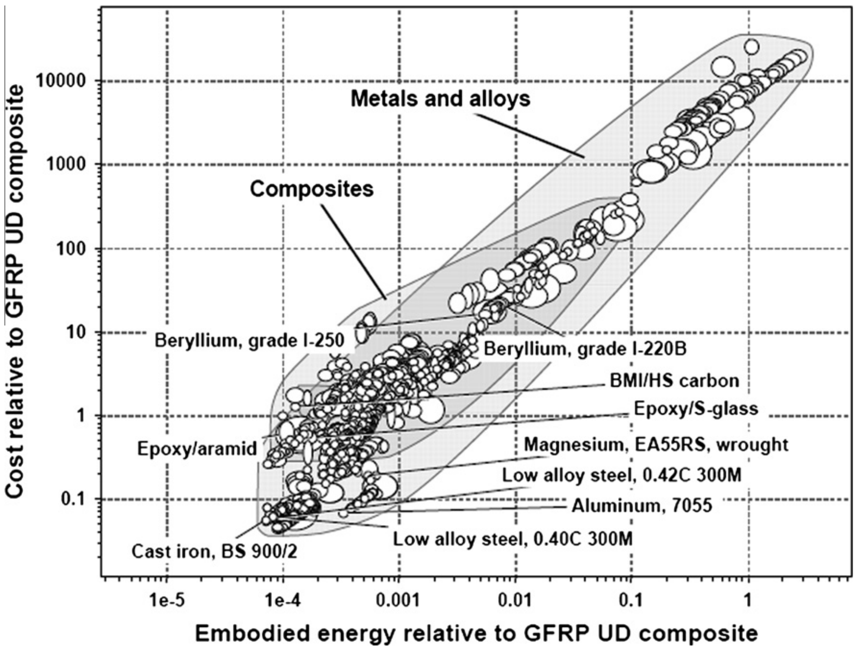

Fig. 8. Normalized cost and embodied energy of blade material.

respectively. Though it is an arbitrary selection, its relative emphasis is supported by established norms of the design community and based on the commands of energy economics and corresponding manufacturing industry. As highlighted by Breton and Moe [19] and Dutton et al. [20], rotor mass is a potential design factor for further development of the entire onshore and offshore wind turbine industry. In like manner, light weight but greater length blade development is a primary focus from manufacturing landscape, particularly, because the amount of harvested power increases squarely with the increase in blade length. If this blade length extension increases the weight, the system emerges more vulnerable to fatigue; also gravity load increases severely in addition to implied increase in centrifugal, braking and gyroscopic/yaw force. Hence, the mass weight percentage is set at a higher value. Next, from energy economics and investment payback criterion, blade material cost is an additional prime factor. In this regard it is assigned a higher percentage of 20%. Consequently, addressing the scientific consensus on environmental concerns and its grim realities as well as acknowledging the overwhelming appeal of the environmentalists, the carbon footprint minimization is approached with higher weightage in comparison to the embodied energy factor [21]. Table 1, accordingly, highlights the best competitive materials from the weight factor analysis. Minimum index values are shown in bold, and weight factor based calculation is performed for all short-listed materials. The last column highlights the summation of all weight factors for listed materials.

Table 1
Relative material indices with respect to glass fiber reinforced epoxy.

Material	Relative mass index, $\frac{212\rho_1}{\sigma_{f_1}^{2/3}}$	Relative carbon footprint index, $\frac{27.02\rho_1 C_{CO_2,1}}{\sigma_{f_1}^{2/3}}$	Relative cost index, $\frac{10.5\rho_1 C_{CO,1}}{\sigma_{f_1}^{2/3}}$	Relative embodied energy index, $\frac{1.89\times10^{-6}\rho_1 C_{EE,1}}{\sigma_{f_1}^{2/3}}$	$\sum_{i=1}^{n} W_i$
PEEK/IM carbon fiber	**0.259**	0.821	1.71	0.696	0.54
Epoxy/HS carbon fiber	0.3	0.659	0.626	0.728	0.49
Epoxy/Aramid carbon fiber	0.359	0.872	1.09	0.759	0.41
Oak (quercus spp.)	1.52	**0.0868**	0.686	**0.102**	0.41
Lignumvitae (l)	1.98	0.113	0.894	0.133	0.32
Alloy steel, AISI 9255	2.02	0.559	**0.0722**	0.645	0.31
Alloy steel, 0.40C 300M	1.87	0.502	0.102	0.58	0.26
Poly Propylene (42% glass)	1.29	1.11	0.22	1.15	0.19

