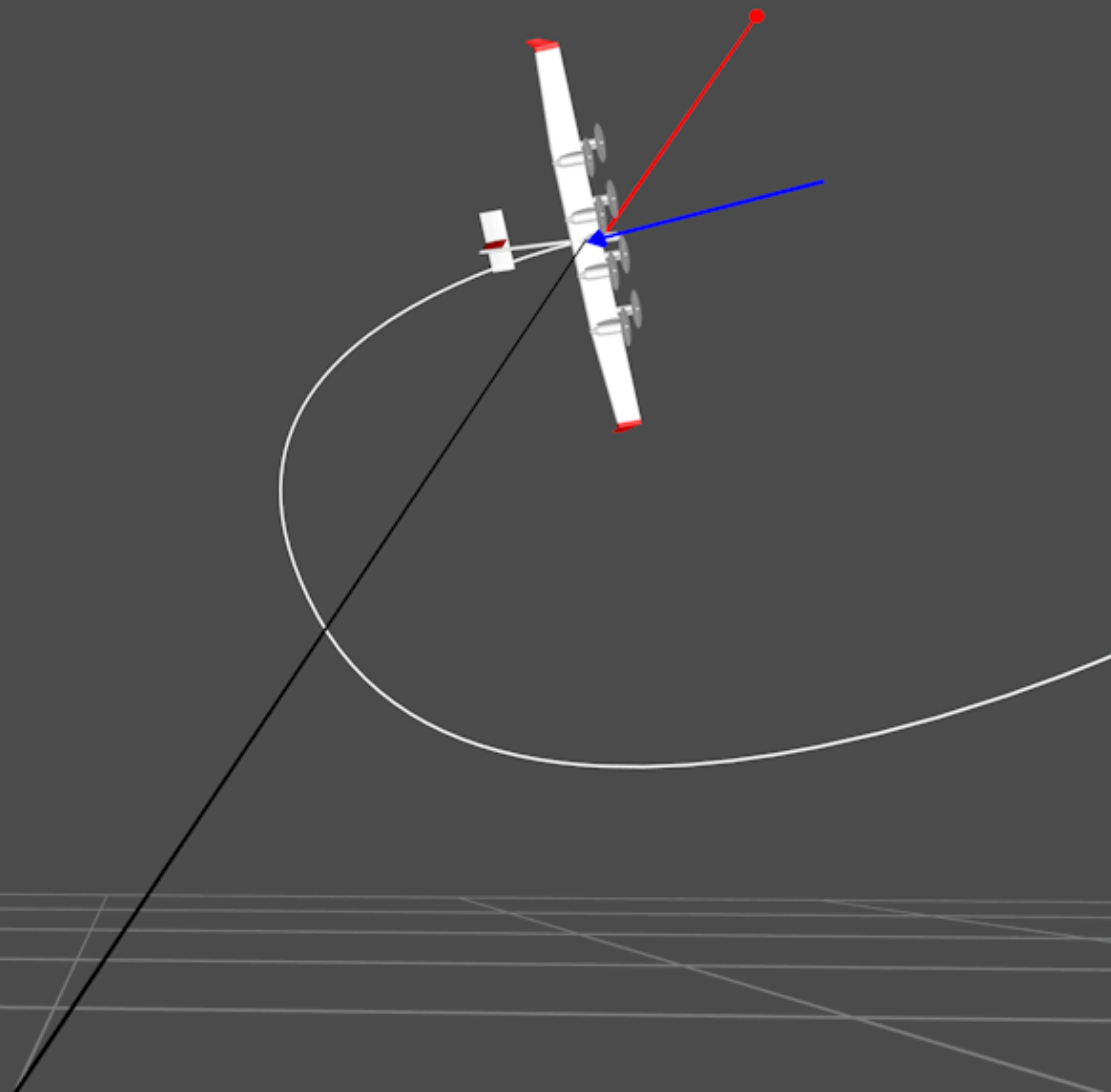
Institute for Electrical Drive Systems and Power Electronics,
Department of Electrical Engineering and Information Technology,
Technische Universität München



Power Curve and Design Optimization of Drag Power Kites

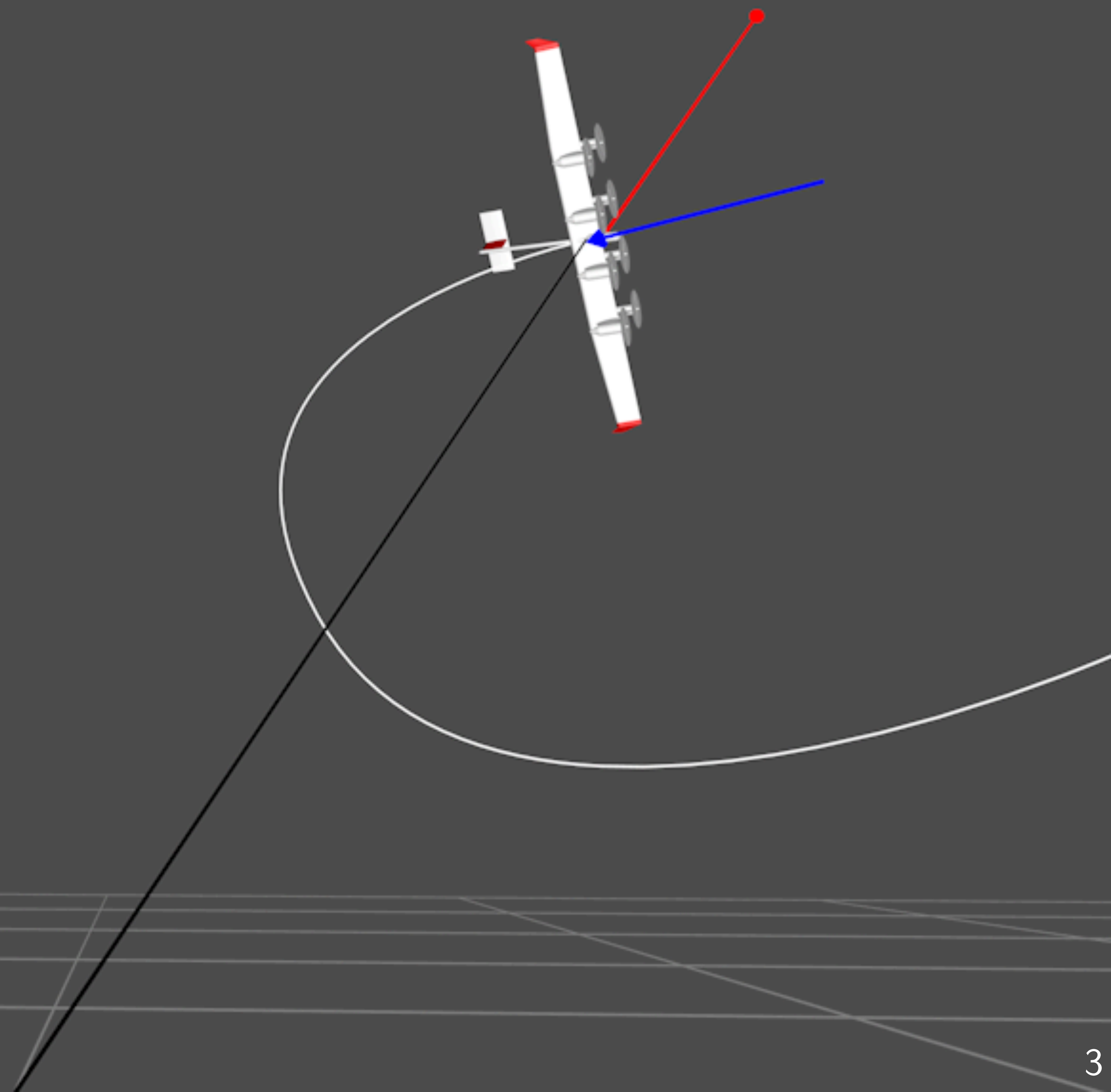
Florian Bauer, R. Kennel, C. Hackl, F. Campagnolo, M. Patt, R. Schmehl
florian.bauer@tum.de,
October 5th, 2017,
Airborne Wind Energy Conference 2017, Freiburg, Germany

How does an optimal drag power kite look like?

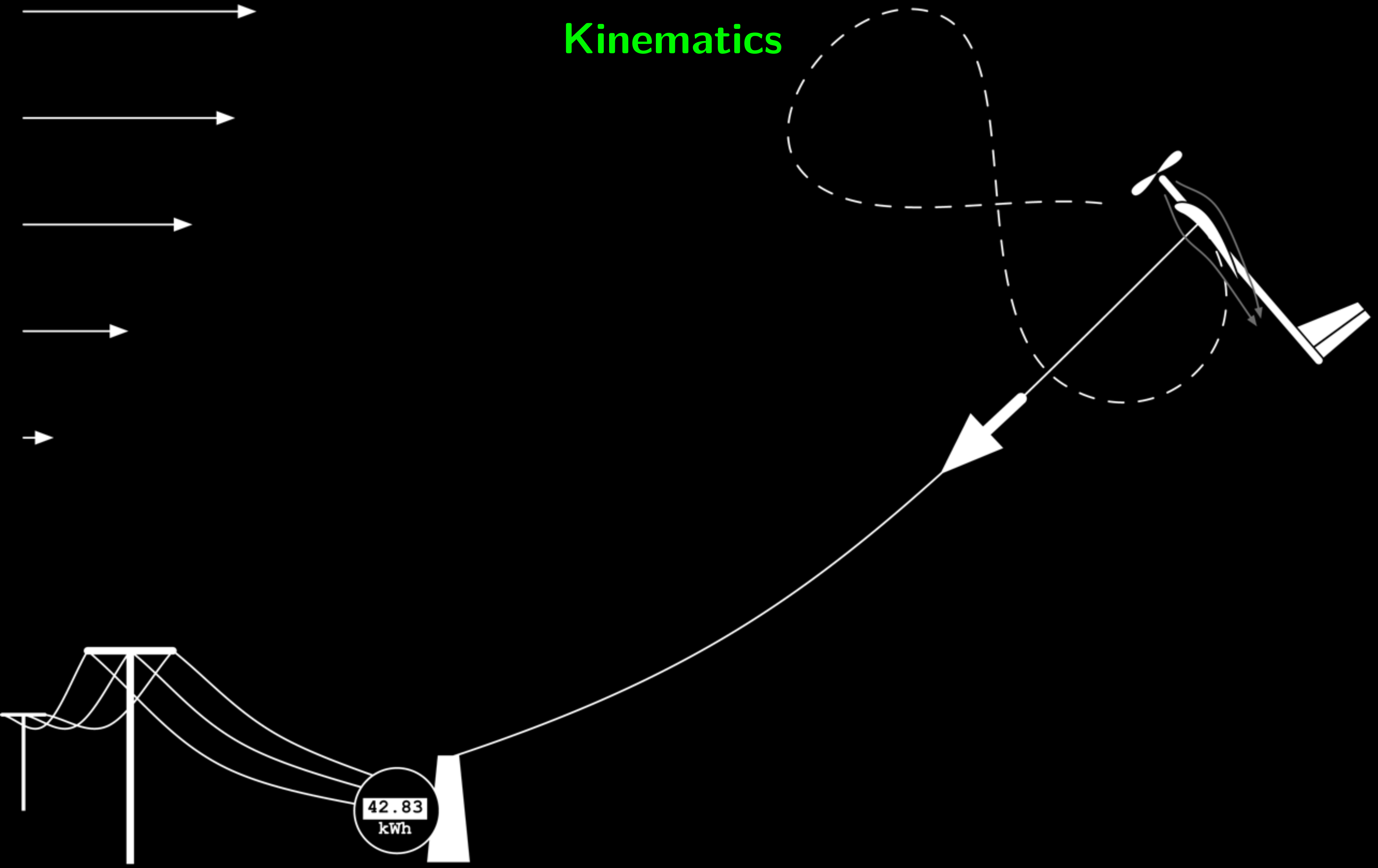
How does an optimal drag power kite look like?

... and what are the sensitivities of design parameters?

Outline



Kinematics



Assumption 1: Loyd's model (extended)

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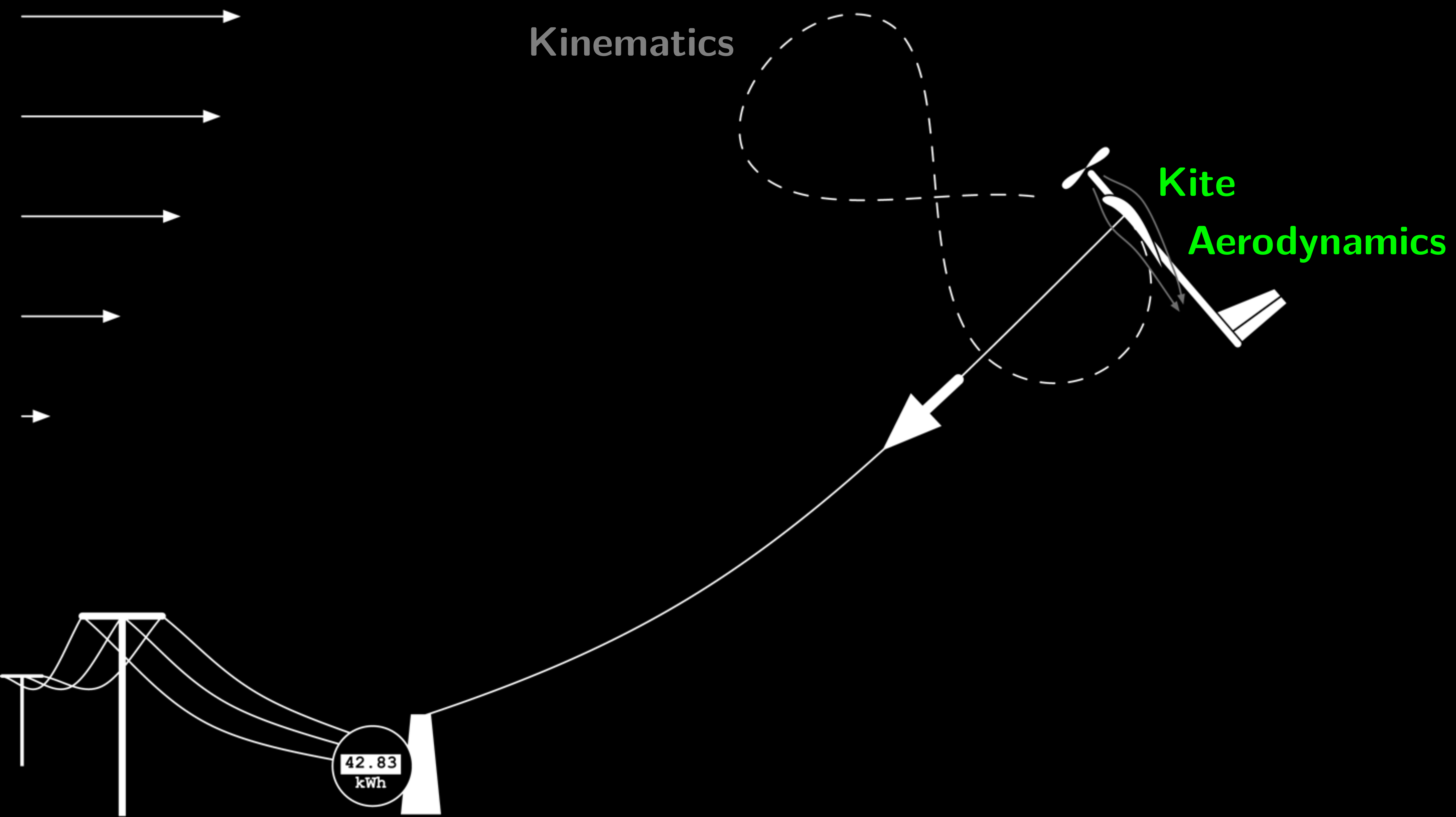
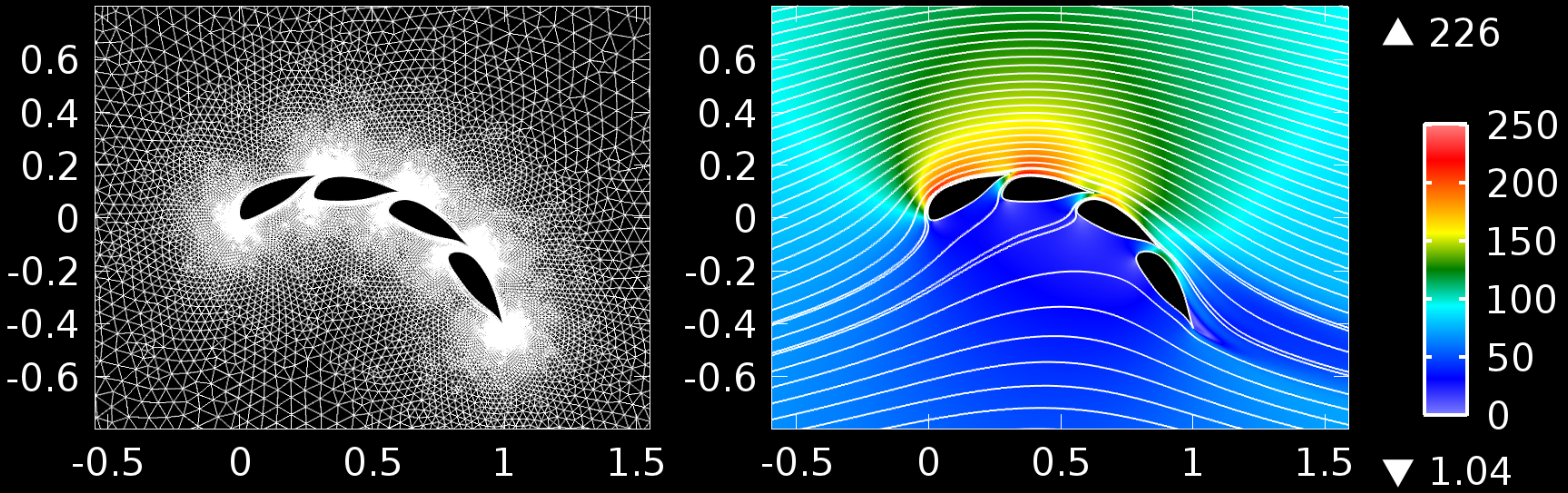
$$v_\mathrm{a} = \cos(\varphi)\cos(\vartheta) v_\mathrm{w} \frac{\sqrt{C_\mathrm{L}^2 + (C_\mathrm{D,eq} + C_\mathrm{D,rot})^2}}{C_\mathrm{D,\Sigma}}$$

Assumption 1: Loyd's model (extended)

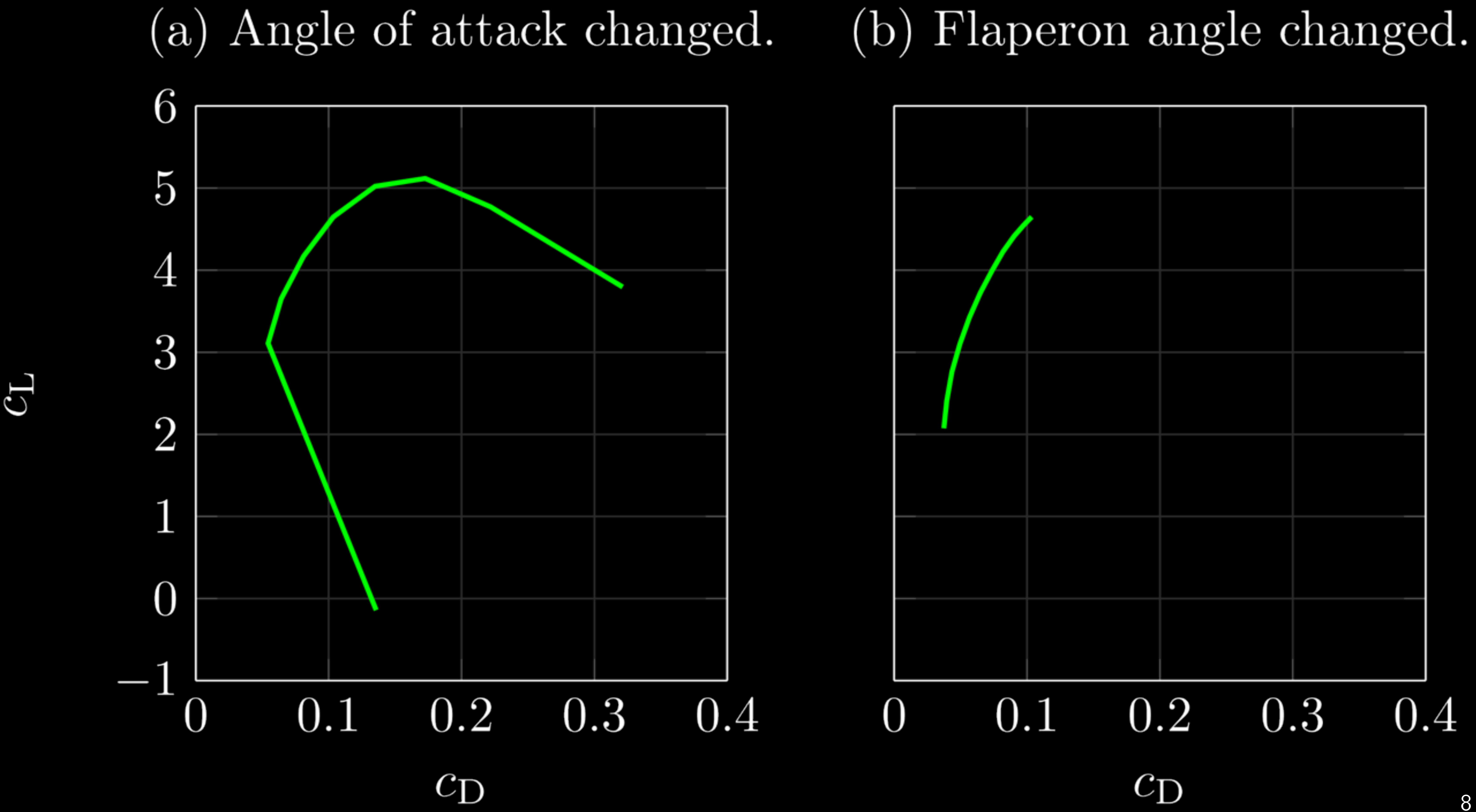
$$v_{\mathrm{a}} = \cos(\varphi)\cos(\vartheta)v_{\mathrm{w}}\frac{\sqrt{C_{\mathrm{L}}^2 + (C_{\mathrm{D,eq}} + C_{\mathrm{D,rot}})^2}}{C_{\mathrm{D},\Sigma}}$$

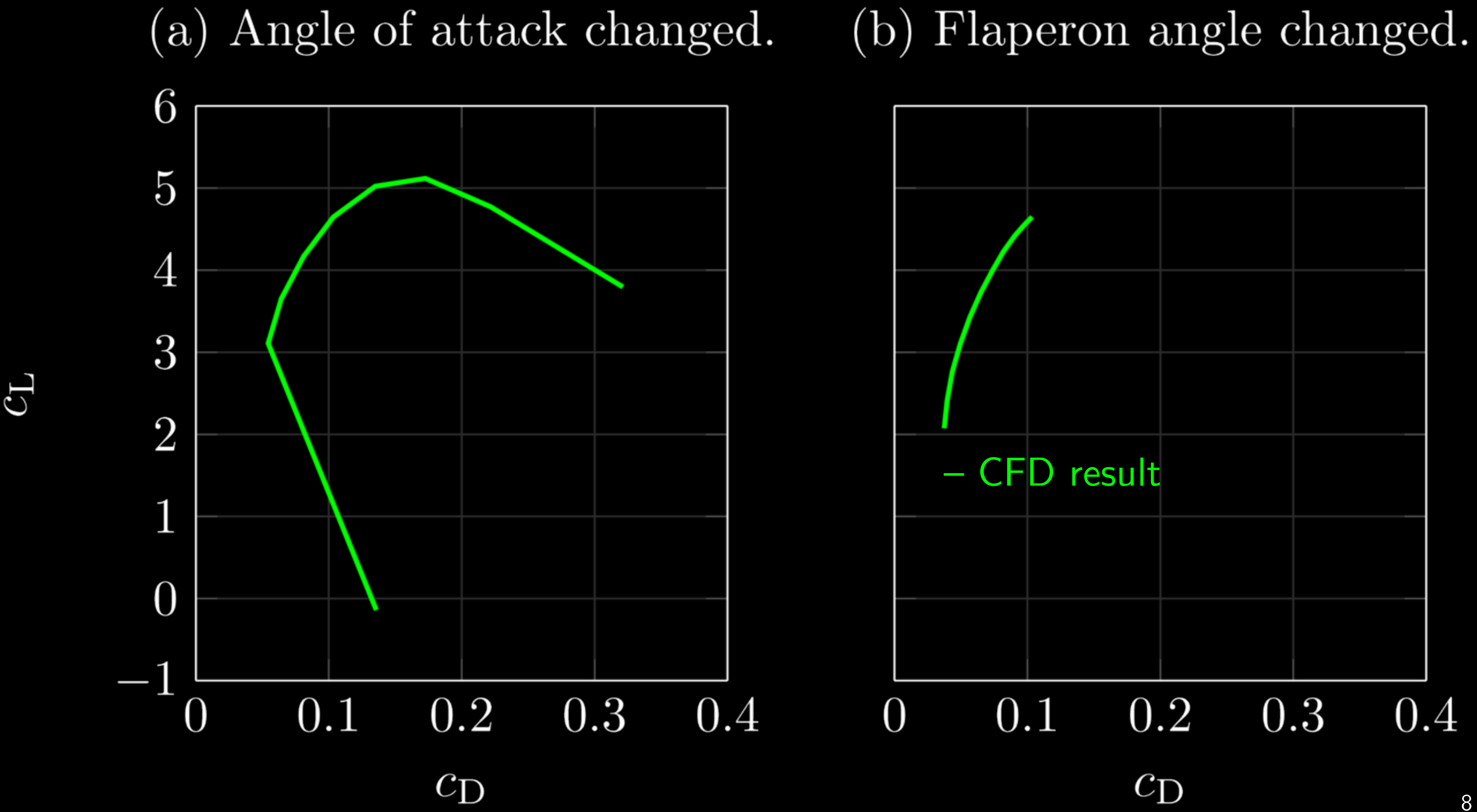
Assumption 2: azimuth and elevation are constant "effective" values


Kinematics
Kite
Aerodynamics
42.83
kWh



cf.: D. Vander Lind. "Airfoil for a flying wind turbine". US Patent 9,709,026. July 2017.


