

The 2nd TSME International Conference on Mechanical Engineering

19-21 October 2011

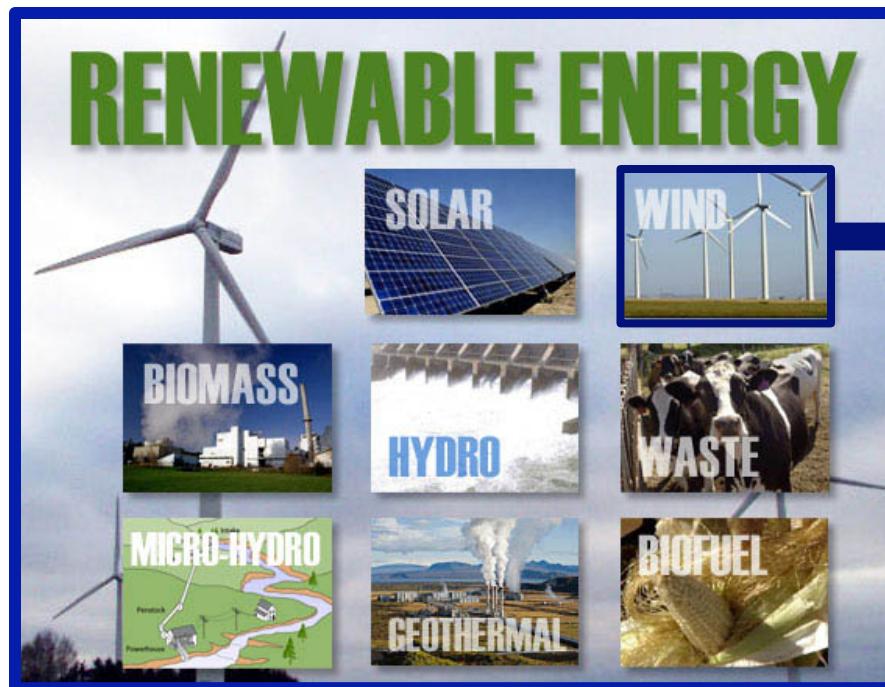
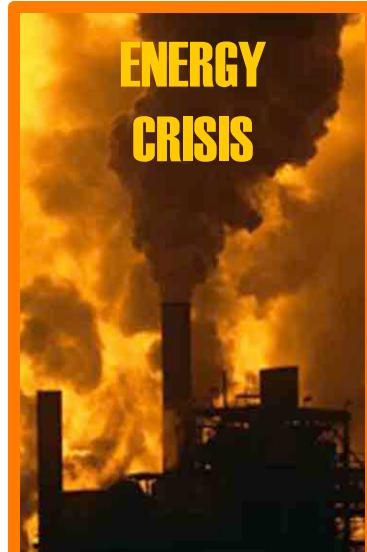


Preliminary Design of 1.5-MW Modular Wind Turbine Tower

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INTRODUCTION



INTRODUCTION (cont.)

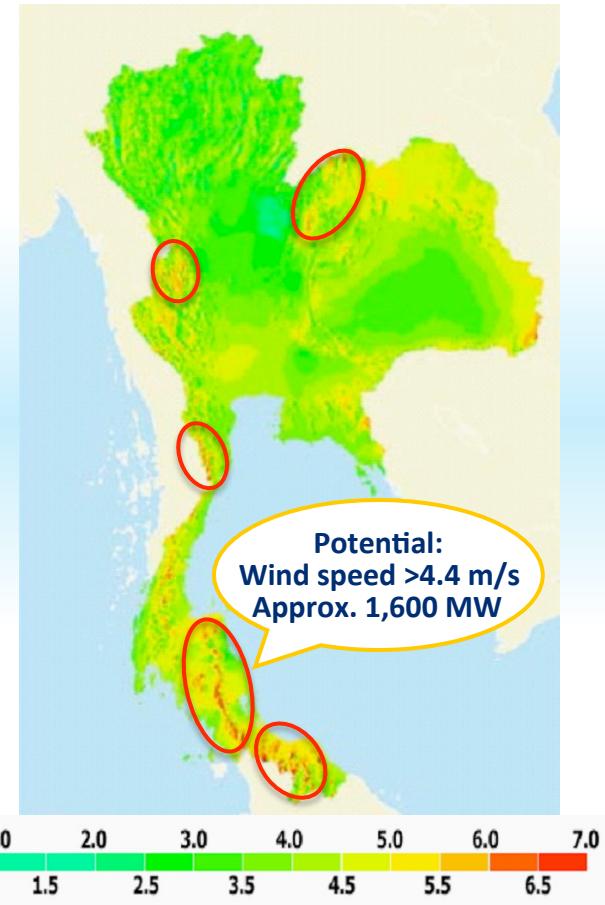
Wind Energy Potential of Thailand

Wind turbine classes according to IEC 61400-1

Wind turbine class	IEC standard (m/s)		
	I	II	III
V_{ref}	50	42.5	37.5
$V_{ave} = 0.2V_{ref}$	10	8.5	7.5 ← Average wind speed
$V_{design} = 1.4V_{ave}$	14	11.9	10.5 ← Rated wind speed
$V_{e50}(z) = 1.4V_{ref} \left(\frac{z}{z_{hub}} \right)^{0.11}$	70	59.5	52.5 ← Survival wind speed
$V_{e1}(z) = 0.8V_{e50}(z)$	56	47.6	42
$V_{50}(z) = V_{ref} \left(\frac{z}{z_{hub}} \right)^{0.11}$	50	42.5	37.5
$V_1(z) = 0.8V_{50}(z)$	40	34	30

Source: International Electrotechnical Commission (2005).
 IEC 61400-1:2005, Wind Turbines –
 Part 1: Design Requirements.

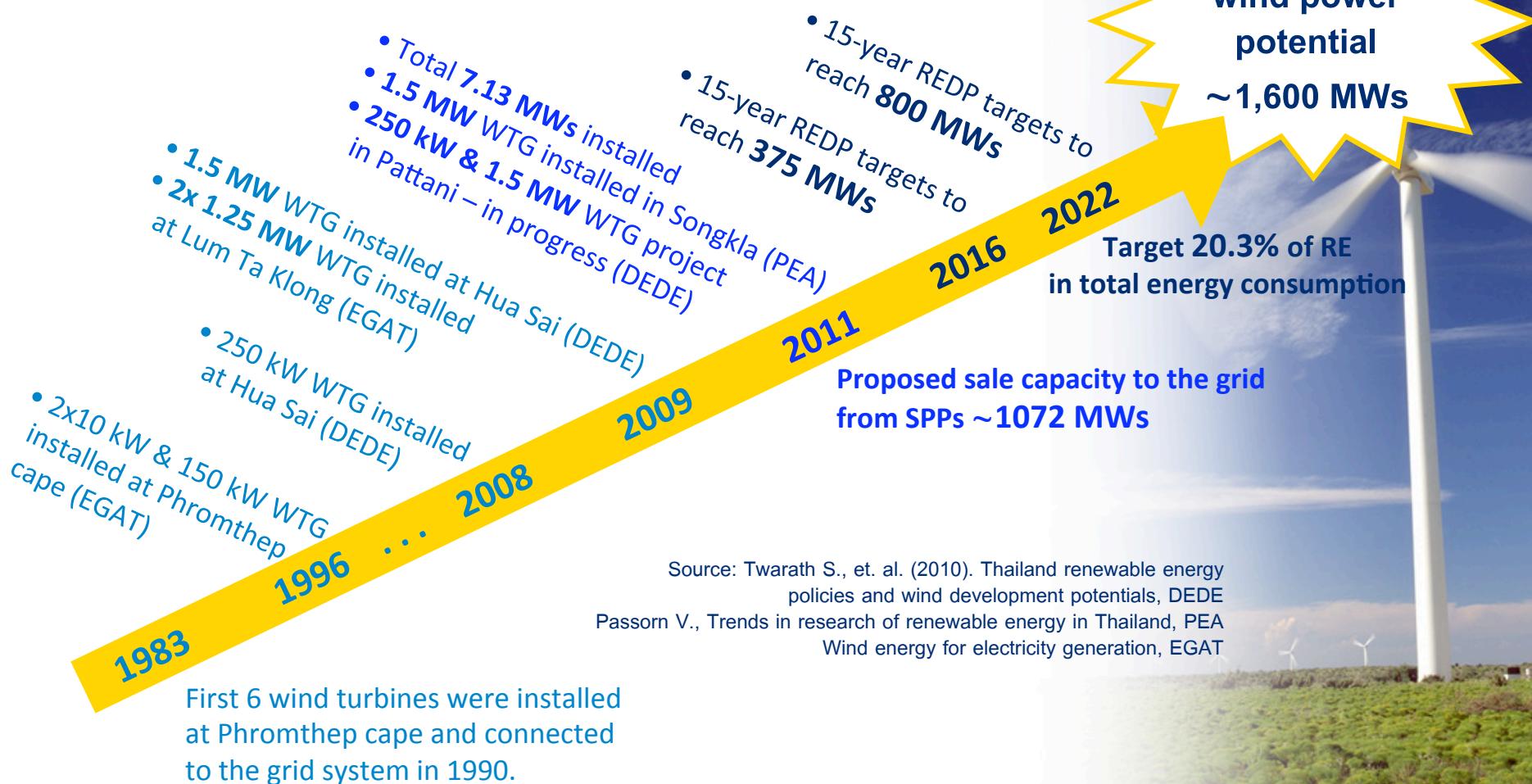
Wind resource map at 90 m above the ground



