Minimizing the Cost of Wind Energy for Vashon Island – a Low Wind Speed Site

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Outline

- Introduction
- Wind Resource Assessment
- Optimum Turbine Design for a Low Wind Speed Regime
- Grid Integration and Energy Storage
- Conclusion

Introduction

- Vashon Island is located in the Puget Sound – a predominantly low wind resource region.

Wind Power Class		Average Wind Speed at 50m
	Class 1	**0 - 5.6m/s**
	Class 2	**5.6 - 6.4m/s**
	Class 3	**6.4 – 7.0m/s**
	Class 4	**7.0 - 7.5m/s**
	Class 5	**7.5 - 8.0m/s**
	Class 6	**8.0 - 8.8m/s**
	Class 7	**8.8 - 11.9m/s**

Introduction

- Most wind farms are developed in Class 4 wind resources or greater to be cost competitive with other energy generation.
  - Class 6: cost competitive
  - Class 4: cost competitive with 1.8¢/kWh PTC
- A wind farm on Vashon Island could not compete with Washington State’s energy mix.
- The Vashon Island community may support the higher cost of energy from a wind farm on the island.

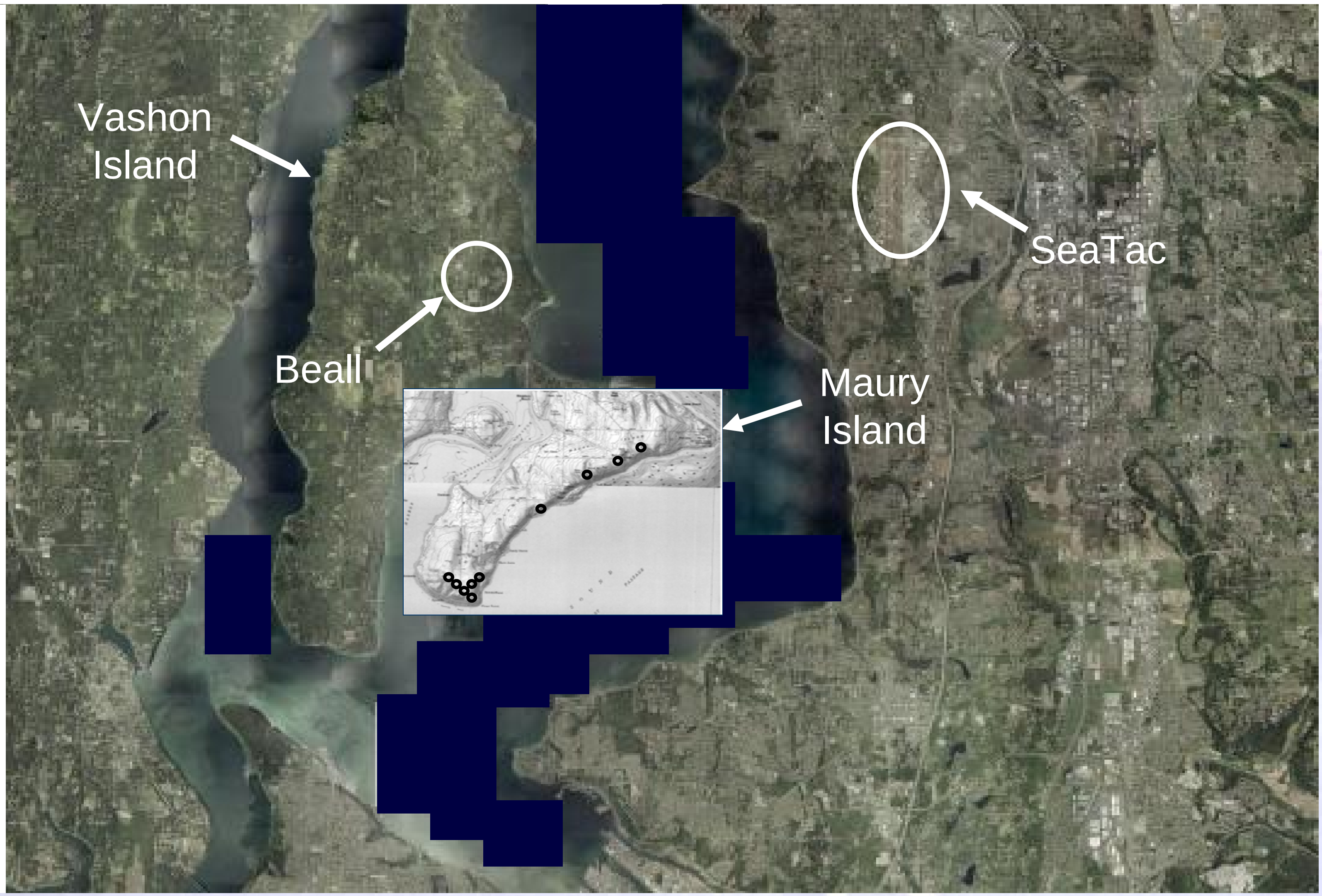
Goal of the Study

- Determine the wind turbine and wind farm design to provide the least cost of energy (COE) for generating 26GWh of electricity annually on the island.
- Predict the reduction in COE over the next 10 years to facilitate deciding the best time to build the wind farm.
- Assess the cost of integrating the wind farm into the existing electrical grid and potential benefits of an energy storage system.

Wind Resource Assessment

- Characterizing the wind resource is the critical task for a wind farm feasibility assessment:
  - 5% error in velocity equates to a ~15% error in power.
- Typically, wind data is collected with an anemometer tower at the proposed turbine sites for at least one year.
- A comparison is then made with long term data from a nearby anemometer.