(a) Angle of attack changed.
(b) Flaperon angle changed.
c_L
c_D
c_D
6
5
4
3
2
1
0
−1
0
0.1
0.2
0.3
0.4
0
0.1
0.2
0.3
0.4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−1
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0.1
0.2
0.3
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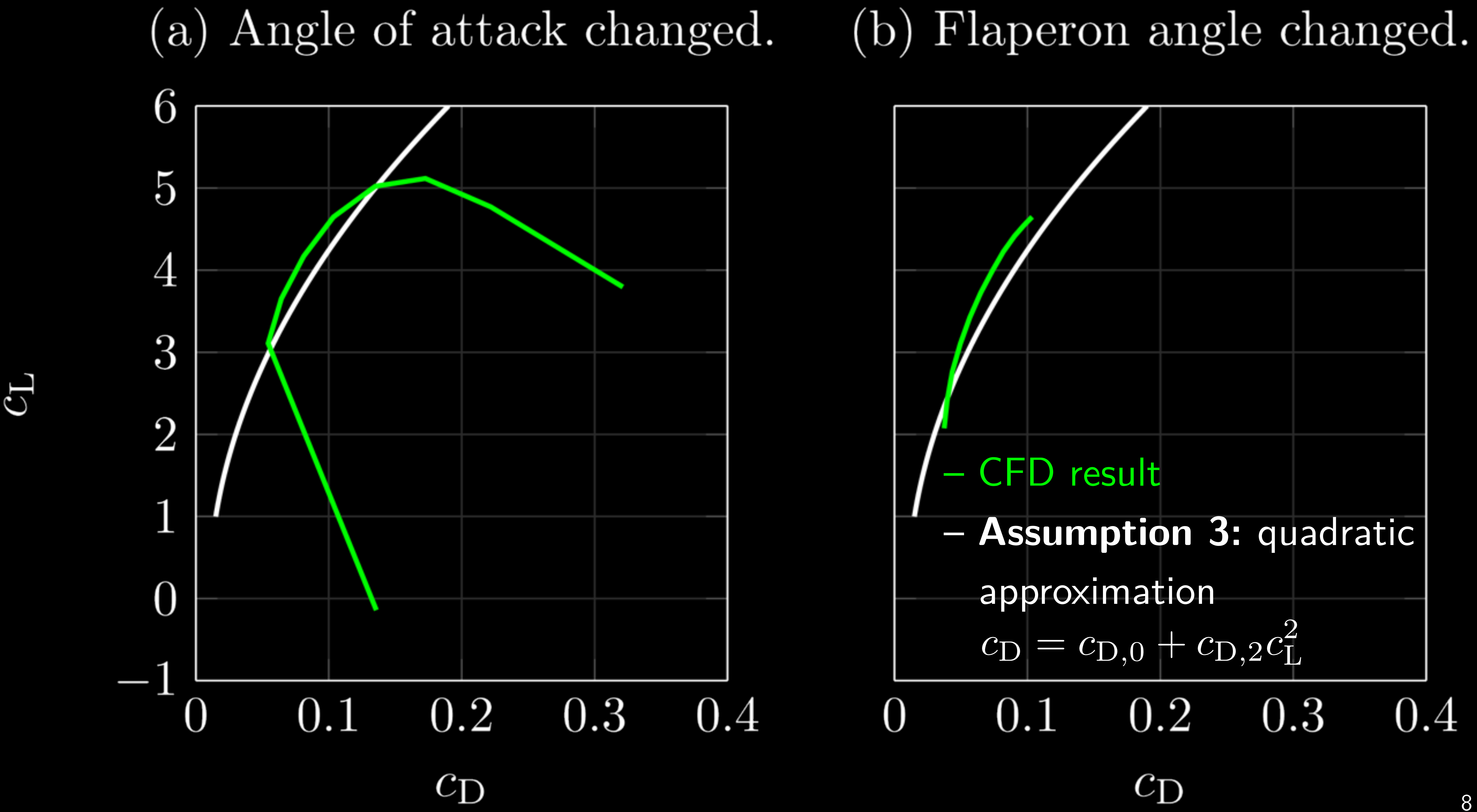
– CFD result



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c_L
6
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0.1
0.2
0.3
0.4
c_D
0
0.1
0.2
0.3
0.4
c_D
– CFD result
– **Assumption 3:** quadratic approximation
$c_D = c_{D,0} + c_{D,2}c_L^2$

Assumption 4: thin airfoil

$$C_{\mathrm{L}} = \frac{c_{\mathrm{L}}}{1 + \frac{2}{\text{Æ}}} \quad \text{with} \quad \text{Æ} = \frac{b^2}{A}$$

$$C_{\mathrm{D,k}} = c_{\mathrm{D}} + \underbrace{\frac{C_{\mathrm{L}}^2}{\pi e \text{Æ}}}_{C_{\mathrm{D,k,i}}}$$

Assumption 4: thin airfoil

$$C_\mathrm{L} = \frac{c_\mathrm{L}}{1 + \frac{2}{\mathit{AR}}} \quad \text{with} \quad \mathit{AR} = \frac{b^2}{A}$$

$$C_\mathrm{D,k} = c_\mathrm{D} + \underbrace{\frac{C_\mathrm{L}^2}{\pi e \mathit{AR}}}_{C_\mathrm{D,k,i}} + C_\mathrm{D,k,a} + C_\mathrm{D,k,o}$$

https://upload.wikimedia.org/wikipedia/commons/f/fe/Airplane_vortex_edit.jpg

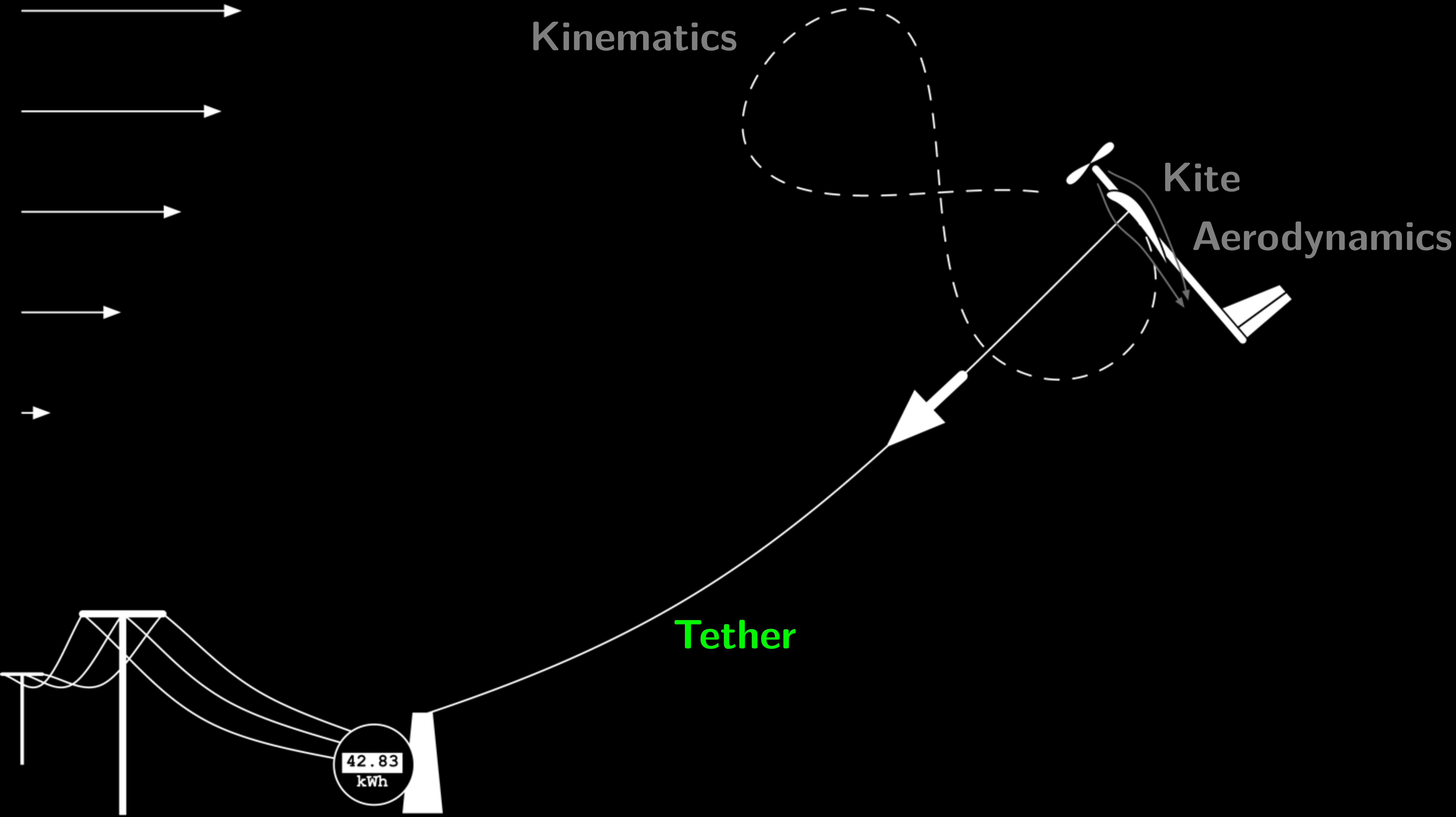
Assumption 4: thin airfoil

$$C_{\mathrm{L}} = \frac{c_{\mathrm{L}}}{1 + \frac{2}{Æ}} \quad \text{with} \quad Æ = \frac{b^2}{A/n_{\mathrm{mw}}}$$

$$C_{\mathrm{D,k}} = c_{\mathrm{D}} + \underbrace{\frac{C_{\mathrm{L}}^2}{\pi e Æ}}_{C_{\mathrm{D,k,i}}} + C_{\mathrm{D,k,a}} + C_{\mathrm{D,k,o}}$$

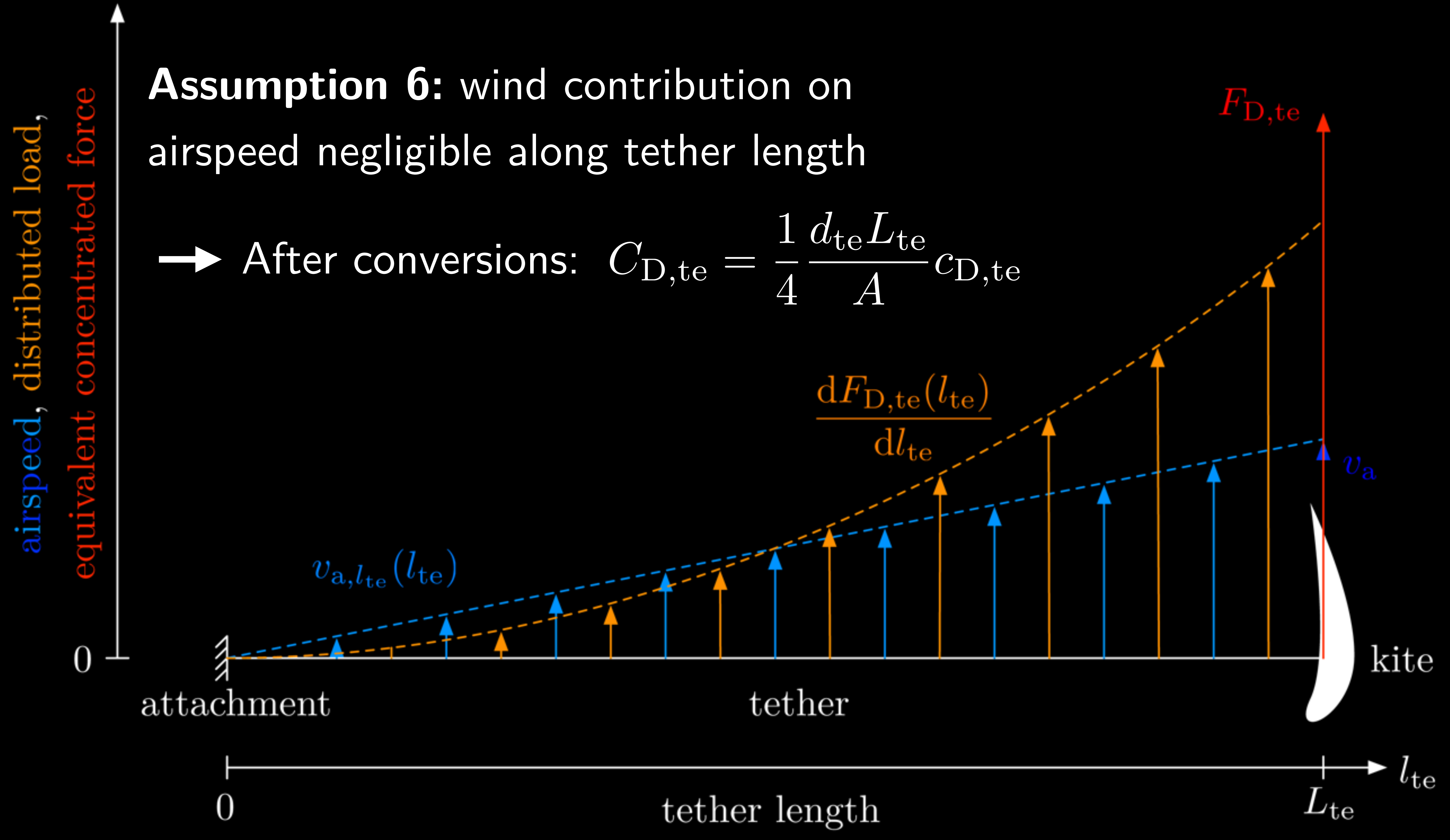
Assumption 5: no interaction between wings and rotors

cf.: J. Katz and A. Plotkin. Low-Speed Aerodynamics. Cambridge Aerospace Series. Cambridge University Press, 2001. ISBN: 9780521665520.

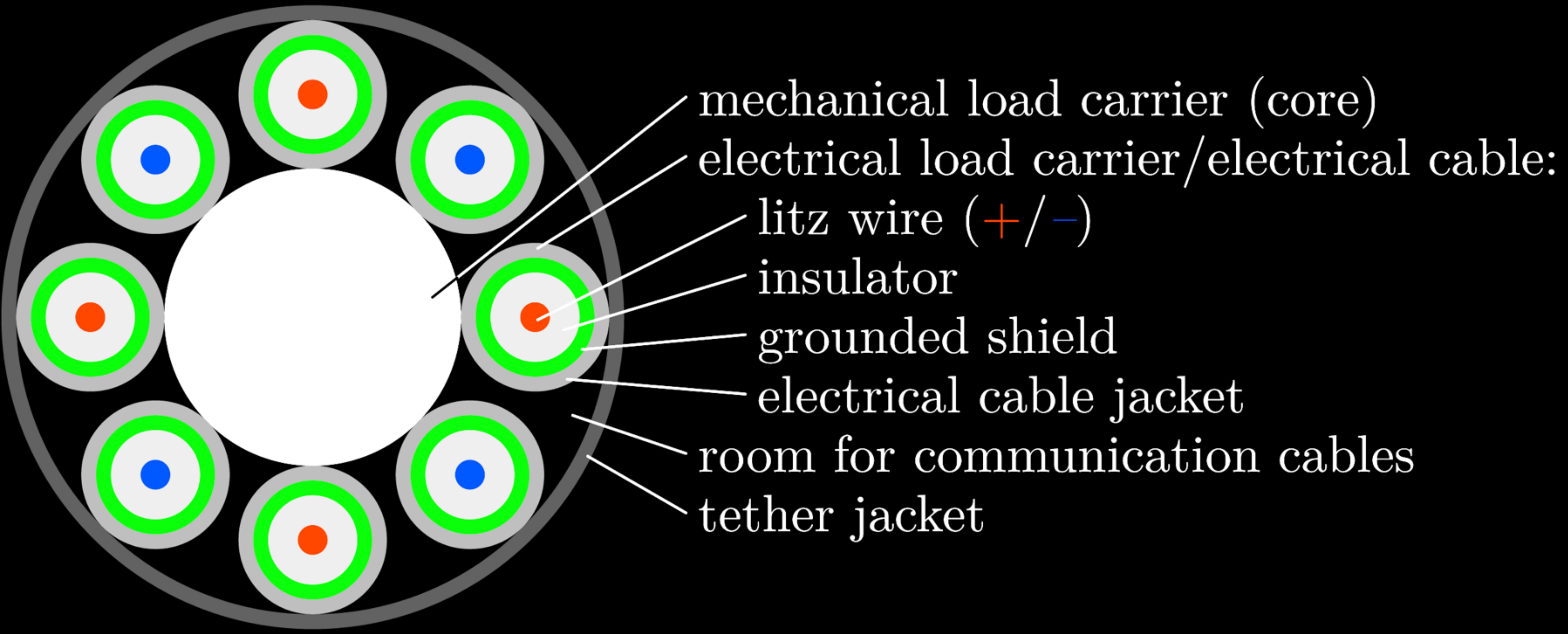

Kinematics
Kite
Aerodynamics
Tether
42.83
kWh

Assumption 6: wind contribution on airspeed negligible along tether length

→ After conversions: $C_{\mathrm{D,te}} = \frac{1}{4}\frac{d_{\mathrm{te}}L_{\mathrm{te}}}{A}c_{\mathrm{D,te}}$



cf. e.g.: B. Houska, M. Diehl, Optimal control for power generating kites, in: Proceedings of the 9th European Control Conference, Kos, Greece, 2007, pp. 3560–3567.


mechanical load carrier (core)
electrical load carrier/electrical cable:
litz wire (+/−)
insulator
grounded shield
electrical cable jacket
room for communication cables
tether jacket

Mechanical strength: $F_{\mathrm{te,max}} \sim A_{\mathrm{te,core}}$

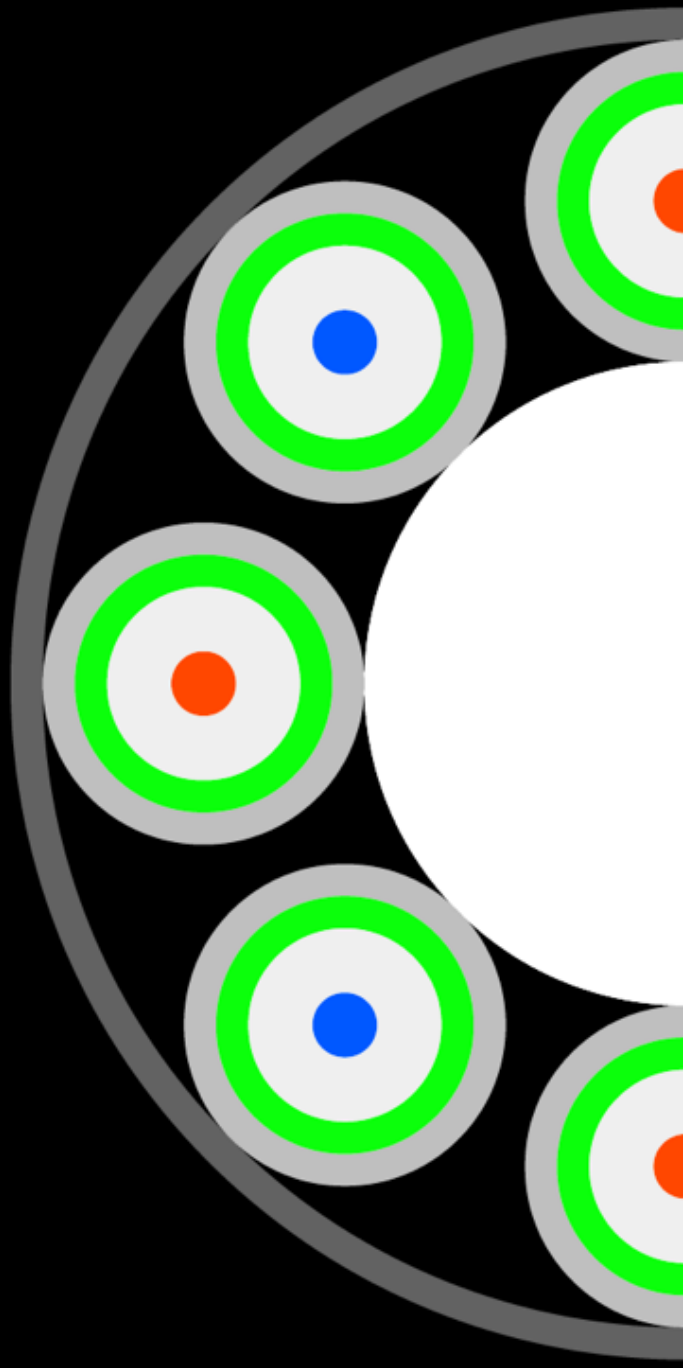
Electrical resistance: $R_{\mathrm{te,wire}} \sim \dfrac{L_{\mathrm{te}}}{A_{\mathrm{te,wire}}}$

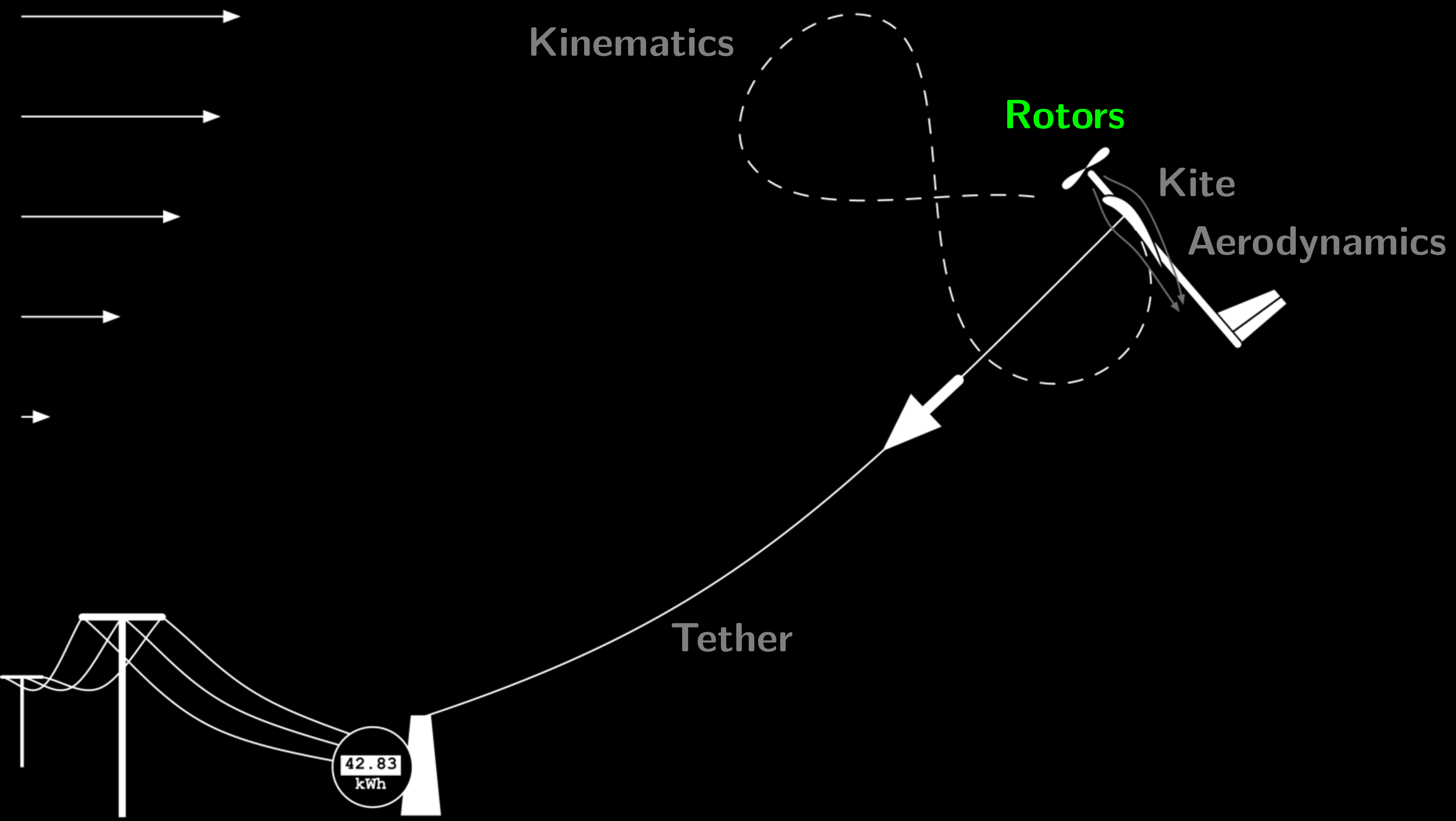
$$R_{\mathrm{te}} = \frac{R_{\mathrm{te,wire}}}{n_{\mathrm{te,c,+}}} + \frac{R_{\mathrm{te,wire}}}{n_{\mathrm{te,c,-}}}$$

Dielectric strength: $E_{\mathrm{te,ins}} = f(U_{\mathrm{te,n}}, r_{\mathrm{wire}}, w_{\mathrm{ins}})$

Total diameter, mass: *[straight-forward summation]*

Feasibility condition: *[no overlapping electrical cables]*




Kinematics
Rotors
Kite
Aerodynamics
Tether
42.83
kWh

“Aerodynamic” power: $$P_\mathrm{a} = \frac{1}{2}\rho A v_\mathrm{a}^3 C_\mathrm{D,rot}$$

