Wind and Ethanol:

Economies and Diseconomies of Scale

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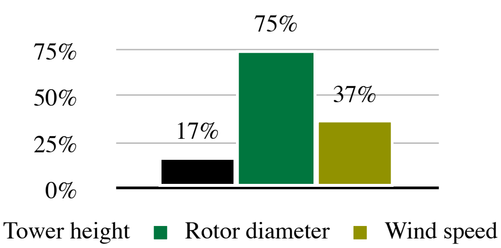
Introduction

Larger renewable energy facilities tend to generate energy at a lower unit cost. This is why the rated capacity of a typical wind turbine has increased from 25 kW in 1981 to 2.5 MW today and the output of a typical ethanol plant has increased from 40 million gallons in 2002 to 100 million gallons in 2007.

However, larger production units also impose potentially significant social costs. The most significant is that bigness encourages, and often requires, absentee ownership. This reduces or eliminates the many benefits that accompany a locally owned facility.[1] Bigness also requires much longer distribution systems for both inputs and outputs, generating environmental as well as social costs.

To date, policy makers have designed renewable energy incentives that offer higher rewards for bigger facilities. They should more closely examine the tradeoffs attendant to large scale production systems. This report argues that the *net* benefits to society from larger scale production may not outweigh the costs from limiting the potential for locally owned energy facilities serving regional needs.

Reduction in power production costs from a doubling of tower height and rotor length, and a 25% increase in wind speed.



Wind

For a single turbine, the potential output and unit cost are based on many factors: turbine hub height, rotor diameter, and wind speed. Siting and design of turbines can significantly impact the efficiency and, ultimately, the cost of power from a wind turbine. For multiple turbines, other efficiency issues arise, such as distance between turbines, interconnection to the electric grid, and transmission distance to the ultimate customer.

Economies of Scale

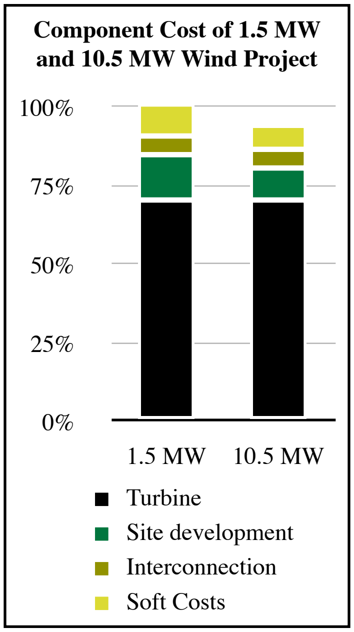
There are three ways to lower the cost of energy from a single turbine.

1. *Increase the height of the turbine hub*. A rule of thumb is that wind speed increases by the 1/7th power of hub height. If a Vestas V66 1650 turbine produced power at 6 cents/kWh, doubling the tower height would cut the production cost by approximately 1 cent/kWh for each doubling.[3]

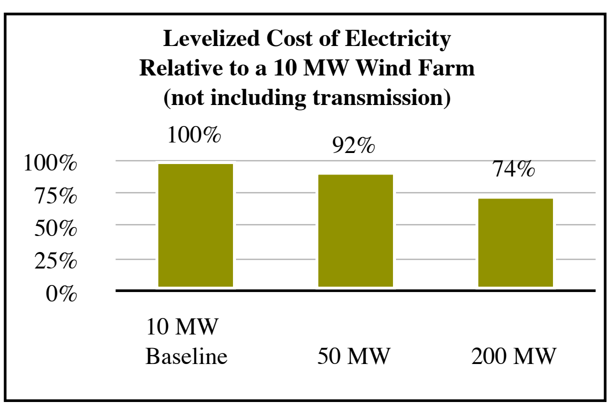
2. *Increase the diameter of the rotor*. Power generation increases by the square of the increase of the rotor diameter.[4] Doubling rotor diameter from 40 to 80 m, for example, could reduce power production costs by about 75% (from 6 cents to 1.5 cents/kWh in our hypothetical example).

