Wind Turbine Systems – Soils, Foundation and Tower

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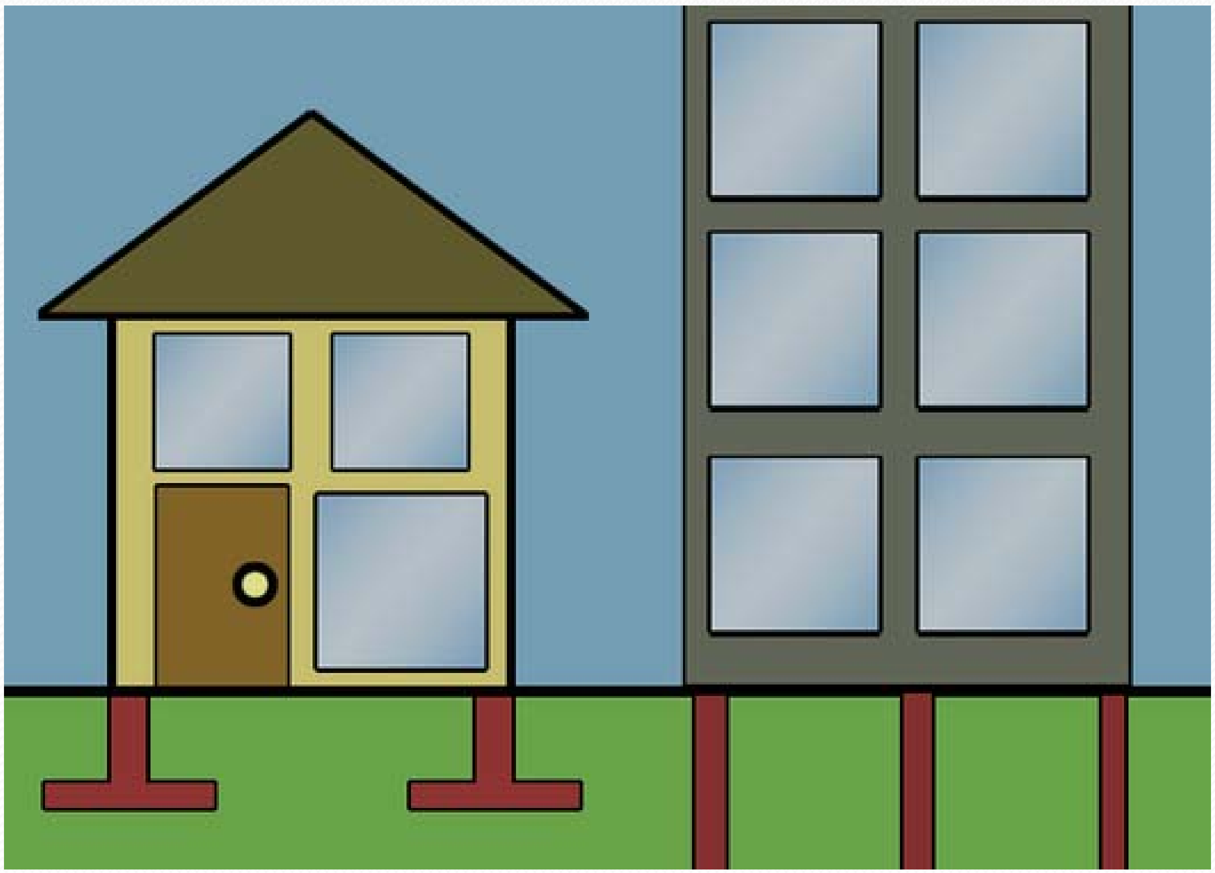
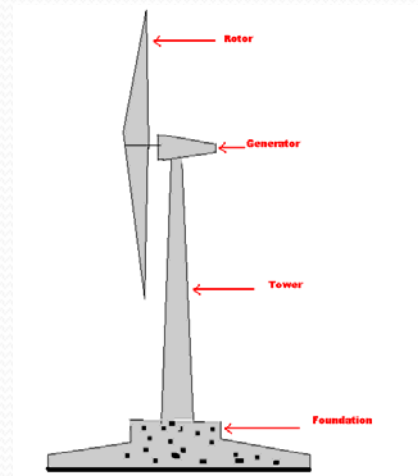
June 5, 2013

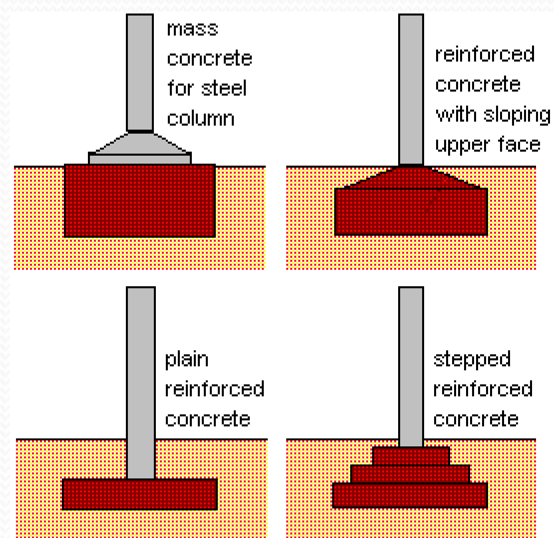
Design vs. construction

- Design process
  - Identify loads and limit states
  - Establish critical demands for all elements
  - Ensure capacity is greater than demand in each element
- Design from the top down
  - Roof → building → foundation
- Construct from the bottom up
  - Foundation → building → roof
- How do you determine the best design solution?

