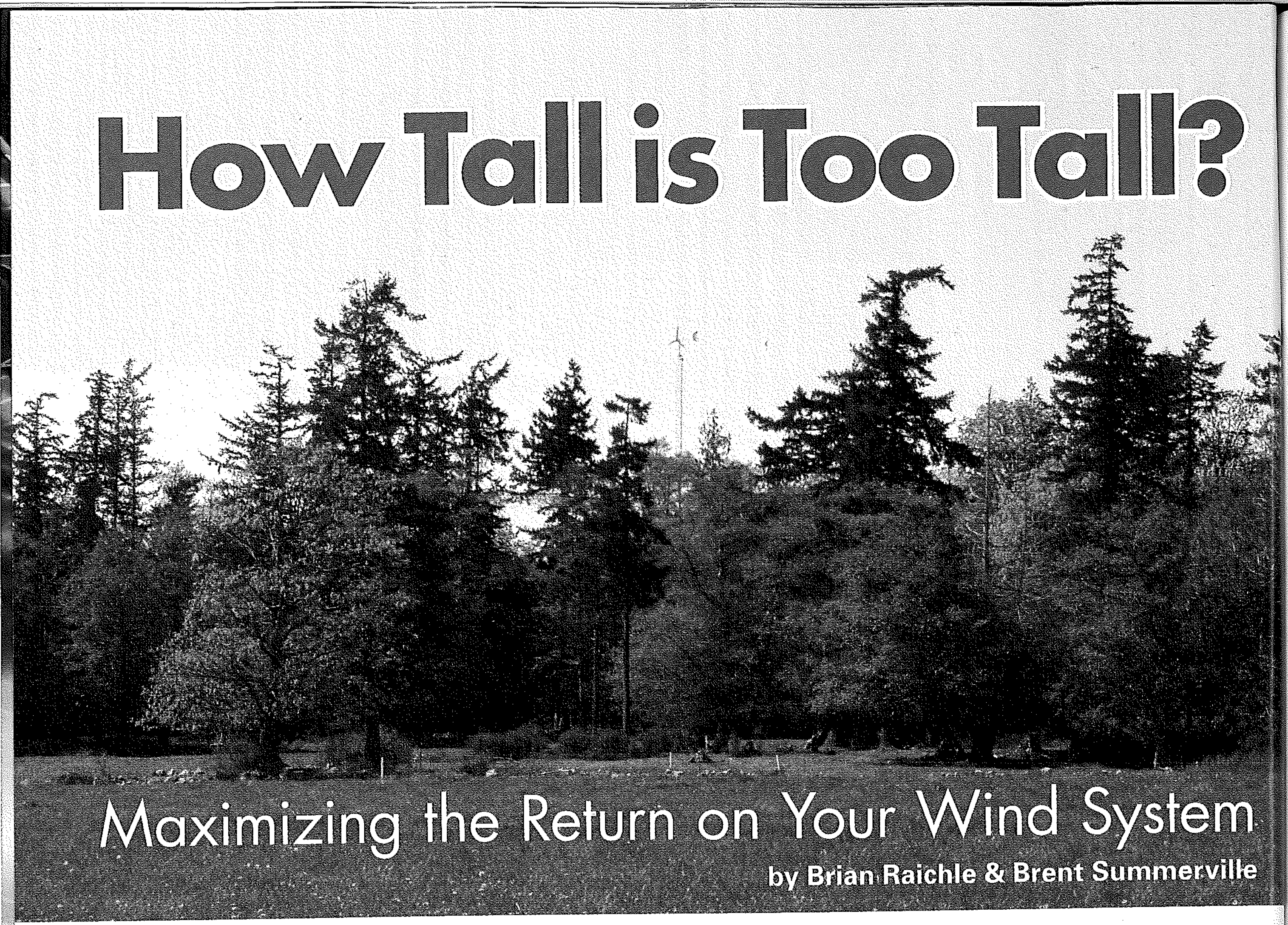
How Tall is Too Tall?

Maximizing the Return on Your Wind System

by Brian Raichle & Brent Summerville



While it looks lost in the trees, the ARE turbine in the distance is actually on a 165-foot, guyed lattice tower that places the turbine more than 40 feet above everything near enough to affect its exposure to the wind.

For a homeowner installing a wind generator, the first question is often, "Which turbine?" The second question is, "What type and how tall of a tower?" The often-repeated mantra is that "taller is better," but taller is also more expensive. So the more relevant question for most on-grid homeowners is, "What tower maximizes my energy output and the return on my investment?" It's this question that we'll answer in this article. (See Access for more tower economics reading.)

According to the experts, the bottom of a wind generator's blades should be at least 30 feet above the tallest obstacle within 500 feet—be it a tree, building, or ridge. For example, if the mature height of a grove of trees that sit 300 feet from your proposed tower site is 60 feet, the minimum height to the bottom of the rotor is 90 feet (60 + 30). For a wind turbine with 6-foot blades, the minimum tower height would be 96 feet (6 + 90).

