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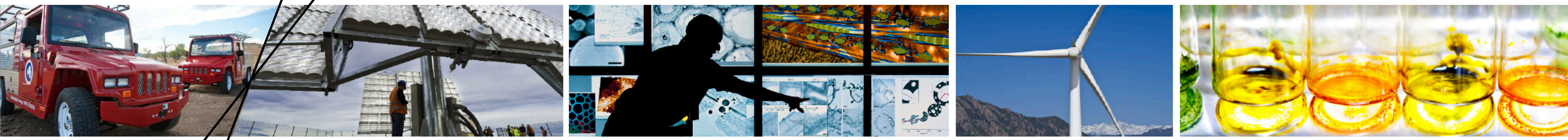
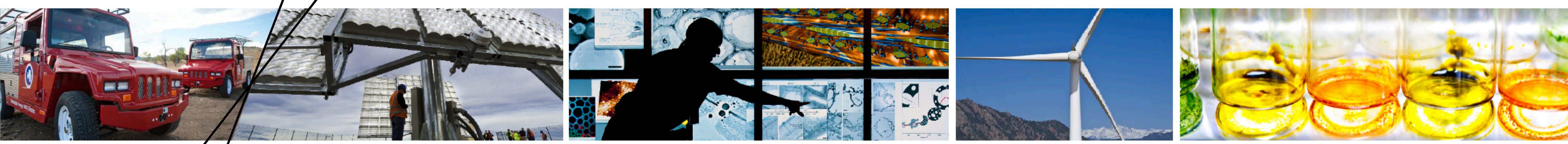
Objectives and Constraints for Wind Turbine Optimization



S. Andrew Ning
National Renewable Energy Laboratory
January, 2013

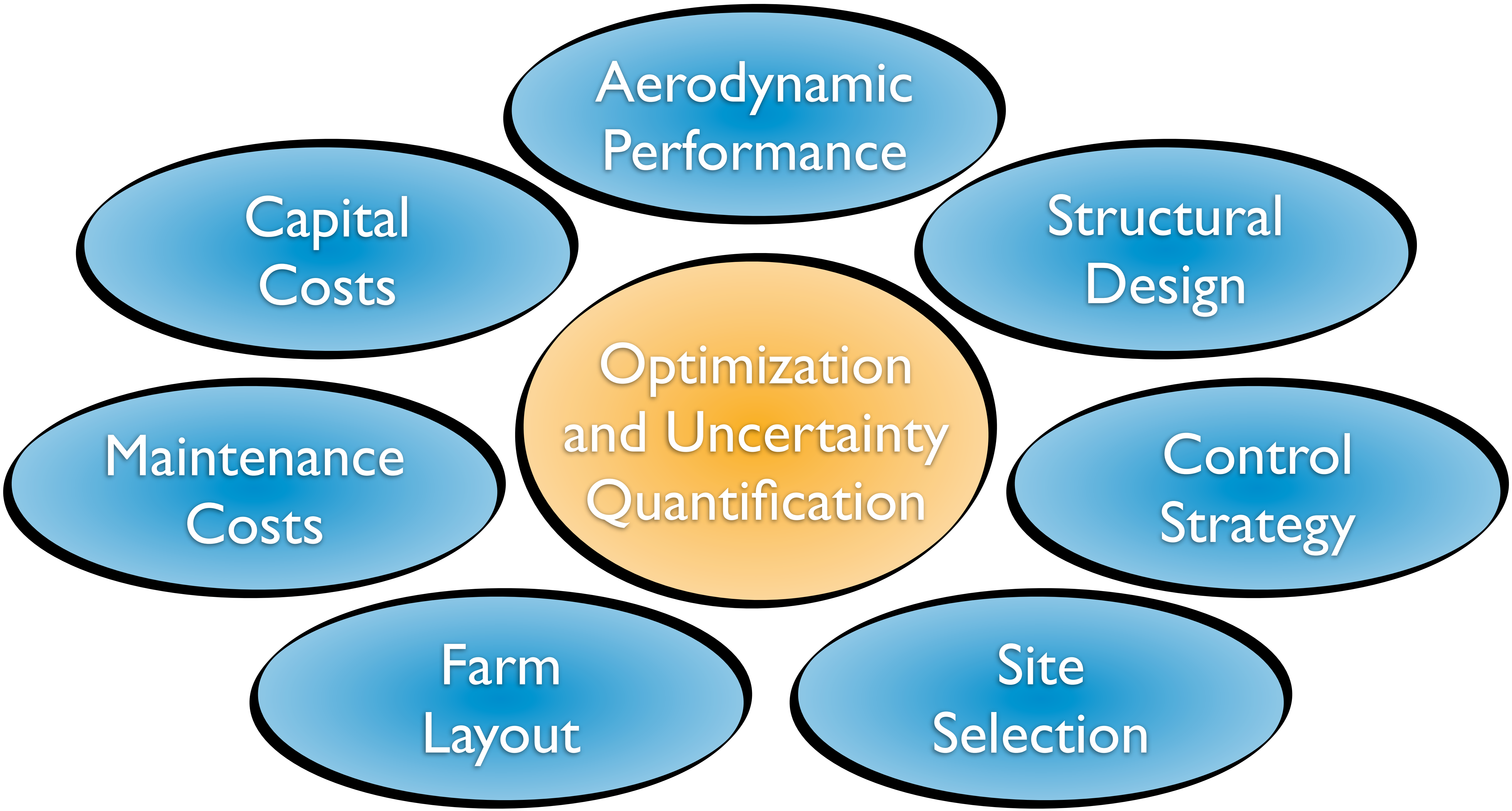
Overview

1. Introduction
2. Methodology (aerodynamics, structures, cost, reference model, optimization)
3. Maximum Annual Energy Production (AEP)
4. Minimum m/AEP
5. Minimum Cost of Energy (COE)
6. Conclusions



Introduction

Wind Turbine Design



Wind Turbine Optimization

Objectives

- Max P/min M_b
- Max AEP
- Min COE

Design Vars

- Blade shape
- Rotor/nacelle
- Turbine

Fidelity

- Analytic
- Aeroelastic
- 3D CFD

Optimization

- Gradient
- Direct search
- Multi-level

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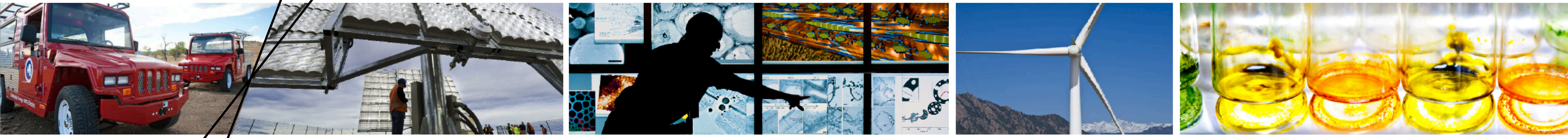


Methodology

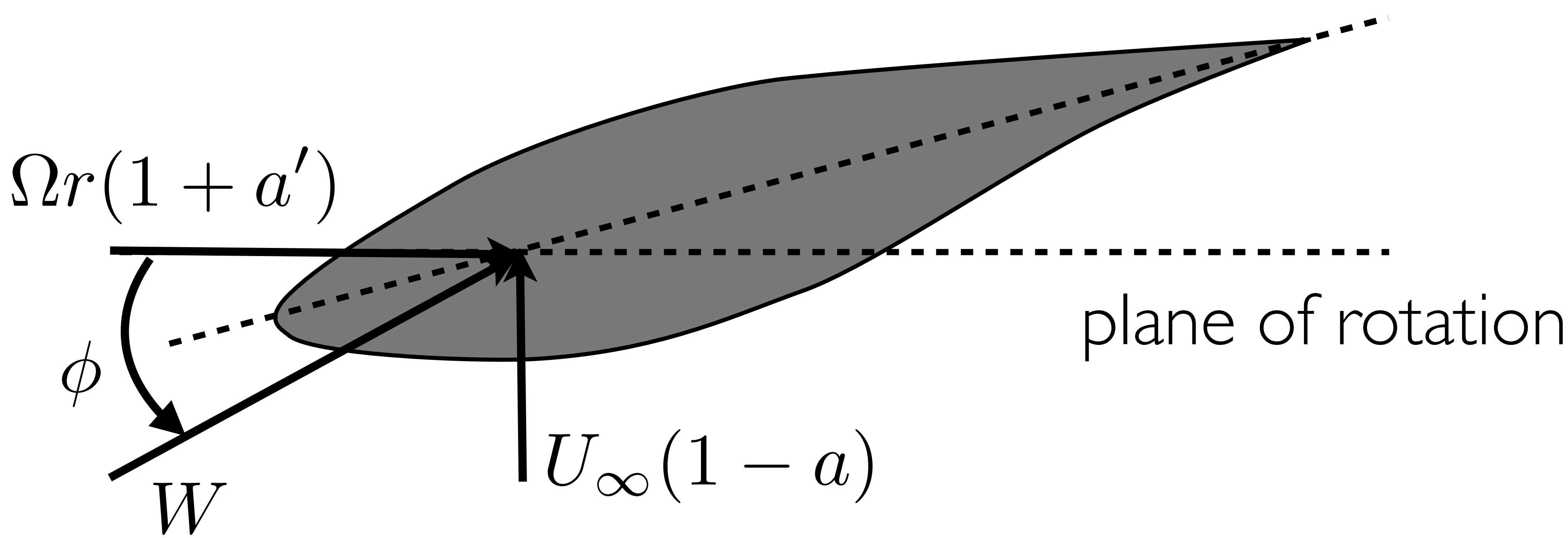
Model Development

1. Capture fundamental trade-offs (physics-based)
2. Execute rapidly (simple physics)
3. Robust convergence (reliable gradients)

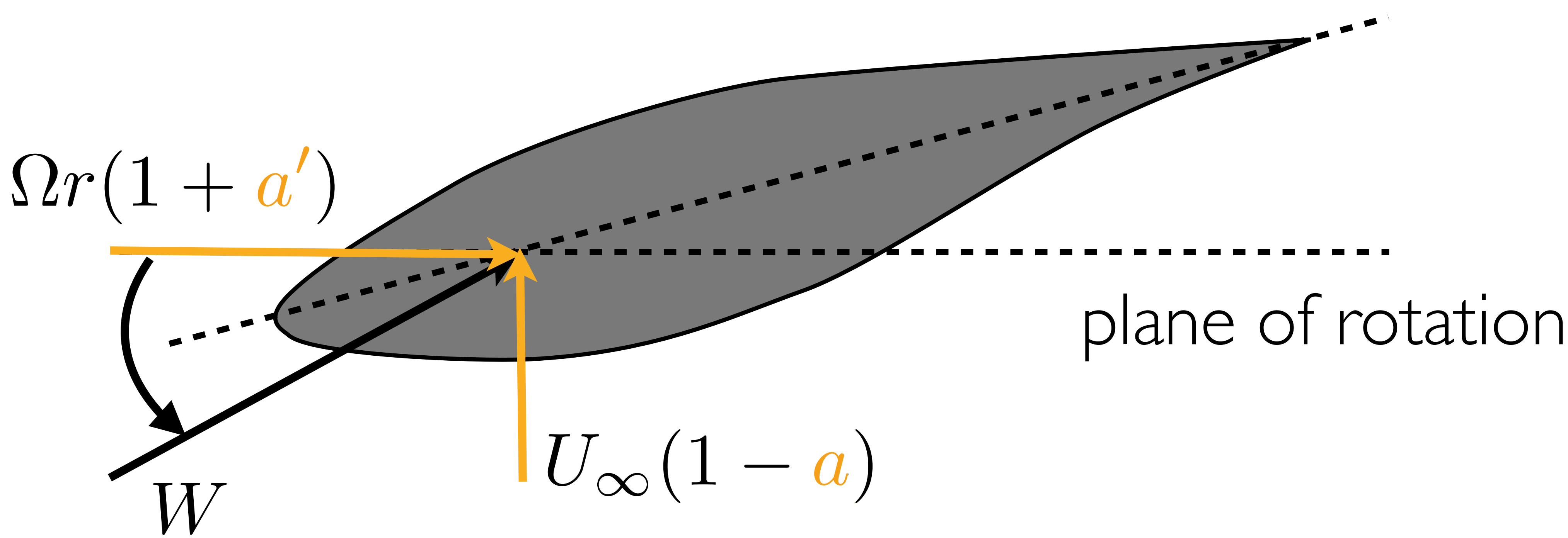
Aerodynamics

- Blade-element momentum theory
  - hub and tip losses, high-induction factor correction, inclusion of drag
  - 2-dimensional cubic splines for lift and drag coefficient (angle of attack, Reynolds number)
- Drivetrain losses incorporated in power curve
- Region 2.5 when max rotation speed reached
- Rayleigh distribution with 10 m/s mean wind speed (Class I turbine)
- Availability and array loss factors