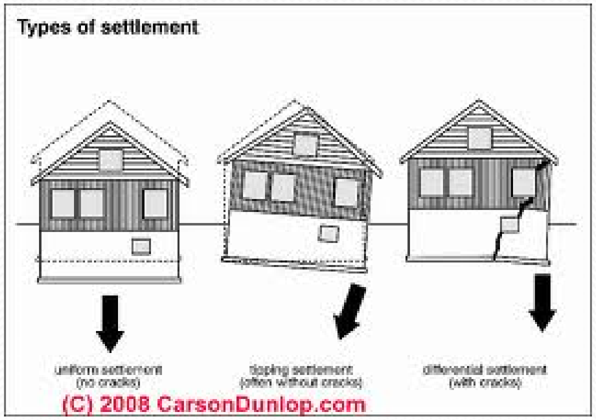
Shallow vs. Deep Foundations

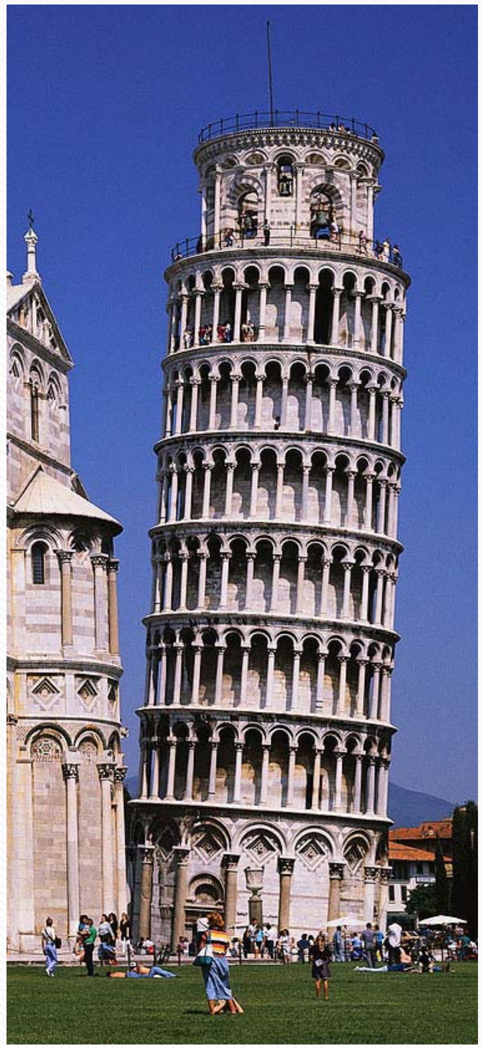


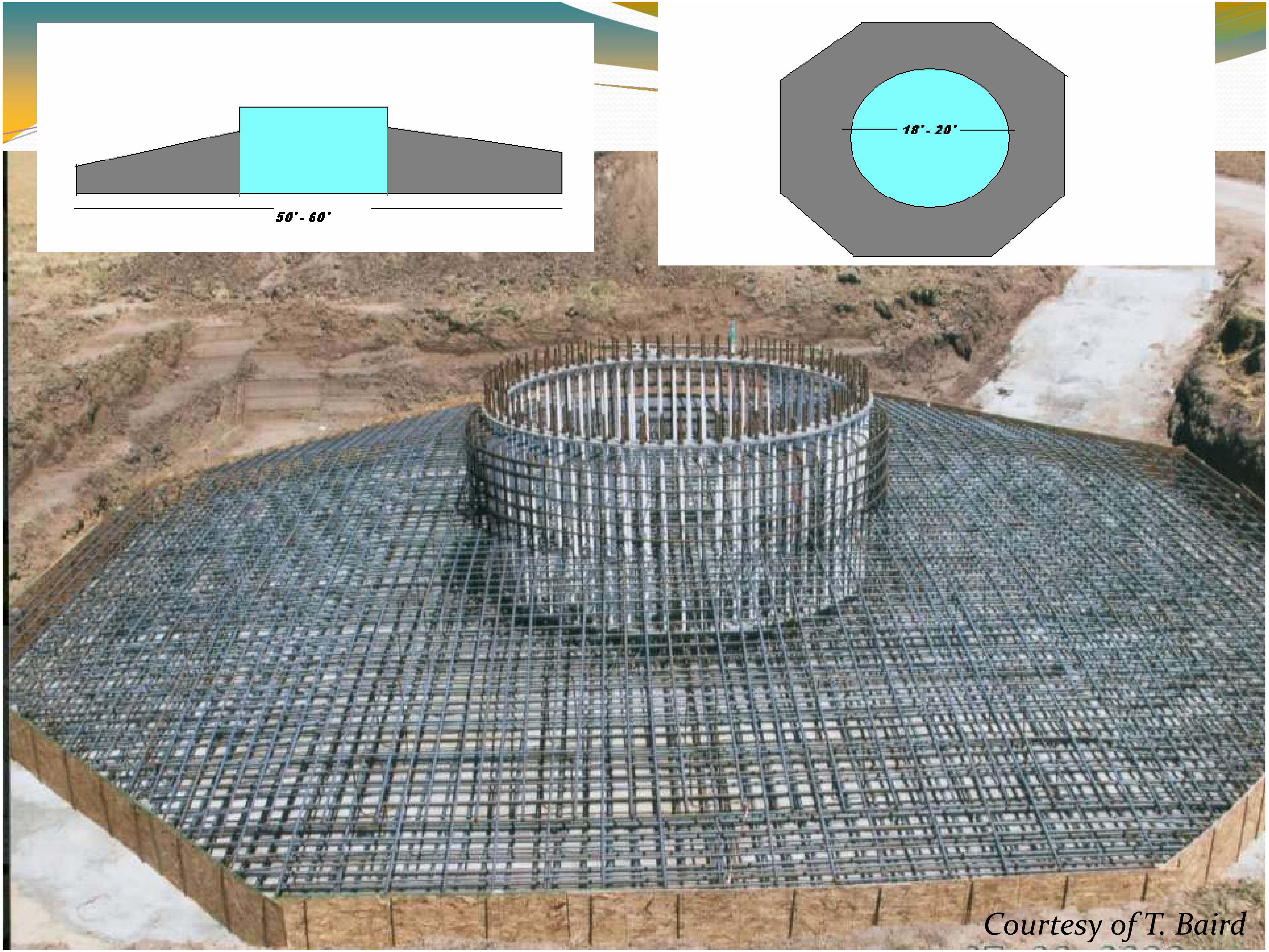




Poorly designed foundations







