ECE 333 – Green Electric Energy

11. Wind Energy Economics

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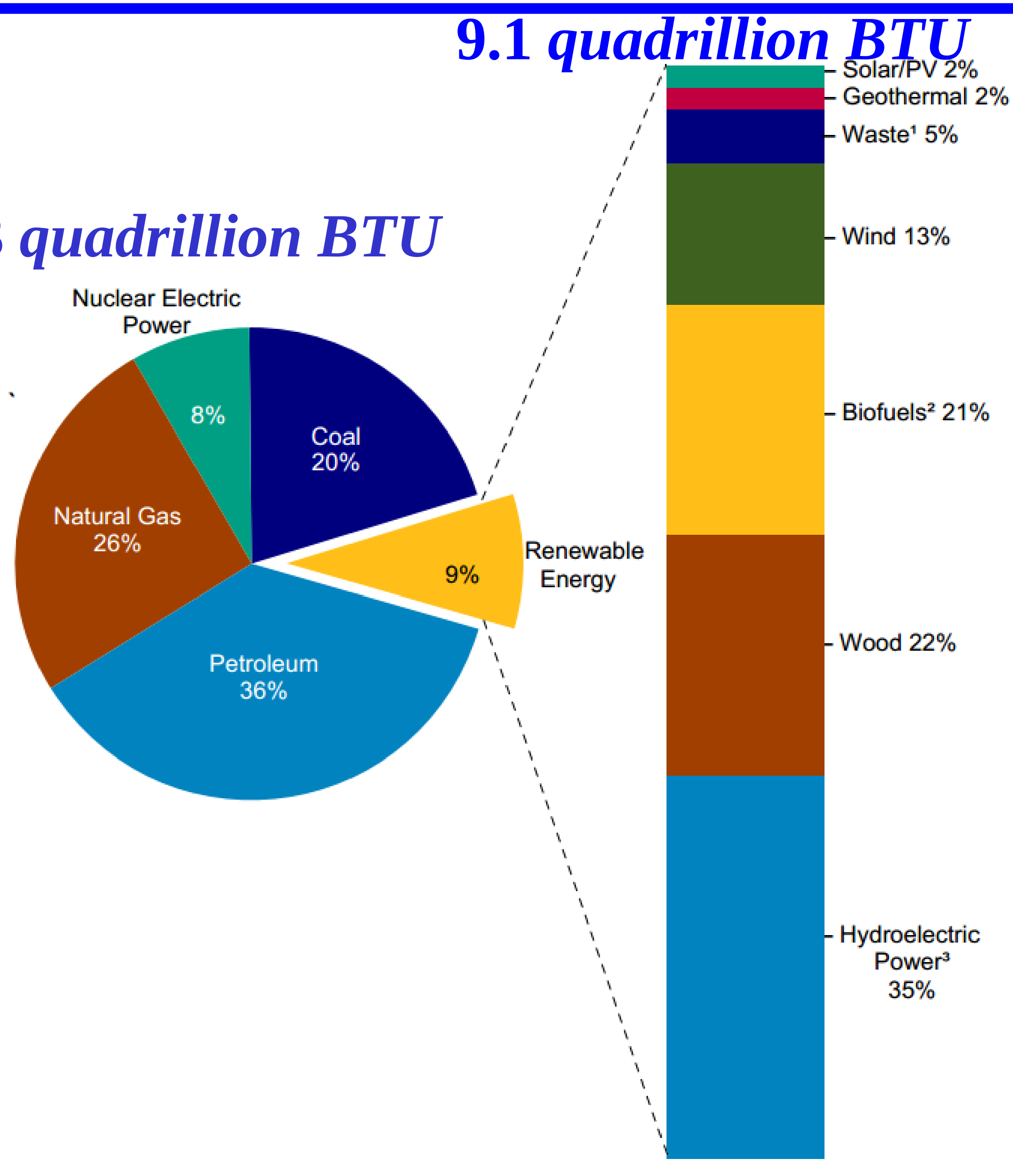
RENEWABLES ARE STARTING TO IMPACT THE *US* ELECTRICITY SUPPLY

RENEWABLES' ROLE IN THE 2013 *US* ENERGY SUPPLY



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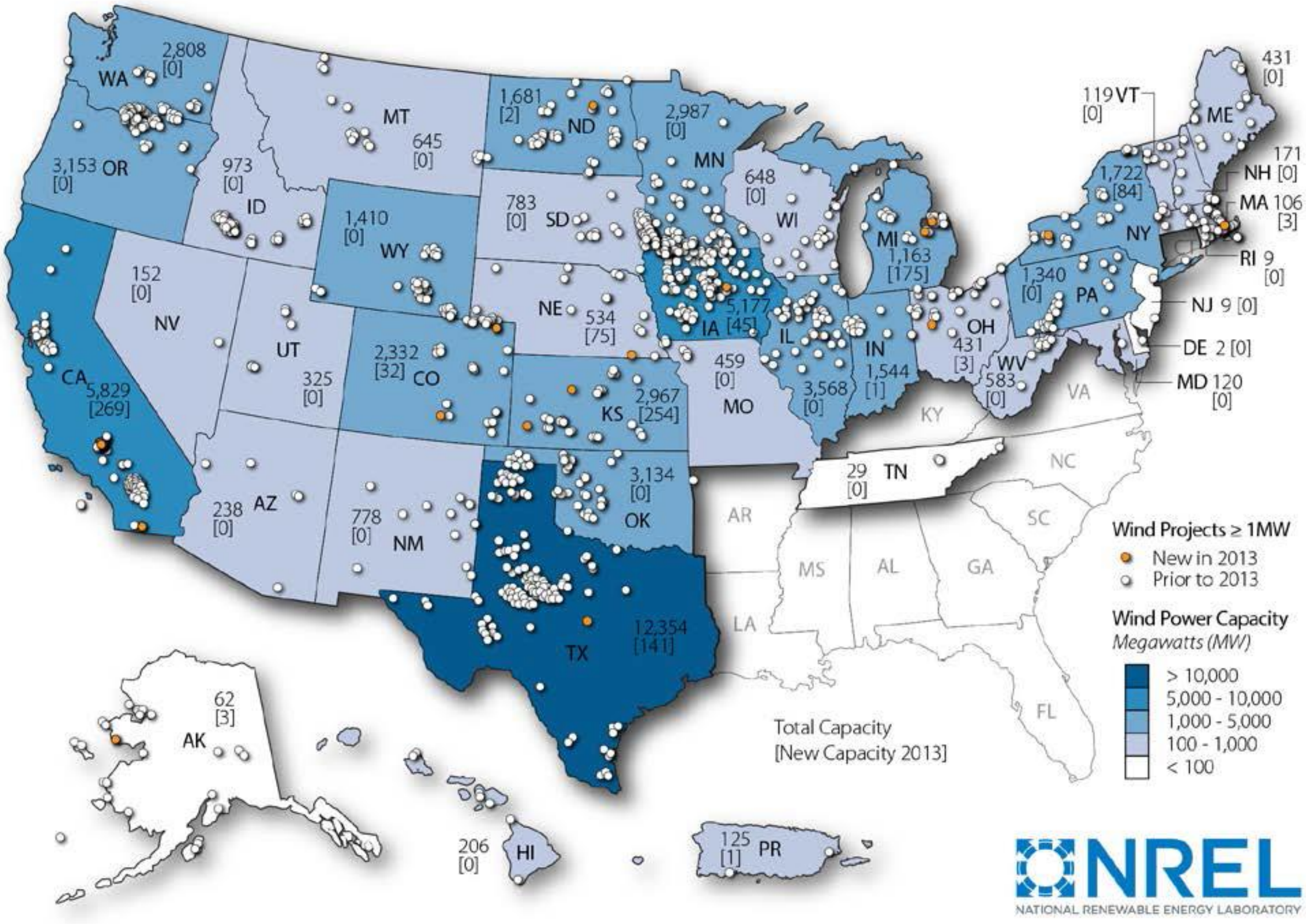
2013 WIND ENERGY STATUS



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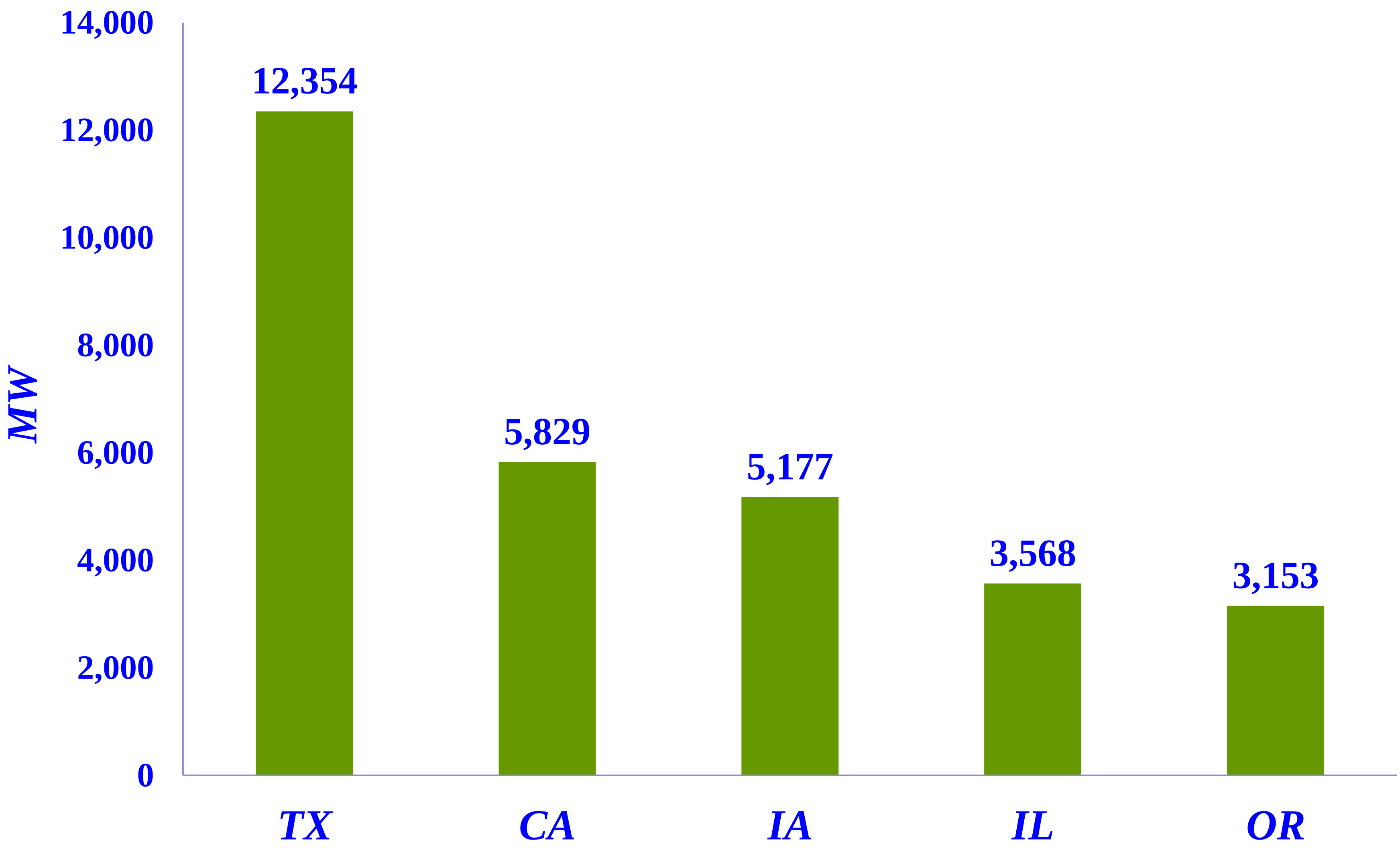
2013 CUMULATIVE WIND CAPACITY: TOP 5 STATES