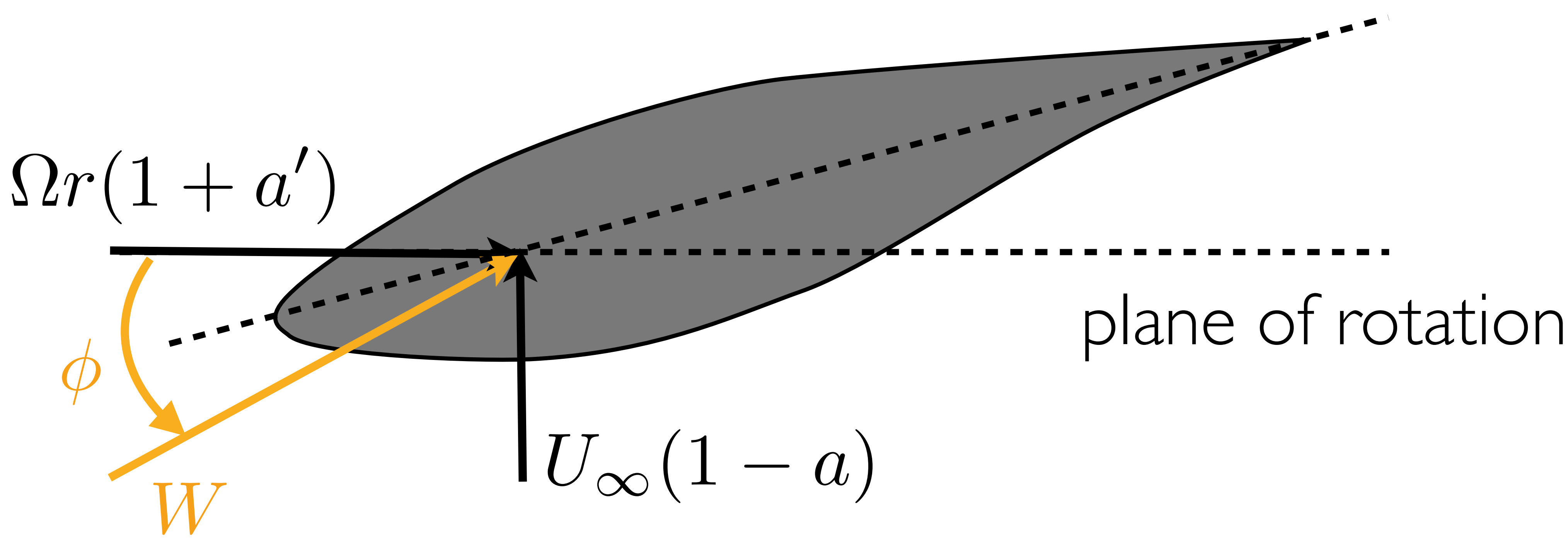
Blade Element Momentum



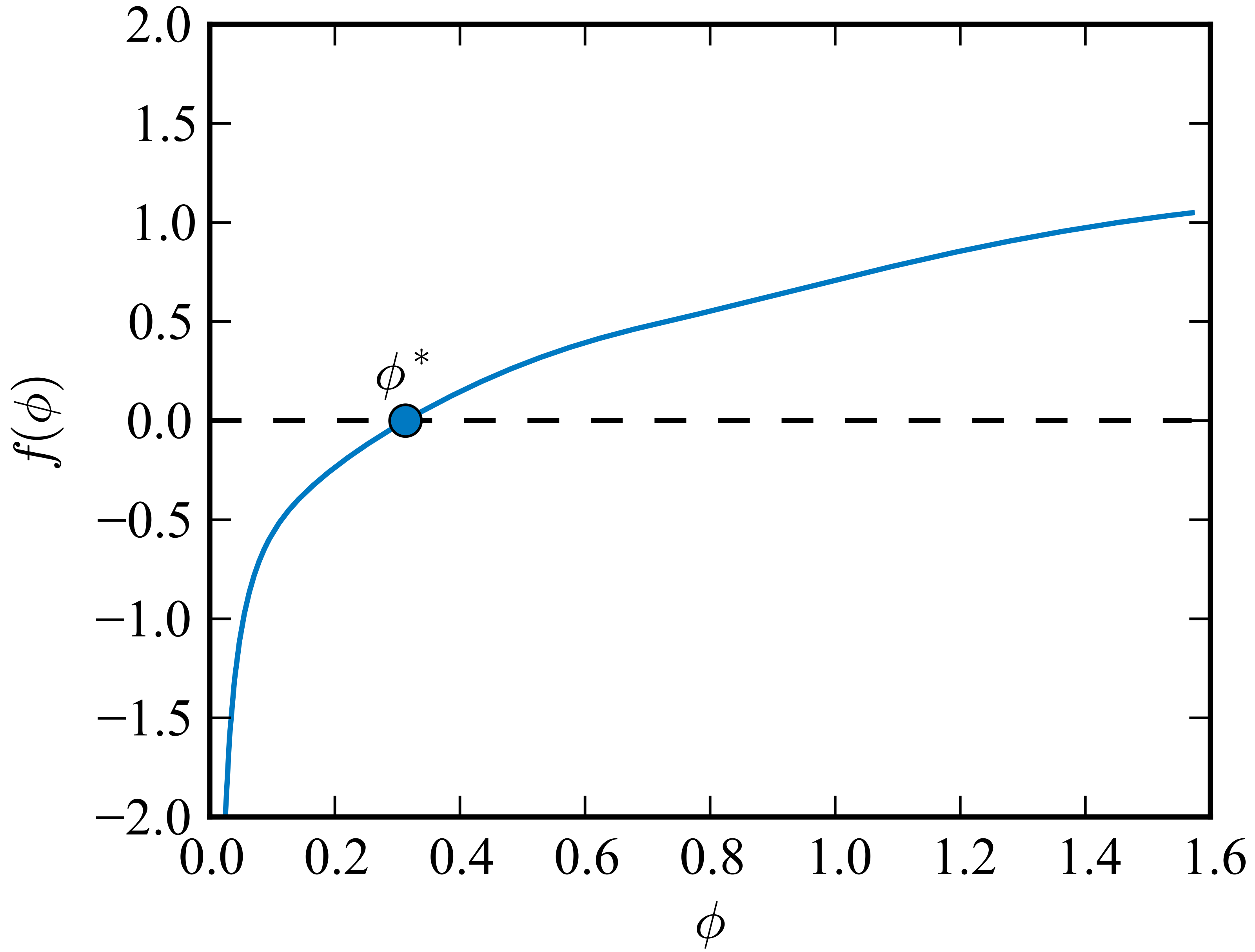
Blade Element Momentum



Blade Element Momentum

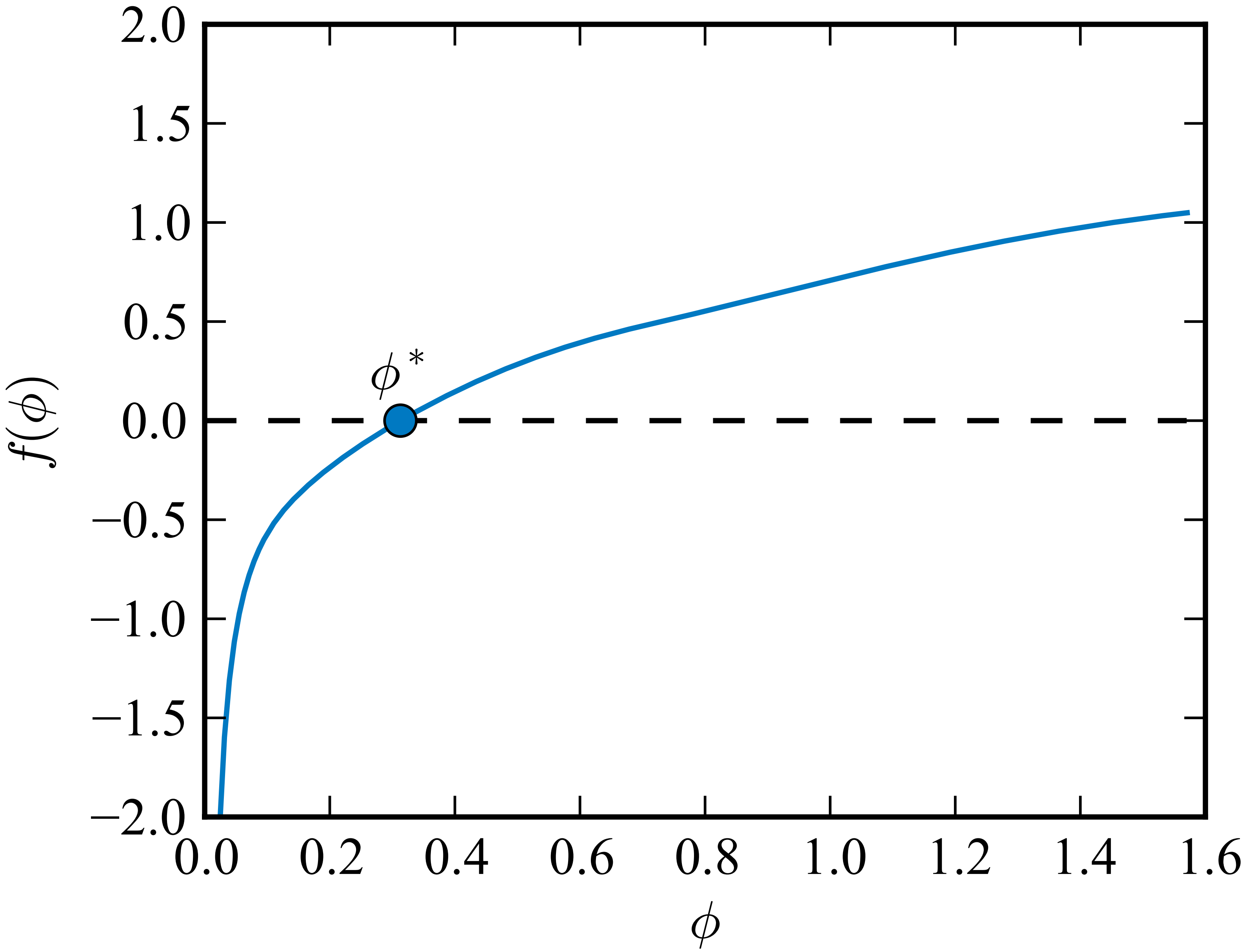


Blade Element Momentum



$$f(\phi) = \frac{\sin\phi}{1 - a(\phi)} - \frac{\cos\phi}{\lambda_r(1 + a'(\phi))} = 0$$