Data Collection and Turbine Sites

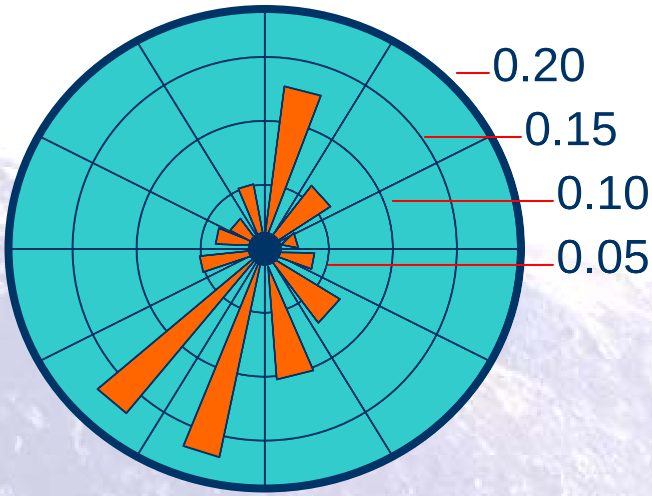


Wind Data Analysis

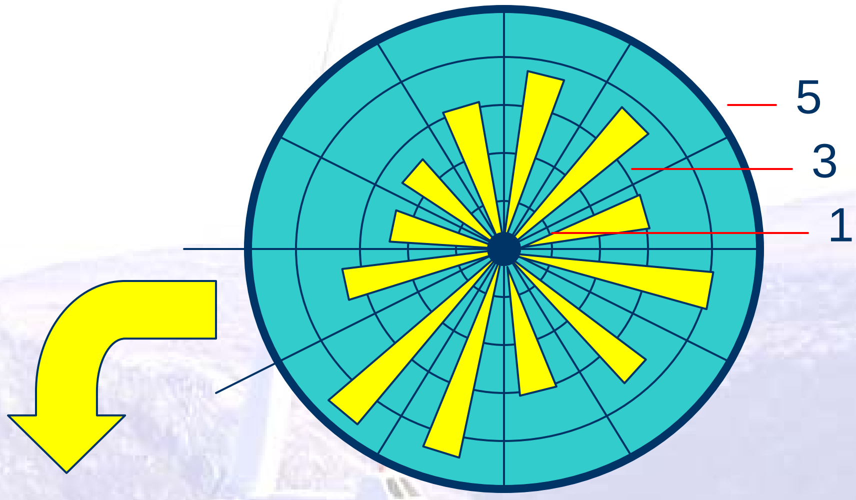
- SeaTac airport anemometer (1996-2004)
  - 10 meter measurement height
- Beall anemometer (12/04 - 5/05)
  - 26, 35, 49 meter measurement heights
- The data is grouped into 30º directional sectors and analyzed for:
  - Sector frequency
  - Average wind speed
  - Distribution of wind speeds (and Weibull fit)

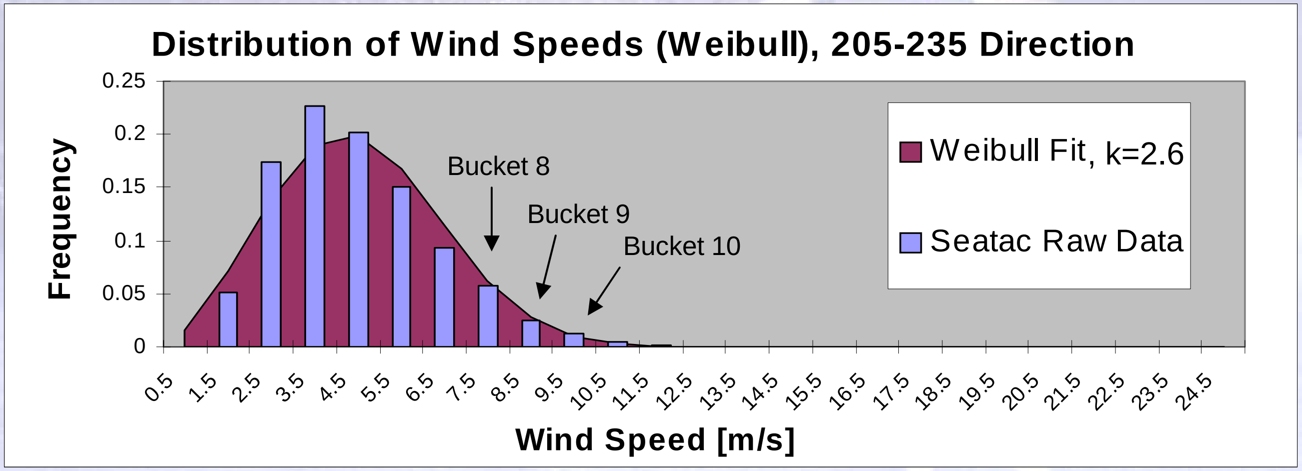
Directional Sector Analysis

Sector Distribution Frequency



Sector Average Wind Speeds [m/s]

