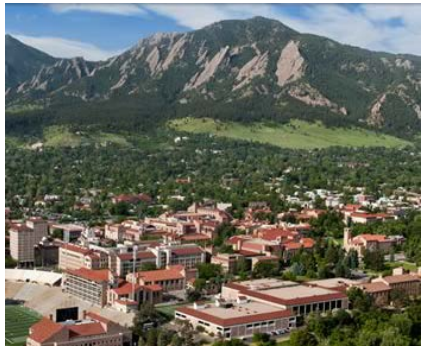
# Boosting Wind and Solar Energy: Opportunities and Technological Challenges




**Lucy Pao**

**Palmer Endowed Chair Professor**

**Electrical, Computer, & Energy Engineering**



University of Colorado Boulder


7 AFFORDABLE AND CLEAN ENERGY

# How much power do you use?

Mobile phone

~ 1 W

Laptop

~ 10 W


TV

~ 100 W

Coffee machine

Toaster

Microwave

Oven

Dishwasher

Electric kettle

~ 1000 W

( $10^3$ W = 1 kW )

Hair blow dryer

Air conditioner

Area heater

Clothes dryer

Vacuum

Iron

Electric vehicle charging

~ 1 kW to 100 kW

$10^6$ W = 1 MW ~ Small Town

$10^9$ W = 1 GW ~ City

[ images from overstock.com, pcworld.com, apple.com, tesla.com ]

# Units of Power and Energy

## Energy

1 kWh = 1 kW for 1 hour

Coffee machine

Toaster

Microwave

Oven

Dishwasher

Electric kettle

~ 1000 W

( $10^3$ W = 1 kW )

Hair blow dryer

Air conditioner

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~ 1 kW to 100 kW

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# Renewable Energy & The Power Grid

Hydro

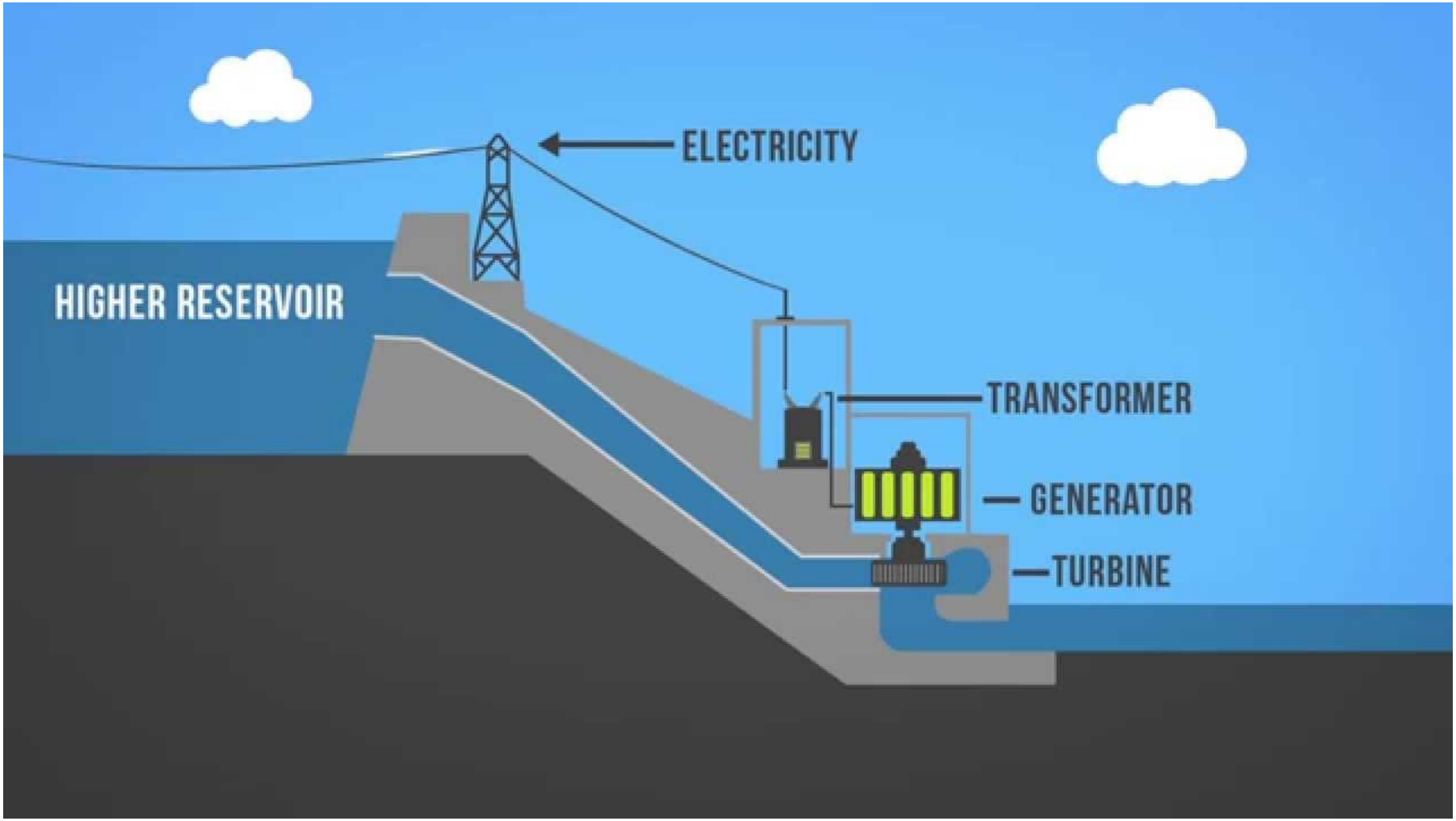
Solar PV

Wind

Grid Integration

[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]

