system design & management

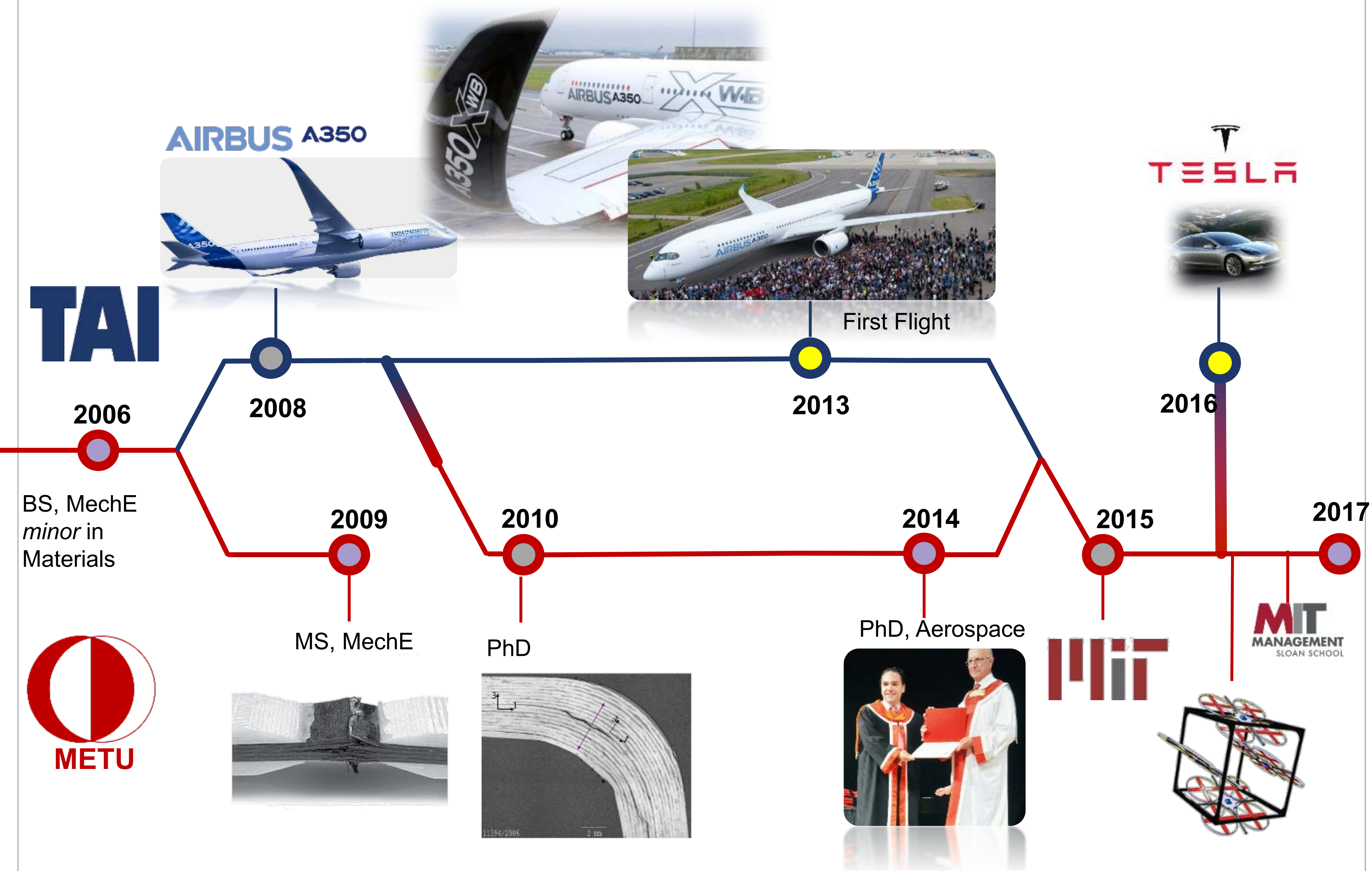
Harnessing Wind Energy

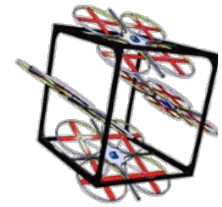
04/24/2017

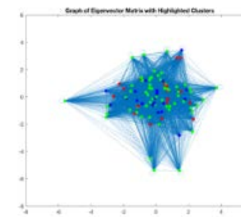
MITsdm

Burak Gozluklu

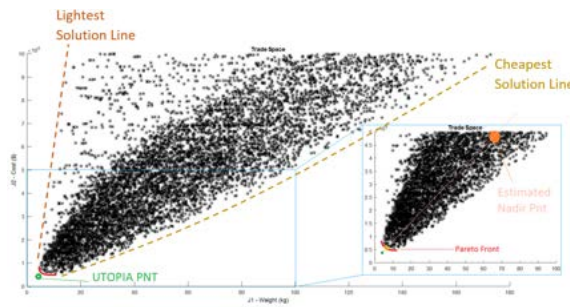
MIT-SDM Fellow and Research Assistant at System Dynamics Group

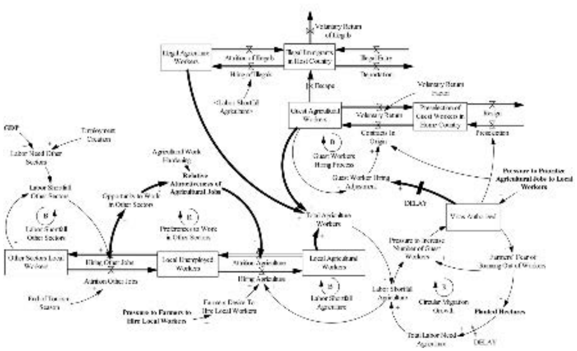

AIRBUS A350
TAI
2006
BS, MechE
minor in
Materials
METU
2008
2009
MS, MechE
2010
PhD
2013
First Flight
2014
PhD, Aerospace
2015
2016
TESLA
2017
MIT
MANAGEMENT
SLOAN SCHOOL

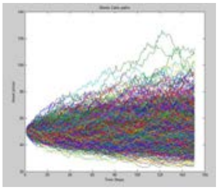




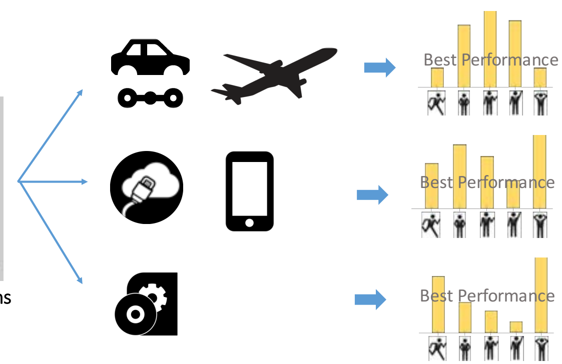
School of Engineering







Monte Carlo Simulations



Aerospace/Automotive

Electronics/IoT

Software

MIT MANAGEMENT SLOAN SCHOOL

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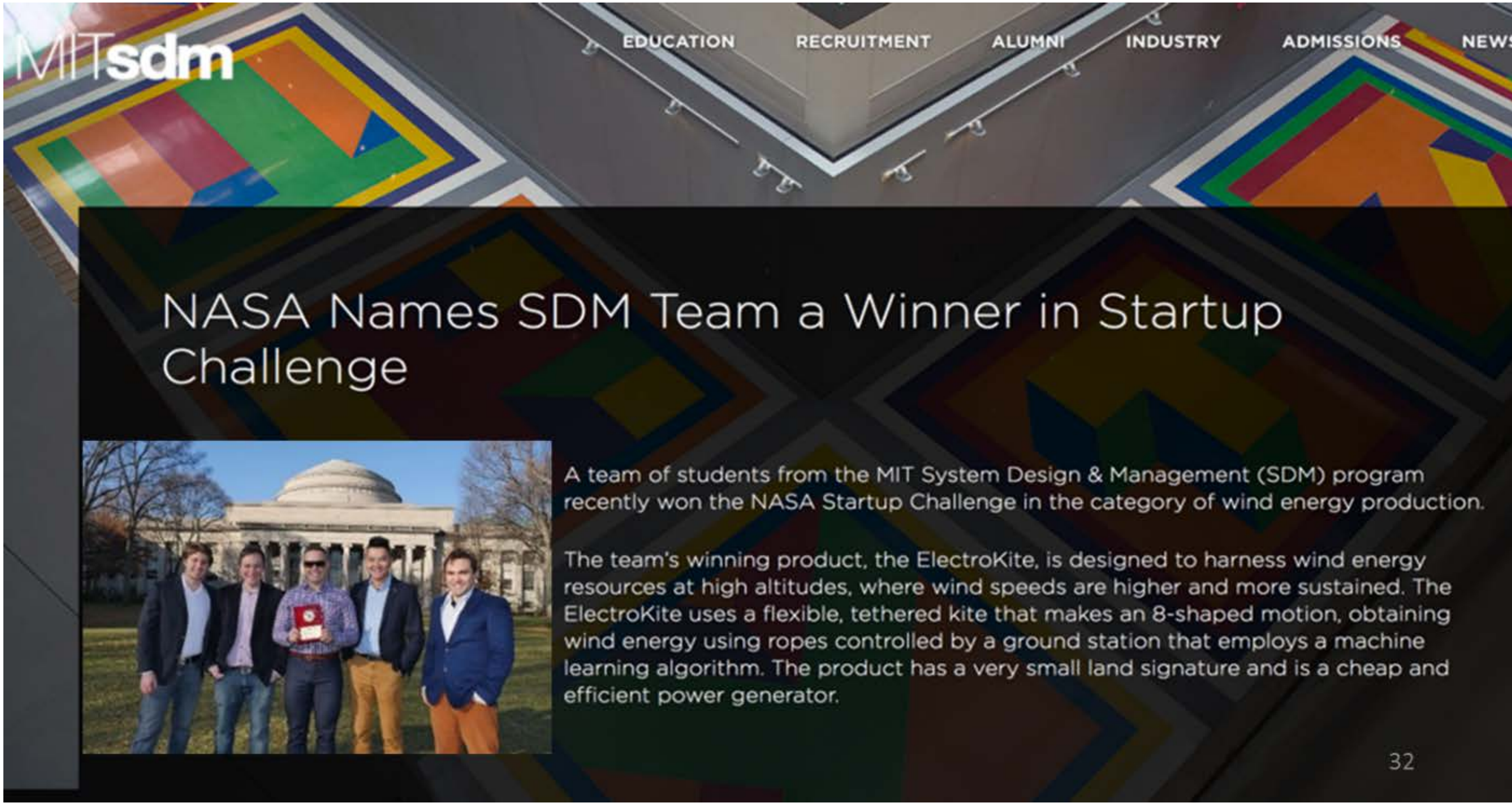

MITsdm EDUCATION RECRUITMENT ALUMNI INDUSTRY ADMISSIONS NEWS

NASA Names SDM Team a Winner in Startup Challenge

A team of students from the MIT System Design & Management (SDM) program recently won the NASA Startup Challenge in the category of wind energy production.

The team's winning product, the ElectroKite, is designed to harness wind energy resources at high altitudes, where wind speeds are higher and more sustained. The ElectroKite uses a flexible, tethered kite that makes an 8-shaped motion, obtaining wind energy using ropes controlled by a ground station that employs a machine learning algorithm. The product has a very small land signature and is a cheap and efficient power generator.

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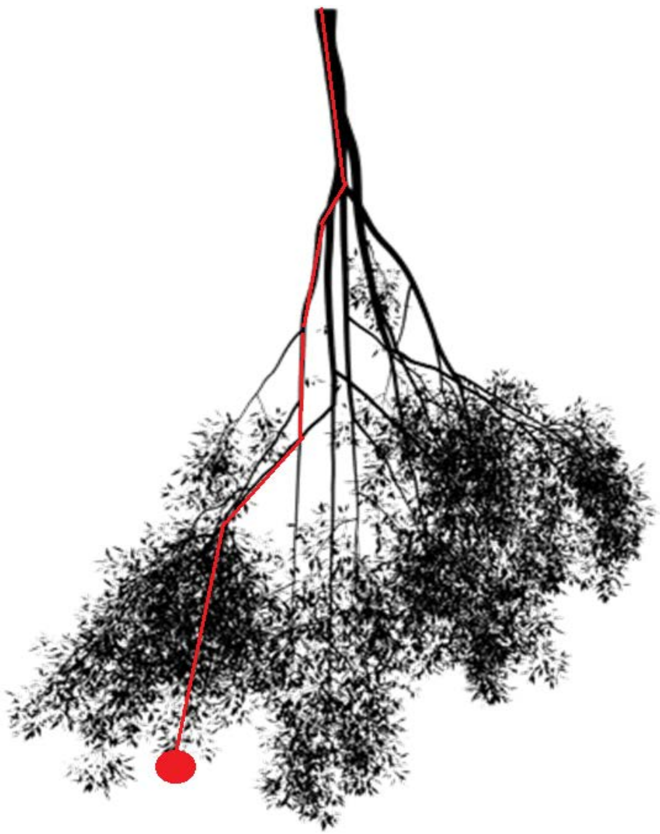
system design & management

Harnessing Wind Energy

MITsdm

Take-Aways



Level-0	Problem Definition
Level-1	Supplying Energy
Level-2	Solar and Wind Energy
Level-3	Wind Energy
Level-4	Airborne Wind Energy

- …
- …
- …

- …


Problem
Definition

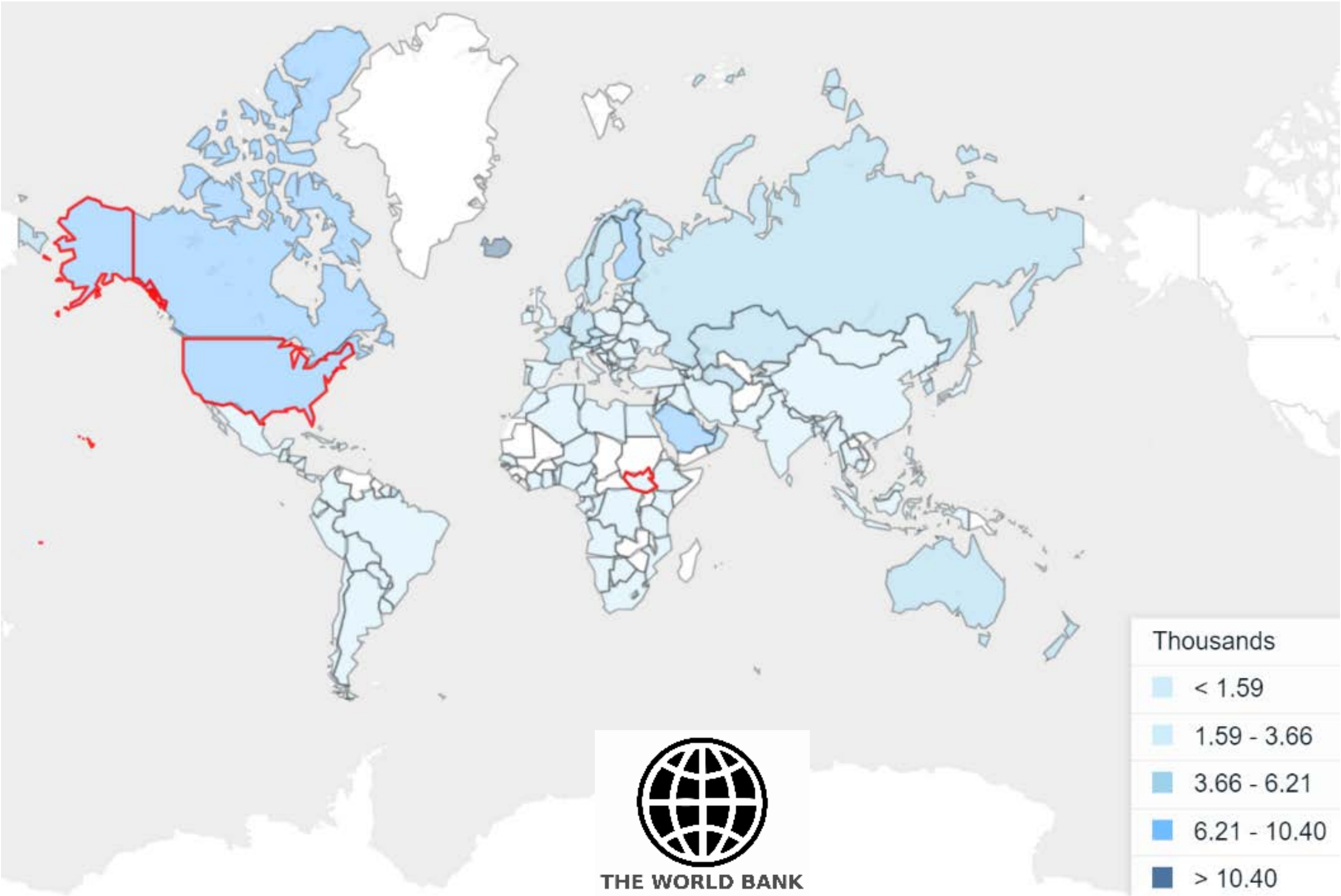
1.1 Billion People

Courtesy of Economist,
Retrieved from: http://www.economist.com/news/international/21693581-new-electricity-system-emerging-bring-light-worlds-poorest-key

