Glass in energy

Glass fibers for wind energy

MAT 498

Lehigh University

Wind energy turbines

Wind turbines convert kinetic energy from wind into mechanical or electrical energy.

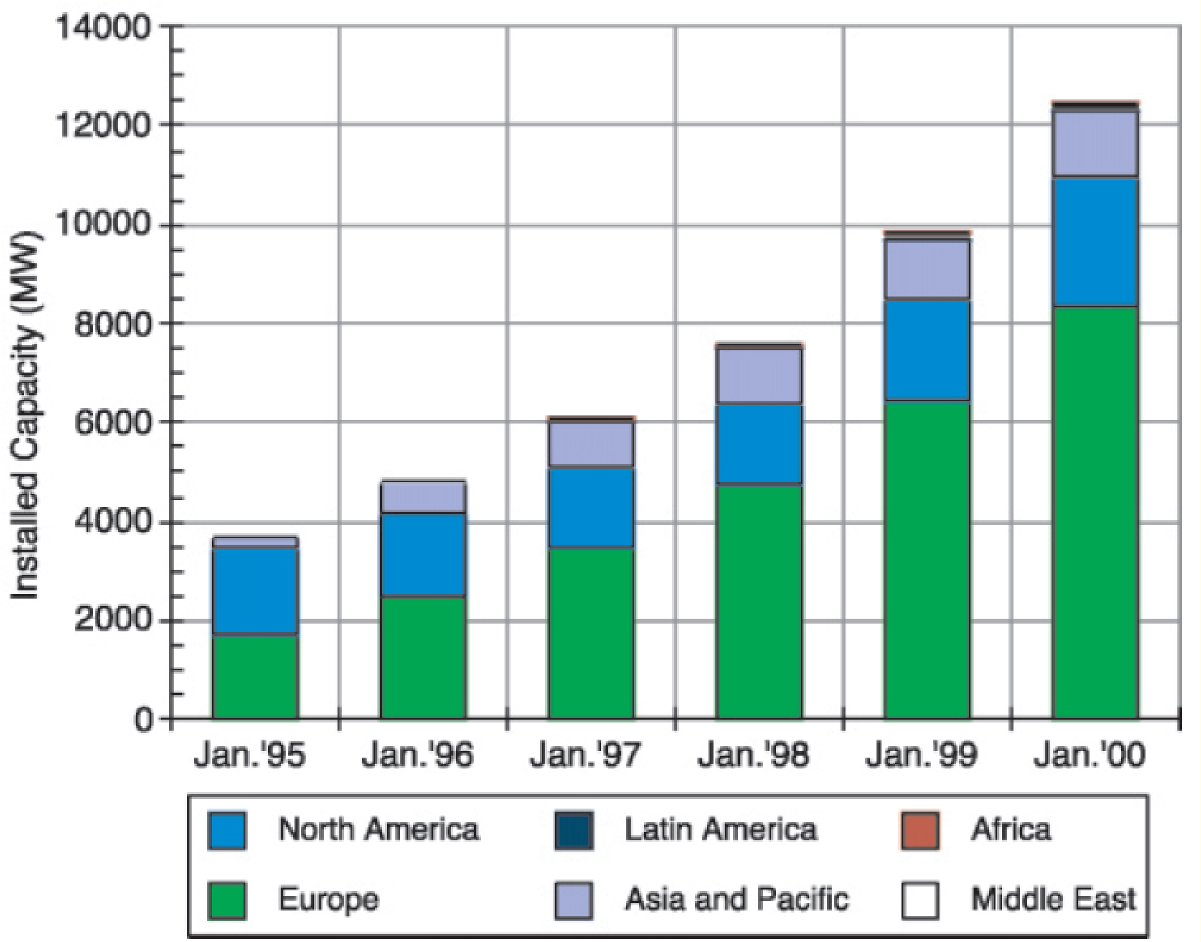
Environmental benefits of wind energy systems include near zero: air and water pollution, production of hazardous waste, radiation effects, use of water and climate change.

With an average annual growth rate > 30%, wind has been the fastest growing power source worldwide on a percentage basis from 1990-2002. Wind energy could supply about 20% of electricity in the US. The theoretical potential, however, is much higher. Wind energy is the lowest costly of the renewable energy sources (namely wind, hydroelectric and solar).

onshore

offshore

Adapted from: http://www.google.pt/search?q=wind+turbines (20 Dec. 2011).



Installed wind-generating capacity by region (1995–2000)

Adapted from: J.G. McGowan, S.R. Connors, Windpower: a turn of the century review, Ann. Rev. Energy Envinm. 25 (2000) 147.

The installed grid-connected capacity has expanded more than five-fold between 1990 and 2000. Most of this increase occurred in Europe, due to incentives for the use of renewable energies.

The 1990s also marked an increased interest in offshore windpower.

Whereas most new wind farm installations remain onshore, The Netherlands, Denmark and Sweden have begun to develop their expertise in offshore applications. It now appears that offshore installations will probably become decisive for the future competitiveness of the wind power industry.