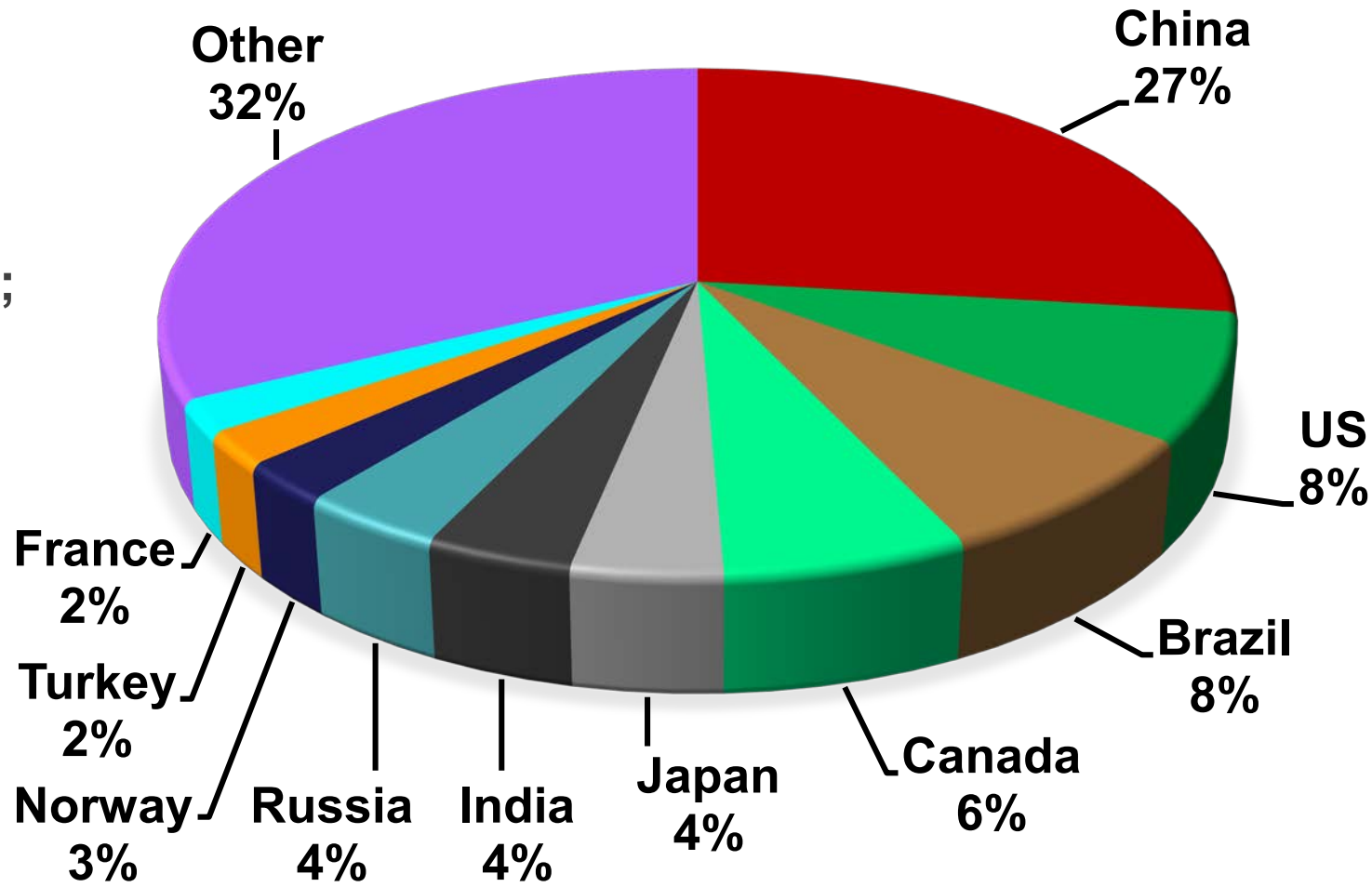
# How does hydropower work?




[ image from Hydropower 101 on yourtube.com ]

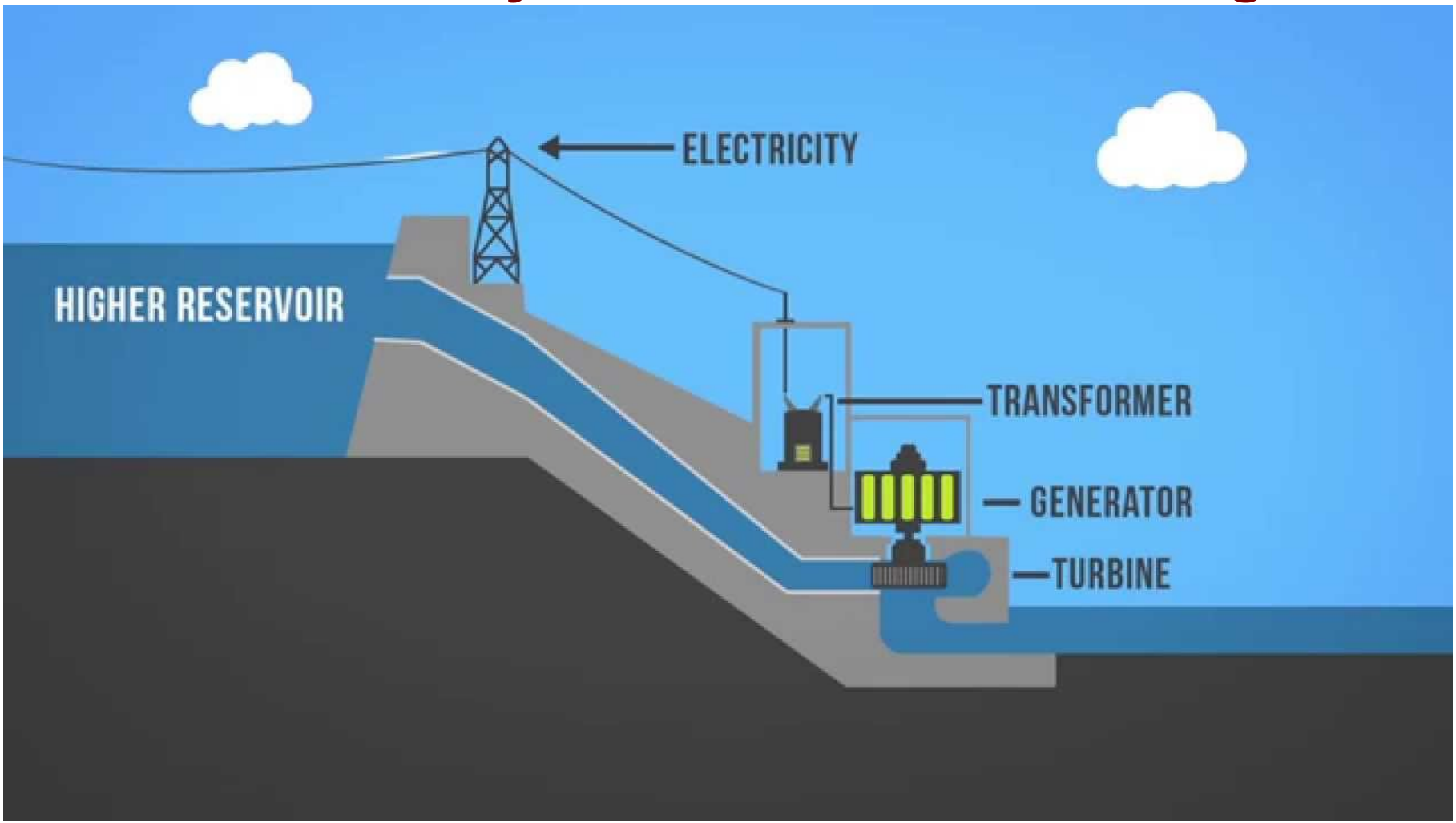
# How much hydropower is there?

- End-of-2017 global installed hydropower capacity was 1,267 GW; expected to increase 3% annually over next 25 years
- EU has 293 GW
- Austria has 14 GW




[ end-of-2017 data from hydropower.org ]

# Hydropower Advantage: if there is sufficient water → can control the amount of power generated in similar way as with coal or natural gas




[ image from Hydropower 101 on yourtube.com ]

