Beyond power and loads: modeling the impacts of active load control *(and wake steering)* on CAPEX, OPEX, and LCOE**

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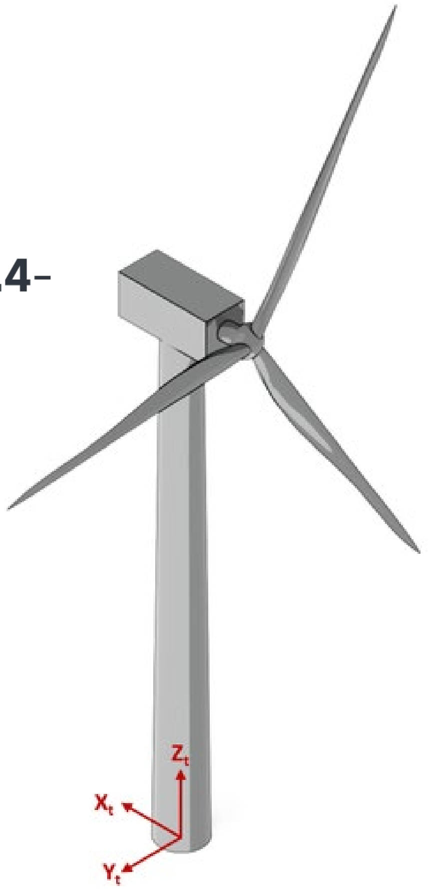
IEAWindTask37/**IEA-3.4-130-RWT**



7th Wind Energy Systems Engineering Workshop

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**Reference: Mishra, I., et al, "Active Load Control Applied to an Upscaled Wind Turbine: Design and Cost Impacts," in review, December 2024.

Costs

Performance

Reliability

Upfront capital cost

Reliability

$$LCOE = \frac{CAPEX + OPEX_{lifetime}}{AEP_{lifetime}}$$

Levelized Cost of Energy ($/kW-hr)

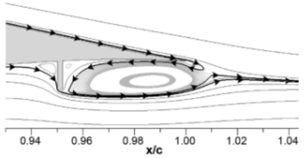
Performance

Introduction: Active Load Control Options

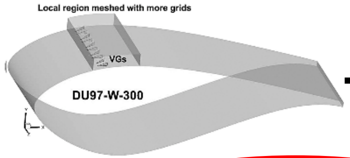
All Wind Turbine Control

- **Wind Turbine Load Control**
  - **Yaw Control** (van Dam et al., 2008)
  - **Variable rotor speed and diameter** (Berg et al., 2007)
  - **Collective pitch control** (Hwas and Katebi,2012; Jonkman et al., 2009)
  - **Generator Torque Control**
  - **Individual Pitch control** (Johnson, 2012; Jonkman et al., 2009)
- **Wind Turbine Active Flow Control**
  - **Trailing edge flaps** (Berg et al., 2007)
  - **Microtabs and Gurney Flaps** (Bach, 2016)
  - **Vortex generators** (Gao et al., 2015)
  - **Dielectric barrier discharge (DBD) plasma actuators** (Fine et al., 2013; Cooney et al., 2016)
  - **Synthetic jets** (Xu et al., 2016)

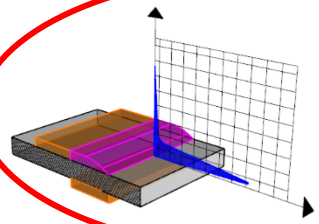
→ **T.E flaps**



→ **Microtabs and gurney flaps**



→ **Vortex generator**



→ **DBD plasma actuator**

This study (ALC):

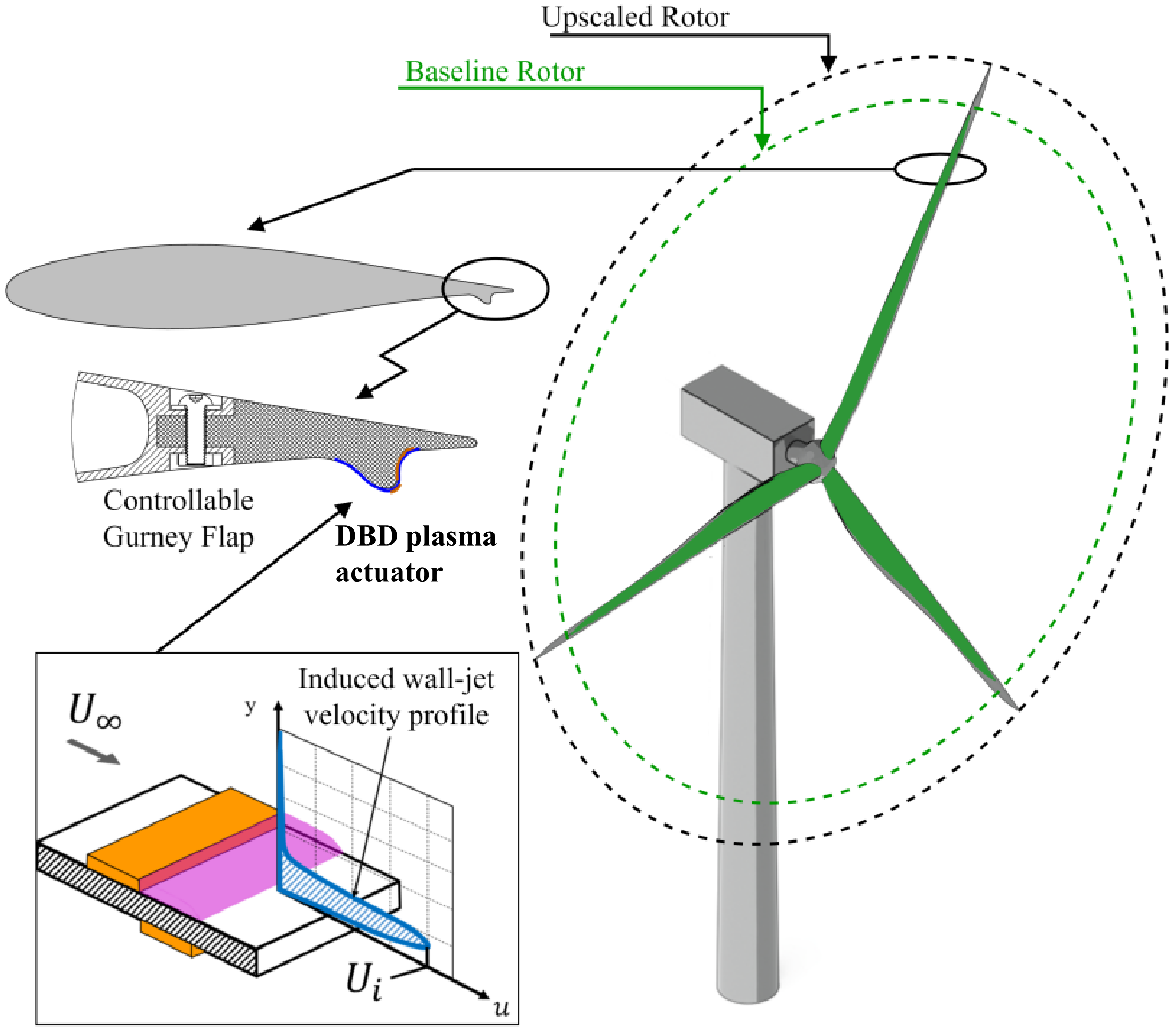
1. Controllable gurney flap (CGF)-based DBD plasma actuator [1]