This rule applies to most locations, but not all. One exception is if you plan to site your turbine near an abrupt change in height of a continuous obstacle, such as a cliff or dense forest next to a field. In this case, you should allow not 500 feet, but 0.6 miles (1 km) for the "edge effect" to subside.

Your tower must be tall enough to at least meet the 30/500 rule. Violating this rule will put your generator in turbulent, low-speed wind, resulting in lower energy output, and increased wear and tear on the wind turbine from turbulent winds.

Wind Shear

Wind generators are installed on towers because the wind speed is always higher and there is less turbulence at increased heights above Earth's surface. This is due to decreased friction between the moving air mass and Earth's surface. As height above the surface increases, surface effects decrease and wind speed increases. This increase in wind speed with height is called wind shear. The most commonly used equation to represent the wind-shear model is a power law relationship:

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^{\alpha}$$

In this formula, "V" represents wind velocity, and "H" represents height, with the subscript numbers representing a specific height and its wind speed. Alpha (α) is the wind-shear coefficient—the wind speed increase with increasing height.

Placing wind generators on taller towers exposes them to higher wind speeds and also reduces turbulence-induced wear and tear—and associated maintenance costs. Just as carpet creates more dragging friction than a polished hardwood floor, rough terrain causes more friction with the air than a smooth field. A smooth, flat topography (open fields; water) has a low wind-shear coefficient (α = 0.1 to 0.15), while a hilly, wooded, or developed region with lots of buildings will have a higher wind-shear coefficient (α = 0.3 to 0.6). Similarly, your turbine will experience higher wind shears if you don't obey the 30/500 siting rule. Knowing the wind-shear coefficient at your tower site is key to evaluating tower economics. Read Paul Gipe's book, *Wind Power*, or Mick Sagrillo's article in *HP40* for help in estimating your wind-shear coefficient (see Access). The Wind-Shear Coefficients table (above) gives general guidelines for estimating wind shear.

Wind-Shear Coefficients

α	Description
0.1	Perfectly smooth (calm water)
0.2	Flat grassland or low shrubs
0.3	Trees or hills, buildings in area
0.4	Close to trees or buildings
0.5	Very close to trees or buildings
0.6	Surrounded by tall trees or buildings

System Costs

Bergey Excel-S

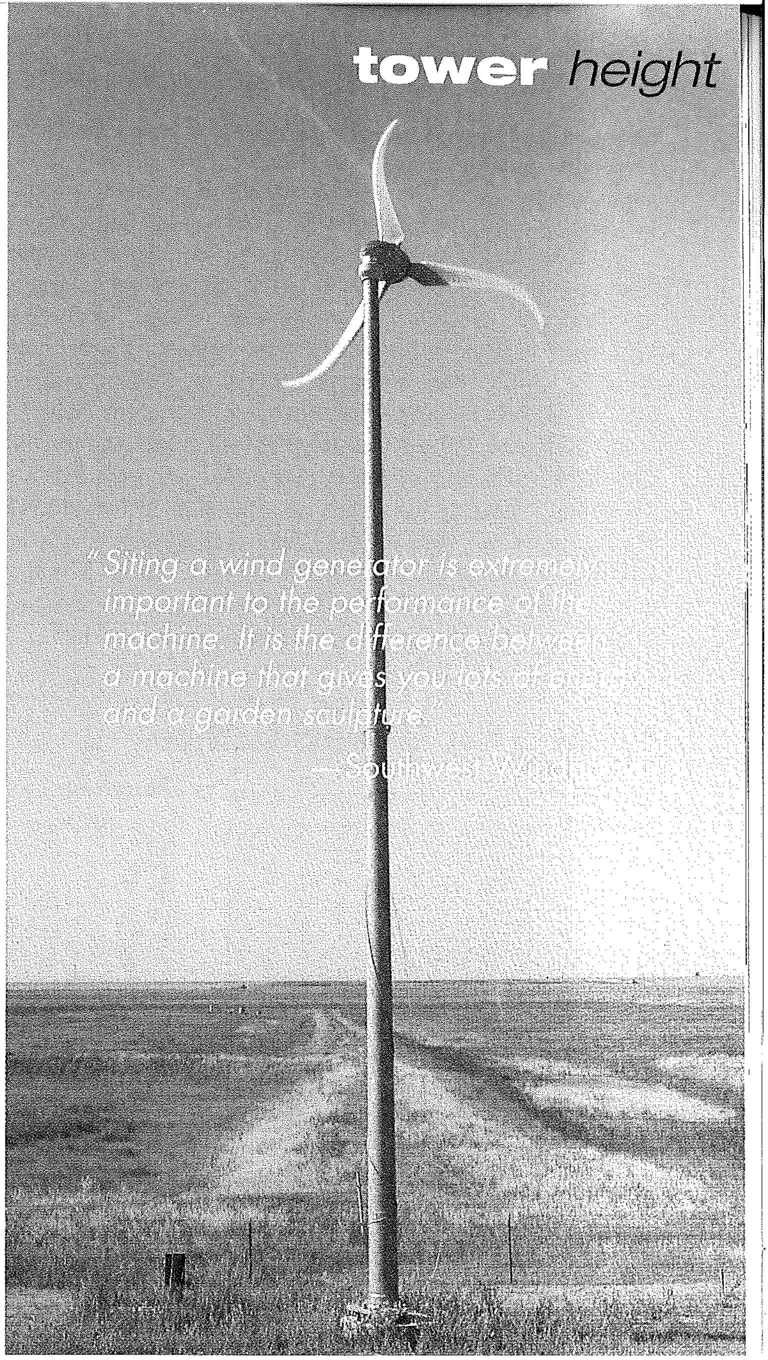
Tower Manufacturer	Tower Type	Height (Ft.)	Cost
Bergey	Monopole	120	$77,720
Bergey	Monopole	90	67,110
Bergey	Freestanding lattice	120	63,170
Bergey	Monopole	60	60,010
Bergey	Freestanding lattice	100	58,900
Bergey	Tilt-up lattice	100	58,600
Bergey	Tilt-up lattice	80	56,430
Bergey	Freestanding lattice	80	55,430
Bergey	Tilt-up lattice	60	55,210
Bergey	Freestanding lattice	60	52,660
Bergey	Guyed lattice	120	52,620
Bergey	Guyed lattice	100	50,900
Bergey	Guyed lattice	80	49,730
Bergey	Guyed lattice	60	48,960