Environmental impacts

Three of the most commonly noted environmental impacts of wind turbines are noise, visual appearance and electromagnetic interference. They can also kill bird species (cf. American Bird Conservancy, …).

The noise produced by wind turbines has diminished as the technology has improved. That is, as blade airfoils have become more efficient, more of the wind energy is converted into rotational energy and less into acoustic noise.

Most wind turbines include a rotor with blades (which convert the wind's energy into rotational shaft energy); a nacelle (enclosure) containing a drive train; and a tower to support the rotor, the drive train and electronic equipment.

Figure 1 The world's largest wind turbine (summer 2004) at Risoe National Laboratory test site, Høvsøre, Denmark. Tower height is 120 m, rotor diameter is 110 m, and generator power is 3.6 MW.

Adapted from: P. Bondsted et al., Composite Materials for wind power turbine blades, Ann. Rev. Mater. Res. 35 (2005) 505.

While there are small and large wind turbines, the latter are the majority of the presently installed machines.

The primary application for the **small** wind turbines has been for battery charging in non-grid-connected systems.

Improved electronics and controls, however, have provided numerous applications in small **hybrid** wind energy systems. These mini-grid systems are generally connected to a diesel engine generator and can also include a photovoltaic generating component.

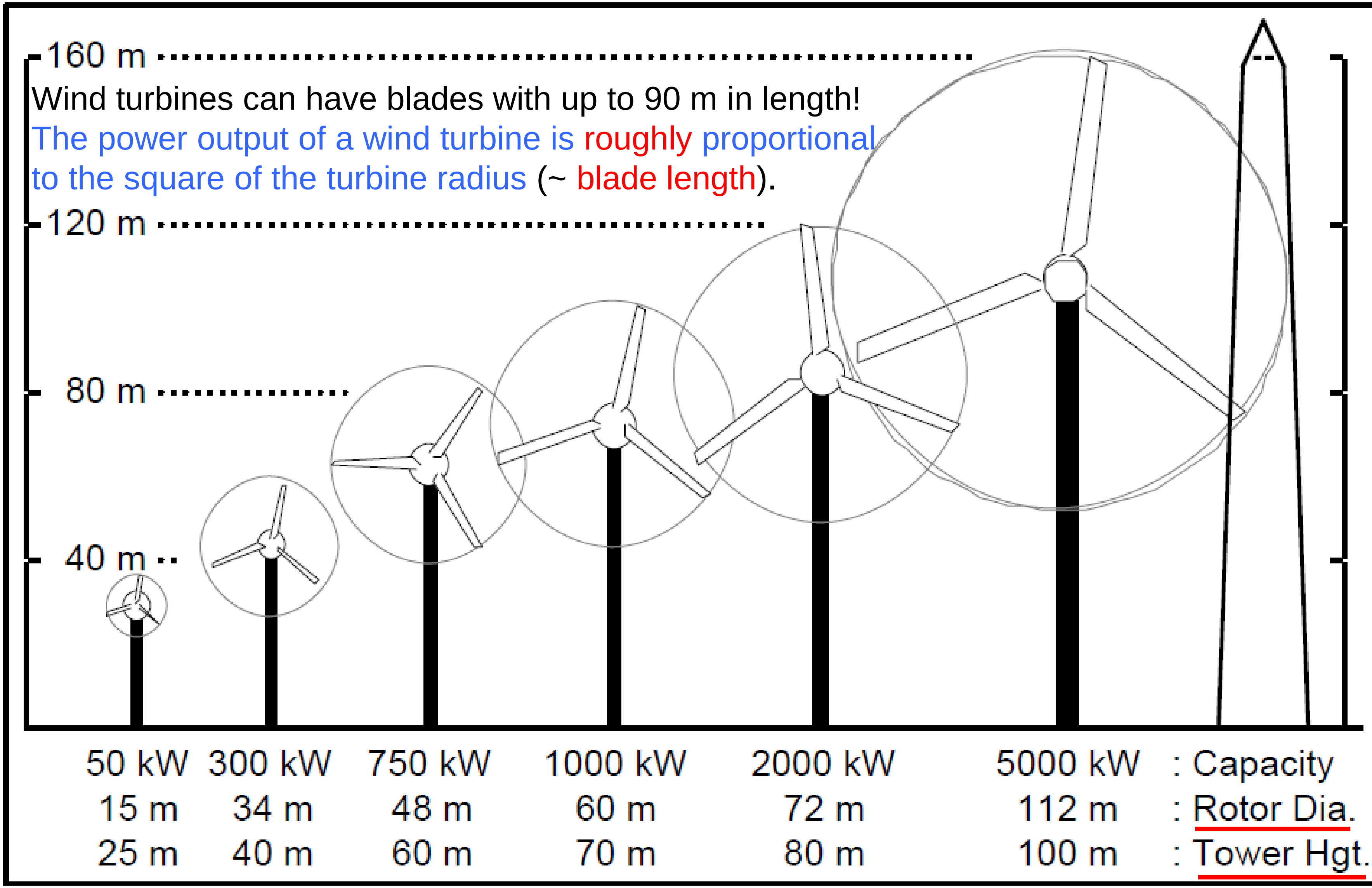
The larger machines are grid-connected and their general design has converged to some degree. A fundamental aspect in the design of a wind turbine is the orientation of the rotor axis - horizontal or vertical. The overwhelming majority of modern wind turbines are horizontal axis machines, for which the rotor axis is parallel to the ground and they usually have three blades (some have two).