Courtesy of T. Baird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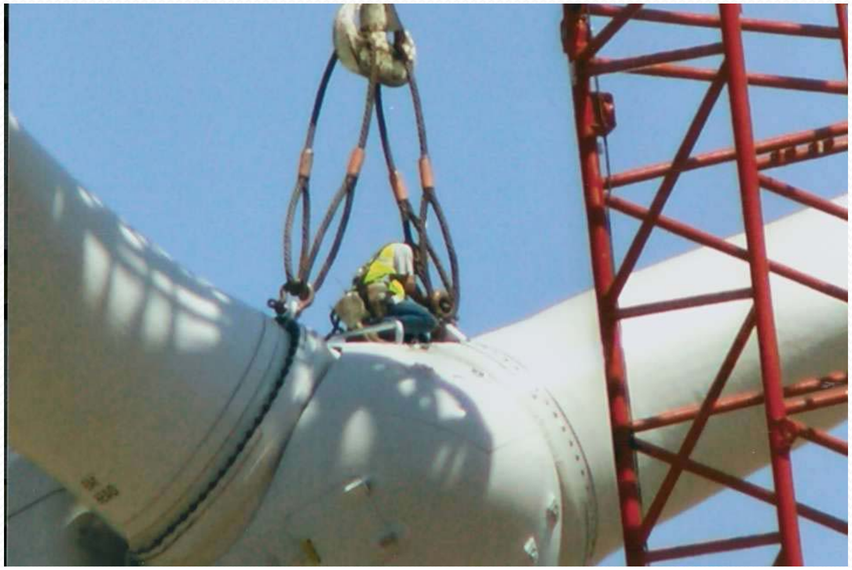
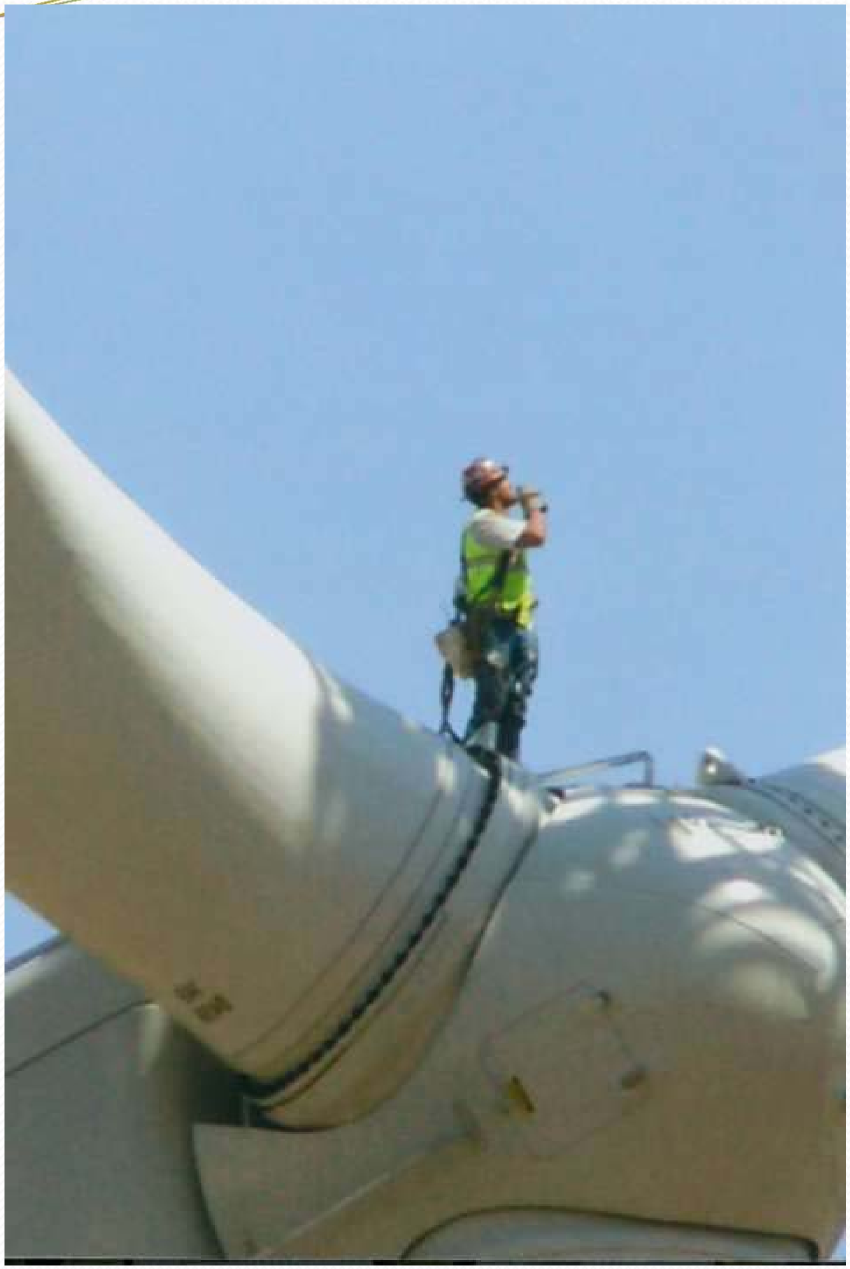