3. *Install the turbine a windier location*. The power in the wind varies by the cube of the increase in the wind speed.[5] Doubling the windspeed thus theoretically increases the turbine power output eightfold, though in practice turbulence and other factors constrain it. Additionally, wind speed variation between sites is usually modest. For example, the average wind speed for a Class 4 wind area is only about 21 percent higher -

5.7 meters per second (mps) vs. 6.9 mps - than a Class 3 wind area. That difference would lead to a reduction in the cost per kWh of about 34%. On the other hand, higher wind speeds can be found on only a limited acreage and sections of the country. Moving from Class 4 to Class 3 might increase the amount of acreage and therefore potential sites available several fold. Thus the tradeoff for the higher cost electricity that comes from siting on lower wind speed areas versus the higher transmission costs of siting on more remote windier areas becomes important. We explore the transmission line issue in more detail below.



Unit cost savings can also occur by constructing and operating multiple turbines. Construction costs are lower per kW since larger projects can buy components in bulk and spread construction costs, legal and permitting fees, and financing over multiple turbines.[6] Bolinger, et al, find a 30% reduction in site preparation and "soft costs" per kW for a 10.5 MW project over a single 1.5 MW turbine. Overall, the 10.5 MW project is approximately 10% cheaper per MW installed, with soft cost savings making up 40% of the reduction and site preparation the remaining 60%.[7] These reductions are more significant as size scales up.[8]



As wind power continues to grow in prominence, however, some of these economies may decrease. Data from Denmark – generating nearly 20% of its electricity from wind – suggests that the cost savings to large projects may decline as wind power gains greater market penetration, and maintenance services are more widely available.[9] Shared cost savings can also be realized with cooperative models like the retail sectors' Ace Hardware cooperative, where purchasing and advertising costs are pooled among member-owners.

A final advantage to scale is that attracting financing may be easier for large wind farms. Corporate financiers of wind projects are not often interested in small-scale turbines or wind farms.[10] They seek projects with substantial generating capacity that can spread the risk and fixed costs over many turbines.

Diseconomies of Scale

Perhaps the biggest single diseconomy of scale arises from transmission costs associated with large projects. Small wind projects can use the power generated on-site or can offset retail purchases via net metering.[11] Large wind projects almost always exceed on-site needs and net metering limits – only eight states allow net metering over 100 kW.[12] Moving power to distant customers often means constructing new high voltage transmission lines.[13] Because many projects are located in rural areas with little local load (demand), they require substantial upgrades to the existing transmission system to get the power to market.

In one study modeling the connection costs for four different wind farms to six urban areas, transmission costs – including substation upgrades – increased by about 0.3 cents per kWh for every additional 100 miles of line.[15] An average of 13 percent of the lines were rebuilt, the vast majority were new construction. Thus a 500 mile delivery could cost 1.5 cents per kWh more than a local delivery.

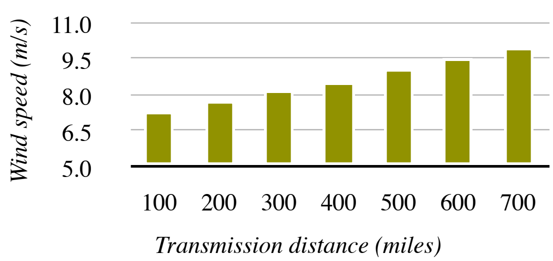
Long distance transmission also results in higher line losses. The combination of transmission and conversion losses reduce delivered power by approximately 1 percent per 100 miles.[16] For a typical project studied, delivered costs increased by about 0.03 cents per kWh per 100 miles of transmission, or about .15 cents per kWh for a 500 mile delivery trip, on top of the 1.5 cents noted above.

Remote Generation is Costly
Wind sites relatively close to the load, even though they have much less energy potential than the high wind sites in the region, can be more economical in many cases...The carrying charges on the expensive HVDC system [used for long distance transmission] typically add about $15 to $20 per megawatt hour to the bus bar cost of the remote wind generation.

Source: Factor and Wind, 35-36.