For a horizontal axis machine, the tower must be at least high enough to keep the blade tips from touching the ground as they rotate. In practice, towers are usually much higher than that.

Also, winds are almost always much stronger and less turbulent as elevation increases. Therefore, all other things being equal, the tower should be as high as practical.

The tendency is to keep the weight of the components low, for a variety of reasons. On the other hand, the resulting turbine must be strong enough to survive any likely extreme events and operate reliably with a minimum of maintenance for a long time.

Wind turbine components, because they are kept light and flexible, tend to experience relatively high, variable stresses. These periodic stresses result in **fatigue damage**, which eventually leads to failure of a component, requiring its repair or replacement. So, with increasing size of wind turbines, fatigue and extreme loads are becoming more and more critical design factors.



Representative size, height and diameter of wind turbines.

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Adapted from: J.G. McGowan, S.R. Connors, Windpower: a turn of the century review, Ann. Rev. Energy Envinm. 25 (2000) 147.

Use of glass

It is the material strength that ultimately governs the size of the turbine blades.

For wind turbine blades, lightweight and strong glass fiber reinforced composites (GFRCs) are normally used.

The glass fiber provides the necessary stiffness to the more compliant polymer (a thermoset or thermoplastic). These composites require ***high strength*** and ***durability***.

Current turbine blades are usually composed of glass fiber reinforced ***polyester laminate***. The polyester is a thermoset polymer resin.

The most commonly used glass fibers for the GRFCs are the so-called E-glass fibers. E-Glass, or electrical grade (high electrical resistivity) glass, was originally developed for insulators for electrical wiring. E-glass was later found to have excellent fiber forming capabilities and is now used almost exclusively as the reinforcing phase in the GFRC material, commonly known as fiberglass.

Hooke's law: $\sigma = E \varepsilon$

Tensile properties of high-performance fibers

Fiber	Density (g/cc)	Tensile Young's Modulus (GPa)	Tensile Strength (GPa)	Manufacturer
T700 Carbon	1.80	228	4.83	Toray
T1000G Carbon	1.80	297	6.38	Toray
E-Glass	2.58	72	3.45	OCF
R-Glass	2.55	85	4.33	Vetrotex
S2-Glass	2.49	87	4.59(1)	OCF
Hollex	1.80	67	3.45(1)	OCF
Fused Silica	2.20	69	3.45	J. P. Stevens
Kevlar 49	1.45	120	3.62	DuPont
Kevlar 29	1.44	58	3.62	DuPont

Adapted from: S.J. Teresa, S.E. Groves, Properties of fiber composites for advanced flywheel energy storage devices, Society for the Advancement of Material and Process Engineering 2001 Symposium, Long Beach, CA, May 5-10, 2001.