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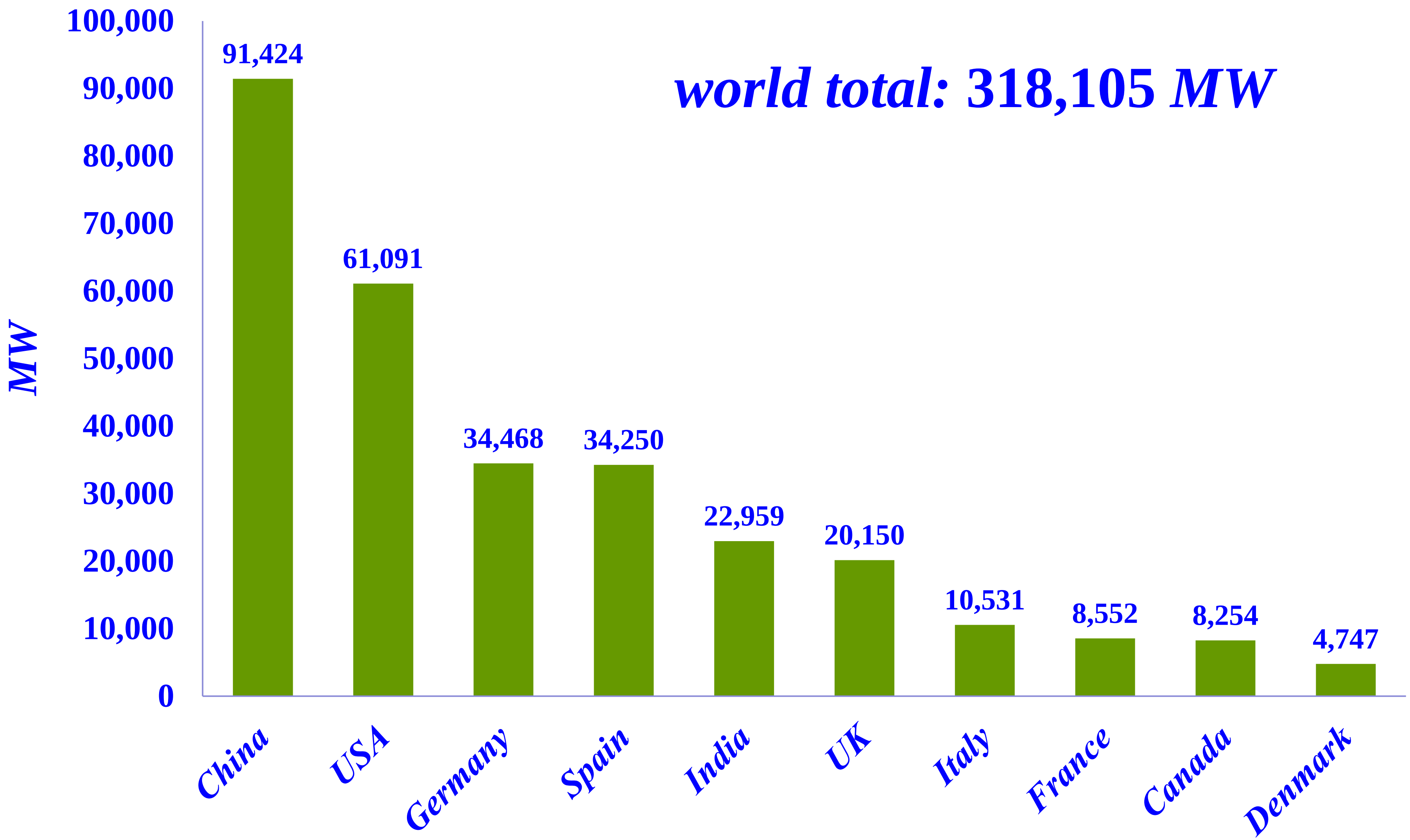
2013 CUMULATIVE WIND CAPACITY – TOP 10 COUNTRIES



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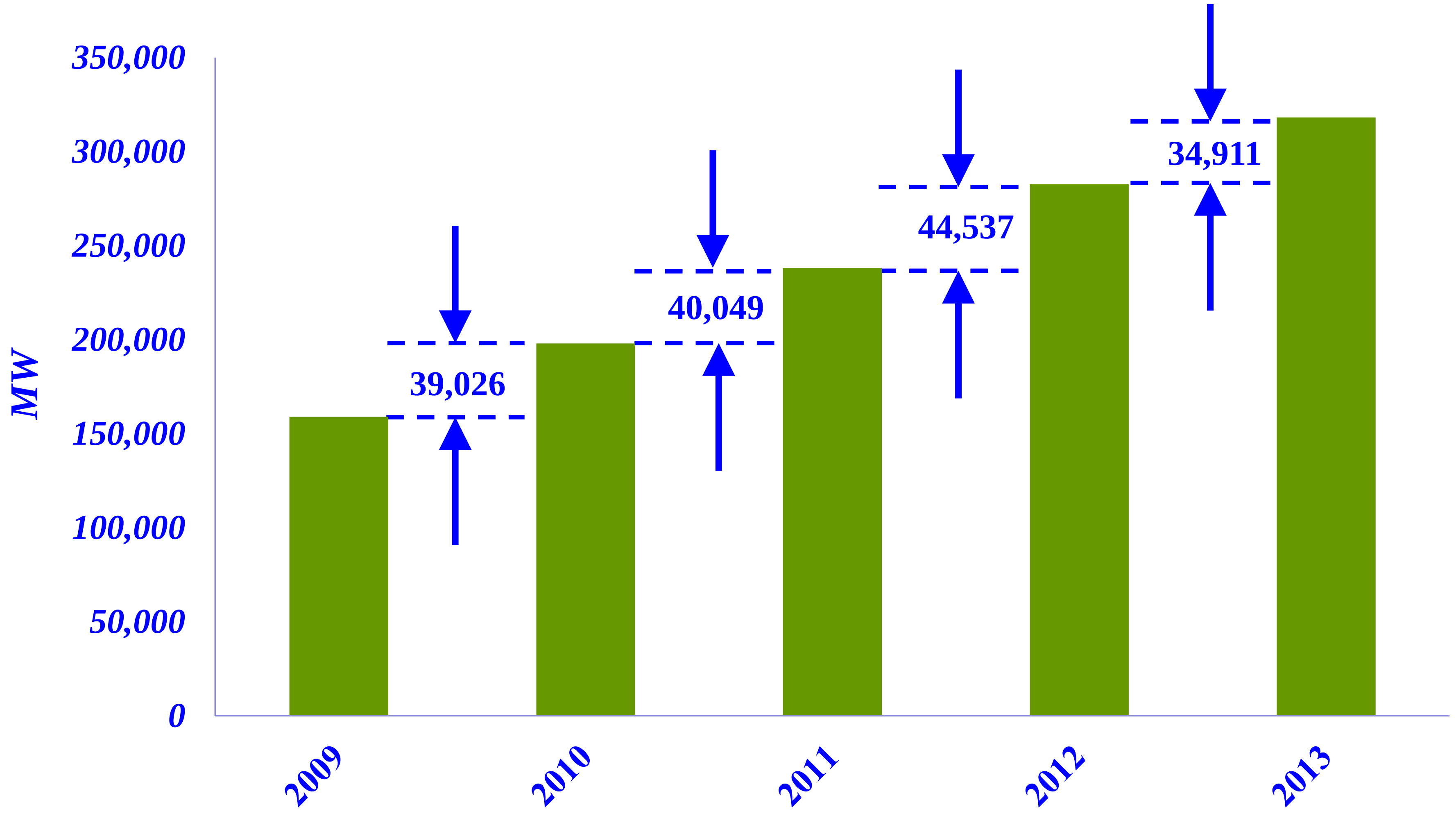
2009 – 2013 GLOBAL CUMULATIVE WIND CAPACITY



Source: www.gwec.net/wp-content/uploads/2014/04/GWEC-Global-Wind-Report_9-April-2014.pdf

2013 *US* WIND STATUS

- The cumulative wind capacity by the end of 2013 was over 61 *GW*
- *TX* remained the leading state in terms of cumulative wind capacity, even though *CA* added the largest number *MW* capacity in 2013
- The wind generated electricity in 9 states constituted 12 % *or more* of each respective state's electricity consumption