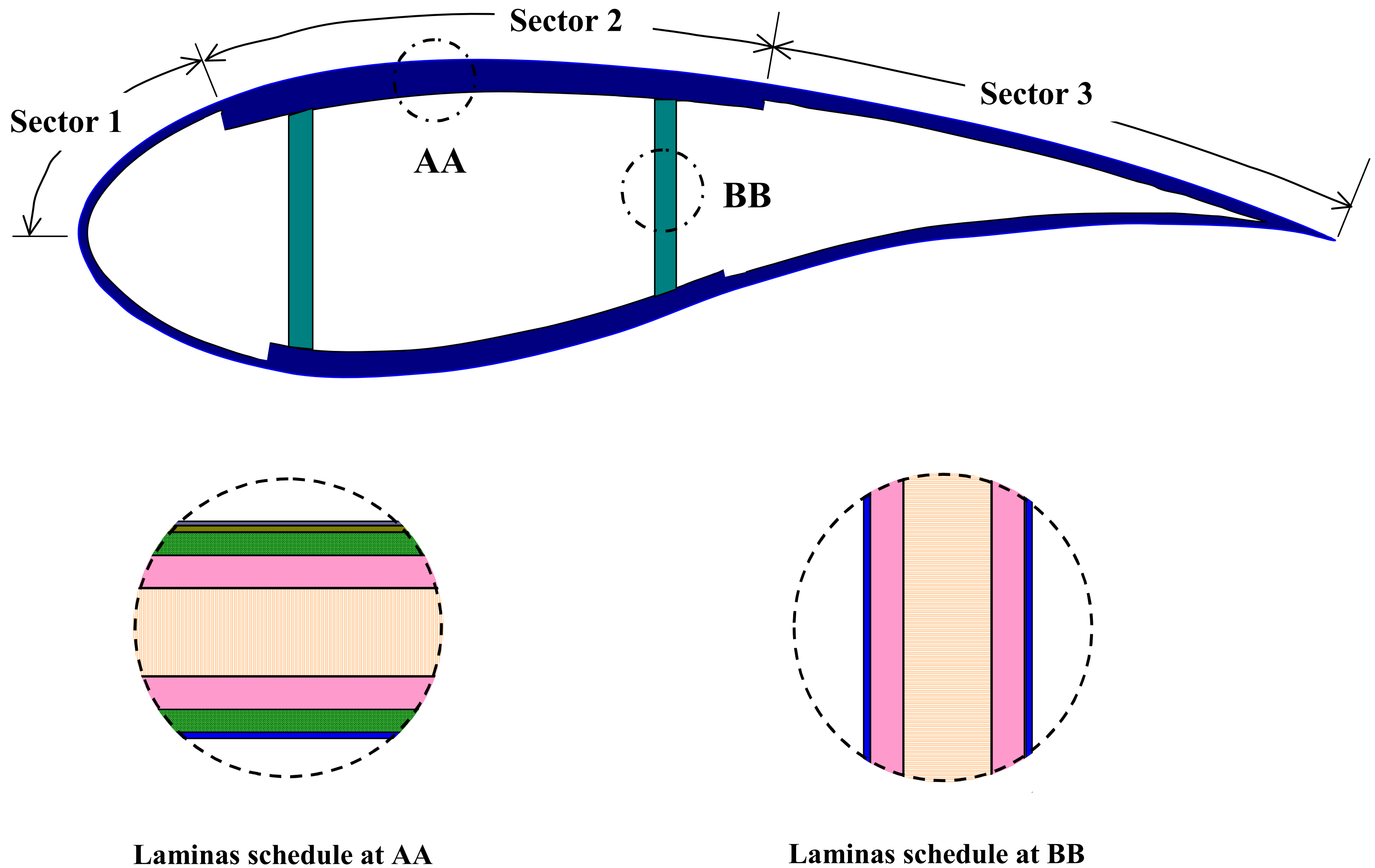
Blade Element Momentum



S. Andrew Ning, "A Simple Solution Method for the Blade Element Momentum Equations with Guaranteed Convergence," Wind Energy, to appear.