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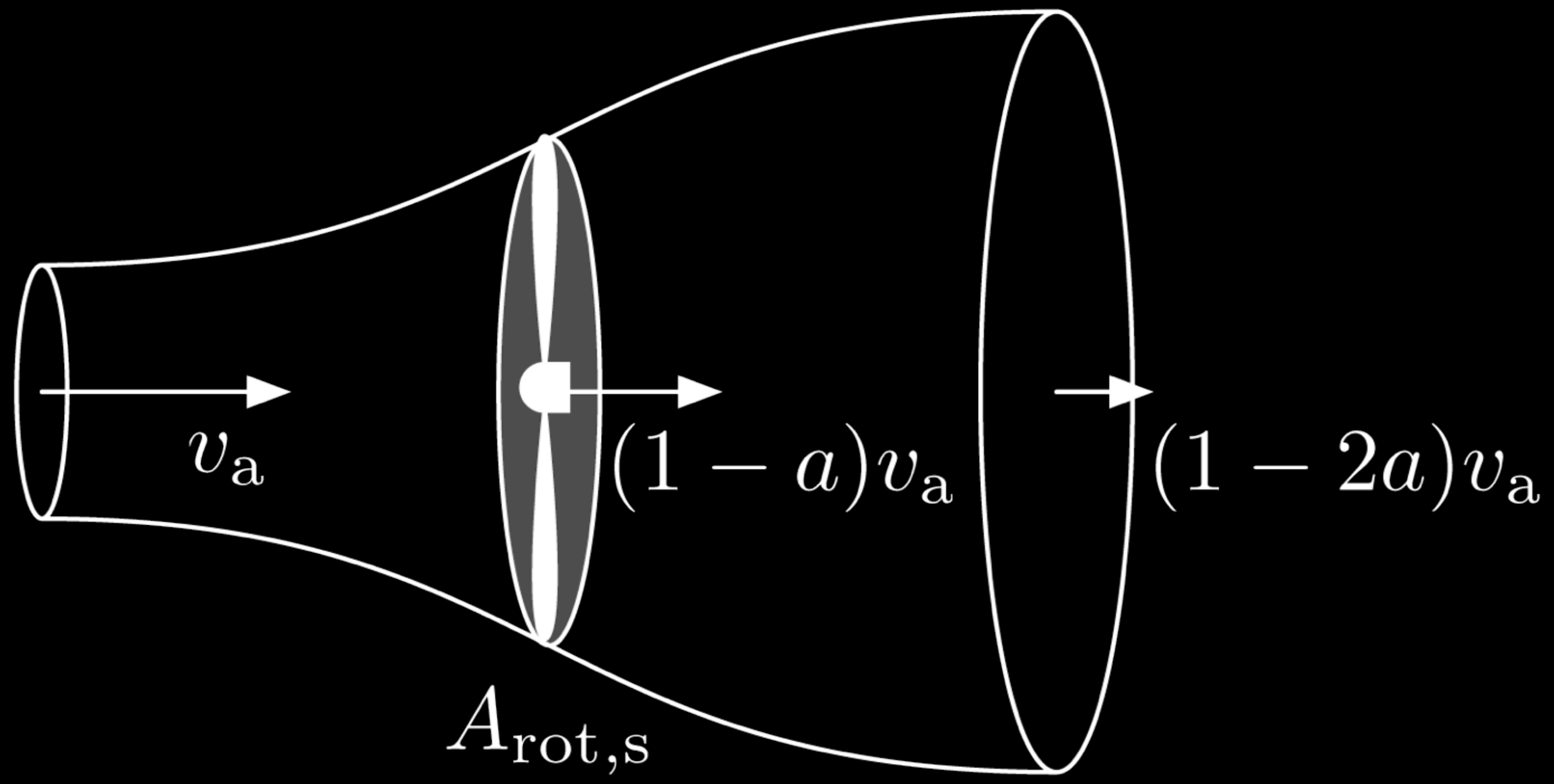
Assumption 7: actuator disk

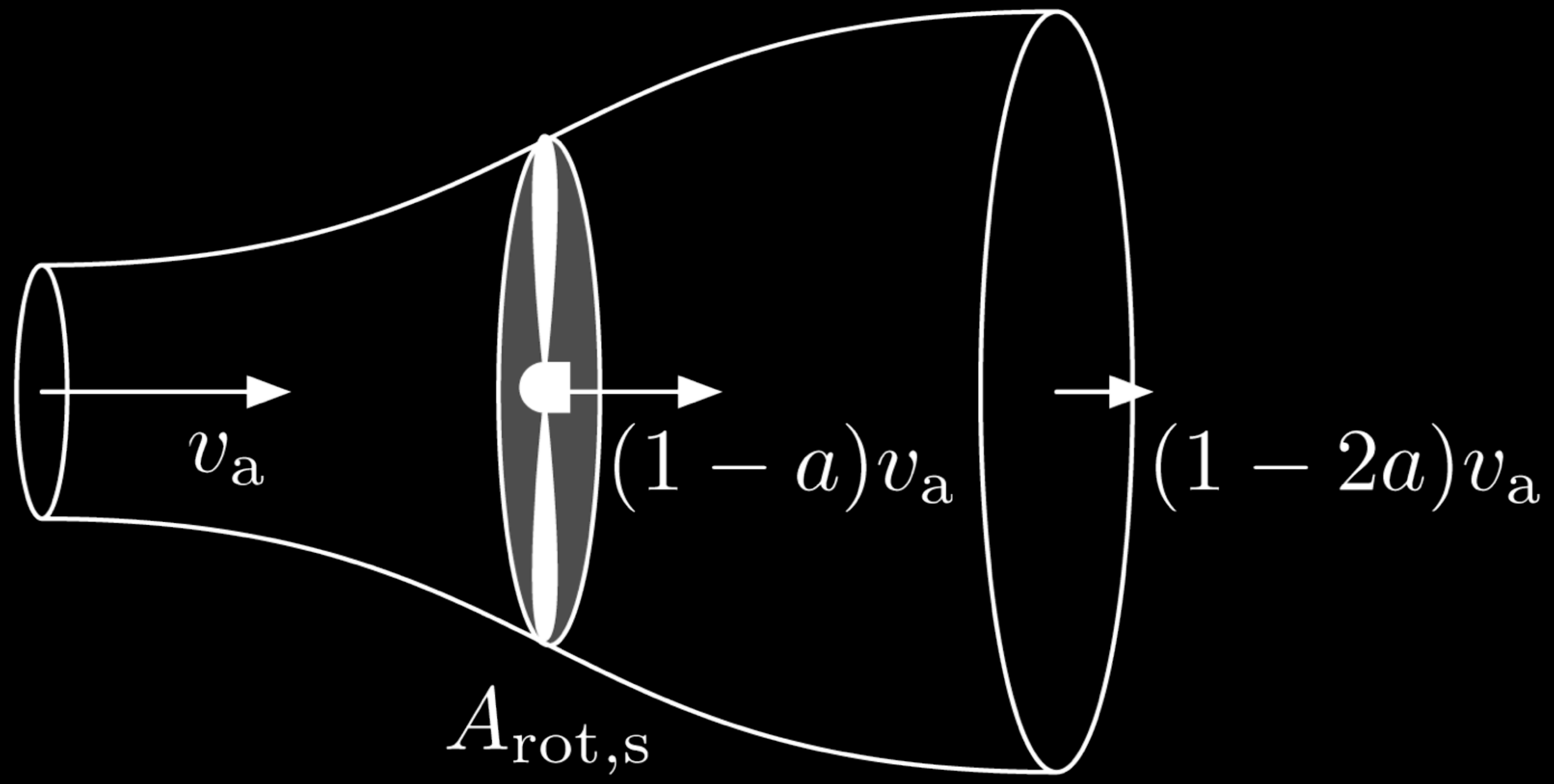


Single rotor:

$$F_\mathrm{rot,s} = 2\rho A_\mathrm{rot,s} v_\mathrm{a}^2 a(1-a)$$
$$P_\mathrm{rot,s} = 2\rho A_\mathrm{rot,s} v_\mathrm{a}^3 a(1-a)^2$$

"Aerodynamic" power: $$P_\mathrm{a} = \frac{1}{2}\rho A v_\mathrm{a}^3 C_\mathrm{D,rot}$$

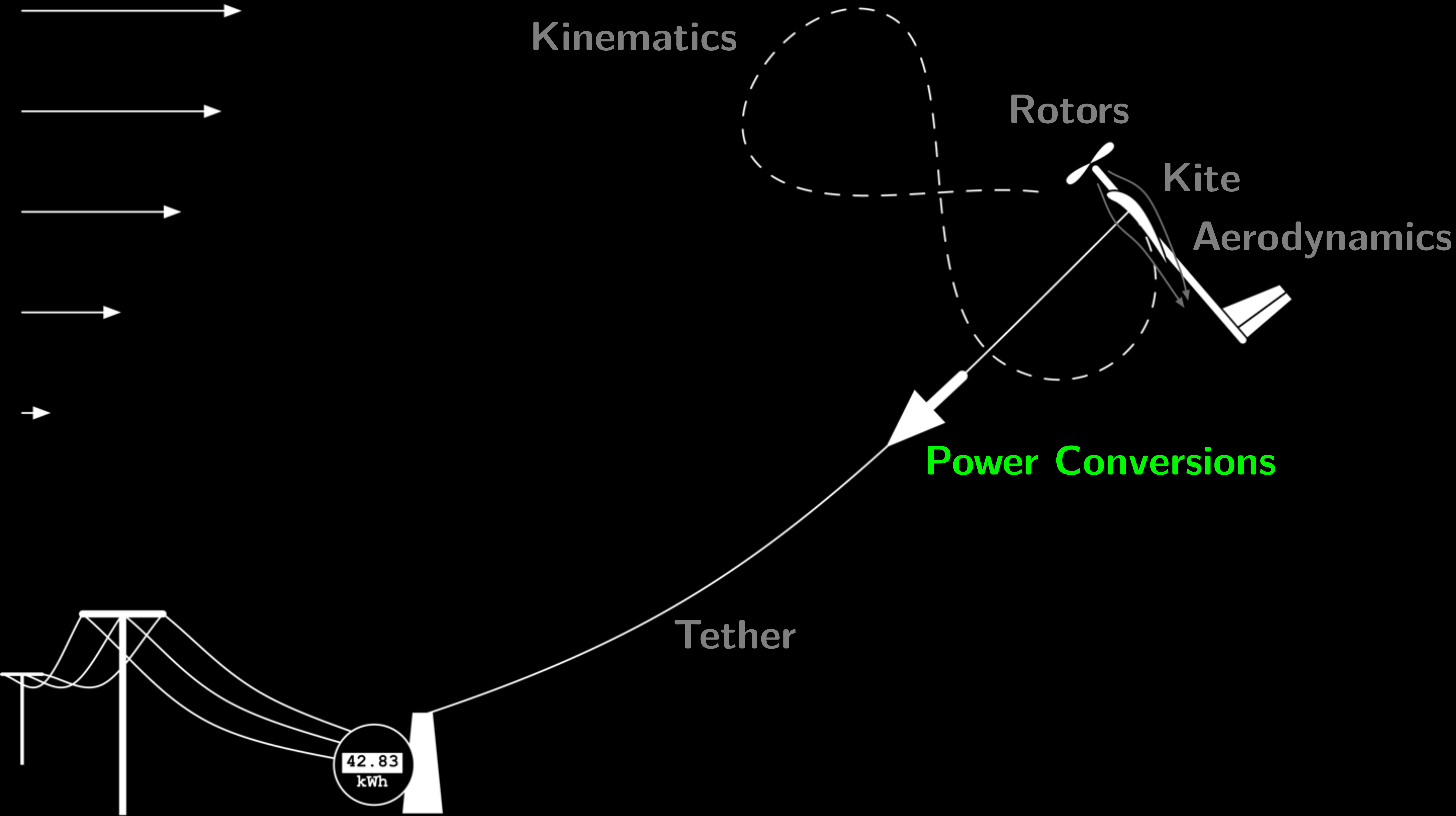
Assumption 7: actuator disk



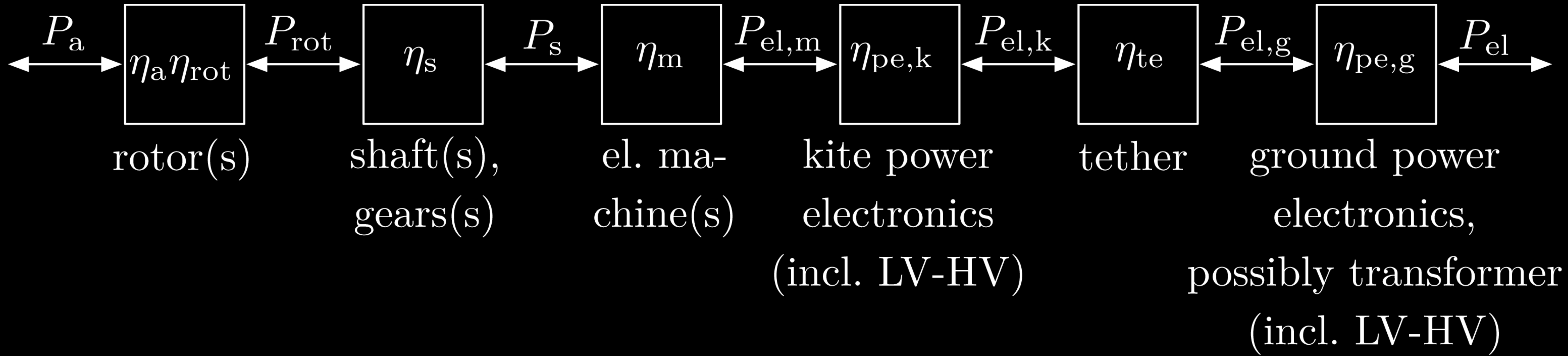
Single rotor:

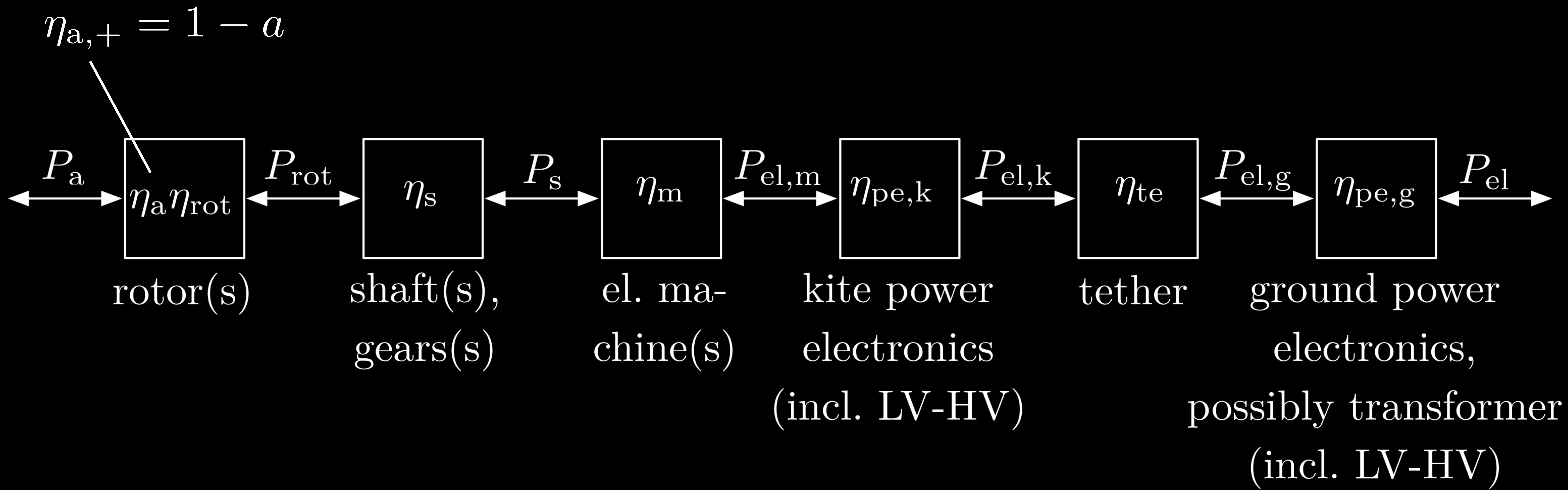
$$F_\mathrm{rot,s} = 2\rho A_\mathrm{rot,s} v_\mathrm{a}^2 a(1-a)$$
$$P_\mathrm{rot,s} = 2\rho A_\mathrm{rot,s} v_\mathrm{a}^3 a(1-a)^2$$

→ After conversions: $$C_\mathrm{D,rot} = 4\underbrace{\frac{n_\mathrm{rot} A_\mathrm{rot,s}}{A}}_{r_\mathrm{rot}} a(1-a) \quad \text{and} \quad \eta_{\mathrm{a},+} = 1-a$$



Kinematics
Rotors
Kite
Aerodynamics
Power Conversions
Tether
42.83
kWh


P_a
$\eta_a \eta_{rot}$
P_{rot}
η_s
P_s
η_m
$P_{el,m}$
$\eta_{pe,k}$
$P_{el,k}$
η_{te}
$P_{el,g}$
$\eta_{pe,g}$
P_{el}
rotor(s)
shaft(s), gears(s)
el. machine(s)
kite power electronics (incl. LV-HV)
tether
ground power electronics, possibly transformer (incl. LV-HV)



$\eta_{\mathrm{a},+} = 1 - a$
P_a
$\eta_\mathrm{a}\eta_\mathrm{rot}$
P_rot
η_s
P_s
η_m
$P_\mathrm{el,m}$
$\eta_\mathrm{pe,k}$
$P_\mathrm{el,k}$
η_te
$P_\mathrm{el,g}$
$\eta_\mathrm{pe,g}$
P_el
rotor(s)
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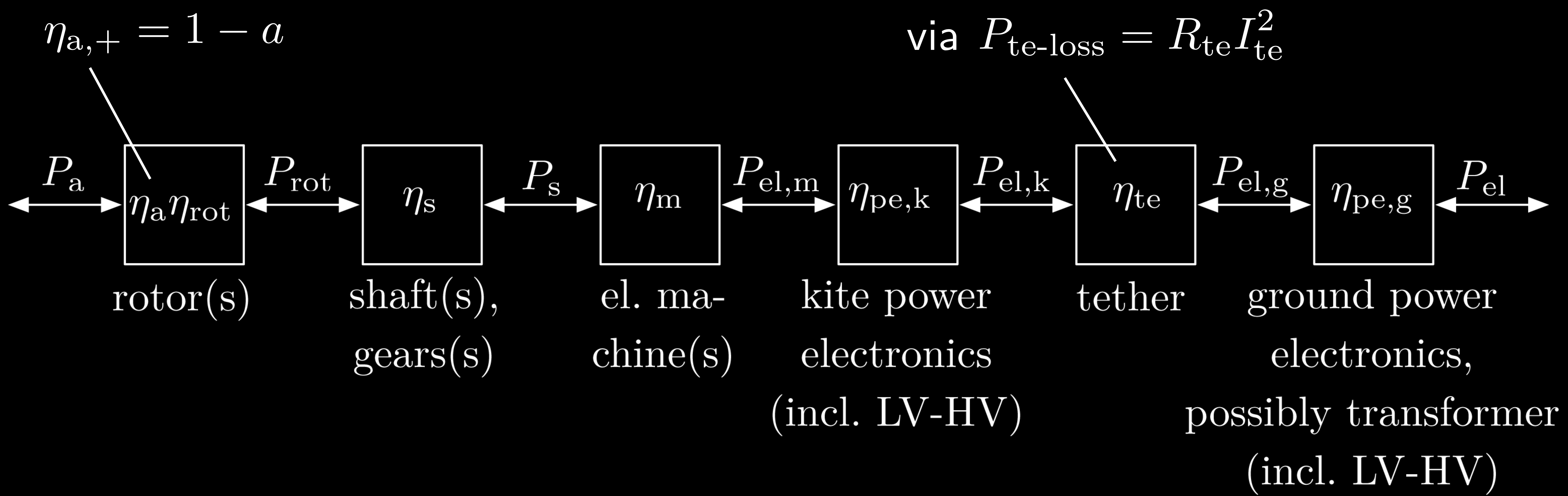

$\eta_{a,+} = 1 - a$
via $P_{\text{te-loss}} = R_{te} I_{te}^2$
P_a
$\eta_a \eta_{rot}$
P_{rot}
η_s
P_s
η_m
$P_{el,m}$
$\eta_{pe,k}$
$P_{el,k}$
η_{te}
$P_{el,g}$
$\eta_{pe,g}$
P_{el}
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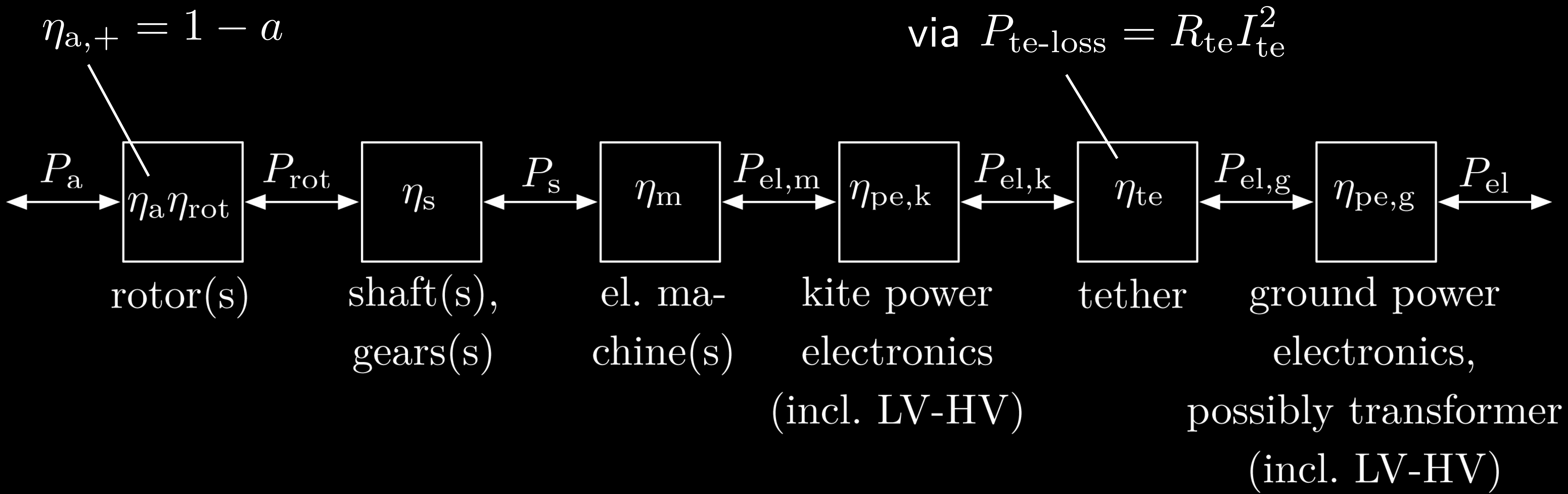
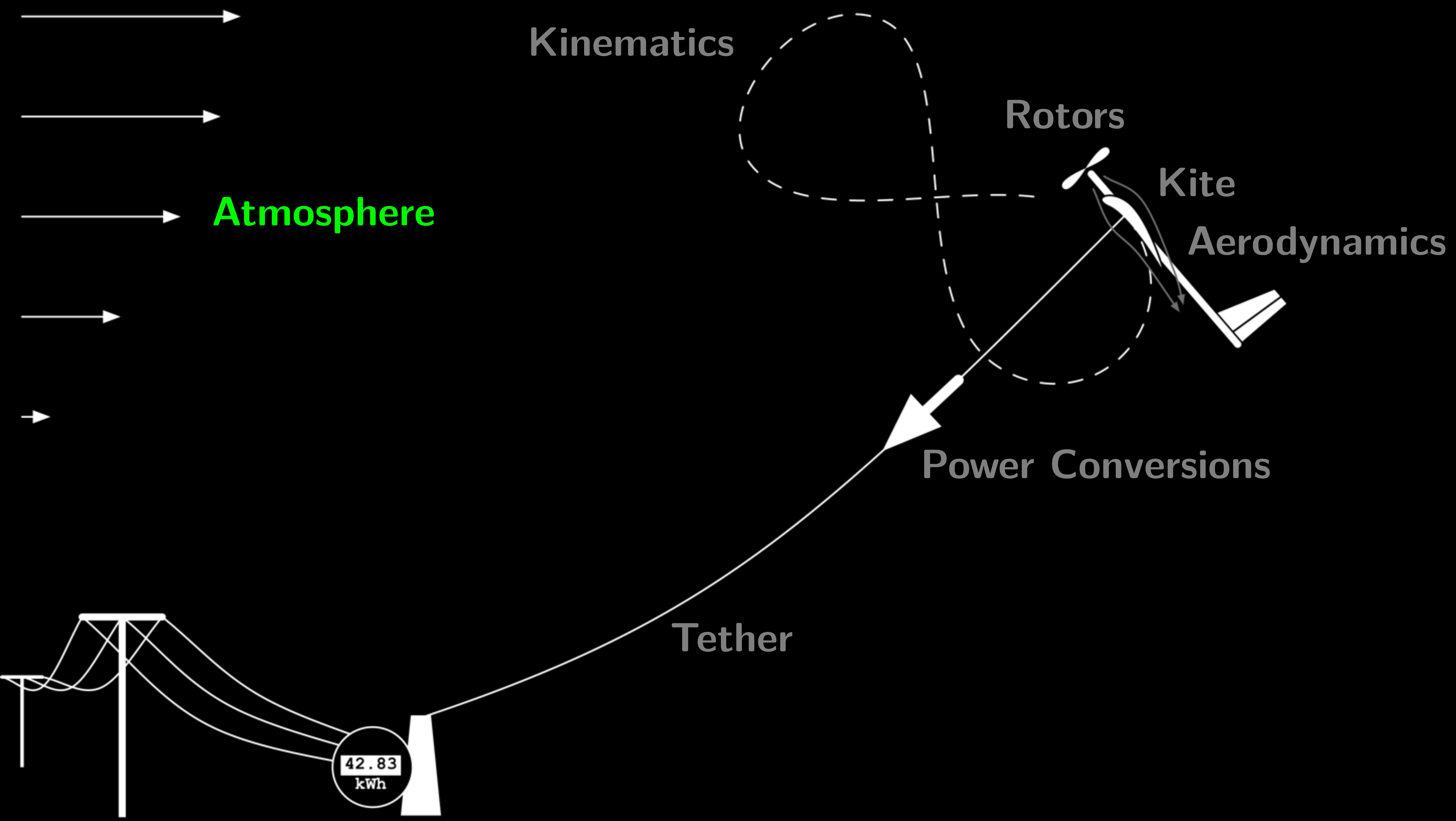


