Preliminary Design of 1.5-MW Modular Wind Turbine Tower

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INTRODUCTION

ENERGY CRISIS

WIND ENERGY
SOLUTION

RENEWABLE ENERGY

SOLAR
WIND
BIOMASS
HYDRO
WASTE
MICRO HYDRO
GEOTHERMAL
BIOFUEL
## Wind Energy Potential of Thailand

### Wind turbine classes according to IEC 61400-1

<table>
<thead>
<tr>
<th>Wind turbine class</th>
<th>IEC standard (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>$V_{ref}$</td>
<td>50</td>
</tr>
<tr>
<td>$V_{ave} = 0.2 V_{ref}$</td>
<td>10</td>
</tr>
<tr>
<td>$V_{design} = 1.4 V_{ave}$</td>
<td>14</td>
</tr>
<tr>
<td>$V_{50}(z) = 1.4 V_{ref} \left( \frac{z}{z_{hub}} \right)^{0.11}$</td>
<td>70</td>
</tr>
<tr>
<td>$V_{s1}(z) = 0.8 V_{s50}(z)$</td>
<td>56</td>
</tr>
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<td>50</td>
</tr>
<tr>
<td>$V_{1}(z) = 0.8 V_{s50}(z)$</td>
<td>40</td>
</tr>
</tbody>
</table>


Wind resource map at 90 m above the ground

Potential: Wind speed >4.4 m/s Approx. 1,600 MW

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

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

- 1.5 MW WTG installed in Songkla (PEA)
- 1.5 MW WTG installed at Hua Sai (DEDE)
- 2x1.25 MW WTG installed at Lum Ta Klong (EGAT)
- 2x10 kW & 150 kW WTG installed at Phromthep cape (EGAT)
- Total 7.13 MWs installed

- 250 kW WTG installed at Hua Sai (DEDE)
- 250 kW & 1.5 MW WTG project in Pattani – in progress (DEDE)

• 15-year REDP targets to reach 800 MWs
• 15-year REDP targets to reach 375 MWs

INTRODUCTION (cont.)

Proposed sale capacity to the grid from SPPs ~1072 MWs

Target 20.3% of RE in total energy consumption

Source: Twarath S., et. al. (2010). Thailand renewable energy policies and wind development potentials, DEDE
Passorn V., Trends in research of renewable energy in Thailand, PEA
Wind energy for electricity generation, EGAT

Thailand’s wind power potential ~1,600 MWs
Wind Power

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

- \( P \): wind power
- \( C_P \): power coefficient
- \( \rho \): air density
- \( A \): rotor swept area
- \( V \): wind velocity

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.)

Modular Wind Turbine Tower

Panel

Cross section

Transportation

Erection

A-SECTION = 6 PANELS

G-SECTION

F-SECTION

E-SECTION

D-SECTION

C-SECTION

B-SECTION

Source: Northstar Wind Towers specification
OBJECTIVES

- 1.5MW modular wind turbine tower for Thailand
- Overcoming the transportation limit
- Local manufacturability
• 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
• ABAQUS _Finite element analysis (FEA)_

• S355J2, SM490YA with yield strength of 355 MPa

• Maximum panel thickness 46 mm.

• Maximum panel width 2.55 m.
**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
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