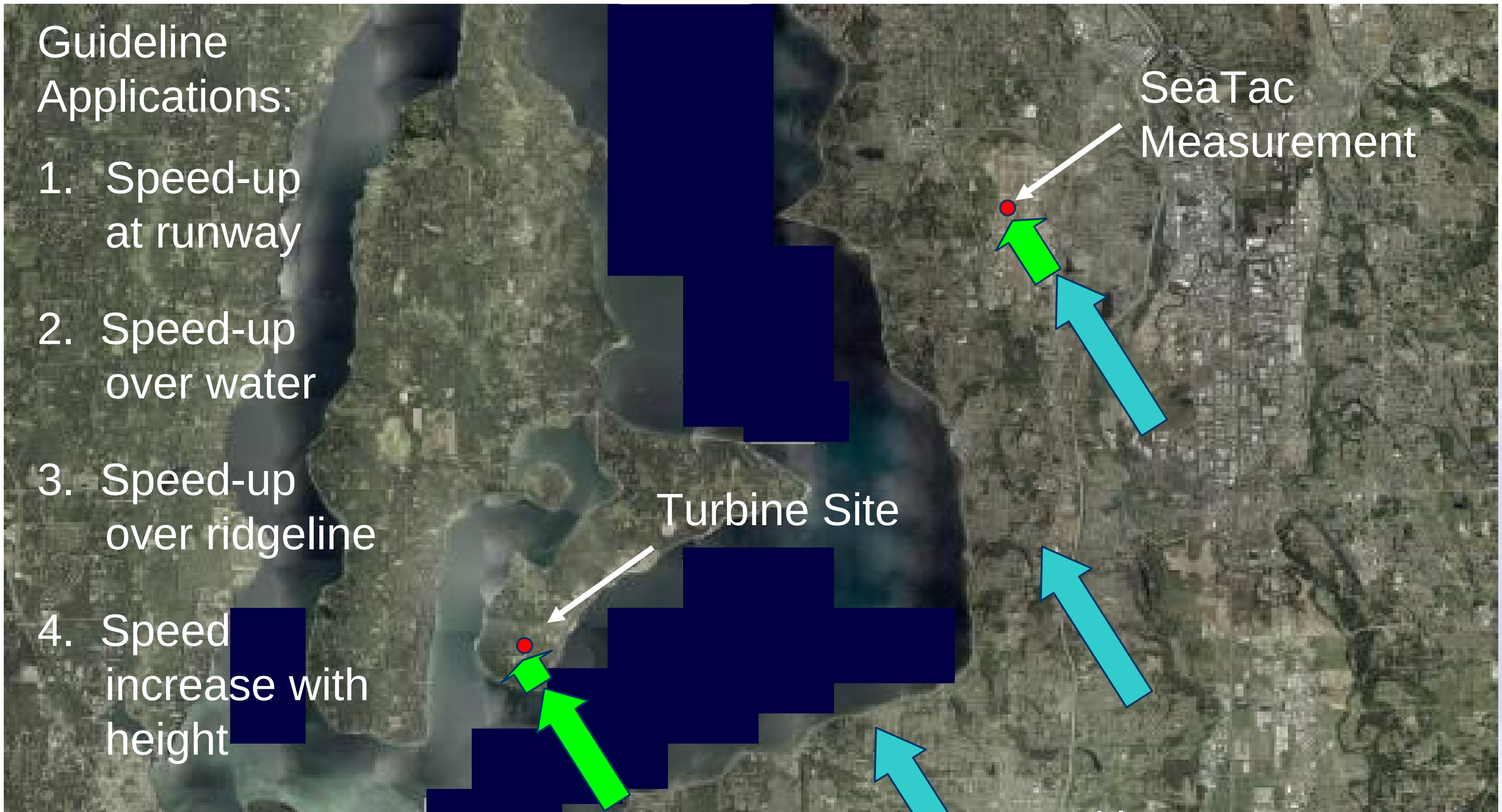




Terrain Effects on Wind Speed

- Wind Farm Development Tool (WFDT) software program normally used to extrapolate data to turbine sites.
- These programs use analytic solutions for adiabatic turbulent boundary layer flow.
- In this study, simple guidelines for boundary layer flow were used to account for:
  - Surface coverage changes
  - Topographic changes
  - Height changes