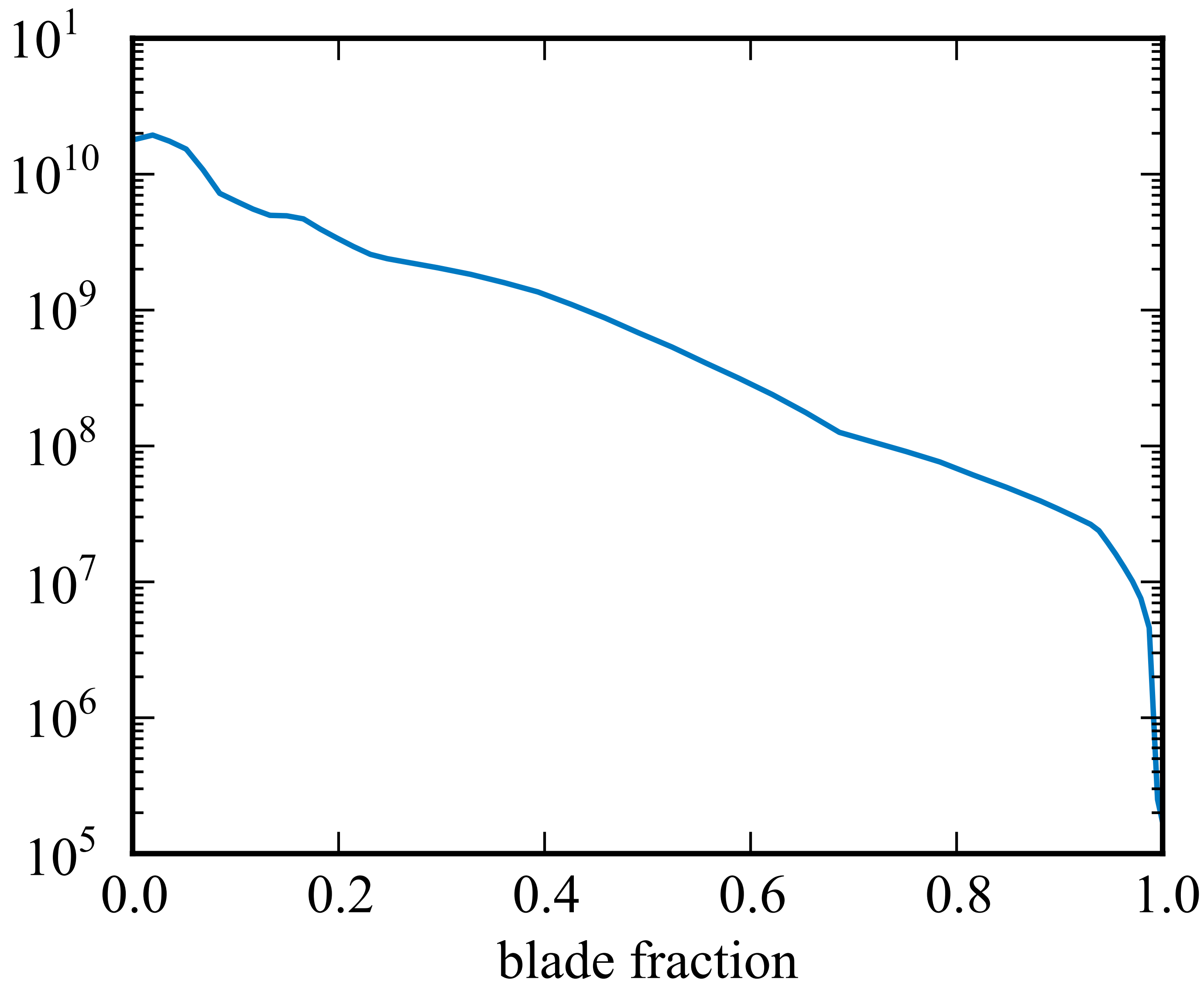
CCBlade

Composite Sectional Analysis



PreComp

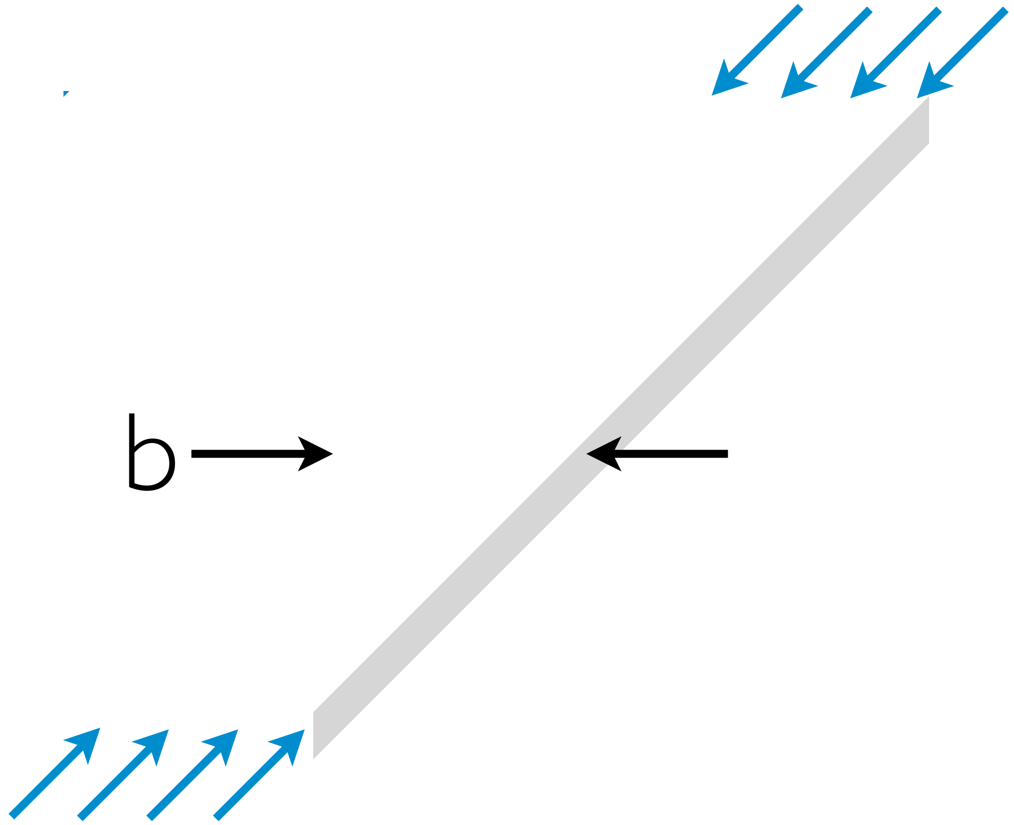
Beam Finite Element Analysis



$$K_{ij} = \frac{1}{L^3} \int_0^1 [EI](\eta) f_i''(\eta) f_j''(\eta) d\eta$$

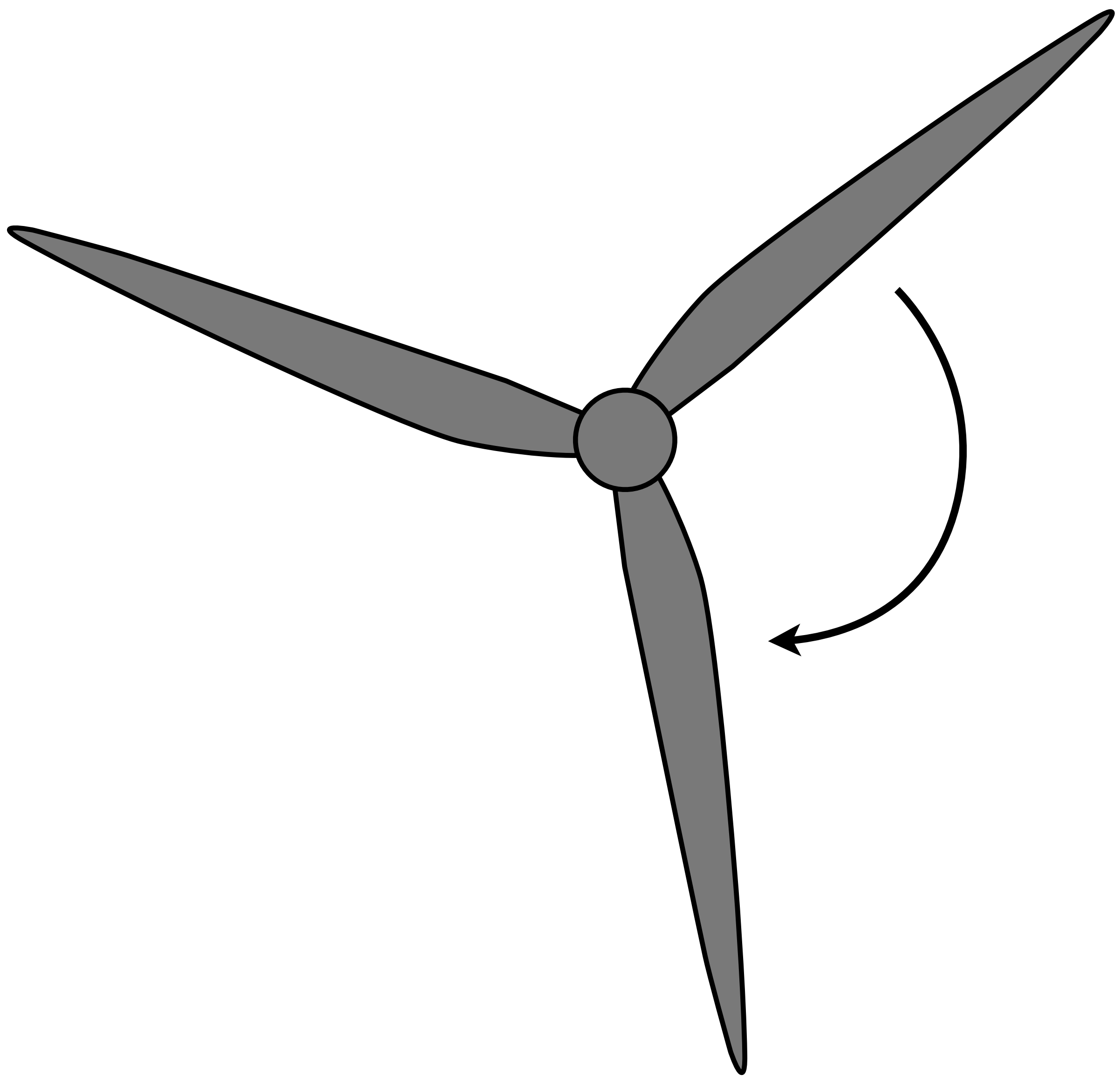
pBEAM

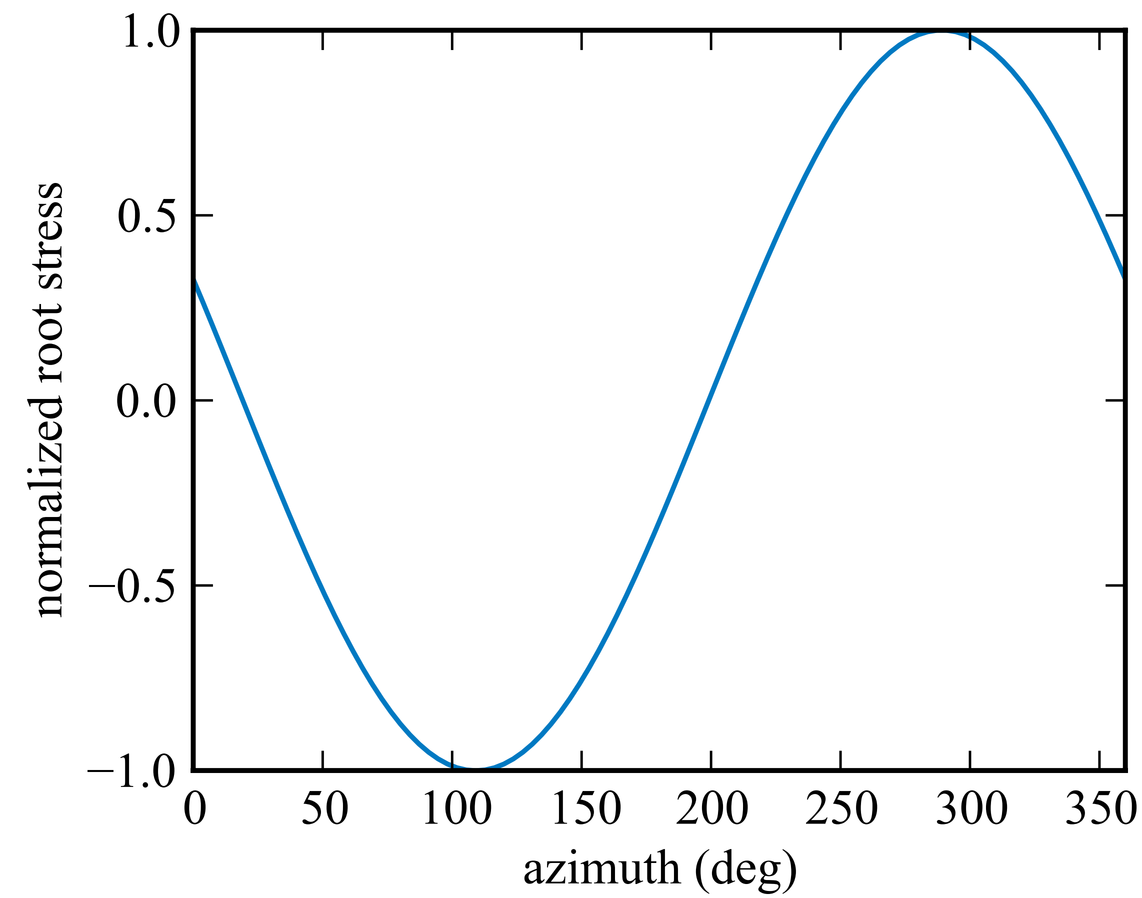
Panel Buckling



$$N_{cr} = 3.6 \left(\frac{\pi}{b}\right)^2 \int \frac{E(\tau)\tau^2}{1 - \nu(\tau)^2} d\tau$$

Fatigue (gravity-loads)





Cost Model

- Based on NREL Cost and Scaling Model
- Replaced blade mass/cost estimate
- Replaced tower mass estimate
- New balance-of-station model

Reference Geometry

- NREL 5-MW reference design
- Sandia National Laboratories initial layup
- Parameterized for optimization purposes

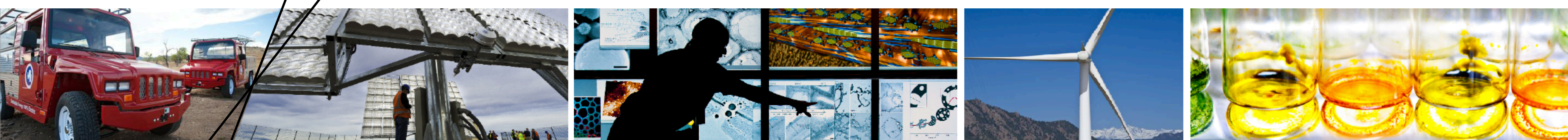
Design Variables

Description	Name	# of Vars
chord distribution	{c}	5
twist distribution	$\{\theta\}$	4
spar cap thickness distribution	{t}	3
tip speed ratio in region 2	λ	1
rotor diameter	D	1
machine rating	rating	1

Constraints

$$
\begin{aligned}
\underset{x}{\text{minimize}} \quad & J(x) \\
\text{subject to} \quad & (\gamma_f \gamma_m \epsilon_{50i})/\epsilon_{ult} < 1,\ i = 1,\ldots,N && \text{ultimate tensile strength} \\
& (\gamma_f \gamma_m \epsilon_{50i})/\epsilon_{ult} > -1,\ i = 1,\ldots,N && \text{ultimate compressive strength} \\
& (\epsilon_{50j}\gamma_f - \epsilon_{cr})/\epsilon_{ult} > 0,\ j = 1,\ldots,M && \text{spar cap buckling} \\
& \delta/\delta_0 < 1.1 && \text{tip deflection at rated} \\
& \omega_1/(3\Omega_{rated}) > 1.1 && \text{blade natural frequency} \\
& \sigma_{\text{root-gravity}}/S_f < 1 && \text{fatigue at blade root (gravity loads)} \\
& \sigma_{\text{root-gravity}}/S_f > -1 && \text{fatigue at blade root (gravity loads)} \\
& V_{tip} < V_{tip_{max}} && \text{maximum tip speed}
\end{aligned}
$$

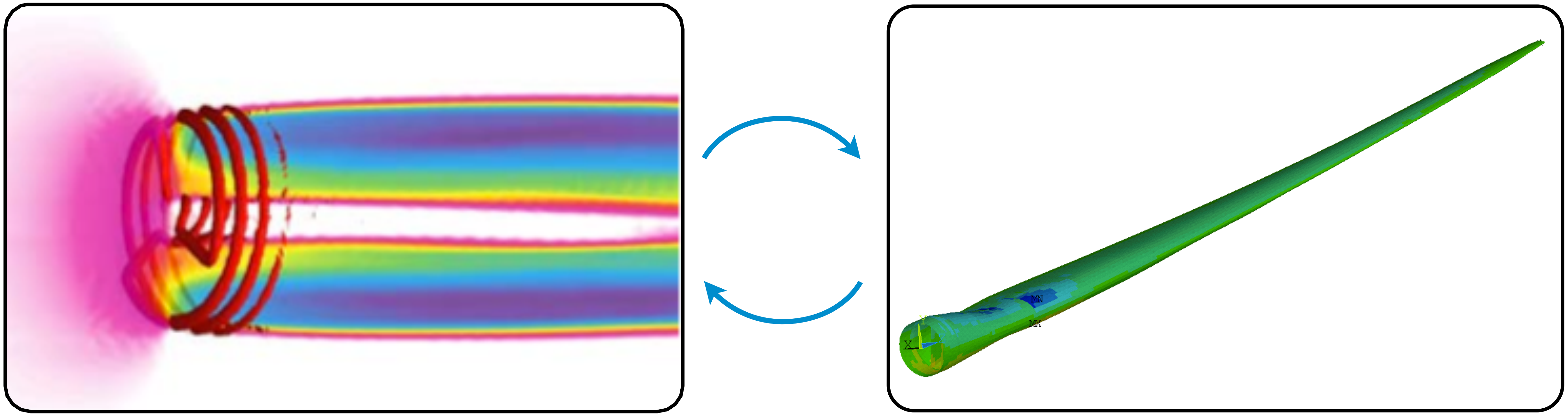
$$c_{set}(x) < 0$$



Maximum Annual Energy Production

Why a single-discipline objective?

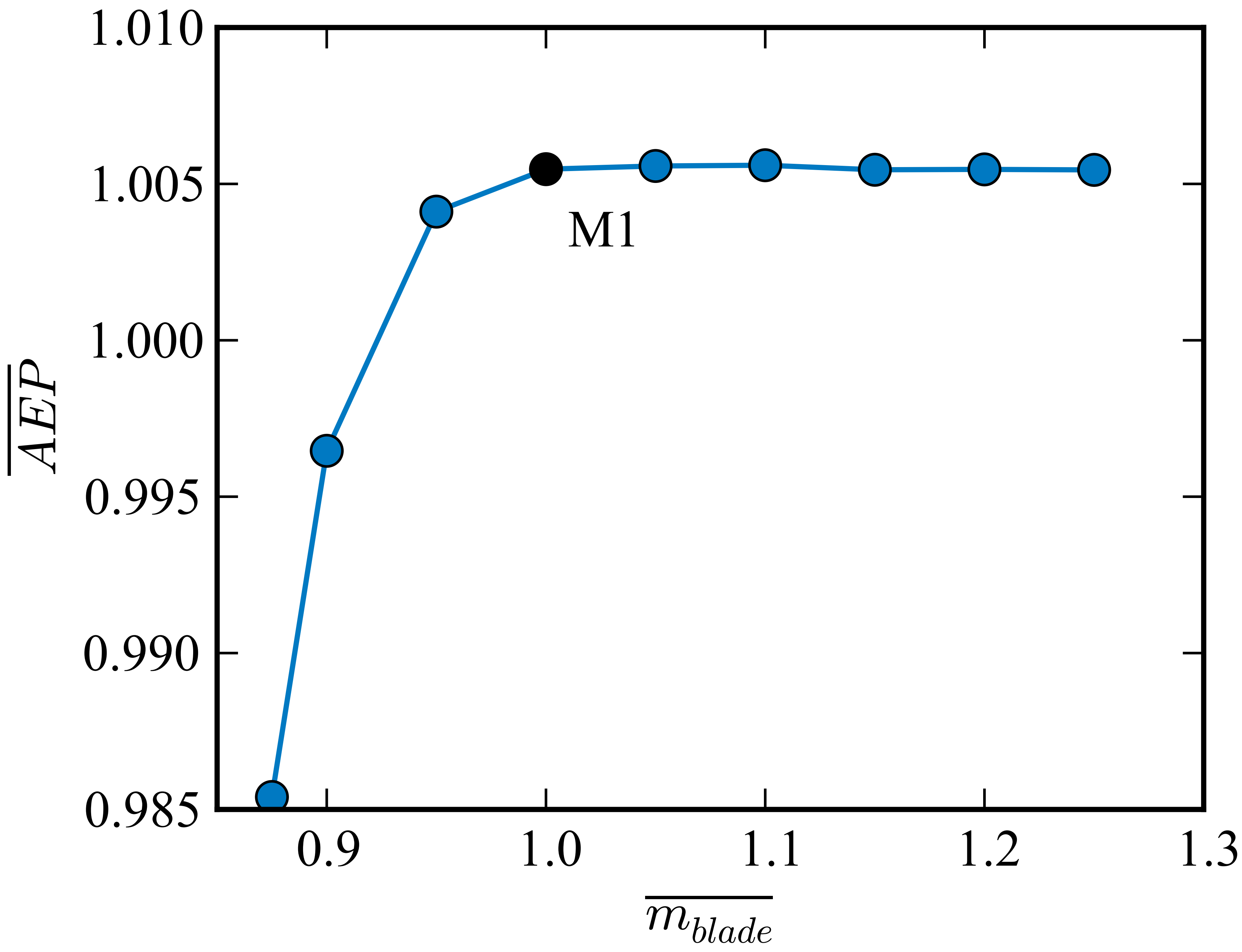
1. No structural model
2. No cost model
3. Organizational structure
4. Computational limitations