<table>
<thead>
<tr>
<th>#</th>
<th>Wind turbine</th>
<th>Rotor diameter (m)</th>
<th>Class</th>
<th>Swept area (m²)</th>
<th>Cut-in / Cut-out wind speed (m/s)</th>
<th>Hub height (m)</th>
<th>Tower mass (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Acciona AW-70/1500</td>
<td>70</td>
<td>IEC IA</td>
<td>3,848</td>
<td>4.0 / 25</td>
<td>60</td>
<td>95</td>
</tr>
<tr>
<td>2.</td>
<td>Carybus 1.5</td>
<td>70.5</td>
<td>-</td>
<td>3,904</td>
<td>3.0 / 25</td>
<td>65.1</td>
<td>89</td>
</tr>
<tr>
<td>3.</td>
<td>Averox AES-M1.5</td>
<td>70.5</td>
<td>IEC IIA</td>
<td>3,904</td>
<td>3.5 / 25</td>
<td>65.1</td>
<td>93.6</td>
</tr>
<tr>
<td>4.</td>
<td>HS-1.5MW70-II</td>
<td>70.5</td>
<td>IEC IIA</td>
<td>3,904</td>
<td>4.0 / 25</td>
<td>65</td>
<td>85</td>
</tr>
<tr>
<td>5.</td>
<td>Acciona AW-77/1500</td>
<td>77</td>
<td>IEC IA</td>
<td>4,657</td>
<td>3.5 / 25</td>
<td>60 / 80</td>
<td>135 (80m)</td>
</tr>
<tr>
<td>6.</td>
<td>GE 1.5sle</td>
<td>77</td>
<td>IEC IIA</td>
<td>4,657</td>
<td>3.5 / 25</td>
<td>61.4 / 64.7 / 80 / 85 / 100</td>
<td>93.5 (Modular 80m)</td>
</tr>
<tr>
<td>7.</td>
<td>NEWUNITE FD-77-1500-III</td>
<td>77</td>
<td>IEC III</td>
<td>4,657</td>
<td>3.0 / 21</td>
<td>68 / 80</td>
<td>90 / 161</td>
</tr>
<tr>
<td>8.</td>
<td>HS-1.5MW77-III</td>
<td>77</td>
<td>IEC III</td>
<td>4,657</td>
<td>3.0 / 21</td>
<td>80</td>
<td>110</td>
</tr>
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<td>9.</td>
<td>Fuhrlaender FL 1500-77</td>
<td>77</td>
<td>IEC III</td>
<td>4,657</td>
<td>3.0 / 20</td>
<td>65 / 80 / 100</td>
<td>164.6 (80m)</td>
</tr>
<tr>
<td>10.</td>
<td>Acciona AW-82/1500</td>
<td>82</td>
<td>IEC IIIB</td>
<td>5,281</td>
<td>3.0 / 20</td>
<td>80</td>
<td>135</td>
</tr>
<tr>
<td>11.</td>
<td>Nordex S82/1500</td>
<td>82</td>
<td>IEC III</td>
<td>5,281</td>
<td>3.0 / 20</td>
<td>70 / 80</td>
<td>151 (Hybrid 80m)</td>
</tr>
<tr>
<td>12.</td>
<td>GE 1.5xle</td>
<td>82.5</td>
<td>IEC IIIB</td>
<td>5,346</td>
<td>3.5 / 20</td>
<td>58.7 / 80 / 100</td>
<td>93.5 (Modular 80m)</td>
</tr>
<tr>
<td>13.</td>
<td>Sinovel SL1500/82</td>
<td>82.9</td>
<td>IEC III</td>
<td>5,398</td>
<td>3.0 / 20</td>
<td>65 / 70 / 80</td>
<td>-</td>
</tr>
</tbody>
</table>
Set a Baseline Tower for Comparison

Tower mass scaling relationship

WindPACT Baseline design:
\[ y = 0.3973x - 1414.4 \]

WindPACT Advanced design:
\[ y = 0.2694x + 1779.3 \]

Examples of modular towers

- Acciona AW-70/1500
- Acciona AW-77/1500
- Acciona AW-82/1500
- Averox AES-M1.5
- Carybus 1.5
- Fuhrlaender FL1500-77
- GE 1.5sl
- GE 1.5xe
- HS-1.5MW 77-III
- HS-1.5MW 70-II
- Newunite FD-77-1500-68
- Newunite FD-77-1500-80

WindPACT design equations

Source: Fingersh, L. et. al. (2006). Wind Turbine Design Cost and Scaling Model, NREL
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 Model