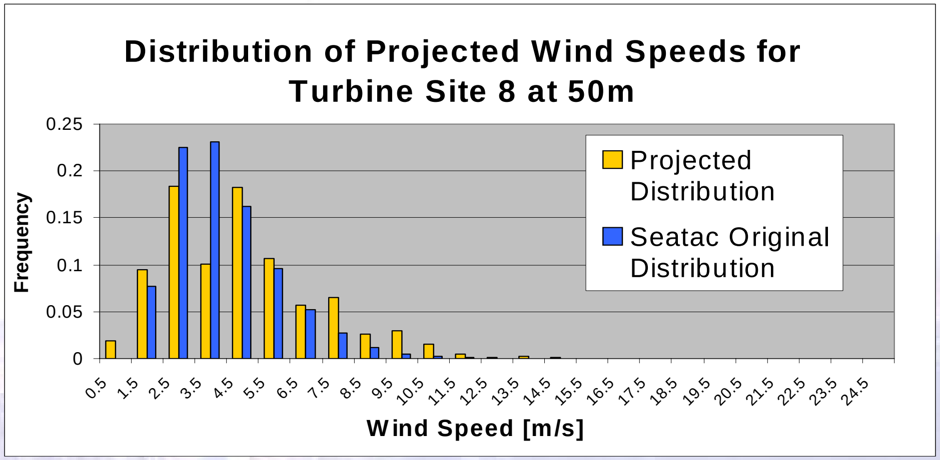
Application of Guidelines

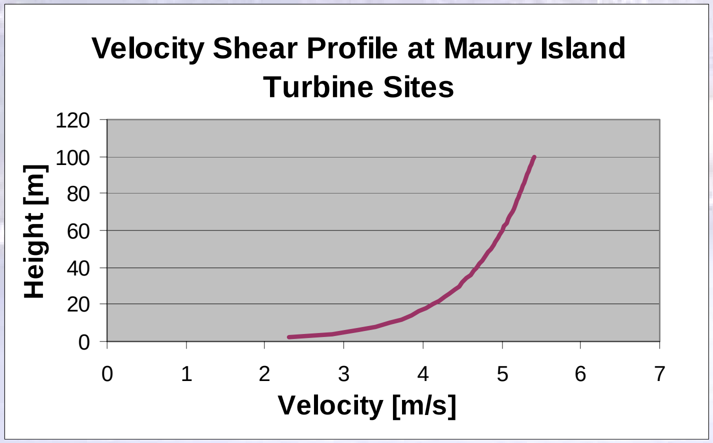


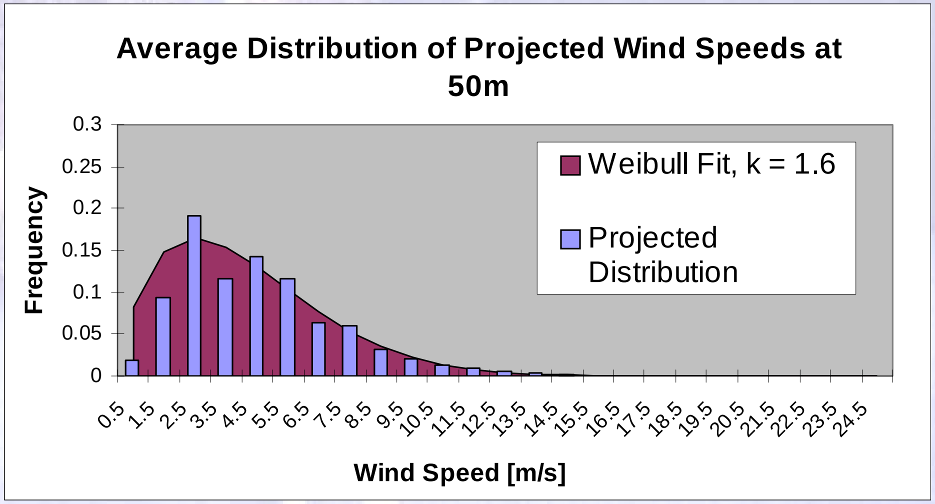
The guidelines are used to project the speed of each wind speed buckets for each directional sector from the collection sites to the speed expected at each of the ten turbine sites.

Wind Resource Results

Height [m]	Average Wind Speed [m/s]
50	4.85
60	5.01
70	5.14
80	5.24
90	5.33
100	5.41







Wind Resource Results

- The Guidelines are only estimates – more accurate results are required for wind farm development.
- The wind resource needs to be characterized better by:
  - Installing an anemometer at the south end of Maury Island for one year
  - Using WFDT to extrapolate this data to the turbine sites

Probabilistic Energy Production Model

Power

$$P_{i,j,k} = \eta_t \eta_g \eta_{pe} \frac{1}{2} \pi \rho_a C_p {U'_{i,j,k}}^3 \frac{D^2}{4}$$

i = the turbine site
j = the directional sector
k = wind speed bucket
$P_{i,j,k}$ = power for the wind speed bucket
η_t = the gearbox efficiency
η_g = the generator efficiency
η_{pe} = the power electronic efficiency
ρ_a = 1.225 kg/m3, the density of air
C_p = 0.50, the aerodynamic rotor power coefficient for state-of-the-art turbines
$U'_{i,j,k}$ = the projected wind speed for the bucket
D = the diameter of the turbine rotor

Probabilistic Energy Production Model

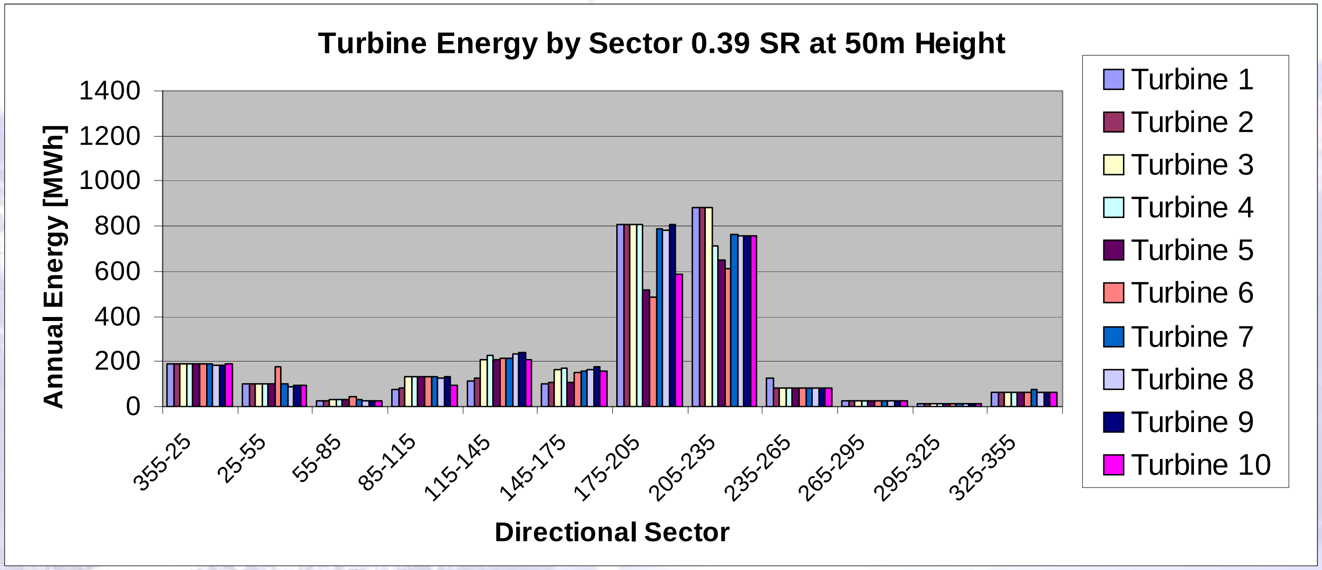
Energy

$$E_i = 8760 * \sum_{j=1}^{12} \sum_{k=1}^{25} P_{i,j,k} * fs_j * fb_{i,j,k}$$

E_i = the annual energy for turbine *i*
$P_{i,j,k}$ = the power for the wind speed bucket
fs_j = the frequency of the sector
$fb_{i,j,k}$ = the frequency of the wind speed bucket