Source: Twarath S., et. al. (2010). Thailand renewable energy policies and wind development potentials, DEDE

INTRODUCTION (cont.)

Wind Energy Development in Thailand



First 6 wind turbines were installed at Phromthep cape and connected to the grid system in 1990.

INTRODUCTION (cont.)

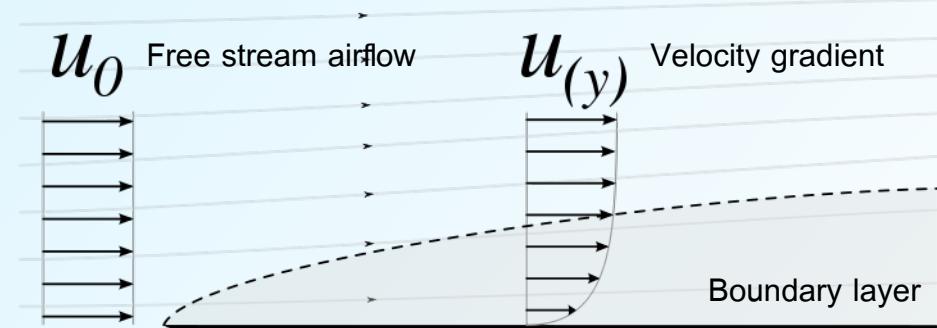


Wind Power

$$P = \frac{1}{2} C_P \rho A V^3$$

- P wind power
 C_P power coefficient
 ρ air density
 A rotor swept area
 V wind velocity

Wind Velocity Variation



Source: REpower 5M specification

INTRODUCTION (cont.)

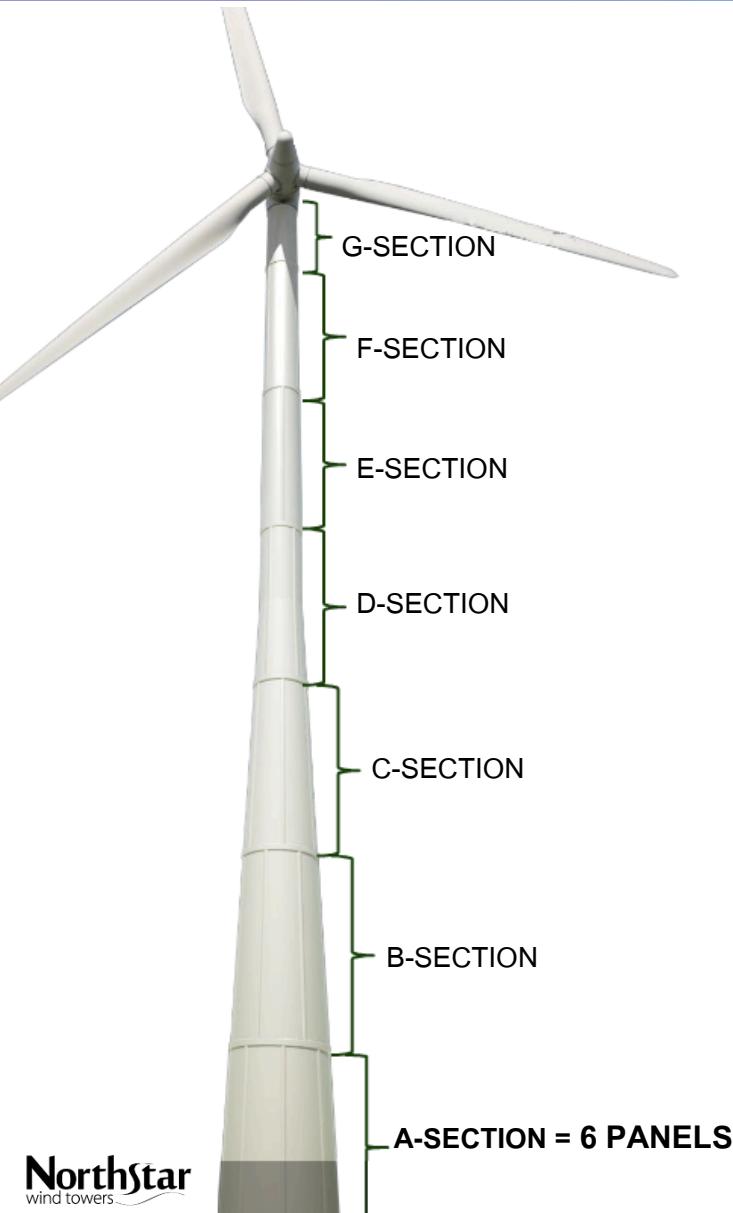
Transportation Restriction of Conventional Tubular Tower



**Tower base diameter limit ~ 4.3 m.
Special transportation is required**

INTRODUCTION (cont.)

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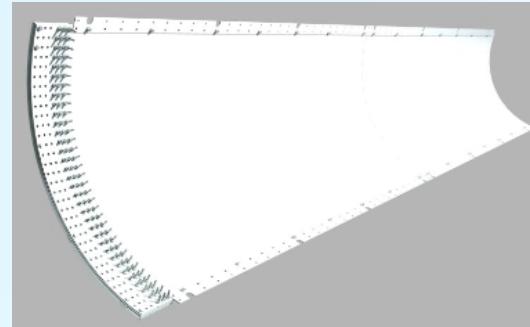


Northstar
wind towers

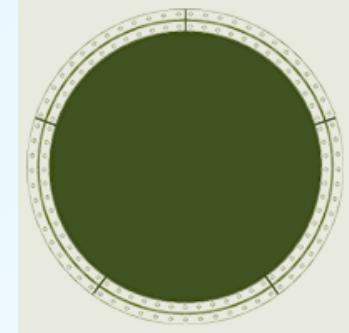
Source: Northstar Wind Towers specification

Modular Wind Turbine Tower

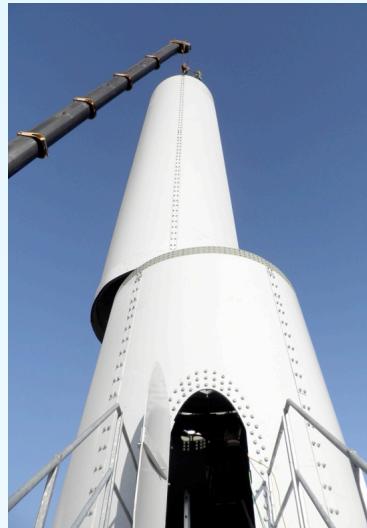
Panel



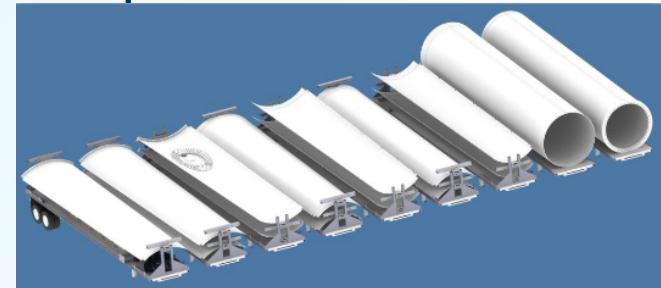
Cross section



Erection



Transportation



OBJECTIVES

- 1.5MW modular wind turbine tower for Thailand
- Overcoming the transportation limit
- Local manufacturability



SCOPES

- IEC Class III wind turbine
- Capacity of 1.5 MW
- Standards: IEC 61400-1, Eurocode 1, DNV-RP-C202
- Tapered tubular shape consisting of curved panels



SCOPES (cont.)