### Baseline tower

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower height, $z$</td>
<td>76.9 m</td>
</tr>
<tr>
<td>Hub height, $z_{hub}$</td>
<td>80 m</td>
</tr>
<tr>
<td>External base diameter, $D_b$</td>
<td>4.3 m</td>
</tr>
<tr>
<td>External top diameter, $D_t$</td>
<td>2.6 m</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.0221</td>
</tr>
<tr>
<td>Tower mass, $m$</td>
<td>135,000 kg</td>
</tr>
<tr>
<td>Wall thickness range, $t$</td>
<td>0.015 – 0.025 m</td>
</tr>
</tbody>
</table>

### Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2</td>
<td>7,850</td>
<td>210</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Dimensions of FE baseline model

- $D_t = 2.6$ m, $t_t = 15$ mm
- $D_b = 4.3$ m, $t_b = 25$ mm
Finite Element Model

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

- Boundary conditions

- Elements
Finite Element Model

• Model parts
  – Deformable shell element tower
  – Rigid plate
  – Rigid wire

• Boundary conditions
  – Fixed support

• Elements
Finite Element Model

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

- **Boundary conditions**
  - Fixed support

- **Elements**
  - Tower: 4-node shell elements
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

\[
\sigma_{cr} = 0.33 \frac{E}{R} \frac{t}{R}
\]

- E = modulus of elasticity
- t = wall thickness
- R = radius
Model Validation

- **Natural frequency analysis**
  - Baumeister’s equation:
    \[ f_n = \frac{1}{2\pi} \sqrt{\frac{3EI}{(0.23m_{\text{tower}} + m_{\text{rotor}})L^3}} \]
    - \( f_n \) = tower natural frequency
    - \( E \) = modulus of elasticity
    - \( I \) = second moment of inertia
    - \( m \) = mass
    - \( L \) = tower height
  - Error < 3%

Validation of tower frequency analysis

![Graph showing tower natural frequency vs. top head mass]
Model Validation

- **Stability analysis**
  - Euler’s critical buckling load:
    \[ P_{cr} = \frac{\pi^2 EI}{L_e^2} \]
    - \( P_{cr} \) = critical buckling load
    - \( L_e \) = effective length
    - \( E \) = modulus of elasticity
    - \( I \) = second moment of inertia

  Validation of buckling analysis
  - \( P_{cr, \text{exact solution}} = 40,608 \) kN
  - \( P_{cr, \text{FEA result}} = 40,507 \) kN
  - Error = 0.25%

- **Static stress analysis**
  - Compressive stresses

**Compressive stresses VS Tower height**

![Graph showing compressive stresses vs tower height](graph.png)

- FEA results
- Exact solutions
## RESULTS & DISCUSSION

### Parameter Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Tower ( D_b = 4.30 \text{ m} )</th>
<th>Modular Tower 1 ( D_b = 5.00 \text{ m (6 panels)} )</th>
<th>Modular Tower 2 ( D_b = 5.59 \text{ m (7 panels)} )</th>
</tr>
</thead>
<tbody>
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<td>External base diameter (m)</td>
<td>4.30</td>
<td>5.00 (+16.28%)*</td>
<td>5.59 (+30%)</td>
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<td></td>
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<td>Wall thickness range (mm)</td>
<td>15-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius / tower thickness ratio</td>
<td>85.5</td>
<td></td>
<td></td>
</tr>
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<td>Tower mass (t)</td>
<td>135.02</td>
<td></td>
<td></td>
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<td>Safety factor against bending</td>
<td>3.67</td>
<td>3.67</td>
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<td>7.98</td>
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<td></td>
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<tr>
<td>Maximum deflection (m)</td>
<td>0.648</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower frequency (Hz)</td>
<td>0.387</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