It is evident from weight factor approach that a few composite materials exhibit superior performance in comparison to engineering alloys. Out of these, PEEK/IM carbon fiber, UD composite and epoxy/HS carbon fiber, UD composite tops the list. A close eye-view examination of the properties of PEEK/IM carbon fiber material reveals of its maintaining high yield (2.41–2.43 GPa) and high fatigue strength (1.33–1.58 GPa at 10^7 cycles) which are aspiring properties for blade application. Simultaneously, for epoxy/HS carbon fiber, UD composite the yield strength of 1.74–2.17 GPa and fatigue strength (at 10^7 cycle) of 0.96–1.41 GPa are promising. In turn, within the metal and alloy families, most competitive ones are low alloy based AISI 9255 & 0.40C 300M steels. These alloys possess fatigue strength of 720 and 840 MPa, at 10^7 cycles, respectively, which is lower than aforementioned composite material fatigue strength properties. Nevertheless, concerning the ongoing analysis, PEEK/IM carbon fiber and epoxy/HS carbon fiber composite are best onshore blade materials based on applied weightage. Once the weight factors are changed substantially, new materials will appear to be competitive.

Based on the analysis, the mass of each Vestas V90-3.0 MW turbine blade stands at 1735 kg with PEEK/IM carbon fiber material – that is around 74% reduction from current blade mass (assuming the full blade is made of the aforesaid materials only and nothing else) [22]. Simultaneously, the PEEK/IM carbon fiber blade production process decreases embodied energy consumption by 228 GJ (around 30% reduction) and atmospheric carbon dioxide emission by 9400 kg (around 17% reduction). All these benefits are achievable only with 70% increase in blade material cost. In turn, with epoxy/HS carbon composite, blade cost reduces by 37% with concurrent 70% mass, 34% carbon footprint and 23% embodied energy reduction.

As for onshore small scale wind turbine, hybrid natural materials like oak (quercus spp.) and lignumvitae (l) enter into the design space with lower fatigue strength and lower fracture toughness limiting criteria. These materials outperform all the remaining ones of all material families, except composite ones. Thus, for low scale (<100 kW) onshore turbines, the aforesaid materials can also be accepted as for potential blade application in gentle windy regions. For offshore blade application, these small scale turbines are, however, undesirable, partially because of the increased cost of bottom support structure. Moreover, there are additional infrastructural hindrances in onshore locations as massive size turbines frequently face transportation related problems. Offshore turbines, in turn, rarely face such issues and, hence, it is the industry cluster where the turbine size limit is still a long way to reach. However, fatigue loadings and stress corrosion cracking appear more severe in offshore due to salinity, moisture absorption and thermal gradient issues (between the turbine top and bottom section). Particularly the presence of atmospheric ambient oxygen often drastically affects the above-water environment even in comparison to the immersive state that indubitably affects the offshore wind turbine blade material selection aspects. Thus the moisture absorption permeability plays a very important role in offshore blade design. As within the listed materials in Table 1, intermediate modulus carbon fiber/PEEK composite absorbs moisture at intensely high rate. Its 24 h water absorption permeability value stands at 0.47% which signifies a 0.47% weight gain in each 24 h for the sample immersed in distilled water at room temperature [17]. Rests of the composite materials show much lower water absorption permeability, in the digit of second decimal, which makes them lucrative for offshore blade application. Apart from the base materials used, appropriate protection systems need to be ensured in blade structure to ensure adequate durability and safety of the system.