Courtesy of T. Baird

Wind Turbine Tower Design

Presentation Topics

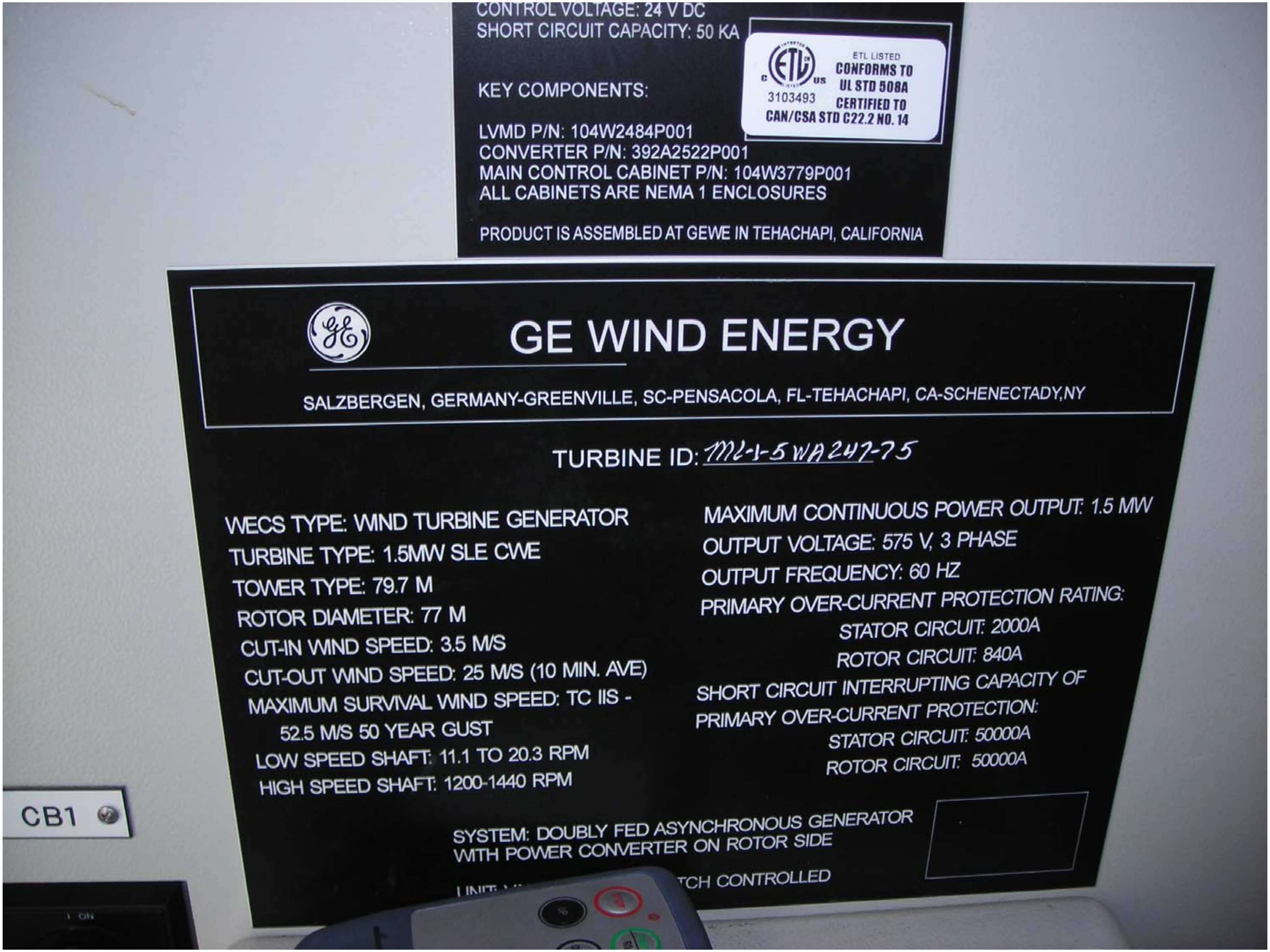
- Material Choices
  - Steel
  - Concrete
  - Hybrid
- Design Methods
  - Limit States/Specifications

Status Quo

Most common design:

- Tubular Steel

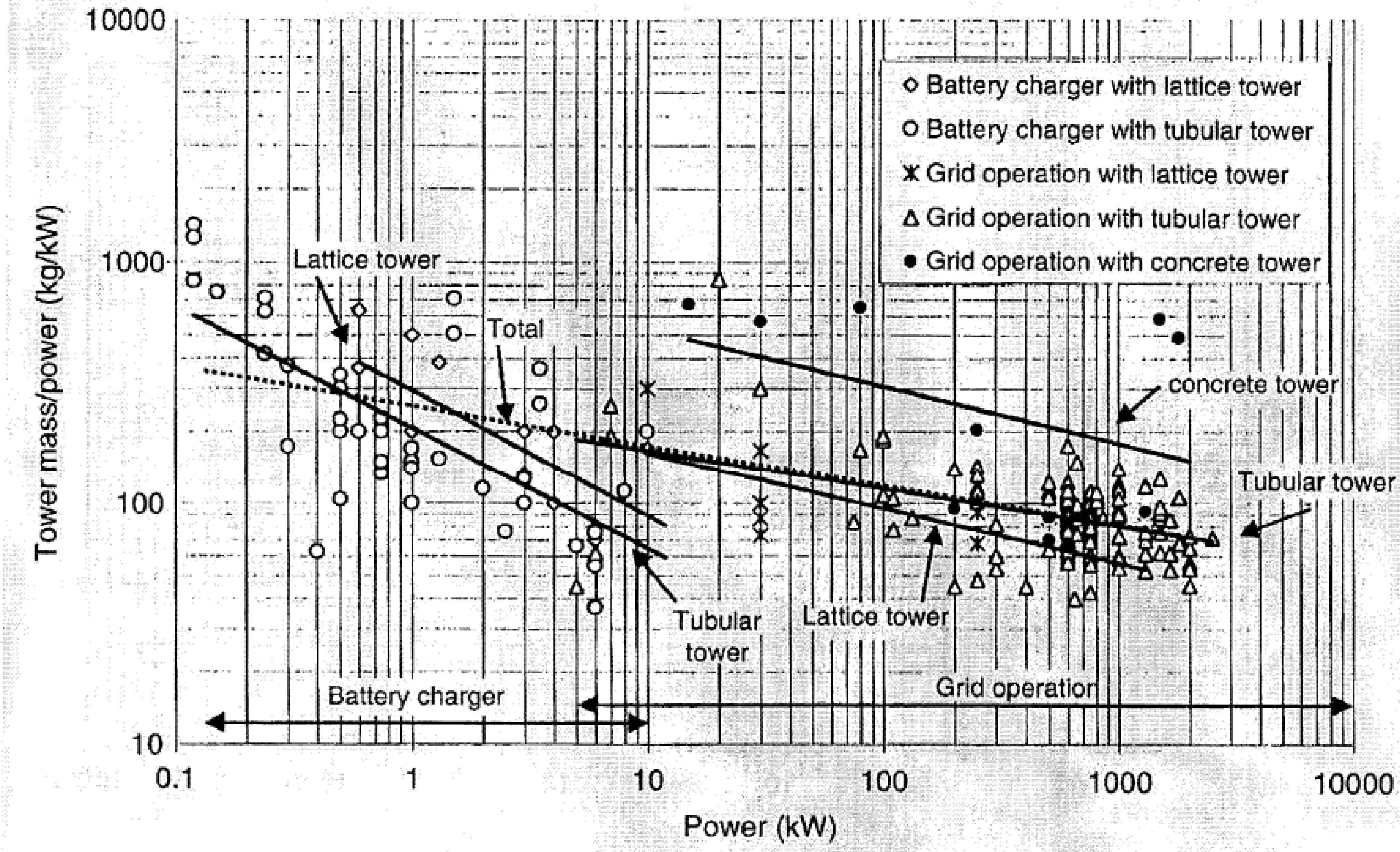
Source: trinitytowers.com


CONTROL VOLTAGE: 24 V DC
SHORT CIRCUIT CAPACITY: 50 KA
KEY COMPONENTS:
LVMD P/N: 104W2484P001
CONVERTER P/N: 392A2522P001
MAIN CONTROL CABINET P/N: 104W3779P001
ALL CABINETS ARE NEMA 1 ENCLOSURES
PRODUCT IS ASSEMBLED AT GEWE IN TEHACHAPI, CALIFORNIA
ETL
3103493
ETL LISTED
CONFORMS TO
UL STD 508A
CERTIFIED TO
CAN/CSA STD C22.2 NO. 14
GE WIND ENERGY
SALZBERGEN, GERMANY-GREENVILLE, SC-PENSACOLA, FL-TEHACHAPI, CA-SCHENECTADY,NY
TURBINE ID:
WECS TYPE: WIND TURBINE GENERATOR
TURBINE TYPE: 1.5MW SLE CWE
TOWER TYPE: 79.7 M
ROTOR DIAMETER: 77 M
CUT-IN WIND SPEED: 3.5 M/S
CUT-OUT WIND SPEED: 25 M/S (10 MIN. AVE)
MAXIMUM SURVIVAL WIND SPEED: TC IIS -
52.5 M/S 50 YEAR GUST
LOW SPEED SHAFT: 11.1 TO 20.3 RPM
HIGH SPEED SHAFT: 1200-1440 RPM
MAXIMUM CONTINUOUS POWER OUTPUT: 1.5 MW
OUTPUT VOLTAGE: 575 V, 3 PHASE
OUTPUT FREQUENCY: 60 HZ
PRIMARY OVER-CURRENT PROTECTION RATING:
STATOR CIRCUIT: 2000A
ROTOR CIRCUIT: 840A
SHORT CIRCUIT INTERRUPTING CAPACITY OF
PRIMARY OVER-CURRENT PROTECTION:
STATOR CIRCUIT: 50000A
ROTOR CIRCUIT: 50000A
SYSTEM: DOUBLY FED ASYNCHRONOUS GENERATOR
WITH POWER CONVERTER ON ROTOR SIDE
CB1
ON

Why is steel popular?

- Most prominent design alternative, established manufacturers
- High strength to weight ratio
- Competitive cost in the current market

Tower Mass vs. Power



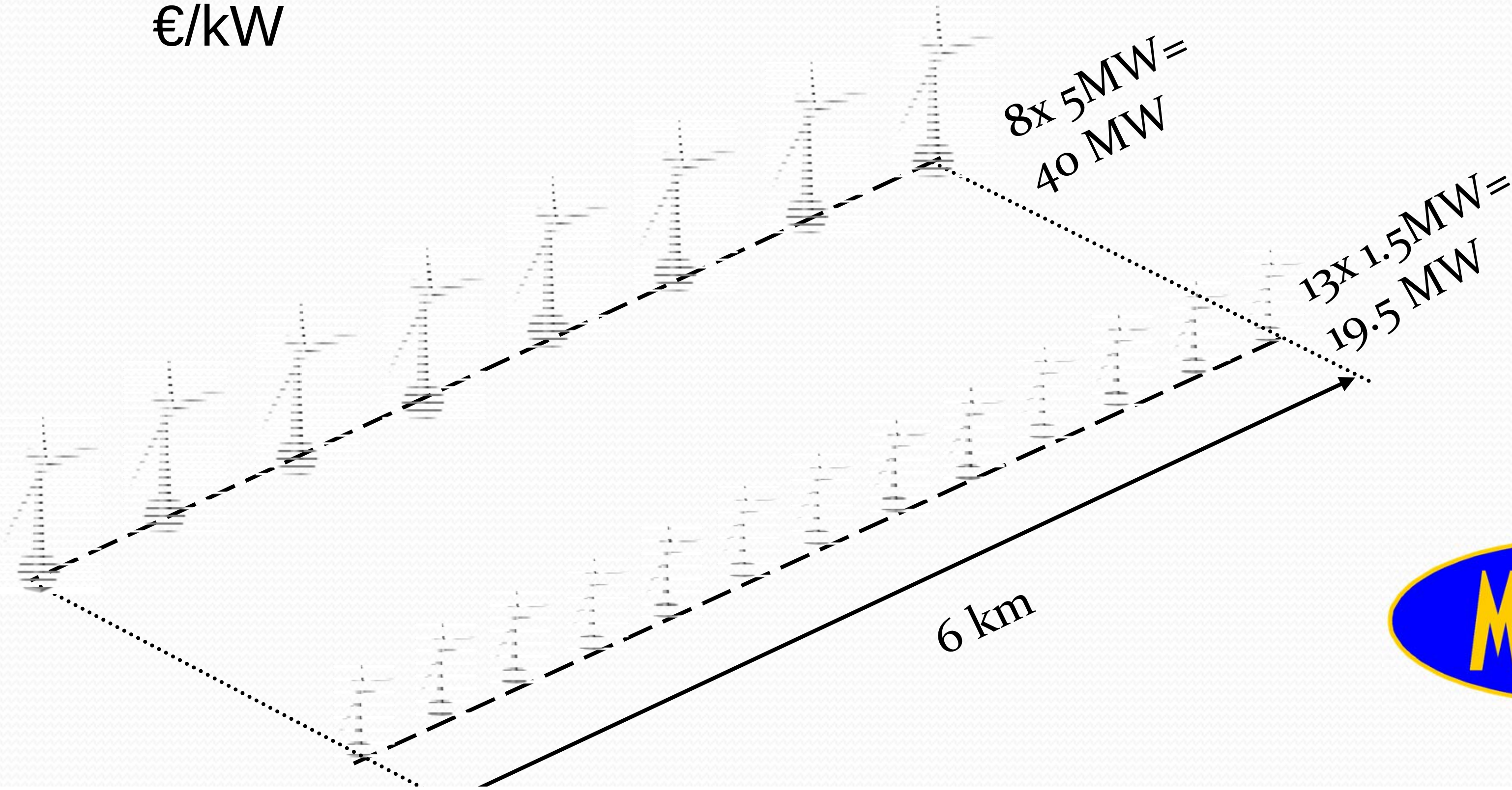
Source: S. Heier, "Grid Integration of Wind Energy Conversion Systems," 2nd edition, Wiley, 2006