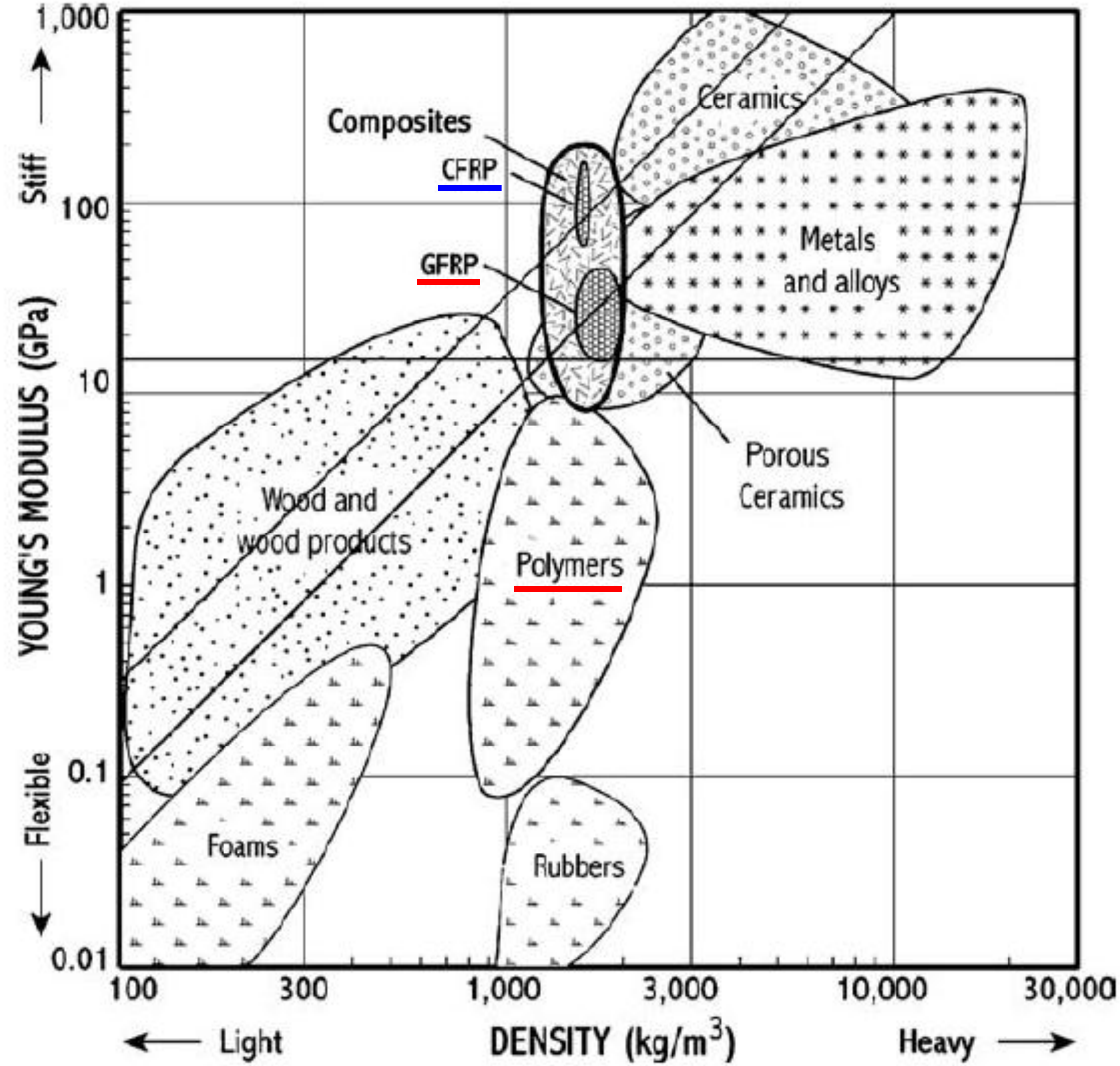

Diagram showing stiffness versus density for all materials. The merit index for a beam $M_b = E^{1/2}/\rho$ is represented by sloping lines with M_b equal to 0.003 (*lower line*) and 0.006 (*upper line*). The criterion for absolute stiffness E = 15 GPa is indicated by the horizontal line (4).

Adapted from: P. Bondsted et al., Composite Materials for wind power turbine blades, Ann. Rev. Mater. Res. 35 (2005) 505.

Composites (FRCs)

TABLE 1 Composite materials based on the fibers listed and a polymer matrix with properties $E_m = 3$ GPa, $\sigma_m = 100$ MPa, and $\rho_m = 1.2$ g/cm^3. The composite properties are calculated from the simple composite theory (law of mixtures); the orientation factor is 1 for aligned composites and 1/3 for random composites

	Fibers			Composites					
Type	Stiffness E_f GPa	Tensile strength σ_f MPa	Density ρ_f g/cm^3	Volume fraction V_f	Orientation θ	Stiffness E_c GPa	Tensile strength σ_c MPa	Density ρ_c g/cm^3	Merit $E_c^{1/2}/\rho_c$
Glass-E	72	3500	2.54	0.5	0°	38	1800	1.87	3.3
				0.3	Random	9.3	420	1.60	1.9
Carbon	350	4000	1.77	0.5	0°	176	2050	1.49	8.9
				0.3	Random	37	470	1.37	4.4
Aramid	120	3600	1.45	0.5	0°	61	1850	1.33	5.9
				0.3	Random	14.1	430	1.27	2.9
Polyethylene	117	2600	0.97	0.5	0°	60	1350	1.09	7.1
				0.3	Random	13.8	330	1.13	3.3
Cellulose	80	1000	1.50	0.5	0°	41	550	1.35	4.7
				0.3	Random	10.1	170	1.29	2.5

Adapted from: P. Bondsted et al., Composite Materials for wind power turbine blades, Ann. Rev. Mater. Res. 35 (2005) 505.

Table 4.1 Typical compositions of commercial glasses (wt %)

Glass	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	BaO	Na_2O	K_2O	SO_3	F_2	PbO	B_2O_3
Flint container	72·6	1·6	0·05	11·0	0·1	—	13·7	0·5	0·2	—	—	—
Amber container	72·7	1·9	0·2[illegible]	[illegible]0	—	—	13·8	1·0	0·03	—	—	—
Green container	72·0	1·1	0·96	8·4	2·1	—	15·1	—	—	—	—	—
Flat	72·8	1·4	0·1	8·2	3·8	—	12·8	0·8	0·3	—	—	—
Borosilicate	80·2	2·6	0·07	0·1	—	—	4·5	0·3	—	—	—	12·3
Lighting ware (opal)	59·9	6·1	0·05	—	—	1·3	14·9	2·3	—	5·8	—	0·8
Full lead crystal	54·9	0·1	0·02	—	—	—	0·2	12·3	—	—	31·9	0·5
Lead crystal	58·5	—	0·02	—	—	—	1·3	13·1	—	—	25·2	1·5
Glass fibre, "A" glass	72·0	2·5	0·5	9·0	0·9	—	12·5	1·5	—	—	—	0·5
Glass fibre, "E" glass	55·2	14·8	0·3	17·7	4·3	—	0·3	0·2	—	0·3	—	7·3

(Adapted from: Glass-making today, P.J. Doyle, Portcullis press, 1979)

E-glass has only 0.5 % (Na + K) oxides.