4. Tower material selection methodology, results and discussion

4.1. Compound objective, multiple constraint based material indexing

Tower material selection is also important as because it is the heaviest component of wind turbine and it endures highly turbulent aerodynamic loads and numerous fatigue cycles over the design life. Other than this, there is additional gravitational loading due to rotor and nacelle structure (both onshore and offshore) and sea-environment loading because of ice sheet, wave and current force (in offshore). Most important ones out of these loadings encompass aerodynamic bending and stability/buckling loads. Accordingly, tower material selection is formulated based on axial deformation and buckling constraints. Fig. 9 demonstrates a tapered tubular tower with height, L, mean outer diameter, D, and mean wall thickness, t. Tapered tubular structure is the most widely used tower shape now-a-days because of its superior structural properties. Next, some structural assumptions are made, viz.:

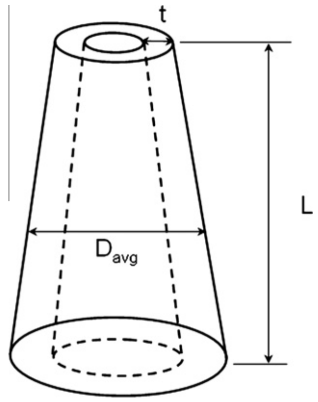

Fig. 9. Schematic diagram of tapered tower with hollow tubular cross-section.

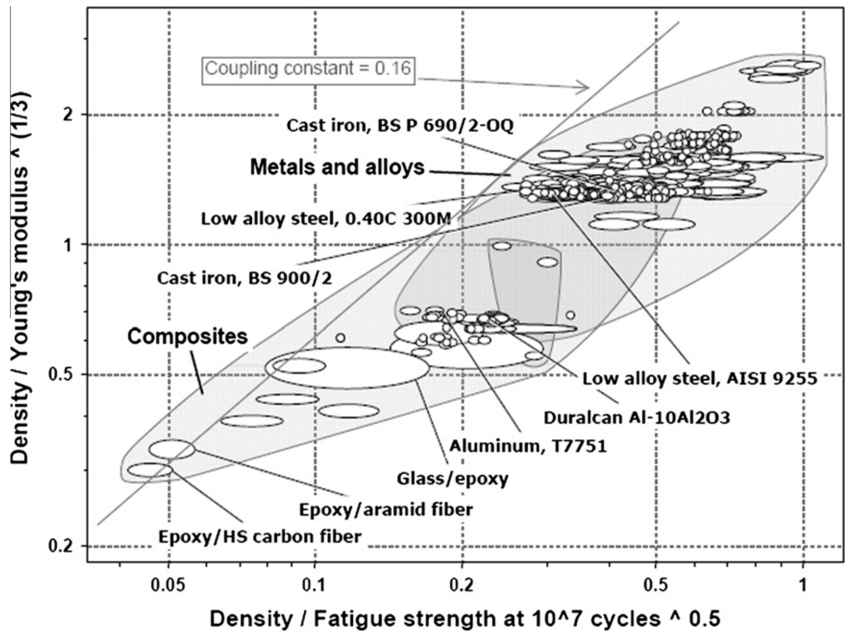

Fig. 10. Material index on buckling vs. material index on bending (mass minimization).