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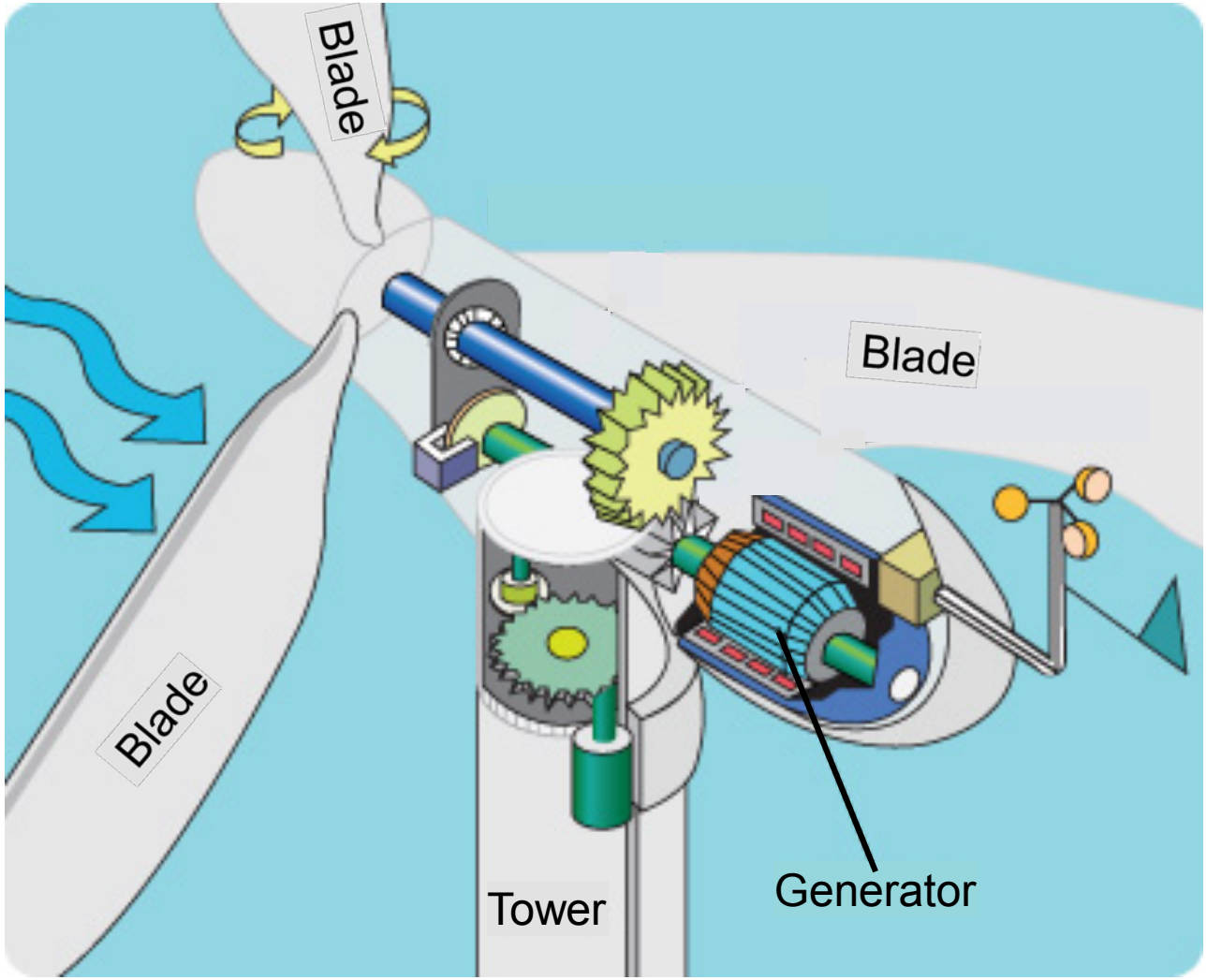
# How does wind power work?



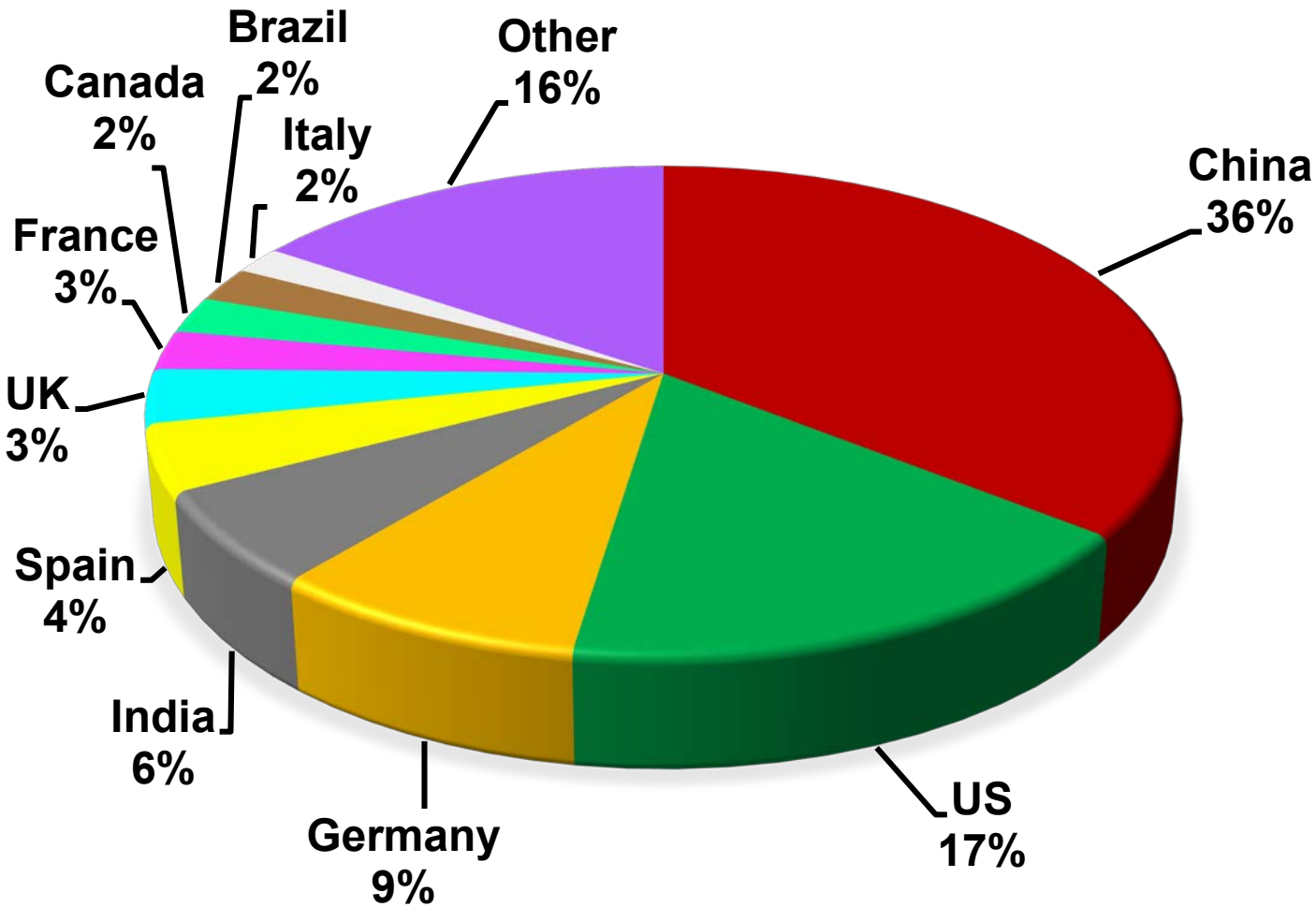

- **Goal is to maximize power generation**

[ figure from www.energyland.emsd.gov.hk based upon original from US Dept. of Energy ]

Hydro: World: 1267 GW
EU: 293 GW
Austria: 14 GW

# How much wind power is there?

- End-of-2017 global installed wind capacity was 539 GW; average annual growth of 16% over last decade
- EU has 169 GW; average annual growth of 10%
- Austria has 2.8 GW; average annual growth of 11%