- ABAQUS Finite element analysis (FEA)
- S355J2, SM490YA with yield strength of 355 MPa
- Maximum panel thickness 46 mm.
- Maximum panel width 2.55 m.



METHODOLOGY

Basic Assumptions

- Fixed support
- Tower material: linearly elastic, isotropic, homogeneous
- Distributed drag force
- Verification: Euler-Bernoulli beam theory, Baumeister's equation
- No plastic deformation
- Secondary effects are neglected



METHODOLOGY (cont.)

Parameter Study

- **Finding:** modular tower design with minimum tower mass
- **Optimisation:**
 - Tower base diameter
 - Wall thicknesses
- **Design criteria:**
 - Von Mises stress, maximum deflection
 - Buckling and local buckling
 - 'Soft tower'
- ❖ The effects of tower connections are beyond the scope of this study



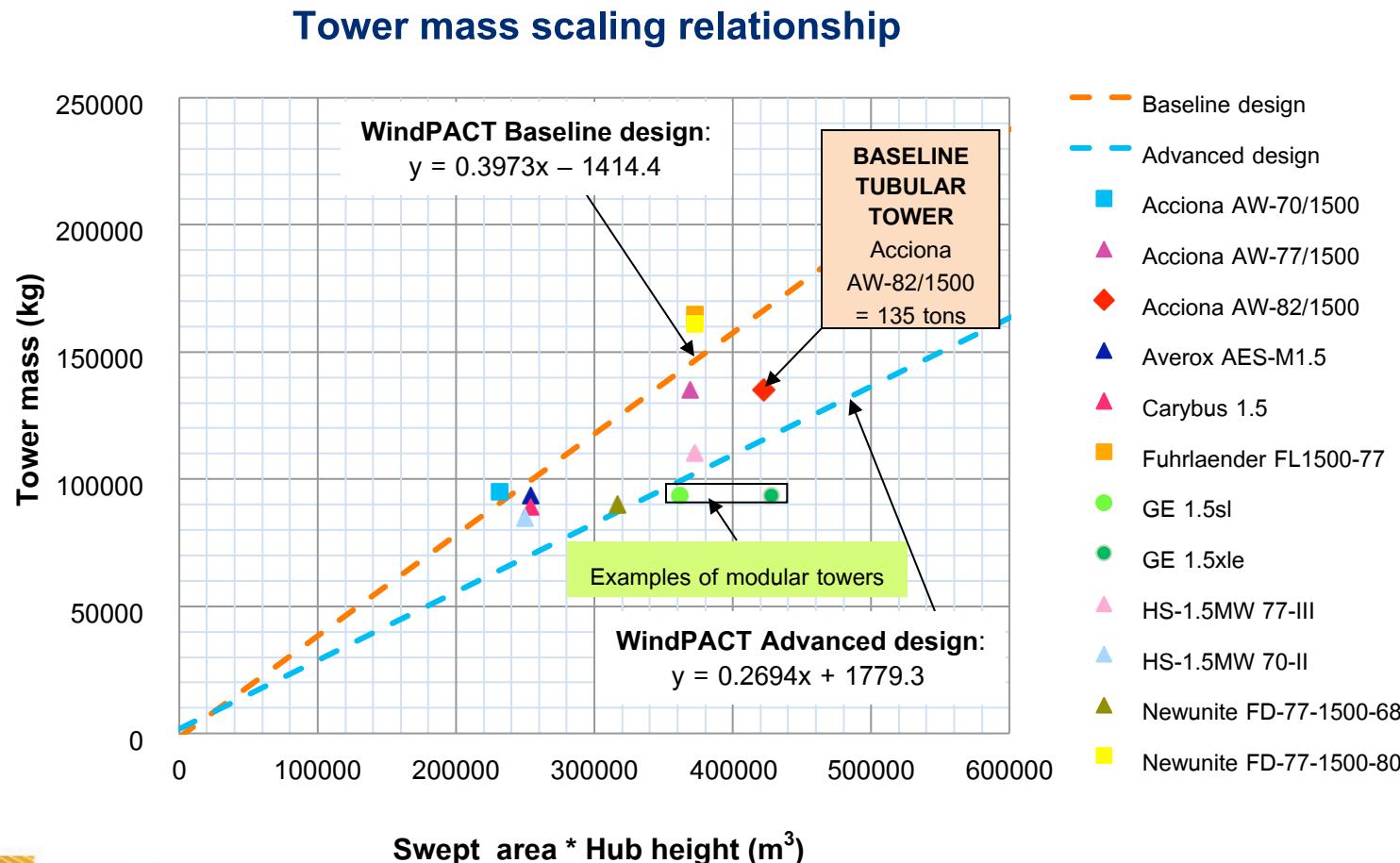
METHODOLOGY (cont.)

1.5 MW Commercial Wind Turbines

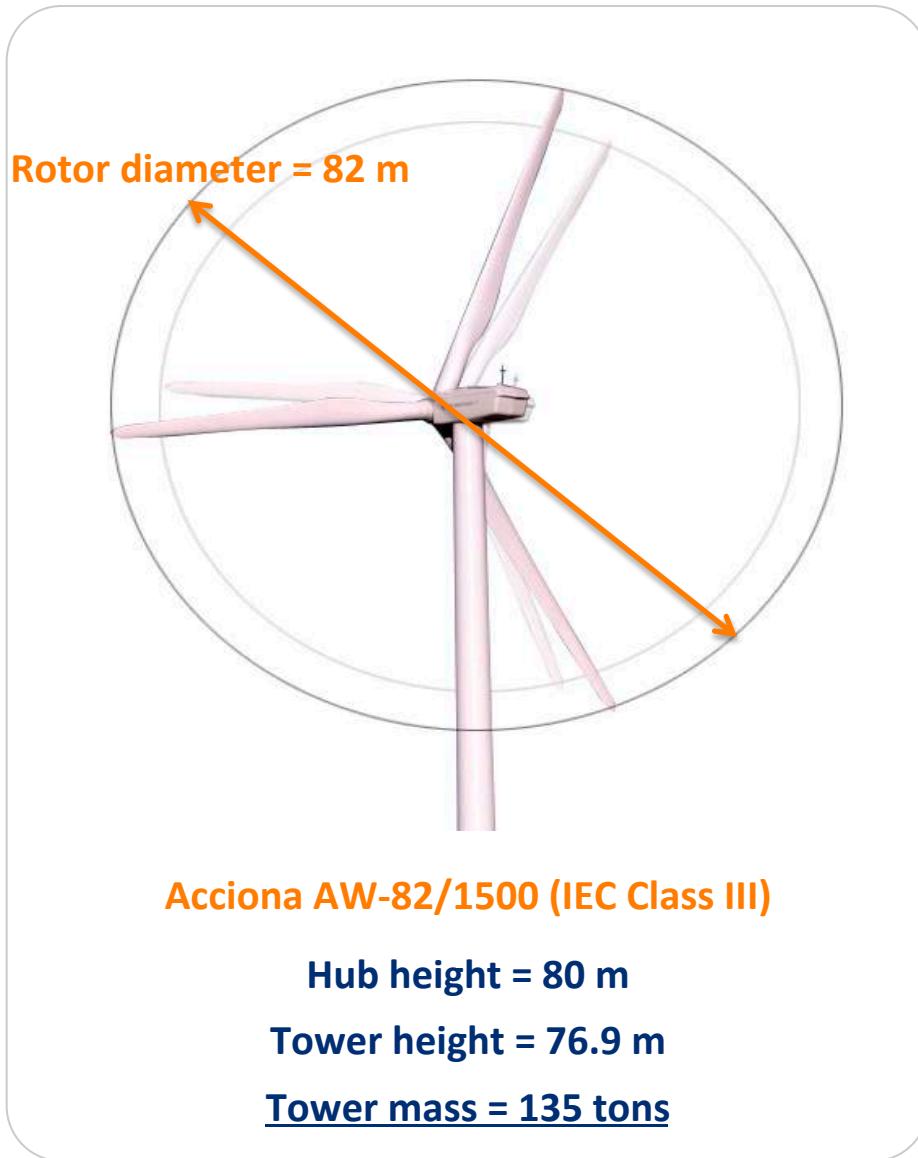
#	Wind turbine	Rotor diameter (m)	Class	Swept area (m ²)	Cut-in / Cut-out wind speed (m/s)	Hub height (m)	Tower mass (ton)
1.	Acciona AW-70/1500	70	IEC IA	3,848	4.0 / 25	60	95
2.	Carybus 1.5	70.5	-	3,904	3.0 / 25	65.1	89
3.	Averox AES-M1.5	70.5	IEC IIA	3,904	3.5 / 25	65.1	93.6
4.	HS-1.5MW70-II	70.5	IEC IIA	3,904	4.0 / 25	65	85
5.	Acciona AW-77/1500	77	IEC IA	4,657	3.5 / 25	60 / 80	135 (80m)
6.	GE 1.5sle	77	IEC IIA	4,657	3.5 / 25	61.4 / 64.7 / 80 / 85 / 100	93.5 (Modular 80m) Modular tower
7.	NEWUNITE FD-77-1500-III	77	IEC III	4,657	3.0 / 21	68 / 80	90 / 161
8.	HS-1.5MW77-III	77	IEC III	4,657	3.0 / 21	80	110
9.	Fuhrlaender FL 1500-77	77	IEC III	4,657	3.0 / 20	65 / 80 / 100	164.6 (80m)
10.	Acciona AW-82/1500	82	IEC IIIB	5,281	3.0 / 20	80	135 Baseline
11.	Nordex S82/1500	82	IEC III	5,281	3.0 / 20	70 / 80	151 (Hybrid 80m)
12.	GE 1.5xle	82.5	IEC IIIB	5,346	3.5 / 20	58.7 / 80 / 100	93.5 (Modular 80m) Modular tower
13.	Sinovel SL1500/82	82.9	IEC III	5,398	3.0 / 20	65 / 70 / 80	-