ARE110

Tower Manufacturer	Tower Type	Height (Ft.)	Cost
ARE	Tilt-up tubular, 4 in.	127	$22,235
ARE	Tilt-up tubular, 4 in.	106	21,470
ARE	Tilt-up tubular, 4 in.	85	19,700
ARE	Tilt-up tubular, 4 in.	64	19,450
ARE	Tilt-up tubular, 4 in.	43	18,750

Skystream 3.7

Tower Manufacturer	Tower Type	Height (Ft.)	Cost
ARE	Tilt-up tubular, 5 in.	127	$18,550
ARE	Tilt-up tubular, 5 in.	106	17,500
ARE	Tilt-up tubular, 5 in.	85	16,000
SWWP	Tilt-up tubular, 5 in.	70	15,000
ARE	Tilt-up tubular, 5 in.	64	14,600
SWWP	Monopole	45	13,750
SWWP	Monopole	34	12,250



> "Siting a wind generator is extremely important to the performance of the machine. It is the difference between a machine that gives you lots of energy and a garden sculpture."
>
> —Southwest Windpower

Courtesy Dr. Nolan Clark

At this low wind-shear site, a 34-foot tower is all that's needed to keep the Skystream in fairly nonturbulent wind.

Tower Types

Your generator will sit on a tower, but what type? Be sure to follow the turbine manufacturer's recommendations and select a reputable tower manufacturer and installer. Commonly available towers are tilt-up, fixed guyed, or freestanding (each including tubular or lattice types). (For more on tower types, see Ian Woofenden's "Wind Generator Tower Basics" article in *HP105*.) Various combinations and permutations within these categories exist, but we'll review the economics of these tower types: tilt-up tubular, tilt-up lattice, guyed lattice, freestanding lattice, and monopole, at heights ranging from 34 to 127 feet. The System Costs table provides basic information about the analyzed towers, including a full system cost for the given turbine and tower.

To provide a useful example, we've compared the economics of installing three wind generators—Bergey Windpower's Excel-S (22-foot-diameter rotor), Southwest Windpower's Skystream 3.7 (12-foot-diameter rotor), and Abundant Renewable Energy's ARE110 (11.8-foot-diameter rotor)—on readily available towers of different heights and in different wind-shear regimes. All machines are for batteryless, grid-tied systems. Economics are reported for an annual average wind speed of 11 mph at 33 feet (10 m) above ground level and at wind-shear coefficients of 0.1 to 0.6. Locations with different shears and the same annual average wind speed at 33 feet will have different wind speeds near the ground, with the low-shear location being much windier.