Assumption 8: constant efficiency factors for others

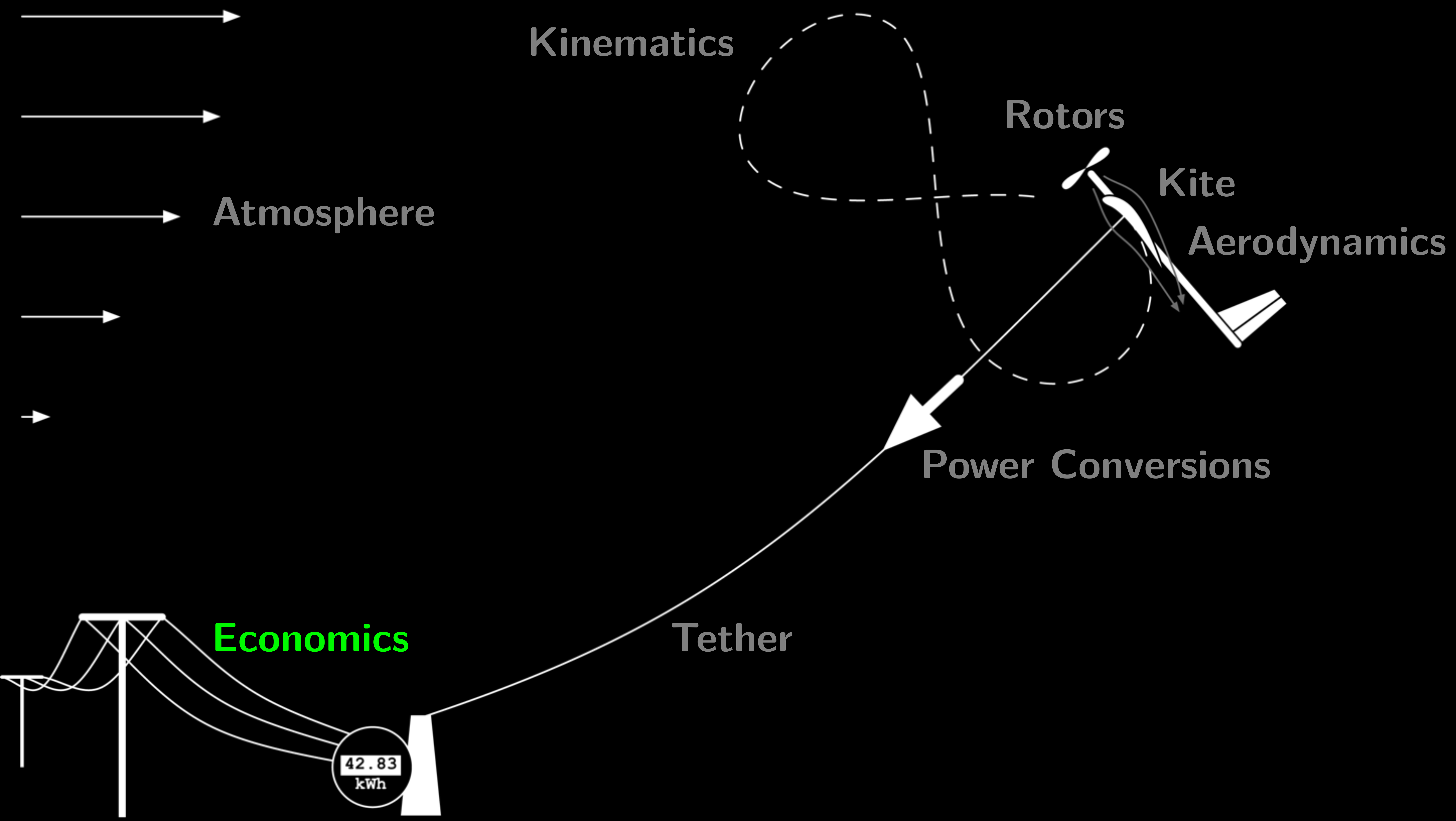

Kinematics
Rotors
Kite
Atmosphere
Aerodynamics
Power Conversions
Tether
42.83
kWh

Assumption 9: logarithmic wind shear

$$v_{\mathrm{w}} = v_{\mathrm{w},h_{\mathrm{ref}}} \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{h_{\mathrm{ref}}}{z_0}\right)} \quad \text{with} \quad h = h_{\mathrm{to}} + L_{\mathrm{te}} \sin(\vartheta)$$

Assumption 10: Rayleigh distribution

$$p(v_{\mathrm{w},h_{\mathrm{ref}}}) = \frac{v_{\mathrm{w},h_{\mathrm{ref}}}}{\tilde{v}^2_{\mathrm{w},h_{\mathrm{ref}}}} \exp\left(-\frac{v^2_{\mathrm{w},h_{\mathrm{ref}}}}{2\tilde{v}^2_{\mathrm{w},h_{\mathrm{ref}}}}\right)$$


Kinematics
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Atmosphere
Aerodynamics
Power Conversions
Economics
Tether
42.83
kWh

Assumption 11: launch & landing energy consumption negligible

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Year energy yield: $$E_{\mathrm{el,yr}}[\mathrm{Wh/yr}] = \frac{8,760\,\mathrm{h}}{1\,\mathrm{yr}} \cdot \int_0^\infty p(v_{\mathrm{w},h_{\mathrm{ref}}}) P_{\mathrm{el,+}}(v_{\mathrm{w},h_{\mathrm{ref}}}) \mathrm{d}v_{\mathrm{w},h_{\mathrm{ref}}}$$

Assumption 11: launch & landing energy consumption negligible

Year energy yield: $$E_{\mathrm{el,yr}}[\mathrm{Wh/yr}] = \frac{8,760\,\mathrm{h}}{1\,\mathrm{yr}} \cdot \int_0^\infty p(v_{\mathrm{w},h_{\mathrm{ref}}}) P_{\mathrm{el},+}(v_{\mathrm{w},h_{\mathrm{ref}}}) \mathrm{d}v_{\mathrm{w},h_{\mathrm{ref}}}$$

LCOE: $$k_{\mathrm{LCOE}} = \frac{k}{E_{\mathrm{el,yr}}}$$

Assumption 11: launch & landing energy consumption negligible

Year energy yield: $$E_{\mathrm{el,yr}}[\mathrm{Wh/yr}] = \frac{8,760\,\mathrm{h}}{1\,\mathrm{yr}} \cdot \int_0^\infty p(v_{\mathrm{w},h_{\mathrm{ref}}}) P_{\mathrm{el},+}(v_{\mathrm{w},h_{\mathrm{ref}}}) \mathrm{d}v_{\mathrm{w},h_{\mathrm{ref}}}$$

LCOE: $$k_{\mathrm{LCOE}} = \frac{k}{E_{\mathrm{el,yr}}}$$

Yearly costs: $$k = k_{\mathrm{inv}} + k_{\mathrm{op}}$$

$$k_{\mathrm{inv}} = K_{\mathrm{inv}} \frac{I(1+I)^{T/\mathrm{yr}}}{(1+I)^{T/\mathrm{yr}} - 1}$$

$$k_{\mathrm{op}} = I_{\mathrm{op}} K_{\mathrm{inv}}$$

Assumption 11: launch & landing energy consumption negligible

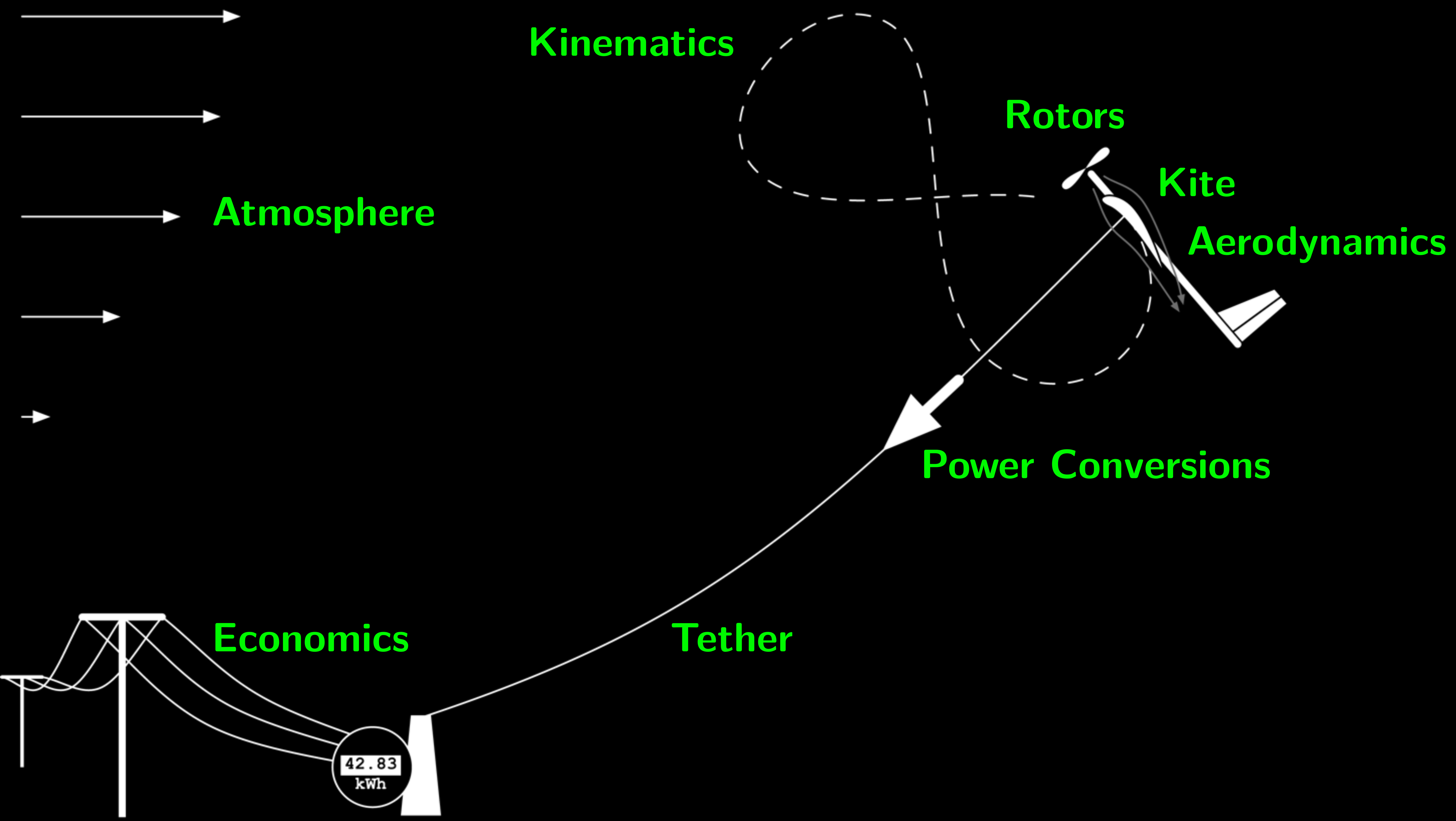
Year energy yield: $$E_{\mathrm{el,yr}}[\mathrm{Wh/yr}] = \frac{8,760\,\mathrm{h}}{1\,\mathrm{yr}} \cdot \int_0^\infty p(v_{\mathrm{w},h_{\mathrm{ref}}}) P_{\mathrm{el},+}(v_{\mathrm{w},h_{\mathrm{ref}}}) \mathrm{d}v_{\mathrm{w},h_{\mathrm{ref}}}$$

LCOE: $$k_{\mathrm{LCOE}} = \frac{k}{E_{\mathrm{el,yr}}}$$

Yearly costs: $$k = k_{\mathrm{inv}} + k_{\mathrm{op}}$$

$$k_{\mathrm{inv}} = K_{\mathrm{inv}} \frac{I(1+I)^{T/\mathrm{yr}}}{(1+I)^{T/\mathrm{yr}} - 1} \qquad k_{\mathrm{op}} = I_{\mathrm{op}} K_{\mathrm{inv}}$$

Total capital costs: $$K_{\mathrm{inv}} = k_{\mathrm{dt}} P_{\mathrm{el,n\text{-}ins}} + K_{\mathrm{inv,o\&p}}$$


Kinematics
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Tether
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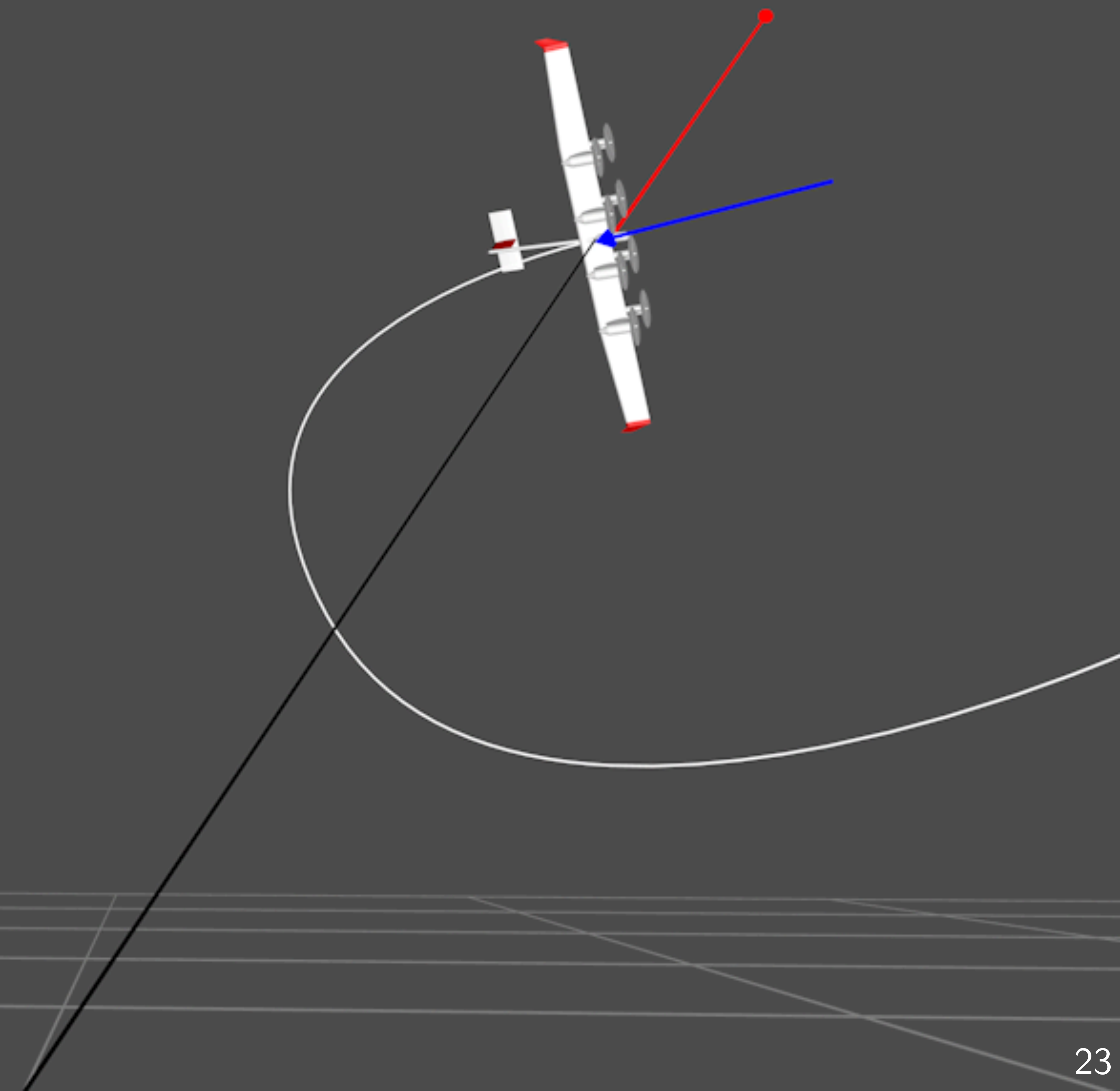
kWh

Outline

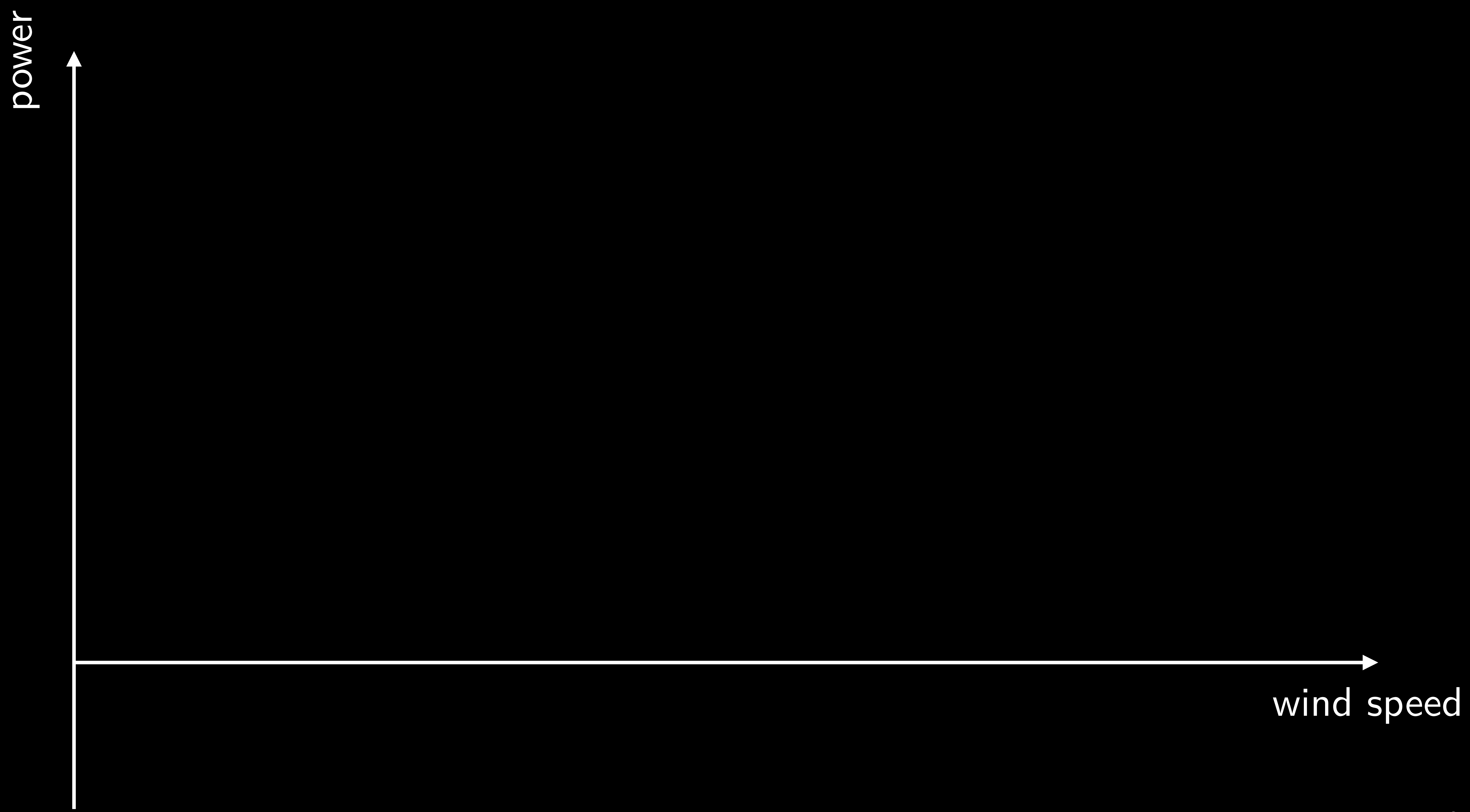
1. Model Derivation
2. Power Curve Optimization
3. Design Parameter Optimization
4. Parameter Studies
5. Conclusions



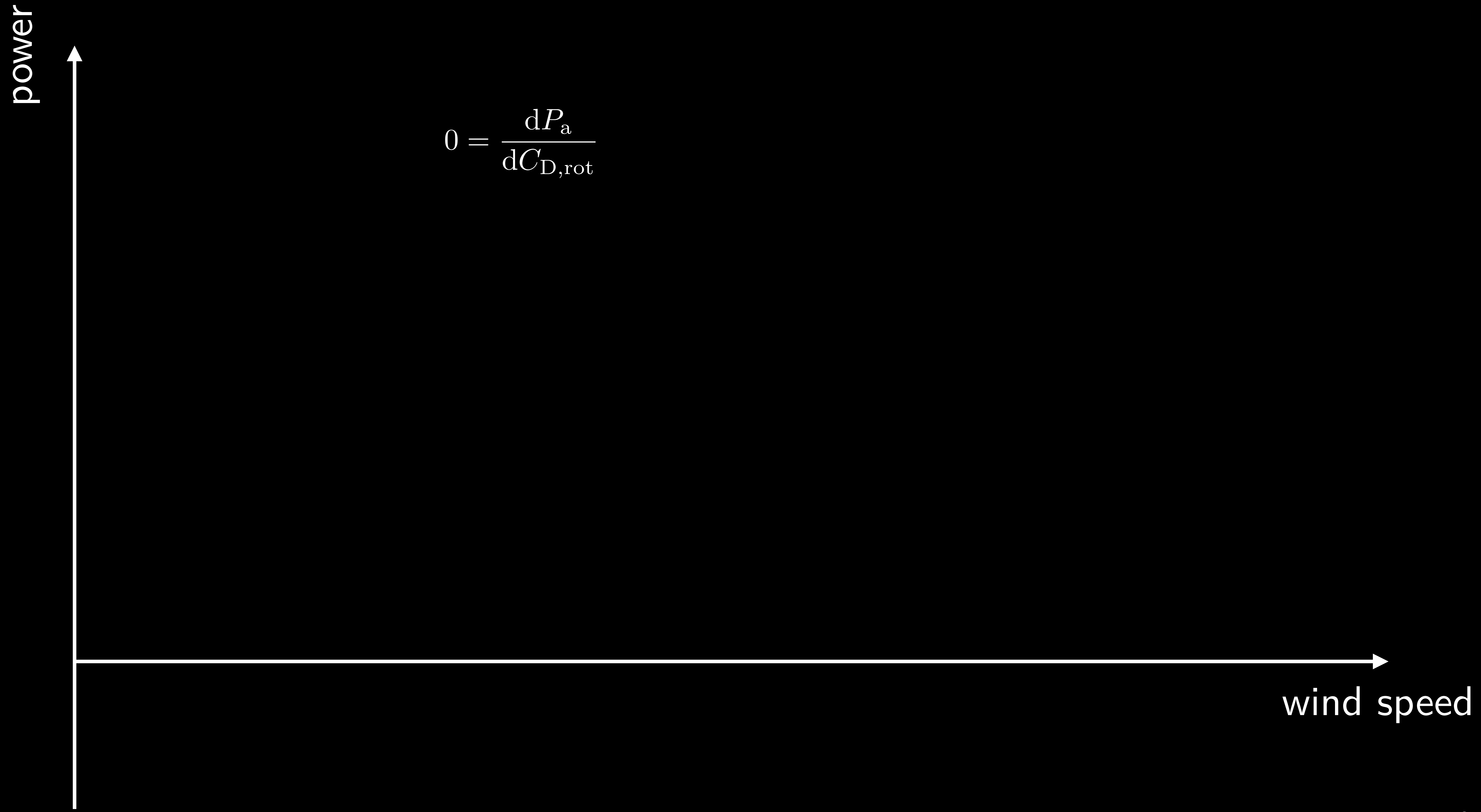
Assumption 12: $\forall v_{\mathrm{w},h_{\mathrm{ref}}} \in [0, v_{\mathrm{w},h_{\mathrm{ref}},\text{cut-out}}] : \arg\{\max_{\boldsymbol{u}} P_{\mathrm{a}}\} \approx \arg\{\max_{\boldsymbol{u}} P_{\mathrm{el}}\}$

Assumption 12: $\forall v_{\mathrm{w},h_{\mathrm{ref}}} \in [0, v_{\mathrm{w},h_{\mathrm{ref}},\text{cut-out}}] : \arg\{\max_{\boldsymbol{u}} P_{\mathrm{a}}\} \approx \arg\{\max_{\boldsymbol{u}} P_{\mathrm{el}}\}$

Assumption 13: $\sqrt{C_{\mathrm{L}}^2 + C_{\mathrm{D},\Sigma}^2} \approx C_{\mathrm{L}}$