2013 *US* WIND STATUS

- Overall, wind power ranked as the fourth largest source of new generation capacity in 2013 – a big drop from 2012, when it was the *largest source*
- Before the end of 2013, 12,000 *MW* was under construction – a clear signal of improvement in the 2014 and 2015 wind capacity additions

WIND ENERGY TRENDS

2012 WIND TURBINE STATUS

manufacturer	*largest unit for*	
	onshore	*offshore*
Gamesa	5.0 *MW*	5.0 *MW*
GE	2.85 *MW*	4.1 *MW*
Mitsubishi	2.4 *MW*	7.0 *MW*
Siemens	3.6 *MW*	6.0 *MW*
Suzlon	2.1 *MW*	6.15 *MW*
Vestas	3.3 *MW*	8.0 *MW*

IMPACTS OF ADVANCES IN TECHNOLOGY AND BETTER SITING

year	1981	2000	2013
rated capacity (kW)	25	1,650	1,868
rotor diameter (m)	10	71	96.9
total costs (k$)	65	1,300	1,800
costs per kW ($/kW)	2,600	790	1,630

KEY TRENDS

- turbines are bigger
- capacity factors are improving
- system costs have declined

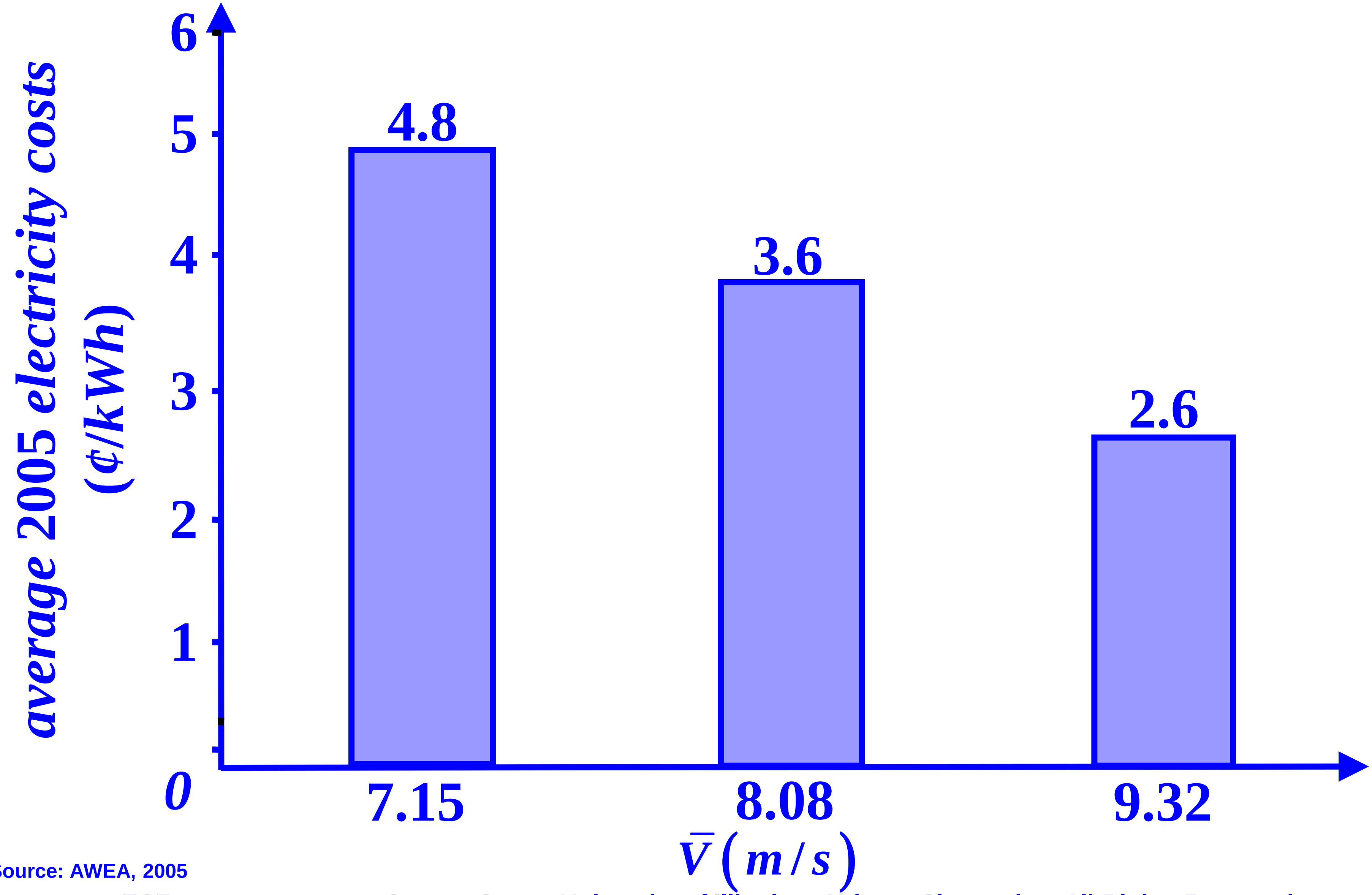
$\Rightarrow$ wind is today a very cost effective renewable energy technology

predictions are for wind to become competitive with today's conventional energy resources without any specialized incentives

AVERAGE WIND SPEED IS IMPORTANT

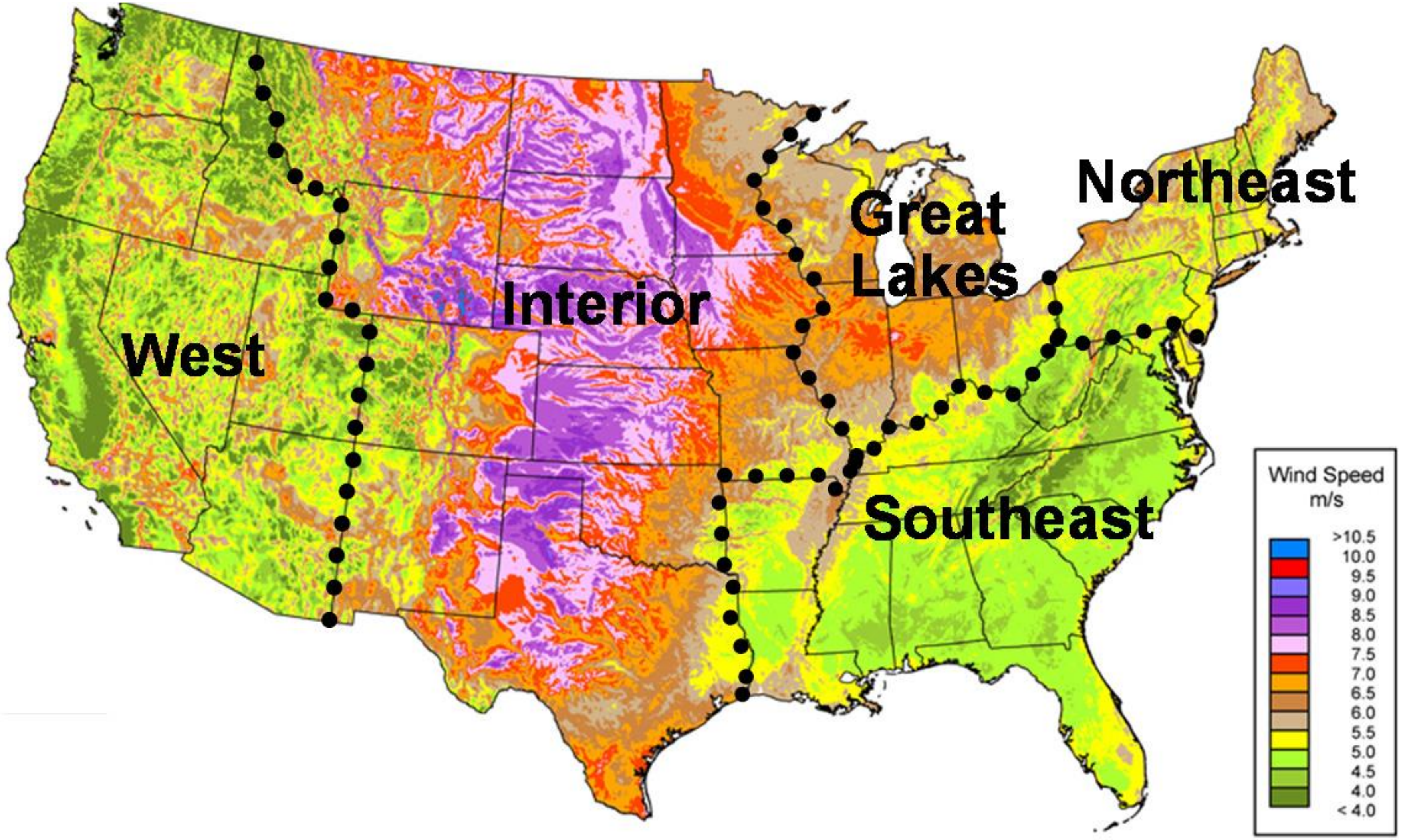
- Since energy is a function of $(\bar{V})^3$, a slight increase in $\bar{V}$ has major impacts: a change in $\bar{V}$ from $14\ m.p.h.$ to $16\ m.p.h.$ results in a nearly $50\ \%$ increase in energy generation, with all other parameters remaining unchanged
- The 2005 costs, for a $51 - MW$ wind farm the costs figures including the current wind production tax credits are

AVERAGE WIND SPEED IS IMPORTANT



Source: AWEA, 2005

AVERAGE ANNUAL WIND SPEED AT 80 METERS



Source: http://www.energy.gov/sites/prod/files/2014/08/f18/2013%20Wind%20Technologies%20Market%20Report_1.pdf