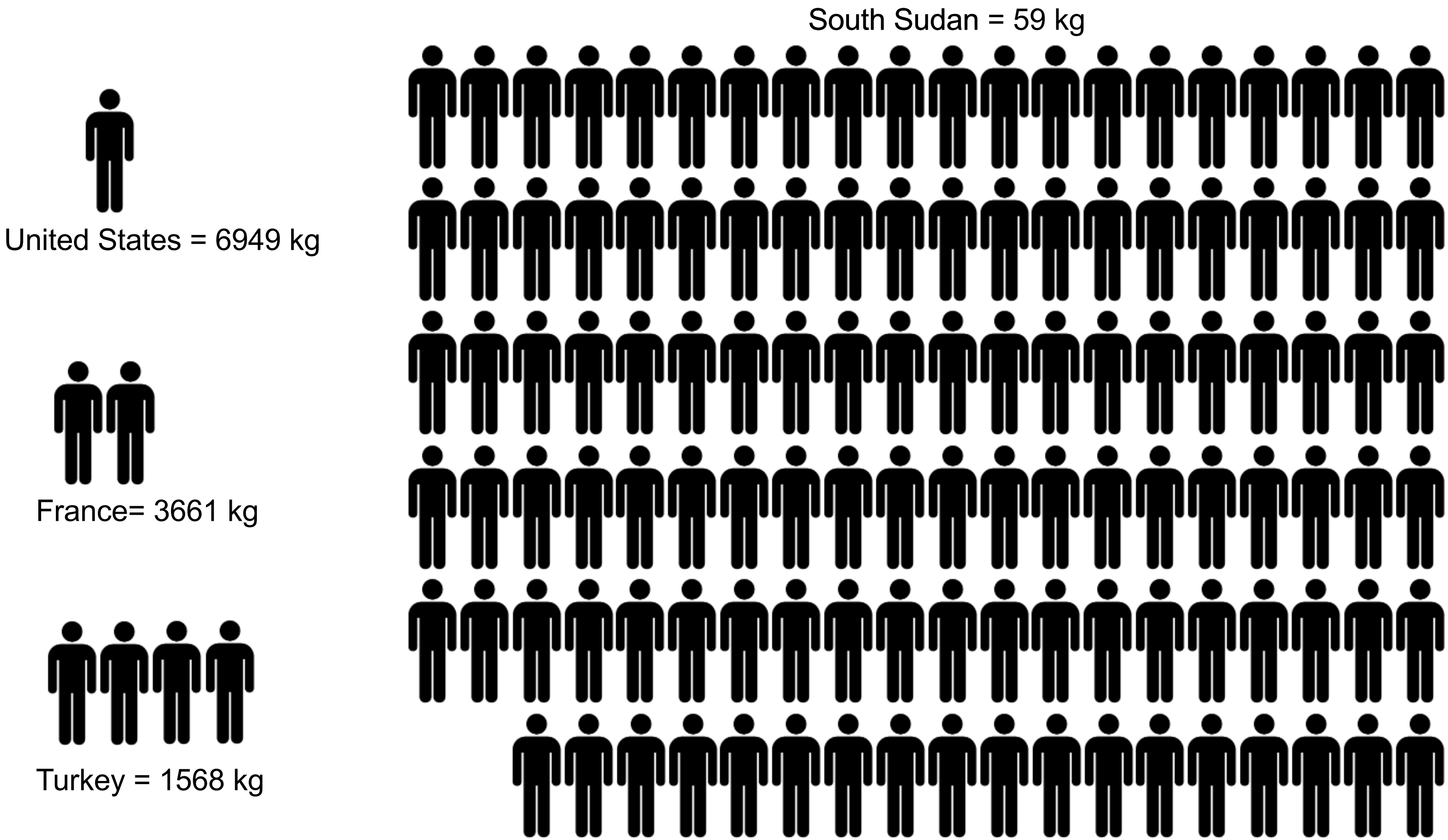
Courtesy of NDTF Profit,
Retrieved from: http://profit.ndtv.com/news/nation/article-grid-failures-fuel-scarcity-spell-gloom-for-power-sector-in-2012-315342

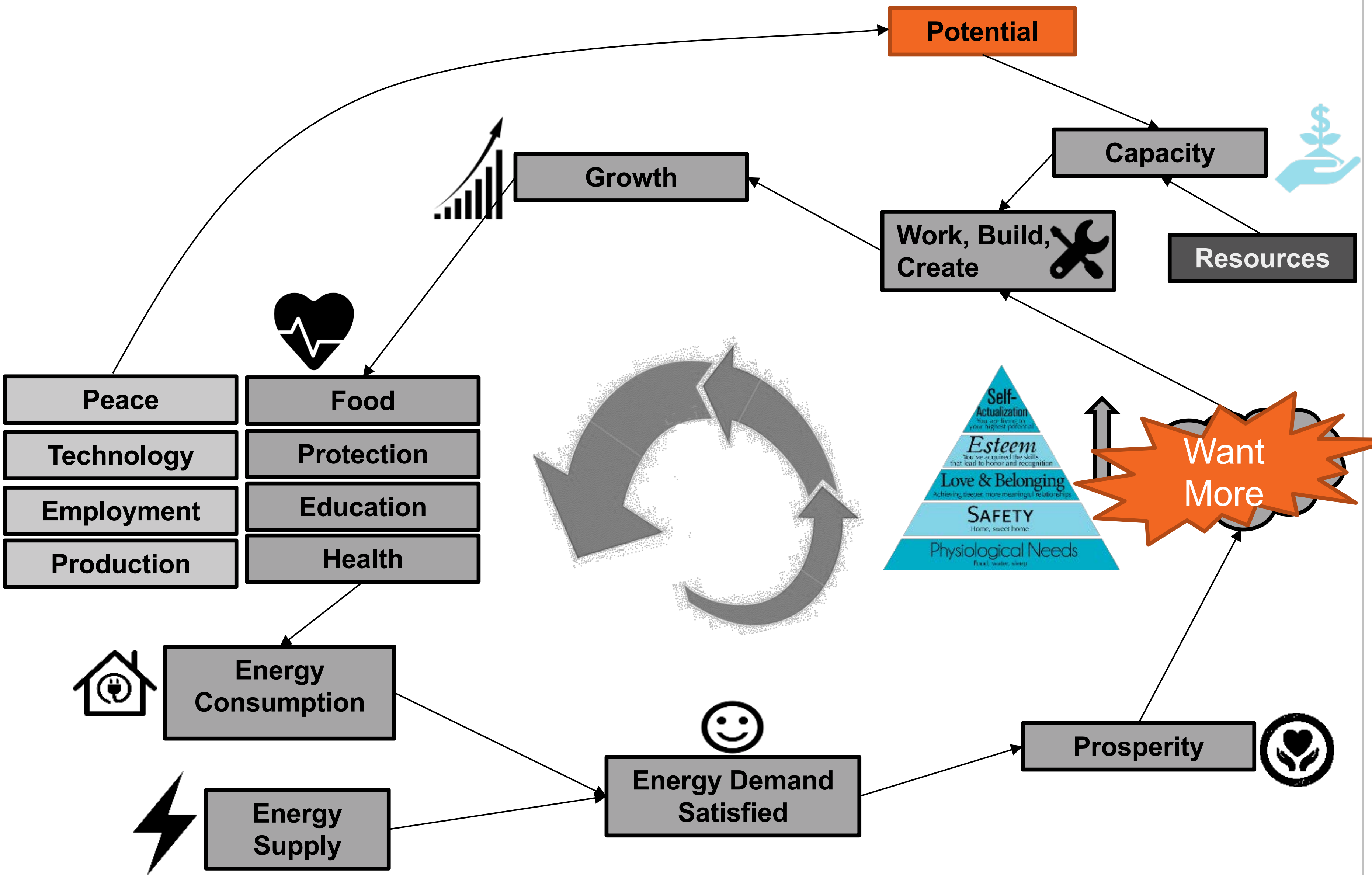
- The deficit is concentrated in rural areas of sub-Saharan Africa and South Asia, as well as East Asia. (IIED/Hivos, 2016)

Annual energy usage (kg of oil equivalent per capita)

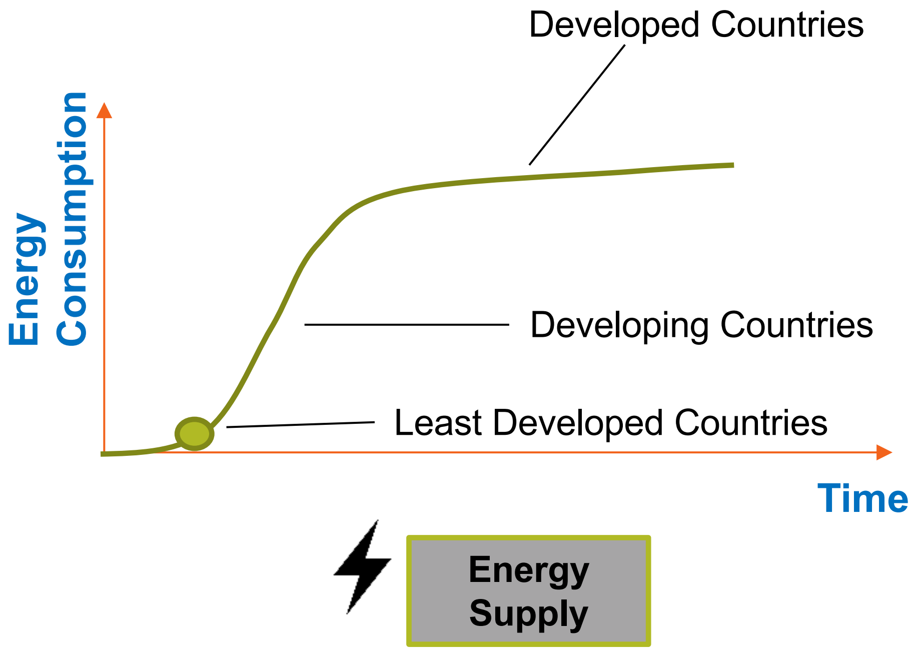


Retrieved from As of 21st of April, 2017
http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE?end=2014&locations=SS-WS-US&name_desc=true&page=1&start=2012&view=map


South Sudan = 59 kg
United States = 6949 kg
France= 3661 kg
Turkey = 1568 kg

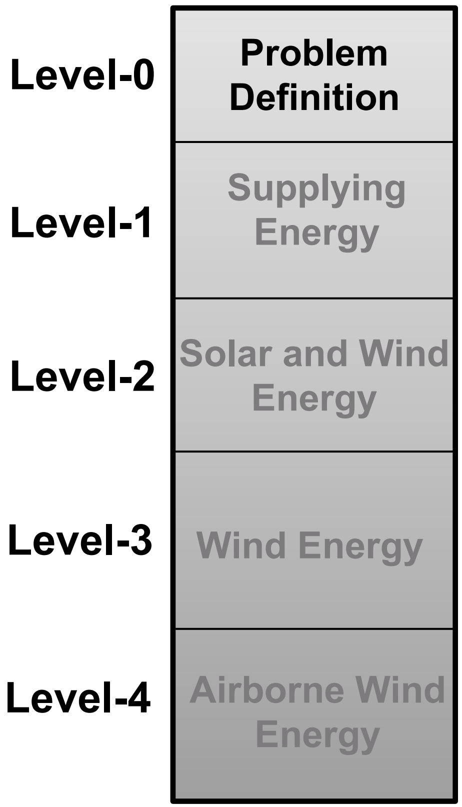

Potential
Capacity
Growth
Work, Build, Create
Resources
Peace
Technology
Employment
Production
Food
Protection
Education
Health
Self-Actualization
Esteem
Love & Belonging
SAFETY
Physiological Needs
Want More
Energy Consumption
Energy Supply
Energy Demand Satisfied
Prosperity

***USD 50 billion a year** is needed to achieve universal access to electricity and clean cooking facilities **by 2030** (IEA, 2011, 2012, SE4All 2015a)".* (IIED/Hivos, 2016)



- **Mid-Presentation Level-0 Conclusions**
- Huge inequality in energy consumption. Why?
- A snapshot of energy consumption of developing and least developed countries do not reflect the real market.
- Invest to their potentials, provide the energy in an increasing way…

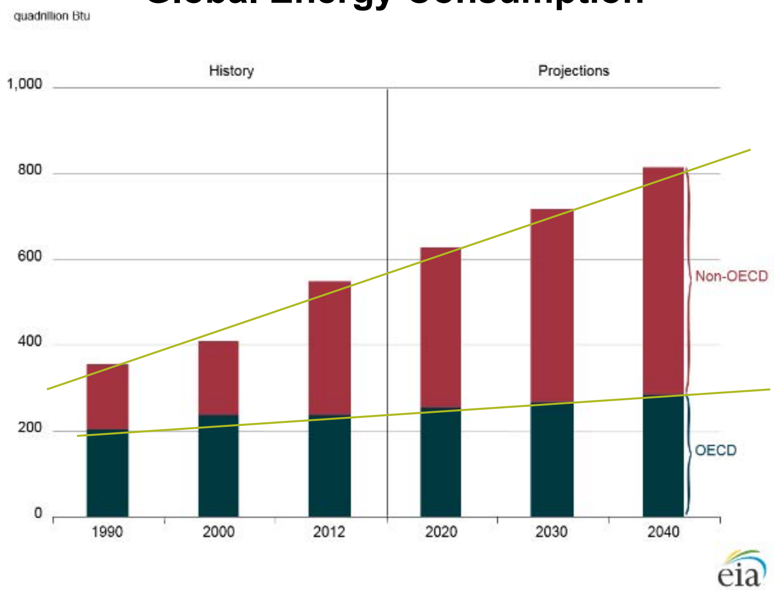
Take-Aways



- Outstanding energy and investment potential
- A snapshot of current market needs is inadequate.

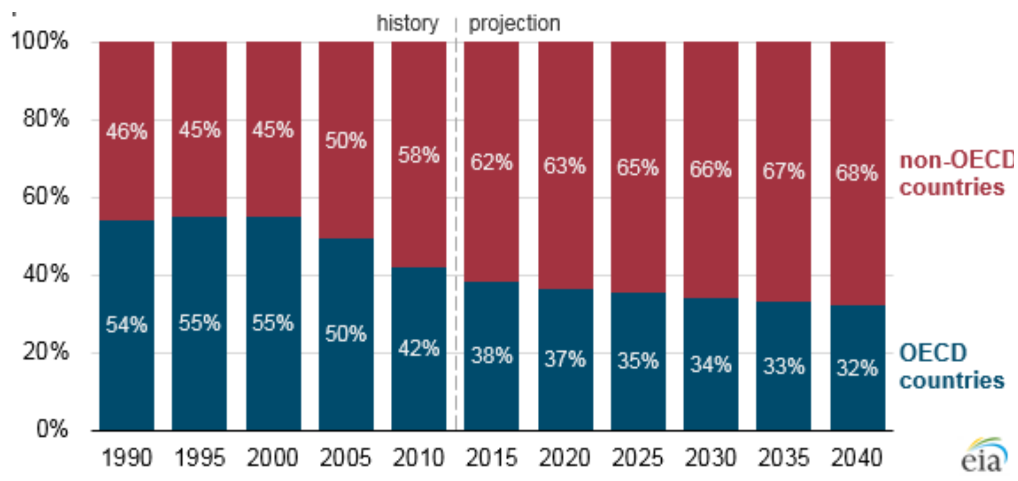

SUPPLYING THE ENERGY

Global Energy Consumption



Non-OECD countries will dominate the energy need.