Calculating Wind Speed from Known Data

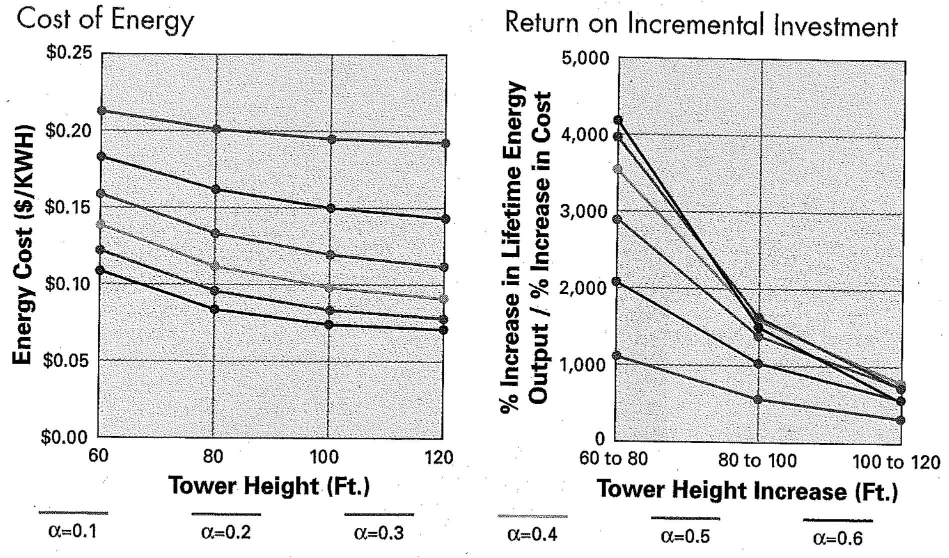
Assume a Midwestern farm site, which is mostly flat grassland, has a wind-shear coefficient of 0.2 ($\alpha = 0.2$) and your 50-foot-high anemometer (H_1) has recorded an annual average wind speed of 15.6 mph (V_1).

What annual average wind speed (V_2) can you expect at turbine hub height on a 75-foot tower (H_2)?

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^{\alpha} ; \; V_2 = V_1\left(\frac{H_2}{H_1}\right)^{\alpha} ; \; V_2 = 15.6 \text{ mph}\left(\frac{75 \text{ ft.}}{50 \text{ ft.}}\right)^{0.2}$$

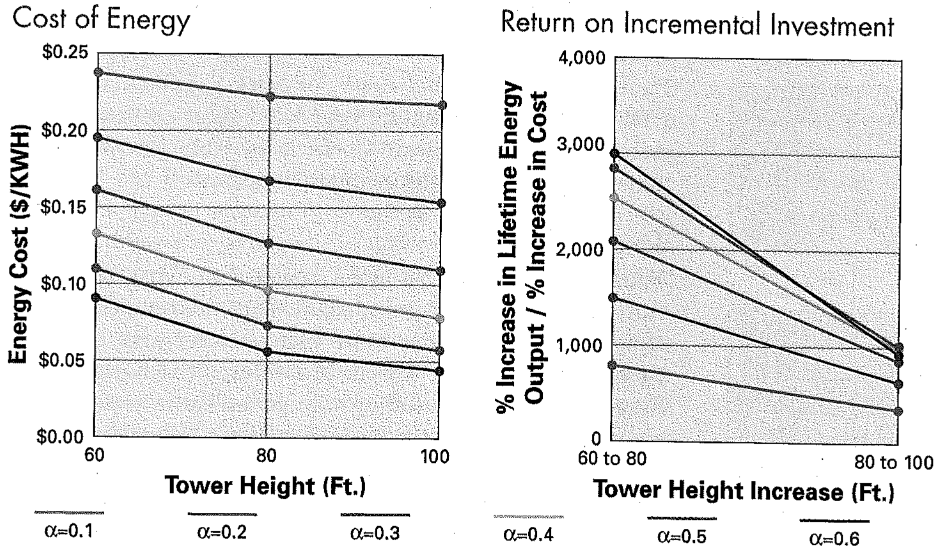
$$V_2 = 16.9 \text{ mph}$$

Excel-S on Guyed Lattice


Cost of Energy

Return on Incremental Investment

Excel-S on Tilt-Up Lattice


Cost of Energy

Return on Incremental Investment

The annual energy output—the number of KWH of energy the turbine will produce in one year—was calculated using each turbine's power curve (provided by the manufacturer) and a typical distribution of wind speeds, with an average annual wind speed of 11 mph at 33 feet. The annual energy outputs in KWH (assuming air density for an elevation of 1,000 feet) are shown on the Annual Energy Output table on the opposite page.

System cost estimates include turbine, controller, inverter, tower, wiring, concrete, shipping, and installation. These costs can vary significantly.

The cost of energy in dollars per KWH was calculated by dividing the total system cost by the energy output over an estimated lifetime of 20 years. The original spreadsheets used to perform these calculations are available from the authors.