METHODOLOGY (cont.)

Set a Baseline Tower for Comparison



METHODOLOGY (cont.)



Technical Data of Baseline

Operating data

• Rated capacity:	1.5 MW
• Wind class:	IEC IIIB
• Cut-in wind speed:	3 m/s
• Cut-out wind speed:	20 m/s
• Rated wind speed:	10.5 m/s
• Survival wind speed:	52.5 m/s

Rotor

• Number of rotor blades:	3
• Rotor diameter:	82 m
• Swept area:	5,281 m²

Tower

• Hub height:	80 m
• Tower height:	76.9 m
• Base diameter:	4.3 m
• Top diameter:	2.6 m
• Material:	S335J2

Mass

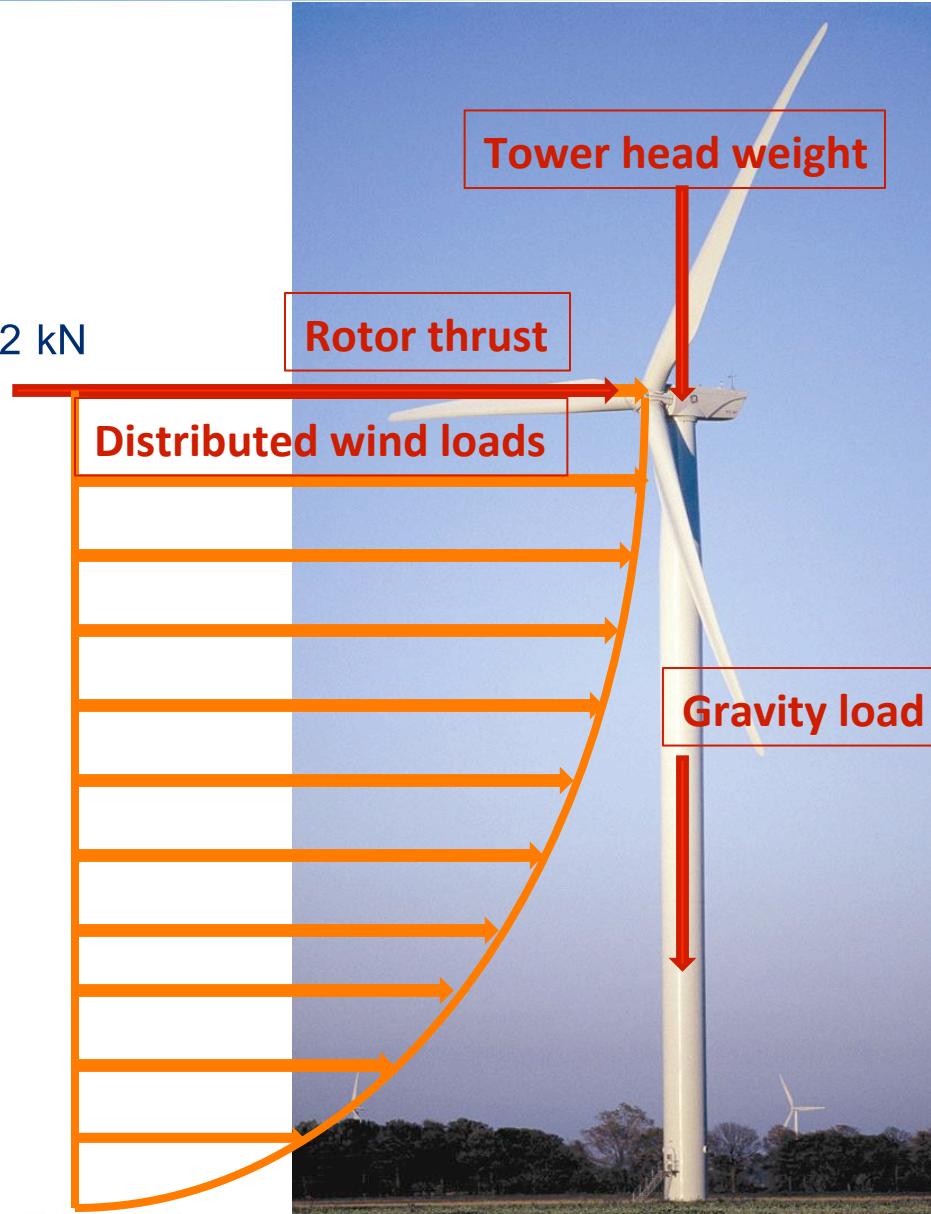
• Rotor:	32.34 ton
• Nacelle:	52.5 ton
• Tower head:	84.84 ton
• Tower:	135 ton

Source: Acciona AW-82/1500 Specification

METHODOLOGY (cont.)

Load Calculations

- **Self weight of tower components:**
 - Top head weight (rotor & nacelle) = 832 kN
 - Tower weight, $g = 9.81 \text{ m/s}^2$
- **Aerodynamic loads at cut-out wind speed of 20 m/s:**
 - Rotor thrust = 369 kN
 - Wind loads acting on tower (IEC 61400-1 & Eurocode 1)



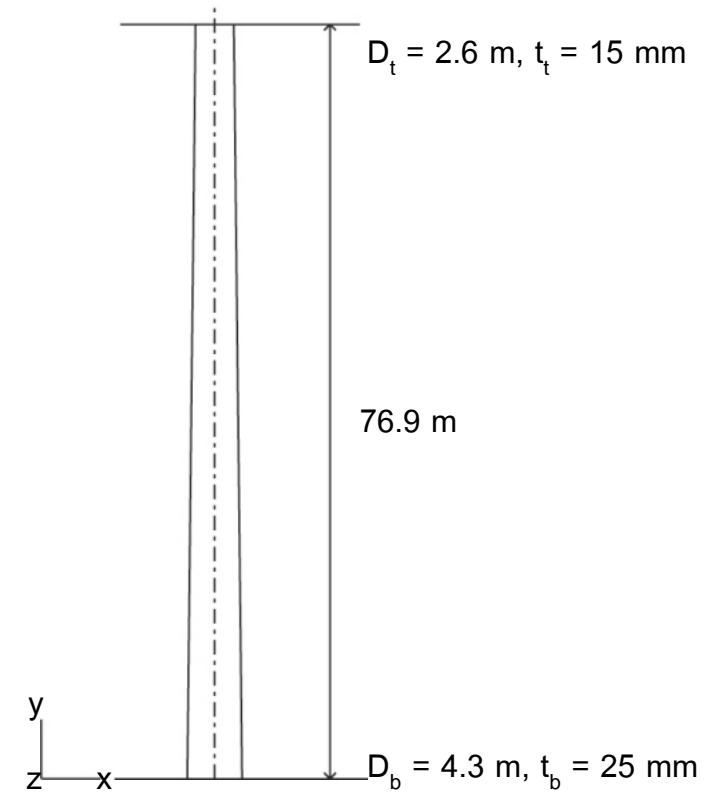
FINITE ELEMENT ANALYSIS

Finite Element Model

Baseline tower

Parameter	Dimension
Tower height, z (m)	76.9
Hub height, z_{hub} (m)	80
External base diameter, D_b (m)	4.3
External top diameter, D_t (m)	2.6
Taper ratio	0.0221
Tower mass, m (kg)	135,000
Wall thickness range, t (m)	0.015 – 0.025