It is basically an alkali-free, low silica Ca Mg Al B silicate **glass**.

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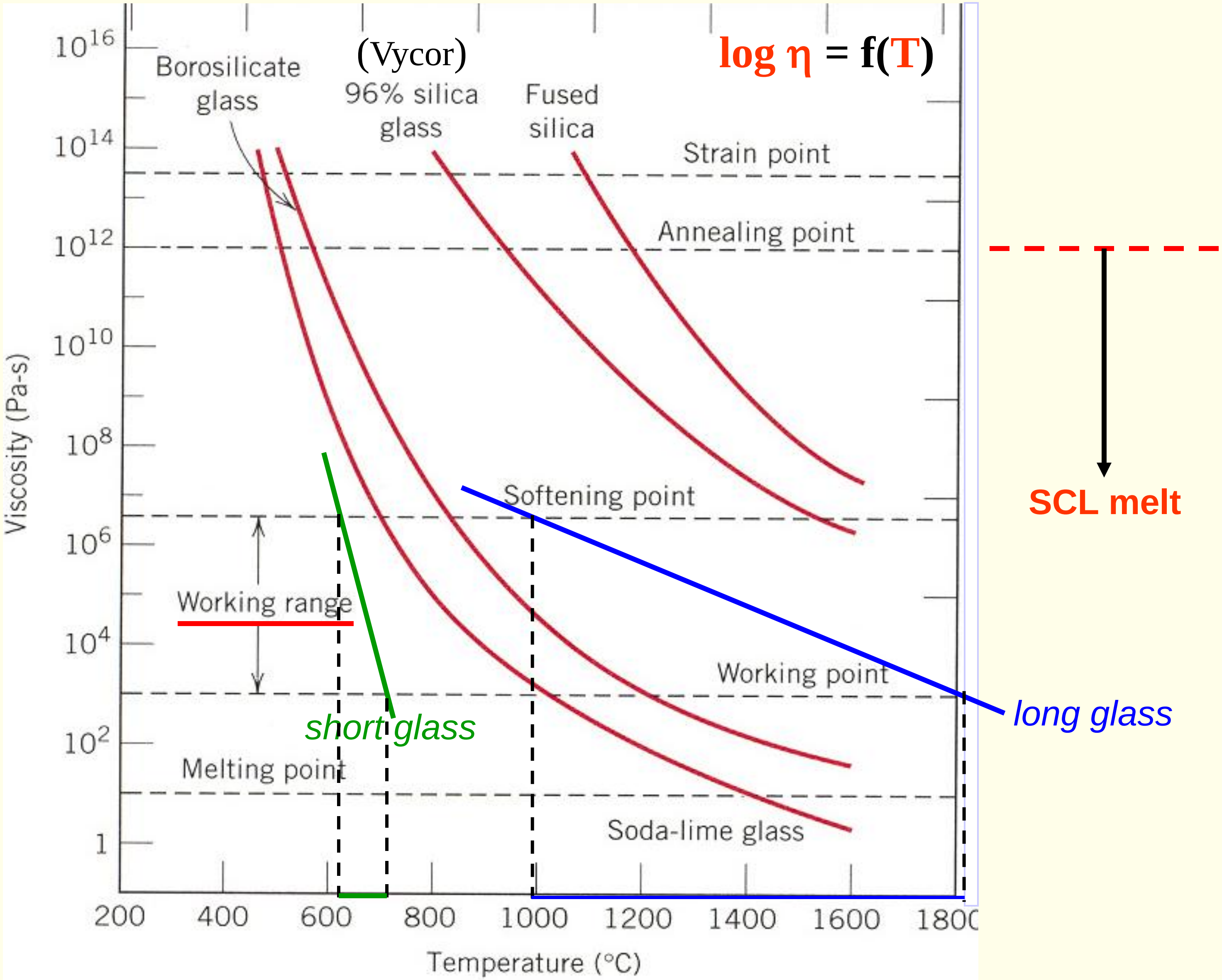
Glass fiber fabrication

E-glass fibers are generally produced using melt spinning techniques. These involve melting the glass composition into a platinum crown which has small holes for the molten glass to flow. Continuous fibers can be drawn out through the holes and wound onto spindles, while short fibers may be produced by spinning the crown, which forces molten glass out through the holes centrifugally.