[data from gwec.net, navigant.com, and 2017 Wind Technologies Market Report (LBNL)]

# Renewable Energy & The Power Grid

Hydro

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[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]

# How does solar PV work?

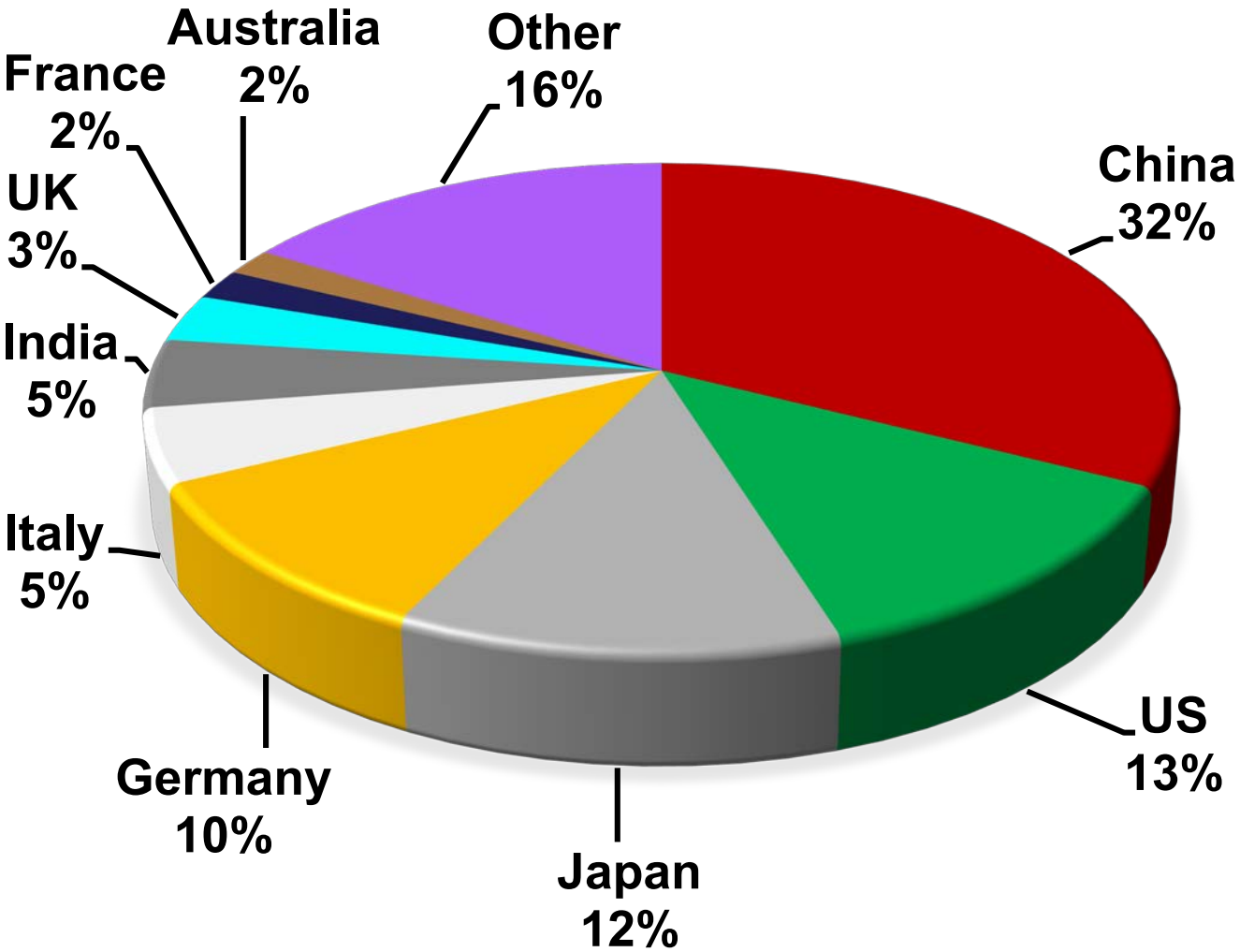
- PV panel consists of layers of material that produce electricity when light shines on it
- Lower-end PV solar cells now achieve about 14-17% efficiency
- Higher-end solar cells can achieve about 20-30% efficiency
- Research laboratories have demonstrated > 40%
- Goal is to maximize power generation

[ en.wikipedia.org/wiki/Solar_cell ]

Wind: World: 593 GW
EU: 169 GW
Austria: 2.8 GW

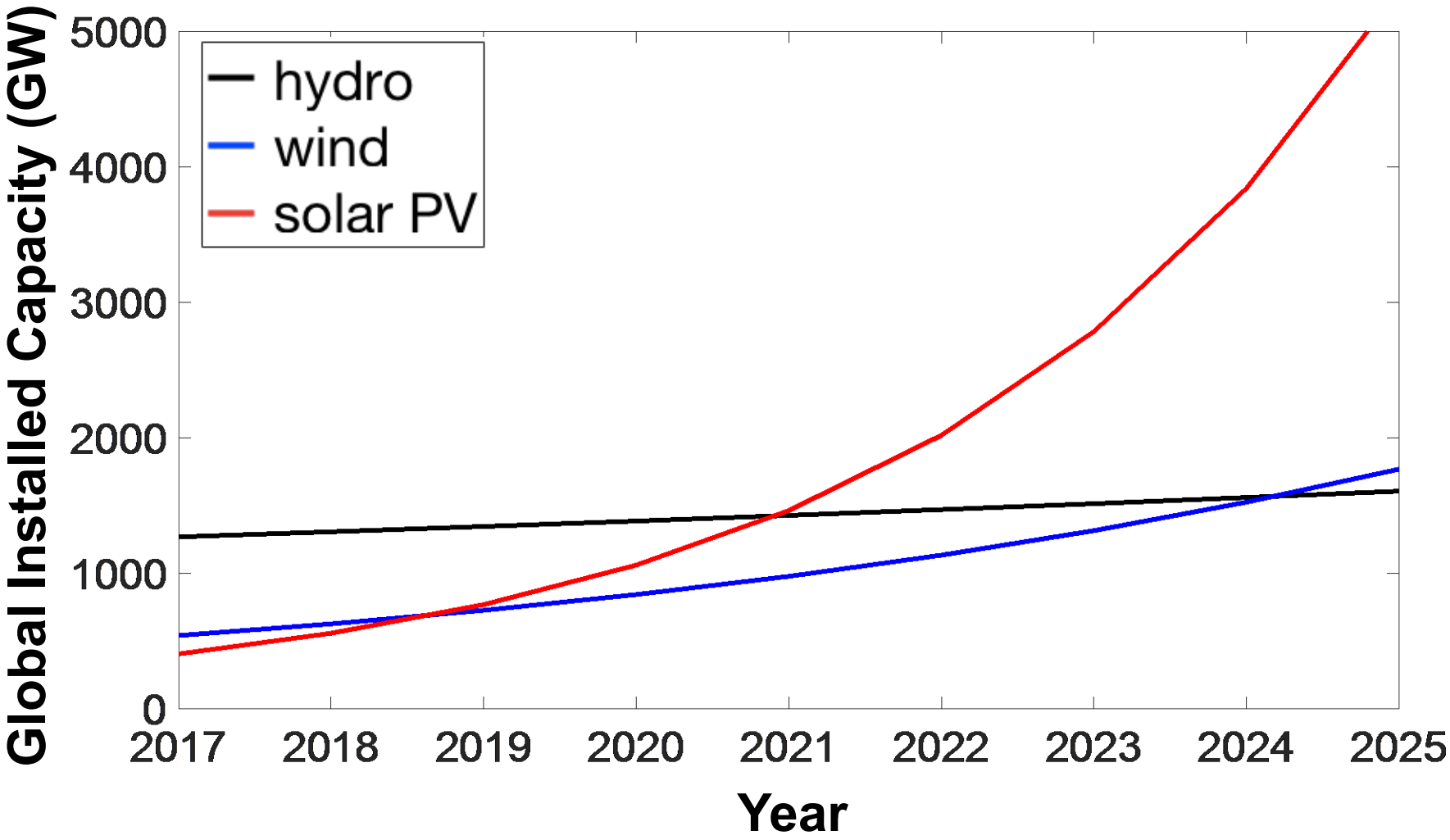
# How much solar PV power is there?