Maximize AEP at Fixed Mass

$$\begin{aligned} &\text{maximize} && AEP(x) \\ &\text{with respect to} && x = \{\{c\}, \{\theta\}, \lambda\} \\ &\text{subject to} && c_{set} < 0 \\ & && \overline{m_{blade}} = m_c \end{aligned}$$

Maximize AEP at Fixed Mass



AEP First

$$\begin{array}{ll} \text{maximize} & AEP(x) \\ \text{with respect to} & x = \{\{c\}, \{\theta\}, \lambda\} \\ \text{subject to} & V_{tip} < V_{tip_{max}} \end{array}$$

AEP First

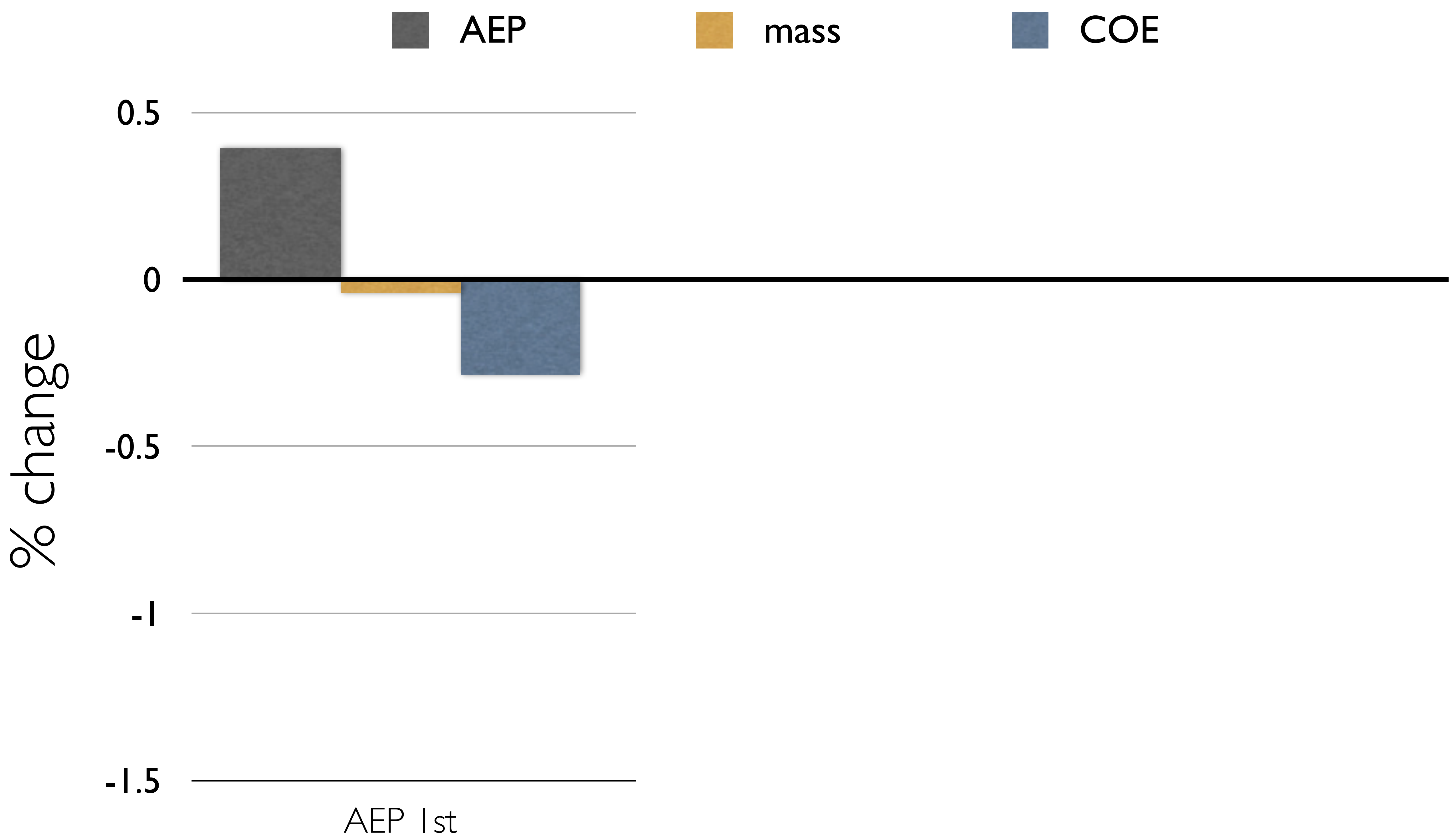
$$
\begin{aligned}
&\text{maximize} && AEP(x) \\
&\text{with respect to} && x = \{\{c\}, \{\theta\}, \lambda\} \\
&\text{subject to} && V_{tip} < V_{tip_{max}} \\
& && i_{aero} < i_{aero0} \qquad \left(i_{aero} \equiv \int \frac{M_b}{t} dr\right) \\
& && S_{plan} < S_{plan_0} \\
& && \sigma_{root} < \sigma_{root0}
\end{aligned}
$$

AEP First

$$
\begin{array}{ll}
\text{maximize} & AEP(x) \\
\text{with respect to} & x = \{\{c\}, \{\theta\}, \lambda\} \\
\text{subject to} & V_{tip} < V_{tip_{max}} \\
& i_{aero} < i_{aero0} \\
& S_{plan} < S_{plan_0} \\
& \sigma_{root} < \sigma_{root0}
\end{array}
$$

$$
\begin{array}{ll}
\text{minimize} & m(x) \\
\text{with respect to} & x = \{t\} \\
\text{subject to} & c_{set}(x) < 0
\end{array}
$$

Comparison Between Methods



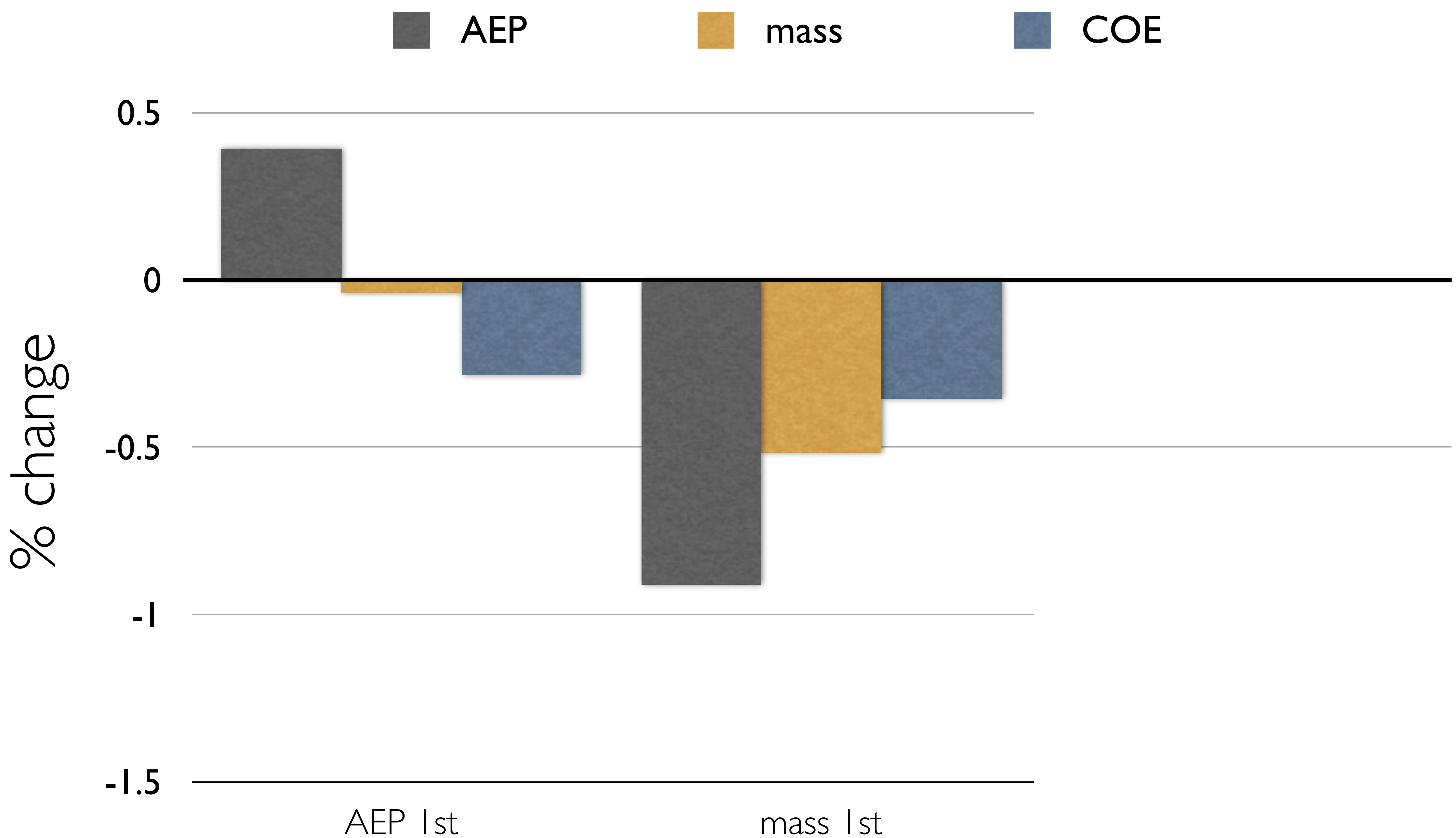
Mass First

$$\begin{aligned} &\text{minimize} && m(x) \\ &\text{with respect to} && x = \{\{c\}, \{t\}\} \\ &\text{subject to} && c_{set}(x) < 0 \end{aligned}$$

$$\begin{aligned} &\text{maximize} && AEP(x) \\ &\text{with respect to} && x = \{\{\theta\}, \lambda\} \\ &\text{subject to} && V_{tip} < V_{tip_{max}} \end{aligned}$$

$$\begin{aligned} &\text{minimize} && m(x) \\ &\text{with respect to} && x = \{\{c\}, \{t\}\} \\ &\text{subject to} && c_{set}(x) < 0 \end{aligned}$$