Results—Excel-S

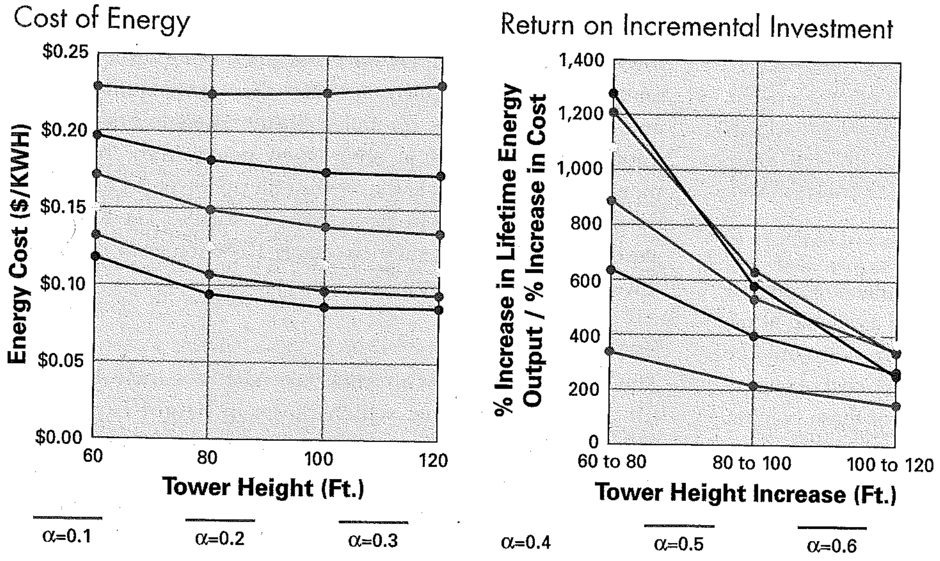
The cost of energy (COE) in dollars per KWH was calculated for six wind-shear scenarios for the four available tower configurations: guyed lattice, tilt-up tubular, freestanding lattice, and monopole. These towers are available from Bergey Windpower at heights of 60, 80, 90, 100, and 120 feet. The results are shown for an average annual wind speed of 11 mph at 33 feet.

Annual Energy Output (in KWH) for Various Wind-Shear Coefficients

Height (Ft.)	Bergey Excel-S						Skystream 3.7						ARE110					
	α=0.1	α=0.2	α=0.3	α=0.4	α=0.5	α=0.6	α=0.1	α=0.2	α=0.3	α=0.4	α=0.5	α=0.6	α=0.1	α=0.2	α=0.3	α=0.4	α=0.5	α=0.6
34	–	–	–	–	–	–	3,017	3,048	3,080	3,112	3,144	3,177	–	–	–	–	–	–
43	–	–	–	–	–	–	–	–	–	–	–	–	4,262	4,549	4,848	5,157	5,476	5,804
45	–	–	–	–	–	–	3,269	3,569	3,885	4,217	4,563	4,922	–	–	–	–	–	–
60	11,506	13,369	15,423	17,649	20,021	22,497	–	–	–	–	–	–	–	–	–	–	–	–
64	–	–	–	–	–	–	3,604	4,294	5,048	5,854	6,696	7,554	4,688	5,455	6,278	7,140	8,022	8,900
70	–	–	–	–	–	–	3,692	4,490	5,367	6,302	7,271	8,240	–	–	–	–	–	–
80	12,369	15,321	18,651	22,260	25,984	29,605	–	–	–	–	–	–	–	–	–	–	–	–
85	–	–	–	–	–	–	3,889	4,931	6,081	7,294	8,507	9,639	5,006	6,151	7,381	8,637	9,847	10,928
90	12,736	16,167	20,056	24,226	28,402	32,234	–	–	–	–	–	–	–	–	–	–	–	–
100	13,070	16,946	21,342	25,988	30,469	34,293	–	–	–	–	–	–	–	–	–	–	–	–
106	–	–	–	–	–	–	4,119	5,453	6,922	8,420	9,806	10,921	5,262	6,714	8,256	9,762	11,083	12,066
120	13,661	18,337	23,613	28,968	33,667	36,970	–	–	–	–	–	–	–	–	–	–	–	–
127	–	–	–	–	–	–	4,312	5,896	7,619	9,298	10,697	11,592	5,475	7,185	8,965	10,608	11,877	12,573

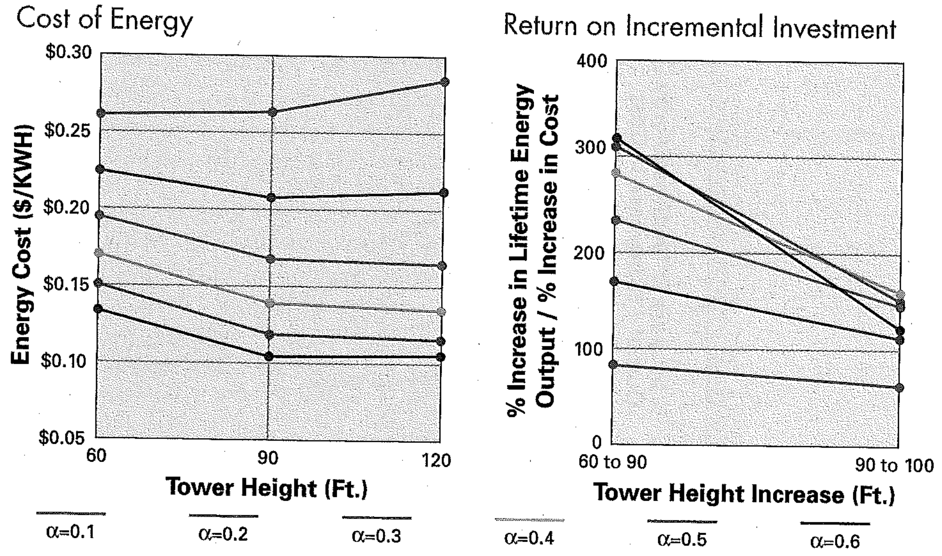
Based on annual average wind speed of 11 mph at 33 ft (10 m).