- End-of-2017 global installed solar PV capacity was 403 GW; average annual growth of 38% over last decade
- EU has 107 GW; average annual growth of 26%
- Austria has 1.25 GW; average annual growth of 44%

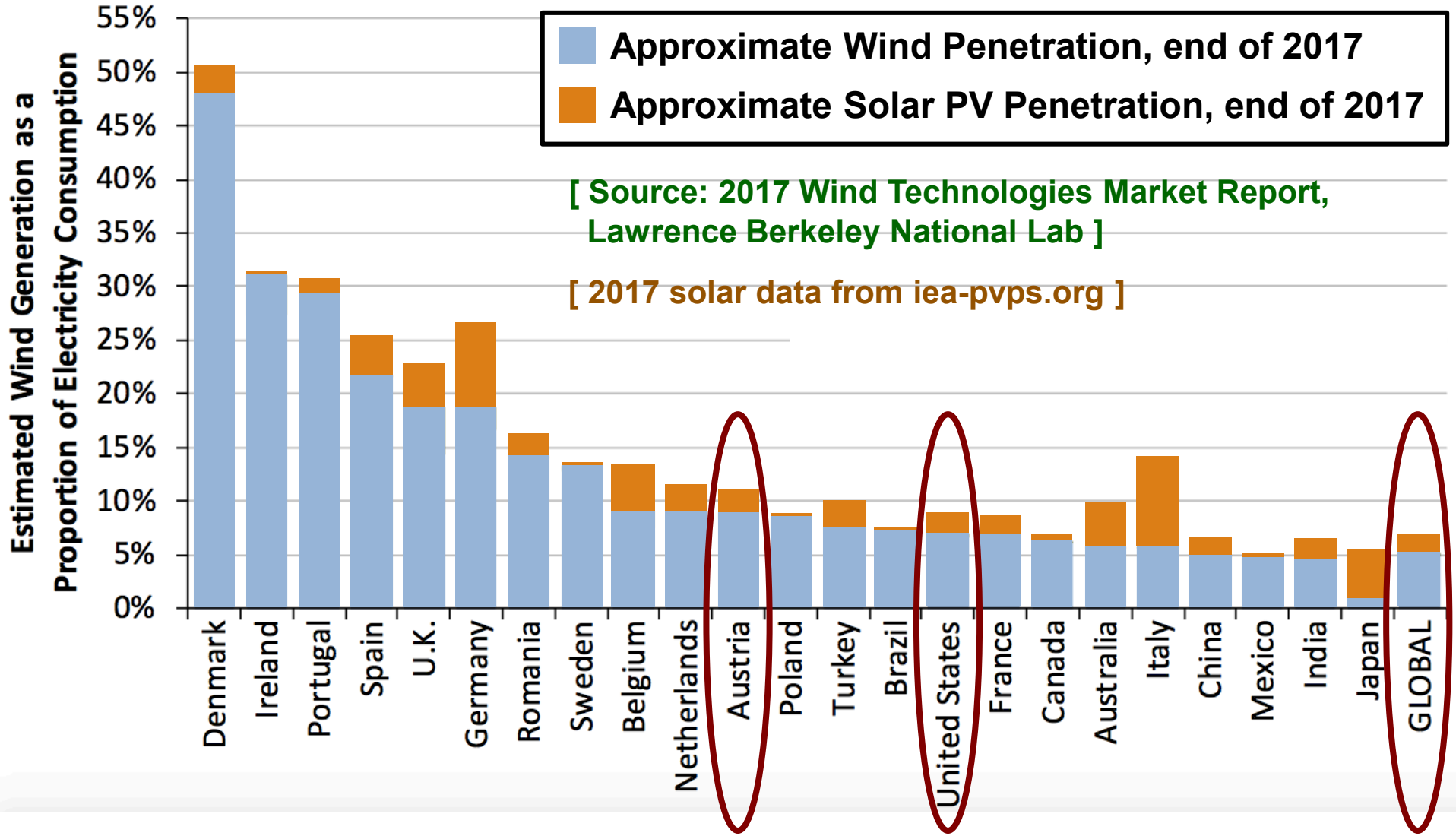



[ Data from iea-pvps.org ]

# Growth of Hydro, Wind, and Solar PV



# Wind and Solar PV Penetration



# Renewable Energy & The Power Grid

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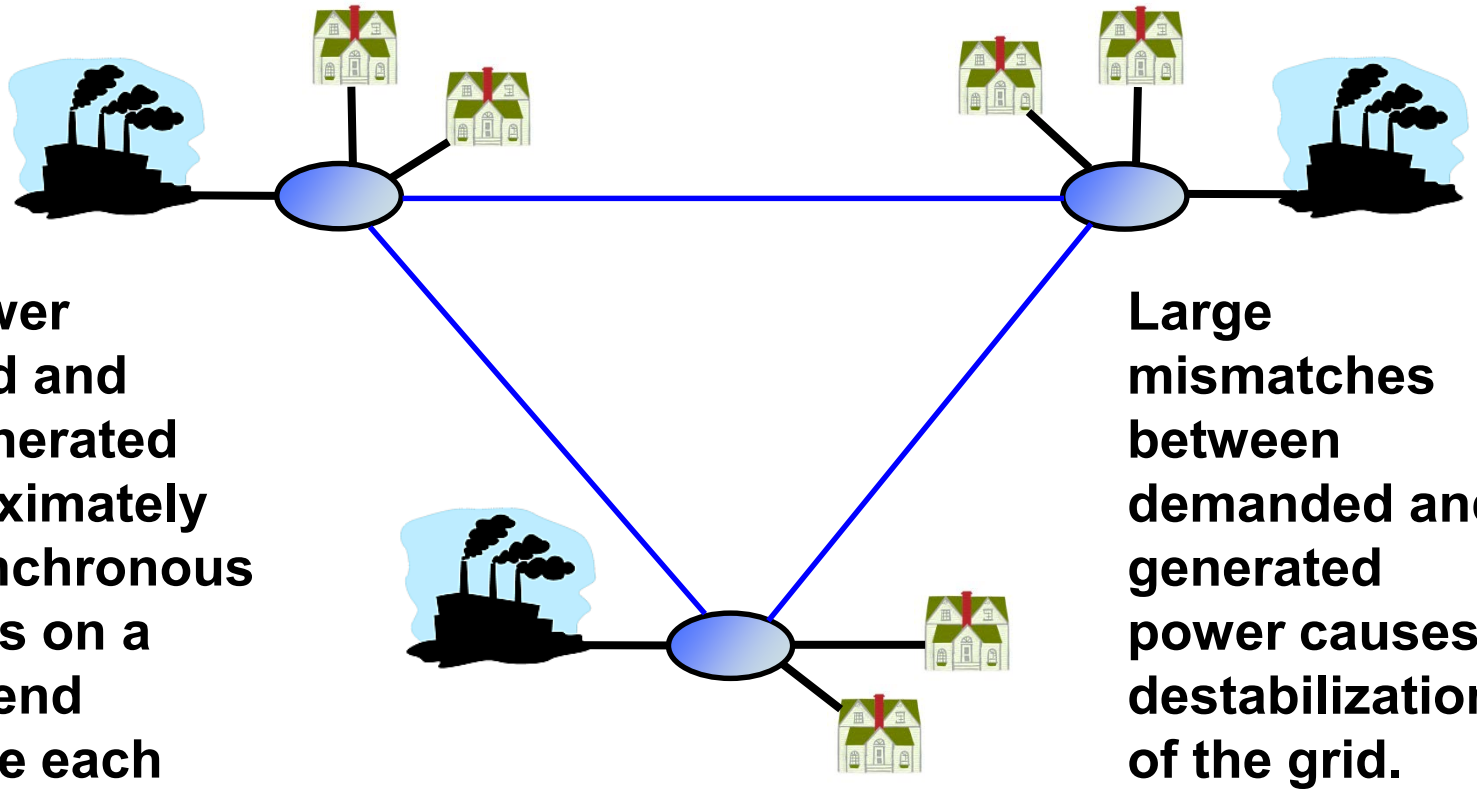
# Power Systems