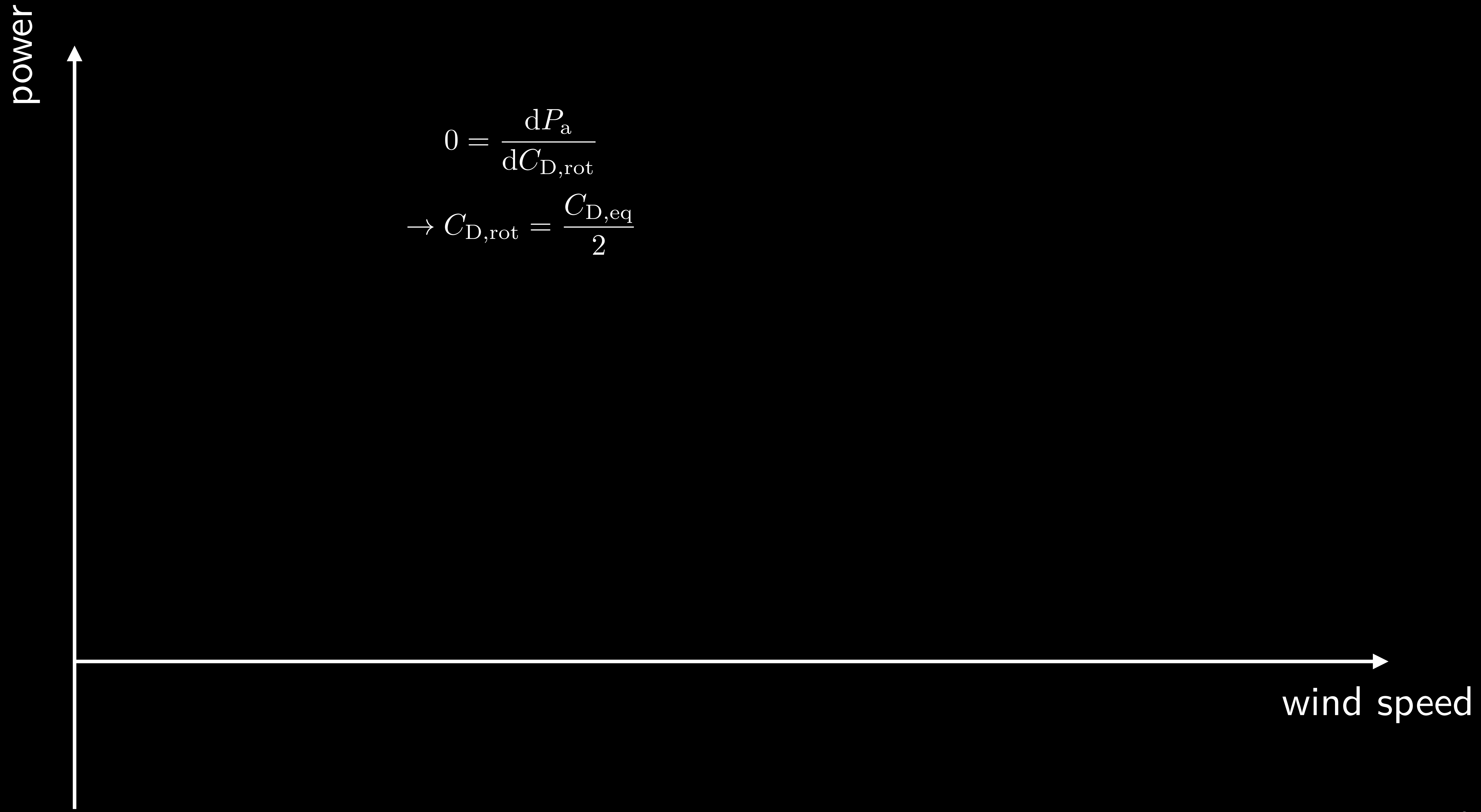

power
wind speed

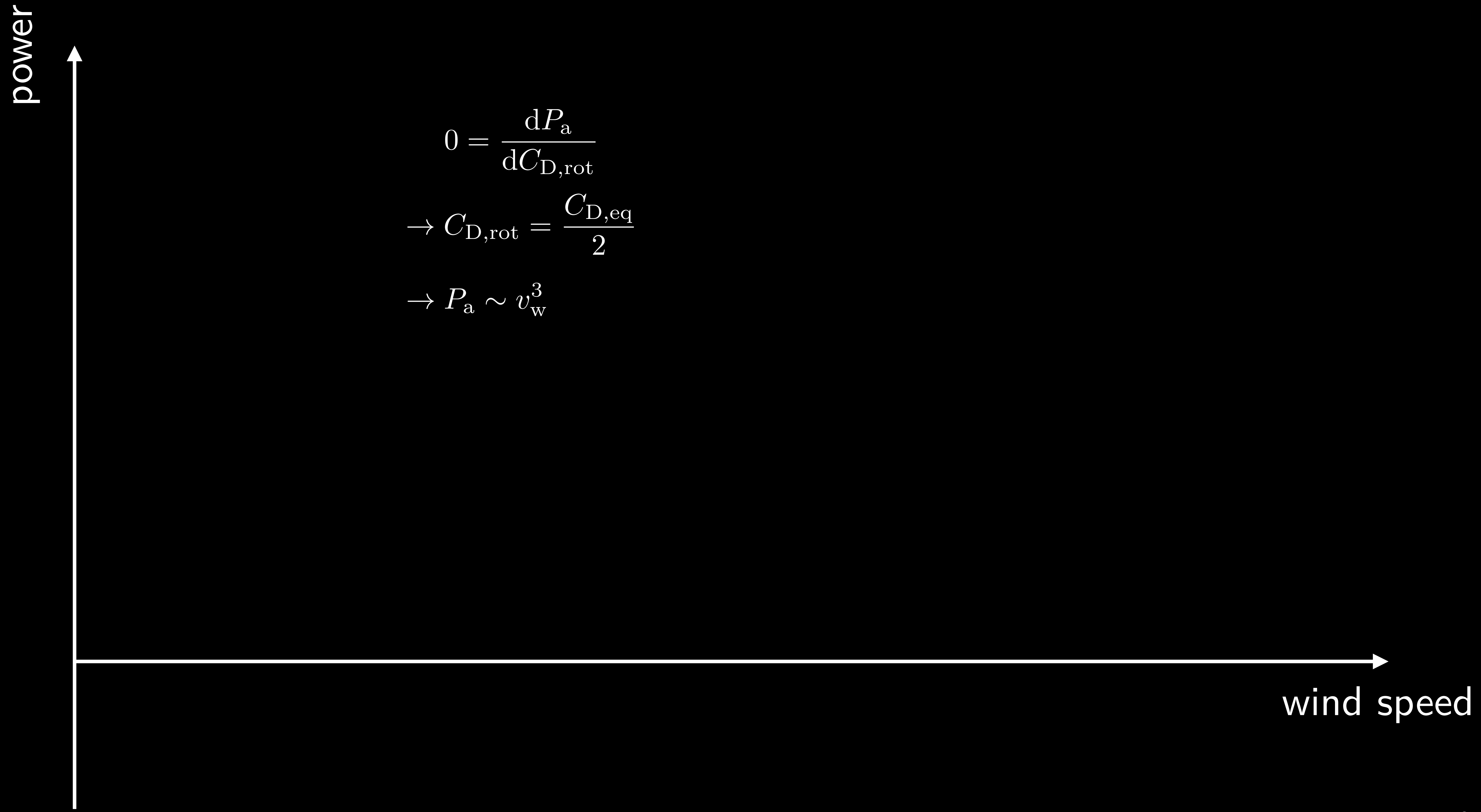
$$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$$



$$0 = \frac{\mathrm{d}P_{\mathrm{a}}}{\mathrm{d}C_{\mathrm{D,rot}}}$$

$$\rightarrow C_{\mathrm{D,rot}} = \frac{C_{\mathrm{D,eq}}}{2}$$





$$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$$

$$\rightarrow C_\mathrm{D,rot} = \frac{C_\mathrm{D,eq}}{2}$$

$$\rightarrow P_\mathrm{a} \sim v_\mathrm{w}^3$$

$$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$$

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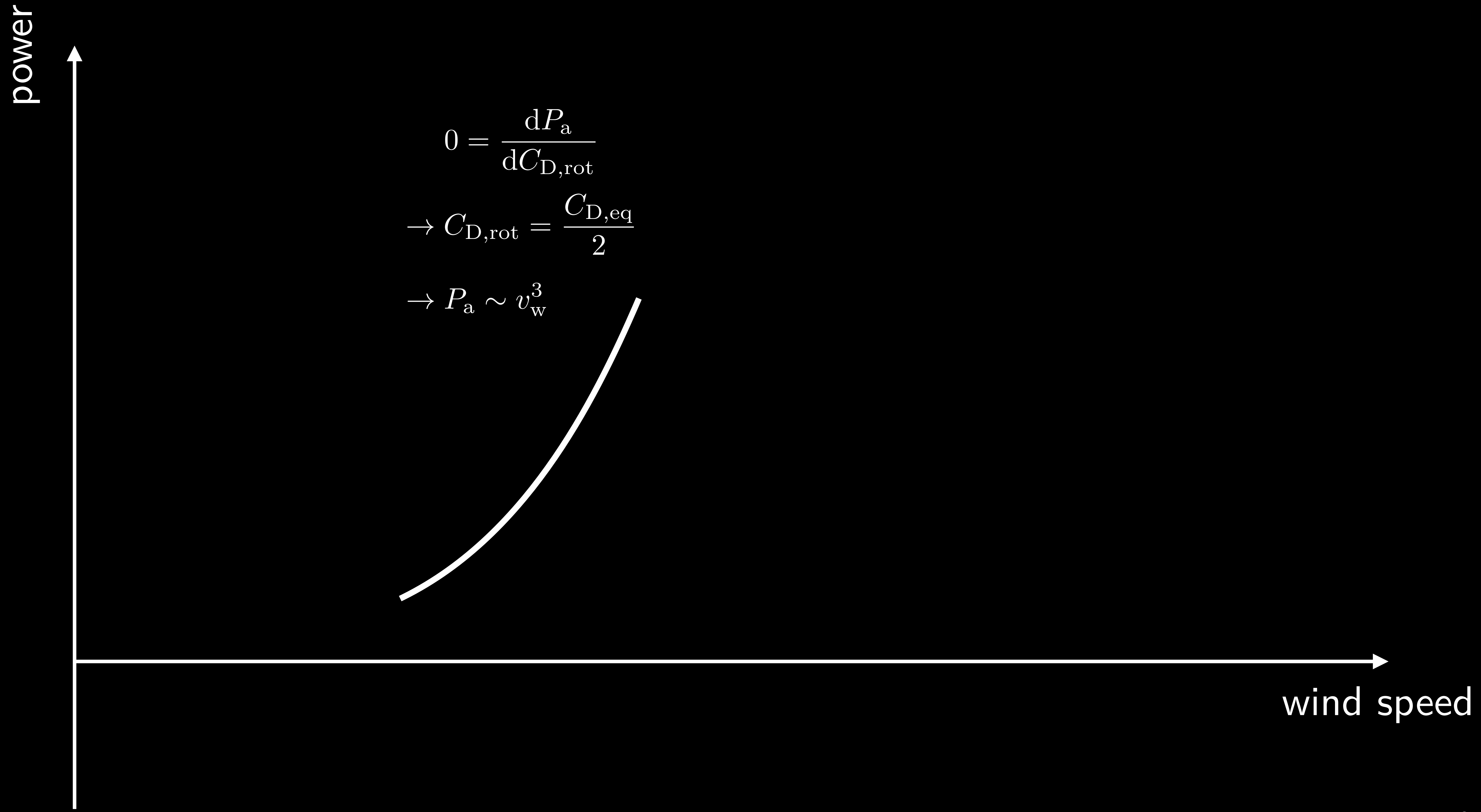
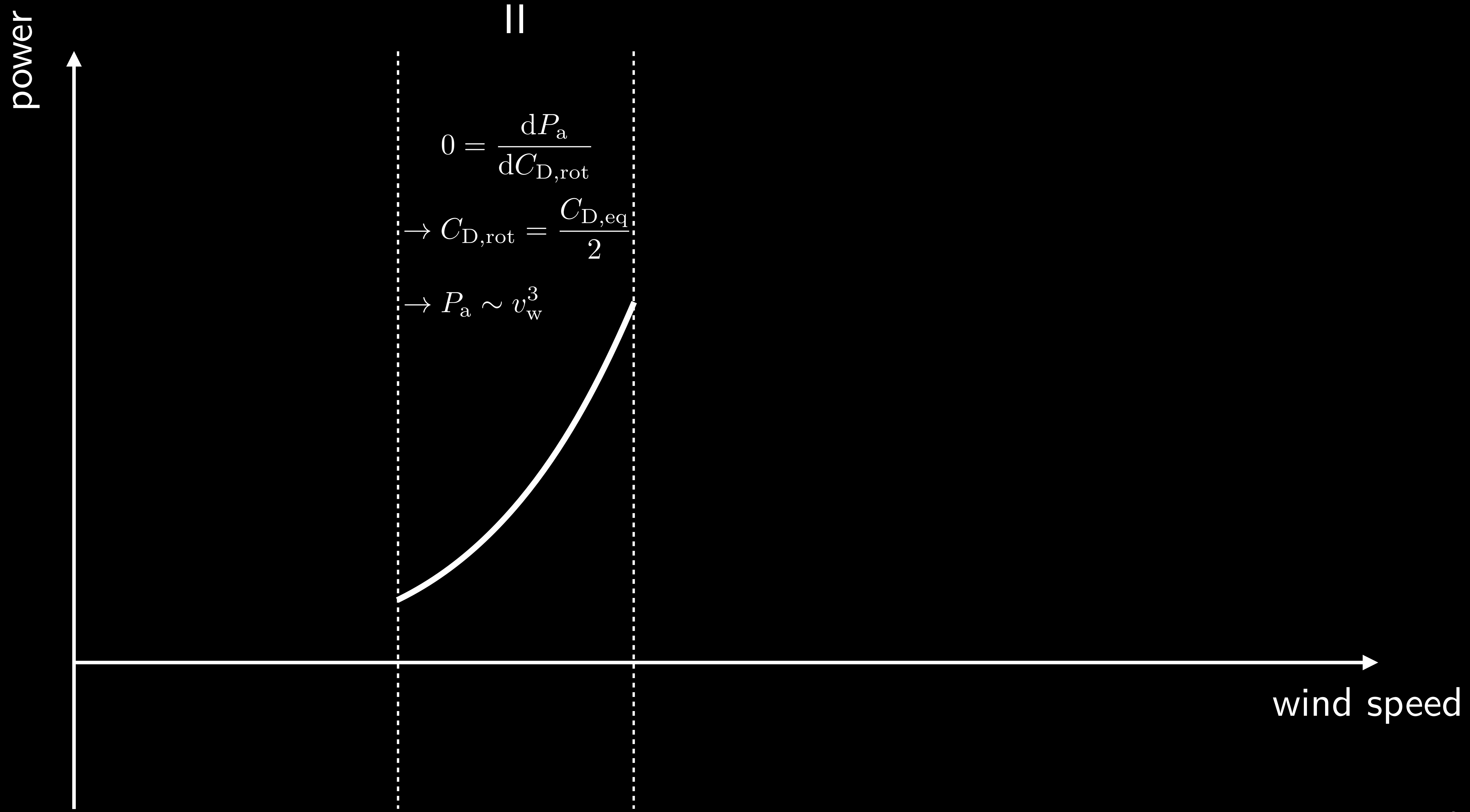
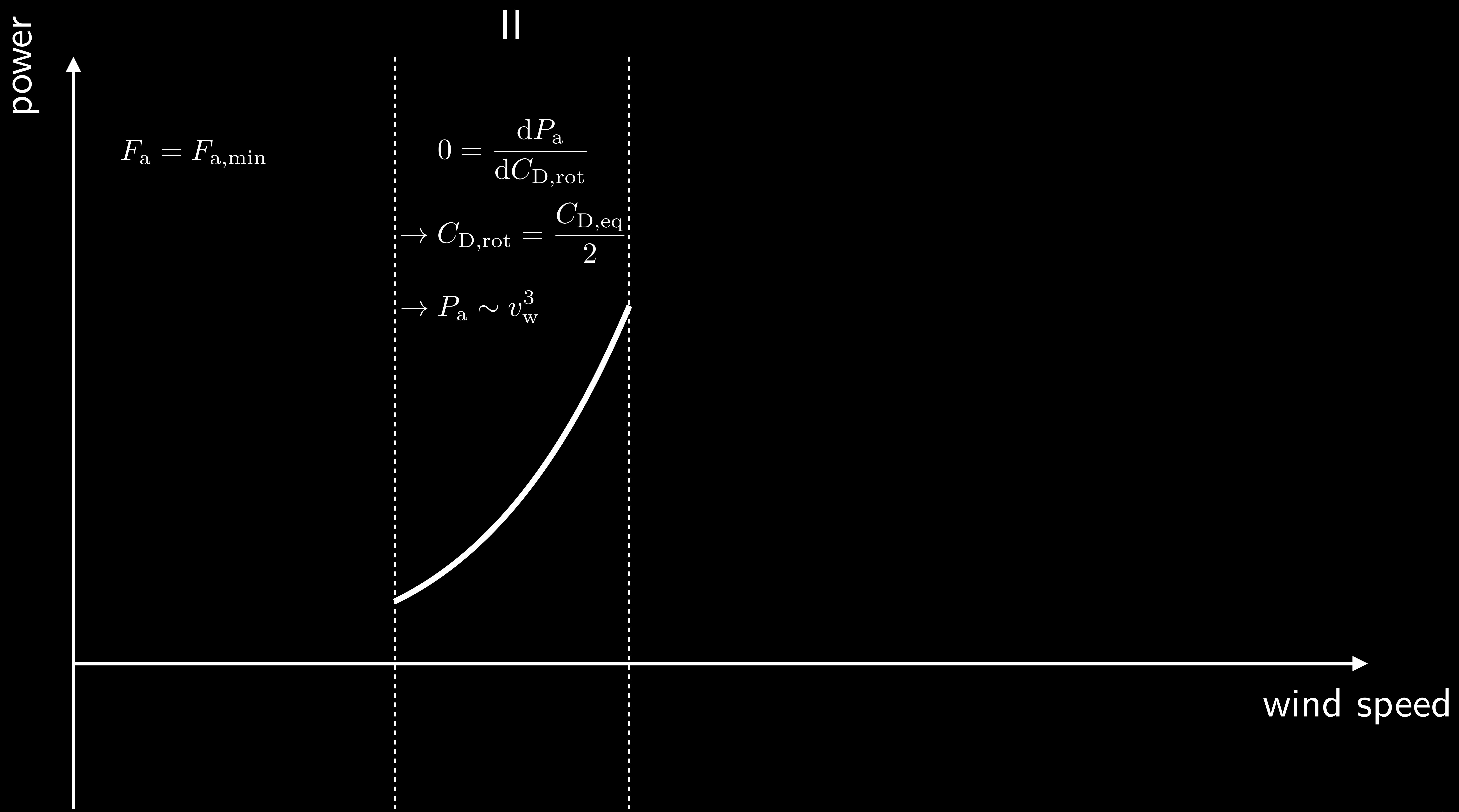
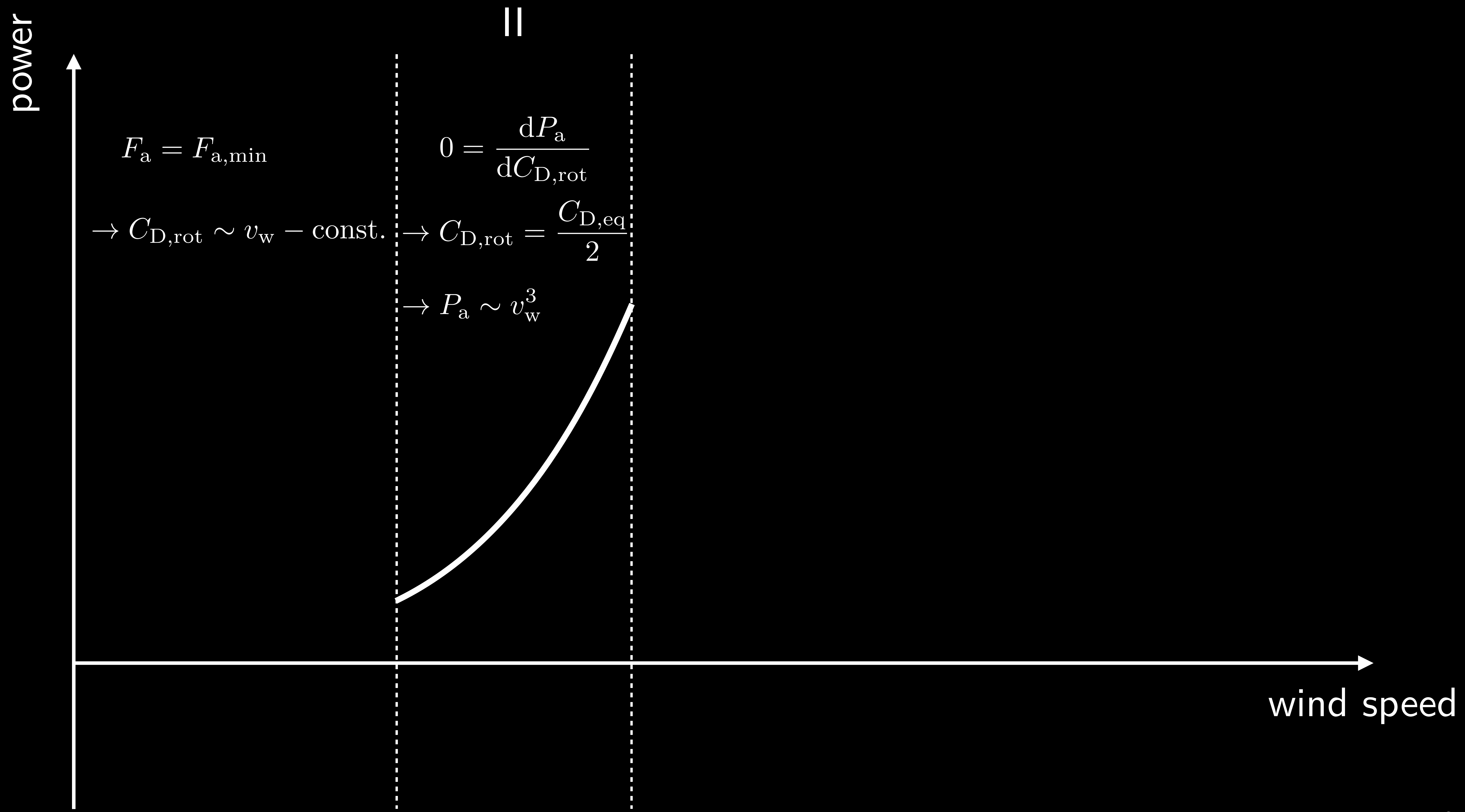
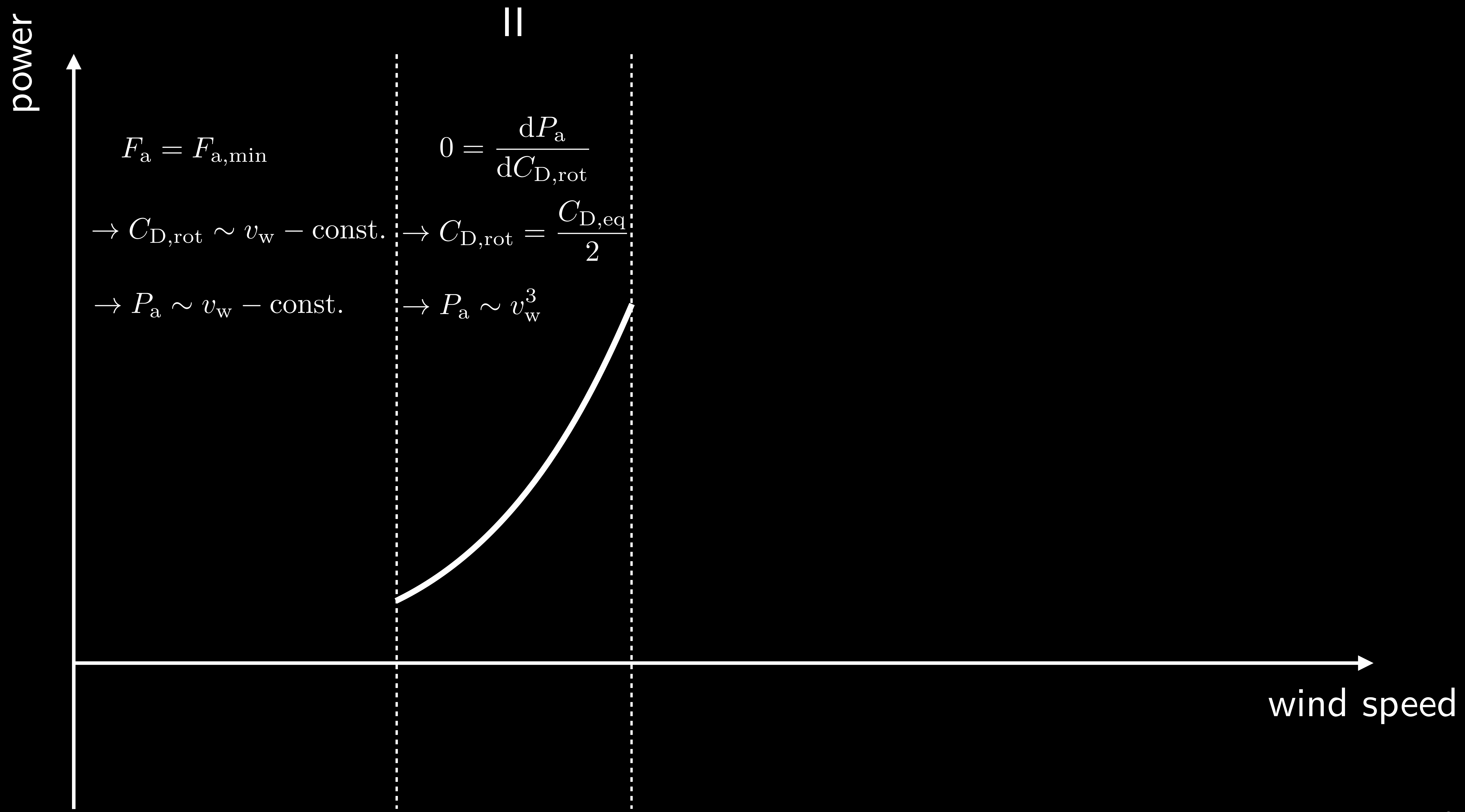


