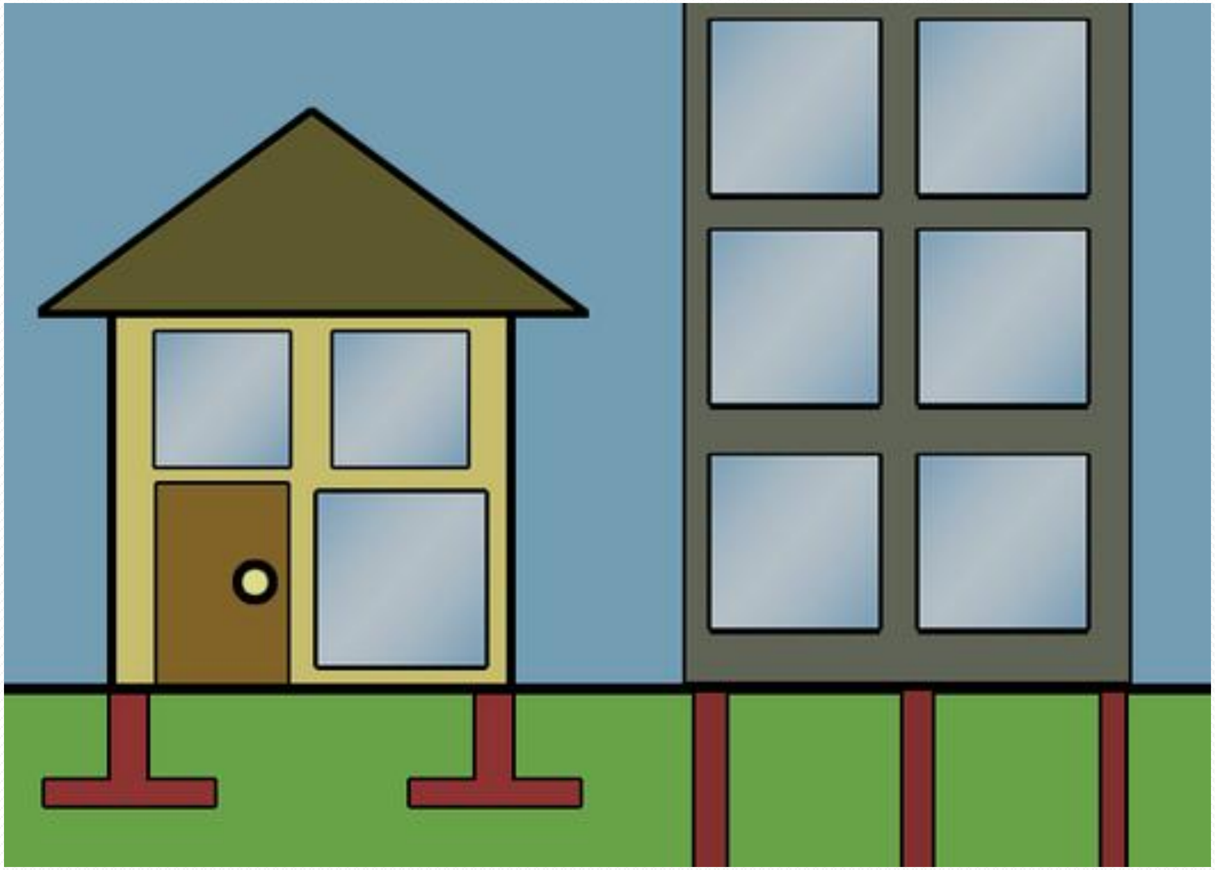
Wind Turbine Systems – Soils, Foundation and Tower