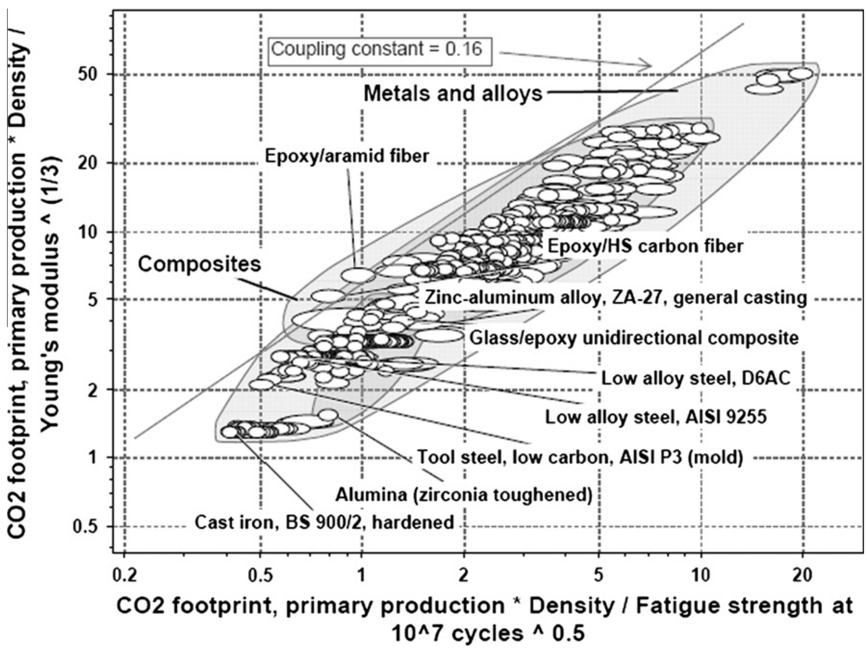

Fig. 11. Material index on buckling vs. material index on bending (carbon footprint minimization).

- Tower mean outer diameter, D is the arithmetic mean of the tower top outer diameter, D_{top} and tower bottom outer diameter, D_{bottom}.
- Tower top outer diameter, D_{top} has been assumed as 50% of the tower mean outer diameter, D.

Tower mass can be expressed as:

$$m_{tower} = \pi DLt\rho \tag{15}$$

For bending constraint, tower length, L, and mean wall thickness, t, are considered fixed whereas mean outer diameter, D, is assumed as free variable. Hence, the bending stress due to aerodynamic forces can be expressed as:

$$\begin{aligned} \sigma &= \frac{M_{bend}C}{I} = \frac{FL * \frac{D}{2}}{\frac{\pi D^3 t}{8}} \\ \Rightarrow D^2 &= \frac{4FL}{\pi * \sigma * t} \end{aligned} \tag{16}$$

whereas F indicates aerodynamic force on rotor and M_{bend} symbolizes tower base bending moment due to corresponding force. Aerodynamic force on tower is considered negligible in comparison to the same on rotor. From Eqs. (15) and (16):

$$m_{tower} = \left\{4\pi(F)(L^3 t)\left(\frac{\rho^2}{\sigma}\right)\right\}^{0.5}$$

Thus, the material index for mass minimization due to axial deformation can be expressed as:

$$MI_{bend,mass} = \frac{\rho}{\sigma^{0.5}} \tag{17}$$

Next, bucking load can be expressed as:

$$P = \frac{\pi^2 EI}{L_e^2} = \frac{\pi^3 ED^3 t}{32L^2} \quad \Rightarrow D^3 = \frac{32PL^2}{\pi^3 Et} \tag{18}$$

From Eqs. (15) and (18):

$$m_{tower} = \left(\frac{32PL^5 t^2 \rho^3}{E}\right)^{1/3} = \left\{32(P)(L^5 t^2)\left(\frac{\rho^3}{E}\right)\right\}^{\frac{1}{3}}$$

Hence, the material index for mass minimization due to buckling can be represented as:

$$MI_{buckle,mass} = \frac{\rho}{E^{1/3}} \tag{19}$$

As evident from Eqs. (17) and (19), blade mass will be minimized with lower value of the material indices. Like blade study, density, ρ, can be replaced with ρC_{CO_2}, ρC_{EE} and ρC_{CO} to get appropriate material indices of carbon footprint, embodied energy, and cost minimization, respectively.

4.2. Final tower material selection by coupling equation and weight factor approach

It appears from Section 4.1 that there are two material indices for each performance objective due to multiple constraint design (more constraints than free variable). Nevertheless, for the same objective, multiple constraint based different equations should provide only one unique property measure as tower material ultimately maintains uniquely one numerical value of weight, cost, carbon footprint or embodied energy consumption. Hence, available material indices need to be coupled to find only one measure. From Eqs. (17) and (19):

$$\frac{MI_{bend,mass}}{MI_{buckle,mass}} = \frac{\{32(P)(L^5 t^2)\}^{1/3}}{\{4\pi(F)(L^3 t)\}^{0.5}} = C_C \tag{20}$$

whereas C_C indicates coupling constant. Specifications of a Vestas V90-3.0 MW turbine are collected from manufacturer website to evaluate the coupling constant, C_C, of this turbine [22]:

$$C_C = \frac{MI_{bend,mass}}{MI_{buckle,mass}} = \frac{\{32 * 1099.7 * 10^3 * 90^5 * 0.28^2\}^{1/3}}{(4\pi * 0.96 * 10^6 * 90^3 * 0.28)^{0.5}} = 0.16$$