Moving Forward

- Department of Energy's 20% Wind Energy by 2030: "Continued reduction in wind capital cost and improvement in turbine performance"
- A call for towers of greater height
  - Faster wind loads
  - Higher power output/more efficient
  - Increase in turbine capacity

MultiMW wind turbines

- Twice as much rated power by applying 5 MW machines
- Relatively lower costs for grid connection, land, road construction and wind farm operation
- Lower Total Costs of Energy when WT-price of 5 MW < 1150 €/kW



Moving Forward

- There is evidence showing economical benefits of increased tower heights
  - E.g., Hybrid tower designed by ATS
    - 100m Steel Tower vs. 133m Steel/Concrete Hybrid Tower
    - 100m: 5090 MWh/yr vs. 133m: 5945 MWh/yr (17%, $110,00 increase in income per year)
    - Additional $450,000 to build 133m tower (~4 year cost recovery time vs. 20+ year typical turbine life)

Moving Forward

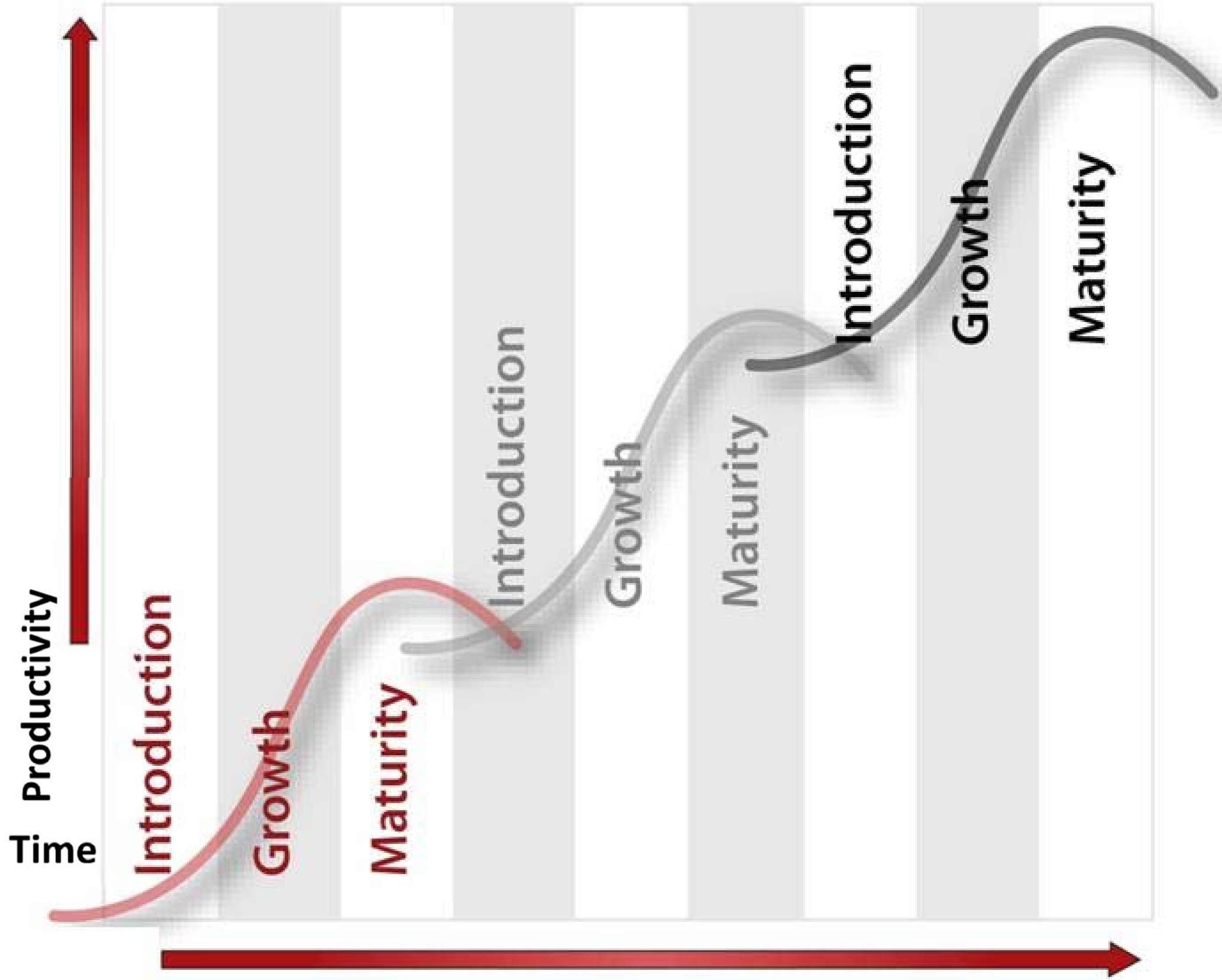
- Challenges of steel construction
  - Large sections necessary for taller towers
  - Transportation concerns/increased costs
    - Transportation limits diameters to 14.1 ft (4.3m)
  - Higher site development cost
  - Large crane requirement
  - Potentially long lead time

100m Steel Tower (ISU Design)