% Share of Global CO2 Emissions

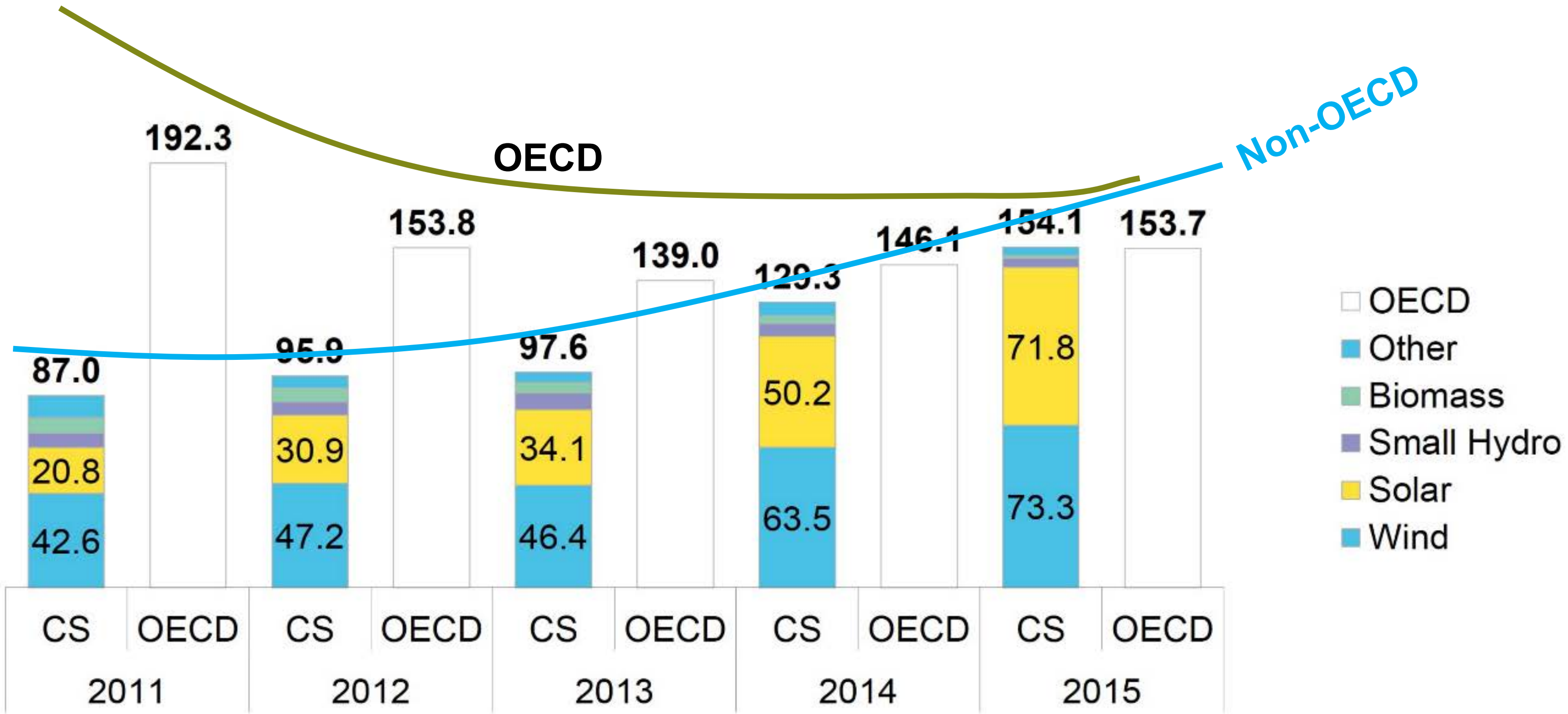


The huge energy demand of non-OECD will be likely to be supplied by Fossil Fuels.

Courtesy of eia Independent Statistics & Analysis U.S. Energy Information Administration

Taken from https://www.eia.gov/analysis/

Annual clean energy investment (Billion $)



CS: Climate Scope Countries: 58 emerging nations in Africa, Asia, the Caribbean, Latin America and the Middle East.

Clean energy investment to non-OECD will dominate OECD.

Courtesy of CLIMATESCOPE 2016

Taken from http://global-climatescope.org/en/summary/

Along with Humanitarian Issue

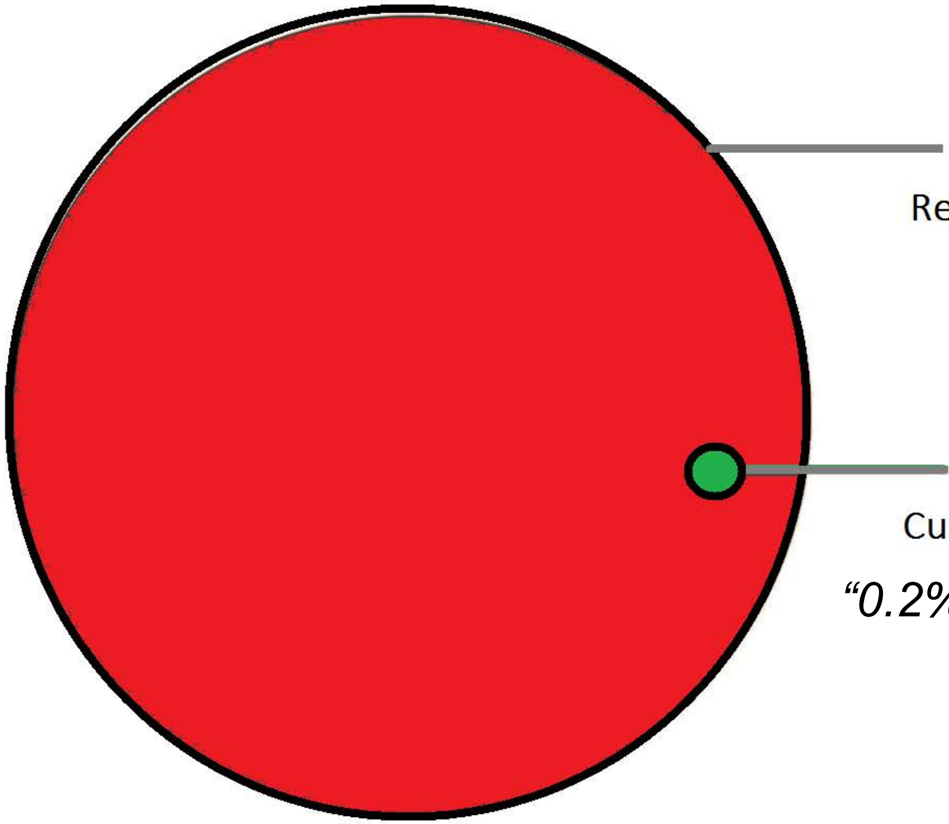
- Global Warming
- Economy

On-Grid and Centralized Electricity won't be an answer

Courtesy of the Guardian newspaper. Retrieved from https://www.theguardian.com/environment/2012/jan/05/solar-power-billion-without-electricity

Sharan Pinto installs a solar panel on the rooftop of a house in Nada, a village near the southwest Indian port of Mangalore, India. (Photograph: Rafiq Maqbool/AP)

Investment in Off-Grid Energy



"0.2% of what is necessary"

- **Mid-Presentation Level-1 Conclusions**
- Energy investment in non-OECD will dominate OECD countries.
- CO_2 will be a huge problem if the cheap fossil fuels are employed.
- Off-grid solutions, mobile and "easy-to-use" green energy solutions are necessary.

Take-Aways

Level-0	Problem Definition
Level-1	Supplying Energy
Level-2	Solar and Wind Energy
Level-3	Wind Energy
Level-4	Airborne Wind Energy

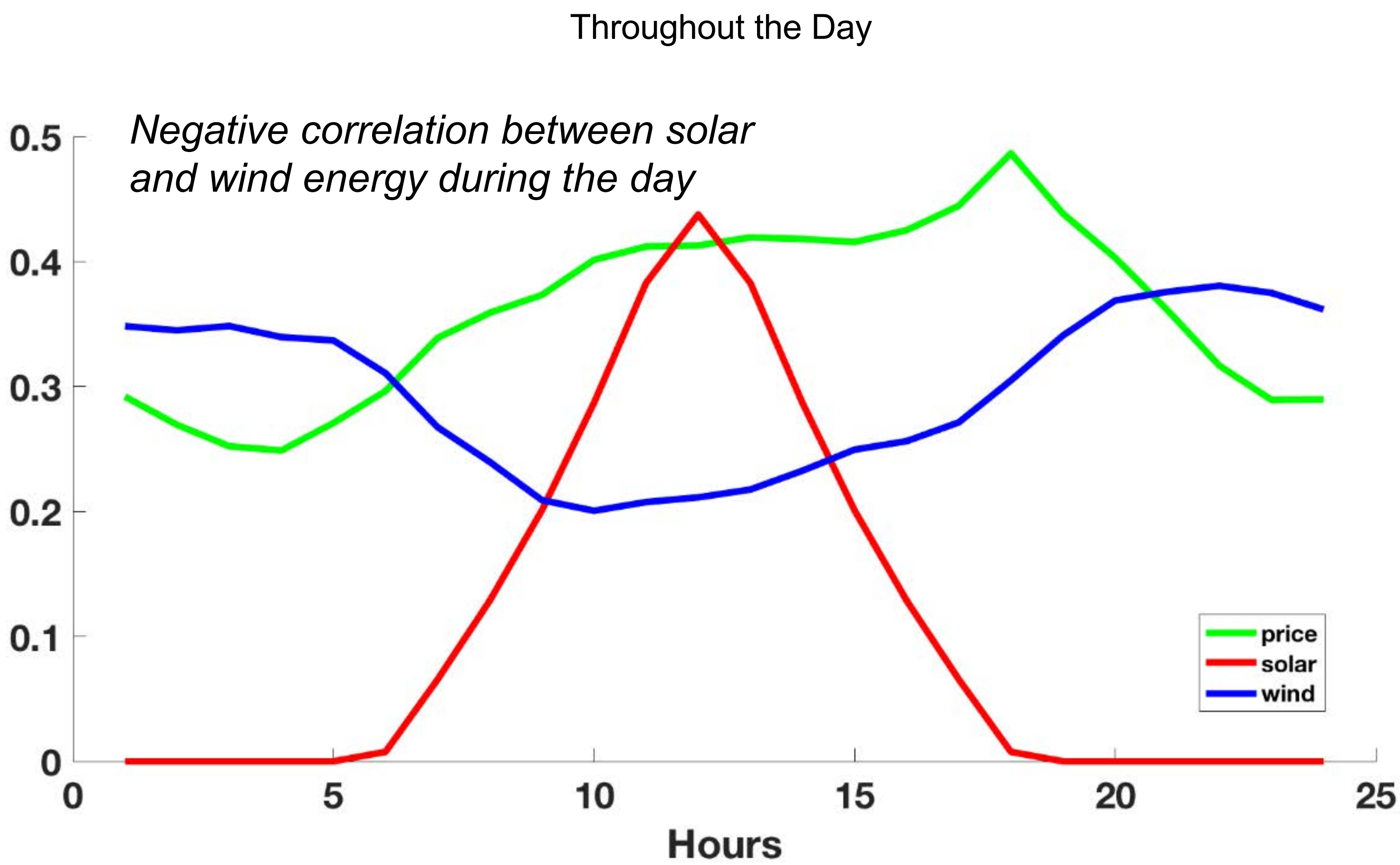
- Outstanding energy and investment potential
- A snapshot of current market needs is inadequate.

- A green energy solution is required for non-OECD's.
- Off-grid and easy to deploy solutions are needed.

SOLAR and WIND ENERGY

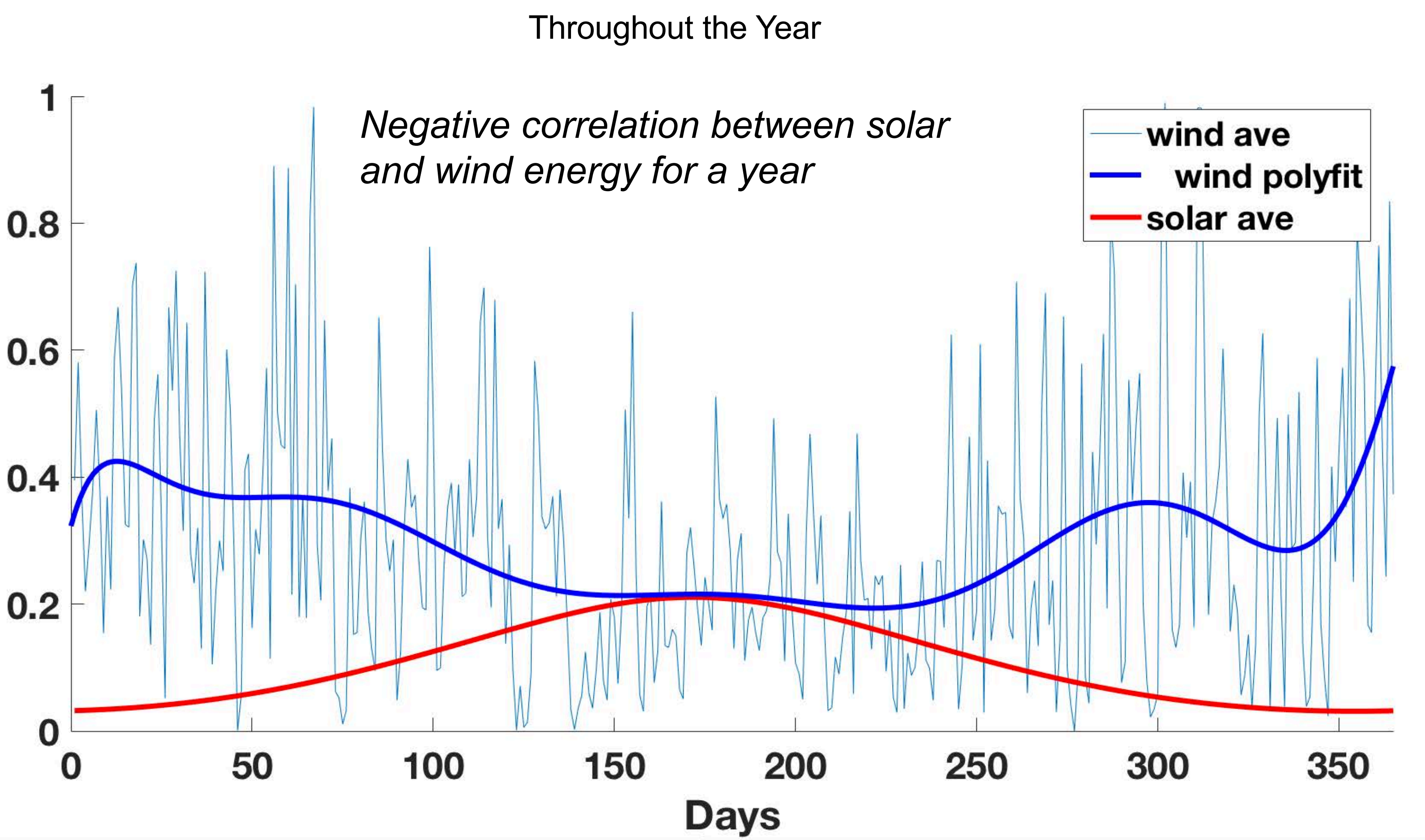
?