Probabilistic Energy Production Model

Height [m]	Energy [%]
Turbine 3	100
Turbine 2	97
Turbine 1	97
Turbine 9	96
Turbine 4	92
Turbine 7	90
Turbine 8	88
Turbine 10	76
Turbine 6	72
Turbine 5	67



Optimizing Turbine Design

- Wind turbines are not designed to be optimized for such low wind speed regimes.
- To minimize the cost of energy, turbine designs are often tailored for an application including:
  - Rotor diameter
  - Generator rating
  - Tower height
- Often, turbines are tailored by specific power:

$$Specific\ Power = \frac{Generator\ Rating}{Rotor\ Swept\ Area}$$

Turbine Model

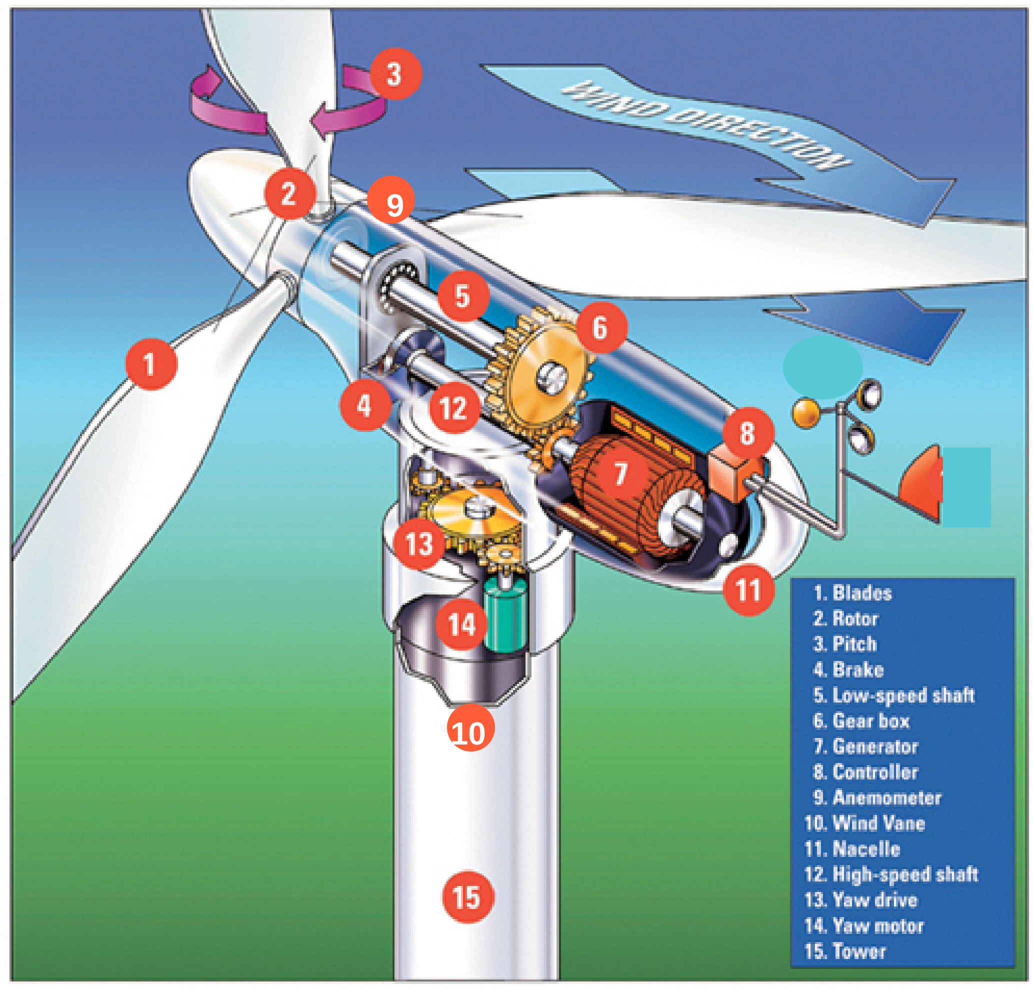
- A turbine design and cost model tool was developed that is scalable with rotor diameter, generator rating and tower height.
- The most important structural loads are:
  - Rated torque:

$$Q_R = \frac{1}{16}\rho_a C_p \pi \frac{V_R^3}{V_T} D^3$$

  - Extreme thrust on the rotor:

$$T_R = \frac{1}{8}\rho_a (0.85 * V_{EX})^2 C_D S \pi D^2$$

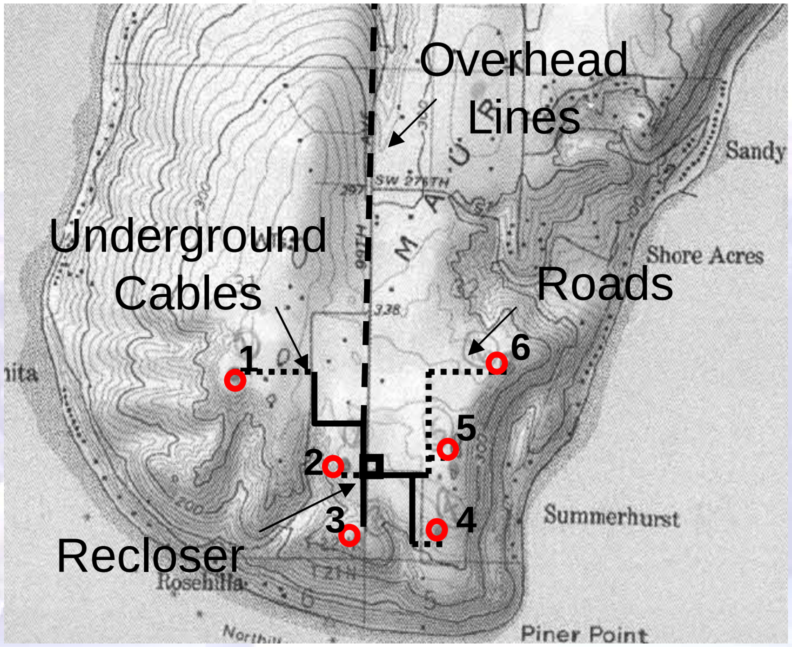
Turbine Components and Systems



1. Rotor Blades
2. Hub
3. Pitch Mechanism
4. Mechanical Brake
5. Low-speed Shaft
6. Gearbox
7. Generator
8. Controls and Safety System
9. Main Bearings
10. Variable Speed Electronics
11. Nacelle Cover and Bedplate
12. High-Speed Shaft, Coupler
13. Yaw Drive and Bearing
14. Electrical Connections
15. Tower
16. Hydraulic and Lubrication System