Dimensions of FE baseline model



Material properties

Material	Density (kg/m ³)	Modulus of elasticity (GPa)	Poisson's ratio
S355J2	7,850	210	0.3

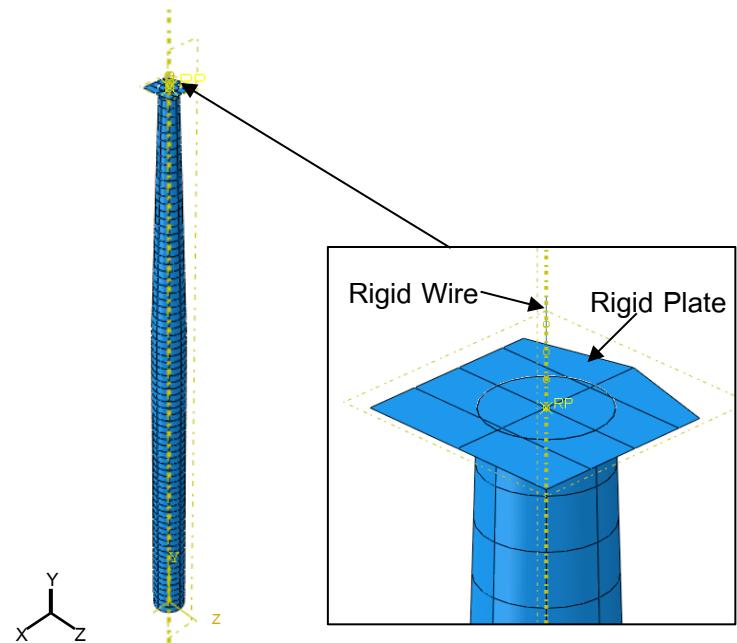
FINITE ELEMENT ANALYSIS (cont.)

Finite Element Model

- **Model parts**
 - Deformable shell-element tower
 - Rigid plate
 - Rigid wire

- **Boundary conditions**
- **Elements**

FE model parts

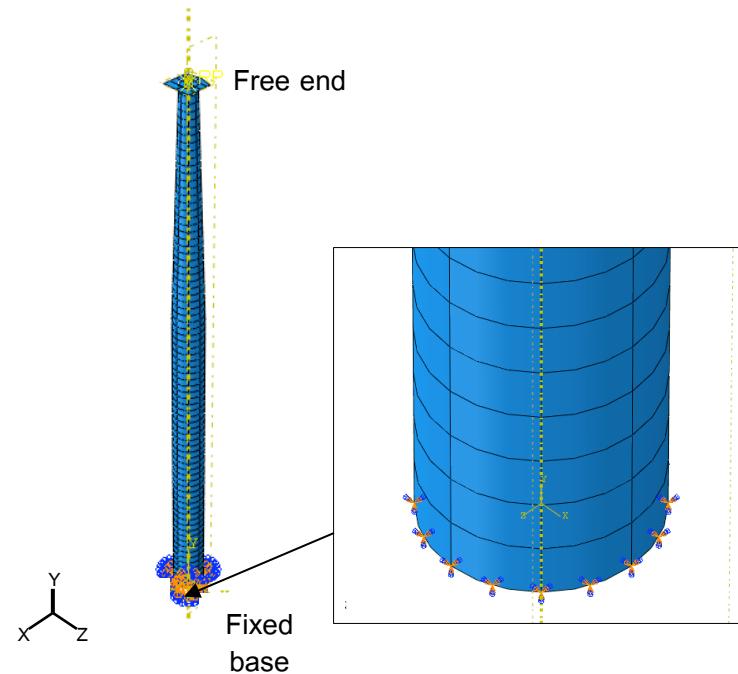


FINITE ELEMENT ANALYSIS (cont.)

Finite Element Model

- **Model parts**
 - Deformable shell element tower
 - Rigid plate
 - Rigid wire
- **Boundary conditions**
 - Fixed support
- **Elements**

Boundary conditions

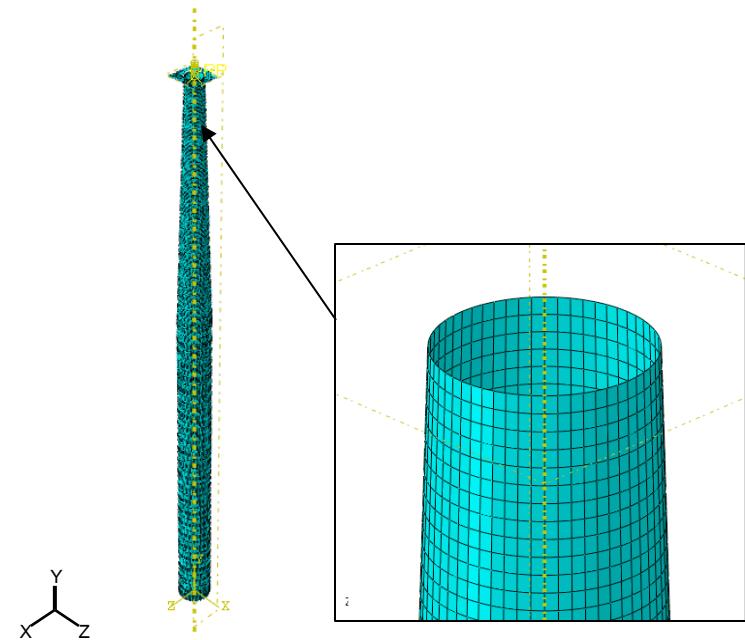


FINITE ELEMENT ANALYSIS (cont.)

Finite Element Model

- **Model parts**
 - Deformable shell element tower
 - Rigid plate
 - Rigid wire
- **Boundary conditions**
 - Fixed support
- **Elements**
 - Tower: 4-node shell elements

Elements



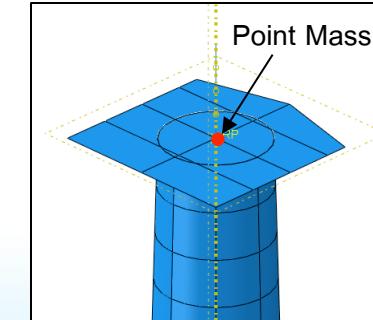
FINITE ELEMENT ANALYSIS (cont.)

Tower Response Analysis

- **Natural frequency analysis**
 - Concentrated mass of nacelle and rotor mass at the top
 - *Soft tower*

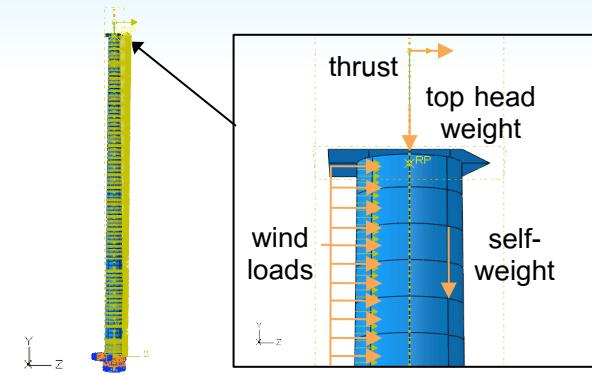
- **Stability analysis**
 - Global buckling
 - Brazier's theory: critical local buckling stress

- **Static stress analysis**
 - Von Mises stress
 - Maximum horizontal deflection



$$\sigma_{cr} = 0.33 E \frac{t}{R}$$

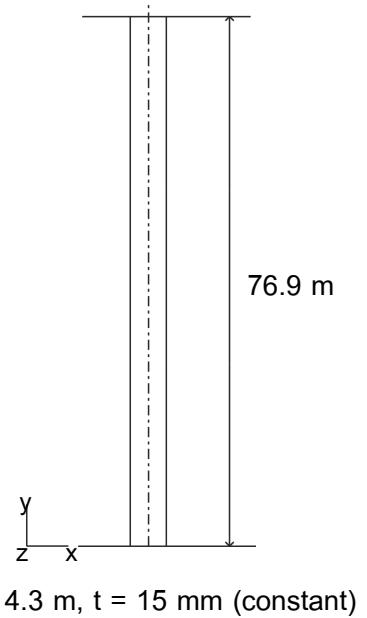
E = modulus of elasticity
t = wall thickness
R = radius



FINITE ELEMENT ANALYSIS (cont.)