Another drawback of large wind farms is the interference between the wind turbines. This interference, called "array losses," is caused when turbines are in the wake of other turbines. Research differs on the full effect of array losses. More recent assessments cite the losses of modern wind projects at 2-4% with properly spaced turbines.[17] The Department of Energy has the most nuanced research, estimating that turbine arrays in Class 4 wind speeds may have array losses around 5% due to effects between rows of turbines. Turbine arrays in Class 6 or higher wind speeds will have very low losses, especially in a single-file arrangement.[18] Wind and Factor also use 5-8% for array losses, higher for larger arrays.[19] Using the 5% figure, the lost generation associated with array losses increases the cost of electricity by about 0.15 cents/kWh.[20]

Wind Speed Required to Offset Transmission Losses (7 m/s at turbine)



Overall, transmission and array losses increase the cost of power production. A project 500 miles distant would cost about 1.8 cents/kWh more than a local project. Higher wind speeds could lower generation costs to offset or exceed these higher transmission-related costs. A wind speed 5.3 percent higher would be needed to offset a 500 mile trip.

The second diseconomy of scale for wind farms can occur in higher infrastructure and maintenance costs. While large projects save on site development and legal costs by spreading them over several turbines, a single, smaller turbine may avoid certain costs. Legal costs depend heavily on the number of turbines and landowners involved. A single owner-operator with one turbine can avoid legal and permitting fees (about $20/kW).[21]

Maintenance can be both a diseconomy and an economy of scale. Larger wind installations can spread maintenance costs over many turbines and experience smaller reductions in capacity from single-turbine outages. However, these advantages are more pronounced in wind farms with smaller wind turbines, because the impact of an individual turbine outage is a smaller percentage of total output. Furthermore, smaller turbines have lower maintenance costs because they don't require a large, expensive crane to remove the turbine if repairs require it.[22]

Finally, scaling up turbine size and installing large numbers of turbines also imposes engineering, transportation, and construction diseconomies, although these tend to be modest.

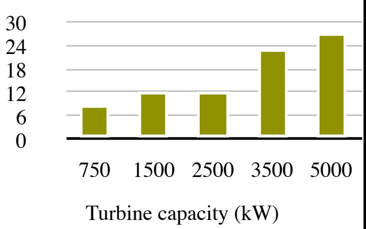
While engineering expertise has allowed turbines to scale up to 3 MW and above, the size scaling can hit "breakpoints" where the cost increases become exponential. For example, for a NEG Micon 2000/72 turbine, the cost of increasing tower height seems to scale easily. The Danish Wind Industry Association estimated that increasing tower height cost approximately $15,000 per additional 10 meters (in 2002).[23] Adjusting for steel price increases, this would be approximately $50,000 per 10 m in 2007.[24] If costs simply scaled linearly as this suggests, the NEG turbine could produce power at a hypothetical 5 cents/kWh at the standard 64 m hub height and reduce that to 4.6 cents/kWh at the outlandish height of 150 m.

However, this example is oversimplified. In tower construction, the breakpoints occur in the transportation and construction of the tower. Most turbine parts are delivered by flatbed truck, traveling directly to the site with reasonable cost (for a 1.5 MW turbine, transport is 3% of total costs - $37/kW).[25] However, larger turbines can exceed standard trailer dimensions (4.1 m high by 2.6 m wide, with a maximum cargo weight around 19,000 kg).[26] If a turbine weighs over 19,000 kg (but less than 84,000 kg) it can still be sent via truck, but at 10 times the cost. One rotor for a Vestas V82 turbine, for example, weighs 43,000 kg.

Building a tower too high also imposes significant costs. An 86 m turbine tower for a 1.5 MW turbine has a base diameter of 4.9 m, which not only exceeds standard trailer dimensions (4.1 m height) but also the trigger height for police escort and/or temporary utility wire disconnection (4.83 m). Certain jurisdictions can simply refuse to allow such disruptive cargo, adding expense as the truck must take a more circuitous route.[27]

The turbine nacelle can also be costly to ship because of the weight. The nacelle for an 84 m rotor diameter turbine weights the maximum (84,000 kg) for truck transport and, even with the gearbox removed, a 115 m rotor diameter nacelle would be at the limit as well.[28] These transportation limitations account for dramatic cost increases when scaling already-large turbine towers. While an 80-meter tower costs ~$400,000 for materials, transportation and installation, a 120-meter tower costs nearly $1.2 million.[29] This may explain why even the largest turbines produced by GE, Vestas, and Suzlon have hub heights no greater than 105 m.[30]

Crane Costs for Constructing a 50-turbine wind farm ($/kW)



In addition to exponentially increasing transportation and construction costs, turbines also face cost breakpoints when installation becomes more challenging. Increasing tower heights create the need for substantially larger and more expensive cranes to do installation. Crane costs for a 50-turbine wind farm increase from $9/kW for 750-kW turbines to $27/kW for hypothetical 5000-kW turbines.[31] In both cases, the cost (spread over 10 years) is less than 1/10th cent per kWh.