Balance-of-Station Model

1. Electrical Interface
2. Roads and Civil Works
3. Crane Pad
4. Foundation
5. Transportation
6. Crane Cost
7. Assembly and Installation
8. Permitting Costs
9. Engineering Costs
10. Surveying Costs
11. Inspection Costs
12. Manufacturer Mark-up



COE Model

$$COE = \frac{(FCR * ICC)}{AEP_{net}} + O\&M$$

COE = Levelized cost of energy ($/kWh)

FCR = Fixed charge rate (0.106/year)

ICC = Initial capital cost ($)

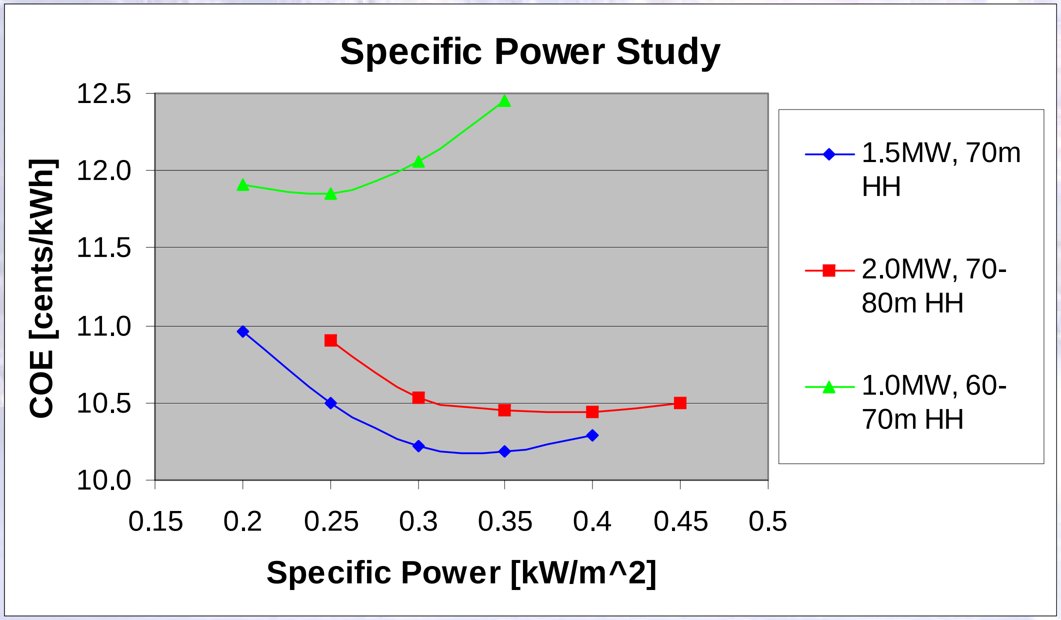
AEP_{net} = Net annual energy production (kWh/yr)

O&M = Operating and maintenance cost ($/kWh)

COE and Optimum Turbine

Ten 1.5MW turbines would will provide 25GWh at the least COE.

Increasing or decreasing the turbine rating results in an unbeneficial compromise between energy production to costs.



Optimum Turbine Design	
Rotor Diameter [m]	83.5
Generator Rating [MW]	1.5
Tower Height [m]	70
Specific Power [kW/m^2]	0.325
COE [¢/kWh]	10¼

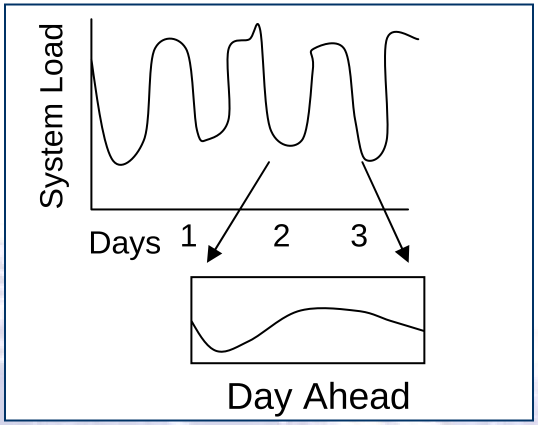
Future Component Cost Reductions

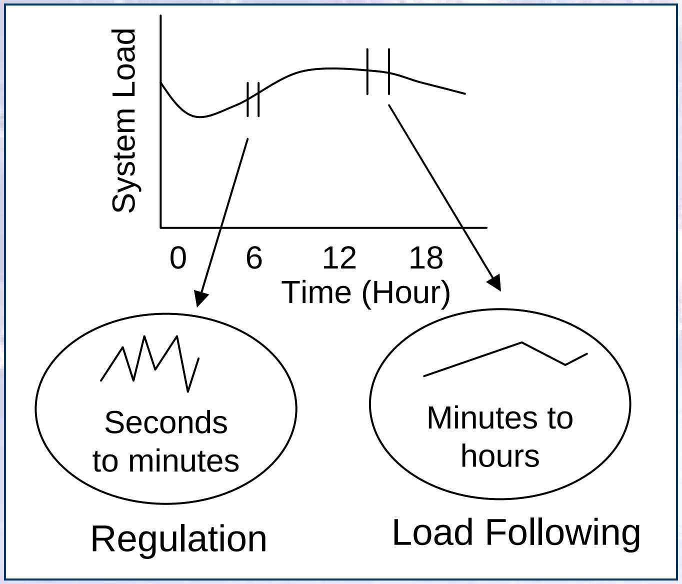
- Improvements in components and systems are likely to decrease the overall COE including:
  - Drivetrain
  - Power Electronics System
  - Rotor Blades and Controls
  - Tower and Nacelle Installations
- A COE of 8¢/kWh or a 25% reduction of COE is calculated from reductions in component and system costs determined by previous studies.