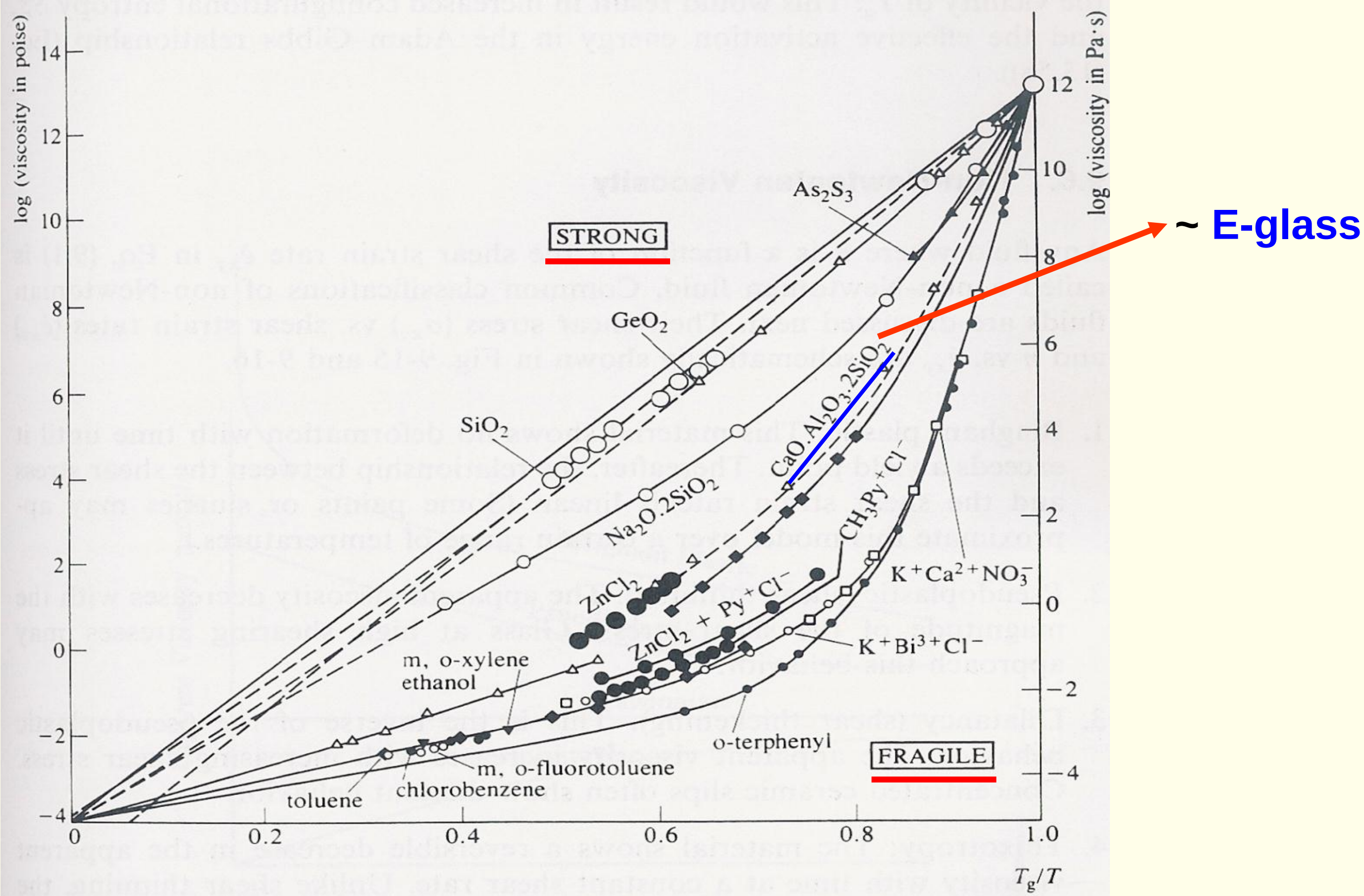
Fiber dimension and to some extent properties can be controlled by the process variables such as melt temperature (hence viscosity) and drawing/spinning rate. The temperature window that can be used to produce a E-glass melt of suitable viscosity is quite large, making this composition suitable for fiber forming.

Such kind of glass is usually called a “long” glass, because it has a long working range (working T interval), as opposed to “short” glasses which have a short working range. A long working range is usually associated with low values of the activation energy for viscosity, E_η. E-glass is a low silica glass (only 55 weight% SiO_2) which is relatively *fragile*, with low E_η at high melt temperatures.

Effect of temperature and composition on glass viscosity



(Adapted from: *Materials Science and Engineering*, W.D. Callister, John Wiley, 1994)



Variation of log(viscosity) versus T_g/T for "strong" and "fragile" liquids. (After Angell [19]. Reproduced with permission of Elsevier Science Publishers.)