Overall, larger wind turbines are indisputably more economical than smaller ones: doubling tower height and rotor size decreases production costs by up to 80%. The economies are less clear regarding wind farm size. Increasing a wind farm from 10 MW to a 200 MW can lower levelized costs by 25% (1.5 cents/kWh off a baseline price of 6 cents). However, the remote location of most large wind farms incurs significant diseconomies related to the need for increased transmission - at 500 miles, the transmission costs and losses (1.8 cents/kWh) offset the size economies.

Ethanol

As the ethanol industry expands, plants are growing ever larger, with new dry mill plants approaching and even exceeding 100 million gallons per year (MGY).[32] While larger plants enjoy some economies of scale in the production and distribution of ethanol, they are modest and likely do not affect the wholesale price of ethanol.

Economies of Scale

Scaling Capital Costs		
Plant capacity	40 mgy	100 mgy
Capital costs (millions)	$62.8	$135.7
Debt service ($/gal)	$0.153	$0.133
Cost savings over 40mgy	--	2.0 cpg

As with many manufacturing industries, the conventional wisdom in ethanol production is that bigger is more efficient. The first advantage of size is a reduction in capital costs per gallon. Although not as scalable as other industries, where a 1% expansion of production capacity only increases capital costs by 0.6%, ethanol production does have an economy of scale. A 1% expansion in ethanol production is accompanied by a 0.84% increase in capital costs.[33] As shown in the table, this economy of scale corresponds to slightly smaller financing costs per gallon of ethanol produced. A 100 MGY plant will save 2.0 cents per gallon (cpg) in finance payments. One reason ethanol plants may not scale as well as other manufacturing types is that production costs rely heavily on the cost of the feedstock – primarily corn. No matter how big the plant, it tends to pay the prevailing market price for corn and for energy inputs (electricity and natural gas).[34]

There are some savings on other costs however; larger-scale plants may have production economies of scale from relatively lower labor and administrative costs

Average ethanol plant operating cost (per gallon)[37]	
Feedstock (corn)	$1.09
Electricity & natural gas	$0.29
Debt service	$0.15
Capital depreciation	$0.13
Labor	$0.05
Enzymes	$0.04
Maintenance	$0.04
Denaturant	$0.03
Administrative costs	$0.03
Chemicals	$0.02
Waste management	$0.01
Yeast	$0.004
Other	$0.004
Water	$0.003

per gallon produced. "A 50 [MGY] ethanol plant on average will employ between 35 and 40 employees [one for every 1.25 million gallons], whereas a 100 [MGY] plant needs about 55 to 60 employees [one for every 1.67 million gallons]."[35] However, labor costs are only about 2-3 percent of total plant expenses.[36] Another study based on engineering estimates found decreasing production costs to scale for ethanol plants up to 100 MGY, whether powered by natural gas, coal, or biomass. Each type of plant saw a 2-3 cpg reduction in production costs when scaled up from 50 MGY to 100 MGY.[38]

Once ethanol is produced, large plants may also have advantages in marketing and transportation of the product. However, there are virtually no studies of this advantage and ethanol marketing groups tend to even the playing field.

On the transportation side, larger producers may benefit from price and logistical advantages of having more product to ship. With 30,000-gallon tanker cars, a unit train (95 cars) holds 2.85 million gallons of ethanol and it takes substantial production to fill it quickly. A 100 MGY plant can fill a unit train about every 10 days. Unit train rates are less expensive than "mixed trains," where the ethanol may be one of several products or the ethanol may come from several different plants. For a BNSF railroad shipment from SW Minnesota to Watson, CA, for example, rates are 10 percent lower for unit trains than for mixed trains - $4,500 per car instead of $5,000.[39]