Model Validation

Dimensions of validation model



- Natural frequency analysis

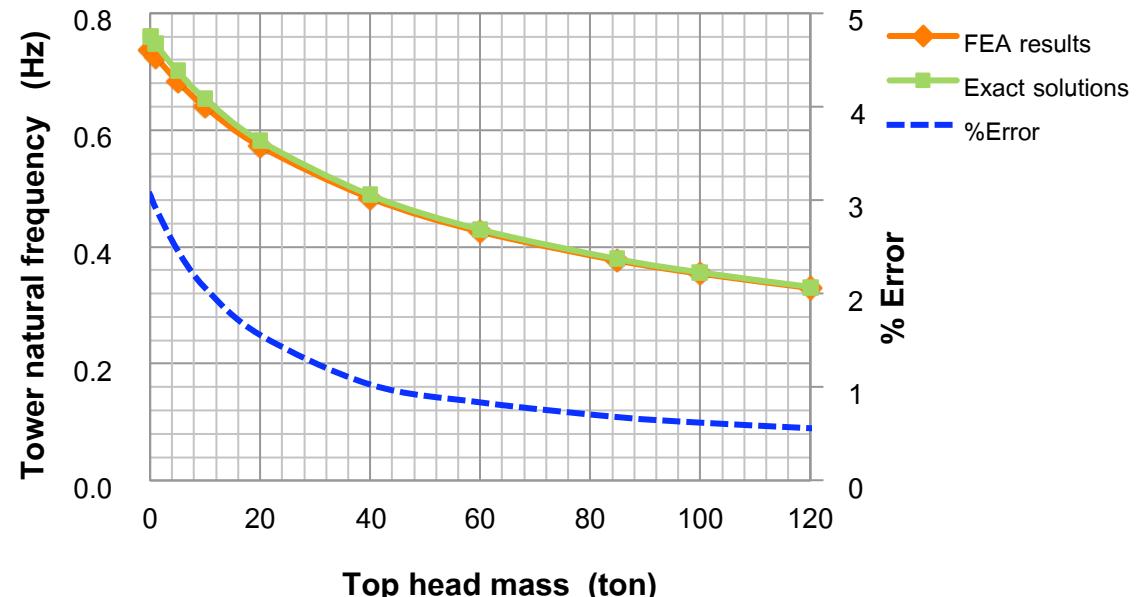
- Baumeister's equation:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{3EI}{(0.23m_{tower} + m_{rotor})L^3}}$$

- Error < 3%

f_n = tower natural frequency
 E = modulus of elasticity
 I = second moment of inertia
 m = mass
 L = tower height

Validation of tower frequency analysis



FINITE ELEMENT ANALYSIS (cont.)

Model Validation

- **Stability analysis**
 - Euler's critical buckling load:
- **Static stress analysis**
 - Compressive stresses

$$P_{cr} = \frac{\pi^2 EI}{L_e^2}$$

P_{cr} = critical buckling load
 L_e = effective length
 E = modulus of elasticity
 I = second moment of inertia

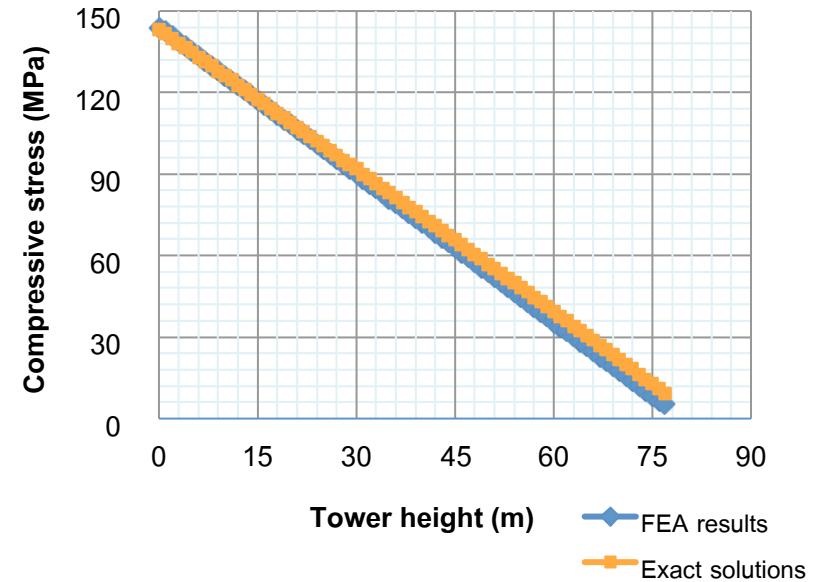
Validation of buckling analysis

$$P_{cr, \text{exact solution}} = 40,608 \text{ kN}$$

$$P_{cr, \text{FEA result}} = 40,507 \text{ kN}$$

$$\text{Error} = 0.25\%$$

Compressive stresses VS Tower height



RESULTS & DISCUSSION

Parameter Study

Parameter	Baseline Tower $D_b = 4.30 \text{ m}$	Modular Tower 1 $D_b = 5.00 \text{ m (6 panels)}$	Modular Tower 2 $D_b = 5.59 \text{ m (7 panels)}$
External base diameter (m)	4.30	5.00 (+16.28%)*	5.59 (+30%)
Taper ratio	0.022		
Wall thickness range (mm)	15-25		
Radius / tower thickness ratio	85.5		Find out = ?
Tower mass (t)	135.02		
Safety factor against bending	3.67	3.67	3.67
Safety factor against local buckling	7.98		
Maximum deflection (m)	0.648 L/119		
Tower frequency (Hz)	0.387		

*Note that the percentages shown in this table are obtained by comparing the values of modular towers to the baseline values.

RESULTS & DISCUSSION (cont.)