2. CGF device has no moving parts, controlled by an active control system (coined as sectional lift controller (SLC)

1. *Chetan M, Sakib MS, Griffith DT, Gupta A, Rotea MA. Design of a 3.4-MW wind turbine with integrated plasma actuator-based load control. Wind Energy 2021.*

Motivation and Objectives

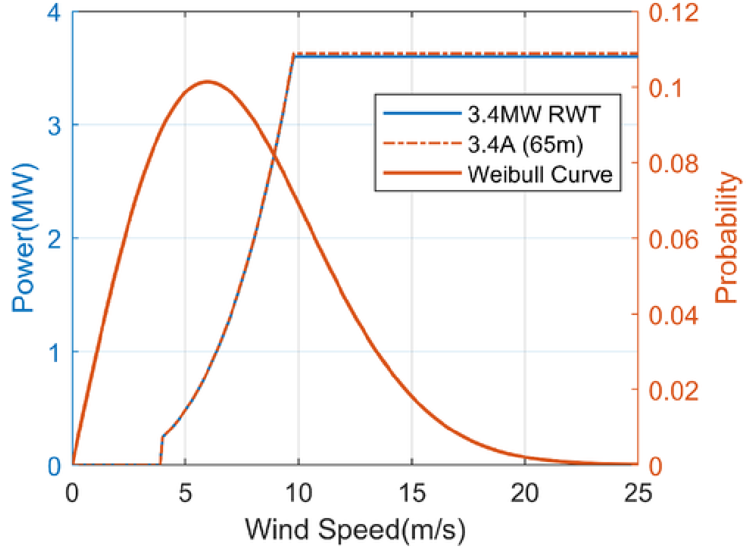
1. **Identify best ways to utilize ALC, especially ALC combined with upscaling**
2. **Evaluate different utilization / implementation strategies[1] :**
   1. Upscaling
      1. No upscaling (A-series, retrofit)
      2. Upscaled (B-series, two cases)
   2. Operating range for ALC
      1. Region 3 only
      2. Region 2 and Region 3 (full range)
3. **Quantify effects of ALC + upscaling**:
   1. Loads: mean loads and DELs
   2. Power → AEP
   3. Costs
      1. CAPEX, OPEX, and LCOE

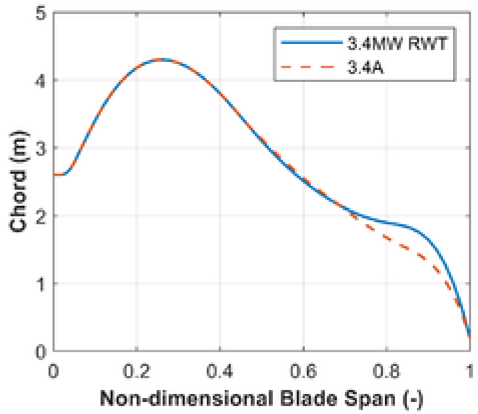


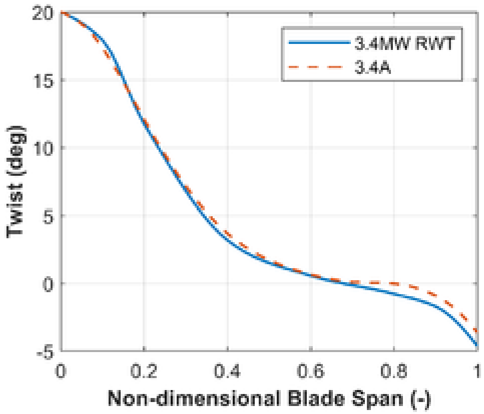
Gurney Flap Integration: Power Curves and Aero Definition