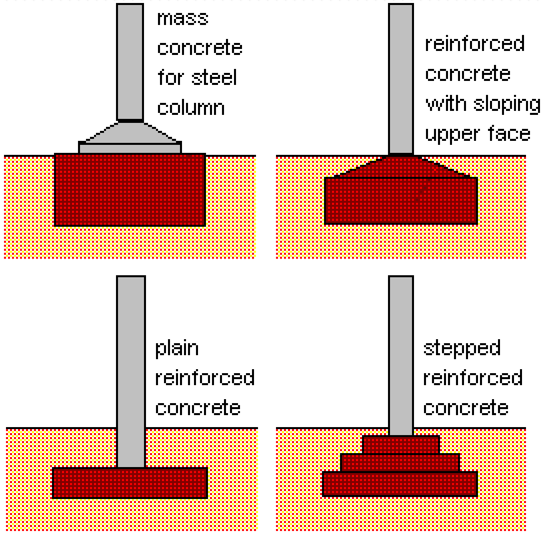
Sri Sritharan
Wilson Engineering Professor
Civil, Construction and Environmental Engineering
June 2, 2011

Design vs. construction

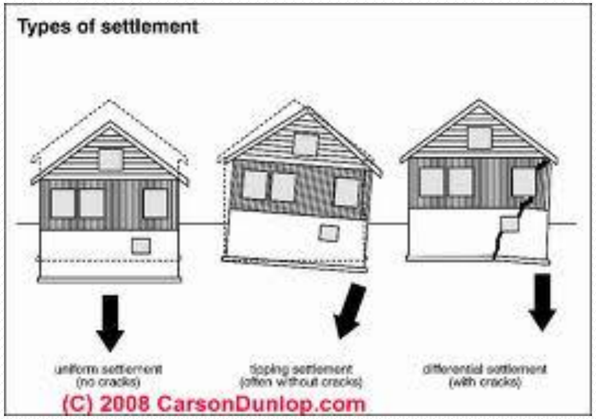
- Design process
  - Identify loads and limit states
  - Establish critical demands for all elements
  - Ensure capacity is greater than demand in each element
- Design from the top down
  - Roof → building → foundation
- Construct from the bottom up
  - Foundation → building → roof
- How do you determine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