(Adapted from: *Fundamentals of inorganic glasses*, A.K. Varshneya, Academic Press, 1994)

The temperature dependence of the viscosity of *fragile* liquids cannot be described by the Arrhenius equation and more complex expressions become necessary, such as the Vogel-Fulcher-Tammann equation, valid for $T > T_o$ (T_o, adjustable parameter ~ T_g):

$$\eta = \eta_o \exp[Q/(T-T_o)] \qquad \text{(Q independent of T)}$$

Fabrication of continuous glass fibers

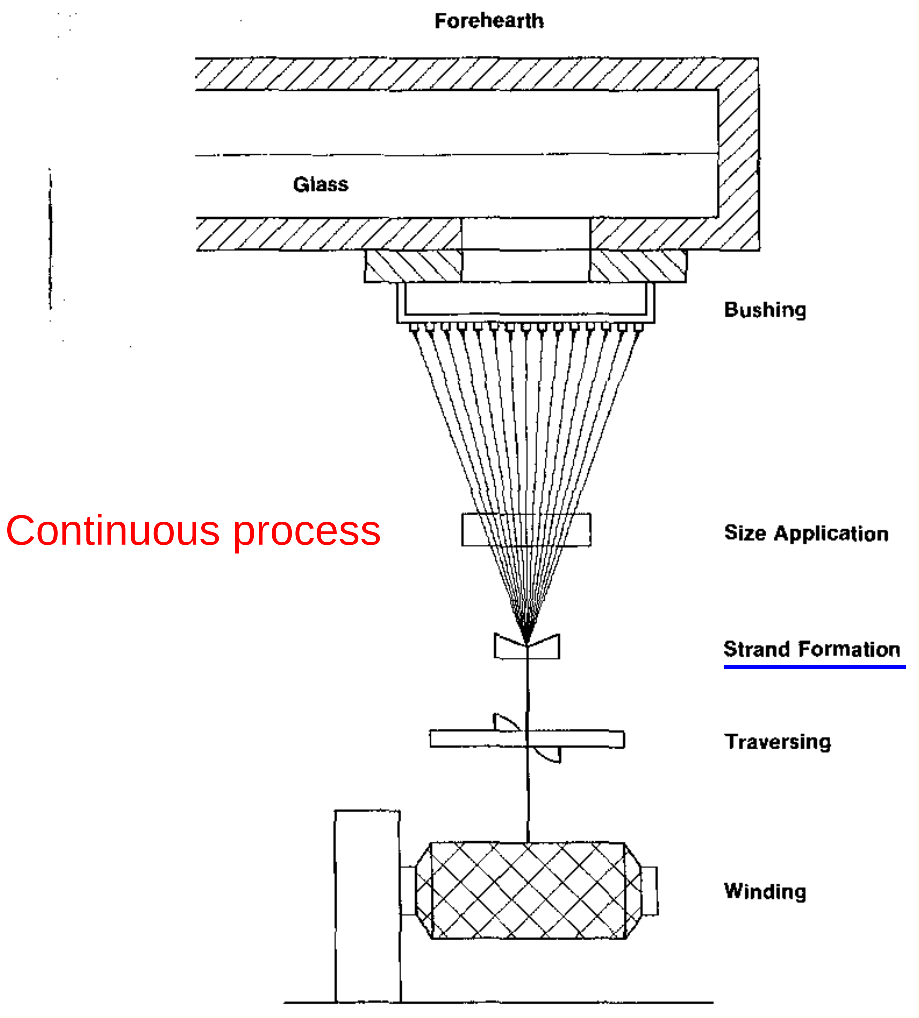
In GRPCs, optimal strength properties are gained when straight, continuous fibers are aligned parallel in a single direction. To promote strength in other directions, laminate structures can be constructed, with fibers aligned in other directions.

As fibers are being produced, they are normally treated with sizing and coupling agents. These reduce the effects of fiber-fiber abrasion which can significantly degrade their mechanical strength. Coupling agents are used to promote adherence of the matrix material to the fiber.

Continuous glass fiber fabrication

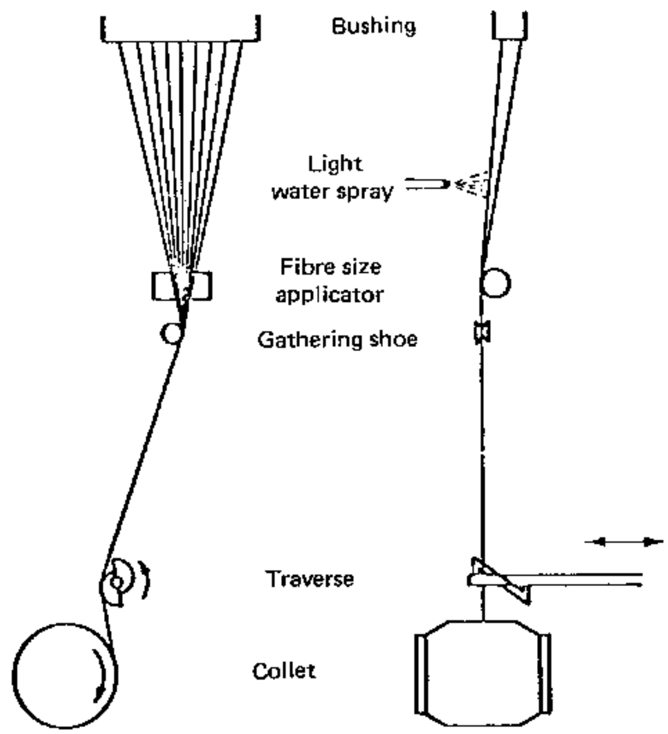
The number of nozzles per bushing may vary from ~ 100 nozzles for the finest fibers (~ 3 – 5 μm), to ≥ 6,000 nozzles for the thickest. To the individual filaments, a size coating is applied first (to prevent abrasion) and they are then combined into one strand, which is wound on a rotating cylinder.