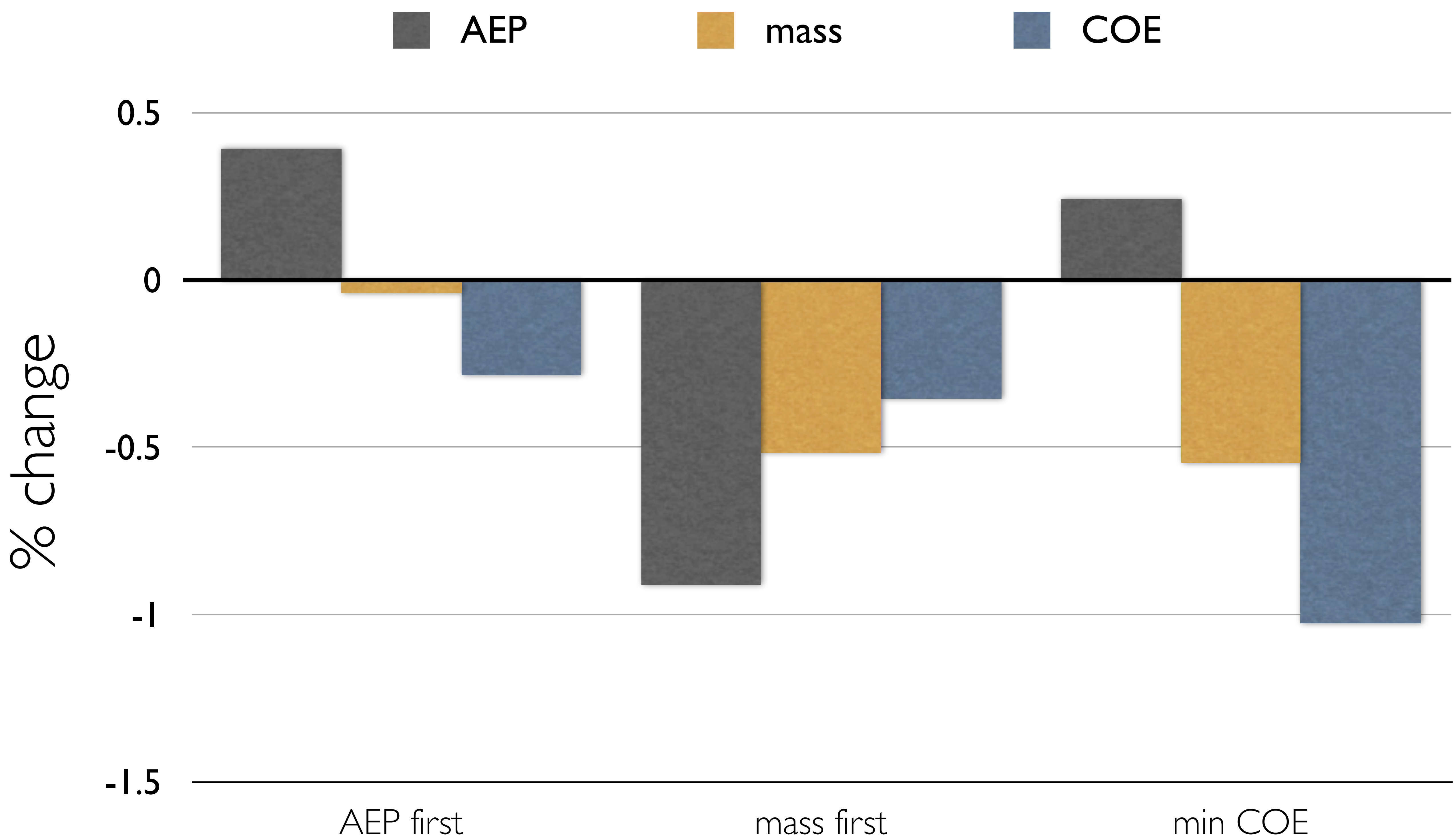
Comparison Between Methods



Minimize COE

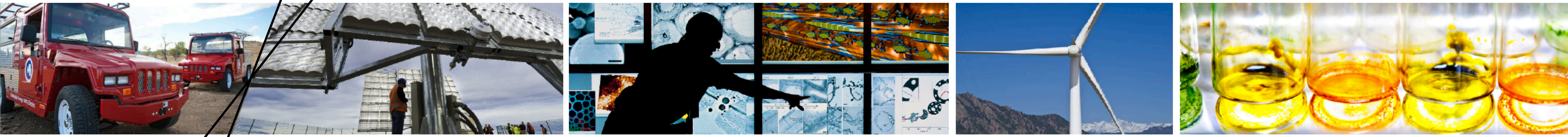
$$
\begin{array}{ll}
\text{minimize} & COE(x) \\
\text{with respect to} & x = \{\{c\}, \{\theta\}, \{t\}, \lambda\} \\
\text{subject to} & c_{set}(x) < 0
\end{array}
$$

Comparison Between Methods



Conclusions

1. Similar aerodynamic performance can be achieved with feasible designs with very different masses.
2. Sequential aero/structural optimization is significantly inferior to metrics that combine aerodynamic and structural performance.



Minimum Turbine Mass / AEP

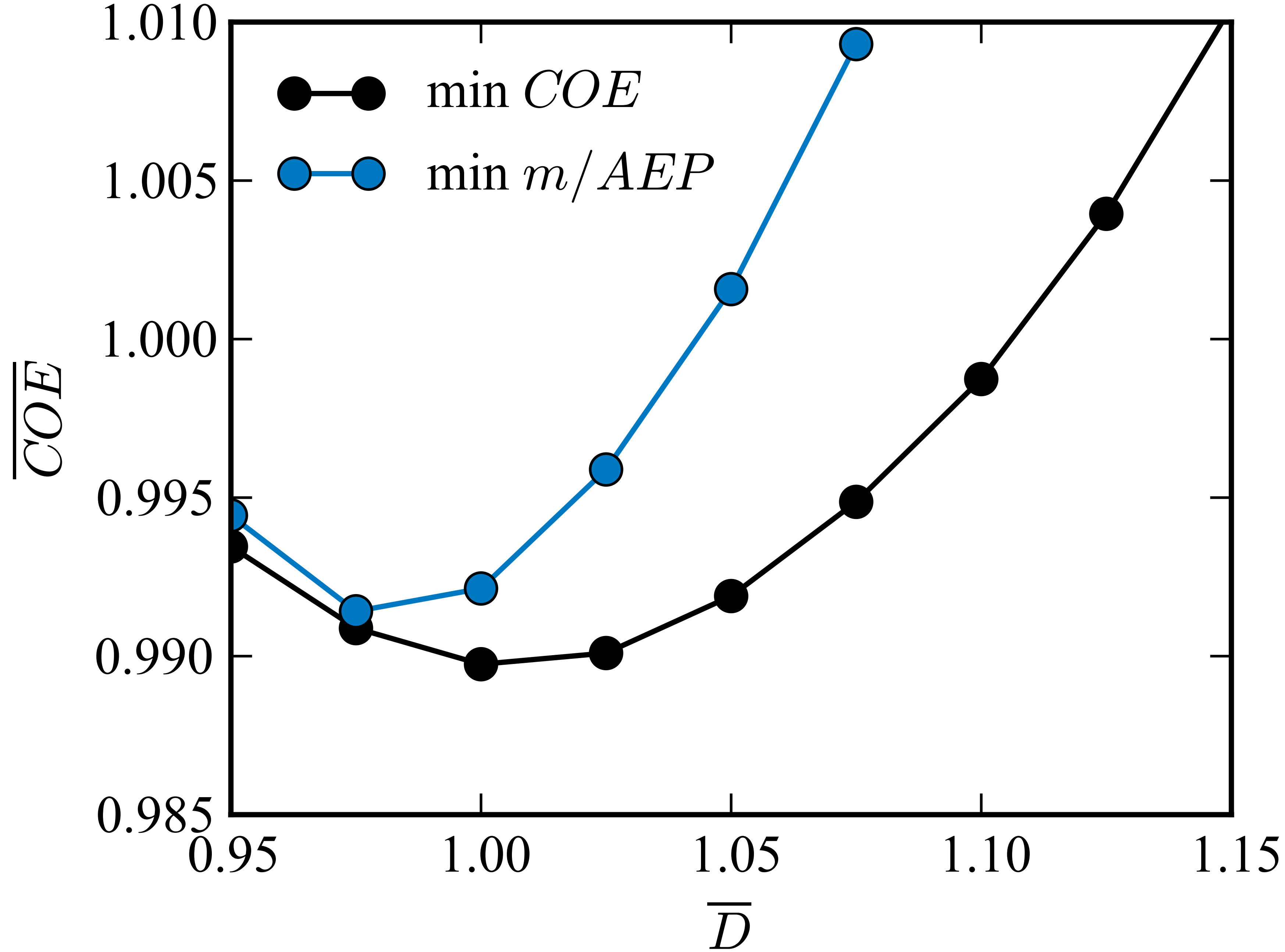
Cost of Energy

$$\text{COE} = \frac{\text{FCR (TCC + BOS) + O\&M}}{\text{AEP}} \approx \frac{m_{turbine}}{\text{AEP}}$$