WIND FARMS

WORLD'S LARGEST WIND FARM

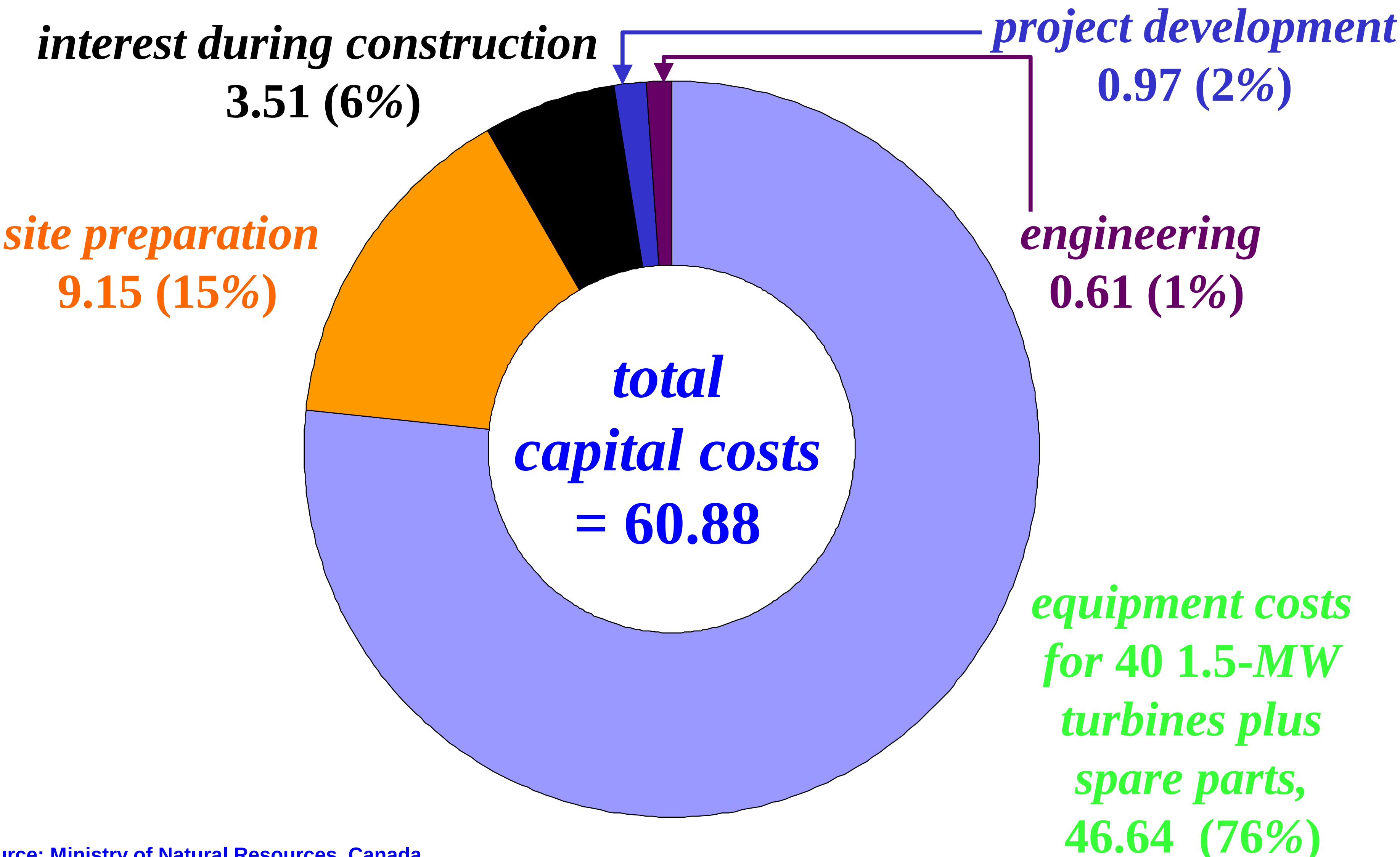
- Alta Wind Energy Center in Tehachapi Pass of the Tehachapi Mountains in California has 490 wind turbines with a total generation capacity of 1,320 *MW*

- The farm has 100 *Vestas* 1.5 – *MW* wind turbines and 390 *Vestas* 3.0 – *MW* wind turbines
- The turbines are owned by Citibank, Barclays Capital, and Credit Suisse

ECONOMIES OF SCALE

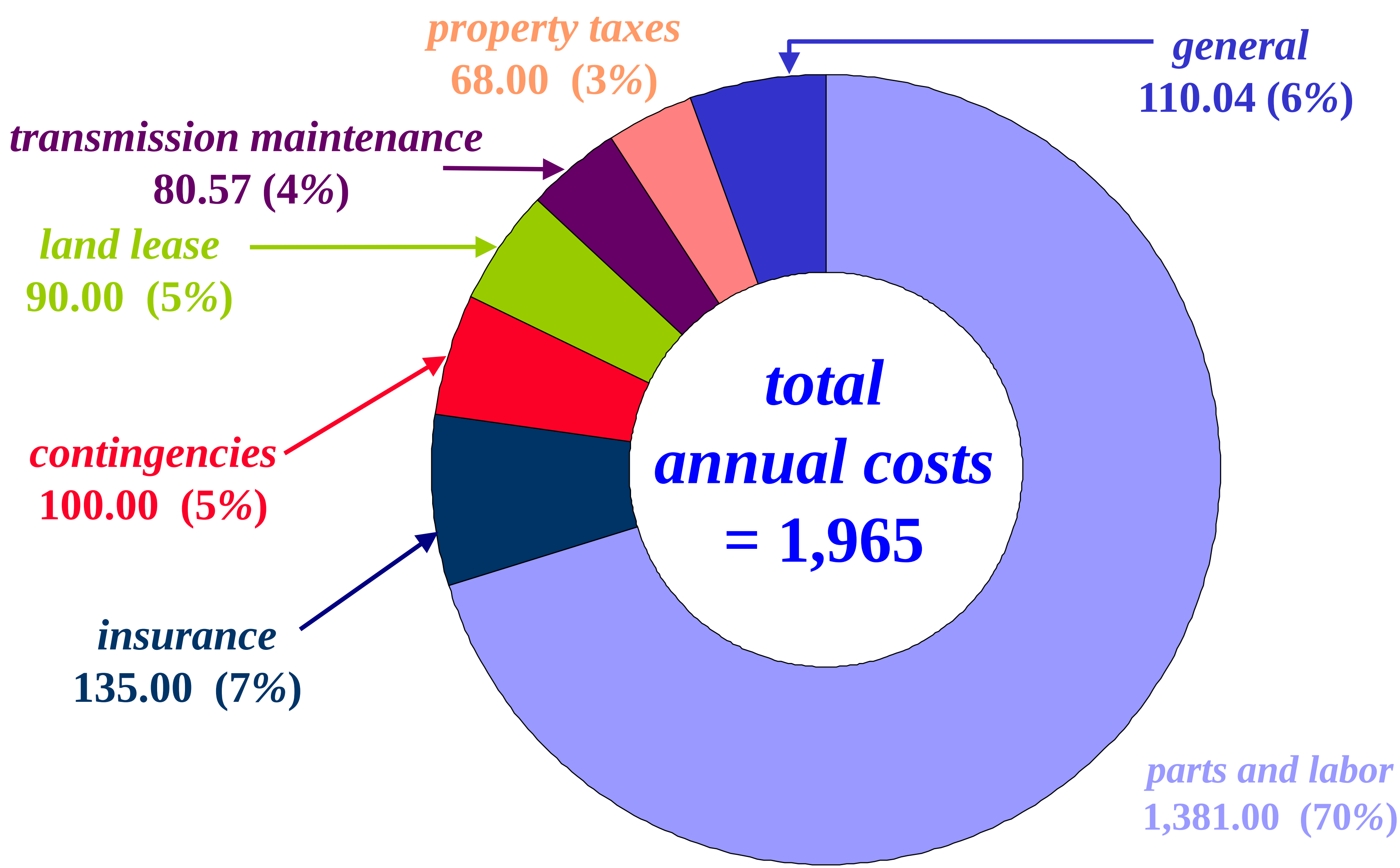
- Typically, a large wind farm produces electricity more economically than a small operation
- The following factors contribute to the lower costs:
  - transaction costs are spread over more *kW* and *kWh* for a large project
  - efficiencies in the management of a larger wind farm typically lower the *O&M* costs
  - possibility of better financing terms for larger projects
  - lower per *kW* permitting costs

WIND FARM EXAMPLE: CAPITAL COSTS IN 2002 *M$*



Source: Ministry of Natural Resources, Canada

WIND FARM EXAMPLE: ANNUAL COSTS IN 2002 *k$*



Source: Ministry of Natural Resources, Canada

WIND ENERGY ECONOMICS

- Generally speaking, the costs of energy wind production has decreased by 20 – 30 % since late 2008 due to
  - improvements in turbine design
  - increased efficiency of wind turbines
  - growth in the equipment production volume
  - improvements in siting of projects
- Future reductions will make wind more competitive without the need of tax subsidies

WIND ENERGY ECONOMICS: KEY FACTORS CONSIDERED

- wind speed at project site
- hub height of the turbine tower
- rotor radius
- project scale
- turbine configuration
- costs of financing