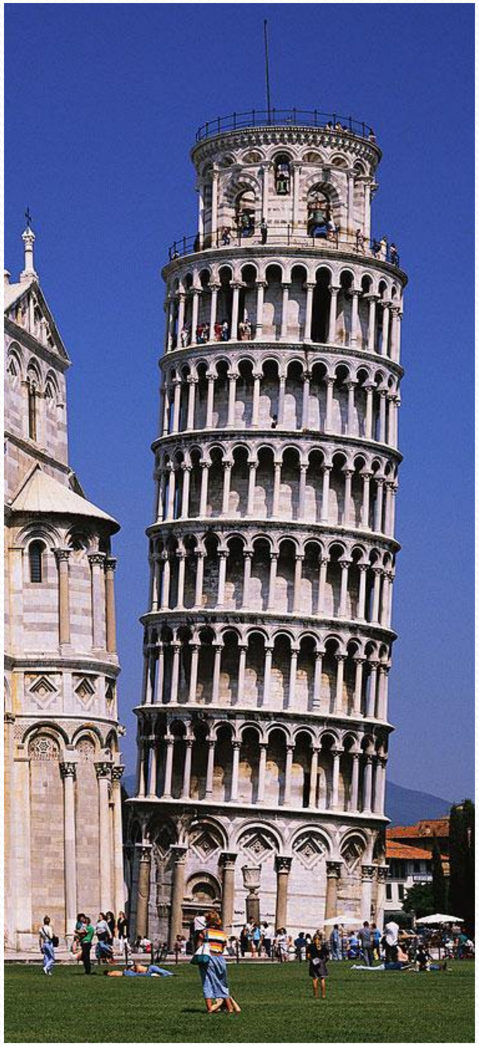
Shallow vs. Deep Foundations





Poorly designed foundations





Courtesy of T. Baird


Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Courtesy of T. Baird

Wind Turbine Tower Design

Presentation Topics

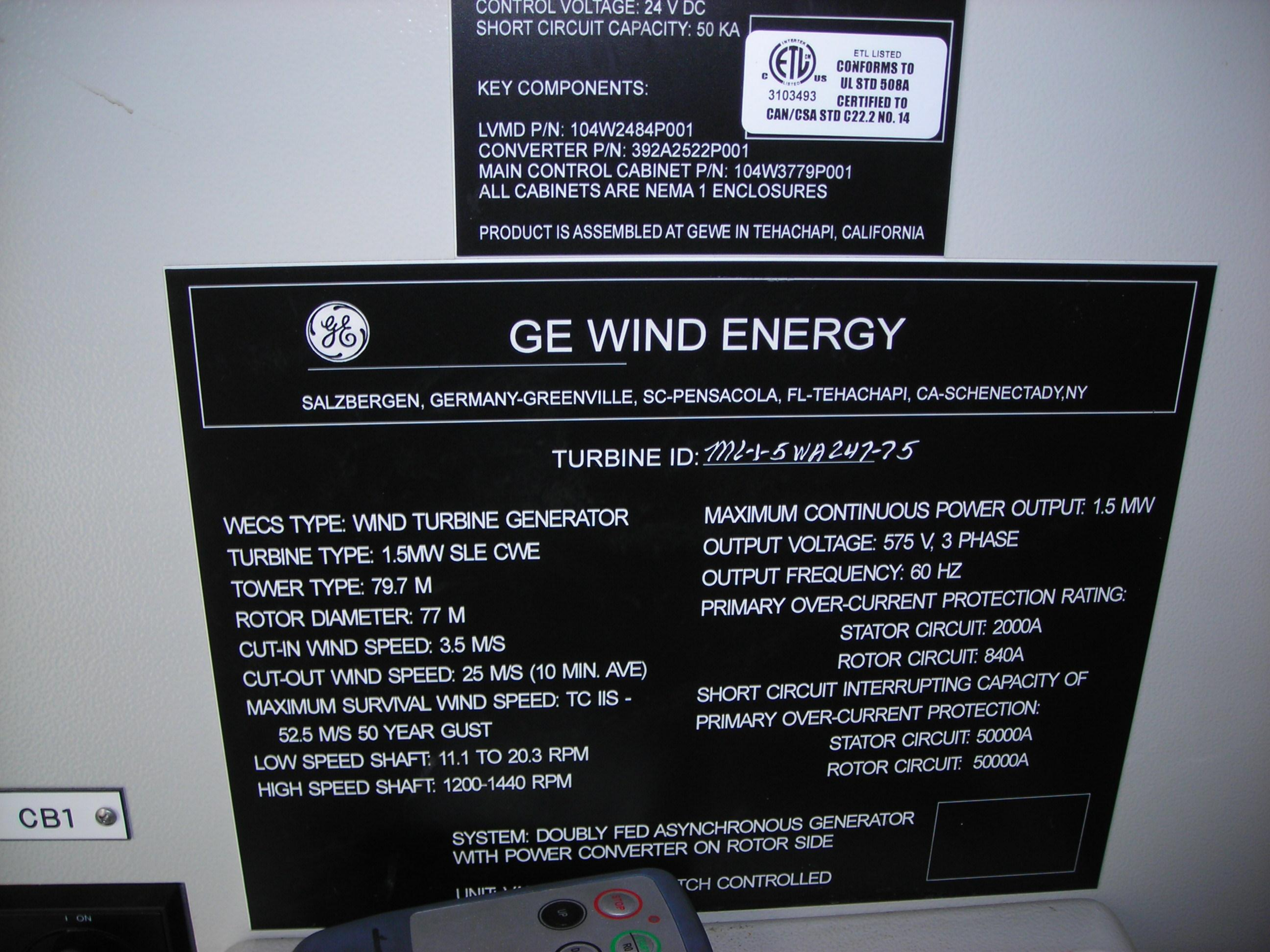
- Material Choices
  - Steel
  - Concrete
  - Hybrid
- Design Methods
  - Limit States/Specifications

Status Quo

Most common design:

- Tubular Steel

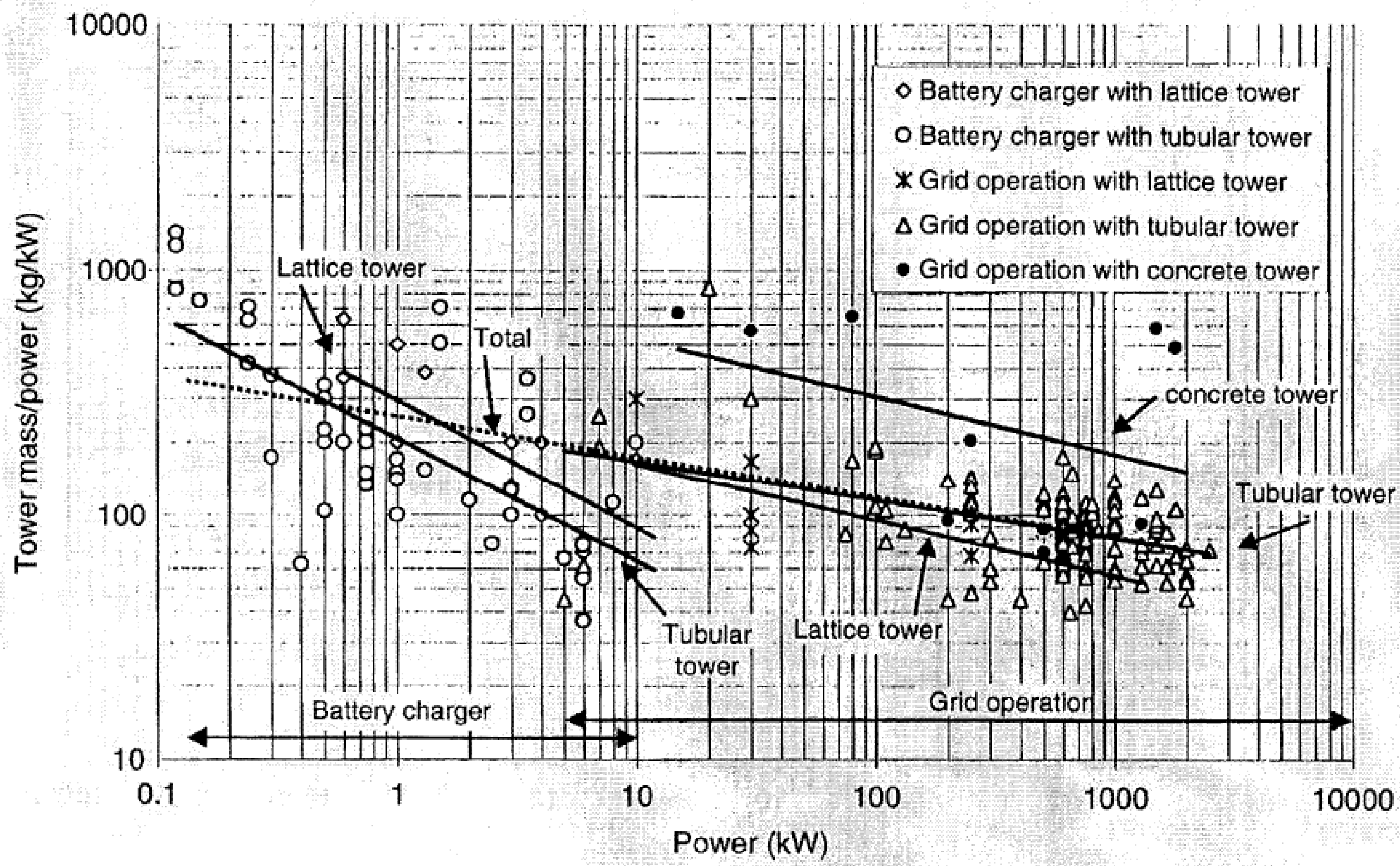
Source: trinitytowers.com


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 LISTED
3103493
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: ML-1-5WA247-75
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
TCH CONTROLLED
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