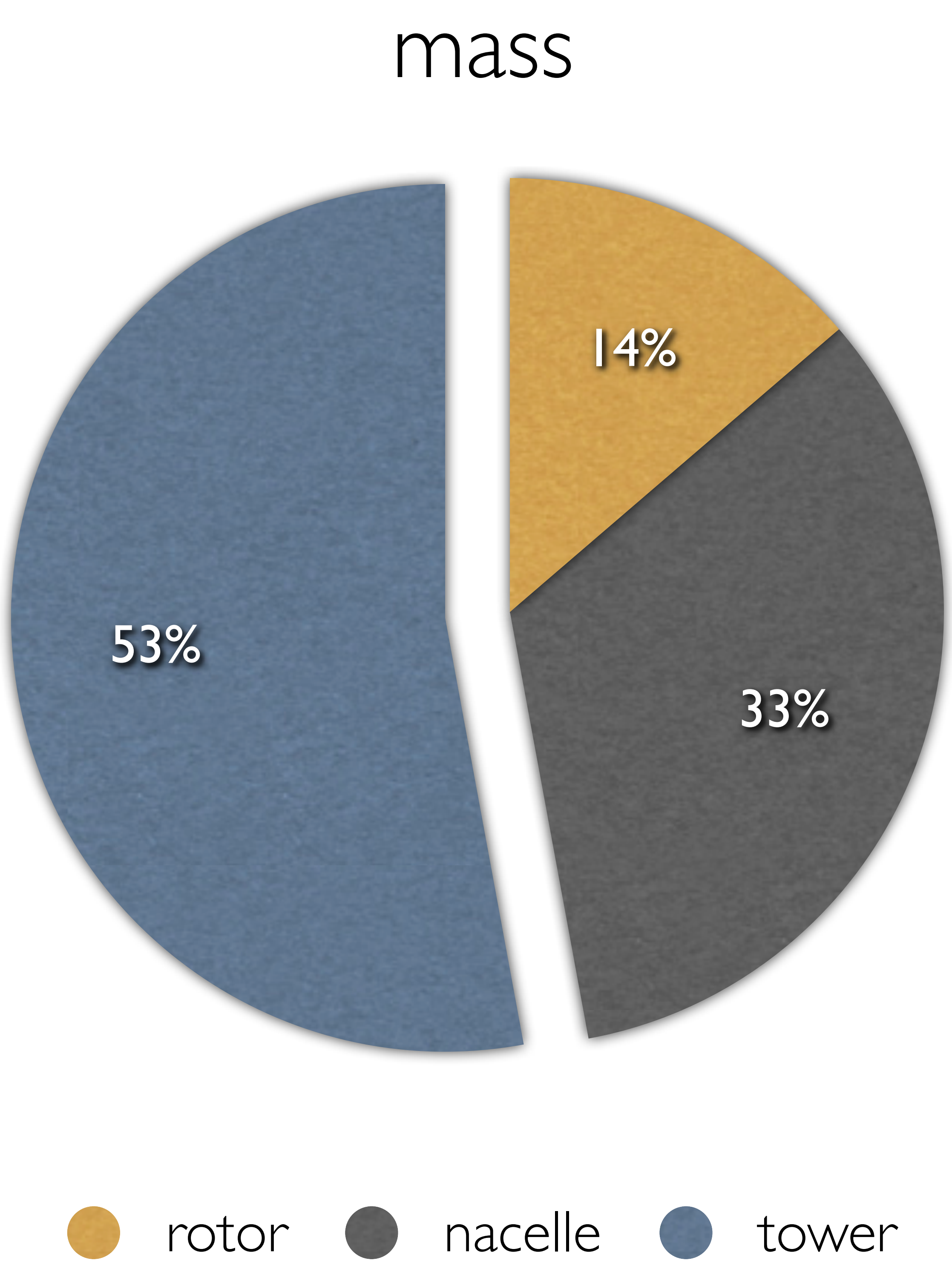
Vary Rotor Diameter

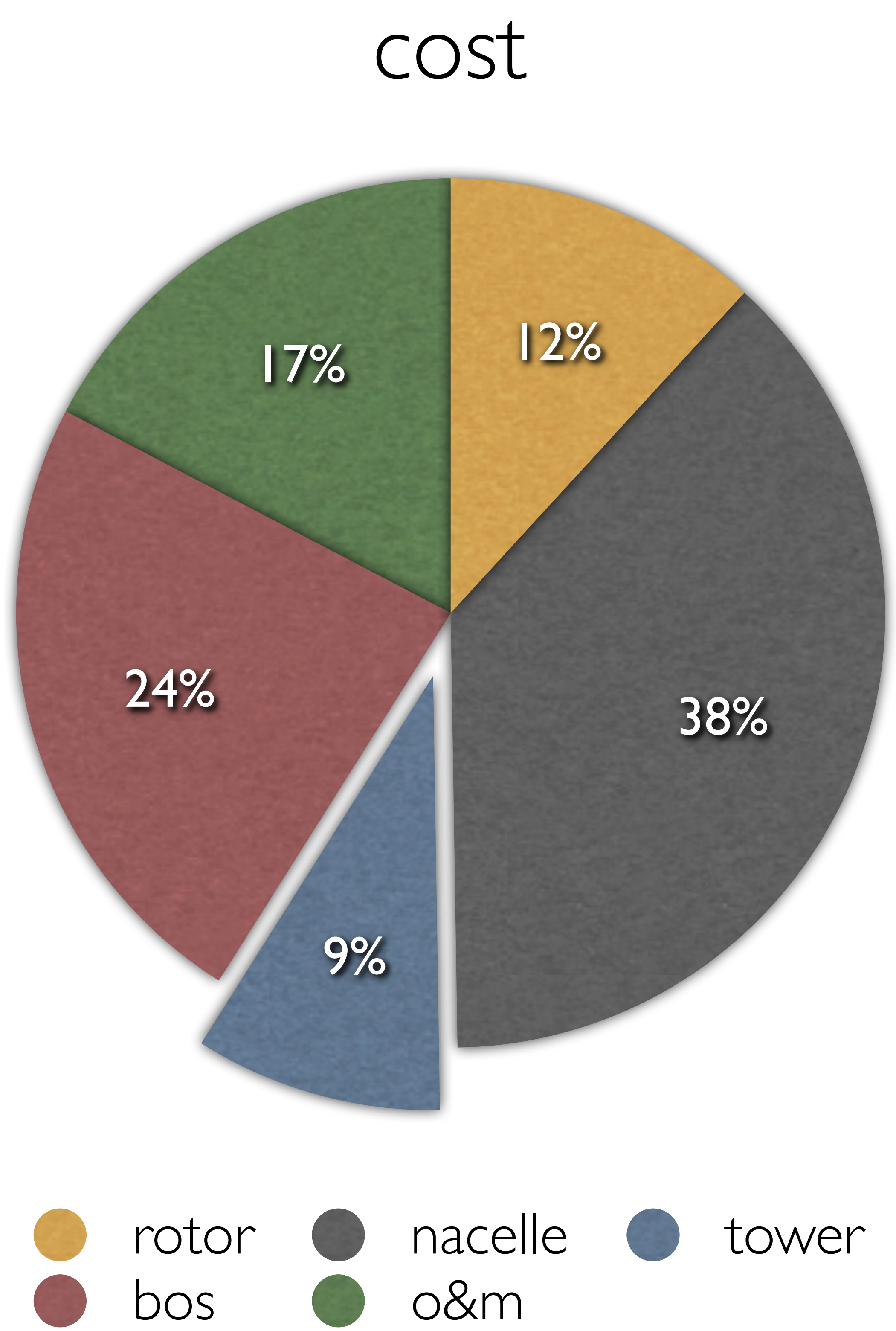
minimize	$COE(x; D)$ or $m(x; D)/AEP(x; D)$
with respect to	$x = \{\{c\}, \{\theta\}, \{t\}, \lambda\}$
subject to	$c_{set}(x) < 0$