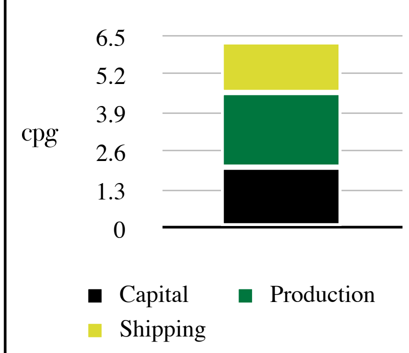
Ethanol Shipping Rates		
	Unit Train	Mixed Train
Train cars	95	30-94
Cost/car ($)	$4,500	$5,000
Car capacity (gal)	30,000	30,000
Cost ($/gal)	15 cents	16.7 cents
Cost for 100 MG	$15 million	$16.7 million

Unit trains generally offer scheduling and pricing advantages, but there are few terminals with the capacity to rapidly unload a unit train – on the West Coast, there is only one.[40] Additionally, an ethanol plant has to build its own loading track and lease or buy its own tank cars, so a large ethanol plant will have significantly higher initial costs in preparing for unit train service.
Another advantage for plants large enough to use unit trains is the avoided cost of coordinating their shipment with other trains. Unit trains move directly from origin to destination. On the other hand, "single cars or small groups of cars are moved less consistently than large groups, taking up to twice as much time to reach their destinations."[41] Mixed trains have to be gathered at terminals or "marshaling yards," which can create shipment delays.[42]

On the other hand, organizations like the Renewable Products Marketing Group (RPMG) provide a way for small producers to combine marketing power. Furthermore, the Ethanol Express by BNSF helps gather ethanol production into unit trains by region, helping improve transportation logistics for smaller producers. So small producers may be narrowing the economies of scale.

Overall, a 100 MGY plant saves 2.0 cpg on capital costs, 2-3 cpg on production costs, and up to 1.7 cpg on shipping costs over a 40 MGY plant. These total economies (4-6 cpg) are significant to the plant owner and investor, but are modest compared to the overall wholesale price of ethanol, which has ranged from $2 to $4 per gallon most of the last two years. It is doubtful that customers would see any reduction in the price at the pump if the ethanol industry were dominated by 100 million gallon per year plants.

Component Related Savings: 100 MGY Ethanol Plant vs. 40 MGY Plant



Diseconomies of Scale

While size seems to offer ethanol producers substantial benefits, there are some aspects of production that suffer from diseconomies of scale. From limited local markets to limited water resources, building large can incur costs that smaller plants won't face.

The largest ethanol plants quickly overproduce local markets for their product. In Minnesota, domestic production exceeded the statewide 10% ethanol mandate by 2002; currently, at least half the product is shipped out of the state. For example, a unit train shipment of domestically produced ethanol from SW Minnesota to BNSF's Minnesota terminal costs $2600 per tank car. The same shipment to Ft. Worth, TX, (900 miles) is $3350 per car; to Watson, CA (1,900 miles), it costs $4500 per car.[43] It's half as much to ship locally (8.7 cpg) as to ship long distance (16.7 cpg to Watson).

The limited local market for ethanol's co-products can create a stumbling block for larger-scale ethanol production. The most significant co-product of ethanol production is distiller's grains, which can be used as livestock feed. In some ethanol plants, these are left as distiller's wet grains (DWG) and must be sold and consumed within a few days (three days in warm weather and six in cooler temperatures).[44] Otherwise, the plant must apply a preservative – extending shelf life to 14 days for about $4/ton – or use natural gas to dry the distiller's grains (creating DDG), for an average cost of $10/ton.[45] DDG can be stored and shipped much longer distances. A 40 MGY plant will produce approximately 126,000 tons of DDG per year.[46]

There are several scale limitations on the market for DWG and DDG. First, distiller's grains are essentially corn kernels stripped of their starch, leaving a much higher concentration of protein – a key feed ingredient. However, because the processing also changes the balance of amino acids and phosphorous in addition to starch and protein, distiller's grains can only provide part of the feed for livestock.[47]"Feed inclusion rates for distillers grains are presently as high as 40 percent for cattle, 25 percent for swine and 5 percent for poultry,"[48] but feeders typically use less to avoid adverse effects on feed animals. In particular, high inclusion rates can lower the grade quality of beef.[49] On average, a cattle feedlot will provide cattle with three pounds per day of DDG (of a ten pound recommended maximum) – meaning a 40 MGY plant needs 180,000 head of cattle to use all its 126,000 tons of DDGs.[50]