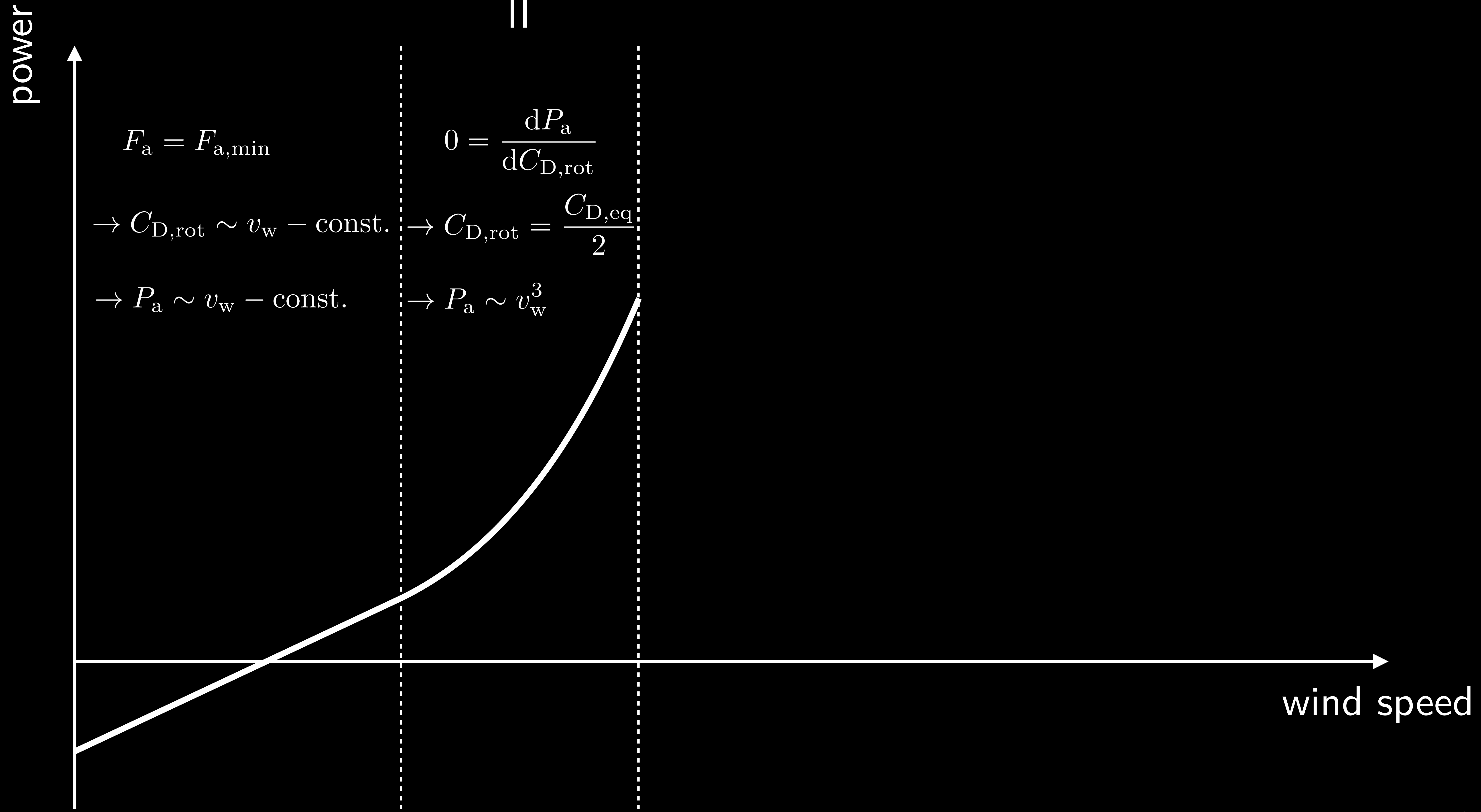

II
power
$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$
$\rightarrow C_\mathrm{D,rot} = \frac{C_\mathrm{D,eq}}{2}$
$\rightarrow P_\mathrm{a} \sim v_\mathrm{w}^3$
wind speed


II
power
$F_a = F_{a,min}$
$0 = \frac{dP_a}{dC_{D,rot}}$
$\rightarrow C_{D,rot} = \frac{C_{D,eq}}{2}$
$\rightarrow P_a \sim v_w^3$
wind speed


II
power
$F_\mathrm{a} = F_\mathrm{a,min}$
$\rightarrow C_\mathrm{D,rot} \sim v_\mathrm{w} - \mathrm{const.}$
$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$
$\rightarrow C_\mathrm{D,rot} = \frac{C_\mathrm{D,eq}}{2}$
$\rightarrow P_\mathrm{a} \sim v_\mathrm{w}^3$
wind speed


II
power
wind speed
$F_\mathrm{a} = F_\mathrm{a,min}$
$\rightarrow C_\mathrm{D,rot} \sim v_\mathrm{w} - \mathrm{const.}$
$\rightarrow P_\mathrm{a} \sim v_\mathrm{w} - \mathrm{const.}$
$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$
$\rightarrow C_\mathrm{D,rot} = \frac{C_\mathrm{D,eq}}{2}$
$\rightarrow P_\mathrm{a} \sim v_\mathrm{w}^3$

II


power
$F_\mathrm{a} = F_\mathrm{a,min}$
$\rightarrow C_\mathrm{D,rot} \sim v_\mathrm{w} - \mathrm{const.}$
$\rightarrow P_\mathrm{a} \sim v_\mathrm{w} - \mathrm{const.}$
$0 = \frac{\mathrm{d}P_\mathrm{a}}{\mathrm{d}C_\mathrm{D,rot}}$
$\rightarrow C_\mathrm{D,rot} = \frac{C_\mathrm{D,eq}}{2}$
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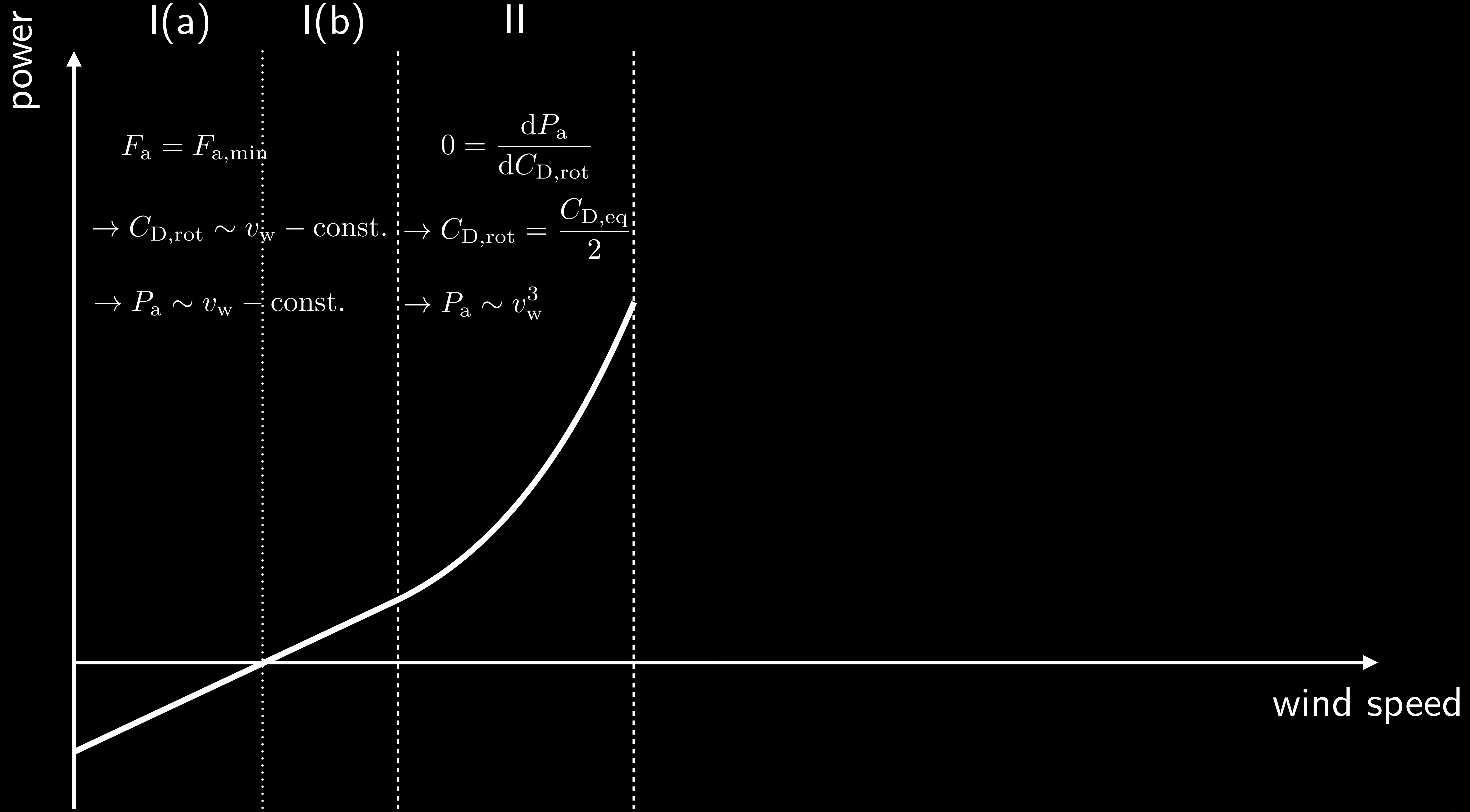
wind speed



I(a)
I(b)
II
power
$F_a = F_{a,min}$
$\rightarrow C_{D,rot} \sim v_w - \text{const.}$
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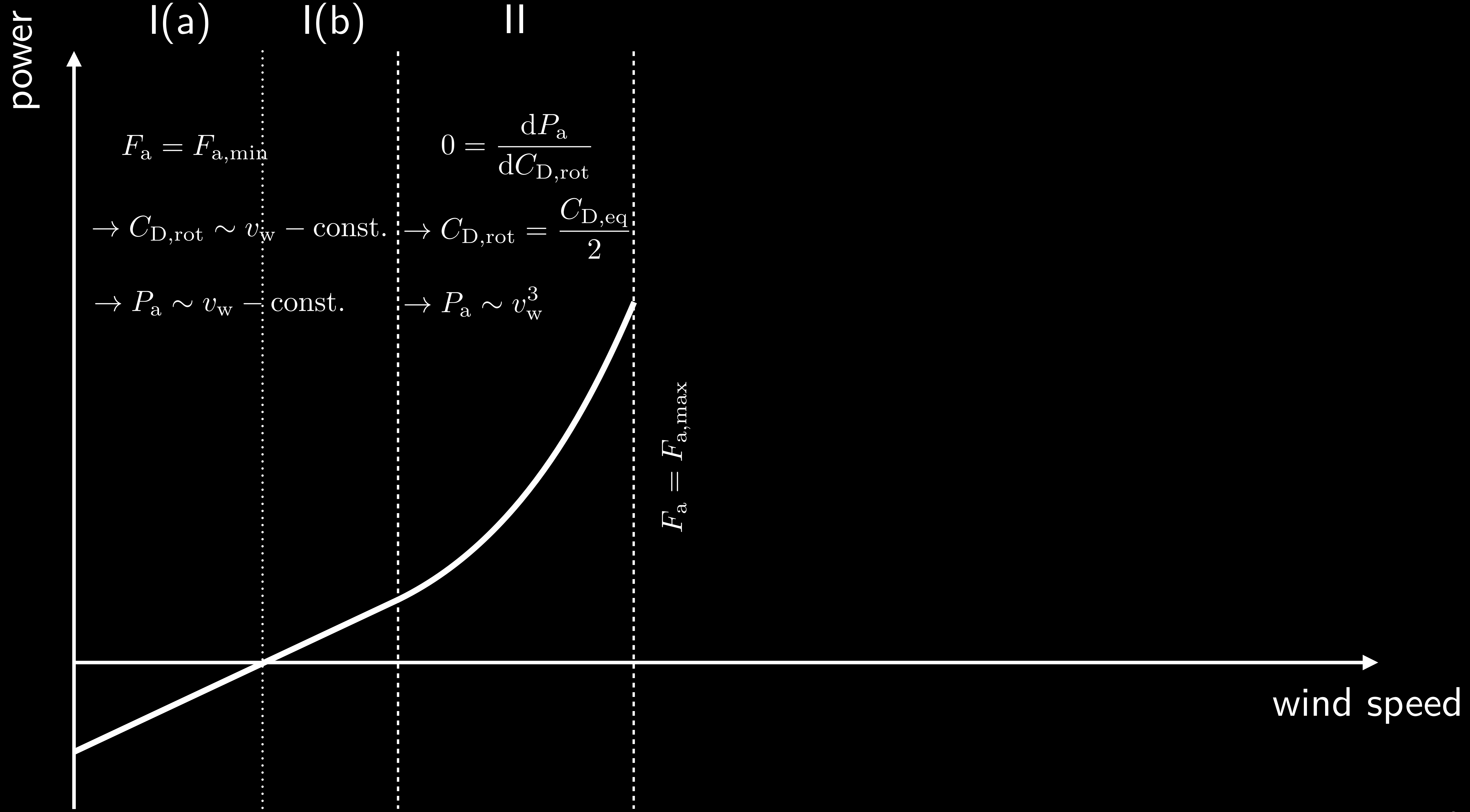

power
I(a)
I(b)
II
$F_\mathrm{a} = F_\mathrm{a,min}$
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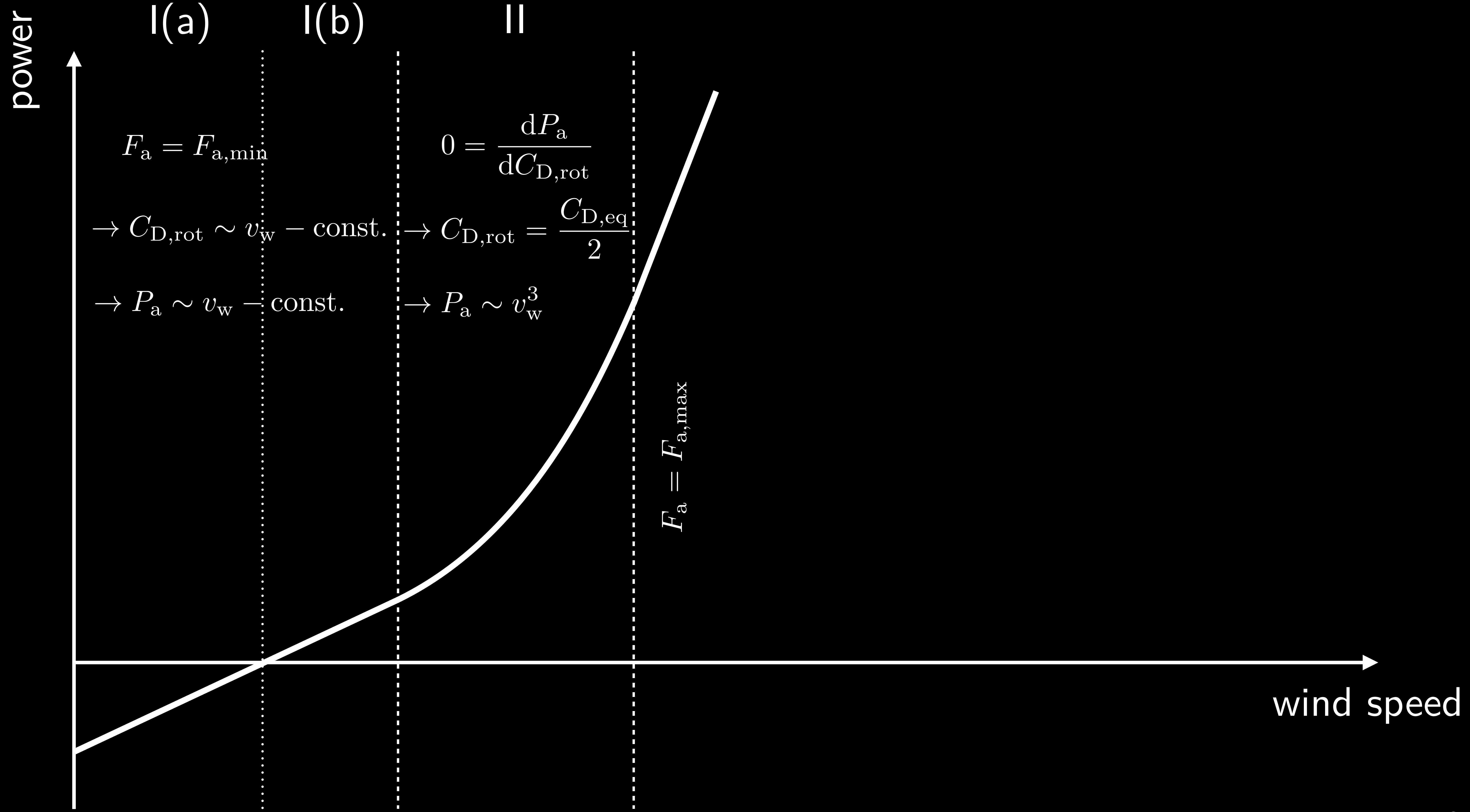

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I(b)
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power
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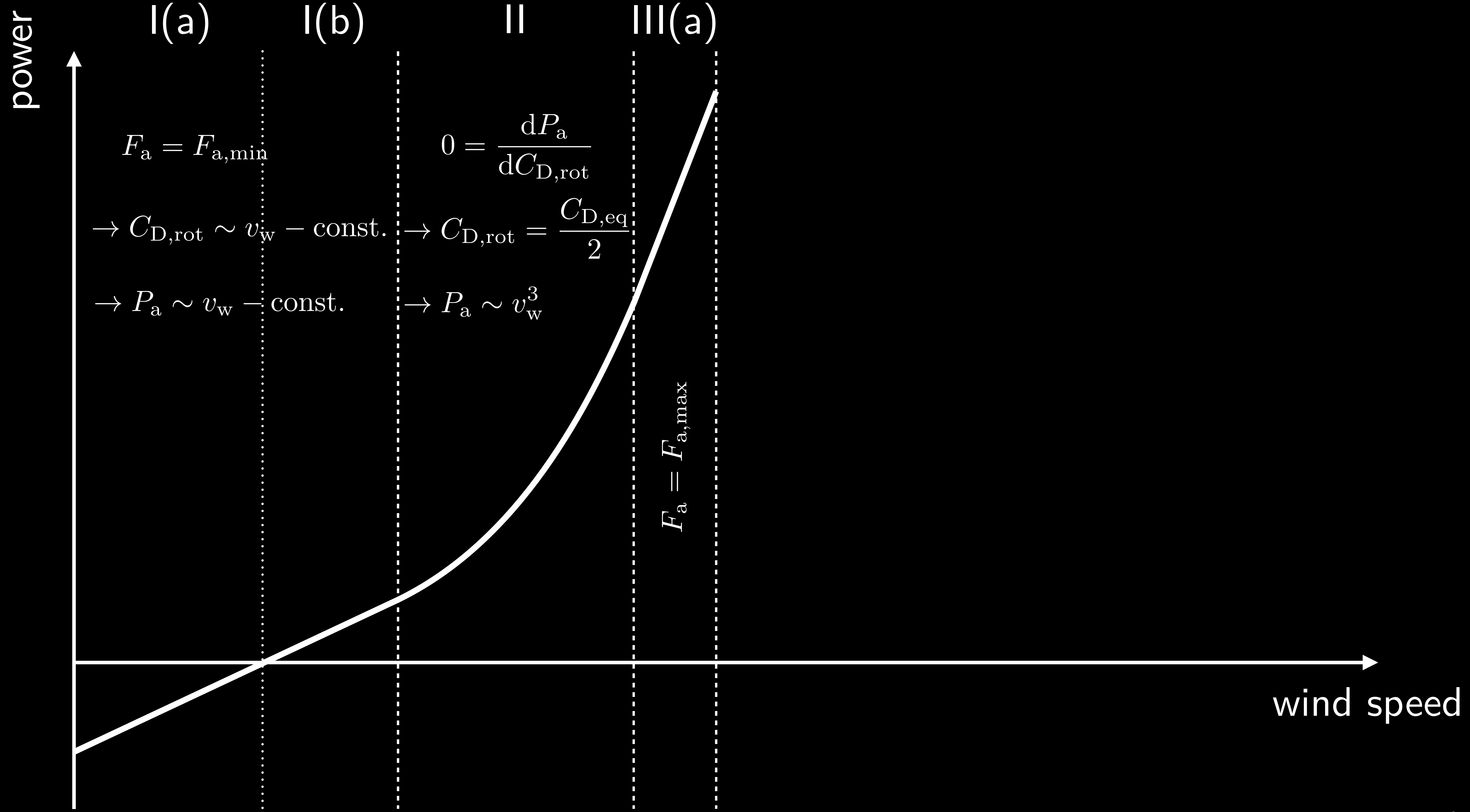

I(a)
I(b)
II
III(a)
power
wind speed
$F_a = F_{a,\min}$
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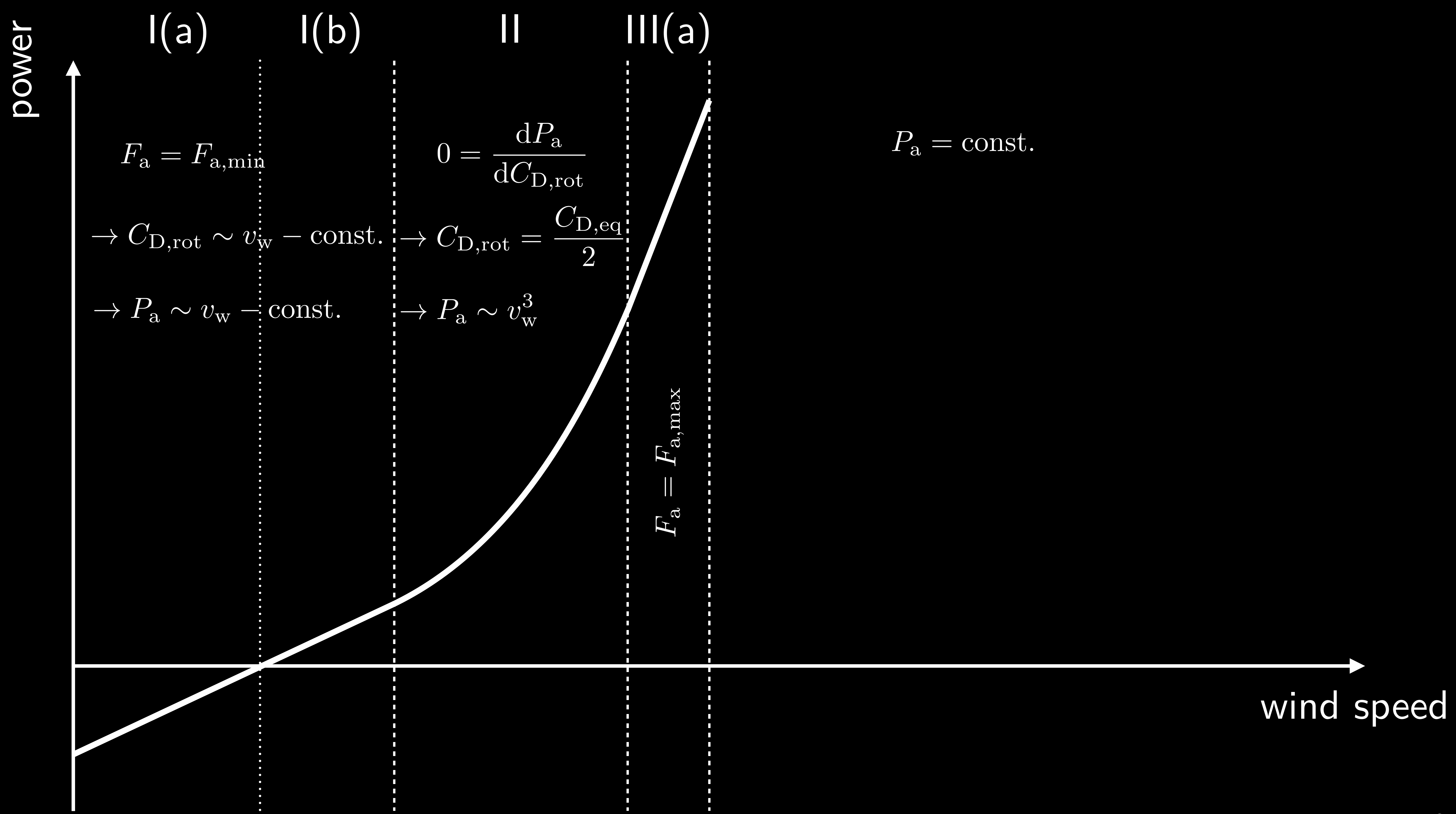