**Loads**

<table>
<thead>
<tr>
<th>Loads</th>
<th>Direction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor thrust</td>
<td>z</td>
<td>369 kN</td>
</tr>
<tr>
<td>Top head weight</td>
<td>-y</td>
<td>832 kN</td>
</tr>
<tr>
<td>Wind loads acting on tower</td>
<td>z</td>
<td>8.39 kN</td>
</tr>
<tr>
<td>Gravity load</td>
<td>-y</td>
<td>9.81 m/s²</td>
</tr>
</tbody>
</table>

**max. Von Mises stress**

= 96.13 MPa

**Safety factor against bending**

= 3.69
(yield strength = 355 MPa)

**Max. deflection**

= 0.56 m (L/137)

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

### Frequency VS RPM

<table>
<thead>
<tr>
<th>Frequency</th>
<th>(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational frequency</td>
<td>0.079 – 0.278</td>
</tr>
<tr>
<td>Tower frequency (1st mode)</td>
<td>0.434</td>
</tr>
<tr>
<td>Blade passing frequency</td>
<td>0.239 – 0.835</td>
</tr>
</tbody>
</table>
Stability Analysis

• Local Buckling Analysis

Critical local buckling stress VS R/t

- Brazier’s critical local buckling stress
- Yield stress of material
- Tubular tower, $D_b = 4.3$ m
- Modular tower 1, $D_b = 5$ m
- Modular tower 2, $D_b = 5.59$ m

Types of tower

<table>
<thead>
<tr>
<th>Types of tower</th>
<th>R/t range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional tubular tower</td>
<td>52 - 146</td>
</tr>
<tr>
<td>Novel modular tower</td>
<td>115 - 195</td>
</tr>
</tbody>
</table>
Comparison of the results for the baseline and modular towers

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>3.70</td>
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<td>Maximum deflection (m)</td>
<td>0.648</td>
<td>0.616 (-4.91%)</td>
<td>0.560 (-13.39%)</td>
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<tr>
<td>Tower frequency (Hz)</td>
<td>0.387</td>
<td>0.413 (+6.72%)</td>
<td>0.434 (+12.17%)</td>
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*Note that the percentages shown in this table are obtained by comparing the values of modular towers to the baseline values.*
Comparison of tower mass for the baseline and modular towers

Tower mass scaling relationship

WindPACT Baseline design:
\[ y = 0.3973x - 1414.4 \]

Baseline design
Advanced design
Acciona AW-70/1500
Acciona AW-77/1500
Acciona AW-82/1500
Averox AES-M1.5
Carybus 1.5
Fuhrlander FL1500-77
GE 1.5sl
GE 1.5xle
HS-1.5MW 77-III
HS-1.5MW 70-II
Newunite FD-77-1500-68
Newunite FD-77-1500-80

WindPACT Advanced design:
\[ y = 0.2694x + 1779.3 \]

- Modular tower 1, \( D_b = 5 \) m
- Modular tower 2, \( D_b = 5.59 \) m
Comparison of the results for the baseline and modular towers

<table>
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<tr>
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<td>3.70</td>
</tr>
<tr>
<td>Maximum deflection (m)</td>
<td><strong>0.648</strong>(L/119)</td>
<td><strong>0.616 (-4.91%)(L/125)</strong></td>
<td><strong>0.560 (-13.39%)(L/137)</strong></td>
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<tr>
<td>Tower frequency (Hz)</td>
<td><strong>0.387</strong>(L/119)</td>
<td><strong>0.413 (+6.72%)(L/125)</strong></td>
<td><strong>0.434 (+12.17%)(L/137)</strong></td>
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*Note that the percentages shown in this table are obtained by comparing the values of modular towers to the baseline values.*
Effects of a larger tower base diameter on tower structure

- Modular tower design:
  Thinner wall thicknesses $\rightarrow$ Lower tower mass $\rightarrow$ Lower material cost

- Improves the structural stabilities:
  - Higher tower natural frequencies
  - Lower maximum tip deflection

- Dominant criterion:
  Max. Von Mises stress $\rightarrow$ 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

• This work is supported by National Research Council of Thailand.