Continuous process



Adapted from: Commercial glasses, Advances in Ceramics, Vol. 18, ed. D.C. Boyd and J.F. MacDowell (The American Ceramic Society, Columbus, Ohio, 1986).

The GFRCs for wind turbine blades contain continuous E-fibers with diameters in the range of 5 – 20 μm, which are fabricated by feeding remelted glass marbles, or using a direct melt process where the molten glass is fed into a fiber-forming furnace, called bushing, which contains a large number of small orifices or nozzles (~ 1 – 3 mm in diameter) through which the molten glass is drawn into fibers at speeds up to ~ 200 km/h. The bushing is made of a Pt alloy and the furnace is electrically heated.

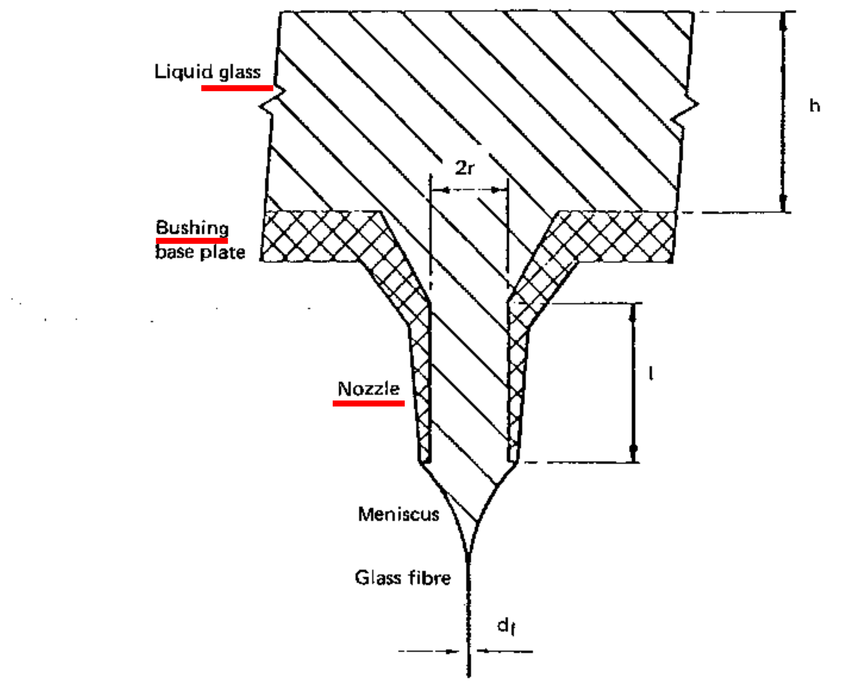


Schematic representation of mechanical attenuation for the forming of continuous glass fibres. The bushing is fed either with marbles, or directly with liquid glass from a fore-hearth

Adapted from: P.J. Doyle, *Glass-making today*, Portcullis Press (Redhill, UK, 1979).

Using LFT (longfiber technology) reinforcements in the composite processing enables molders to produce structural parts, compounding the fiber glass in-line with injection or compression molding techniques.

Single nozzle



The nozzle in a base plate of a bushing showing the meniscus formed during attenuation of the glass into fibre

Adapted from: P.J. Doyle, *Glass-making today*, Portcullis Press (Redhill, UK, 1979).

The cost of E-glass fiber composites is typically one to two orders of magnitude less than the other high-performance fibers. However, this and other glass composites suffer from inefficient fiber strength and degradation under stress-corrosion conditions. The exceptional tensile properties of glass filaments that are measured at low temperature, low-humidity environments demonstrate a large potential for improved composite performance in these lost-cost materials. The strength of pristine S2-glass filaments, e.g., is reported to be as high as 11.6 GPa at liquid nitrogen temperature.

The inferior performance of the low-cost E-glass fibers can be improved to some extent by retarding the stress-corrosion of the material due to moisture and practical approaches to mitigating this corrosion are being addressed. One such approach to improving the strength and the stress-rupture lifetimes of glass fibers at ambient conditions is through the use of coatings. (Studies of optical fibers have shown that extremely high strengths can be achieved at ambient conditions if the surface of the fiber is first dried and hermetically sealed with metal coatings).

The chemical durability, weathering and environmental effects on the glass (solarization) are ultimately compositionally dependent and are also influenced by the geographic location of the wind energy system.

Also, many flywheel designs are actually limited not by fiber failure, but by matrix-dominated failure modes.

In summary: carbon fibers are generally preferred for highest performance and E-glass fibers for lowest cost.

If ultra-high strength, high modulus glass compositions, including more environmentally friendly B-free formulations, are developed to replace E-glass, these should be able to compete well with the carbon fibers.

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