## Most traditional power plants have synchronous generators.



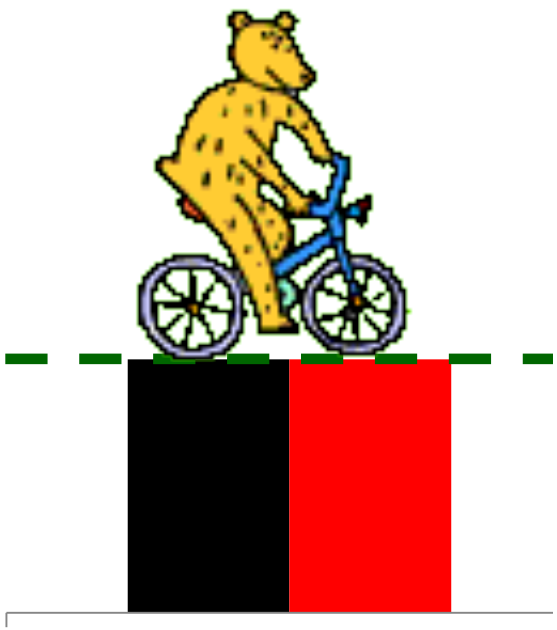
When power demanded and power generated are approximately equal, synchronous generators on a network tend to stabilize each other.

Large mismatches between demanded and generated power causes destabilization of the grid.

[Based upon a slide from Mark Ahlstrom of WindLogics]

# Grid Frequency Fluctuations

$f_{grid}$ = 50 Hz

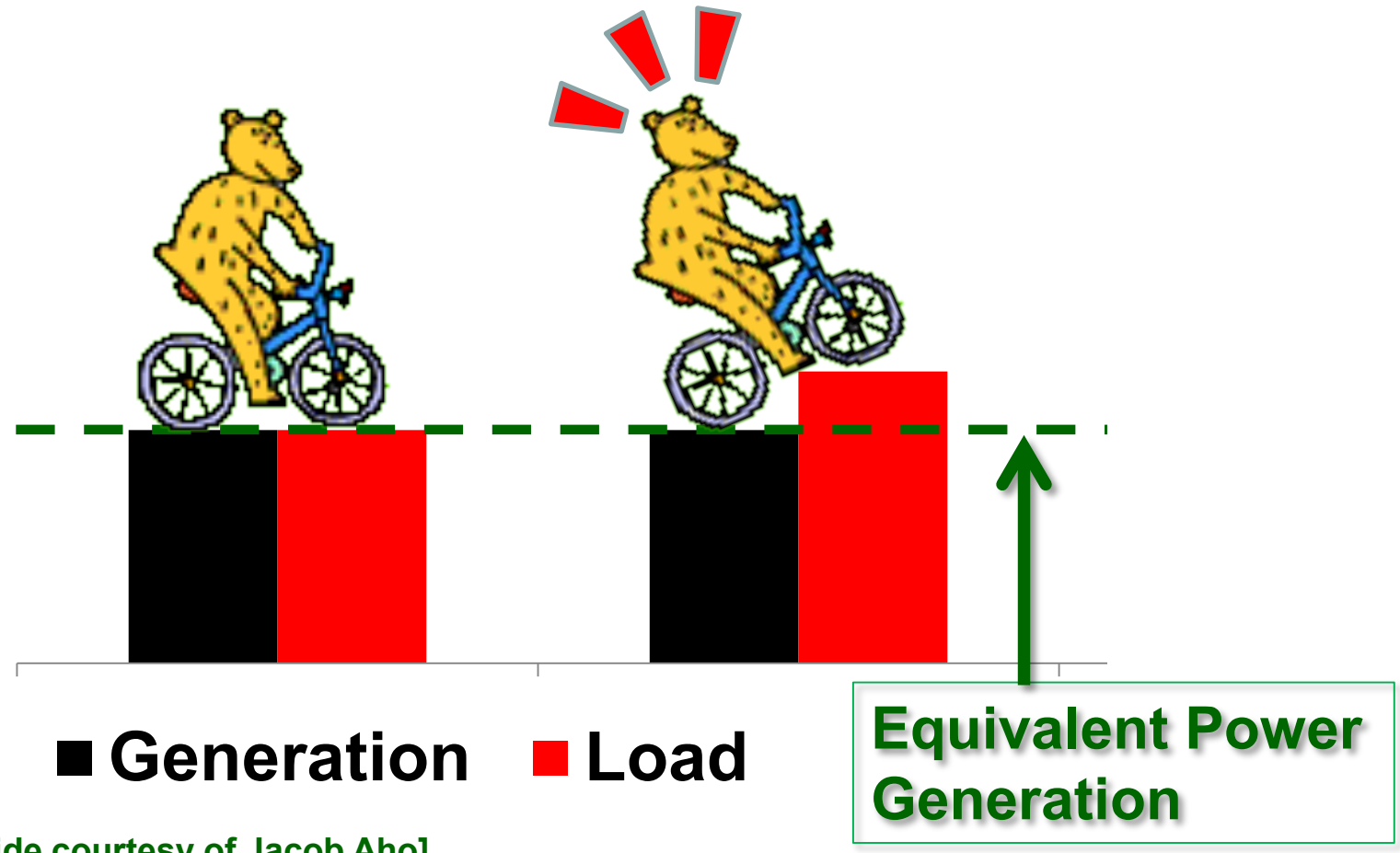


■ Generation ■ Load

[Slide courtesy of Jacob Aho]