Grid Integration and Energy Storage

- Energy generation must be balanced with grid load by the grid operator in real time.
- Balancing generation and load occurs over a significant range of timescales:
  - Grid operators plan which generators should be on-line the following day based on capacity and economic considerations
  - Automatic generation control (AGC) software ramps generators up or down to correct quick fluctuations
- The stochastic nature of wind energy makes balancing of the grid more difficult.

Three Timescales for Grid Operation





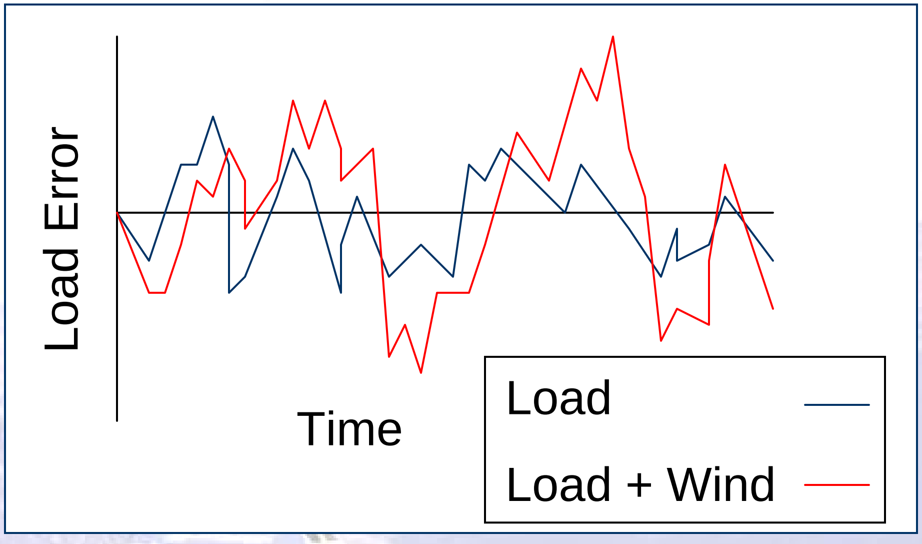
- Day-ahead (unit commitment):
  - One day, with one-hour time increments
  - Generators scheduled 12 hours in advance of the subject day.
- Load following:
  - One hour, with five to 10-minute increments
  - Economic-dispatch model every five to 10 minutes
- Regulation:
  - One minute, with one to five-second increments
  - AGC are used to match generation to load

Integration of Wind Power

- The grid load is not entirely predictable.
- Load forecasts errors dictate that traditional generating sources must be online that may be ramped up down to balance load and generation (ancillary services).
- Similarly, wind farms use forecasting techniques to predict power output for the three timescales, and have associated forecast errors.

Integration of Wind Power

- Overall, wind power tends to increase forecast errors slightly depending on the wind penetration level.



- Since wind power mitigates load forecast errors about 50% of the time, the grid operator must balance aggregate load and generation.

Costs of Wind Integration

- The necessary increase of ancillary services with the integration of wind energy is passed onto the wind farm.
- These costs are estimated by using:
  - wind forecasting techniques
  - statistical methods
  - and yearly data
- A table correlating wind data at SeaTac airport for 1997 to power output for the Maury Island wind farm is developed.

Forecast Error Calculations

- Day-ahead forecast error:

$$E_{day-ahead} = \frac{\sum_{n=1}^{24} \left| P_{ave} - P_{hour,n} \right|}{24 P_{ave}}$$

Pave:
- – daily power (lower bound)
- – monthly power (upper bound)

- Load following error:

$$\hat{P}_{hour,n} = P_{hour,n-1}$$

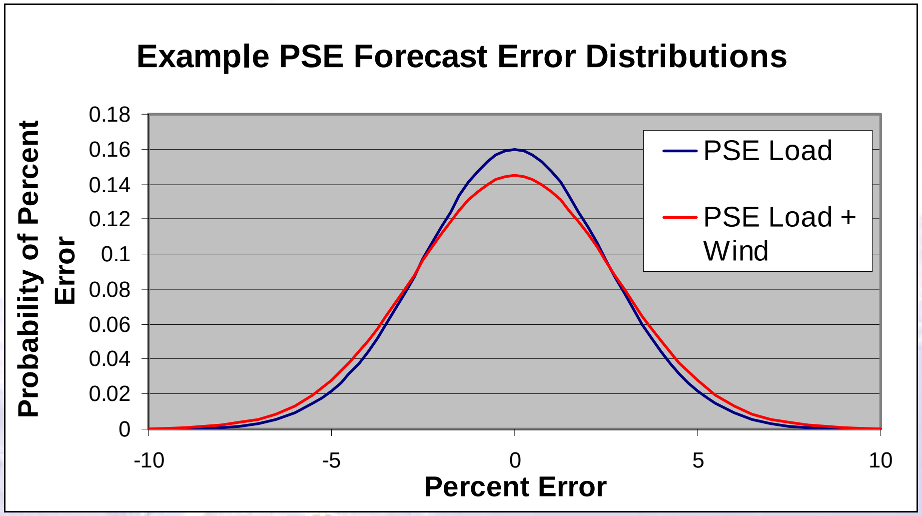
← Persistence forecast model

$$E_{load-follow} = \left| P_{hour,n} - \hat{P}_{hour,n} \right|$$

- Assume a normal distribution.