Plymouth, Massachusetts



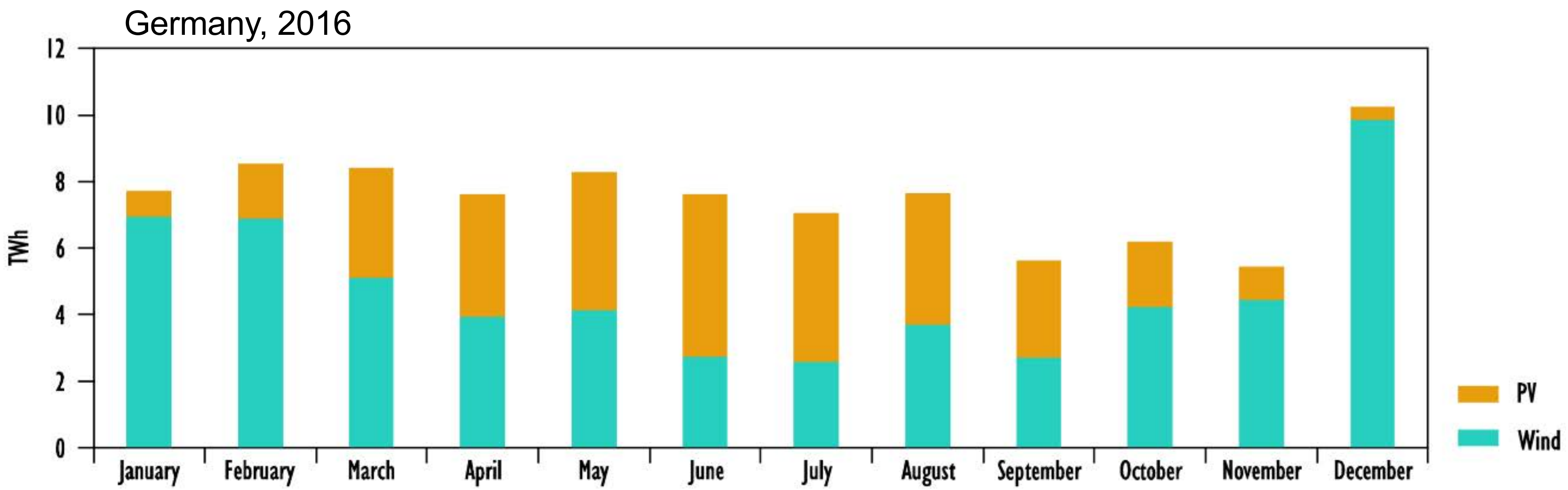
Coutesy of Carlos Damas, calculated using data in http://www.nrel.gov/

Plymouth, Massachusetts



Coutesy of Carlos Damas, calculated using data in http://www.nrel.gov/

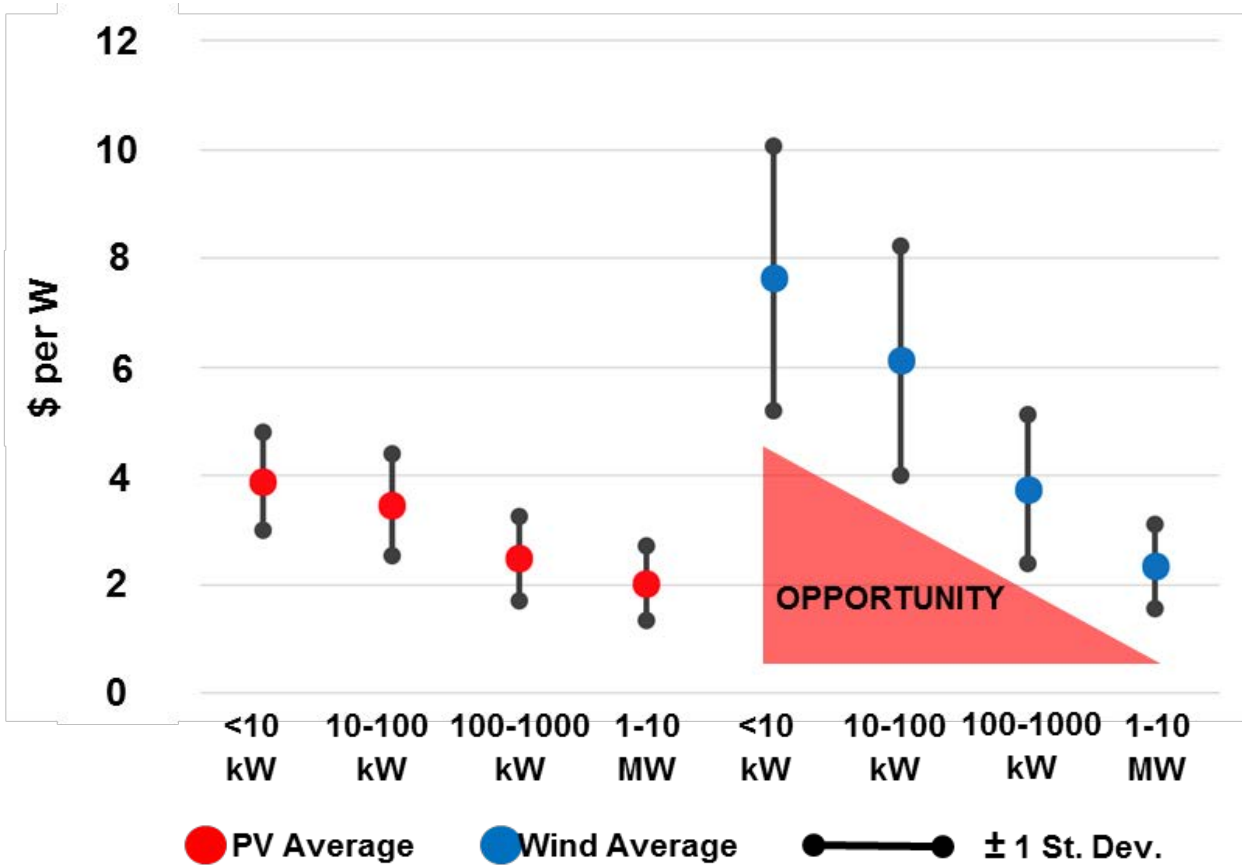
Share of Renewable Energy Obtained in Germany



*taken from International Energy Agency, Next-generation wind and solar power, 2016.

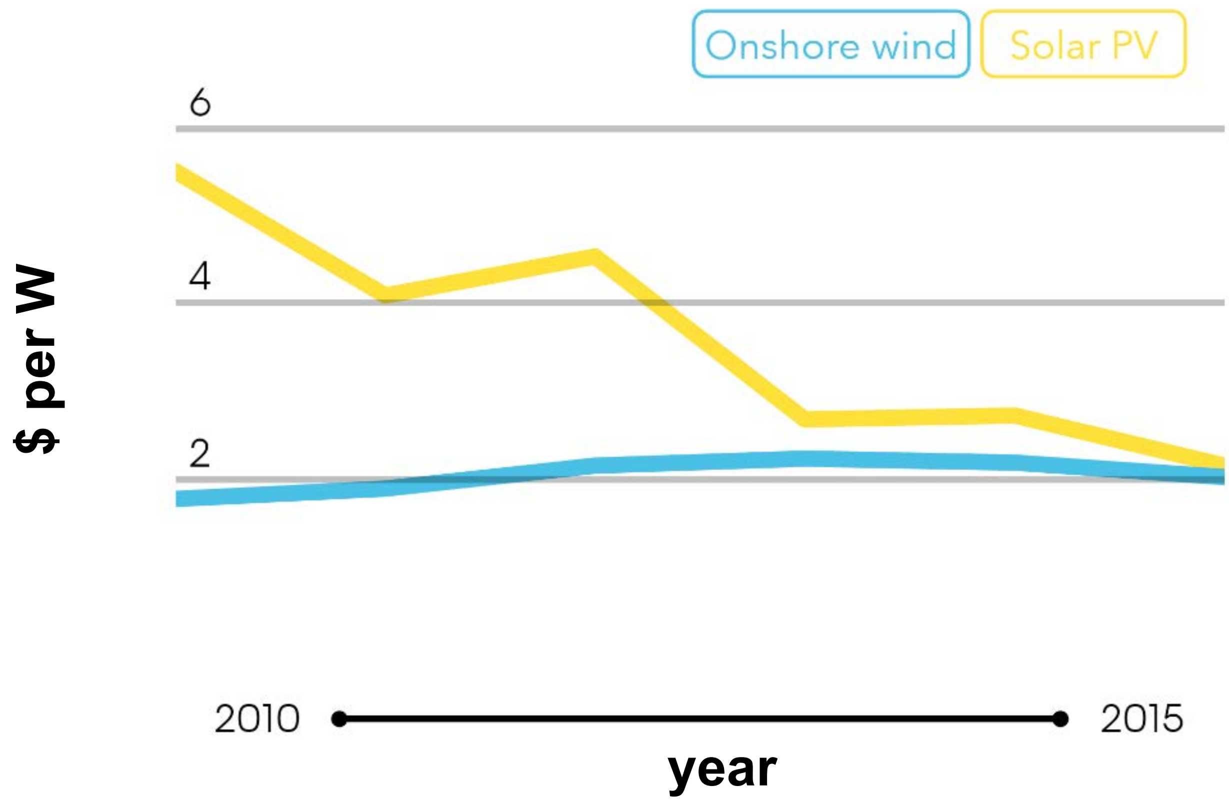

A hug for you, my friend

Installation Cost for Renewables



Source: NREL Feb. 2016

Cost Reduction by Years



Courtesy of CLIMATE SCOPE 2016

Retrieved from https://www.bnef.com/dataview/climatescope-2016/index.html

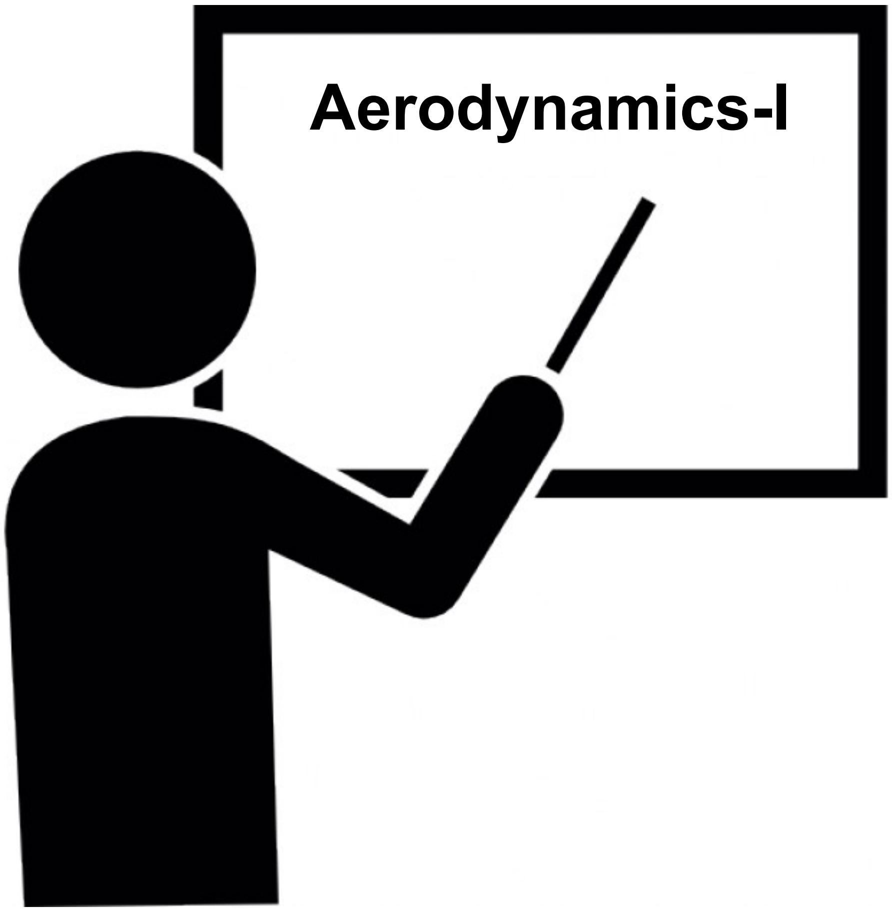
- **Mid-Presentation Level-2 Conclusions**
- Solar and wind energies are compatible, not substitutional.
- Solar power is getting cheaper every year.
- Conventional on shore wind turbines are expensive and looks like now getting cheaper.

Take-Aways

Level-0	Problem Definition	- Outstanding energy and investment potential - A snapshot of current market needs is inadequate.
Level-1	Supplying Energy	- A green energy solution is required for non-OECD's. - Off-grid and easy to deploy solutions are needed.
Level-2	Solar and Wind Energy	- Solar and wind energies are substitutionary. - Low capacity on-shore wind turbines are not cost competitive.
Level-3	Wind Energy	
Level-4	Airborne Wind Energy	

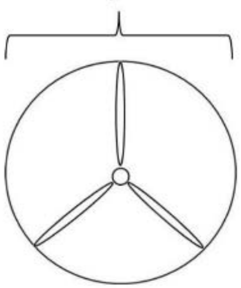

WIND ENERGY

Crash Course - 1



Wind Energy is Stored as **Kinetic Energy (KE):**

V: Wind Speed
ρ: Air Density
A: Swept Area



$$KE = \frac{1}{2} M V^2$$

$$KE = \frac{1}{2} (\rho \cdot Vol) V^2$$

$$KE = \frac{1}{2} (\rho \cdot A \cdot V \cdot t) V^2$$

$$\boldsymbol{\frac{KE}{t} = Power = \frac{1}{2} A \rho V^3}$$

$$\boldsymbol{Power \propto Swept\ Area}$$

$$\boldsymbol{Power \propto Air\ density}$$

$$\boldsymbol{Power \propto Capacity\ Factor}$$

$$\boldsymbol{Power \propto Wind\ Speed^3}$$

"Betting on Wind Speed would have a bigger effect than the combined influence of swept area and capacity factor"

$$\boldsymbol{Maximum\ Harnessable\ Power = C \frac{1}{2} A \rho V^3}$$

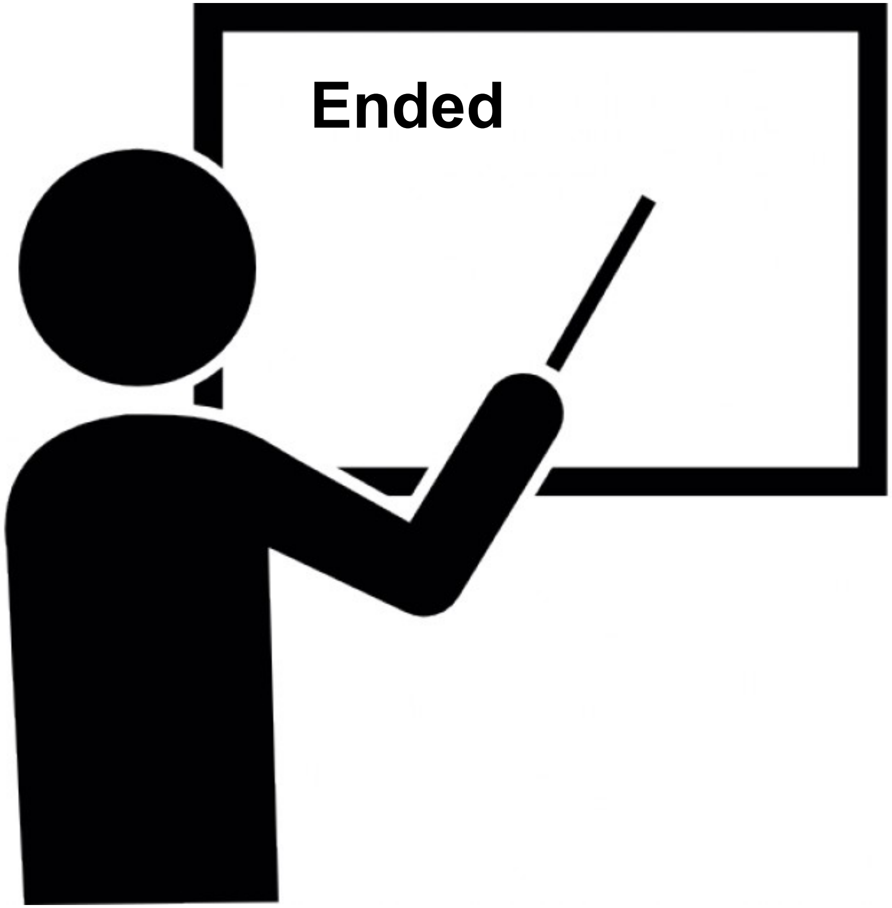
Betz Capacity Factor , C = 59.3%

$$\boldsymbol{Harnessed\ Power = \eta C \frac{1}{2} A \rho V^3}$$

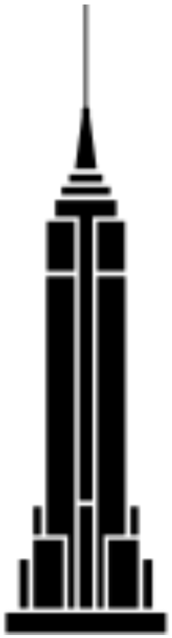
Capacity, factor, ηC = 40%-50% (wind turbines)