# Frequency Drops if Electrical Power Generated < Electrical Load

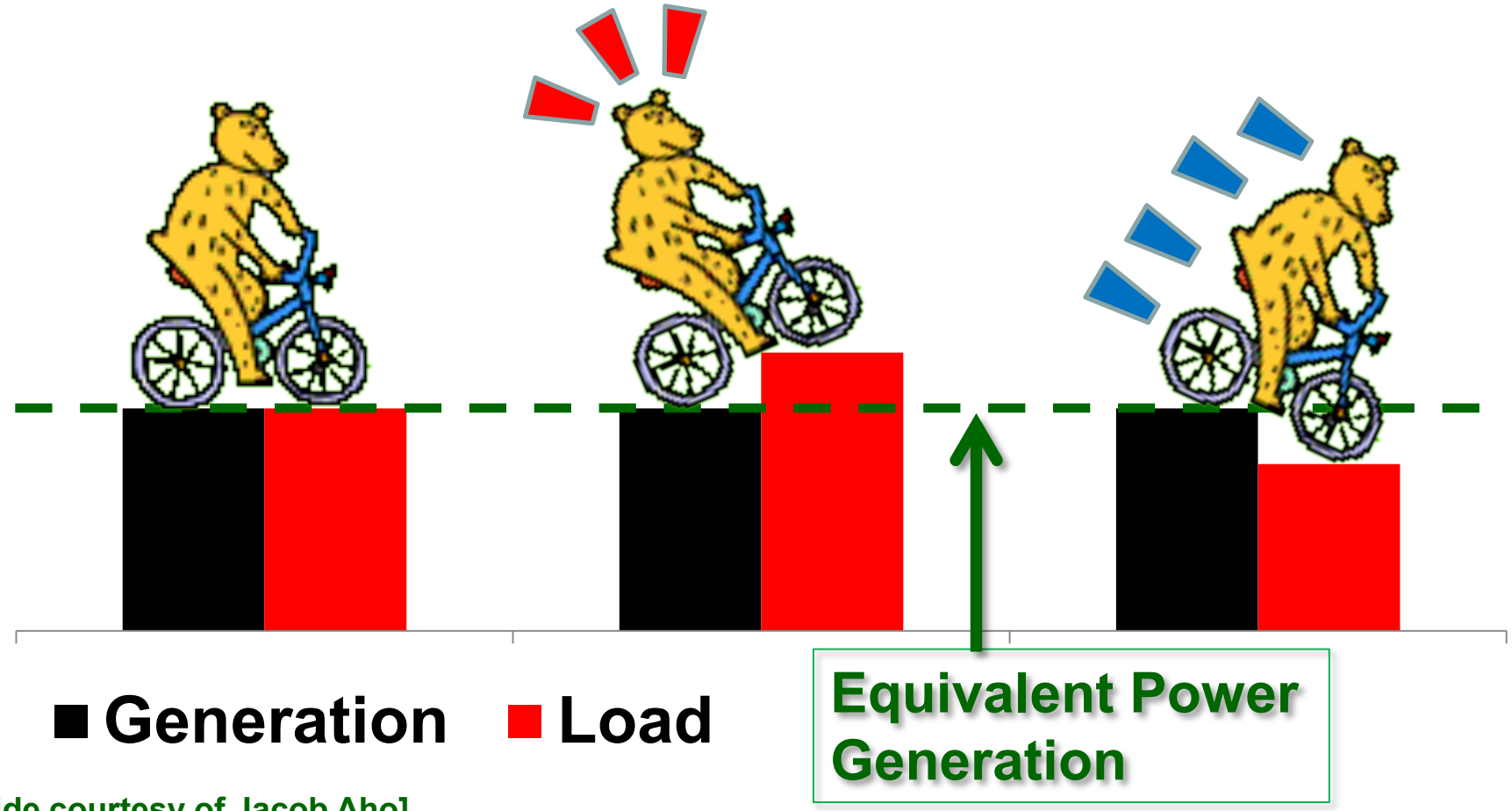
$f_{grid} = 50$ Hz $\quad f_{grid} < 50$ Hz




[Slide courtesy of Jacob Aho]

# Frequency Rises if Electrical Power Generated > Electrical Load

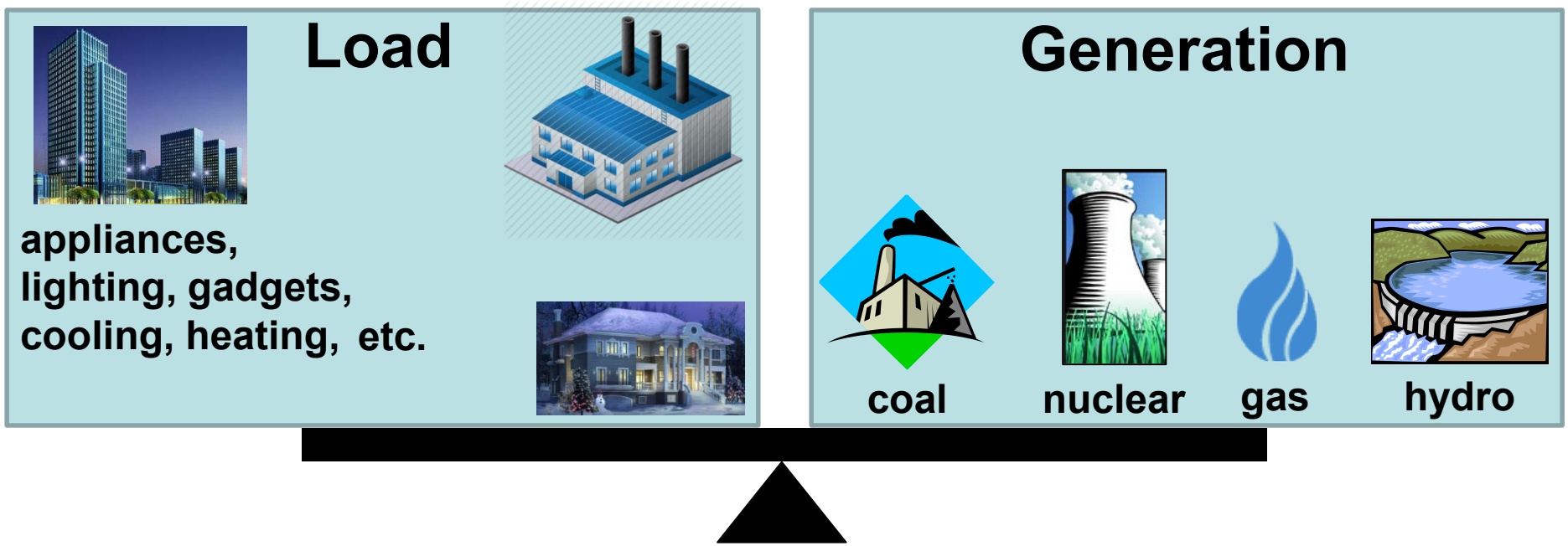
$f_{grid}$ = 50 Hz  $f_{grid}$ < 50 Hz  $f_{grid}$ > 50 Hz




[Slide courtesy of Jacob Aho]

# Balancing Electrical Generation and Load

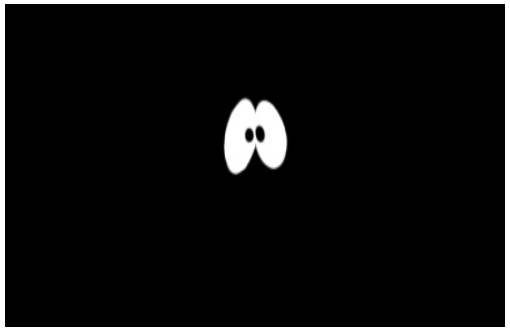
- **Traditionally, generation is controlled to match varying load**
  - Operational reserves needed
  - Imbalance causes frequency variations on utility grid