A-series, no upscaling

3.4A

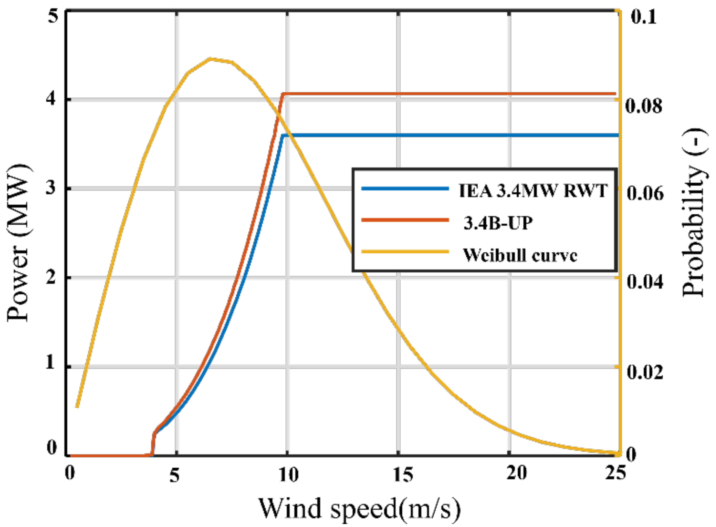




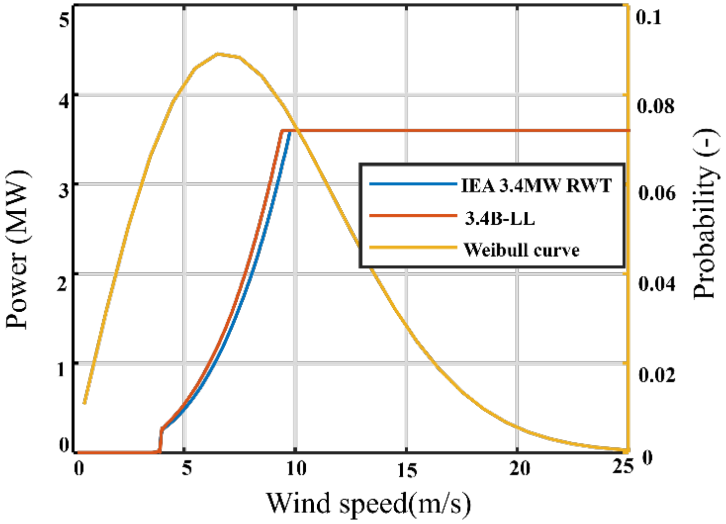


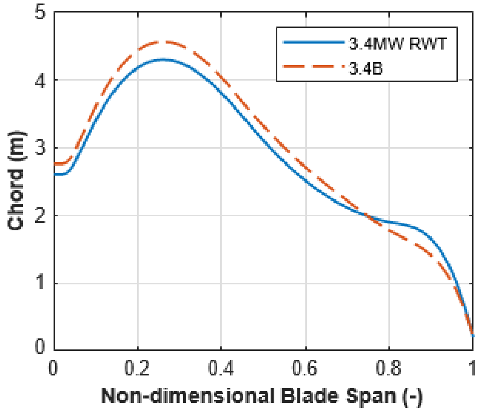
B-series, upscaled

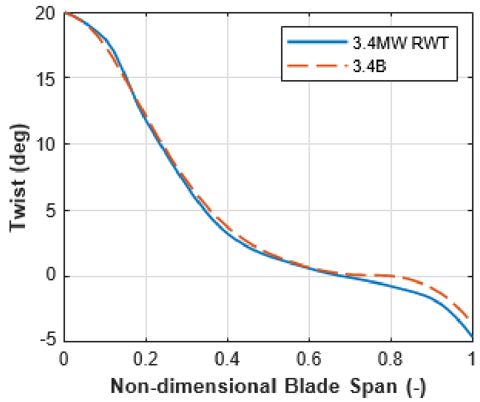
3.4B-UP (uprated)



3.4B-LL (load-limited)