The coupling constant will maintain the same decimal values of 0.16 for other objectives like carbon footprint, cost and embodied energy minimization. It is to be noted that though onshore wind turbine experiences less wind speed (Hellman exponent is high) and more turbulence in comparison to their offshore counterpart; Vestas V90-3.0 MW turbine is designed for both onshore and offshore categories and, hence, the value of the coupling constant is applicable for both categories with reasonable accuracy. A fatigue limit (σ_f) and fracture toughness (K_{IC}) based search criterion is applied, henceforward, to rank the best materials like the blade study:

$$\sigma_f \geqslant 150 \text{ MPa} \tag{21}$$

$$K_{IC} \geqslant 15 \text{ MPa} \sqrt{\text{m}} \tag{22}$$

Finally, a logarithmic plot of mass based indices is plotted in Fig. 10 based on Eqs. (17), (19)–(22). The logarithmic form, log $(MI_{bend,mass}) = \log(MI_{buckle,mass}) + \log 0.16$ is a family of straight parallel lines of slope 1 on a plot $\log(MI_{bend,mass})$ against log $(MI_{buckle,mass})$ with selection guideline corresponds to a value of $C_C = 0.16$. All materials on this selection line perform equally well for optimal tower design.

As evident from Fig. 10, only a small number of materials are left above the selection line. Consequently, the selection area is expanded to some extent (around 5%) to include more materials in the design space. Composite materials appear to out-perform other material families in ensuring minimum mass design (Fig. 10). Out of these materials, epoxy/HS carbon fiber performs best. Compared to steels, it offers almost seven times weight reduction. Aluminum alloys also perform better in comparison to other alloy genres. Fig. 11 highlights material indices relevant to carbon footprint minimization. In this setting, cast iron alloys and various steel grades excel other materials in establishing lower carbon footprint. Epoxy/HS

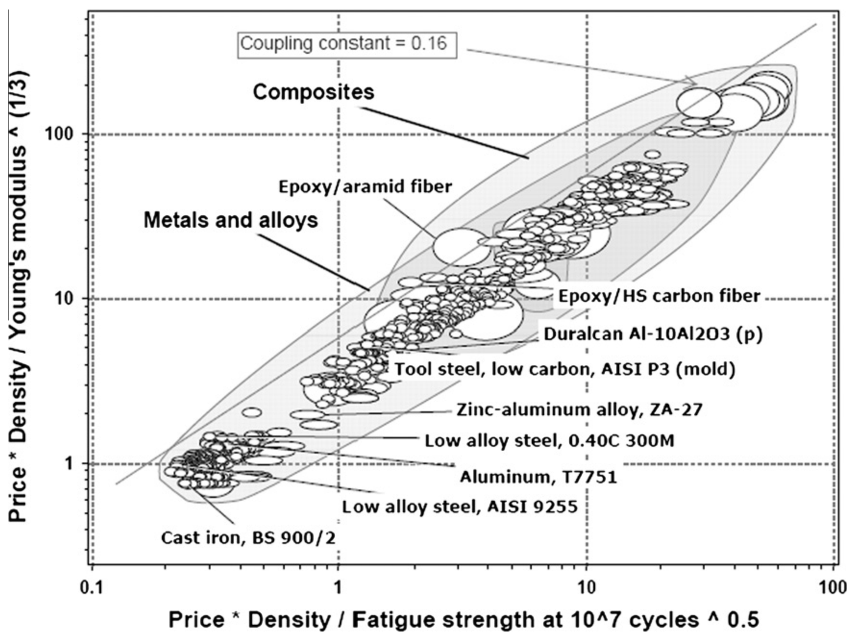

Fig. 12. Material index on buckling vs. material index on bending (cost minimization).