The significant number of cattle required to consume an ethanol plant's DDG means that the market for distiller's grains varies greatly. "Given the saturation of ethanol plants in many areas, feasibility studies for new ethanol plants are placing minimal value on this byproduct because of the difficulty in finding willing buyers."[51] The bigger the plant, the more buyers are needed. First, this means that more of the DWG must be dried, since DWG can only be used in nearby markets. Second, it means that the resulting DDG must be shipped further from the plant to reach available feedlots. The most pressing problem resulting from outstripping the local feed market is that DDG can clog railroad hopper cars. While this initially meant a more laborious transport process, since the DDG caked into "fine grain concrete" with high temperatures and humidity, railroads eventually made ethanol plants lease or buy their own railcars for DDG, adding $6/ton to the shipping cost.[52] Additionally, shipping DDG is more expensive than shipping corn, since DDG is less dense.

The combination of flooding the local market and increased transportation costs can create a diseconomy of scale for a large ethanol plant. The box below offers a simulation of how two ethanol plants - 40 MGY and 100 MGY - would operate in a regional market capable of absorbing 20 million gallons of ethanol and 50,000 tons of DDG (requiring over 70,000 head of cattle).

Comparative Drying and Shipping Costs for DDG and Ethanol in a Limited Local Market

- Ethanol demand: 20 million gallons
- DDG demand: 50,000 tons
- Local ethanol shipped via rail to blending facility.
- Excess ethanol shipped via rail to Watson, CA terminal
- Excess DDG dried and shipped via rail to Kansas feedlots

	40 MGY	100 MGY
Ethanol shipping	13.3 cpg	13.7 cpg
DDG drying	1.9 cpg	2.7 cpg
DDG shipping	5.5 cpg	9.9 cpg
	20.7 cpg	**26.2 cpg**

As we can see, the 100 million gallon plant has an increase in shipping and DDG drying costs that come to about 5.4 cents per gallon, offsetting much of the production cost savings of the larger facility.

Some ethanol plants have found alternatives to drying and shipping DDG to avoid the cost. Burning the distillers grains to fuel the plant's energy needs can displace natural gas, and save on drying and shipping costs.

Water use is also a concern for larger ethanol plants. Each gallon of ethanol produced uses 5-6 gallons of water, although Minnesota ethanol producers have, on average, reduced this to 4.2 gallons in 2005.[53] For some of the early plants producing 20-40 MGY, this meant 100-240 million gallons of water used per year. For one plant in Granite Falls, MN, the water demand has outstripped the capacity of the local aquifer, causing plant officials to seek permission to get water from the nearby Minnesota River and to cancel expansion plans.[54] Another proposed plant near Pipestone, MN, was scrapped because the municipal water system lacked the capacity for the 100 million gallon facility.[55] The intensive water use of ethanol plants has led some states to track ethanol plant water use (Minnesota) or to carefully study local water availability before siting plants (Iowa). In some areas, such as Dodge City, KS, or Champaign, IL, local residents and municipalities have raised concerns about competing demands for water and the impact on the local water table.[56] In general, smaller plants will have a smaller impact on the local water supply than large plants.

Conclusion

The most significant economies of scale in renewable energy production are in individual wind turbines, with larger towers and blades capturing significantly more energy than smaller machines and reducing unit costs substantially (by 13% for doubling tower height and by 75% for doubling rotor diameter). There are modest savings involved in moving from single to multiple turbines since many of the same savings can be gained from a cooperative service and maintenance arrangement among many local owners.

Some studies show as much as a 25% reduction in unit costs for electricity generation in large wind farms, but sending wind farm power long distances can increase costs by 10-25%. Local generation of wind power - from dispersed turbines serving a local and regional market using the existing distribution grid - can sometimes be cheaper despite lower wind speeds.

For ethanol plants the scale advantages are also limited. Increasing plant size from 40 to 100 MGY can reduce production costs by 4-6 cents per gallon. However, outstripping local markets and having to ship the product long distance can increase costs by 5-6 cents per gallon.

In sum, economies of scale are real, but in most cases, modest. The most significant diseconomy of scale is that bigness leads to absentee ownership, significantly reducing the benefits to rural communities of harnessing renewable energy. Public policymakers should decide whether the loss of those rural development benefits is worth the small decrease in production costs.

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