AN APPROXIMATE EXPRESSION FOR WIND *c.f.*

- Under the assumption that the wind speed in a region is Rayleigh distributed, the expression

$$c.f. = 0.087\bar{V} - \frac{p_R}{d^2} \qquad (\dagger)$$

rated power kW

wind speed m/s

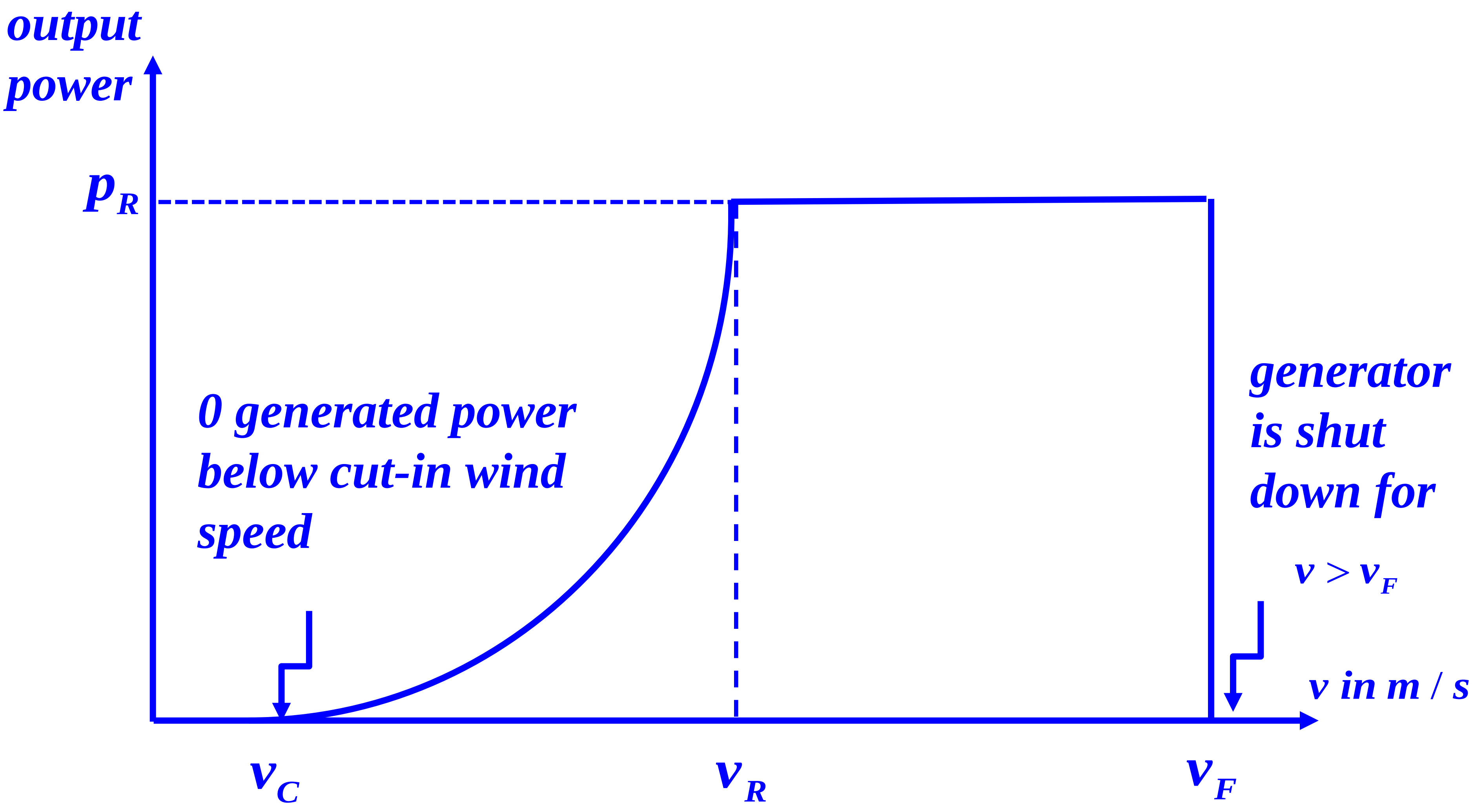
rotor diameter m

provides a useful approximation of the *capacity factor* of wind resources

AN APPROXIMATE EXPRESSION FOR WIND *c.f.*

- The relation in (†) is often used to estimate wind production by a turbine or collection of turbines
- Conceptually, a larger *c.f.* implies that much of the wind energy is harnessed in the flat, wind – shedding region of the ideal power curve above the rated wind speed; while the wind output is relatively constant, the implication is that a large fraction of wind energy is simply not captured

THE IDEALIZED WIND TURBINE POWER CURVE



AN APPROXIMATE EXPRESSION FOR WIND *c.f.*

- It is not always true, but a better alternative is to have a larger generator capture those higher speed winds albeit with a lower *c.f.* and therefore deliver more energy to the grid
- The annual energy is estimated to be using (†) as

$$\mathcal{E} = p_R (8{,}760\ h)(c.f.)$$

$$= 8{,}760 * p_R * (0.087\bar{V} - \frac{p_R}{d^2})$$

where $\mathcal{E}$ is in kWh, p_R is in kW, $\bar{V}$ is in m/s and d is in m.

ANNUALIZED WIND GENERATED ELECTRICTY COSTS

- The annual costs are computed from the capital costs allocated to each year over a project's life time plus the $O\&M$ costs
- The use of debt for financing a project allows the annualization of capital costs by using the appropriate capital recovery factor

$$A = P \left(\frac{i}{1-\beta^{n}} \right)$$

A: *annualized cost over each of n years*; *P*: *present worth*; $\frac{i}{1-\beta^{n}}$: *capital recovery factor*

ANNUALIZED WIND GENERATED ELECTRICTY COSTS

where

$$\beta = \frac{1}{1+i}$$

- **Recall that the** ***capital recovery factor*** **measures the speed with or rate at which the initial investment is repaid and can be found in tabulated form in many readily available sources**

EXAMPLE: SMALL WIND TURBINE

- We consider a $900-W$ wind turbine with a $2.13-m$ blade installed at a hub height where the average wind speed is $6.7\ m/s$
- The turbine costs $\$1{,}600$ and the installation and other capital costs involve an additional $\$900$
- The $\$2{,}500$ total capital are financed by a $15-$year $7\ \%$ loan

EXAMPLE: SMALL WIND TURBINE

- The annual $O\&M$ costs are $\$100$

- The capital recovery factor for $i = .07$, $n = 15$ is

$$\frac{0.07}{1-\beta^{15}} = 0.1098$$

resulting in annual payments of

$$A = (2{,}500)(0.1098) = \$\,274.49$$

- The total annual costs are

$$\$\,274.49 + \$\,100 = \$\,374.49$$

EXAMPLE: SMALL WIND TURBINE

- We use the capacity factor (*c.f.*) approach with

$$\kappa = 0.087\bar{V} - \frac{p_R}{d^2} = (0.087)(6.7) - \frac{0.9}{(2.13)^2}$$

$$= 0.385$$

to estimate the energy delivered by the turbine

$$energy = (0.9)\, kW \cdot (8{,}760)\, h \cdot (0.385) = 3{,}035\ kWh$$

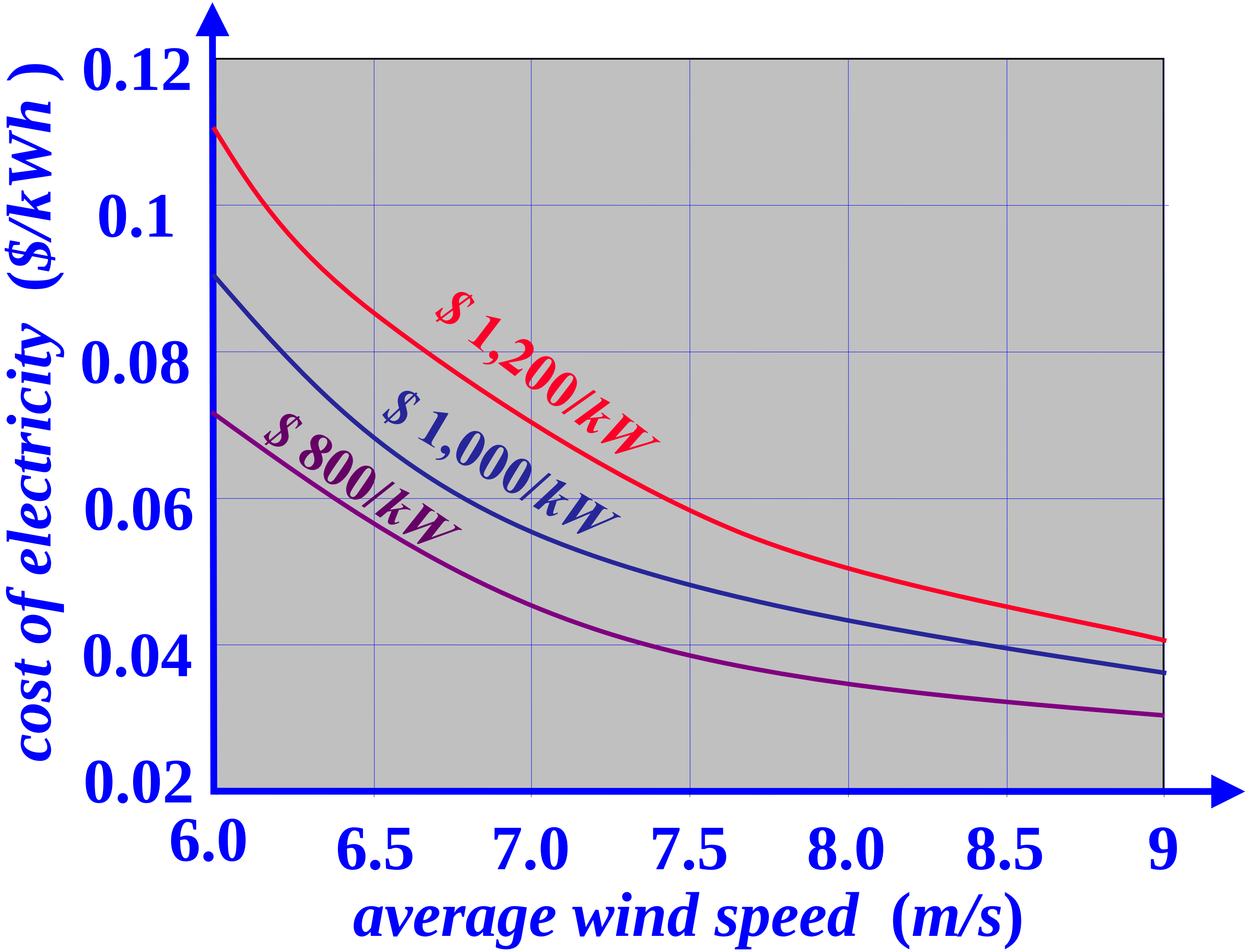
- We compute the *average* costs per kWh

$$\frac{total\ annual\ costs}{energy} = \frac{374.49}{3{,}035} = 0.123\ \$/kWh$$

EXAMPLE: $1500-kW, 64-m$ BLADE TURBINE

- We consider the installation of a $1500-kW, 64\ m$ blade turbine at various different sites
- The financial aspects are
  - $7\ \%$ loan repaid over $20\ years$
  - levelized $O\&M$ is $3\ \%$ of capital costs
- The average costs of electricity for three different capital costs are plotted as a function of average wind speed $\bar{V}$