Excel-S on Freestanding Lattice


Cost of Energy

Return on Incremental Investment

Excel-S on Monopole


Cost of Energy

Return on Incremental Investment

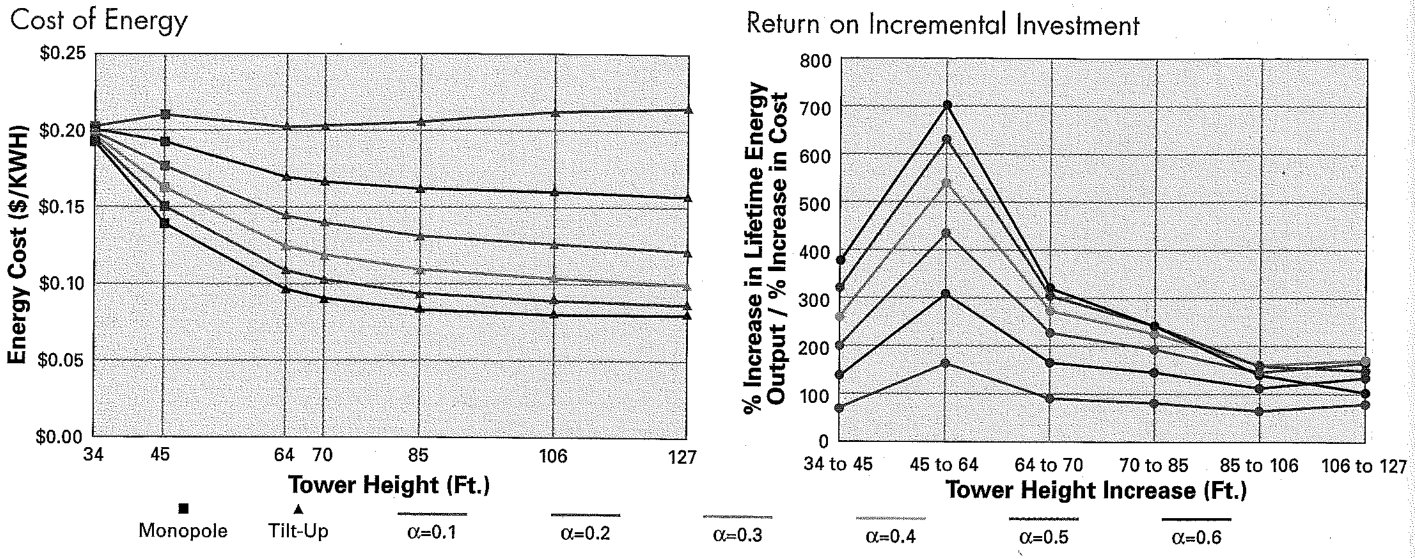
For guyed and tilt-up lattice towers (see graphs at left), the COE generally decreases with increasing tower height across the wind-shear range. With the freestanding lattice tower, COE increases at the lowest shear. Cost of energy with the monopole tower increases with tower height at the lowest two shears and bottoms out with the 90-foot tower.

An alternative way to evaluate the economics of using a taller tower is to compare the incremental increase in lifetime energy output to the incremental cost associated with purchasing the taller tower, or in other words, the return on incremental investment (ROII). By "incremental increase," we mean the additional KWH generated on a taller tower. By "incremental cost," we mean the additional cost to invest in a taller tower.

As an example, the cost of Excel-S installed on an 80-foot tower is 1.6% higher than on a 60-foot tower. However, the taller tower system will generate 6.2% more energy in a 0.1 shear, and 26% more energy in a 0.6 shear. That's a 388% and 1,640% ROII, respectively. The ROIIs are shown for an Excel-S on the four tower types at similar heights over a range of shears for each tower.

What investor wouldn't be happy with a 1,000% return on their investment? While the ROII decreases with further increases in tower height, the return in all cases is greater than 200%. It's worth noting that with all towers, the ROII for the

Skystream on Monopole & Tilt-Up



highest shears increases at a lower rate for taller towers. However, if you're not driven purely by economics—for example, you need to maximize energy generation—then a decreased ROII and increased cost per kilowatt-hour shouldn't be a deterrent.