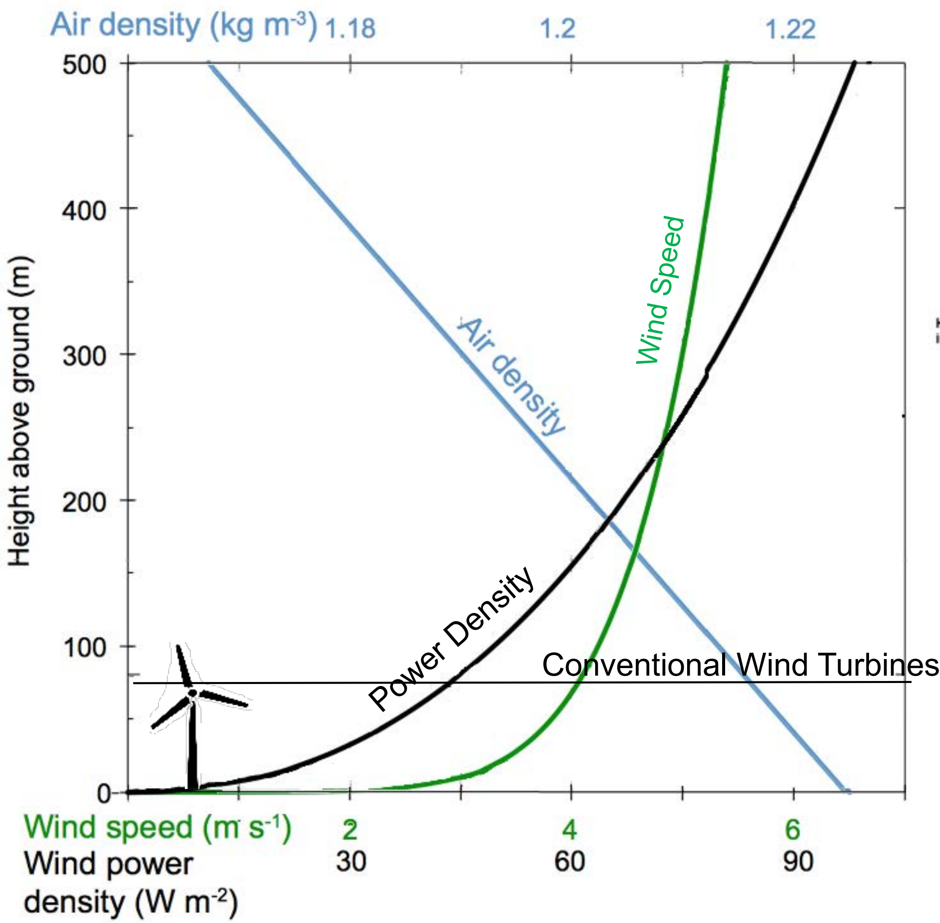
Efficiency Factor, η = 70%-80% (wind turbines)

Crash Course - 1

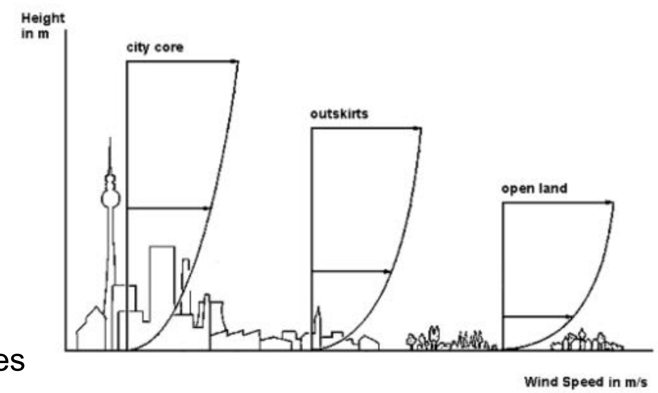


Wind Properties with Altitude



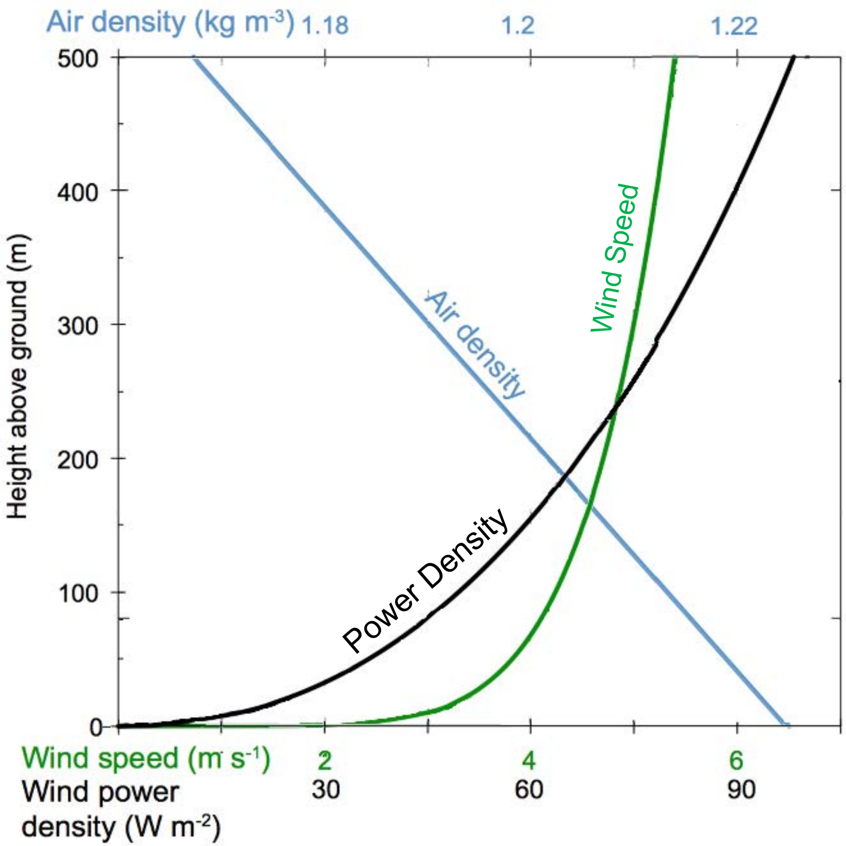


$$Power = \frac{1}{2} A \rho V^3$$



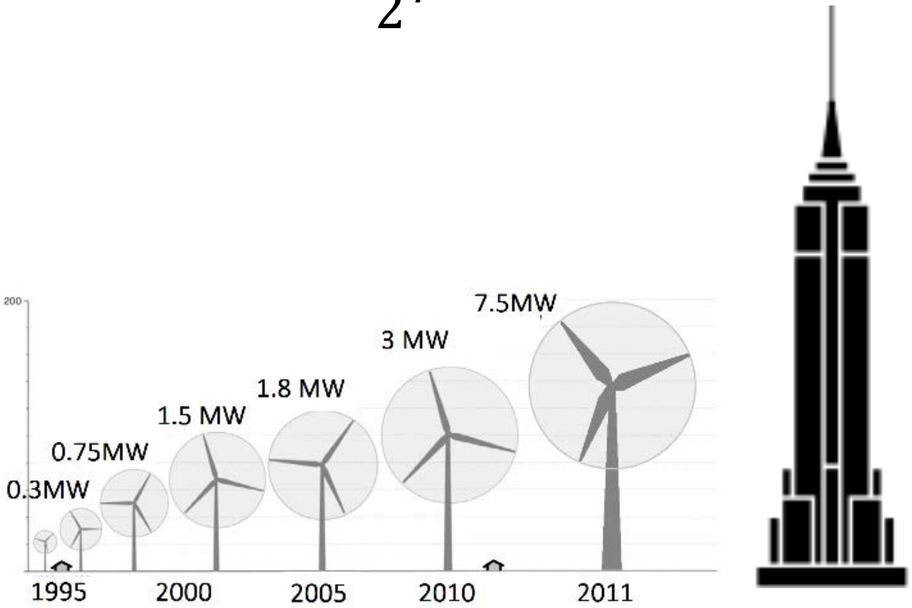
Ahrens, Uwe, Moritz Diehl, and Roland Schmehl, eds. *Airborne wind energy*. Springer Science & Business Media, 2013.

"Bigger is better for Wind Turbines"



Ahrens, Uwe, Moritz Diehl, and Roland Schmehl, eds. *Airborne wind energy*. Springer Science & Business Media, 2013.

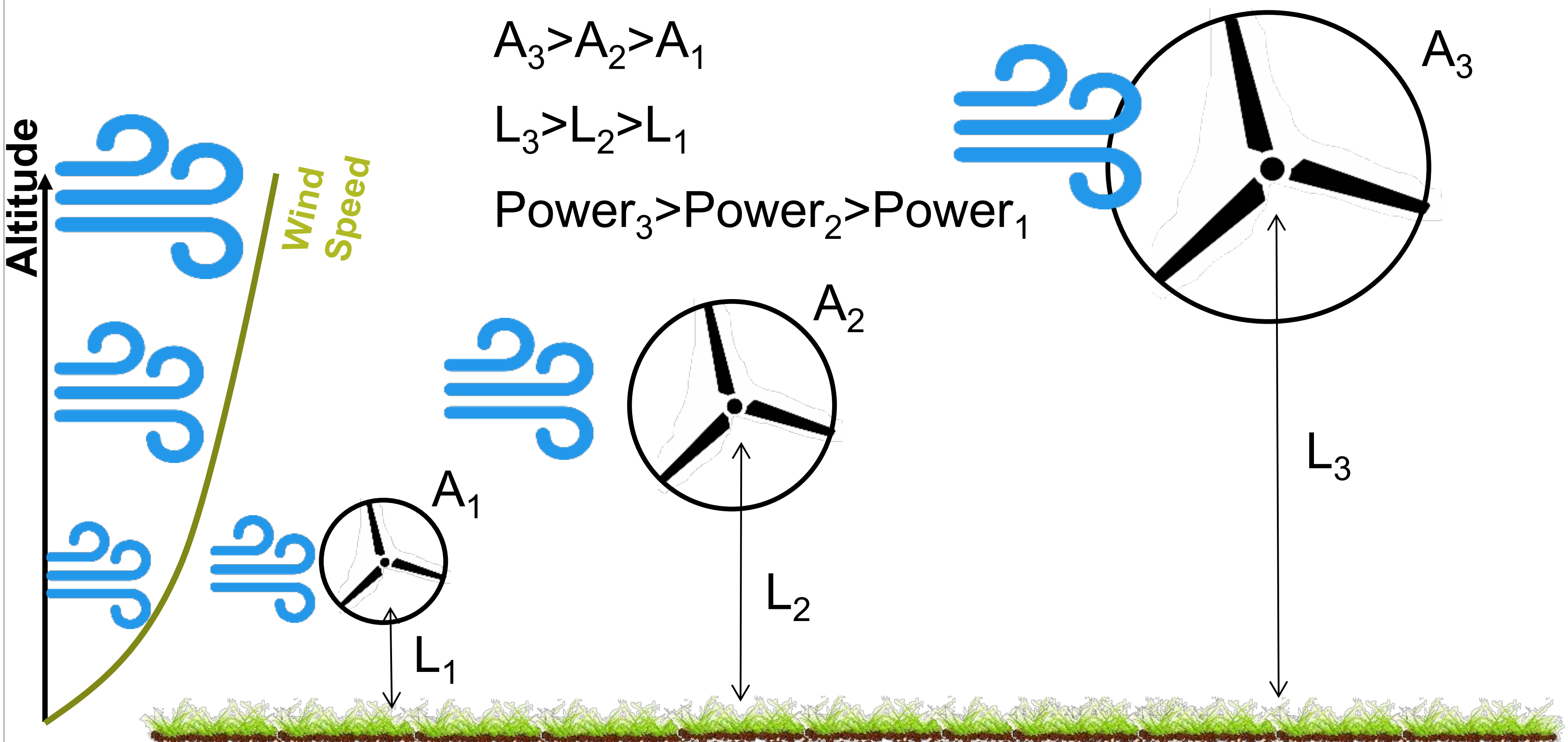
$$Power = \frac{1}{2}\rho A V^3$$



https://commons.wikimedia.org/wiki/File:Wind_turbine_size_increase_1980-2010.png

Optimization Problem: Maximize $\text{Power} = \frac{1}{2}\rho A V^3$

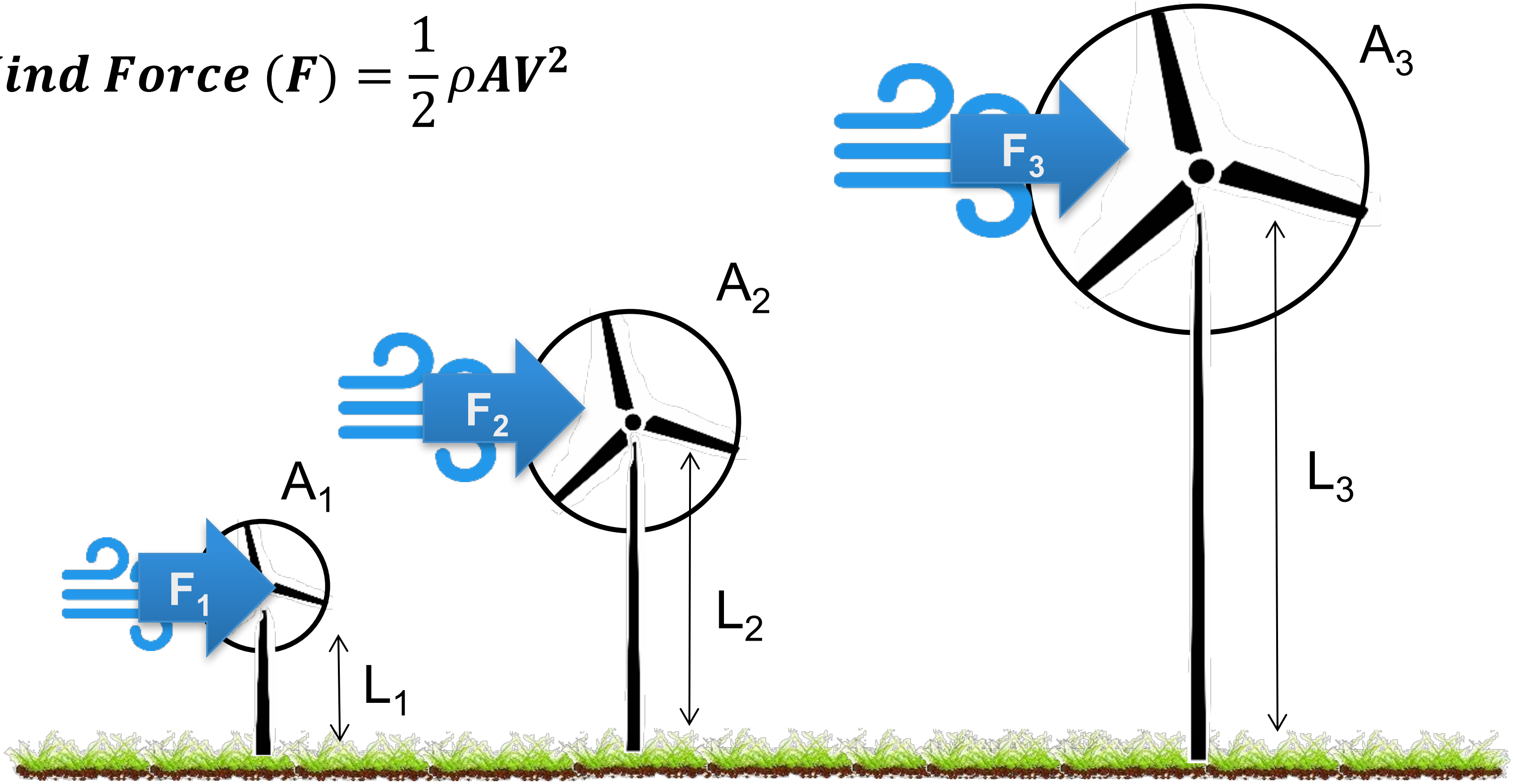
- **Objective 1**: Max. Sweep Area (A)
- **Objective 2**: Max. Altitude, L (to maximize wind speed)



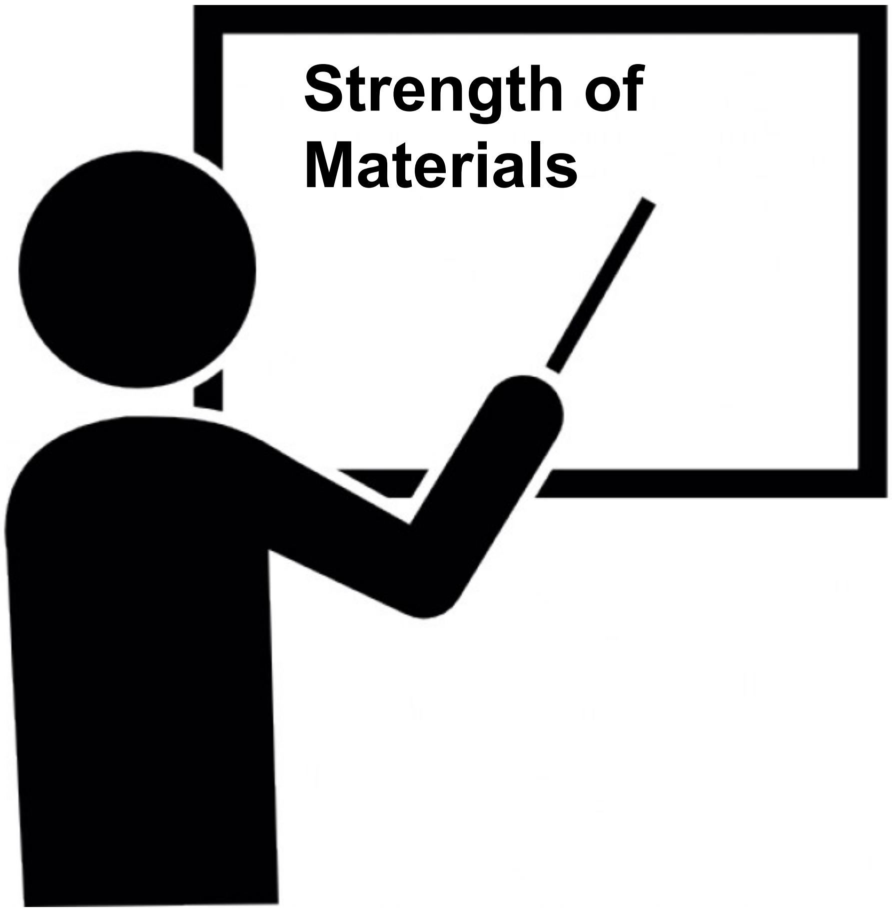
Optimization Problem: Maximize $\text{Power} = \frac{1}{2}\rho A V^3$