EXAMPLE: $1500 - kW$, $64 - m$ BLADE TURBINE



EXAMPLE: WIND FARM GENERATION

- We investigate the feasibility of a 40 – unit wind farm project
  - using $1.5 - MW$ turbines with $64 - m$ blades
  - sited at a location with $\bar{V} = 8.5\ m/s$
- The total capital costs are $\$\ 60\ M$ and the levelized annual $O\&M$ costs are $\$\ 1.8\ M$
- The financing uses both equity and debt
  - $\$\ 45\ M$ is covered by a loan repaid over 20 years at $7\ \%$ interest
  - $\$\ 15\ M$ equity requires a $15\ \%$ annual return

EXAMPLE: WIND FARM GENERATION

- We compute the capacity factor κ

$$\kappa = 0.087\bar{V} - \frac{p_R}{d^2} = 0.087(8.5) - \frac{1,500}{(64)^2} = 0.373$$

- The annual production is therefore

$$\begin{matrix} annual \\ energy \end{matrix} = (40)(1.5)(8,760)(0.373) = 196,000\ MWh$$

- The annual debt return required is

$$A = \$\,(45)(0.09422) = \$\ 4.24\ M$$

EXAMPLE: WIND FARM GENERATION

- The total annual costs are

$$annual\ costs = 2.25 + 4.24 + 1.8$$

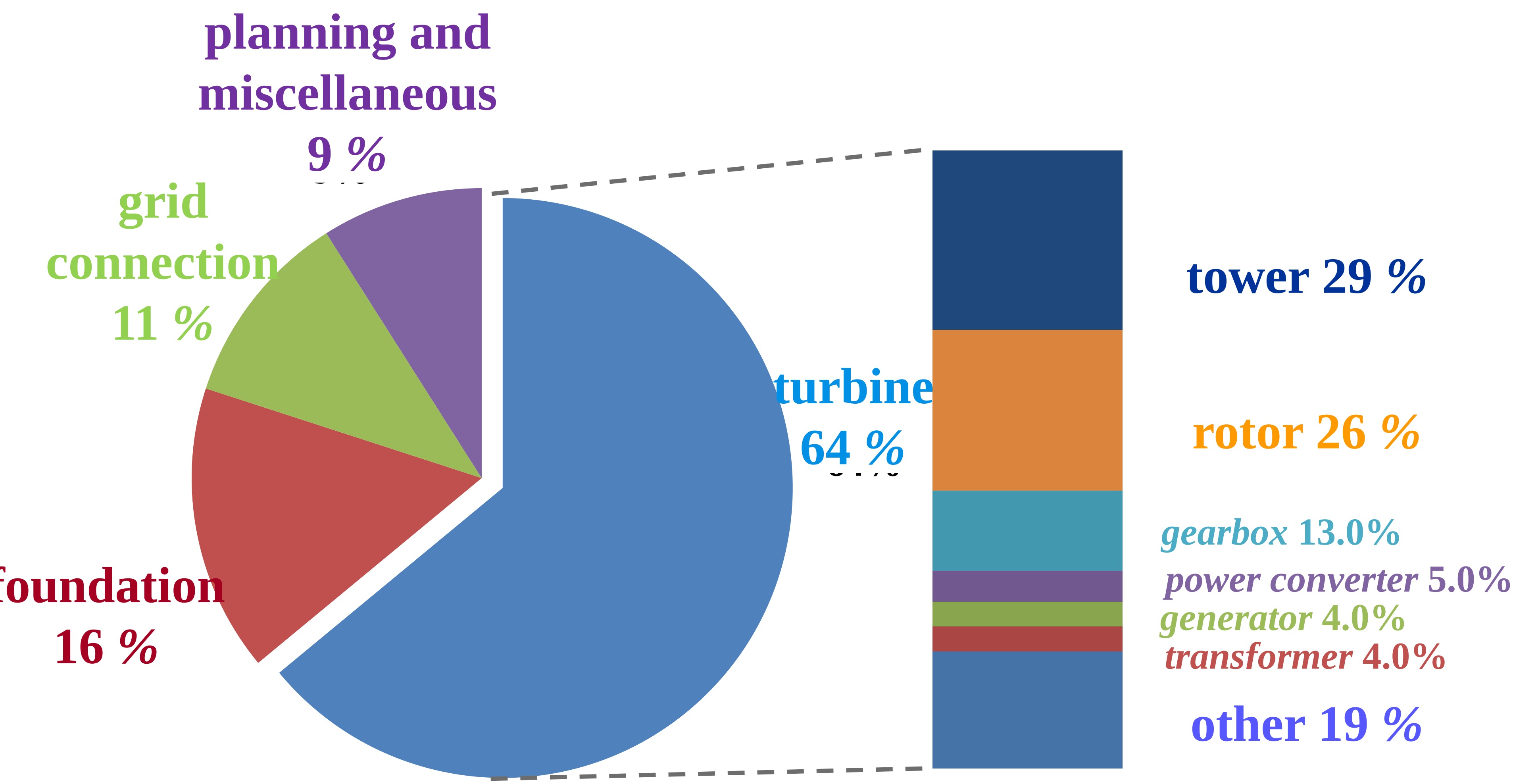
$$= \$\ 8.29\, M$$

- For feasibility, the electricity price must be at the least

$$levelized\ price = \frac{8.29\ M\$}{196{,}000\ MWh}$$

$$= 0.0423\ \$ / kWh$$

2009 WIND RESOURCE COST COMPONENTS



Source: EWEA (2007) and Blanco (2009)

ALLOCATION OF LEVELIZED COST OF ENERGY (*LCOE*) FROM WIND

- **80 % of the *LCOE* is from the capital costs of the wind turbine: capital costs of the complete turbine – blades, generators, tower and foundation, construction, grid inter connection, preliminary project engineering and permitting / licensing costs**
- **20 % of the *LCOE* comes from variable costs – mostly operation and maintenance – and recurring annual costs, such as taxes, insurance, land leasing and overhead**

EXAMPLE: ANNUALIZED COSTS

- We use the data in the table below to compute annualized costs

year	2002	2009	2013	
technology	*standard*	*standard*	*standard*	*low wind*
rated power (MW)	1.5	1.5	1.62	1.62
hub height (m)	65	80	80	100
rotor diameter (m)	70.5	77	82.5	100
installed capital costs ($ / kW)	1,300	2,150	1,600	2,025
operating costs ($ / kW – y)	60	60	60	60
losses (%)	15	15	15	15
discount rate (%)	9	9	9	9

EXAMPLE: ANNUALIZED COSTS

- We investigate the annual costs of a standard turbine installed in 2013 with a $80-m$ elevation for the hub in a wind zone with $\bar{V} = 7 \frac{m}{s}$ at $50-m$ elevation under the assumption of $20-year$ book life and the usual $\alpha = \frac{1}{7}$ value for the wind shear factor

EXAMPLE: ANNUALIZED COSTS

- The average wind speed at the $80-m$ hub is

$$\bar{V}_{80} = \bar{V}_{50}\left(\frac{80}{50}\right)^{\frac{1}{7}} = 7\left(\frac{80}{50}\right)^{\frac{1}{7}} = 7.49\ \frac{m}{s}$$

- The use $(\dagger)$ for the *c.f.* κ results in

$$\kappa = 0.087\bar{V} - \frac{p_R}{d^2} = 0.087(7.49) - \frac{1{,}620}{(82.5)^2} = 0.413$$

EXAMPLE: ANNUALIZED COSTS

- The annual energy delivered to the grid needs to account for the 15 % in losses

$$\mathcal{E} = 0.413\,(1 - 0.15)\,(1{,}620)\,(8{,}760) = 4.96 \times 10^{6}\ kWh$$