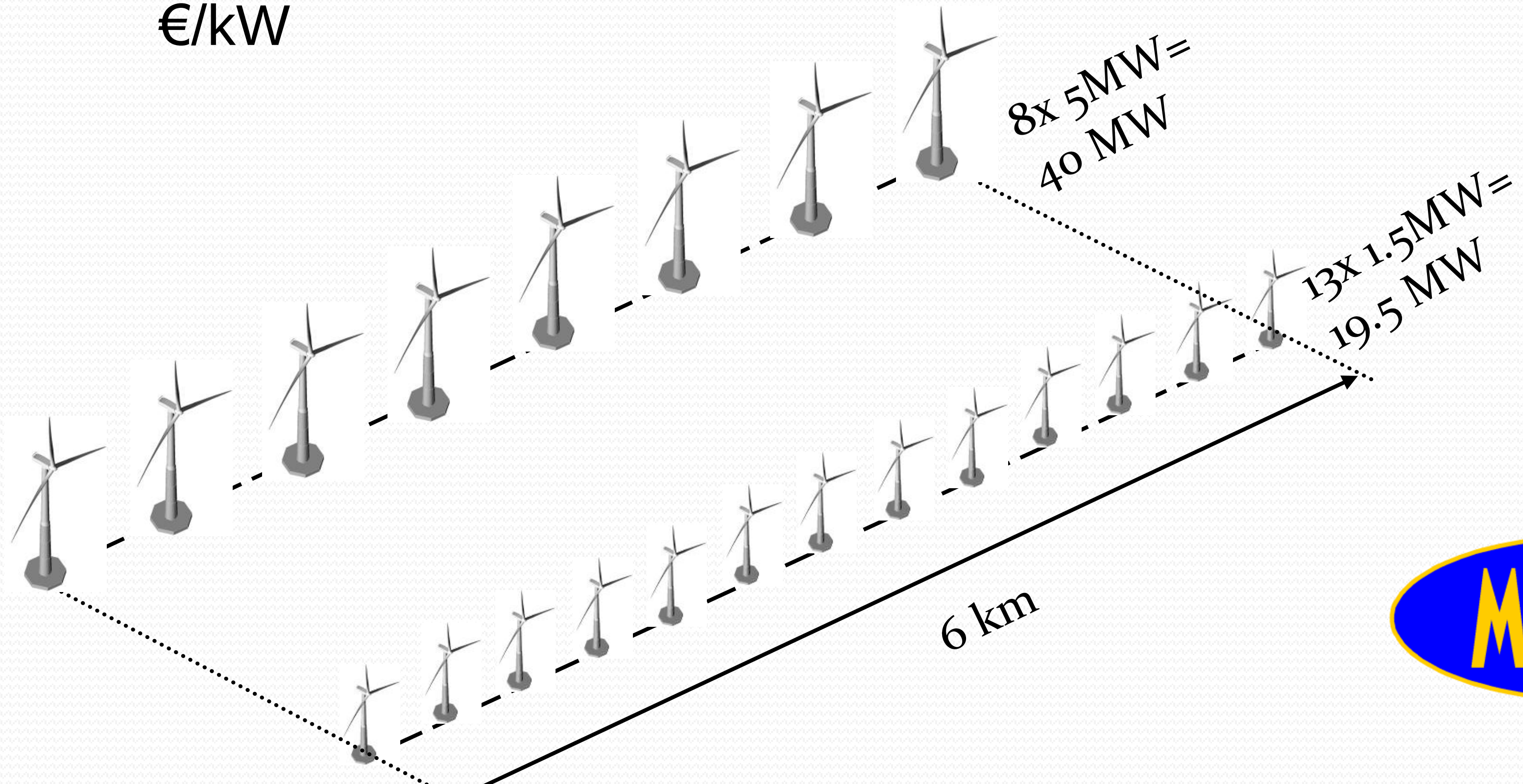
Source: S. Heier, "Grid Integration of Wind Energy Conversion Systems," 2nd edition, Wiley, 2006