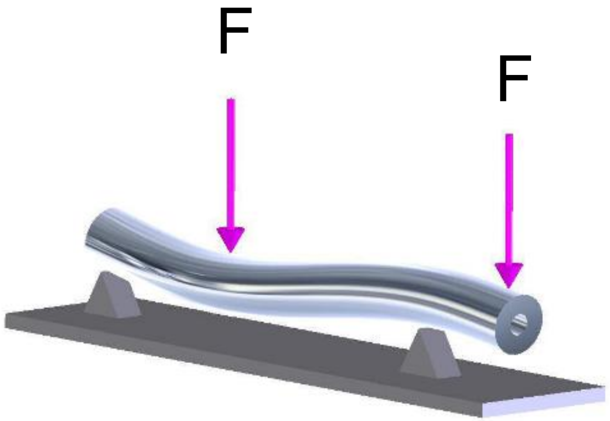
- Objective 1: Max. Sweep Area (A)
- Objective 2: Max. Altitude, L (to maximize wind speed)

$$\textit{Wind Force}\ (F) = \frac{1}{2}\rho A V^2$$

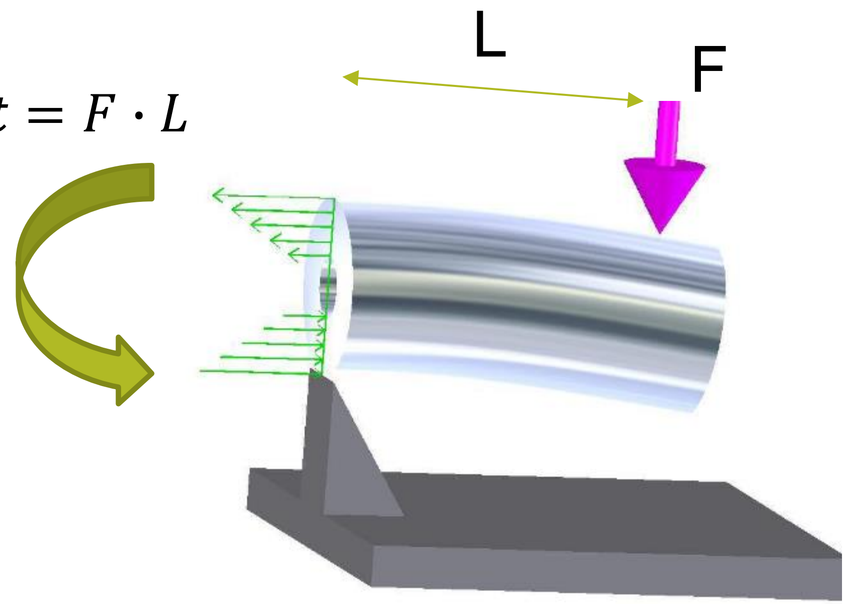


Crash Course - 2





$$\textbf{Moment} = F \cdot L$$

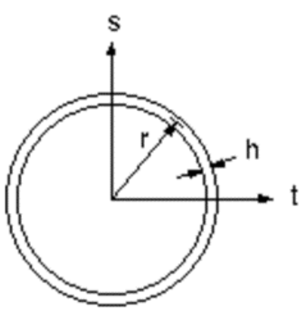


$$\textbf{Stress} = Moment \frac{y}{Inertia}$$

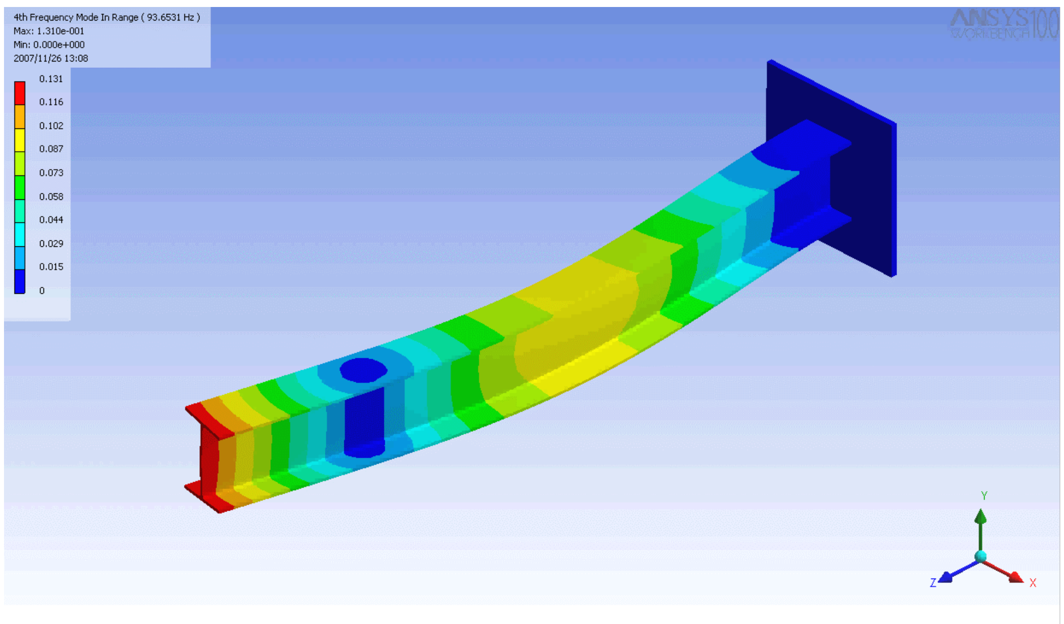
$$\textbf{Stress} \approx \frac{F \cdot L}{2\pi r^2 h}$$

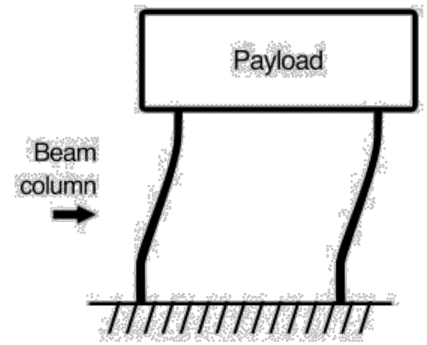
$$\textbf{Stress to Withstand} \propto F$$

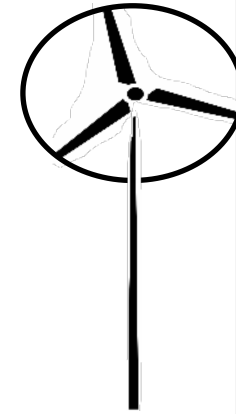
$$\textbf{Stress to Withstand} \propto L$$

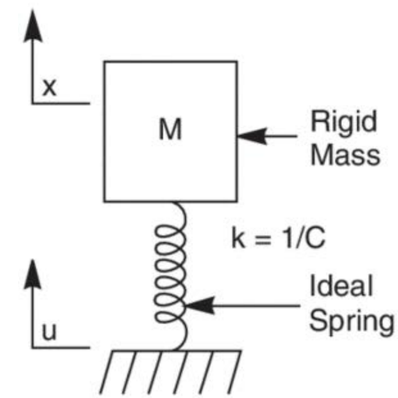


h: Wall thickness
L: Length of the beam
r: Radius of the cross-section

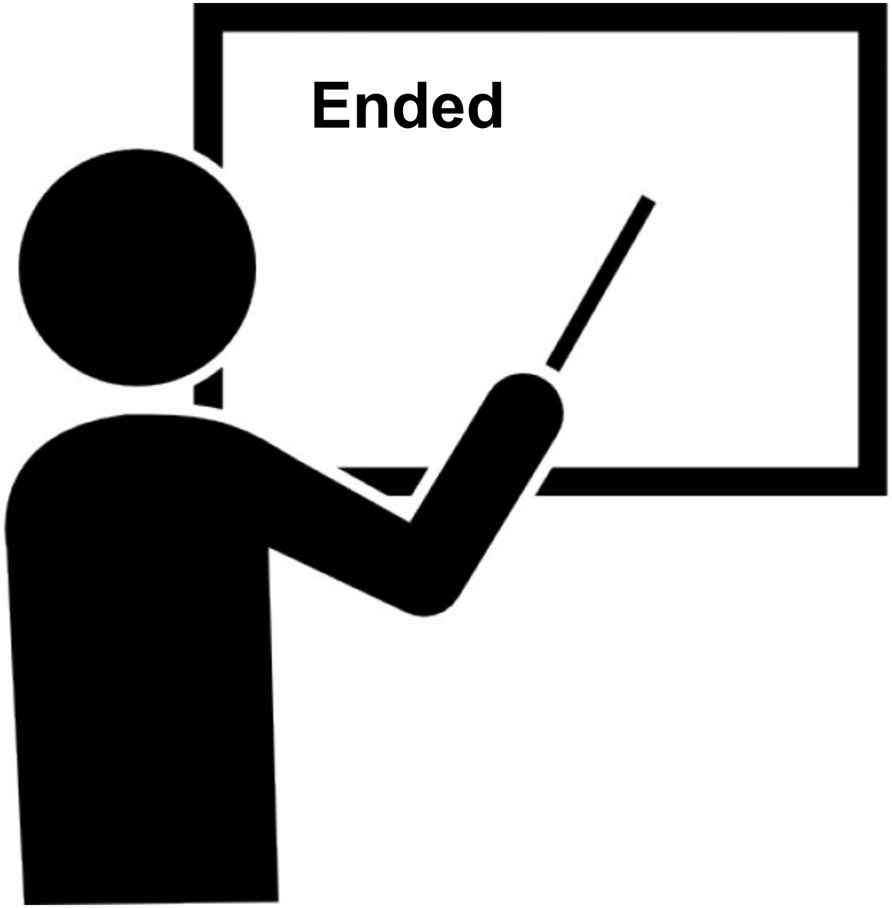

4th Frequency Mode In Range (93.6531 Hz)
Max: 1.310e-001
Min: 0.000e+000
2007/11/26 13:08
0.131
0.116
0.102
0.087
0.073
0.058
0.044
0.029
0.015
0
Y
Z
X


Payload
Beam
column




x
M
Rigid
Mass
k = 1/C
Ideal
Spring
u

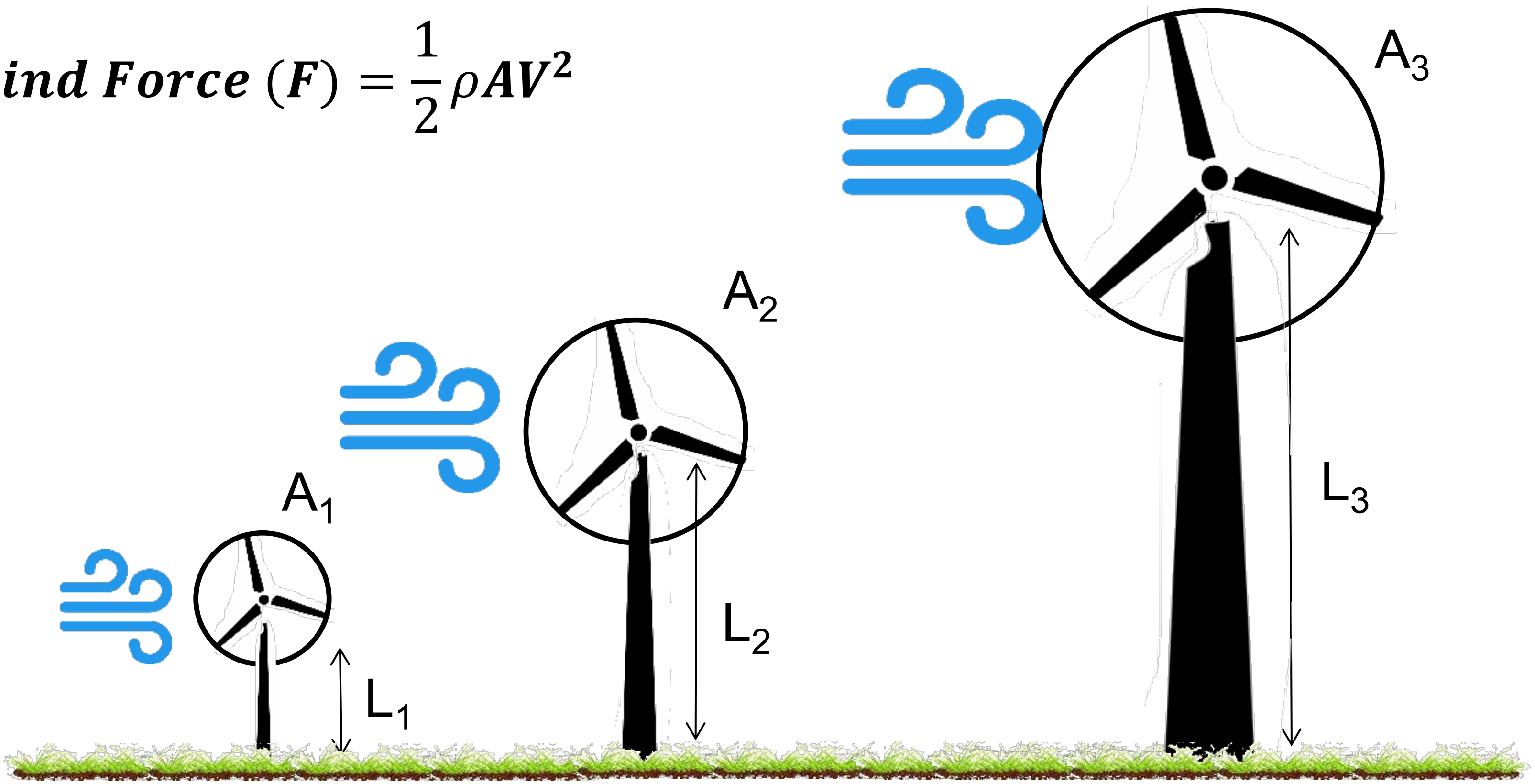
Crash Course - 2



Optimization Problem: Maximize $\text{Power} = \frac{1}{2}\rho A V^3$

- **Objective 1**: Max. Sweep Area (A)
- **Objective 2**: Max. Altitude, L (to maximize wind speed)

$$Wind\ Force\ (F) = \frac{1}{2}\rho A V^2$$

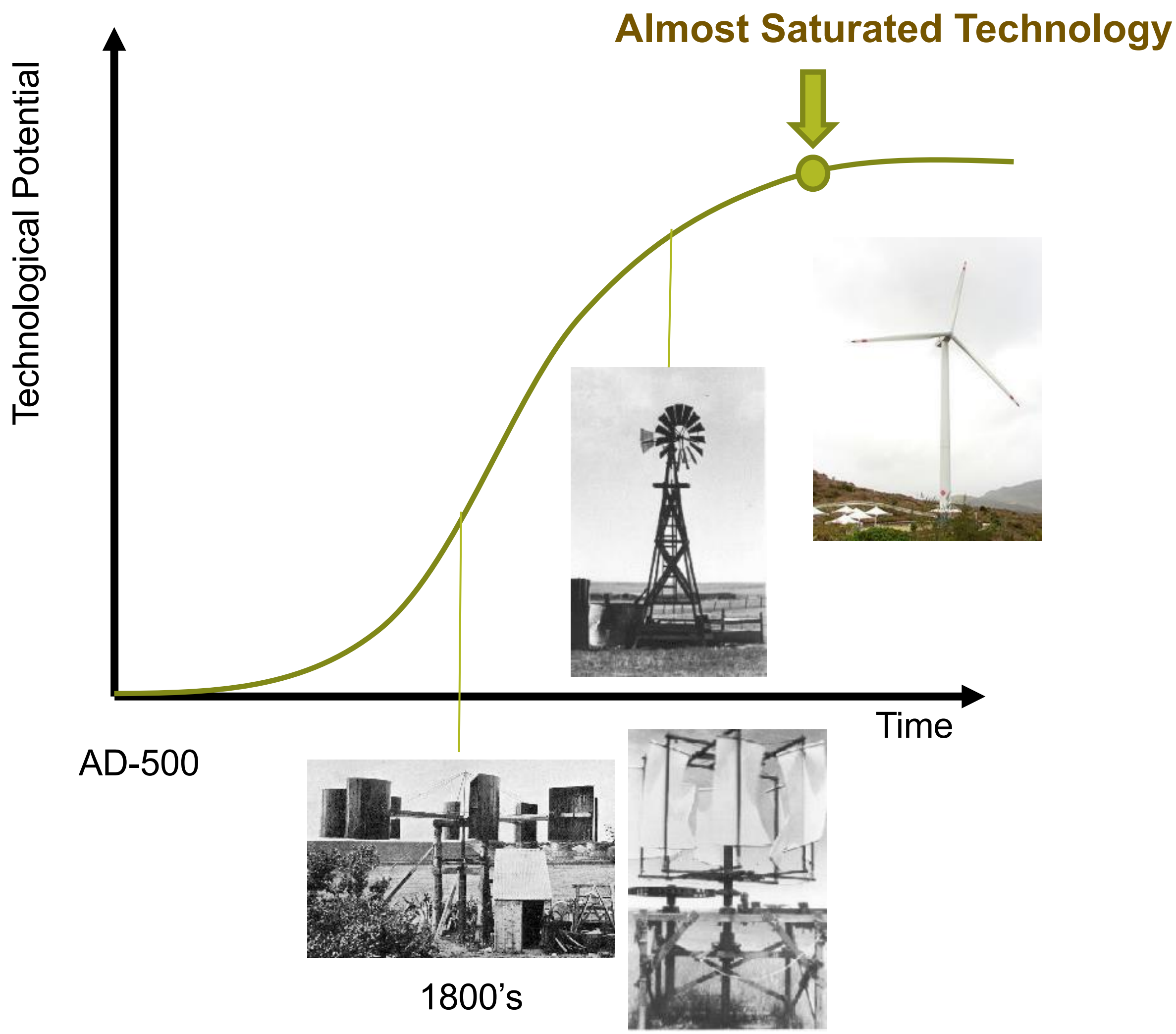


Retreived from
https://www.reddit.com/r/pics/comments/3sbaew/a_casting_mold_for_a_wind_turbine_blade/