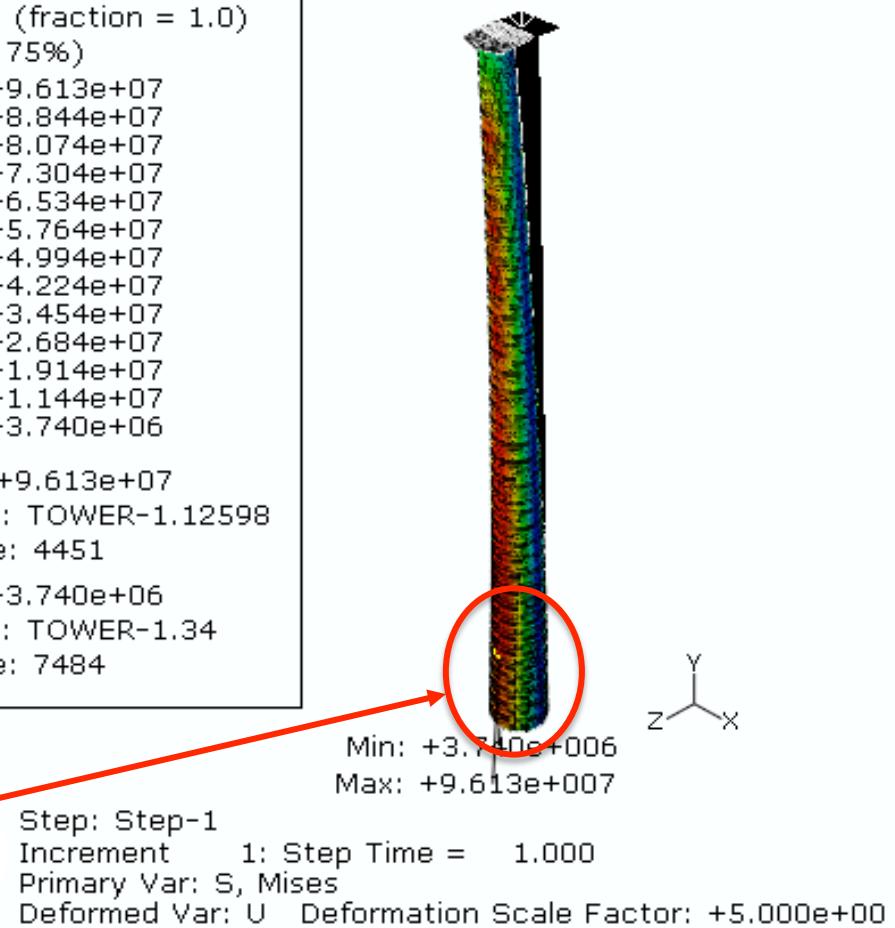
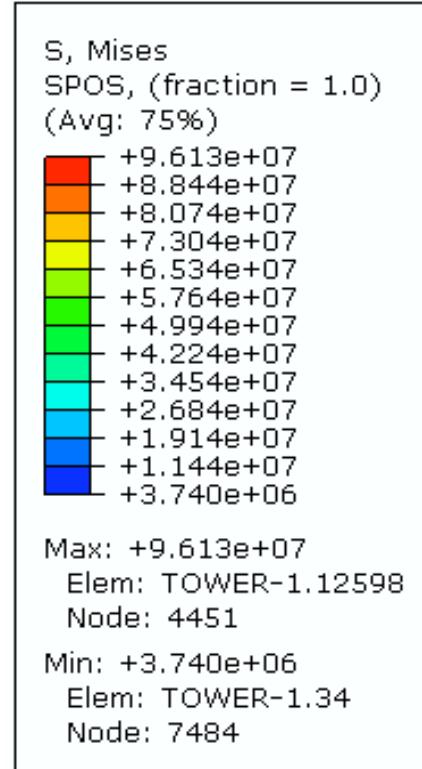
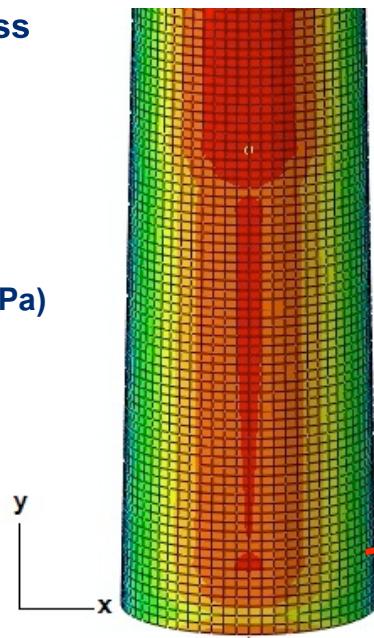
Static Stress Analysis Cut-out wind speed = 20 m/s (Modular tower 2, $D_b = 5.59$ m)

Loads	Direction	Value
Rotor thrust	z	369 kN
Top head weight	$-y$	832 kN
Wind loads acting on tower	z	8.39 kN
Gravity load	$-y$	9.81 m/s ²

Max. Von Mises stress
= 96.13 MPa

**Safety factor
against bending**
= 3.69
(yield strength = 355 MPa)

Max. deflection
= 0.56 m (L/137)

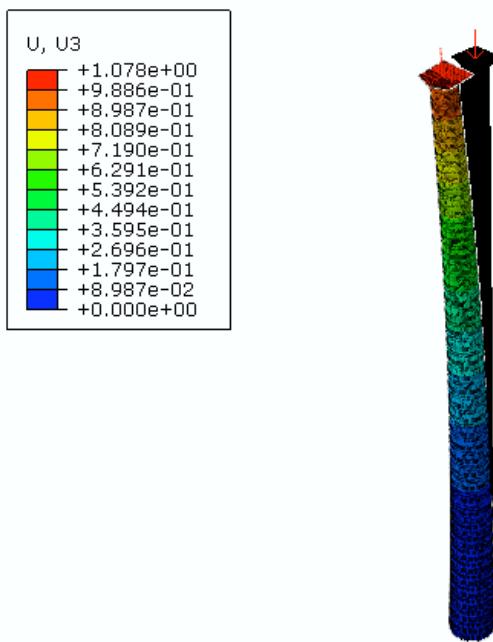


RESULTS & DISCUSSION (cont.)

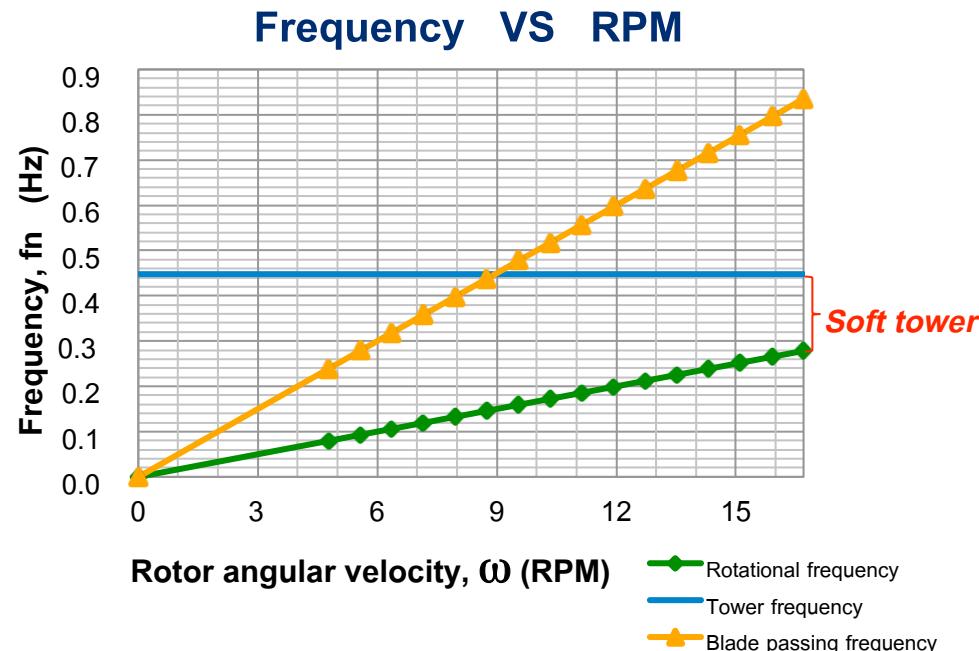
Natural Frequency Analysis (Modular tower 2, $D_b = 5.59$ m)

Top head mass (Point mass) = 84.84 tons

The first eigenmode of the modular tower



ODB: D559m26m_opt2_freq.odb Abaqus/Standard Version 6.8-1
 Step: Step-1 Mode 1: Value = 7.4532 Freq = 0.43450 (cycles/time)
 Primary Var: U, U3
 Deformed Var: U Deformation Scale Factor: +5.000e+00