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

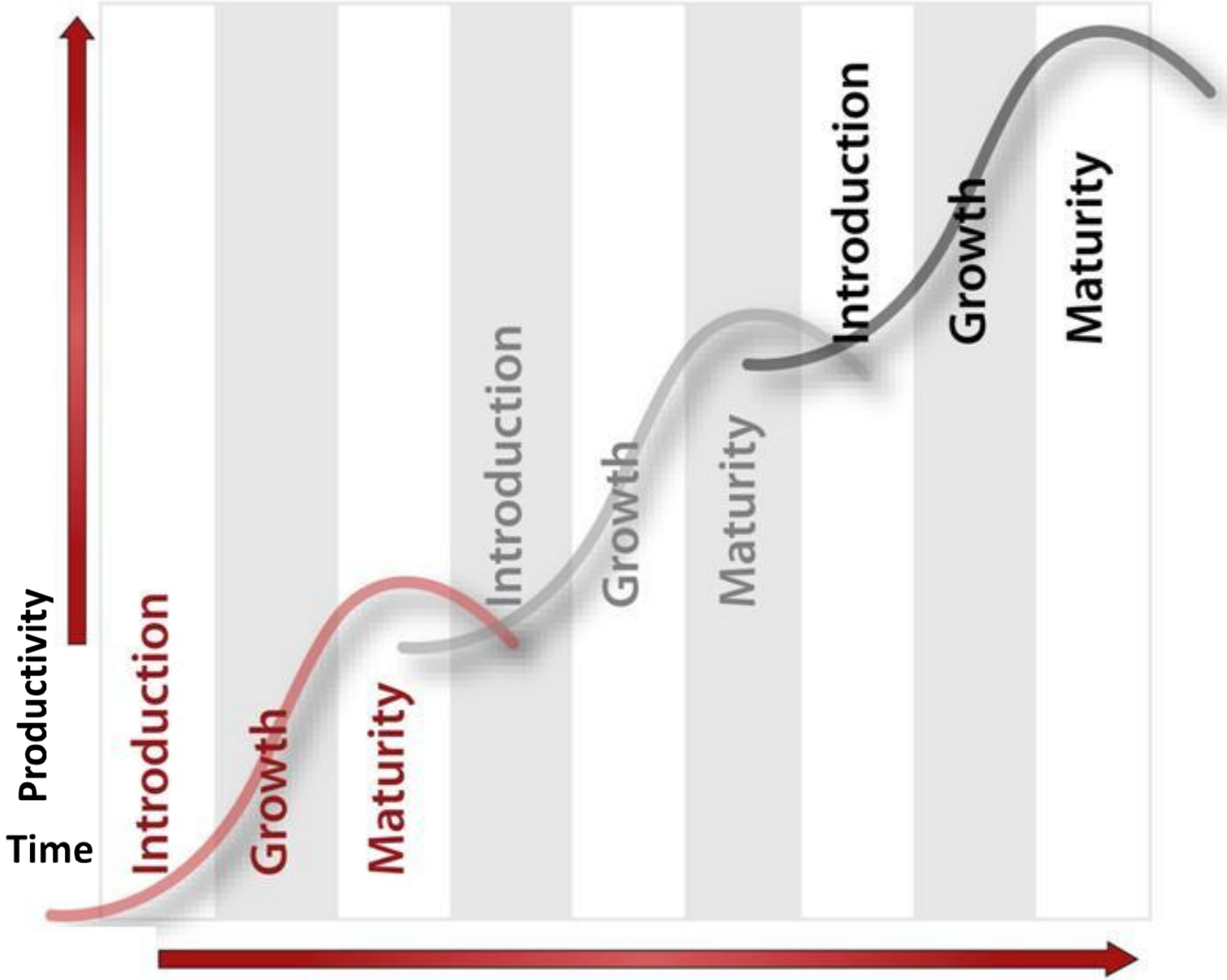
- Challenges of steel construction
  - Large sections necessary for taller towers
  - Transportation concerns/increased costs
    - Transportation limits diameters to 14.1 ft (4.3m)
  - Higher site development cost
  - Large crane requirement
  - Potentially long lead time