Results—Skystream 3.7

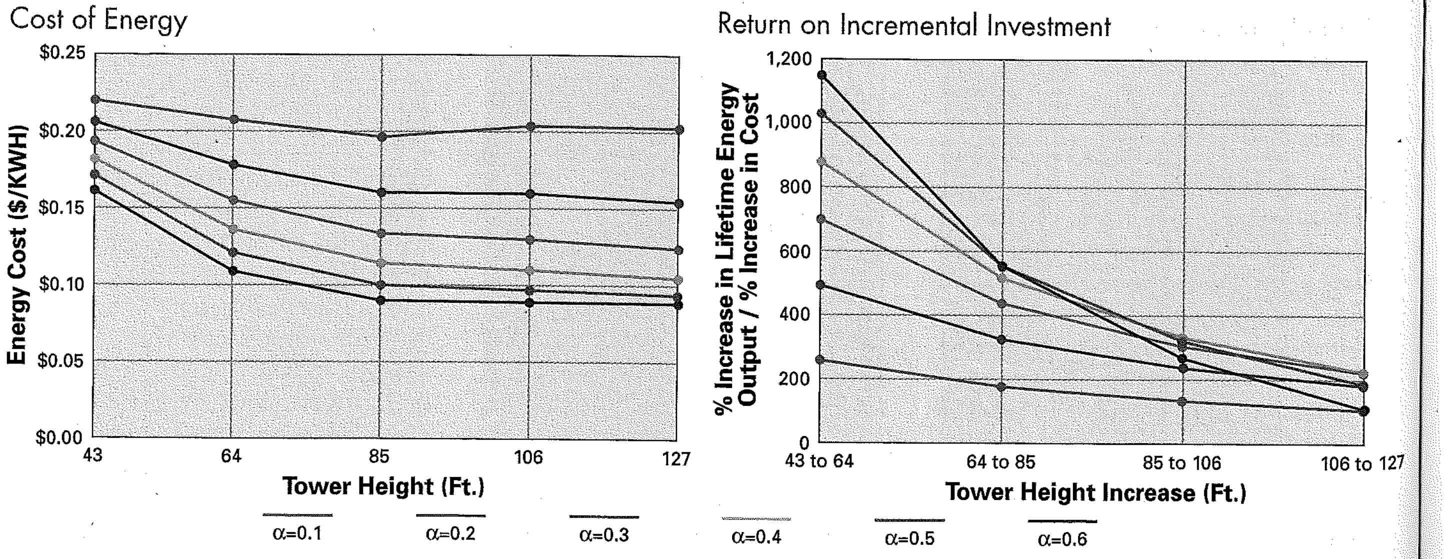
For this turbine, monopole tower kits are available at 34 feet and 45 feet, and tilt-up tubular tower kits are available at 64, 85, 106, and 127 feet. As a result, not all the tower kits could be consistently compared at similar heights. Instead, cost of energy was calculated for shears of 0.1 to 0.6 at each of these heights. COE for an annual average wind speed of 11 mph at 33 feet are reported in the graphs.

The graphs show a slight upward trend in COE at the lowest shear, but improved economics otherwise. Cost of energy decreases rapidly for the short monopole towers and decreases slowly for taller tilt-up towers. A significant improvement in ROII is seen when going from the tallest monopole tower (45 ft.) to the shortest tilt-up tower (64 ft.). Notice the similar tower costs in the Systems Cost table. The ROII then steadily decreases to a still-respectable 100% return at the tallest tower height, except at the very lowest shear.

Results—ARE110

The ARE110 was evaluated on ARE's 4-inch-diameter tilt-up tubular towers, which range in height from 43 to 127 feet. As with the previous systems, there is economic disincentive to purchase the tallest towers for low wind-shear conditions; otherwise, using a taller tower provides a lower cost of energy. The very best ROIIs are above 1,000% and result when "upgrading" from the shortest tower in high wind shears. In all cases, a doubling of incremental investment should be expected. Surprisingly, the lowest ROII for the tallest tower "upgrade" occurred at the highest shear.

ARE110 on Tilt-Up



Shear Genius

In terms of straight economics, is taller better? It depends. In low-shear conditions—on the plains and in coastal regions, for example—simply satisfying the minimum tower height rule may maximize the return on your system investment. In high-shear conditions—in wooded hills and mountainous areas—buy the tallest tower you can erect. The general trends presented are typical for residential-scale systems. Factors not considered in this economic analysis include turbine repairs and reduction in energy production due to greater turbulence at higher shears.