I(a)
I(b)
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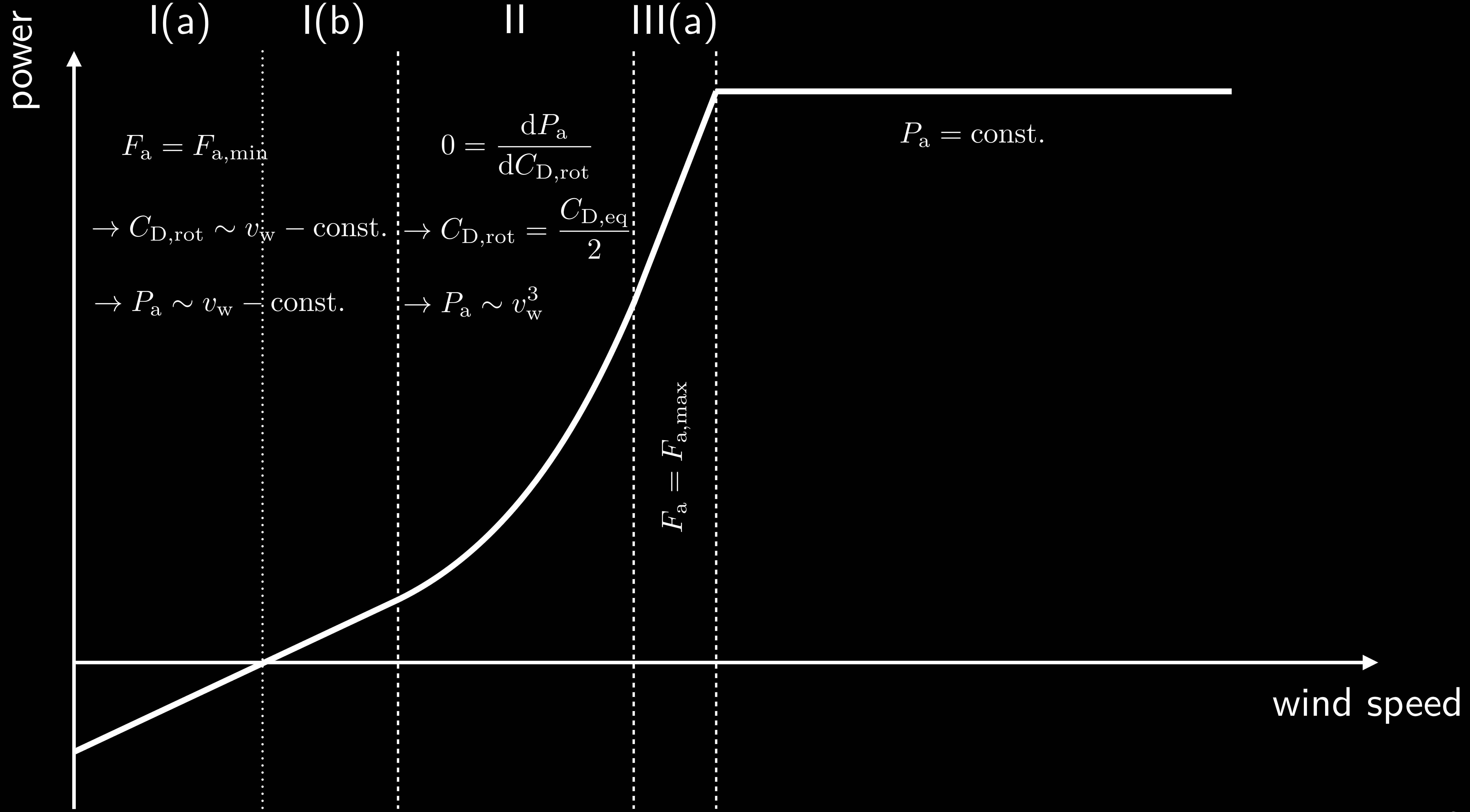
power
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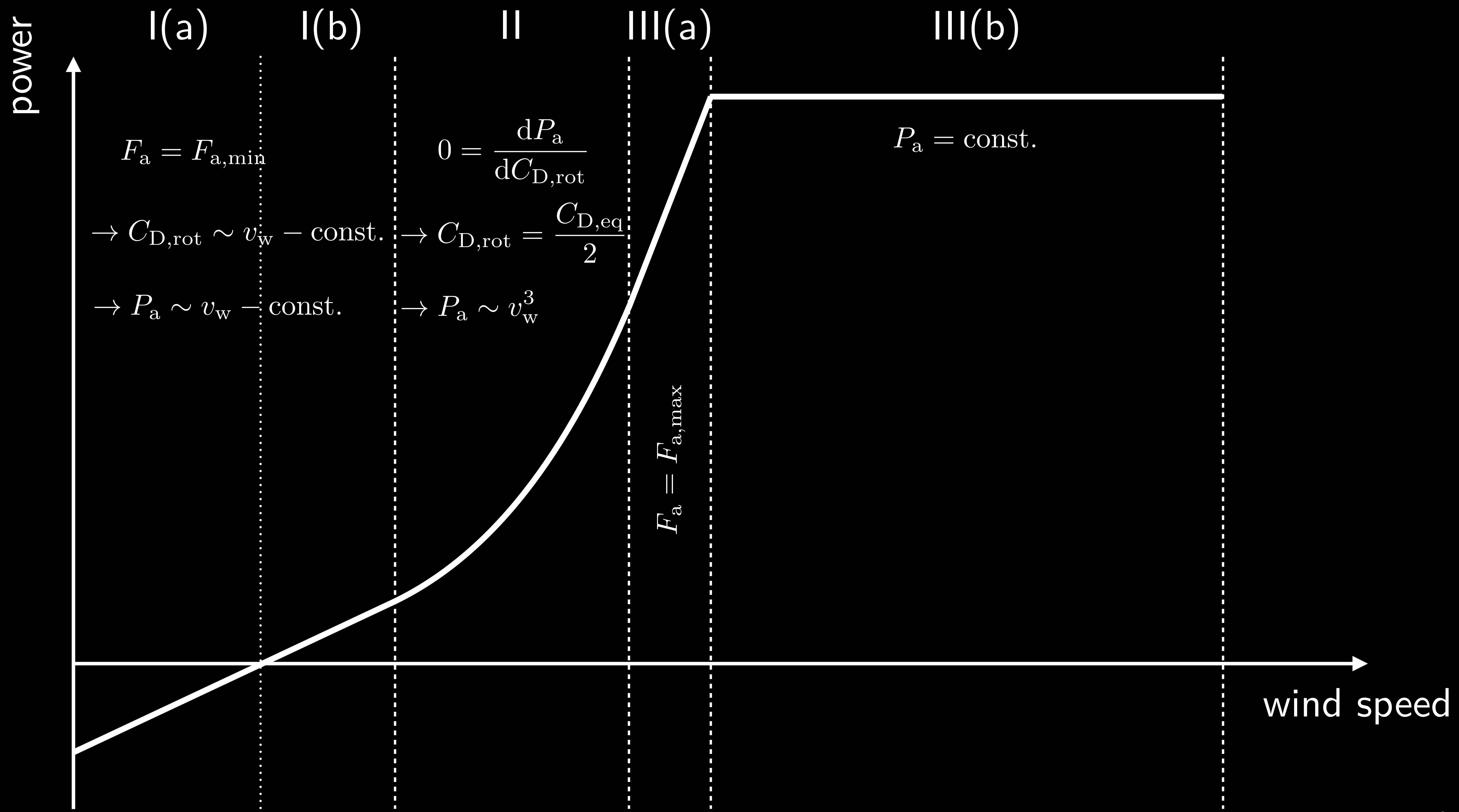

I(a)
I(b)
II
III(a)
III(b)
power
wind speed
$F_\mathrm{a} = F_\mathrm{a,min}$
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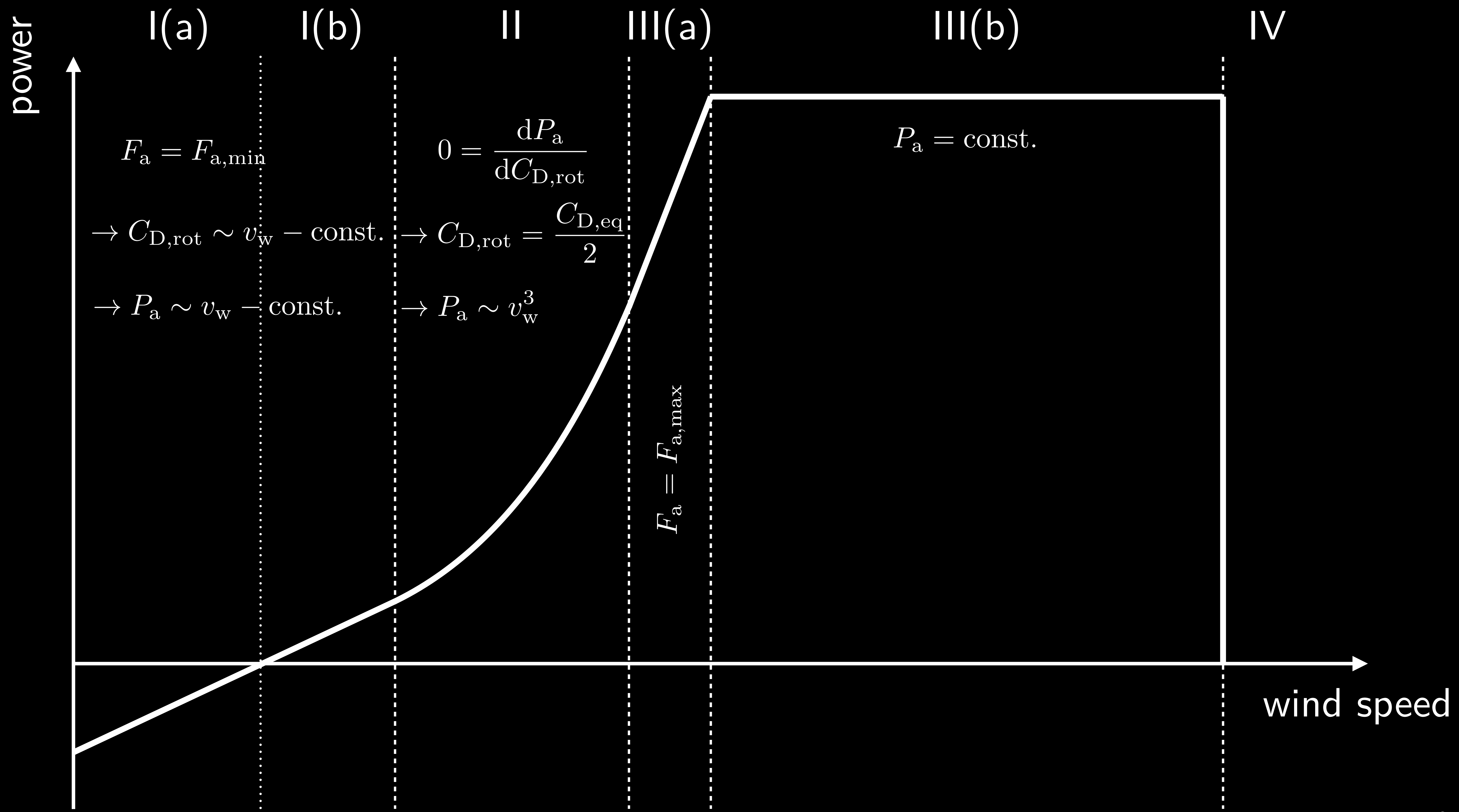

power
I(a)
I(b)
II
III(a)
III(b)
IV
$F_\mathrm{a} = F_\mathrm{a,min}$
$\rightarrow C_\mathrm{D,rot} \sim v_\mathrm{w} - \mathrm{const.}$
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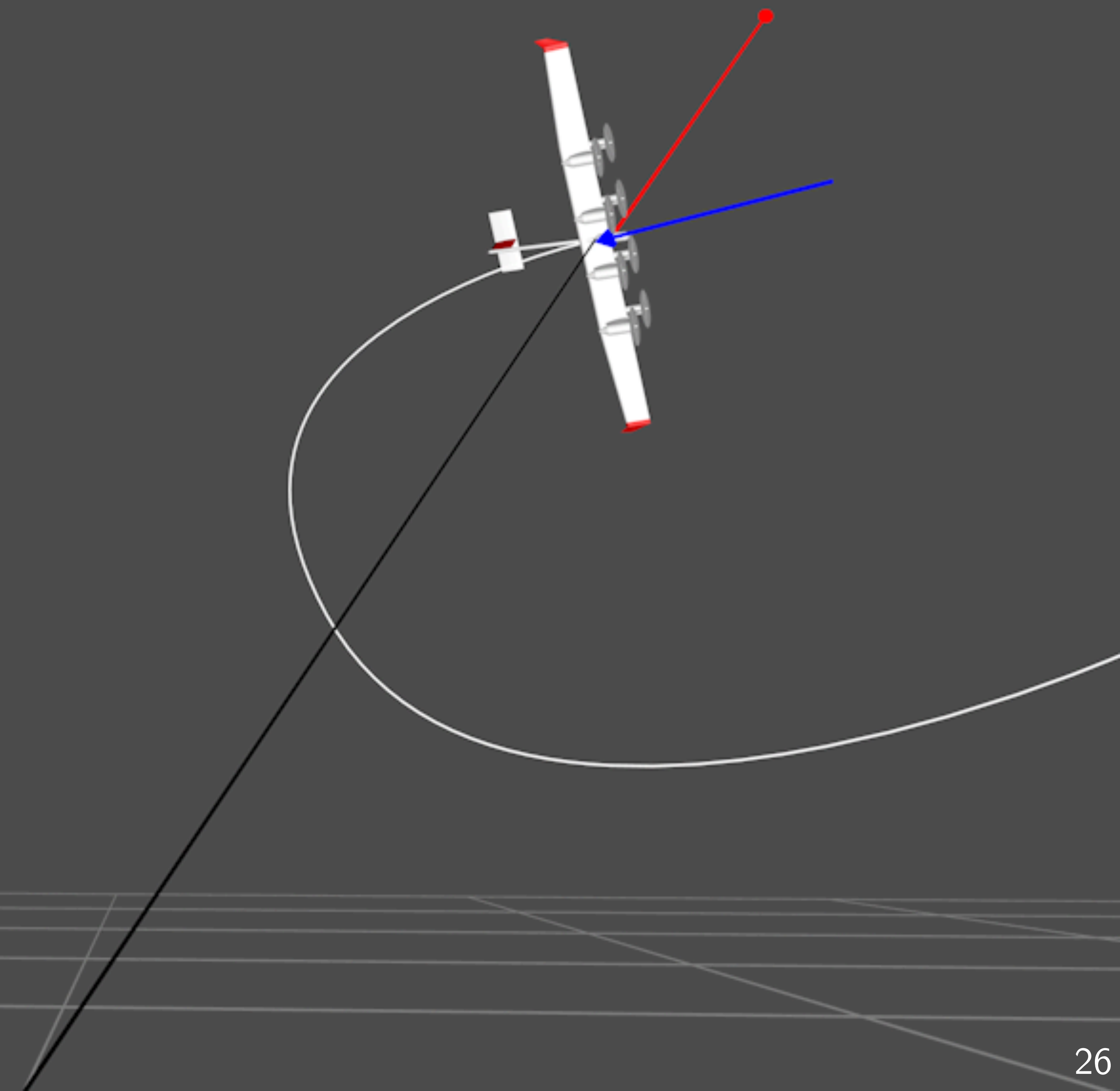

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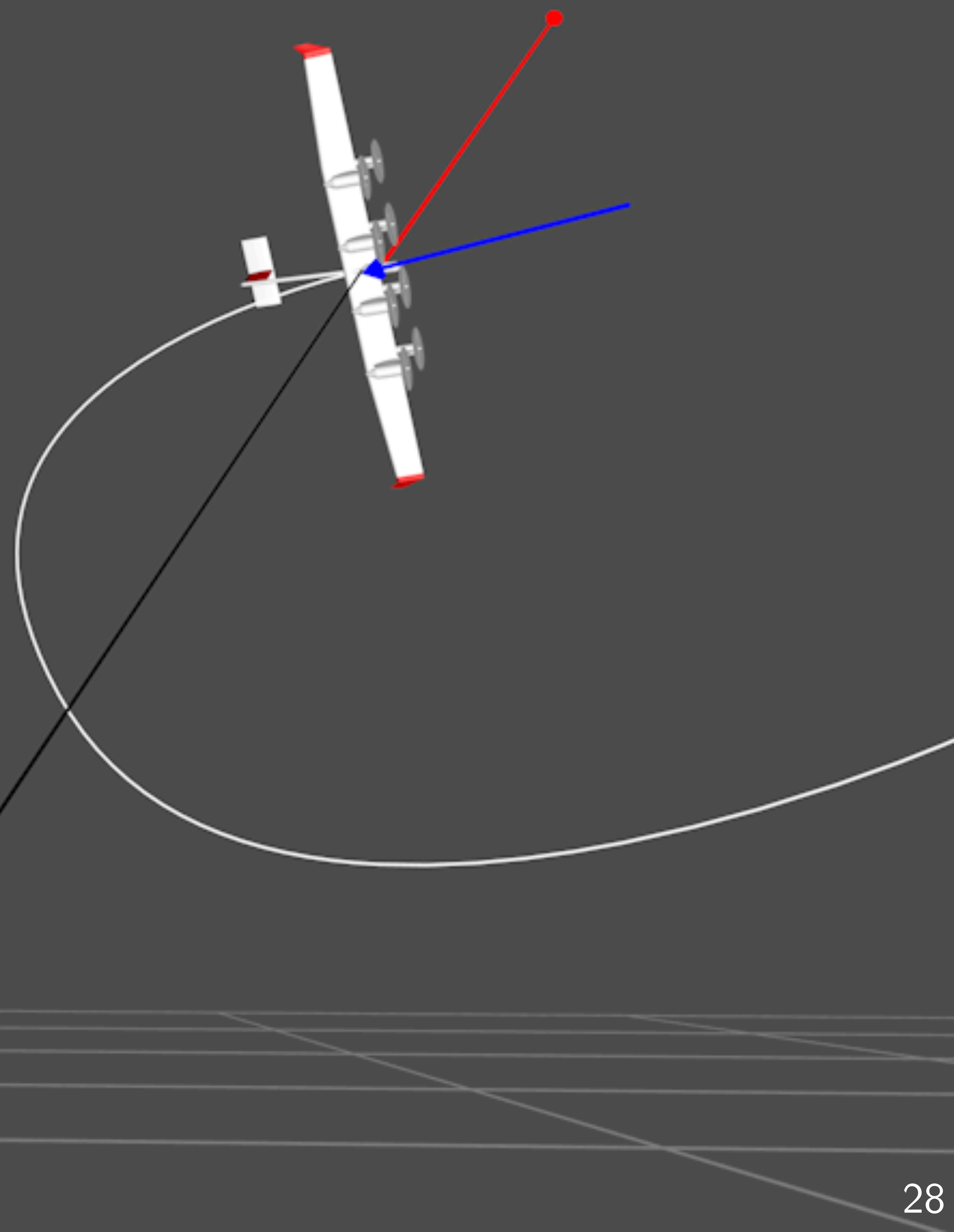
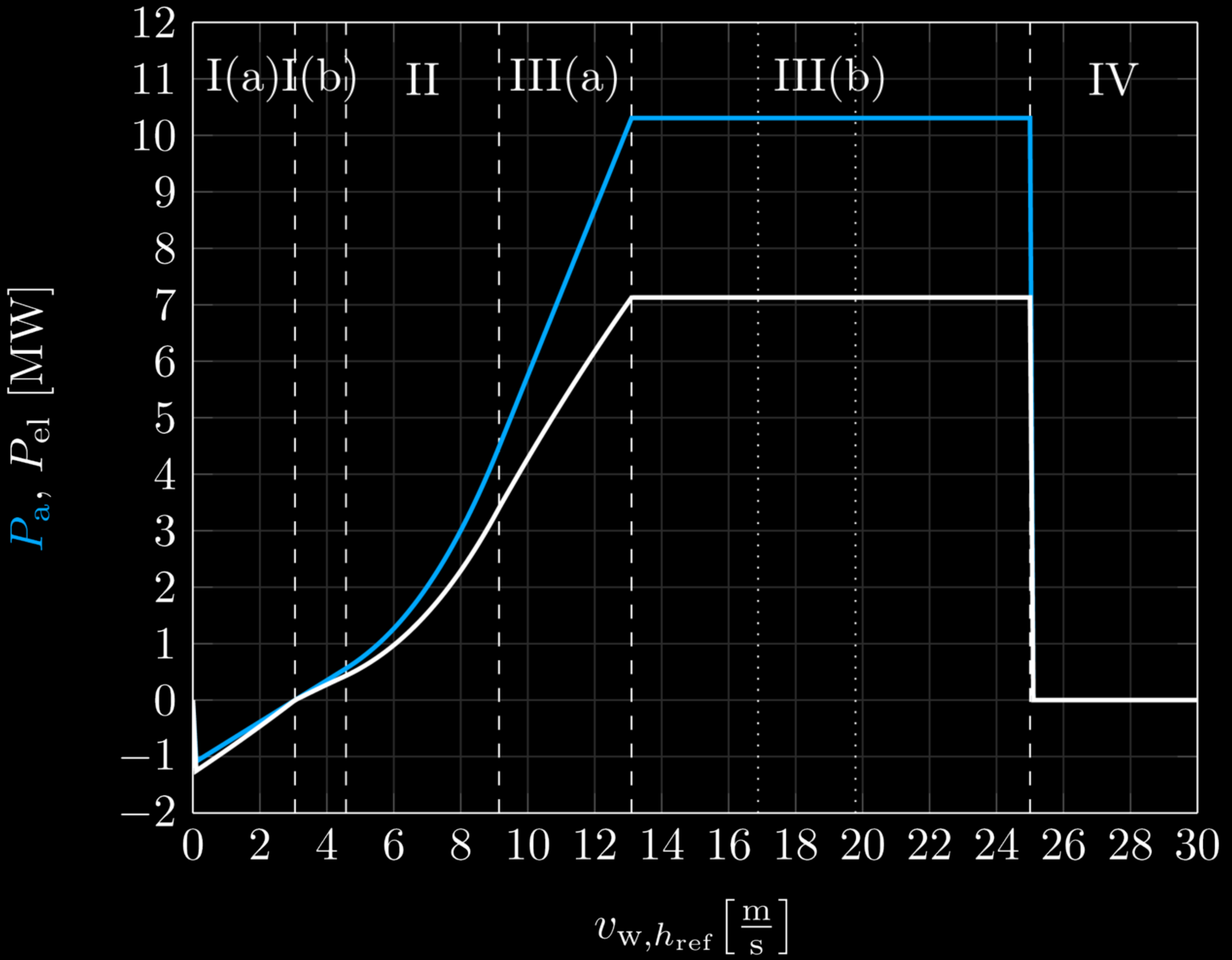
- optimization problem:

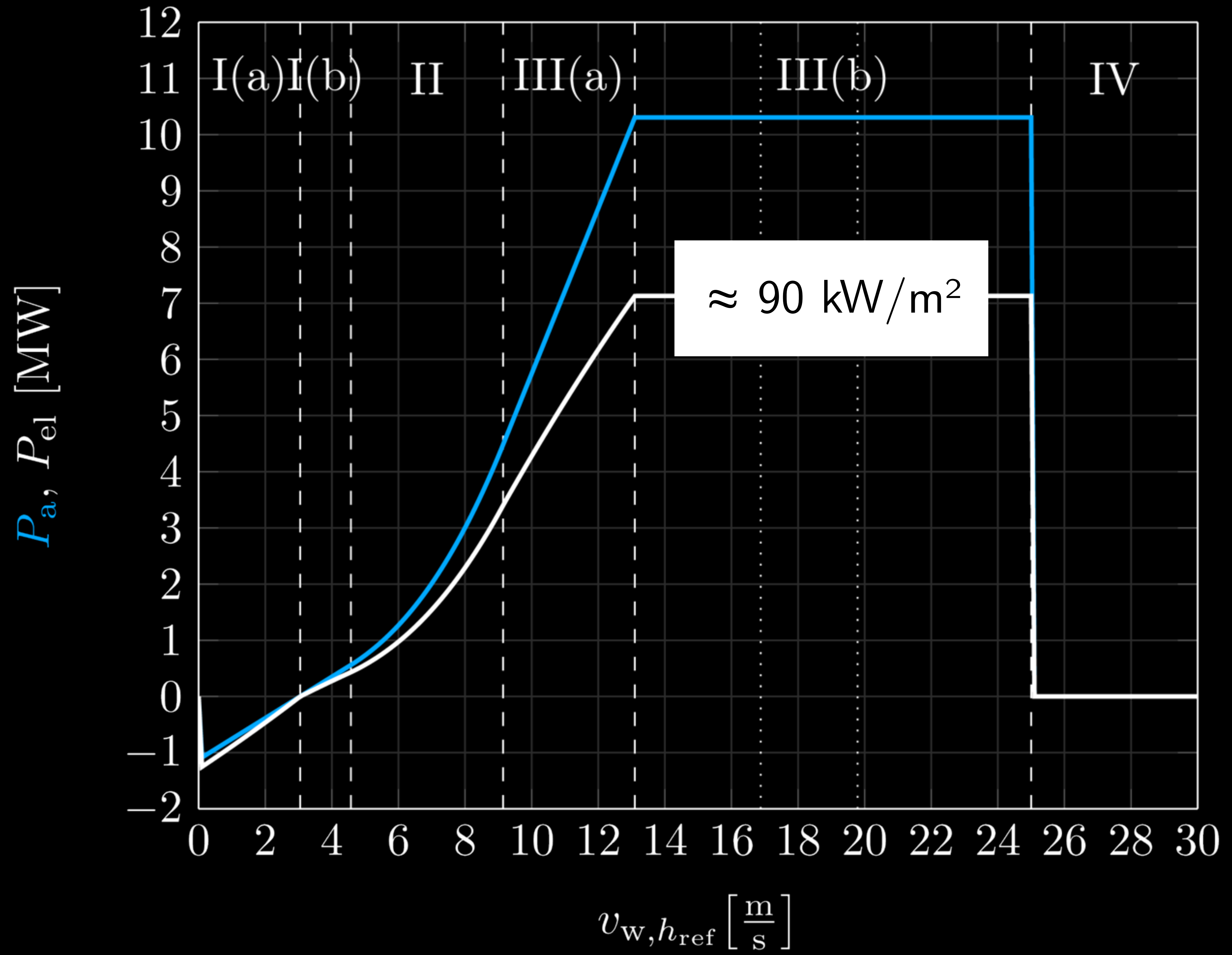
$$\max_{\boldsymbol{y}} \quad \frac{\hat{K}_{\mathrm{inv,o\&p}}}{A}$$
$$\text{s.t.} \quad \underline{\boldsymbol{y}} \leq \boldsymbol{y} \leq \overline{\boldsymbol{y}}$$

Outline





I(a)
I(b)
II
III(a)
III(b)
IV
P_a, P_{el} [MW]
12
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
$v_{w,h_{ref}} \left[\frac{m}{s}\right]$