Retrieved from https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/transport-of-longest-blade-in-the-world

Retrieved from https://www.wind-energy-the-facts.org/transport-and-installation.html

It became a strength of materials problem…



It has systems architectural limits of "Reaching the clouds with a ladder" – we should drop the ladder!

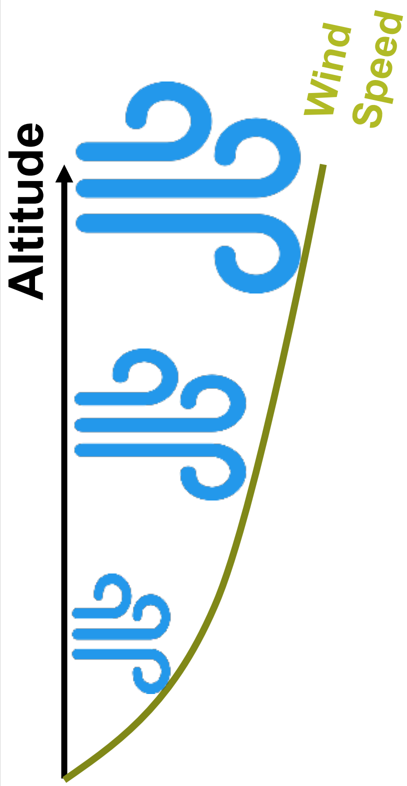
- **Mid-Presentation Level-3 Conclusions**
- Conventional Wind Turbines are only cost competitive at high scale power production – "economics of scale".
- Not mobile, not effective for off-grid applications such as for developing world.
- Not modular, transportation problem.
- Their architecture is not suitable for reaching high altitude high speed winds.

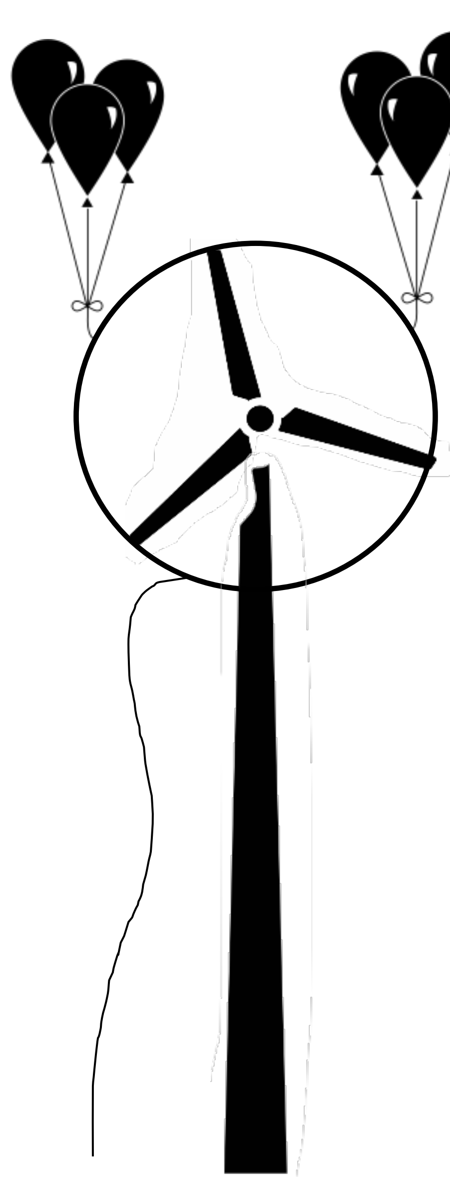
Take-Aways

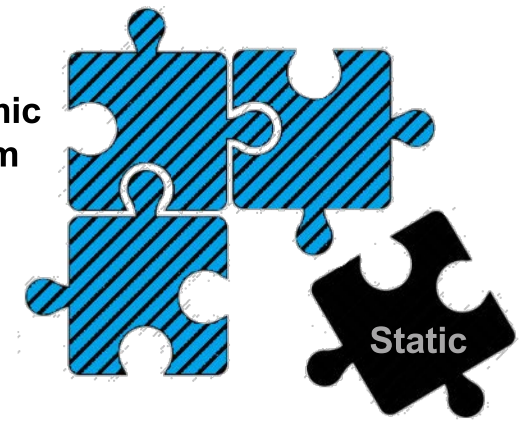
Level-0	**Problem Definition**	- Outstanding energy and investment potential - A snapshot of current market needs is inadequate.
Level-1	**Supplying Energy**	- A green energy solution is required for non-OECD's. - Off-grid and easy to deploy solutions are needed.
Level-2	**Solar and Wind Energy**	- Solar and wind energies are substitutionary. - Low capacity on-shore wind turbines are not cost competitive.
Level-3	**Wind Energy**	- Architecture of conventional wind energy does not allow to reach high potential high altitude winds. - Conv. Wind energy is not mobile and only good at economics of scale.
Level-4	**Airborne Wind Energy**	

Airborne Wind Energy (AWE)

Adopting to a Dynamic System: Wind



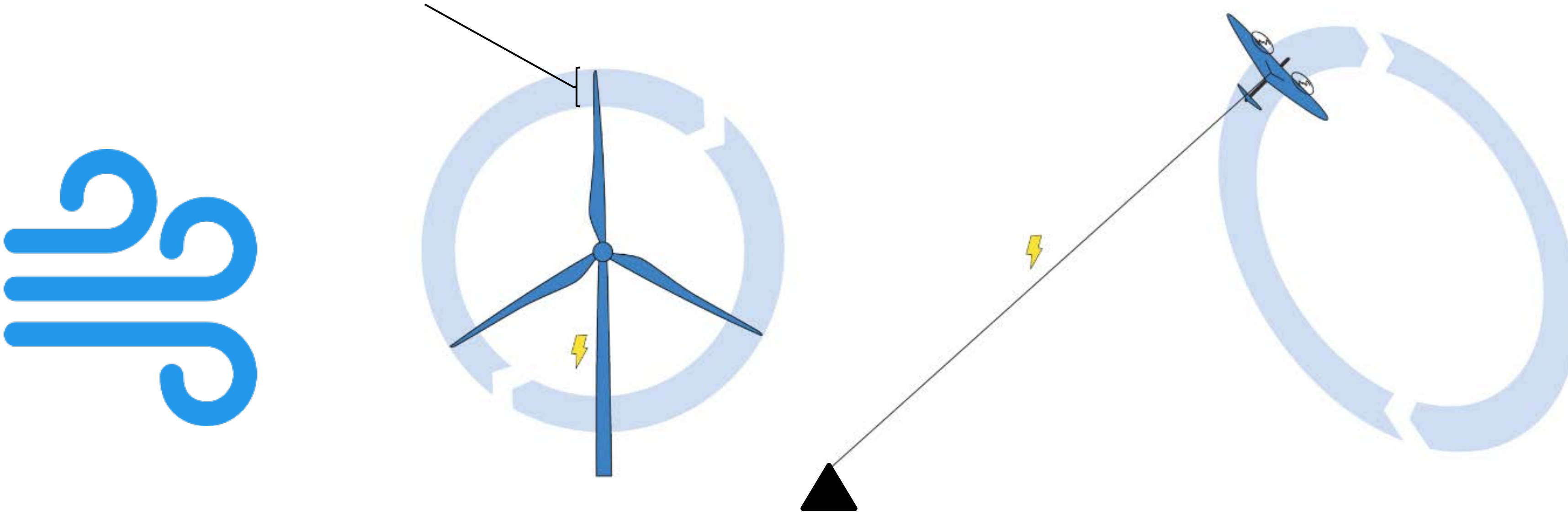




Airborne Wind Energy (AWE)

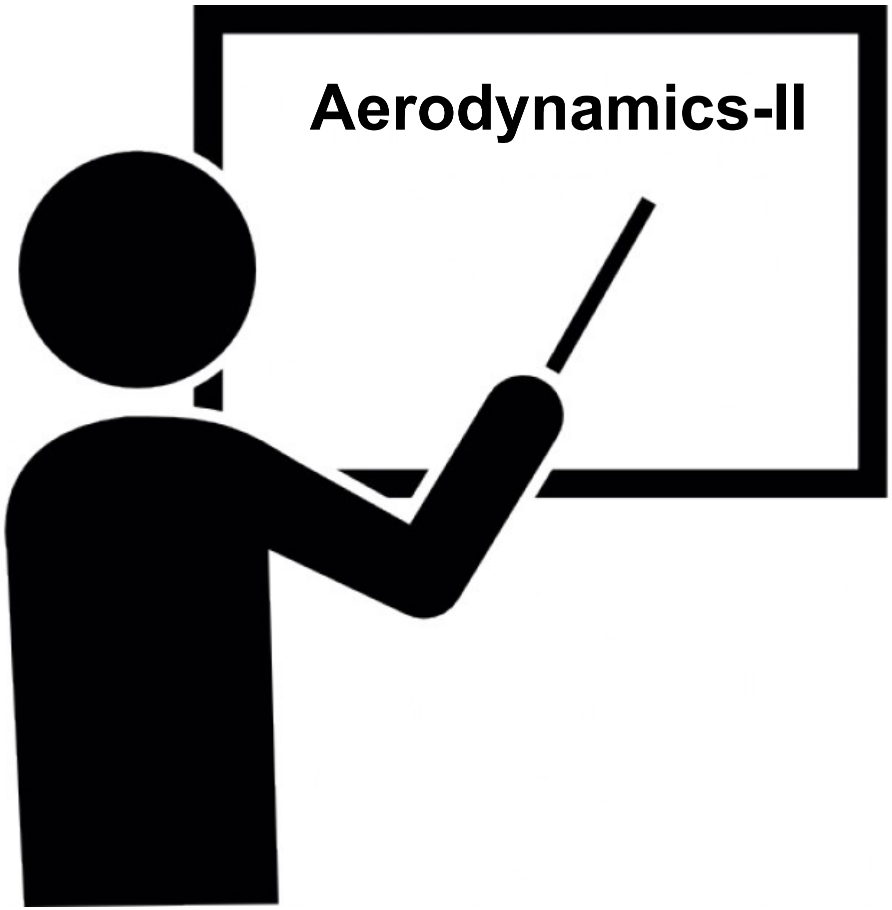
Fastest moving part of blades (30% from the tip provides 50% of energy)

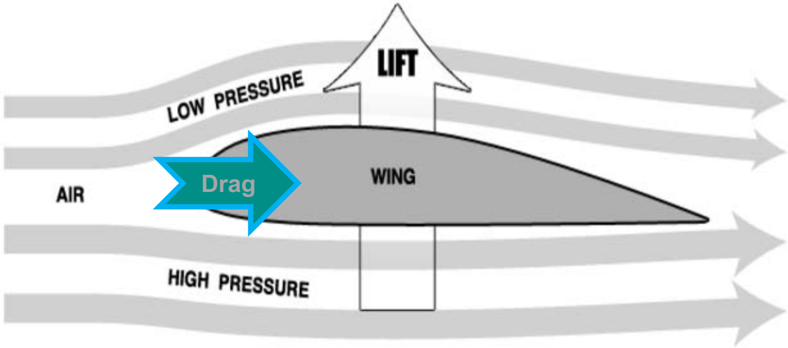
Loyd (1980), crosswind kite power

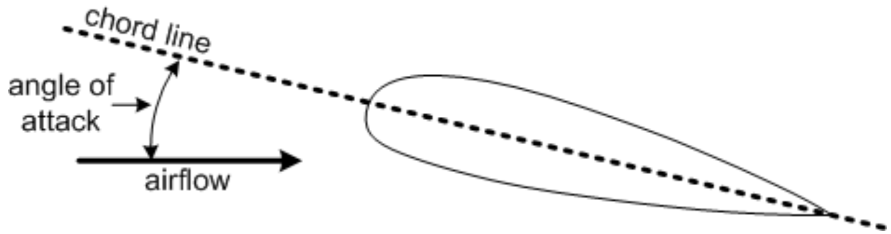


Loyd, M. L.: Crosswind kite power. Journal of Energy 4(3), 106–111 (1980).