- The capital recovery factor with the 9 % discount rate is

$$c.r.f.(9\%, 20\,y) = \frac{(0.09)\,(1 + 0.09)^{20}}{(1 + 0.09)^{20} - 1}$$

$$= 0.1095\ y^{-1}$$

EXAMPLE: ANNUALIZED COSTS

- The total installment costs

$$total\ costs = 1{,}620\,kW \times 1{,}600\,\$\ /\,kW$$

$$= 2{,}592{,}000\,\$$$

- The *c.r.f.* results in annual amortized fixed costs of

$$A = 2{,}592{,}000 \times (0.1095) = 283{,}944\ \frac{\$}{y}$$

EXAMPLE: ANNUALIZED COSTS

- The annual O & M at $60 \$ / kW - y$ results in

$$O\&M = 1{,}620 \times 60 = 97{,}200 \ \frac{\$}{y}$$

- The levelized costs per kWh are

$$LCOE = \frac{283{,}944 + 97{,}200}{4.96 \times 10^{6}}$$

$$= 0.076 \ \frac{\$}{kWh}$$

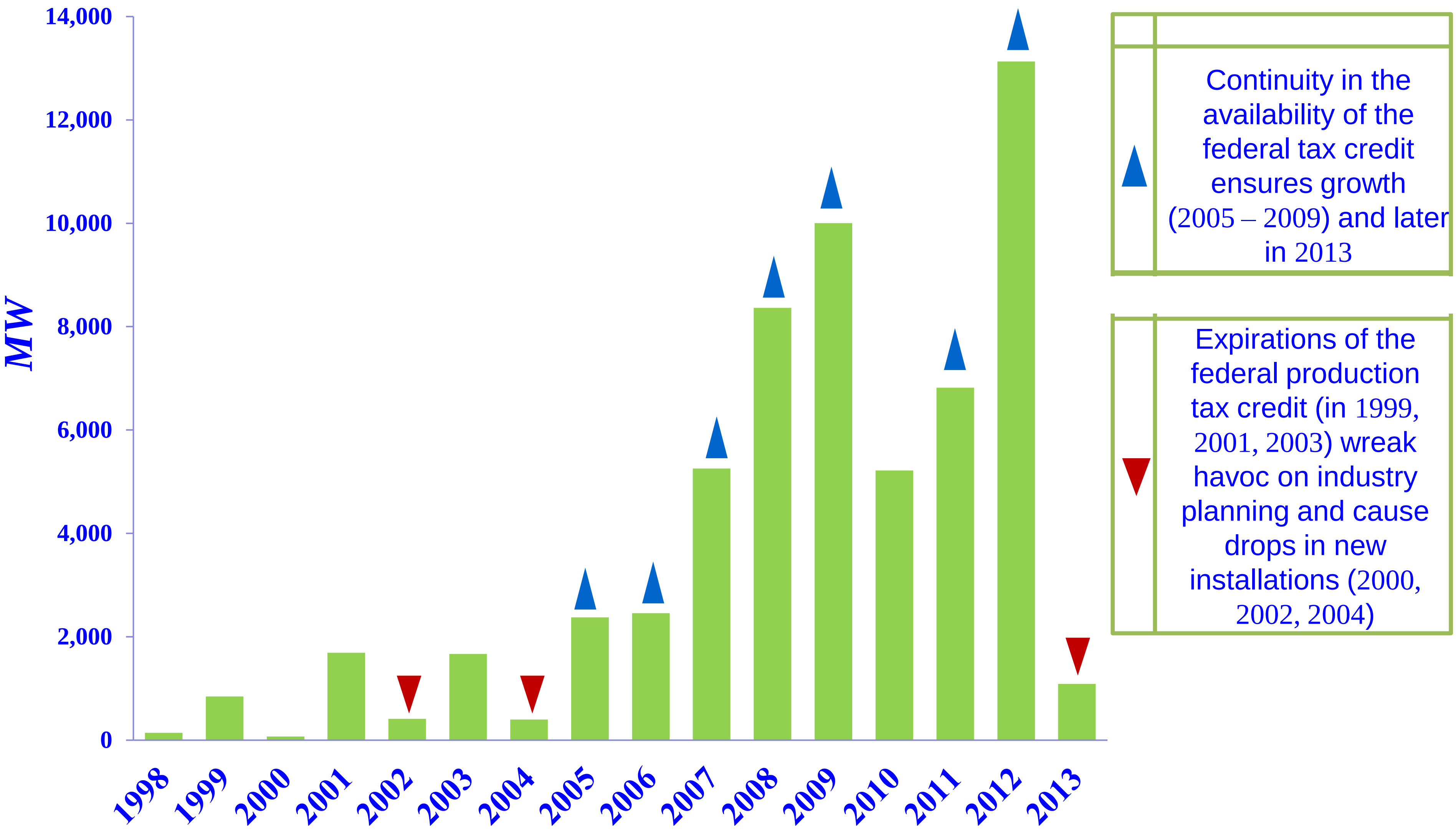
TAX INCENTIVES FOR WIND

- The Energy Policy Act of 1992 includes a production tax credit (*PTC*) for wind and a 5 – year accelerated depreciation for wind turbines
- The *PTC* was set at 1.5 ¢/*kWh* and is inflation adjusted; it is currently 2.2 ¢/*kWh*
- The *PTC* supports electricity generated from utility – scale wind turbines for the first 10 years of operation

TAX INCENTIVES FOR WIND

- The *PTC* may be reduced or cancelled for projects that apply for state incentives
- Critics of the wind industry refer to the *PTC* as a subsidy for the industry
- The expiration of the *PTC* – 3 times so far – caused marked drops in the wind capacity additions; the threat of its non renewal in 2012 was responsible for the huge increase in wind capacity in 2012

ANNUAL INSTALLED WIND CAPACITY



Source: http://emp.lbl.gov/sites/all/files/lbnl-6356e.pdf

EXAMPLE: *PTC* BENEFITS AND *LCOE* IMPACTS

- We continue with the *LCOE* example:
  - installation costs $ 2,592,000
  - annual *O&M* costs $ 97,200
  - annual energy delivered to grid $4.96 \times 10^{6}\ kWh$
  - discount rate is 9 %

EXAMPLE: *PTC* BENEFITS AND *LCOE* IMPACTS

- The table below presents the *PTC* impacts over the 10 *years* they provide benefit at the 2013 level of 2.2 *¢/kWh*

year	*PTC*	*present value of PTC savings*
1	$ 22,000	$ 20,183
2	$ 22,000	$ 18,517
3	$ 22,000	$ 16,988
4	$ 22,000	$ 15,585
5	$ 22,000	$ 14,298
6	$ 22,000	$ 13,118
7	$ 22,000	$ 12,035
8	$ 22,000	$ 11,041
9	$ 22,000	$ 10,129
10	$ 22,000	$ 9,293
total present value of tax savings		$ 141,188

EXAMPLE: *PTC* BENEFITS AND *LCOE* IMPACTS

- The *PTC* benefits in force for 10 *years* for the example result in present value savings of

$$\textit{present worth of tax savings} = \frac{\$\,141{,}888}{1{,}000{,}000} \times 4.96 \times 10^{6}$$

$$= \$\,703{,}116$$

- The net total costs are therefore reduced to

$$\textit{net total costs} = \$\,2{,}592{,}000 - \$\,703{,}116$$

$$= \$\,1{,}888{,}884$$

EXAMPLE: *PTC* BENEFITS AND *LCOE* IMPACTS

which are amortized over the $20 - years$ to

$$A = 1{,}888{,}884 \times 0.1095 = 206{,}833 \frac{\$}{y}$$

- Consequently, the *LCOE* becomes

$$LCOE \Big|_{PTC} = \frac{206{,}833 + 97{,}200}{4.96 \times 10^{6}} = 0.061 \frac{\$}{kWh}$$

and so the *PTC* reduces *LCOE* from 7.6 to 6.1

$¢/kWh$, a nearly 20% reduction

QUESTIONS LANDOWNERS NEED TO ASK IN WIND LAND USE CASES

- **How much do I get – typically, about 7,500 *$ /y per turbine* – and how much land will be tied up and for what period of time**
- **Payment terms**
  - **fixed amount**
  - **royalty revenues based on *kWh* generated**
- **What land rights are given up; and what is still permissible?**

QUESTIONS LANDOWNERS NEED TO ASK IN WIND LAND USE CASES

- Who carries the liability insurance
- What rights is the developer able to transfer without my consent
- What are my and the developer's termination rights
- When the agreement is terminated, what happens to the wind energy structures and related assets

OPERATION AND MAINTENANCE ECONOMICS

- Several challenges are met during the operation of a wind turbine module
- Wind turbine component failures add to the *O&M* cost of operation
- The cold climate under which wind turbines work in certain locations can also cause various problems further impacting the *O&M* economics

ROTOR BLADE FAILURE CAUSES

- Blades experience, due to the random nature of wind, a highly dynamic loading regime, whose cumulative effect may lead to failure
- Blades can fail due to manufacturing defects, non-optimality in their design or damage during transportation or installation
- Environmental factors such as lightning, erosive material transportation through air and ice build up further lead to failure

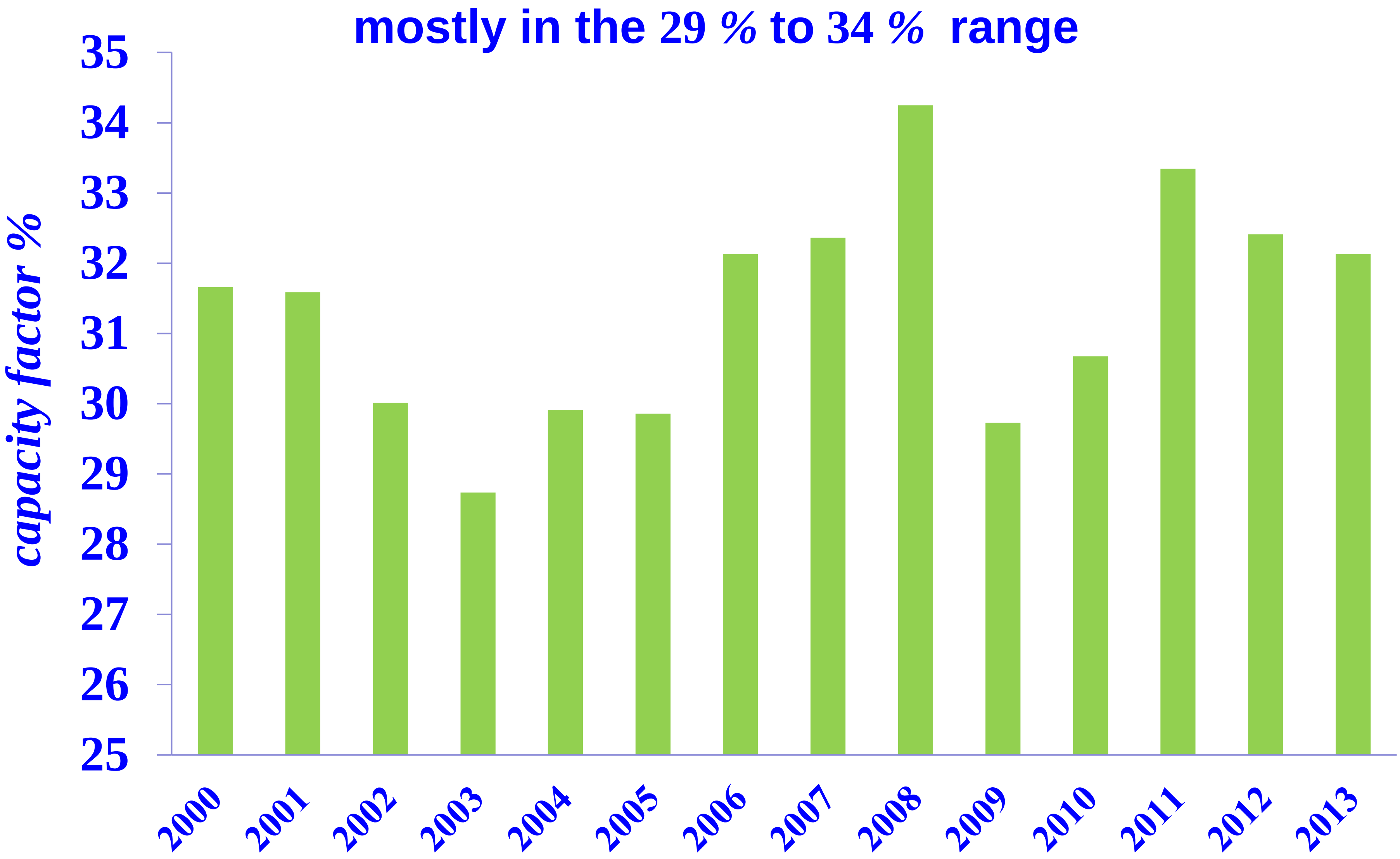
GEARBOX FAILURE CAUSES

- Gearbox deterioration occurs due to higher loading than estimated in the design stage
- Poor lubrication increases meta-to-metal contact and can result in failure
- Reduced material strength due to thermal stress, corrosion and vibrations, as well as large deviations from optimal operating temperatures cause failures
- Presence of water or metal content in the oil is yet another cause of failure