Maximize AEP at Fixed Mass

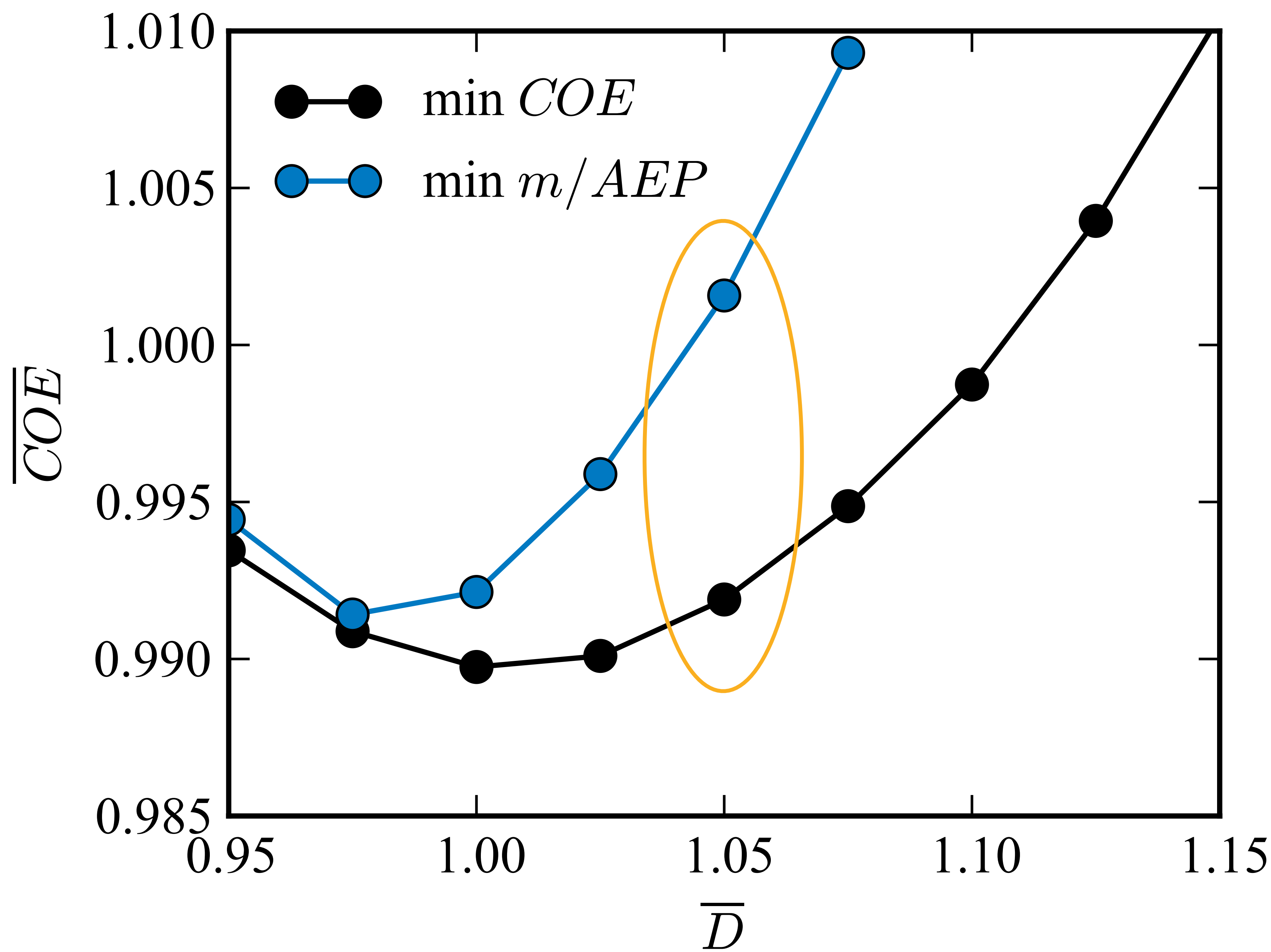


Tower Contributions to Mass/Cost

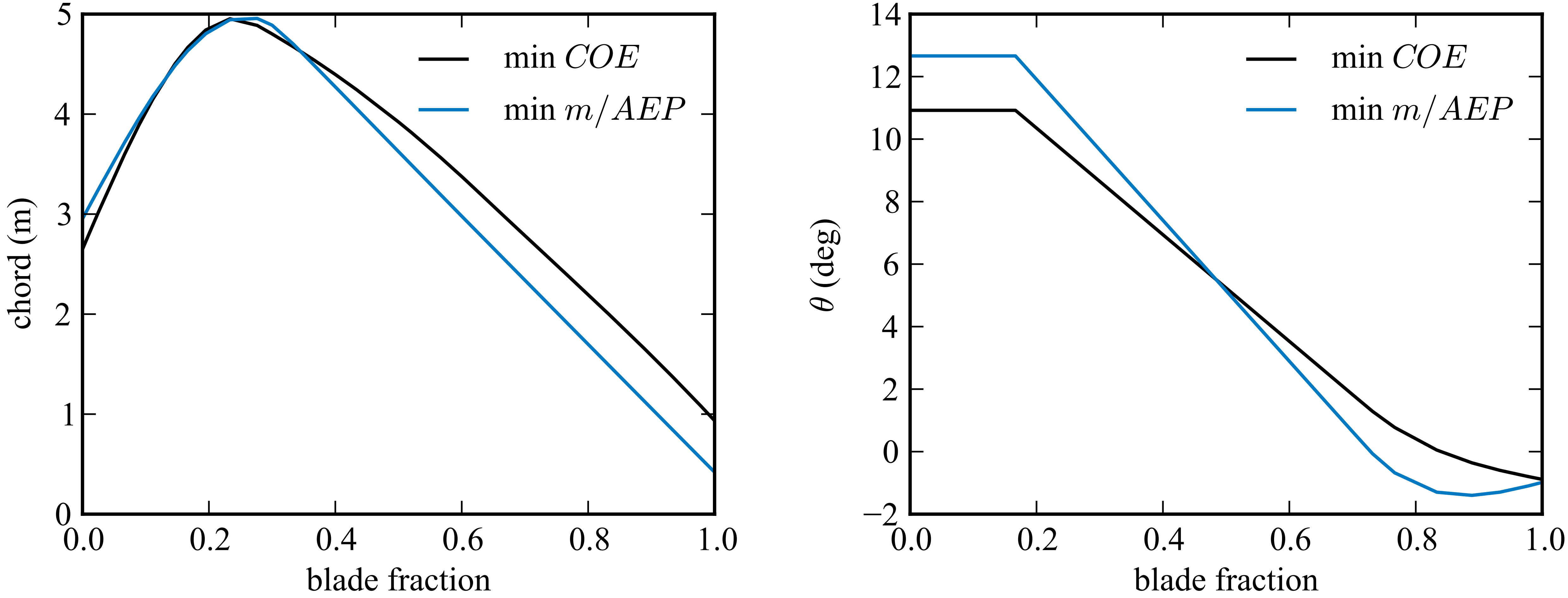




Maximize AEP at Fixed Mass



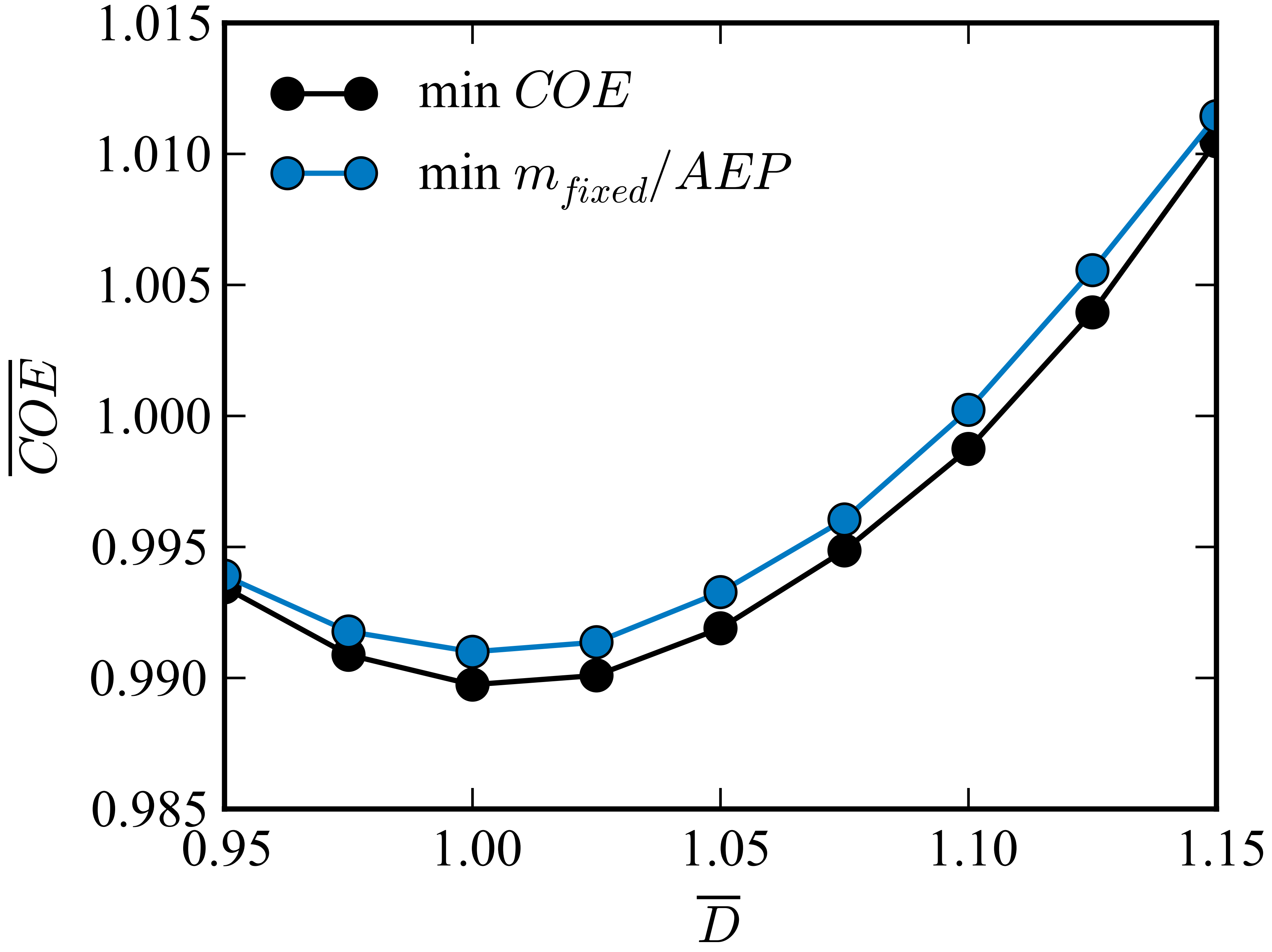
Maximize AEP at Fixed Mass



Fixed Mass

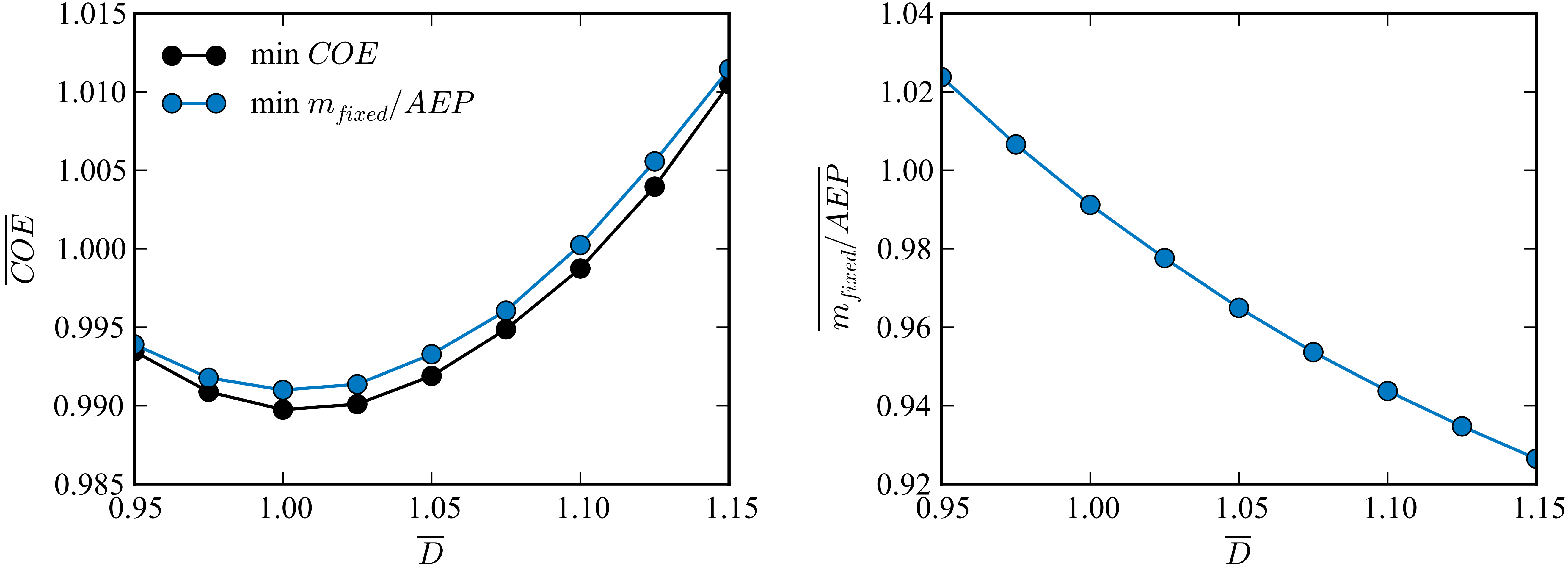
$$m_{fixed} = m_{blades} + m_{other}$$

Fixed Mass



min COE
min m_{fixed}/AEP
1.015
1.010
1.005
1.000
0.995
0.990
0.985
$\overline{COE}$
0.95
1.00
1.05
1.10
1.15
$\overline{D}$

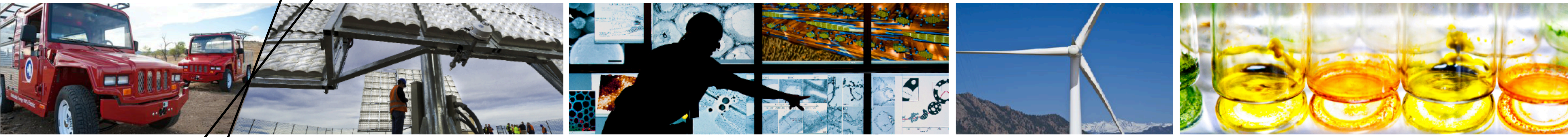
Fixed Mass



min COE
min m_{fixed}/AEP
$\overline{COE}$
1.015
1.010
1.005
1.000
0.995
0.990
0.985
0.95
1.00
1.05
1.10
1.15
$\overline{D}$
$\overline{m_{fixed}/AEP}$
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.95
1.00
1.05
1.10
1.15
$\overline{D}$

Conclusions

1. m/AEP can work well at a fixed diameter but is often misleading for variable diameter optimization
2. Problem must be constructed carefully to prevent over-incentivizing the optimizer to reduce tower mass



Minimum Cost of Energy

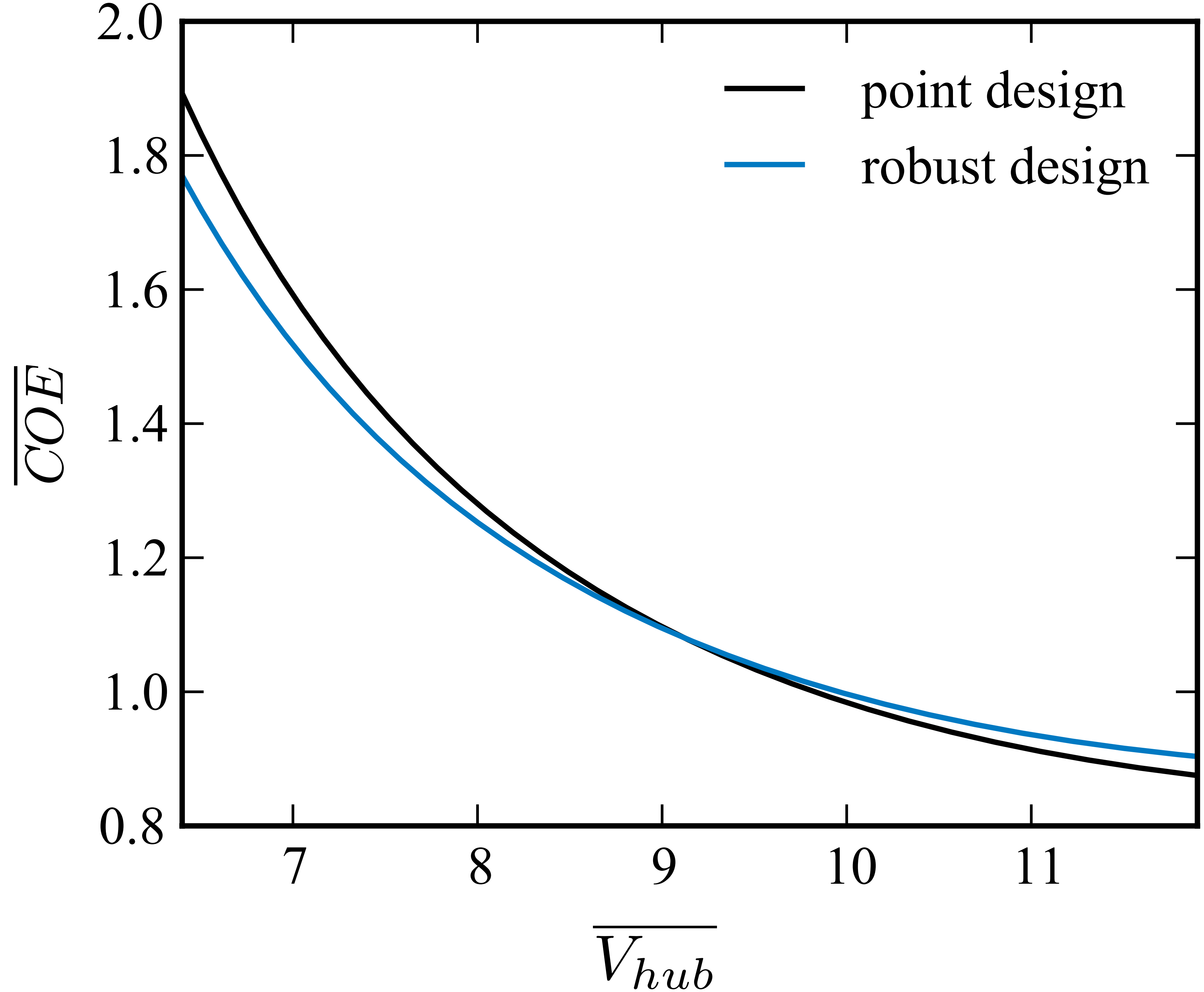
Robust Optimization

Wind Power Class	Wind Speed (50m)
3	6.4
4	7.0
5	7.5
6	8.0
7	11.9

Robust Optimization

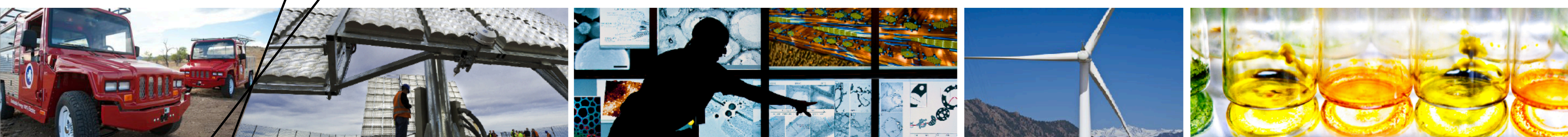
$$
\begin{aligned}
&\text{minimize} && < COE(x; \overline{V}_{hub}) > \\
&\text{where} && \overline{V}_{hub} \sim \mathcal{U}(6.4, 11.9) \\
&\text{with respect to} && x = \{\{c\}, \{\theta\}, \{t\}, \lambda, D, rating\} \\
&\text{subject to} && c_{set}(x) < 0
\end{aligned}
$$

Robust Design



Conclusions

1. Optimization under uncertainty is important given the stochastic nature of the problem
2. Fidelity of the cost model can dramatically affect results



Conclusions

Conclusions

1. Sequential (or single-discipline) optimization is significantly inferior as compared to integrated metrics
2. m/AEP can be a useful metric at a fixed diameter if tower mass is handled carefully
3. High-fidelity cost modeling and inclusion of uncertainty are important considerations

Acknowledgements

- Rick Damiani
- Pat Moriarty
- Katherine Dykes
- George Scott

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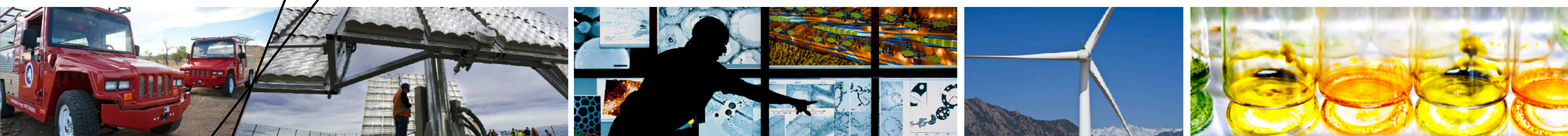

Thank You