- For a 100m tower,
  - Base Shell Thickness: 1.5 in (38.1 mm)
  - **Base Diameter:18 ft (5.5m)**
  - Top Diameter: 10 ft
  - Top Shell Thickness: 0.80 in (20.3 mm)
  - Increases the volume of steel by 2
  - Life span is still limited to 25 years

- **Clearly there is room for innovation in tower design**

Bell curve



Source: http://tfargo.files.wordpress.com

Design Alternatives

Other emerging options:

- Concrete
- Concrete/Steel Hybrid
- Advanced materials

Concrete

Advantages:

- Potential cost savings
  - Transportation/Development
- No local buckling concerns (thicker sections required for concrete strength)
- More corrosion resistance
- Multiple constructions options (more on this to follow)

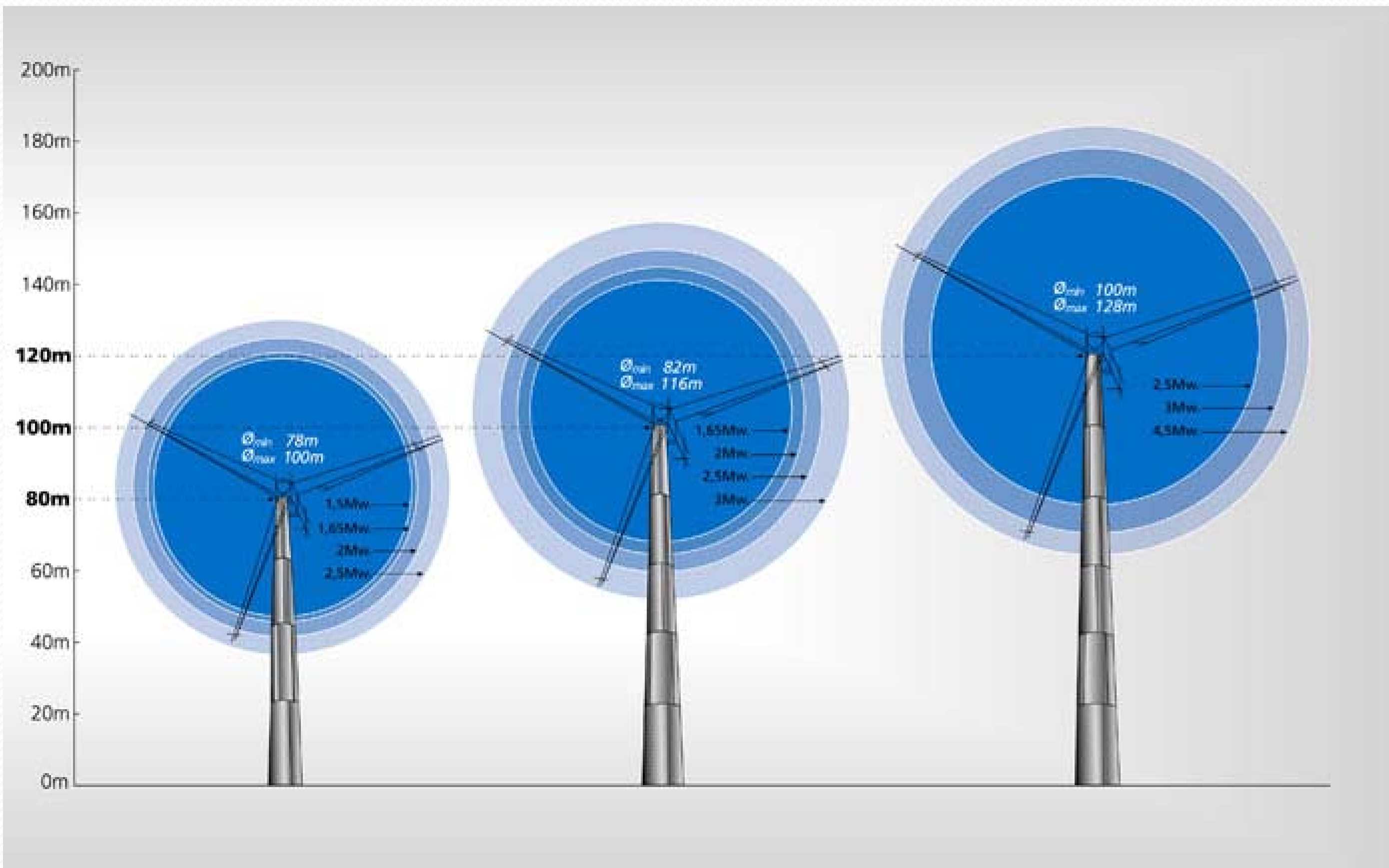
Concrete

- Segmental Construction
  - Multiple precast sections would define the cross section
  - Sections are bolted or post-tensioned together
  - Many precasters available who could produce these sections
  - More competition of suppliers could reduce prices
  - Smaller precast modules could be more easily transported
  - Smaller crane required for construction
  - Re-use: 20 year turbine life vs. 50+ year tower life

Design Alternatives

Cast-in-Place Option

- Industrial chimneys similar in scope, construction
- Could prove to be most competitive in price



Source:
www.inneo.es

Design Alternatives

Advantage of the Hybrid:

- Combines the advantage of steel on top, concrete on bottom
- Large diameter steel-tubes not necessary (fewer transportation difficulties)
- Lower seismic weight than concrete tower
- Self-jacking tower could limit crane costs

Design Alternatives

Source: www.atlasctb.com/anatomy.html

Wind Turbine Tower Design

Topics:

- Design Loads
  - Sources
  - Specifications
- Steel
  - Limit States
  - Specifications
- Concrete
  - Limit States
  - Specifications
- Dynamic Concerns

Design Loads

Need to account for the following loads on the structure:

- Dead Load
- Direct Wind Pressure
  - Applied as a static load
- Turbine Wind Load
  - Applied dynamically, or as an amplified static load
- Earthquake (depending on tower location)

Applicable Design Specifications for Loading

- Direct Wind Loading:
  - IEC 61400-1
  - ASCE 7
- Wind Turbine Loading:
  - Typically specified by turbine manufacturers, or simulated
- Earthquake:
  - ASCE 7