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 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)

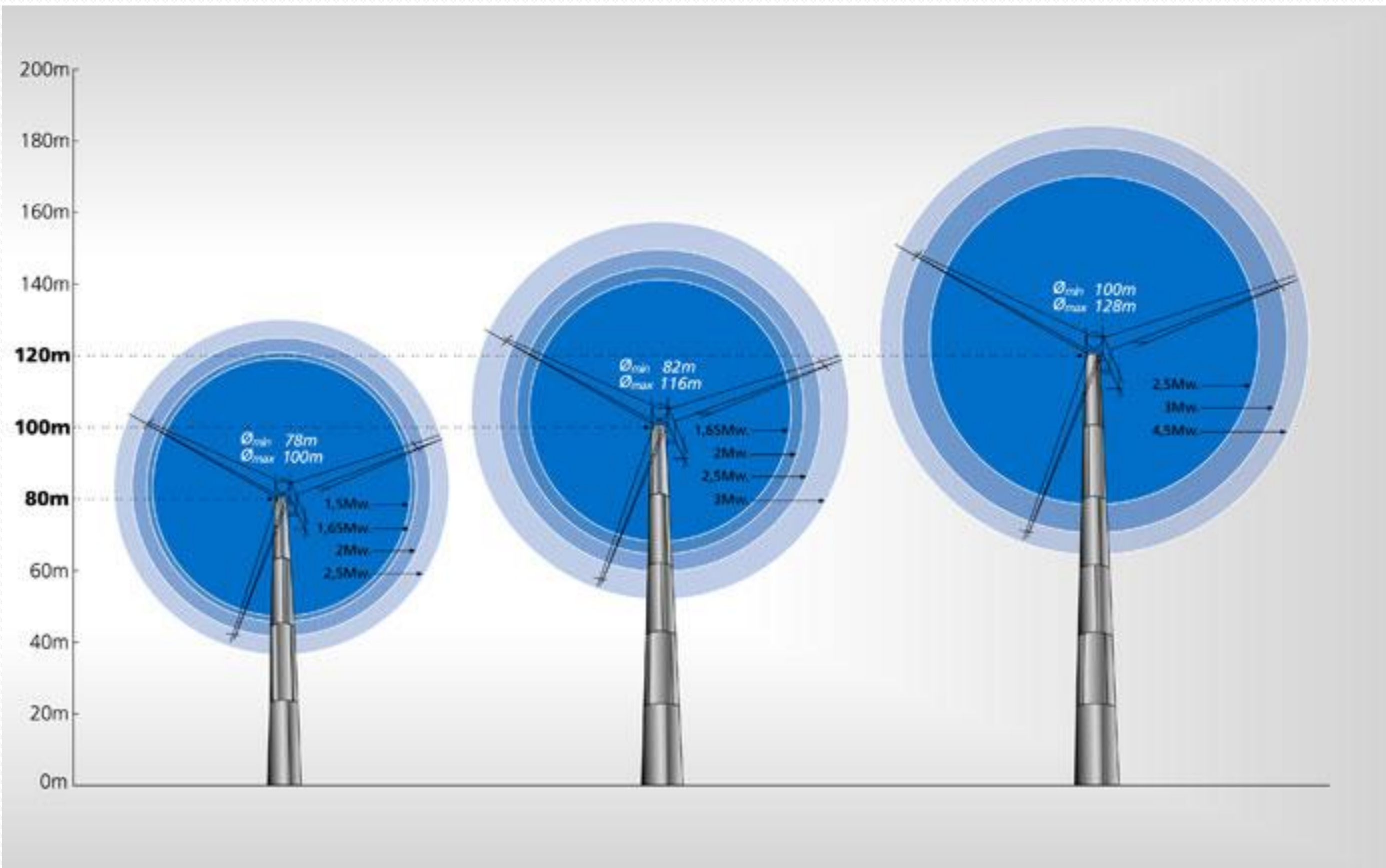
Concrete

- 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