Costs of Ancillary Services

- A probabilistic model estimates the increase in ancillary service costs based on reserve generation costs.



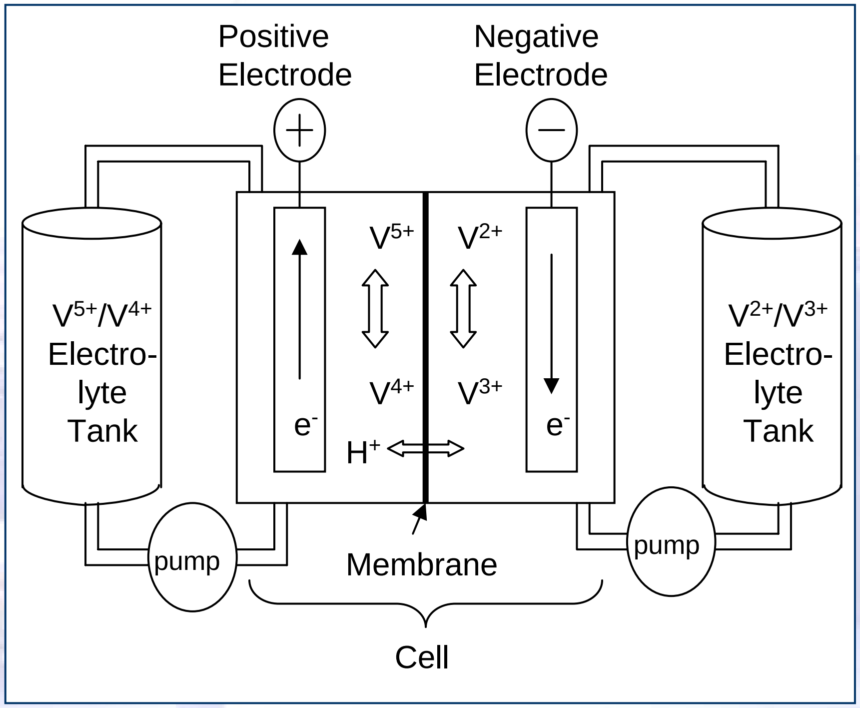
Results	Regulation [$/MWh]	Load-Following Costs [$/MWh]	Day-ahead Costs [$/MWh]	Total [$/MWh]	Total Costs for 26GWh [$]
PSE Study	0.16	2.70	0.84	3.70	96,200
Maury Island Study	0.16	0.052	0.043	0.26	6,630

Energy Storage

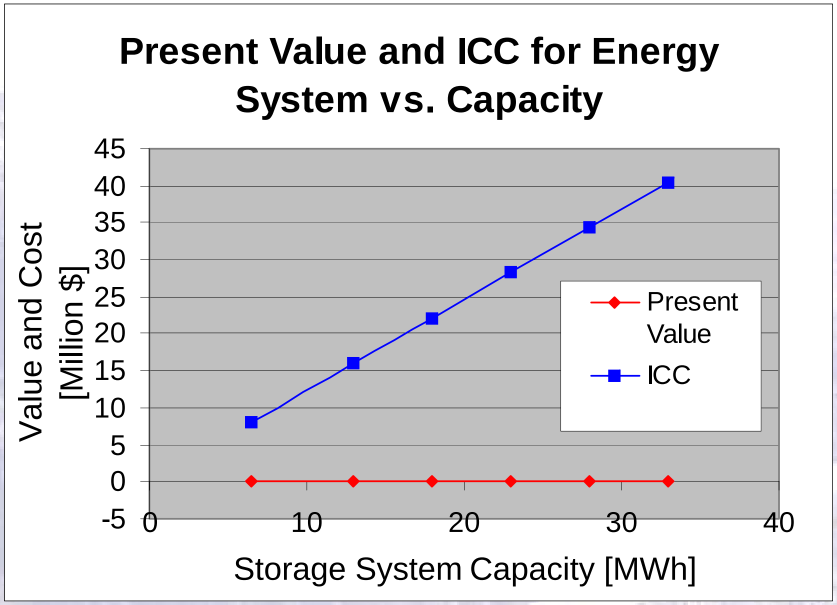
- An energy storage system may be economically beneficial to the Maury Island wind farm by:
  - Reducing ancillary services for the three timescales
  - Shifting generation from off-peak to on-peak times
- Load following support and load shifting capabilities are the most beneficial.
  - Load following ancillary services are the most expensive and the number of cycles are manageable
  - Load shifting revenues have a large potential

Vanadium Redox Flow Batteries

- VRBs applicable characteristics:
  - Scalable
  - Fast response times
  - Able to sustain many cycles
- Operation is similar to a fuel cell, and is a reaction of Vanadium Ions only.
- VRBs are about 75-80% efficient.



Energy Storage Results



- A VRB energy storage system has no economic benefit.
- The benefits of avoided ancillary costs and value of shifted energy are small compared to the system ICC and value of lost energy.

Conclusions

- The average wind speed at 50 meters for Maury island turbines is 4.9m/s.
- 10 turbines could produce 25GWh of electricity at a COE of about 10¢/kWh provided the turbines have:
  - 1.5MW ratings
  - 83.5 meter rotors
  - 70 meter towers
- The COE may drop by 25% over the next 10 years.
- Integrating the wind farm to the PSE grid would cost an additional 0.03 – 0.4 ¢/kWh.
- An energy storage system would not be economically beneficial.

Questions?

Comparison with Other Studies

Specific power results are dependent on both:

- Average wind speed
- Weibull shape parameter

COE results are slightly high:

- Balance-of-Station costs are slightly higher because of turbine locations.
- Conservative assumptions were generally used.