Load Combinations

1.4D (Will not govern)
1.2D + **1.6**W + **1.35**TWL
1.2D + 1.0E
*1.0D + 1.0W + 1.0TWL
**1.0D + ΔTWL

*Serviceability
**Fatigue

Limit States

Steel Limit States:

- Strength (LRFD or ASD)
  - Buckling (local and global), yielding, shear yielding/buckling, torsional yielding/buckling
  - Interaction
- Fatigue
- Serviceability
  - Deflections - Less defined, guidelines for chimneys exist

Applicable Standards for Limit States

No standardized US code for wind turbines

- Strength:
  - ANSI AISC 360-05
  - Eurocode 3
- Fatigue
  - Eurocode
  - Damage Equivalent Load Method

Limit States

Prestressed Concrete Limit States:

- Strength:
  - Cracking/No Tension Service Level Loading
  - Ultimate Capacity – crushing of concrete or fracture of longitudinal steel
  - Shear ultimate capacity – cracking/crushing of concrete, fracture of shear reinforcement (stirrups or fibers)
- Fatigue of concrete, steel
- Serviceability - Deflections

Applicable Standards for Limit States

- Strength:
  - ACI 318
  - Eurocode 2
- Fatigue
  - CEB-FIP Model Code 1990 (U.S. codes do not currently address high-cycle fatigue)
- Serviceability
  - ACI 307 (Design and Construction of Reinforced Concrete Chimneys)

Dynamic Concerns

Natural Frequency of Tower

- Rotor operation produces time varying loads
- Want to avoid excessive dynamic amplification
  - For small damping, resonance condition occurs approx. when driving freq. = natural freq. of structure
  - 1P and 3P
    - For a 3MW turbine,
      - 1P = 0.22 Hz
      - 3P = 0.66 Hz

Source: NREL/SR-500-36777

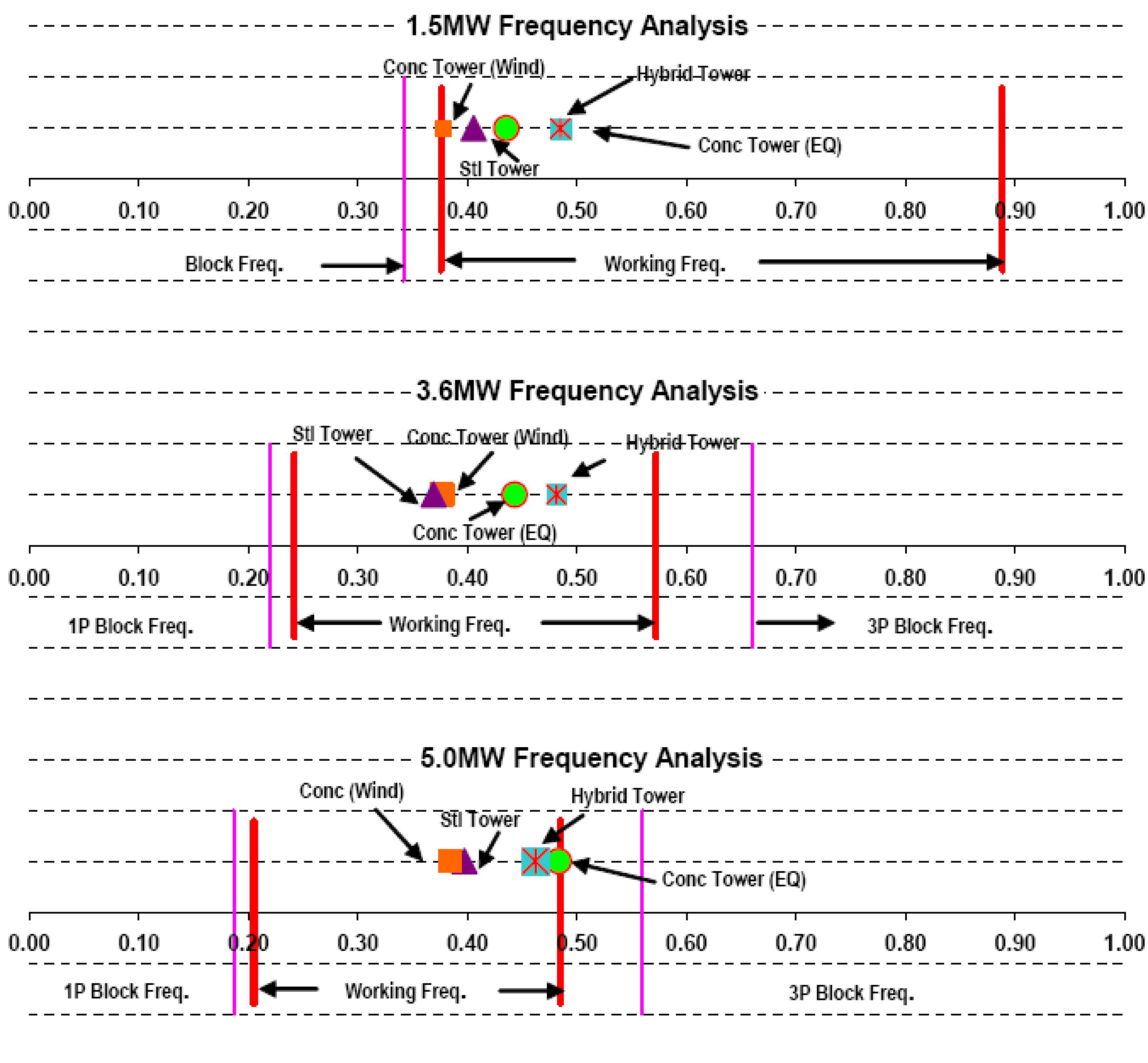


Figure 4.4. Operational frequency ranges for 1.5-, 3.6-, and 5.0-MW turbines

Expected Controlling Limit State

Hybrid:

- Steel fatigue controls the ultimate limit state

Prestressed Concrete:

- In a seismic region, strength controls
- In a wind-controlled region, concrete fatigue and tension strength control

Steel:

- Steel fatigue controls the ultimate limit state

ISU Tower