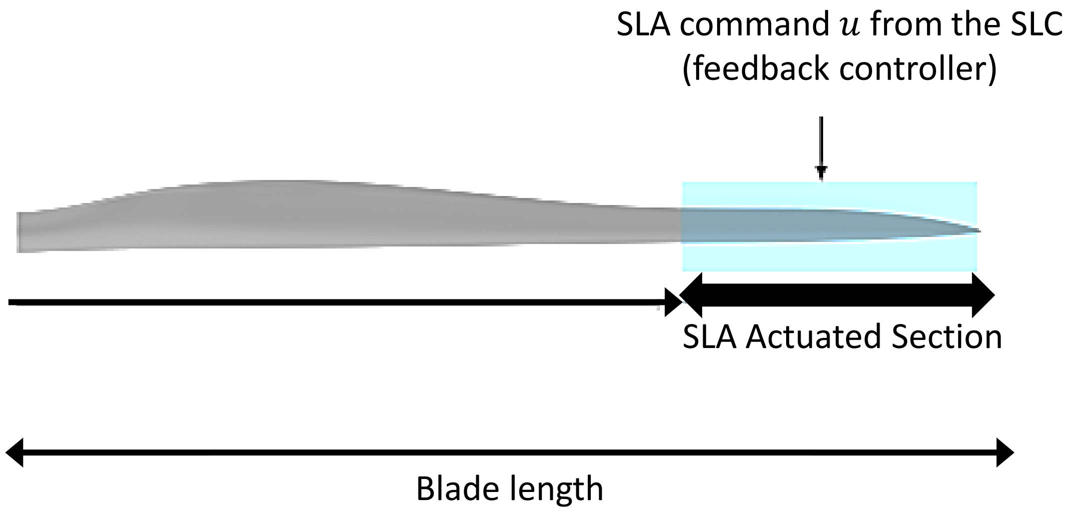




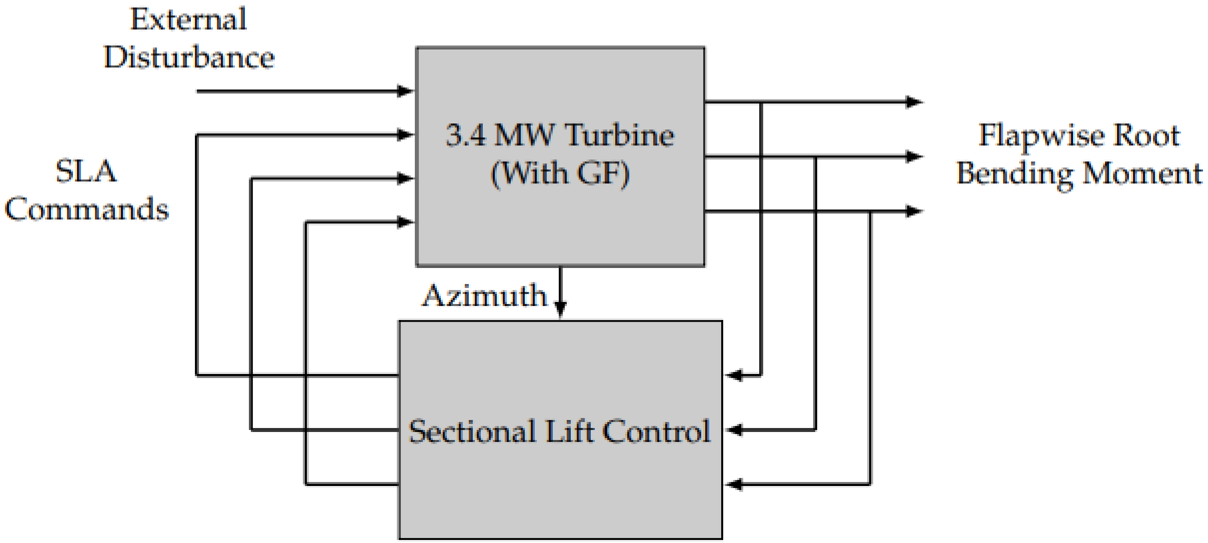
Section Lift Controller (SLC)

Section Lift Controller (SLC):

- SLC is a feedback control strategy to reduce the blade fatigue loads.
- Change the sectional lift coefficients within the range −0.2 to +0.2 from the baseline value.
- Enables local aerodynamic force modification on turbine blades.
- Minimize blade-root bending moment fluctuations caused by wind disturbances through on-blade SLA control.



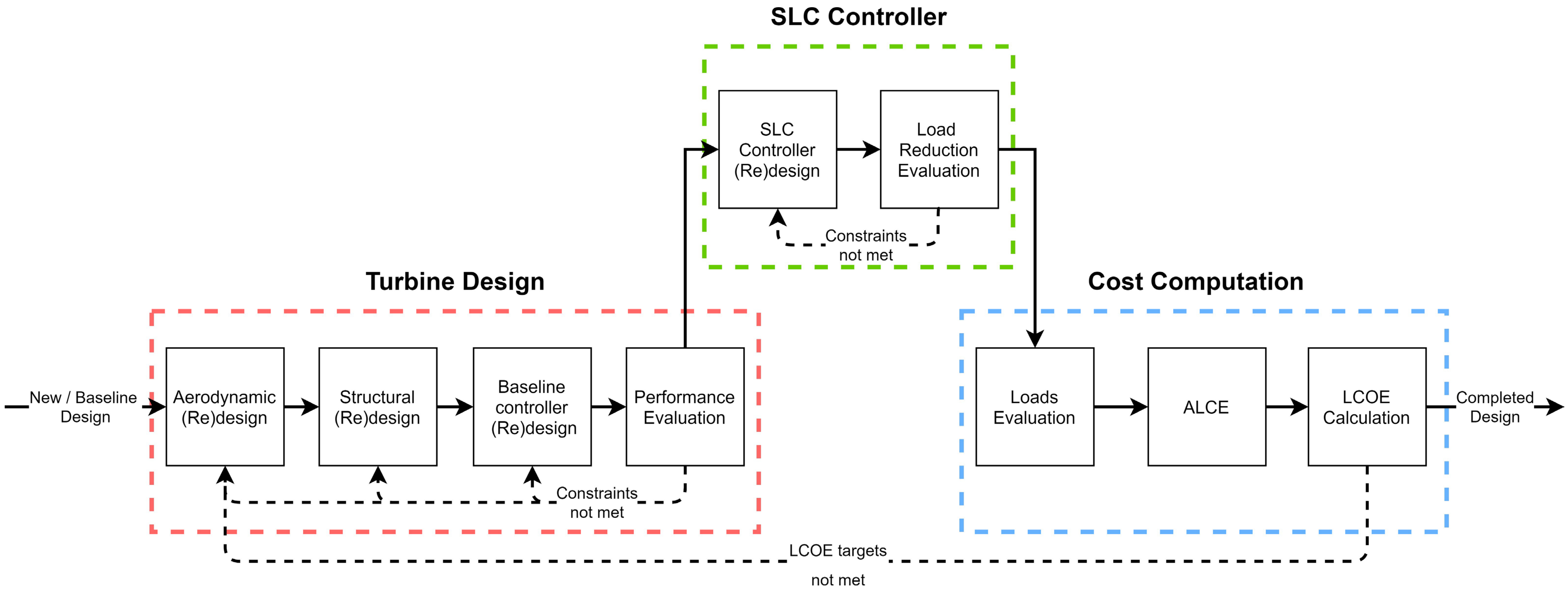
Turbine blade with CGF at approx. 75% of the blade span [2,3]



SLC: Feedback control system configuration [2]

2. Gupta A, Rotea MA, Chetan M, Sakib MS, Griffith DT. A Methodology for Robust Load Reduction in Wind Turbine Blades Using Flow Control Devices. Energies 2021; 14(12): 3500. Number: 12 Publisher: Multidisciplinary Digital Publishing Institute doi: 10.3390/en14123500
3. Gupta A, Rotea MA, Chetan M, Sakib MS, Griffith DT. Effect of wind turbine size on load reduction with active flow control. J Phys Conf Ser [Internet]. 2022;2265(3):032093. Available from: https://dx.doi.org/10.1088/1742-6596/2265/3/032093