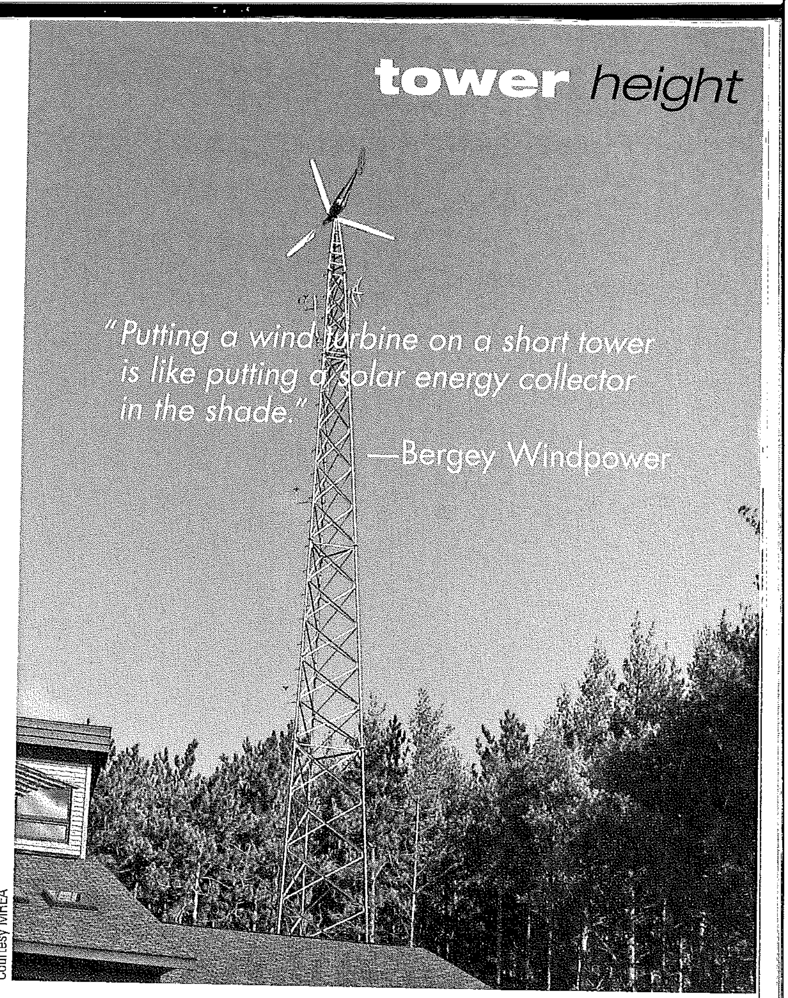
So how can you make practical use of this information? Once you have selected a wind turbine, follow these steps to determine the best tower height at your location:

1. Use sound siting rules to find the best spot to locate the wind turbine (i.e., look at high spots on property, consider upwind obstructions, etc.).
2. Determine your minimum tower height based on the height of the surrounding obstructions, such as trees and buildings. The general rule is that the bottom of the blades should be a minimum of 30 feet above the tallest obstruction within 500 feet.
3. Choose a tower type that meets your budget, site conditions, and aesthetic and practical preferences.
4. Estimate your local wind-shear coefficient using the wind-shear table on page 85.
5. Analyze how incremental increases in tower height impact your cost of energy. Unless your site experiences very low wind shear, investing in a taller tower results in significantly more energy output, which will pay for this incremental investment and result in a quicker payback for the additional expense incurred.
6. Keep in mind that these are general rules that apply to most potential sites. An experienced turbine installer or professional site assessor can determine if your site is an exception to the rule, and help maximize the return on your investment.

As with clothing and beer, cost is not the only factor to consider when choosing a tower. Other factors to consider include local zoning ordinances, aesthetics, size of footprint, and crane access. Make sure you choose a system that suits your wants, not just your needs, and one that you'll enjoy living with for many years to come.

Access

Brian Raichle (raichlebw@appstate.edu) is an assistant professor in the Appropriate Technology program at Appalachian State University. He is involved in wind resource assessment and solar thermal research.



"Putting a wind turbine on a short tower is like putting a solar energy collector in the shade."

—Bergey Windpower

Courtesy MREA

A 100-foot freestanding lattice tower was chosen to clear the 0.6 shear site at the Midwest Renewable Energy Association headquarters in Custer, Wisconsin.

Brent Summerville (wind@appstate.edu) is a renewable energy engineer at Appalachian State University where he manages their Small Wind Research & Demonstration Site and their Anemometer Loan Program, and leads public workshops and presentations on wind energy.

Further Reading:

Wind Power: Renewable Energy for Home, Farm, and Business by Paul Gipe (2004, Chelsea Green Publishing)

"Wind Generator Towers," Ian Woofenden, *HP105*

"Wind Generator Tower Height," Mick Sagrillo, *HP21*

"Tower Economics 101, 102 & 103," Mick Sagrillo *HP37, 38, & 39*

"Site Analysis for Wind Generators, Parts 1 & 2," Mick Sagrillo, *HP40 & 41*

"Small Wind Electric Systems: A U.S. Consumer's Guide," U.S. DOE • www.eere.energy.gov/windandhydro/windpoweringamerica/small_wind.asp

Small Wind Toolbox • www.renewwisconsin.org/wind/windtoolbox.html