GENERATOR FAILURE CAUSES

- Many failures arise from problems in the design and manufacturing process
- The incorrect installation of components may result in component failure under over voltage or over speed conditions and damage the generator
- Lubricant contamination with moisture or dust, extreme heat or cold create hindrances to moving parts and can eventually lead to unit failure
- Incorrect maintenance practices, such as over greasing, can also lead to generator failure

US NET WIND CAPACITY FACTOR (BASED ON ACTUAL GENERATION)



Source: http://www.energy.gov/sites/prod/files/2014/08/f18/2013%20Wind%20Technologies%20Market%20Report_1.pdf

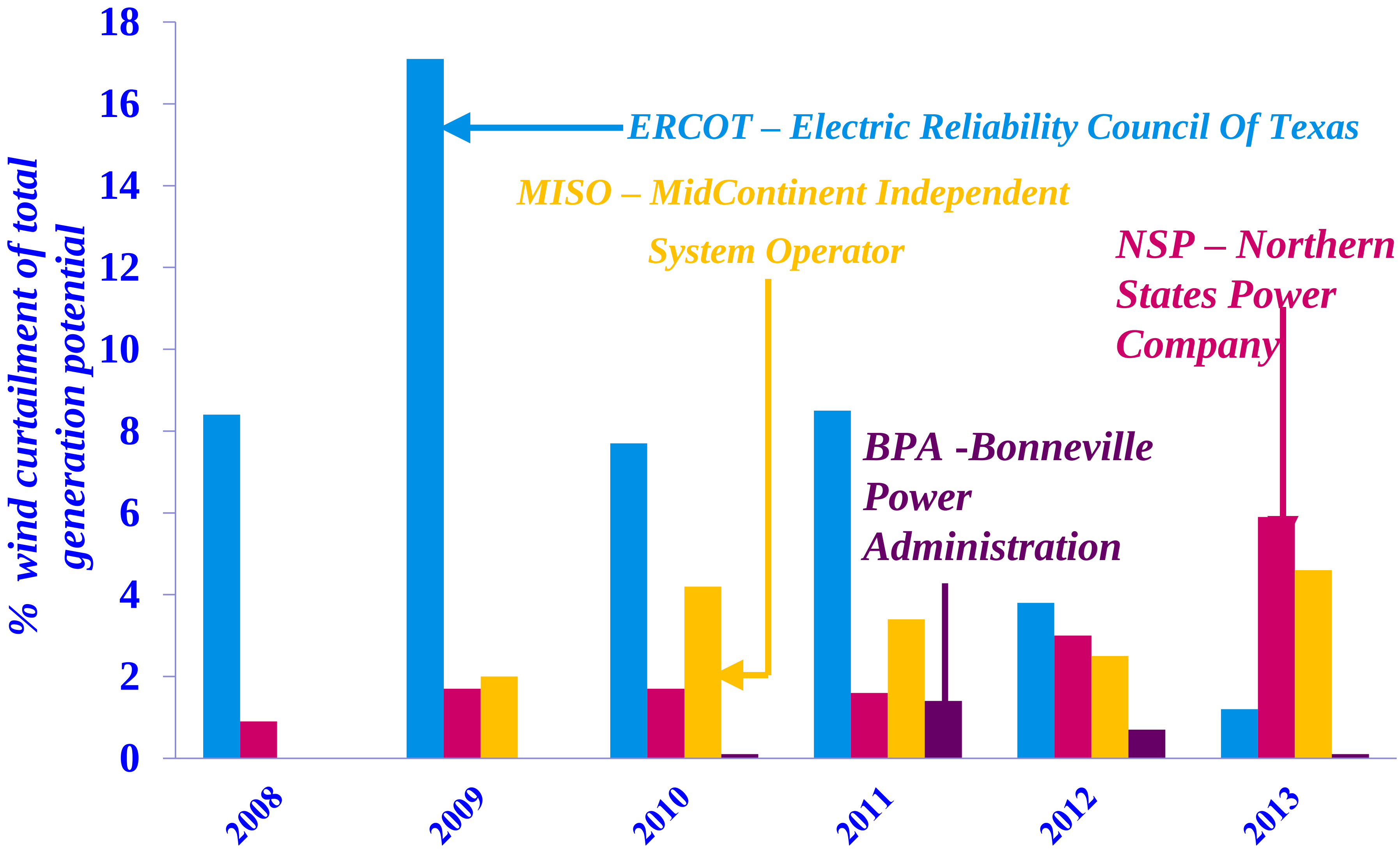
CAPACITY FACTORS DEVELOPMENT

- As larger turbines are being added each year, the expectation is for the *c.f.* to improve over the years; however, such improvement is slow in manifesting itself as the *c.f.* over the past 5 years has been in the 30 % to 35 % range
- This trend is influenced by two main factors: wind power curtailment and the year-to-year variability in the strength of the wind resource

WIND POWER CURTAILMENTS

- Curtailment of wind power takes place due to transmission inadequacy, minimum generation limits and due to negative wholesale pricing
- The situation is now improving in areas where the wind power curtailment has persisted
- *TX* has shown the biggest improvement with only 1.2 % of energy produced by *ERCOT* curtailed as compared to 17 % in 2009
- The decrease in curtailment was due to the competitive renewable energy zone transmission line upgrades

WIND POWER CURTAILMENT



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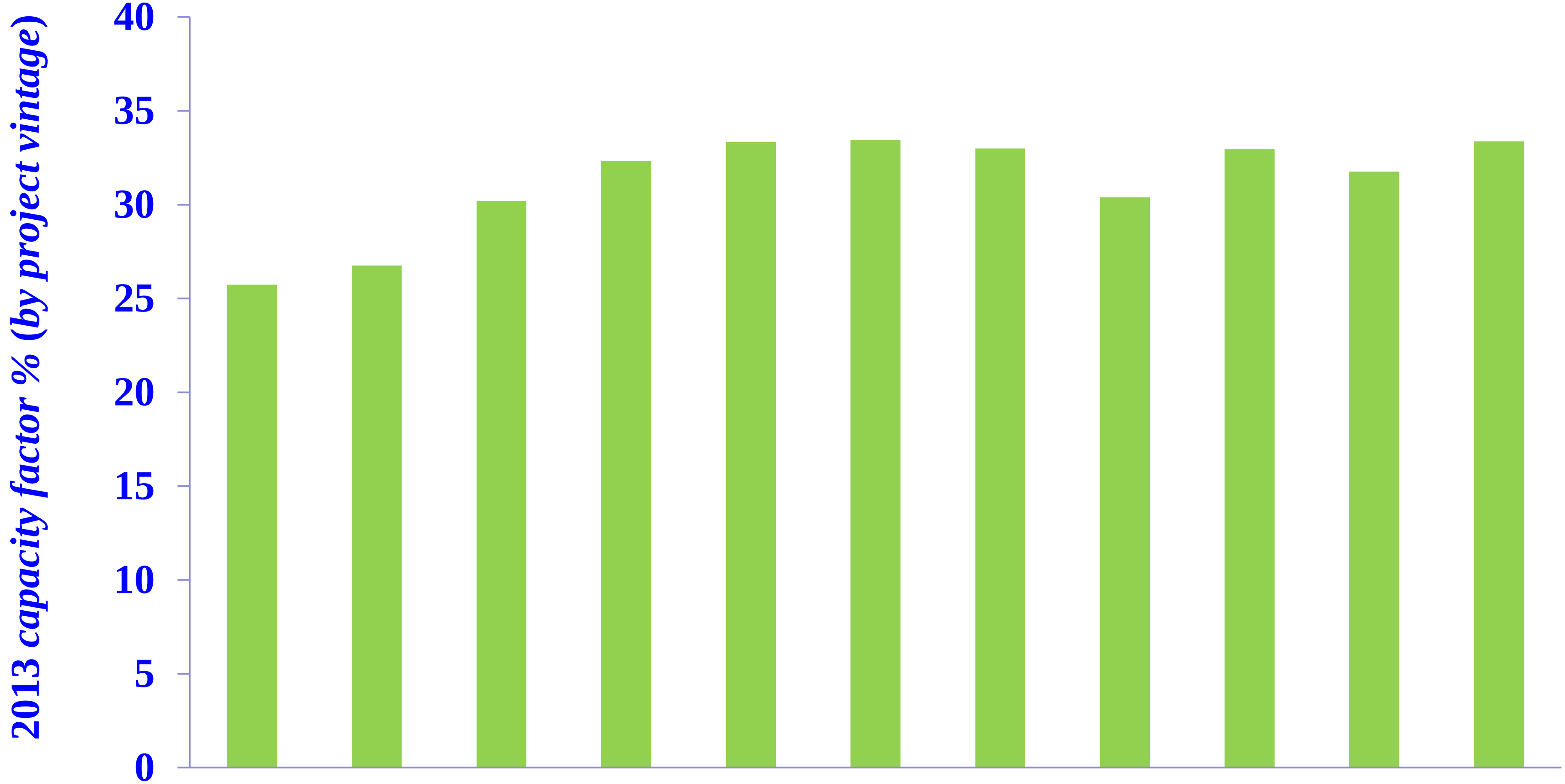
WIND POWER CURTAILMENT



vintage	1999	2001	2003	2005	2006	2007	2008	2009	2010	2011	2012
# of projects	25	27	38	28	22	38	80	95	22	22	22
# *MW*	921	1,765	1,988	3,651	1,739	5,284	8,522	9,426	4,733	5,760	13,368

Source: http://www.energy.gov/sites/prod/files/2014/08/f18/2013%20Wind%20Technologies%20Market%20Report_1.pdf