Sequential Iterative Co-Design

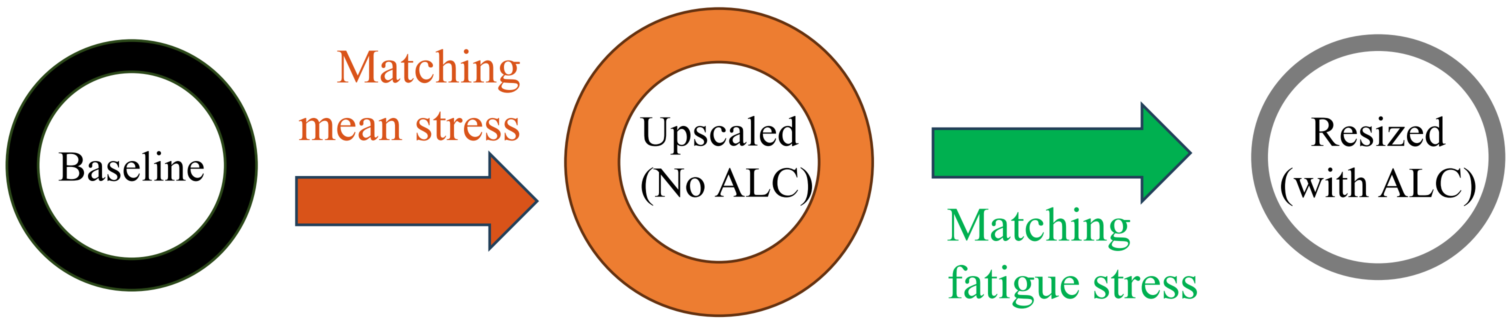


Method: RWT Baseline + Stress/deflection Matching

1. Baseline RWT performance
2. CGF integration and upscaling
3. Re-design: Stress/deflection matching to RWT
4. CAPEX, AEP, OPEX, LCOE

Redesign: Stress/deflection matching for turbine components: 2 step process:

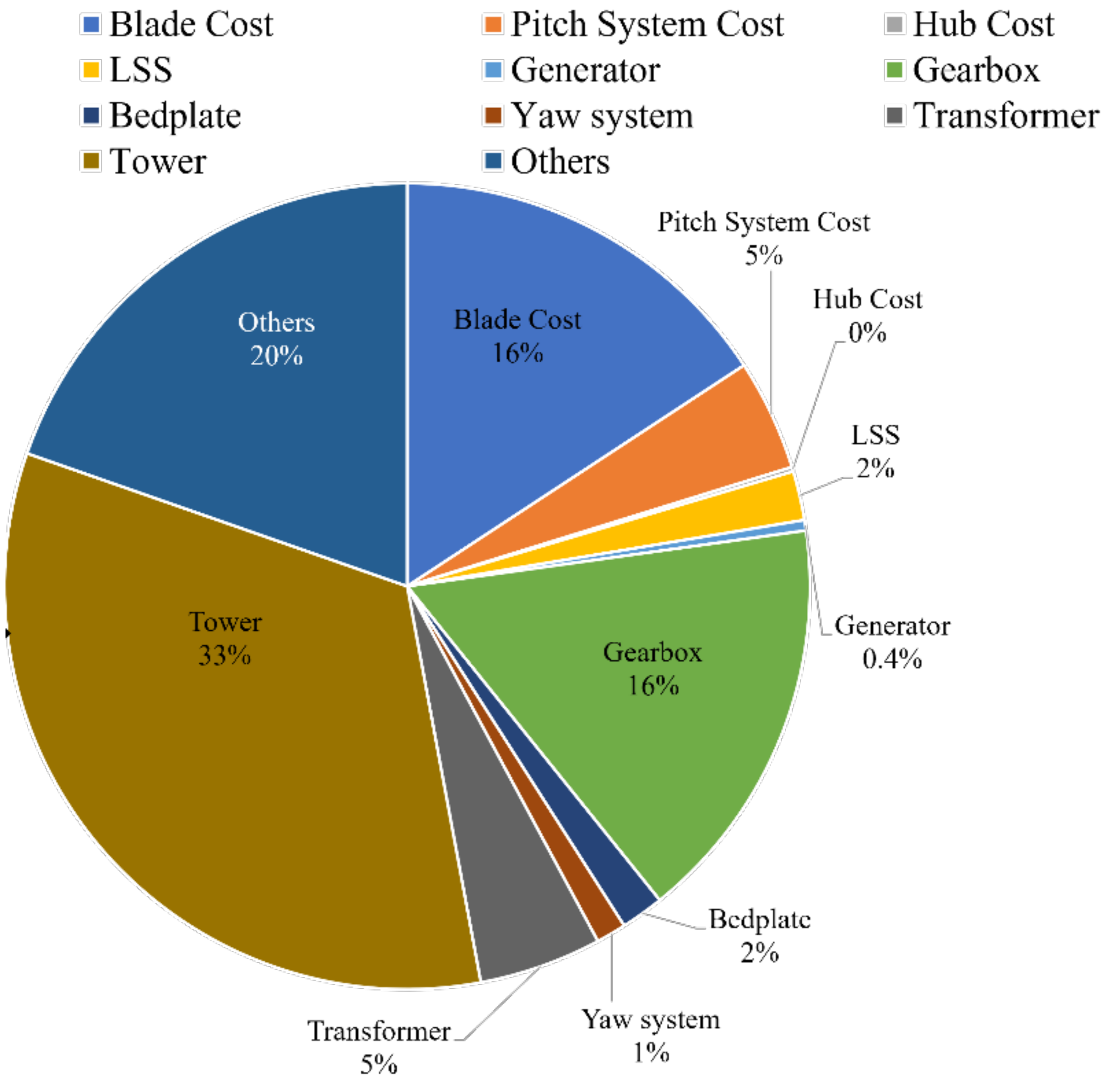
1. **Step 1:** Upscaling Effect
2. **Step 2:** ALC Effect