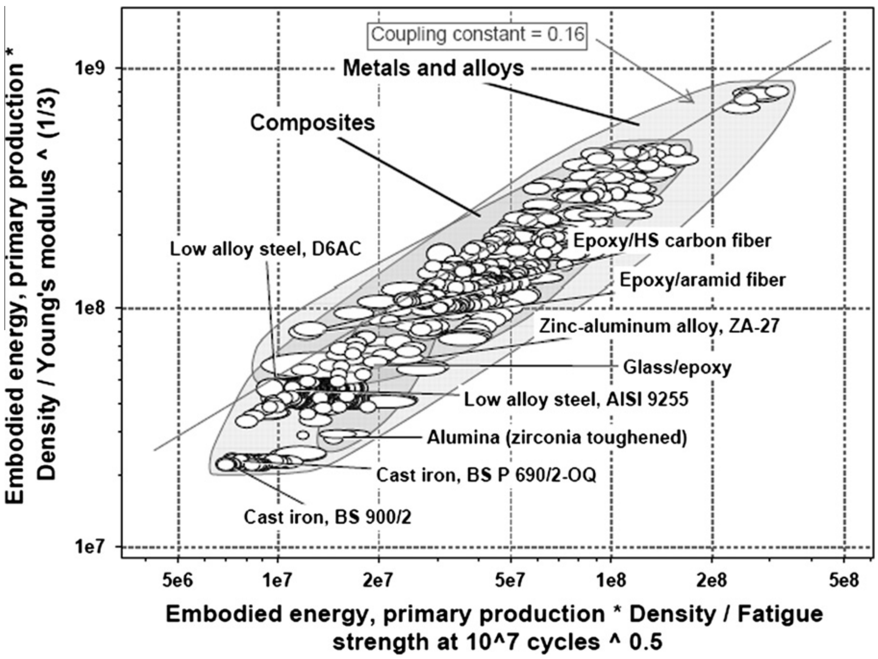

Fig. 13. Material index on buckling vs. material index on bending (embodied energy minimization).

Table 2
Value of the material indices corresponding to bending and buckling load constraints (minimum index values at bold).

Material	$\frac{\rho}{\sqrt{\sigma}}$	$\frac{\rho}{\sqrt[3]{E}}$	$\frac{\rho C_{CO_2}}{\sqrt{\sigma}}$	$\frac{\rho C_{CO_2}}{\sqrt[3]{E}}$	$\frac{\rho C_{EE}}{\sqrt{\sigma}}$	$\frac{\rho C_{EE}}{\sqrt[3]{E}}$	$\frac{\rho C_{CO}}{\sqrt{\sigma}}$	$\frac{\rho C_{CO}}{\sqrt[3]{E}}$	$\sum_{i=1}^{n} W_i$
Epoxy/HS carbon fiber	**0.0459**	**0.301**	0.791	5.18	1.21e7	7.97e7	1.93	12.6	0.62
Cast iron, BS 900/2	0.398	1.29	**0.405**	**1.31**	**6.87e6**	**2.22e7**	0.235	**0.761**	0.58
Steel alloy, AISI 9255	0.293	1.32	0.619	2.79	1.02e7	4.6e7	0.22	0.99	0.45
Steel alloy, AISI 1340	0.309	1.33	0.767	3.29	9.84e6	4.23e7	**0.209**	0.898	0.44
Steel alloy, 0.40C 300M	0.27	1.33	0.571	2.81	9.42e6	4.63e7	0.299	1.47	0.42
Steel alloy, AISI 420	0.308	1.32	1.57	6.71	2.5e7	1.07e8	0.742	3.17	0.22

carbon fiber, which is the best composite material of this category, leaves almost six times more carbon impact in comparison to cast iron, BS 900/2 material. Aluminum alloys also fail to maintain lower carbon footprint. Fig. 12 conversely highlights the material indices for cost optimization. Here, cast iron based alloys dominate all other material families. Some aluminum and magnesium alloys also perform well. In turn, composite materials carry much higher price which makes these less desirable for tower application as MW range wind turbines need massive tower structure to achieve higher power output with increasing wind velocity. Fig. 13, demonstrates embodied energy consumption through per kg material production. Cast iron and carbon steel based materials outperform other material groups in this condition. Composite materials fail to augur much hope as there manufacturing cycles need lots of energy consuming stages.