I(a)
I(b)
II
III(a)
III(b)
IV
≈ 90 kW/m²
P_a, P_{el} [MW]
$v_{w,h_{ref}}$ $\left[\frac{m}{s}\right]$
12
11
10
9
8
7
6
5
4
3
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Parameter	Value
nominal airfoil lift coefficient	4.16
tether length	370.67 m
elevation angle	19.36 °
tether voltage	9.8 kV
maximum allowed investment costs (o&p)/wing area	56 k$/m^2
total maximum allowed investment costs	5.5 Mio. $
energy yield per year	18.5 Mio. kWh
tether mass	1.1 t
maximum allowed kite mass	11.7 t
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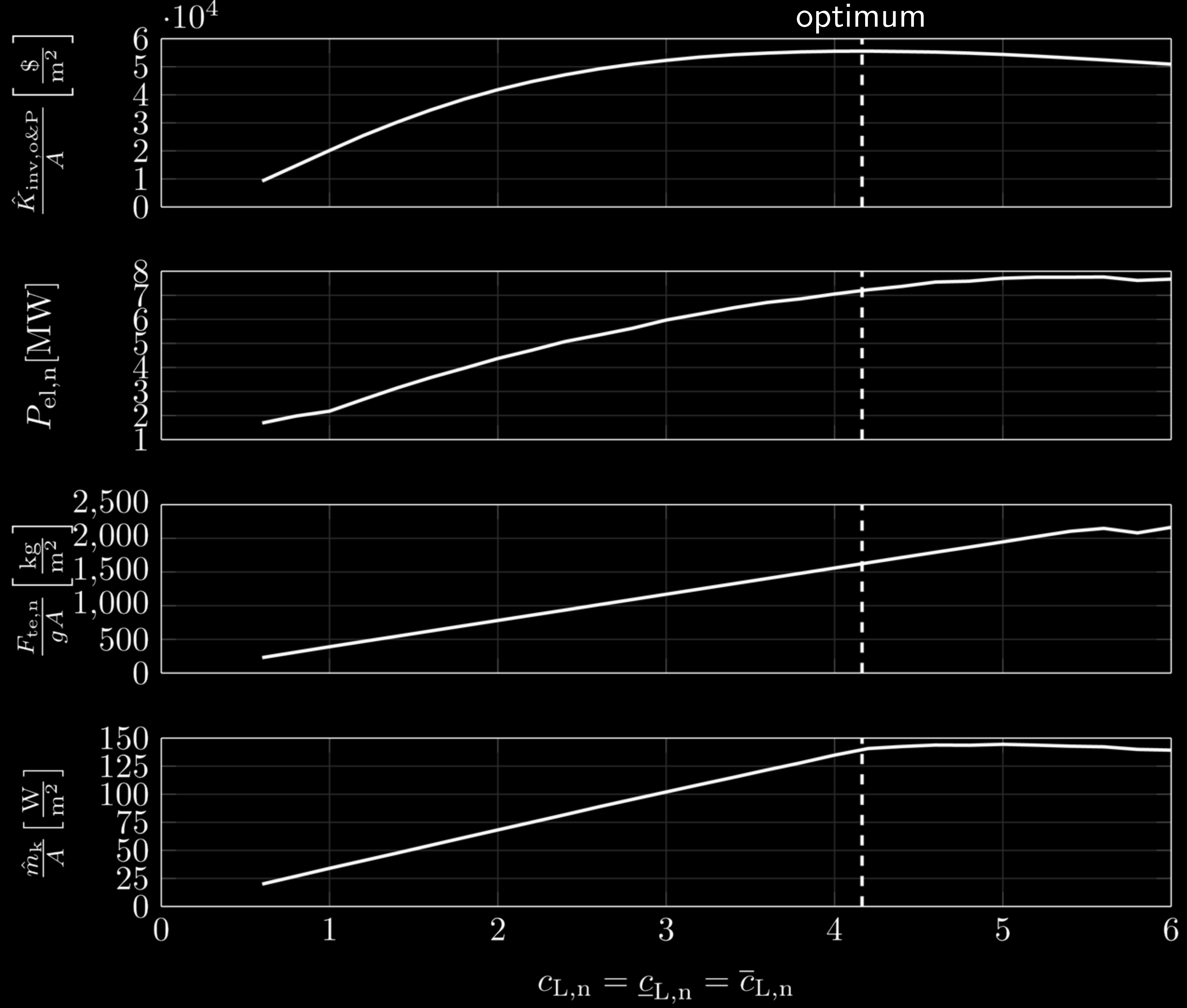

optimum
$\cdot 10^4$
$\frac{\hat{K}_{\mathrm{inv,o\&P}}}{A}\left[\frac{\$}{\mathrm{m}^2}\right]$
$P_{\mathrm{el,n}}[\mathrm{MW}]$
$\frac{F_{\mathrm{te,n}}}{gA}\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right]$
$\frac{\hat{m}_{\mathrm{k}}}{A}\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
0 1 2 3 4 5 6
0 500 1,000 1,500 2,000 2,500
0 25 50 75 100 125 150
$c_{\mathrm{L,n}} = \underline{c}_{\mathrm{L,n}} = \overline{c}_{\mathrm{L,n}}$

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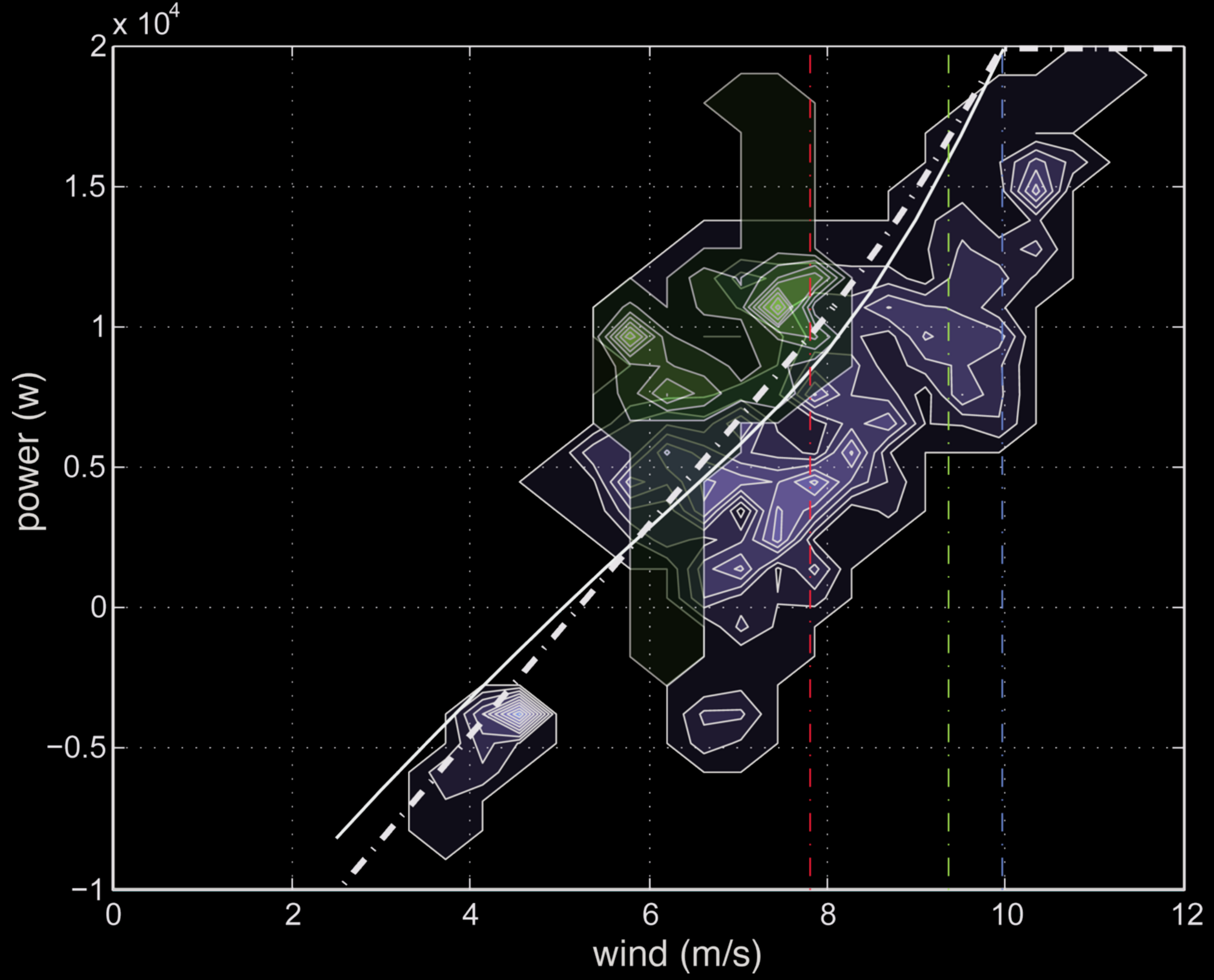
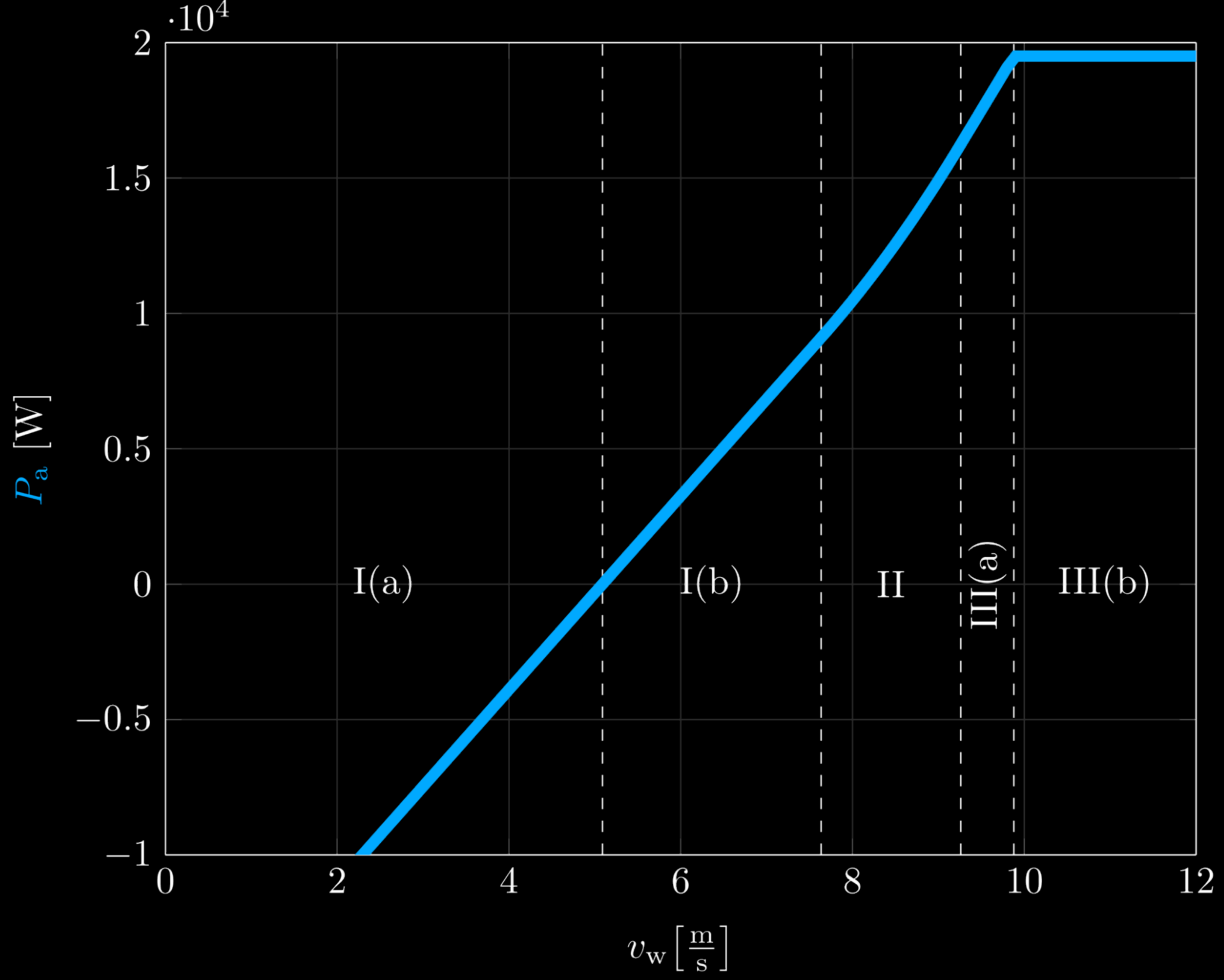
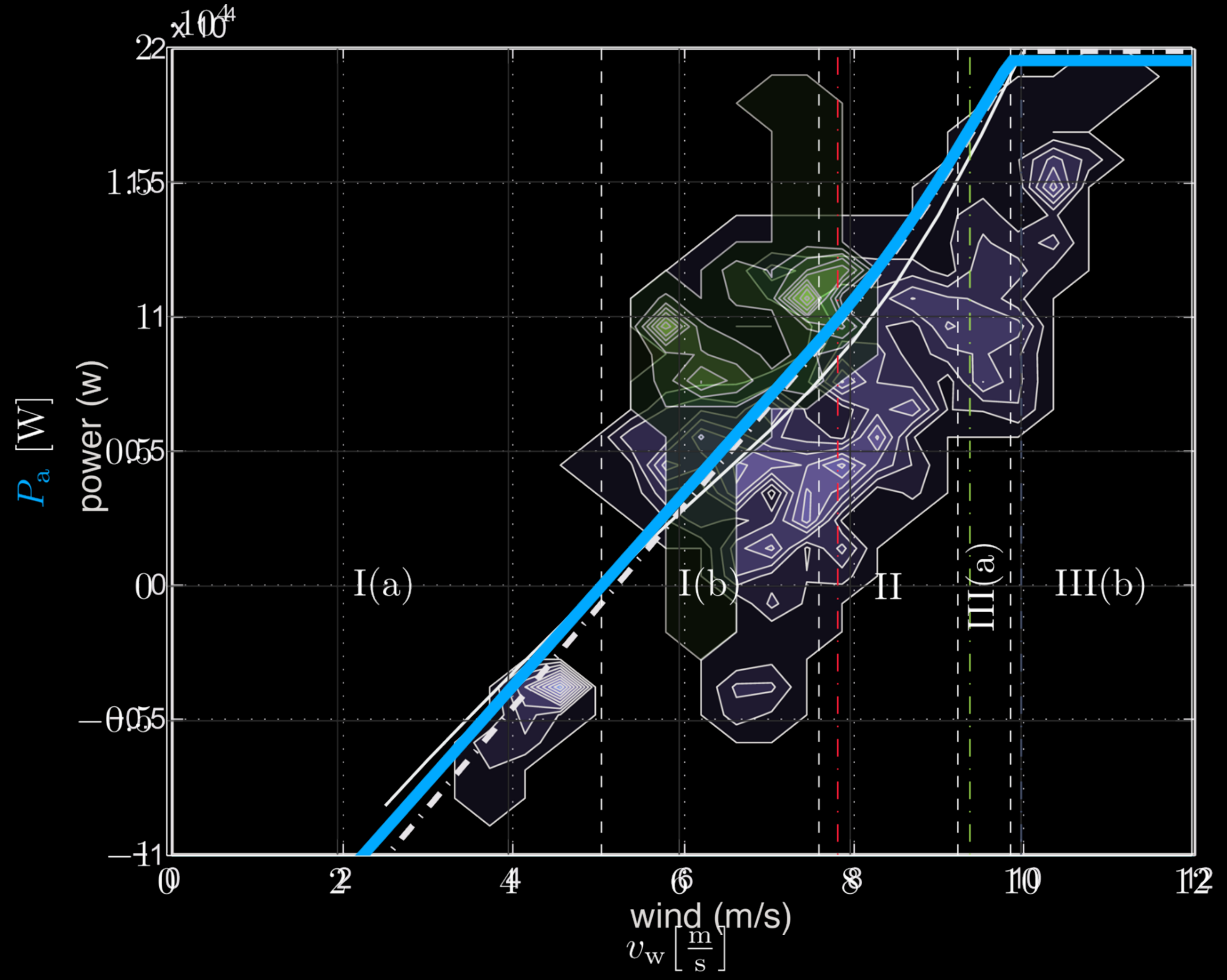
- the model can reproduce measured data by Makani (model verfication, at least in part)





Source of left (bottom) figure: Damon Vander Lind. "Analysis and Flight Test Validation of High Performance Airborne Wind Turbines". In: Airborne Wind Energy. Ed. by Uwe Ahrens, Moritz Diehl, and Roland Schmehl. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013. Fig. 28.12.



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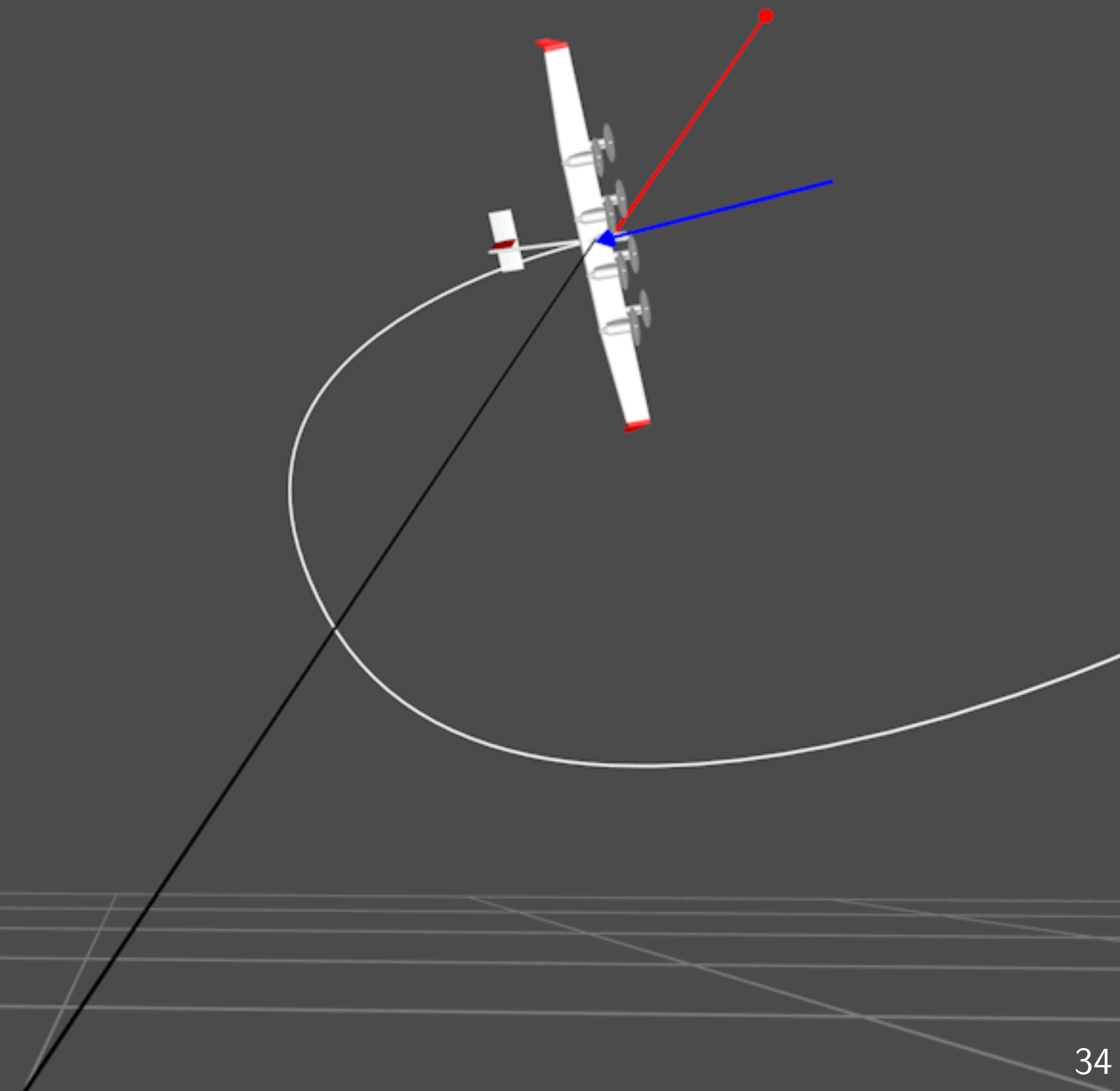

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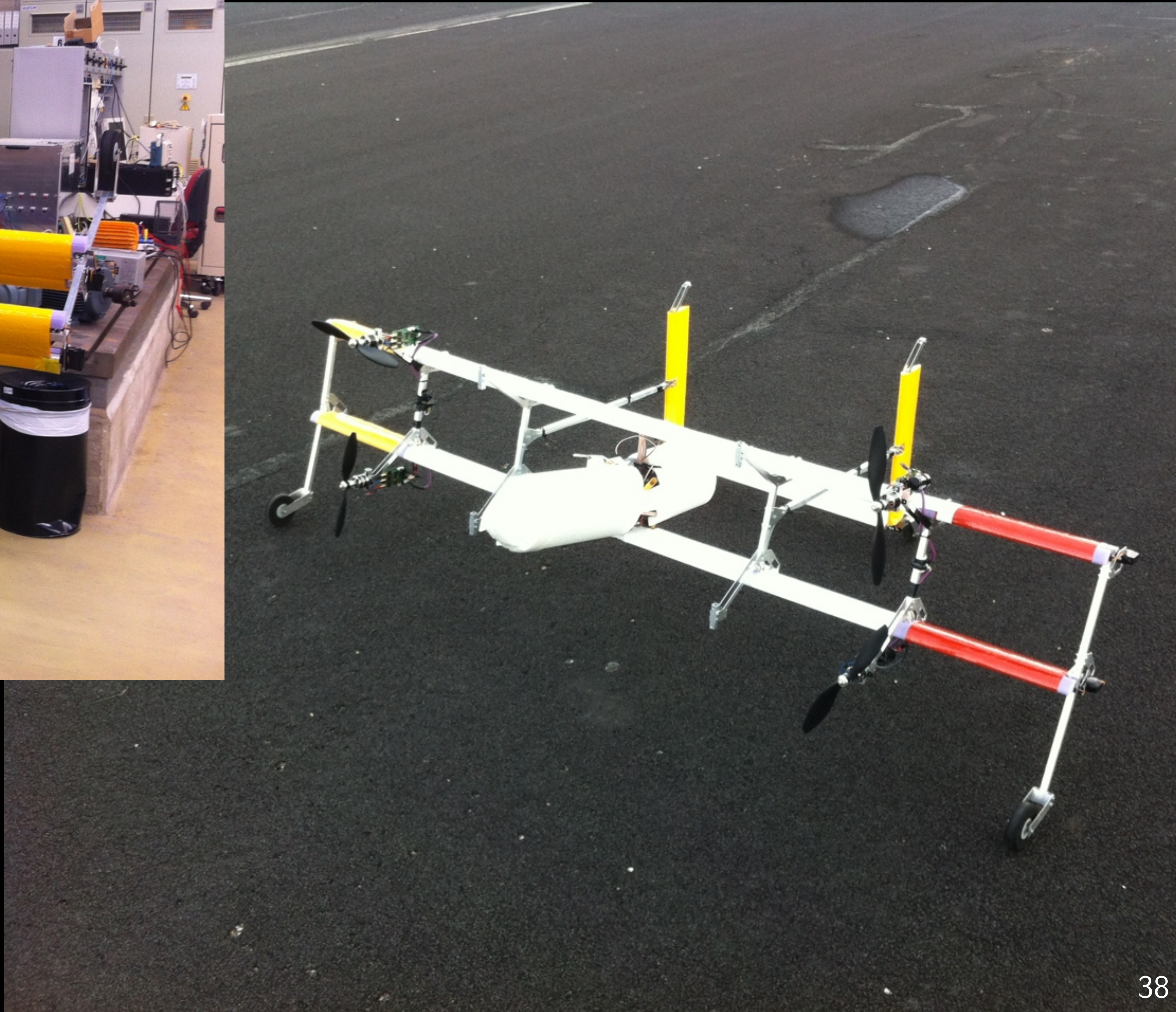
- verifications: wind tunnel, higher fidelity models, tiny-scale (1 kW) kite on the way, small-scale (20 kW) kite planned



Institute for Electrical Drive Systems and Power Electronics,
Department of Electrical Engineering and Information Technology,
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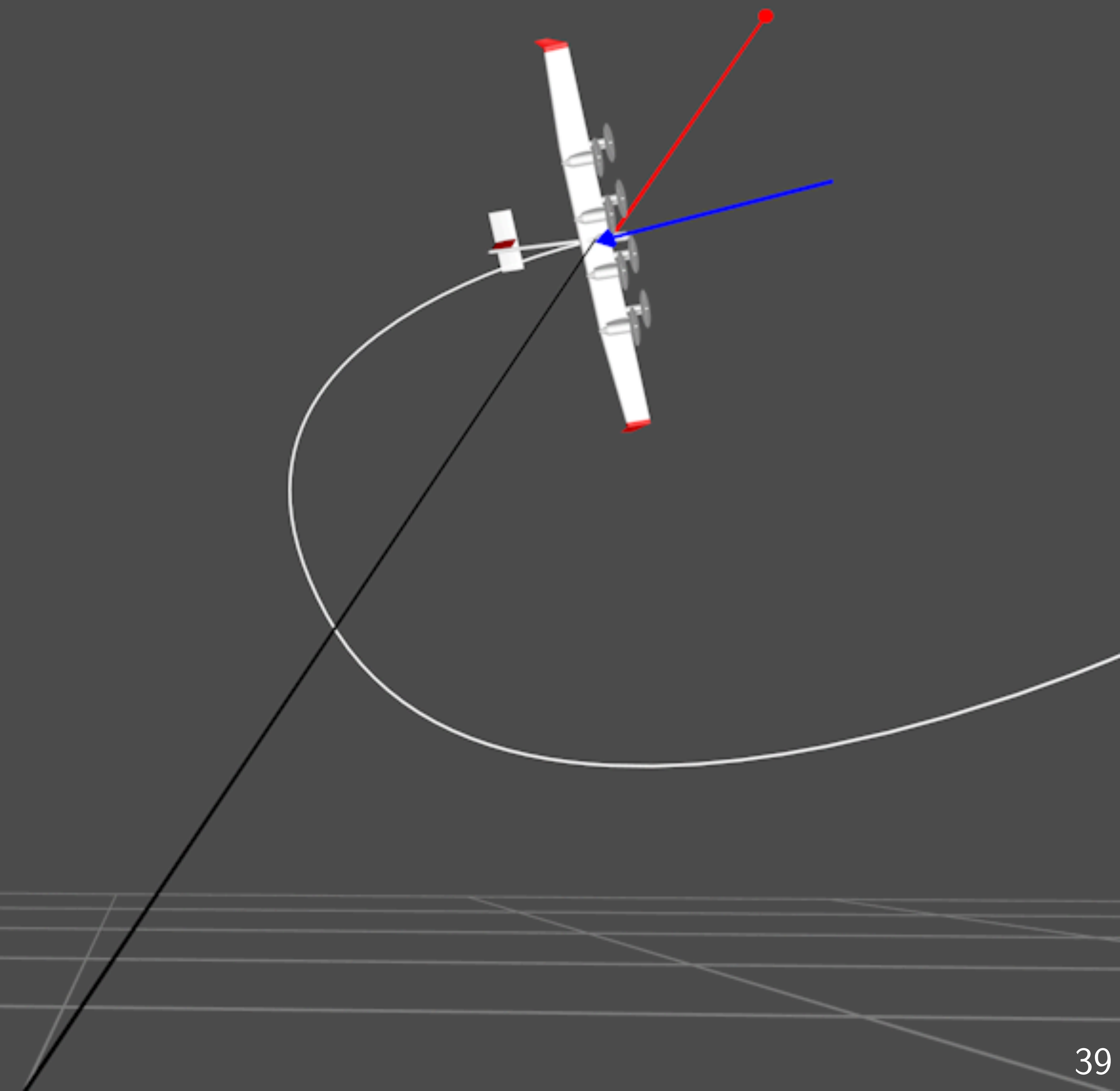
Power Curve and Design Optimization of Drag Power Kites



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florian.bauer@tum.de,
October 5th, 2017,
Airborne Wind Energy Conference 2017, Freiburg, Germany