Crash Course - 1





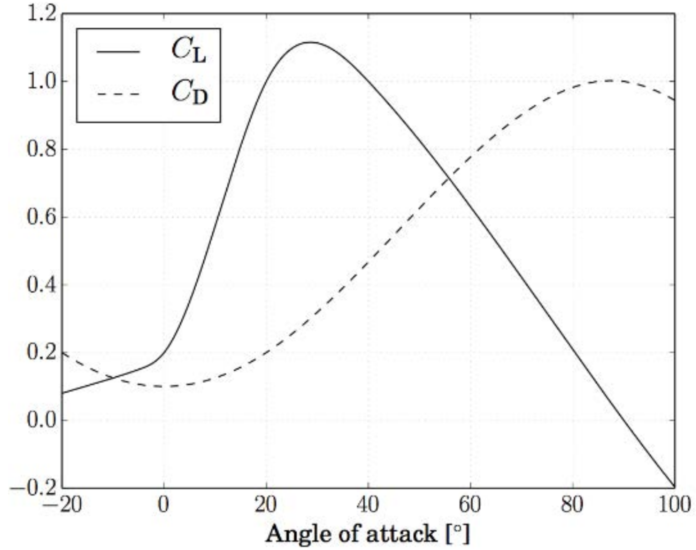


$$Lift = \frac{1}{2}\rho A C_L v_a^2$$

Lift Coefficient (C_L)

$$Drag = \frac{1}{2}\rho A C_D v_a^2$$

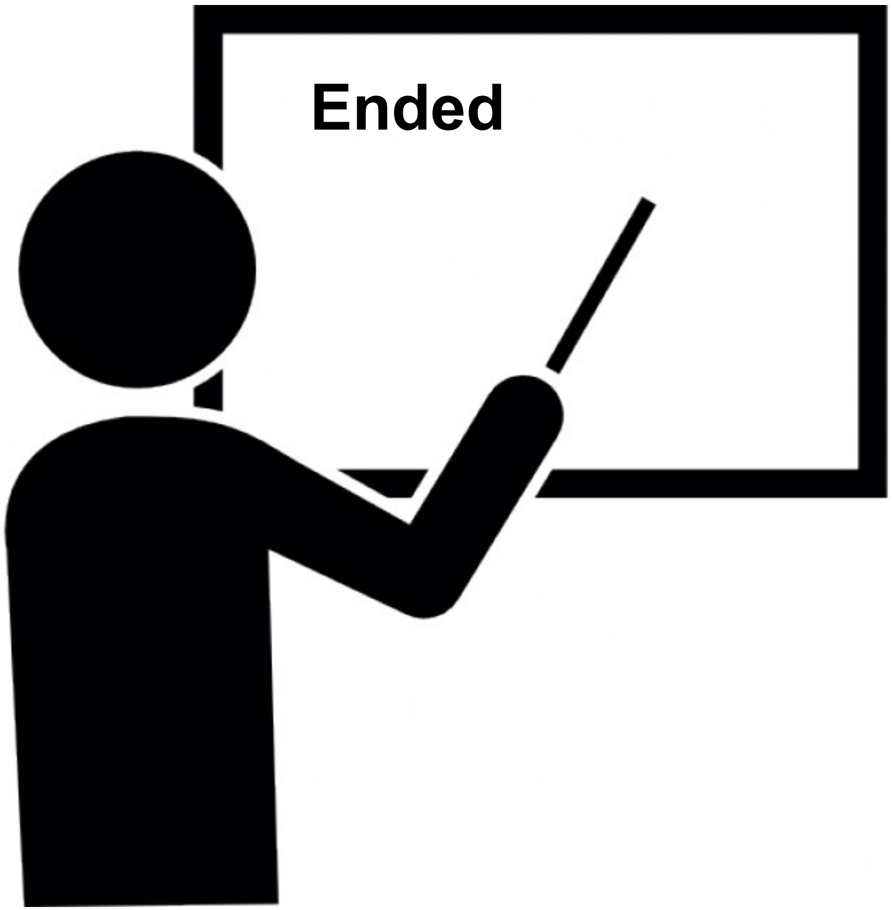
Drag Coefficient (C_D)



v_a: Apparent (relative) wind speed

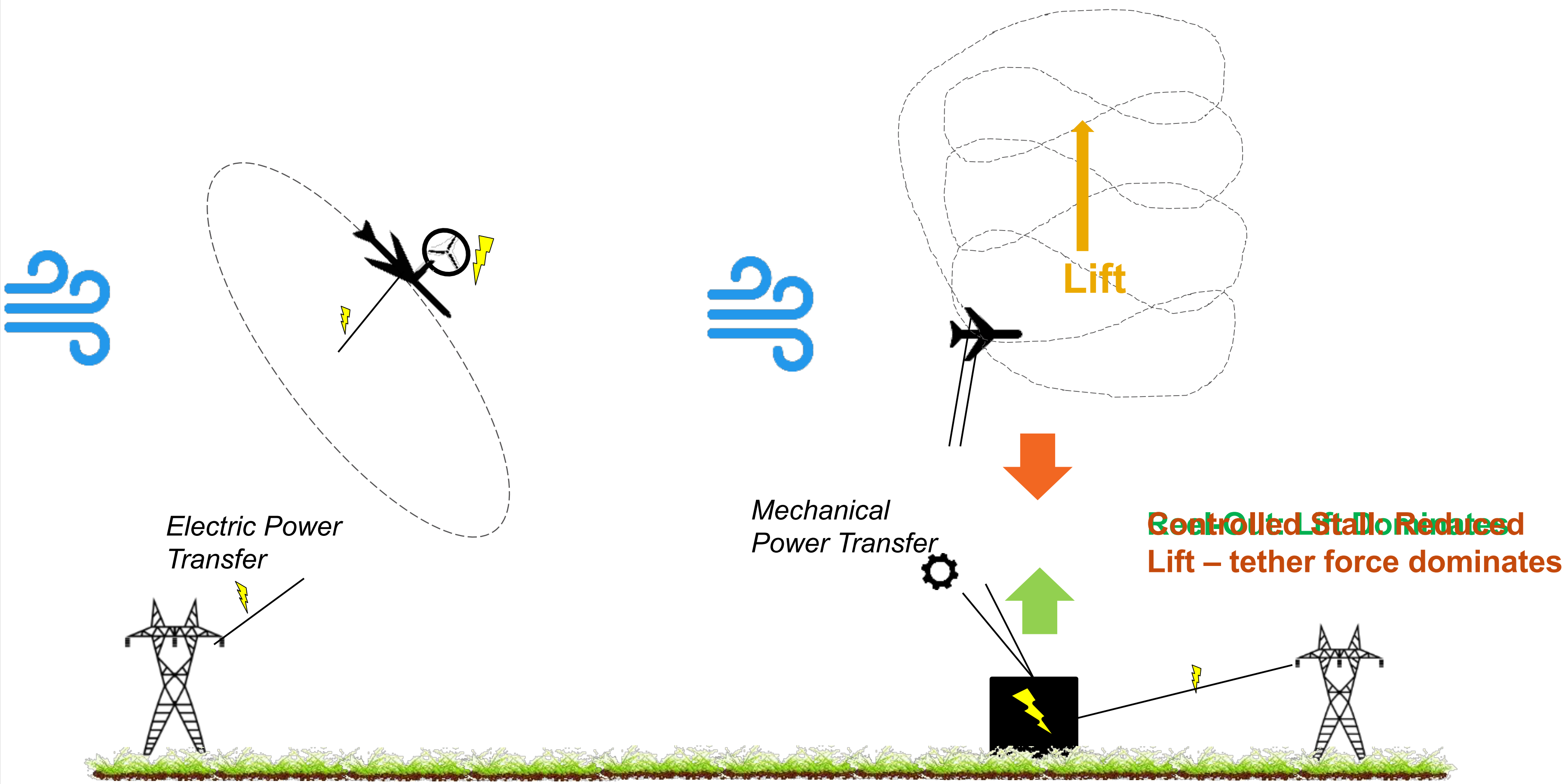
$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k$$

Crash Course - 3

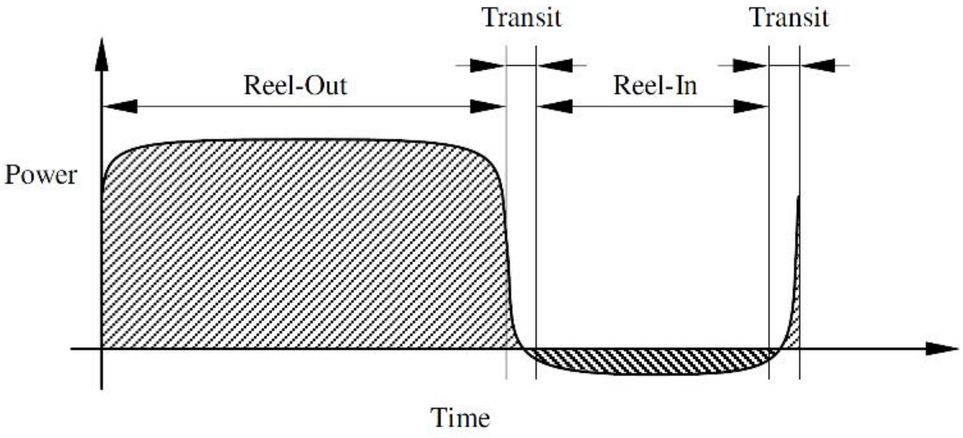


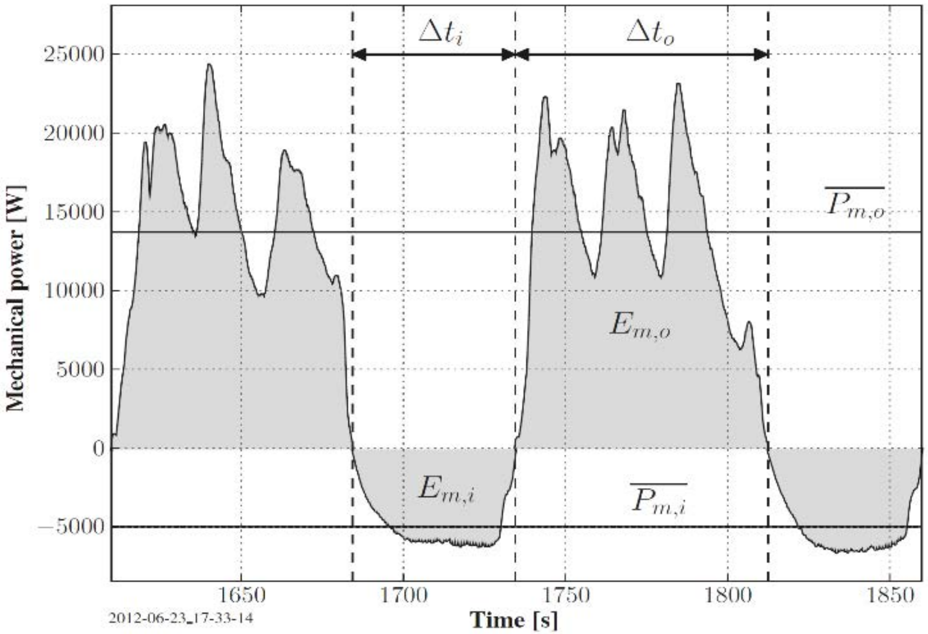
Air Gen - “Drag Mode”

Ground Gen - “Lift Mode”



Energy Generation Profile





Figures are taken from U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology,

Power Capacity

per 1 m^2

6kW

40 kW

Airborne Wind Energy (Capacity Factor = 60%)

<1 kW

Conventional Wind Turbines (Capacity Factor = 40%)

1.3 kW

Solar Power (Capacity Factor = 20%)

U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology,

Installation Cost

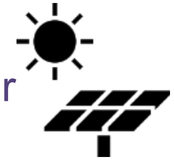
per
1W

2$

Airborne Wind Energy

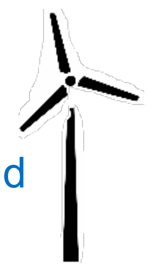
3.8
kW

Solar Power



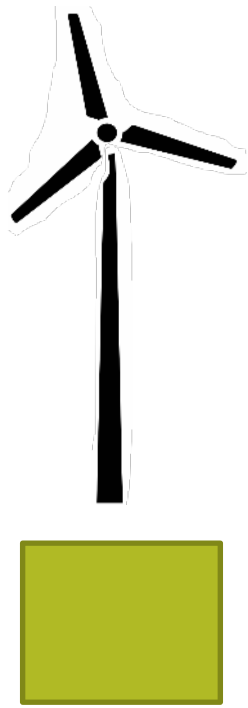
6$

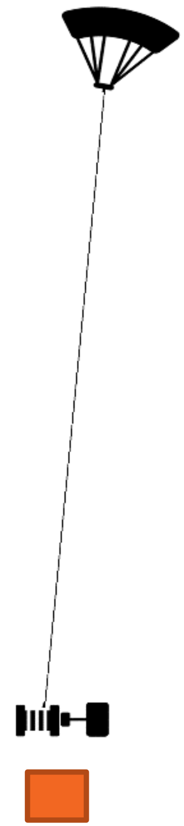
Conventional Wind
Turbines



Manufacturing and Transportation

Conventional
Wind Turbine





10% of material used

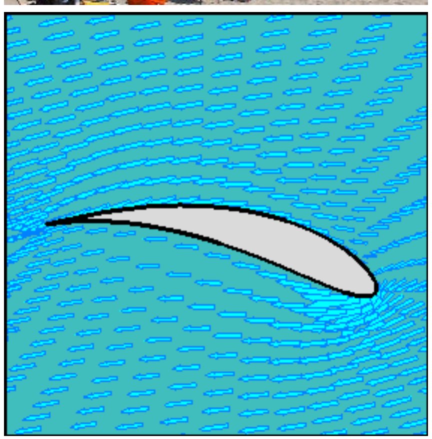
AWE

U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology,

Challenges for AWE

Control System & Reliability

University
of California, Santa Barbara



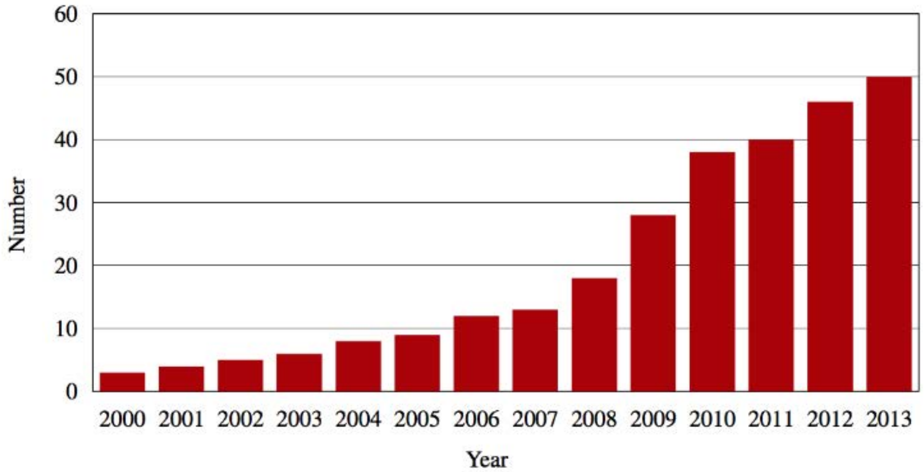
Launching/Landing

Launching of a Lindenberg N-kite on the Rovuma river in 1908 during the German expedition for the exploration of the upper air in tropical East Africa

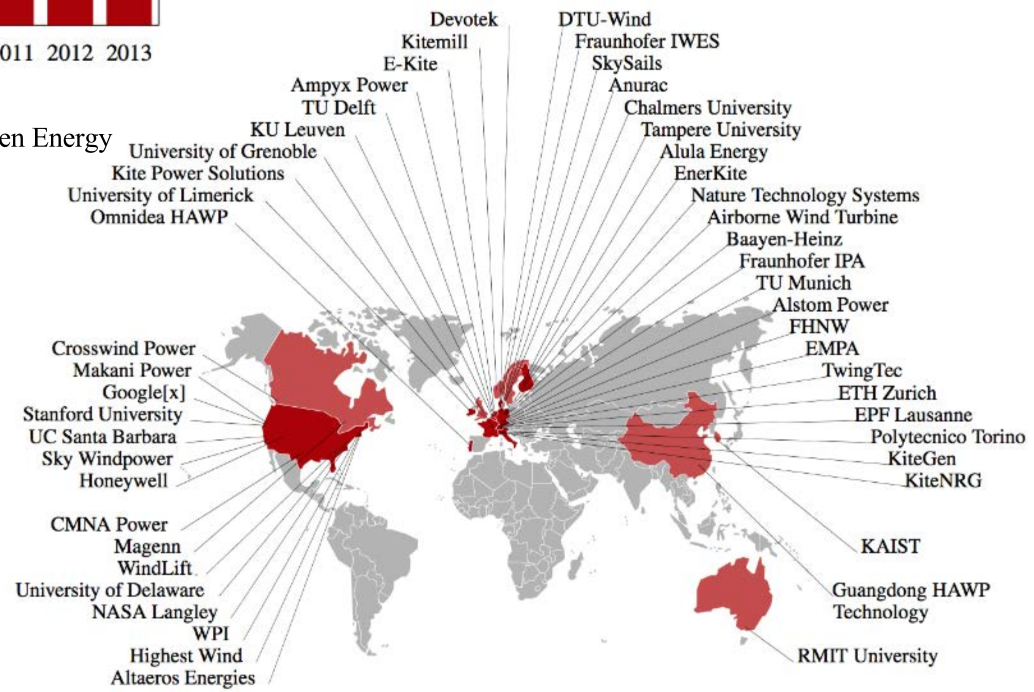
Application in Farms

Some figures are taken from U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology,

Number of Institutions taking place in AWE



Taken from U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology,



Taken from U. Ahrens et al. (eds.), Airborne Wind Energy, Green Energy and Technology, Carlos

MechE

Burak

Aerospace

Jack

MechE

Nan

EECS

Charles

Mechatronics

CLEAN ENERGY PRIZE
10TH ANNUAL

MIT Clean Energy Prize 2017

MIT | Sandbox Innovation Fund Program
Massachusetts Institute of Technology

Take-Aways

Level-0	Problem Definition	- Outstanding energy and investment potential - A snapshot of current market needs is inadequate.
Level-1	Supplying Energy	- A green energy solution is required for non-OECD's. - Off-grid and easy to deploy solutions are needed.
Level-2	Solar and Wind Energy	- Solar and wind energies are substitutionary. - Low capacity on-shore wind turbines are not cost competitive.
Level-3	Wind Energy	- Architecture of conventional wind energy does not allow to reach high potential high altitude winds. - Conv. Wind energy is not mobile and only good at economics of scale.
Level-4	Airborne Wind Energy	- AWE promises outstanding mobility, cost and scalability to OECD, but especially non-OECD countries. - AWE technology has challenges that are being solved.

system design & management

Thank you

MITsdm

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