As evident from these plots, materials are exhibiting multi-faceted performance based on different objectives. Accordingly, a list of candidate materials is presented in Table 2 for further investigation by weight factor approach. Like previous, mass relevant indices have been assigned 50% weightage – with equal share to bending and buckling based index. Other objective measures have, as well, been assigned equal weightage for two constraints. Henceforward, each competitive material weight factors have been summed up, as highlighted in last column of Table 2. The one with highest value of weight factor is the best material.

Likewise blade material study, epoxy/HS carbon composite arises as the best competitive material for both onshore and offshore tower application. Cast iron based nodular graphite alloy, BS 900/2, simultaneously, performs very well. This alloy possesses 3.2–4.1% carbon, 1.8–2.8% Si, 0.8% Mn and very small percentage of phosphorus and silicon. It maintains high yield strength of 750 MPa and high fatigue strength of 325 MPa at 10^7 cycles. Concurrently, it provides significant ductility and strength in compression. On top of all, its carbon footprint and embodied energy consumption are modest comparing to other ferrous alloys. Economically, it is competitive with per unit cost only 12% of epoxy/HS carbon composite. However, in comparison to latter composite material, it provides a heavier design (8.67 times). More steel based alloys will appear superior if weight percentage changes, particularly if mass weightage factor is reduced. Down the perspective, assuming the REpower 5 M turbine (designed for both onshore and offshore) tower as originally made of AISI 316 steel (which is one of the most widely used steel grade worldwide), overall mass, carbon footprint, embodied energy and cost reduction occurs by around 6%, 81%, 80% and 90% respectively with cast iron, nodular graphite BS 900/2 being considered as candidate material [23]. Epoxy/HS carbon composite provides even more weight savings (almost 78%) with simultaneous carbon footprint and embodied energy reduction but at a moderately higher cost (almost 67% increase).

5. Conclusions

"Today engineering designs are increasingly driven by product functionality, usability, mass, cost and environmental sensitivity.

An improper choice of material adversely affects the profit margin of the company and undermines the long-held reputation. Hence, design engineers are always on a lookout to streamline their product design lifecycle. In this article, we explored wind turbine blade and tower material selection strategies based on multiple constraints and conflicting objectives. Final onshore wind turbine blade material stands as PEEK/IM carbon and epoxy/HS carbon fiber composite – for Vestas 3.0 MW blade, PEEK/IM carbon composite exhibits 74% mass, 17% carbon footprint, 30% embodied energy reduction while epoxy/HS carbon ensures 70% mass, 34% carbon footprint, 23% embodied energy with concurrent 37% cost reduction. Hybrid natural materials like oak (quercus spp.), lignumvitae (l) also enter into small scale onshore blade design space for gentle windy regions. In turn, acknowledging the moisture absorption permeability and future massive scale structural requirements, neither PEEK/IM carbon nor hybrid natural materials deem suitable for offshore blade applications, thus leading to an epoxy/HS carbon blade with the eminent potentiality. The same material also performs best for onshore and offshore tower application. Some of the cast iron based alloys, especially BS 900/2 grade, as well, comply well with superior yield, compressive and fatigue strength. As demonstrated in the study, a BS 900/2 grade tower will ensure 6% mass, 81% carbon, 80% energy content and 90% cost reduction in REpower 5 M turbine – this is indeed a major improvement from tower material optimization perspective. Conversely, epoxy/HS carbon composite provides even more weight savings (almost 78%) with simultaneous 26% carbon and energy content reduction but at 67% higher cost.

As an ultimate choice, final outcome of the study ultimately stands as a compromise between candidate materials with each material bringing some advantages as well as disadvantages. As composite material establishes a competitive edge in all blade and tower categories, a better synergy in its multi-directional property and laminate sequence is necessary depending on the structural dynamic behavior, aerodynamic turbulence and condition of the environment (onshore, offshore). Limitations of the study lay in variation of material properties from suppliers' perspective who often intend to publish only the favorable results and also the material cost will vary to some degree once the inflationary effects are accounted for. Linking both material and process route selection simultaneously deserves an attention to the researchers of this field."

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