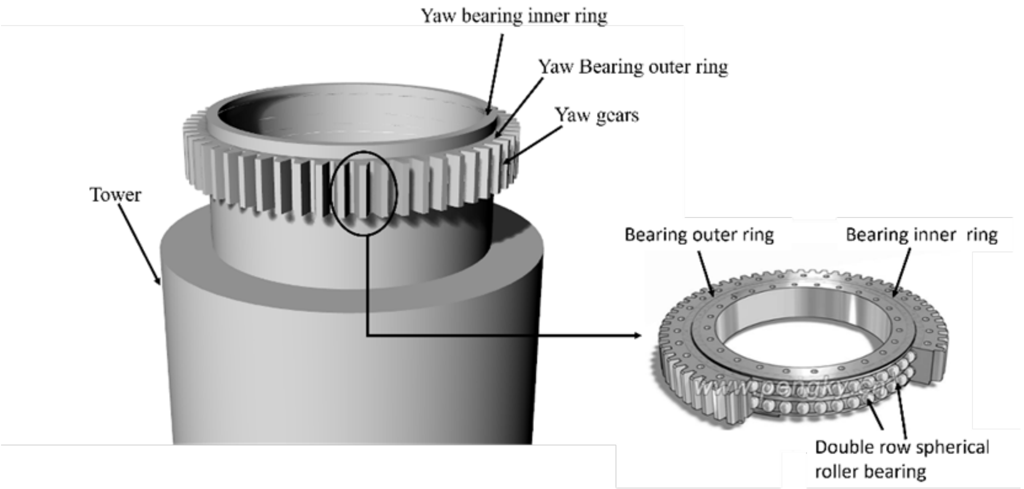


$$\sigma' = \sqrt{(\text{Resultant})^2 + 3(\tau_z)^2}$$

$$\text{Resultant} = \sqrt{{\sigma_{z1}}^2 + {\sigma_{z2}}^2}$$

Turbine CAPEX Breakdown by Component

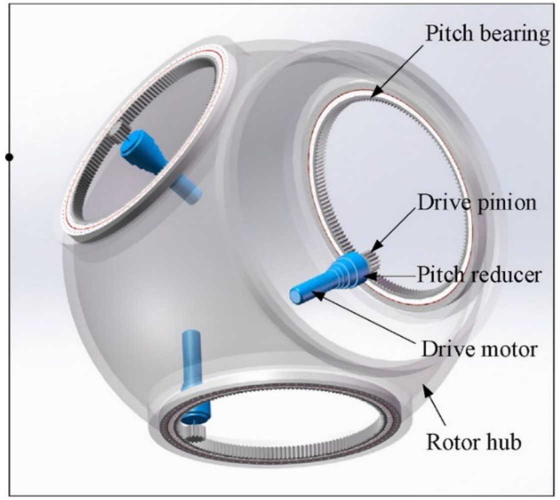




Stress Matching for Pitch and Yaw Systems as well

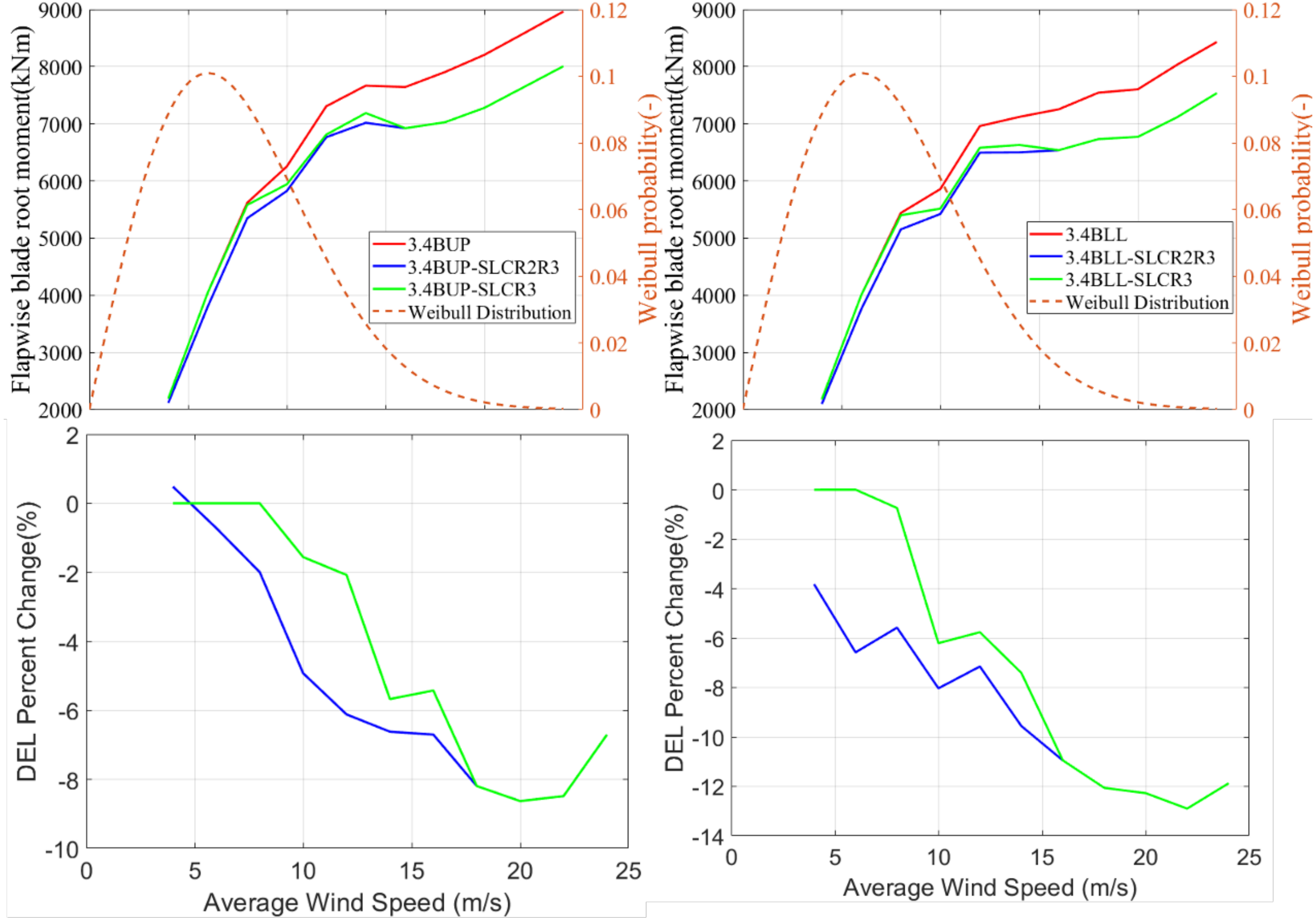
$$\sigma' = \sqrt{(\text{Resultant})^2 + 3(\tau_z)^2}$$