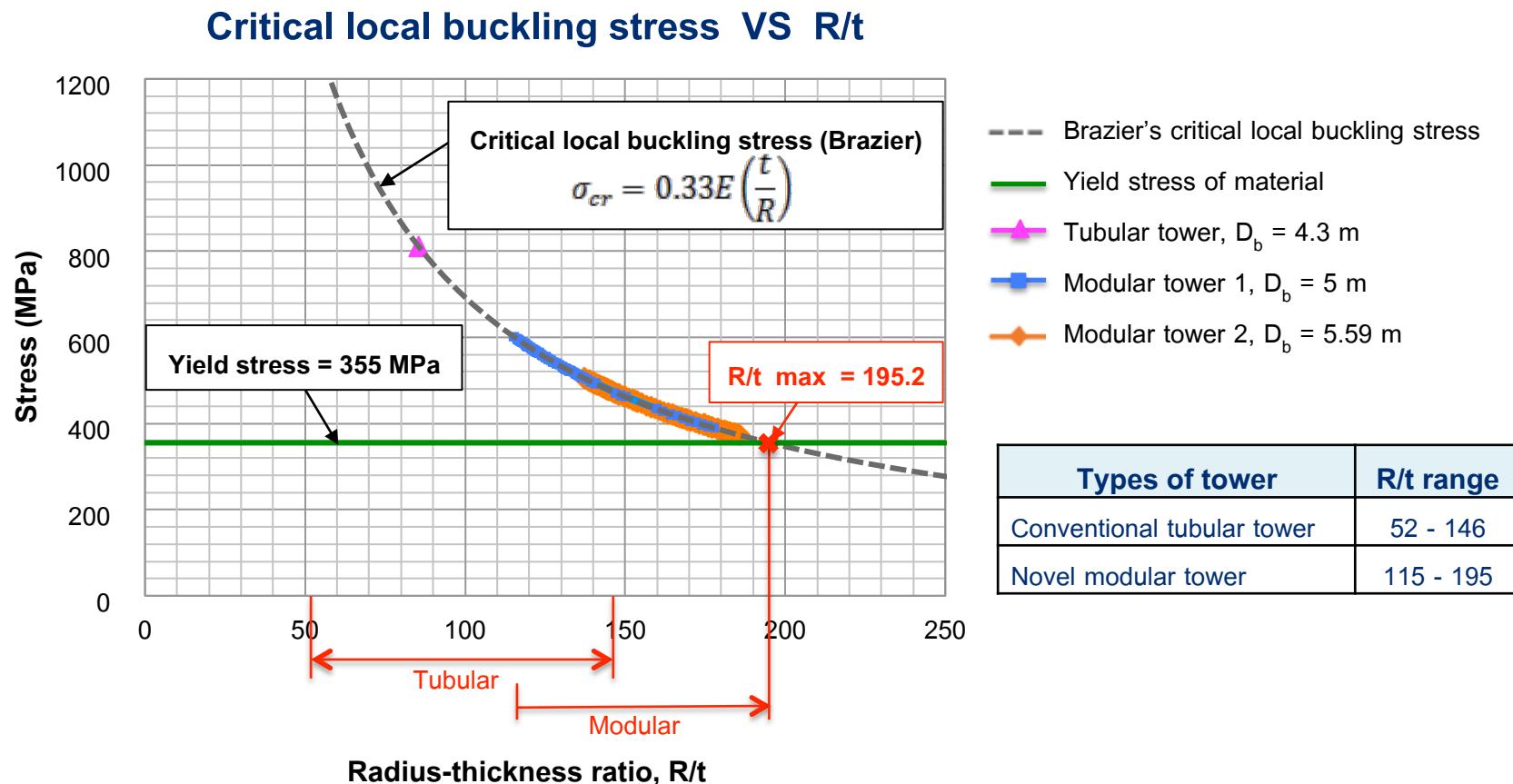


Frequency	(Hz)
Rotational frequency	0.079 – 0.278
Tower frequency (1 st mode)	0.434
Blade passing frequency	0.239 – 0.835

RESULTS & DISCUSSION (cont.)

Stability Analysis

- Local Buckling Analysis



RESULTS & DISCUSSION (cont.)

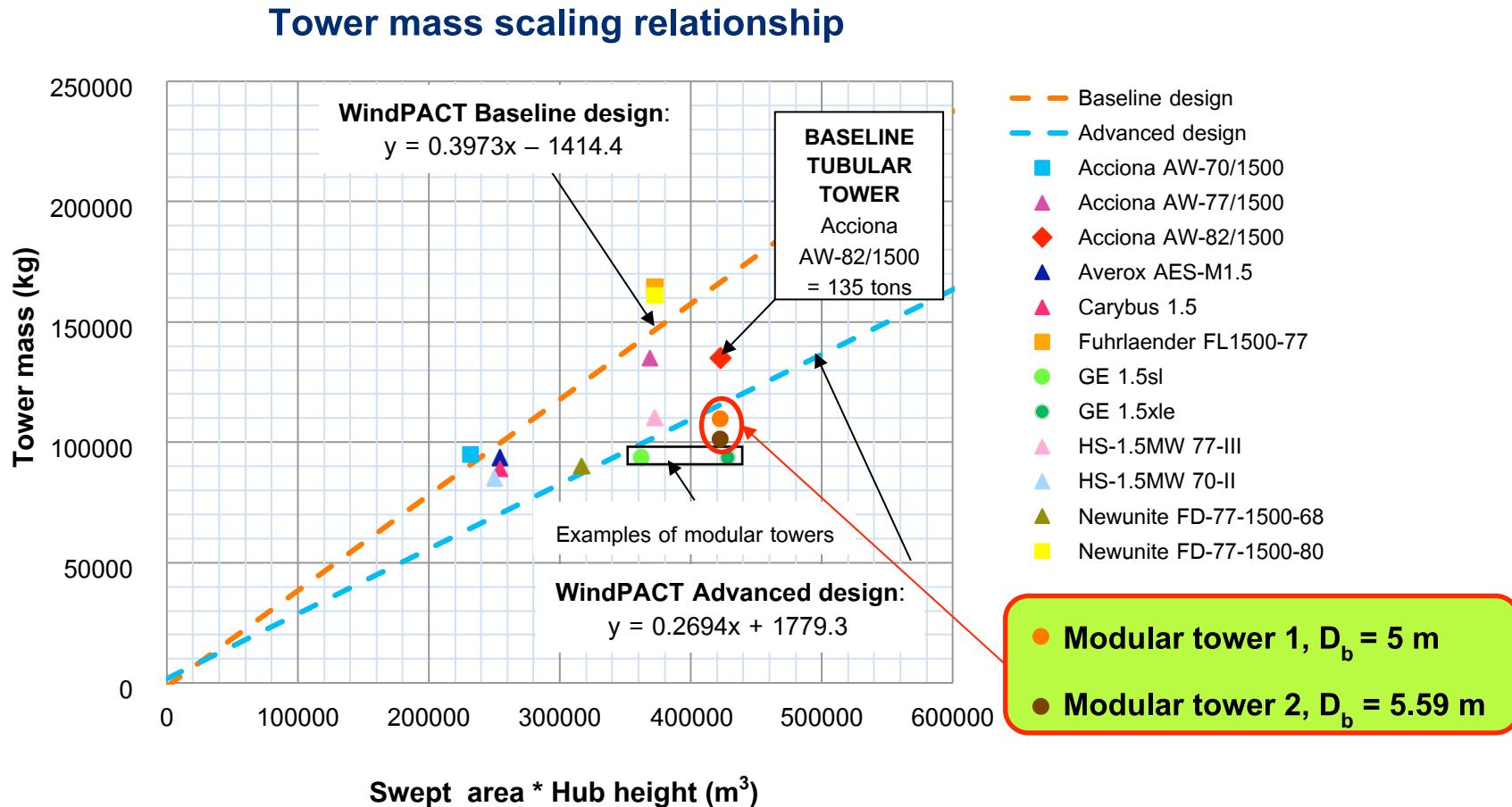
Comparison of the results for the baseline and modular towers

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External base diameter (m)	4.30	5.00 (+16.28%)*	5.59 (+30%)
Taper ratio	0.022	0.031	0.039
Wall thickness range (mm)	15-25	8-19	8-16
Radius / tower thickness ratio	85.5	115.3-177.9	137.2-185.76
Tower mass (t)	135.02	109.56 (-18.85%)	102.47 (-24.11%)
Safety factor against bending	3.67	3.67	3.69
Safety factor against local buckling	7.98	3.83	3.70
Maximum deflection (m)	0.648 L/119	0.616 (-4.91%) L/125	0.560 (-13.39%) L/137
Tower frequency (Hz)	0.387	0.413 (+6.72%)	0.434 (+12.17%)

*Note that the percentages shown in this table are obtained by comparing the values of modular towers to the baseline values.

RESULTS & DISCUSSION (cont.)

Comparison of tower mass for the baseline and modular towers



RESULTS & DISCUSSION (cont.)

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RESULTS & DISCUSSION (cont.)

Effects of a larger tower base diameter on tower structure

- Modular tower design:
Thinner wall thicknesses → Lower tower mass → Lower material cost
- Improves the structural stabilities:
 - Higher tower natural frequencies
 - Lower maximum tip deflection
- Dominant criterion:
Max. Von Mises stress → Local buckling



CONCLUSION

- ✓ Potential to be economically attractive
- ✓ The manufacturing of modular tower is locally feasible
- ✓ Material for modular tower is available in the country
- ✓ All modular tower parts can be transported using standard trailers
- ✓ Strength-to-weight ratio of modular tower is superior to conventional steel tubular tower



ACKNOWLEDGEMENT

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