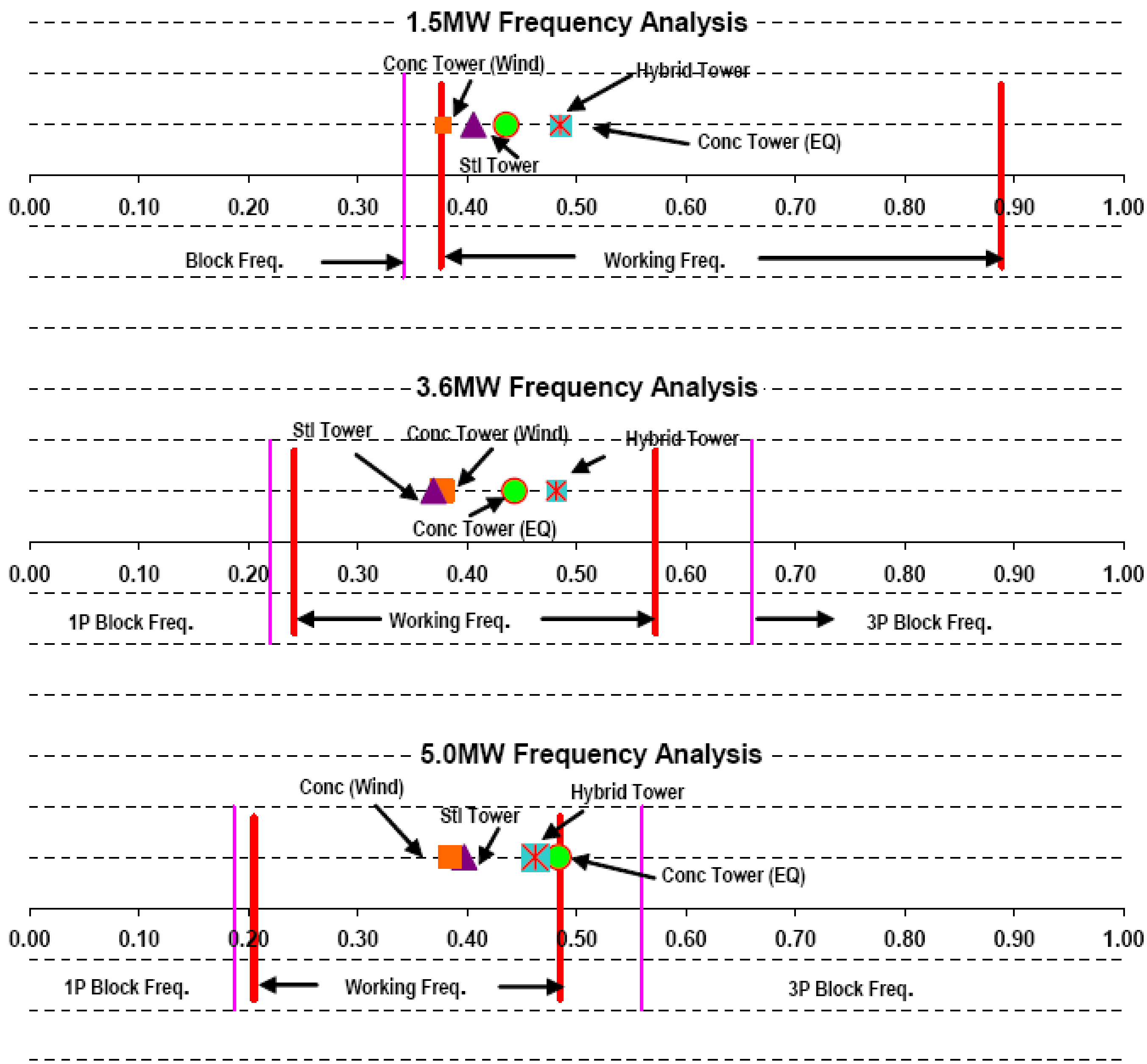


Figure 4.4. Operational frequency ranges for 1.5-, 3.6-, and 5.0-MW turbines

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

Questions?