$$\text{Resultant} = \sqrt{\sigma_{z1}{}^2 + \sigma_{z2}{}^2}$$



Approx. 80% of CAPEX addressed in our re-sizing

DEL effects of ALC



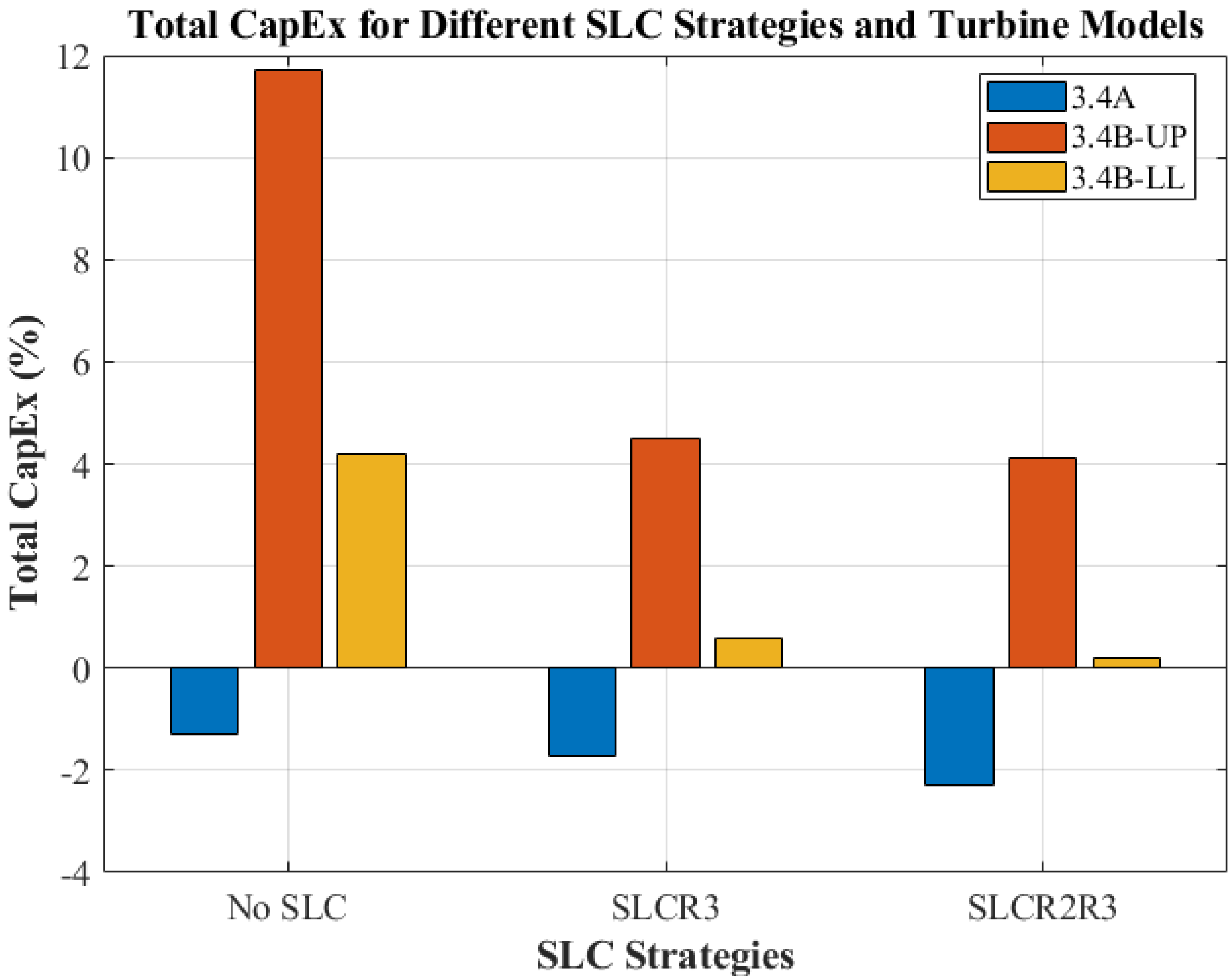
Blade root flapwise DELs shown.

Left: 3.4B-UP (uprated)
Right: 3.4B-LL (load limited)

DELs analyzed also for:

Tower
Low speed shaft
Gearbox
Generator
Pitch system
Yaw system

CAPEX impacts of Upscaling and ALC



3.4A: A-series, no upscaling

3.4B-UP: B-series, Uprated

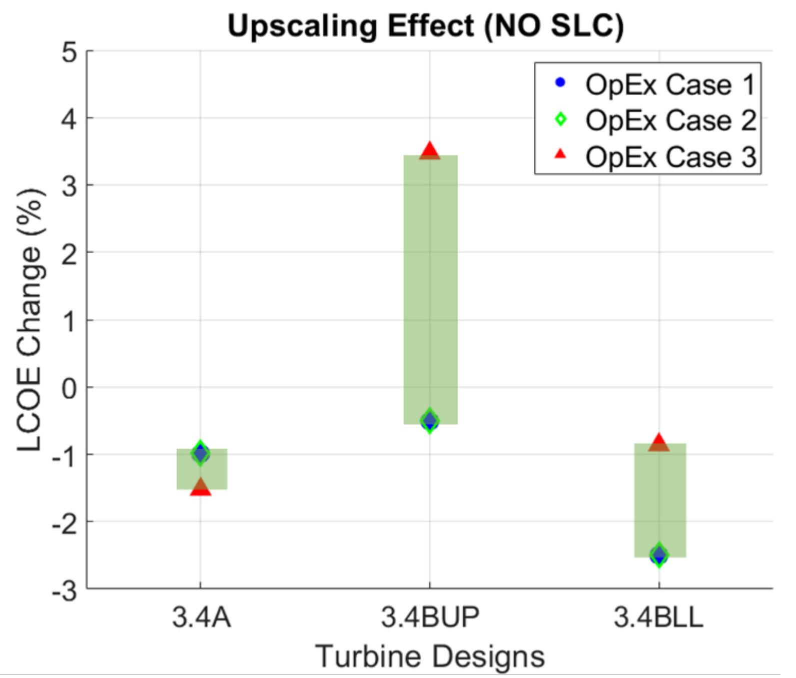
3.4B-LL: B-series, Load-Limited

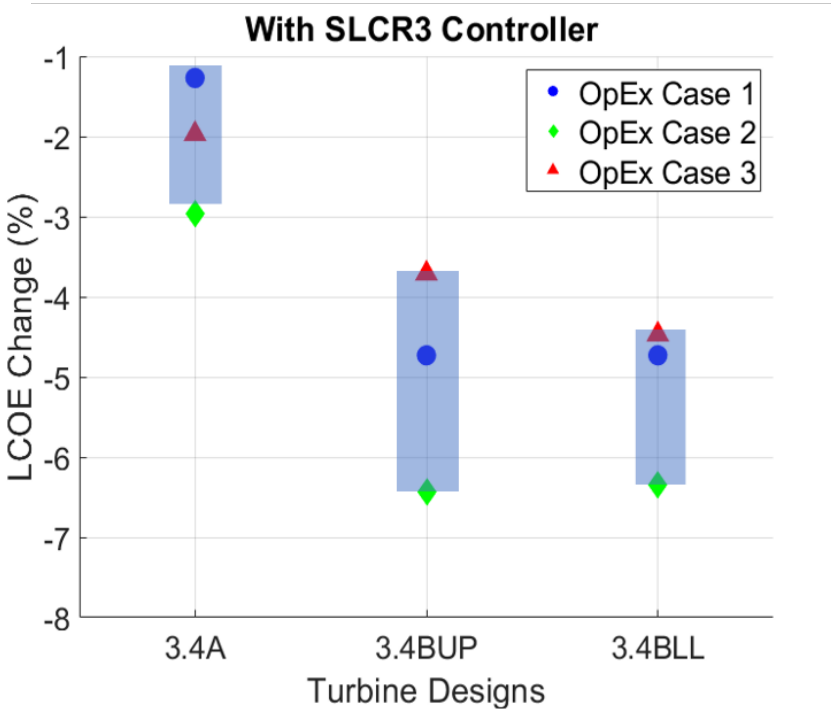
OPEX impacts: Define scenarios / cases

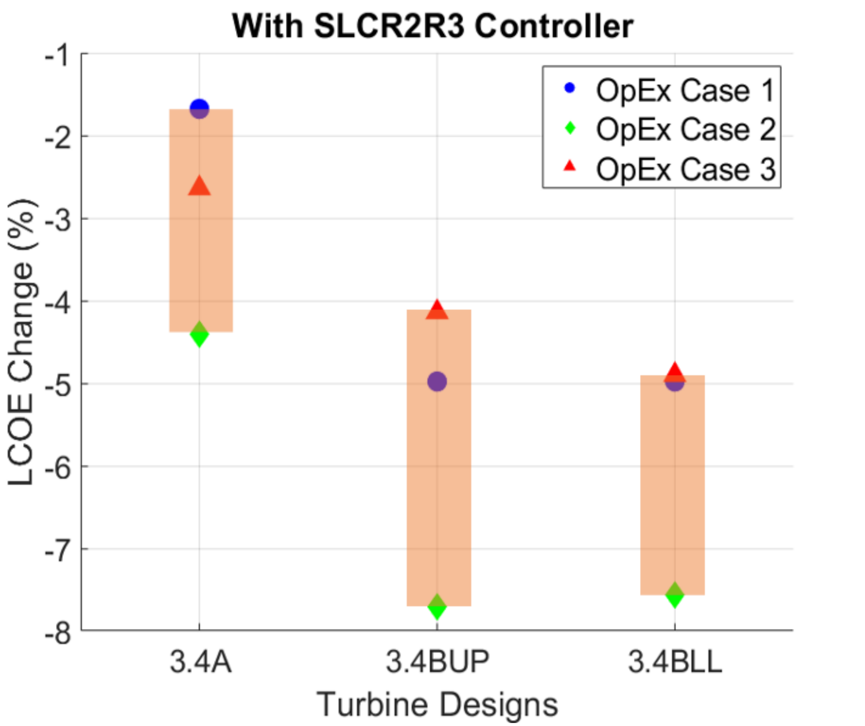
- Three OPEX scenarios to address variability in OPEX costs and OPEX processes:
  - **Case 1:** fixed OPEX of $44/kW of rated power
  - **Case 2:** 5% reduction for ALC in Region 3 (R3) only, 8% reduction for ALC in Region 2 and 3 (R2R3)
  - **Case 3:** OPEX proportional to CAPEX of re-sized components

- Ongoing work to explore new OPEX models

Final LCOE Comparisons and Take-aways







	Units	IEA 3.4MW RWT (Baseline)	3.4B-UP	3.4B-LL
Electrical AEP	GWh	13.90	15.61	14.65
% Change	%	--	+12.3%	+5.4%

Concluding Thoughts: ALC (Active Load Control)

Assessing ways to utilize ALC: Upscaling, wind speed range, etc.

End-end analysis of ALC: loads, power, AEP & DELs, CAPEX, OPEX, and LCOE

For more details, forthcoming publication: **Mishra, I., et al, "Active Load Control Applied to an Upscaled Wind Turbine: Design and Cost Impacts," in review, December 2024.**

A few take-aways:

1. Comprehensive co-design needed
2. Cascading DEL reduction from blades to other components
3. Two upscaling approaches: 3.4B-UP (uprated) (AEP ↑↑ CAPEX ↑↑)
3.4B-LL (load-limited) (AEP ↑ CAPEX ↑)
4. Upscaling: more opportunity for B-series (upscaled) than A-series (retrofit)
5. Full range R2R3 provides 60-76% increase in Weibull-weighted DEL reduction over R3 only

Ongoing/Future Work:

- OPEX models
- Effect of turbine size + ALC: 10MW and 15MW
- Extending methods to wake steering (LCOE impacts)

Thank You
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