# Balancing Electrical Generation and Load

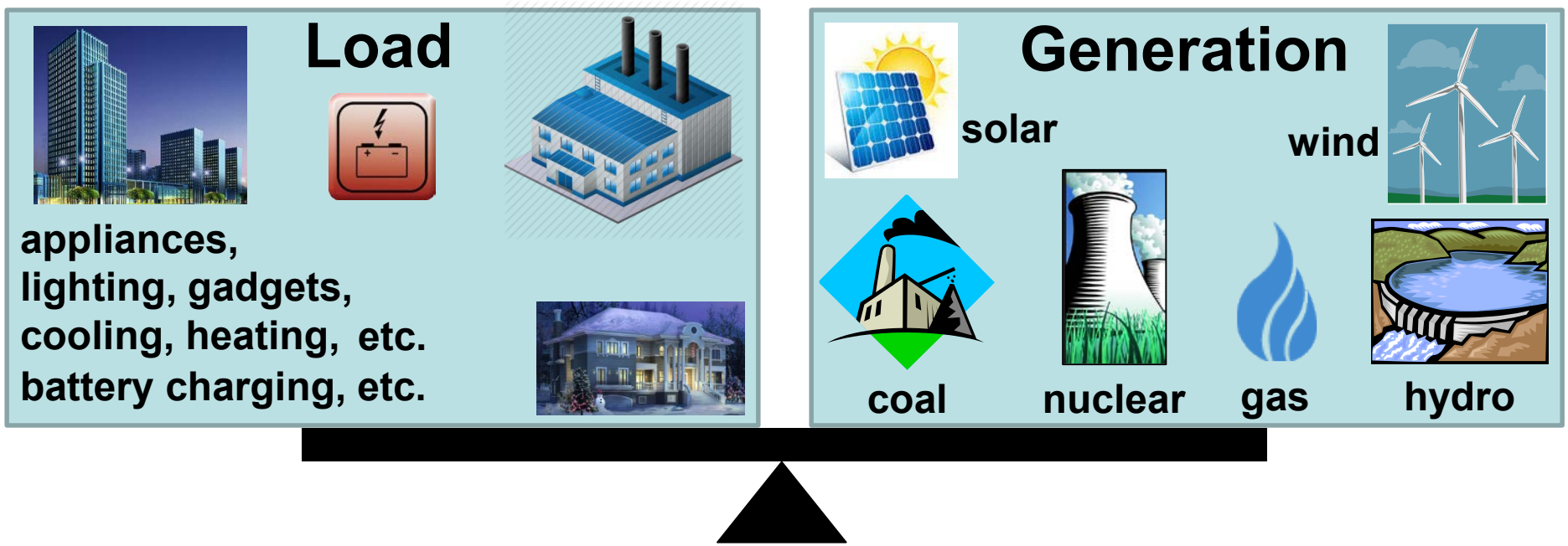
- **Traditionally, generation is controlled to match varying load**
  - **Operational reserves needed**
  - **Imbalance causes frequency variations on utility grid**

**Large frequency fluctuations can cause load shedding, or even blackouts**

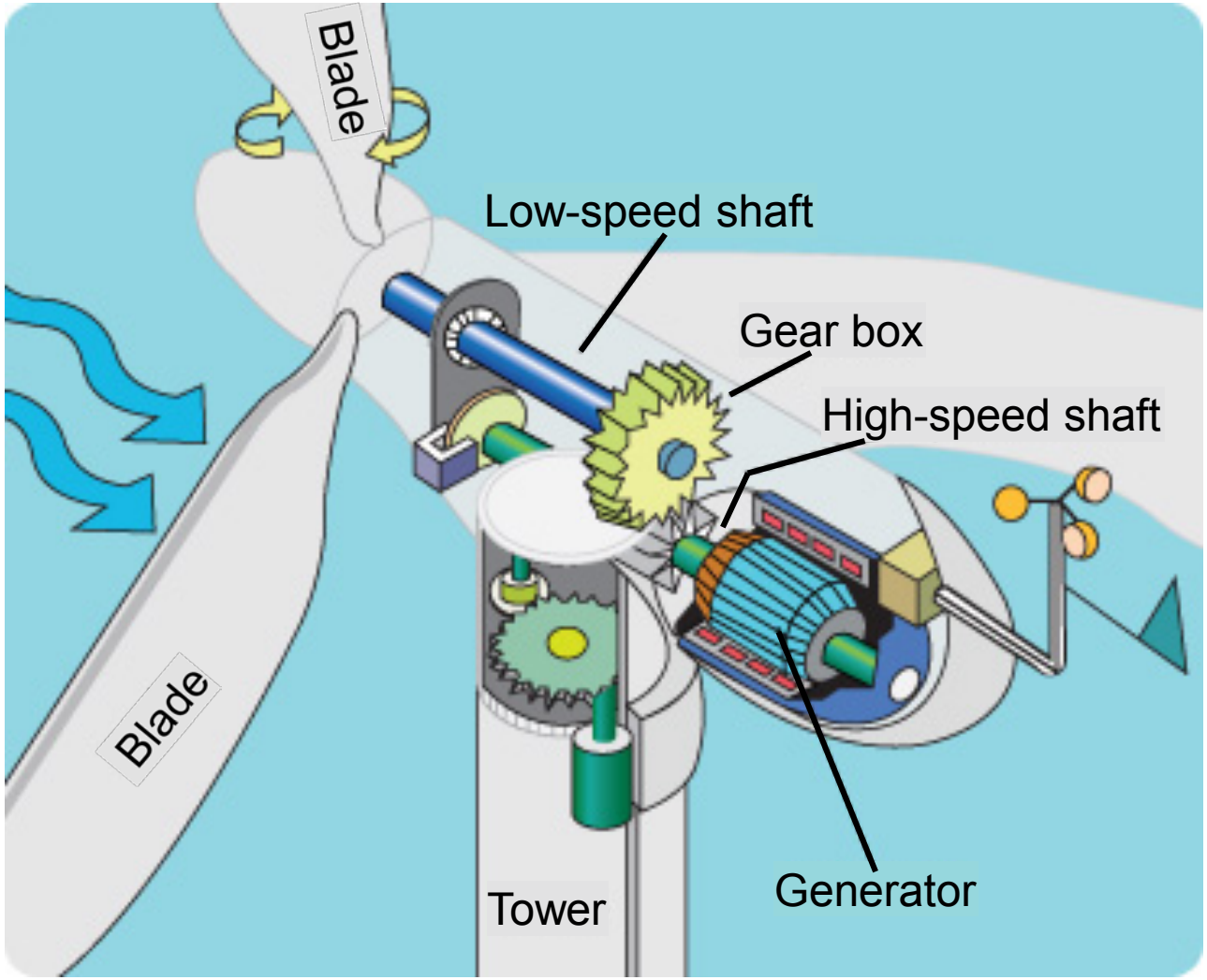


# Changes due to Wind and Solar PV

- **Wind turbines and solar PV arrays are typically decoupled from the grid through their power electronics**
  - **In the past, wind and solar generally have not participated in "balancing services"**
  - **Creates increased burden on remaining generating units**



# How does wind power work?




- Goal is to maximize power generation

[ figure from www.energyland.emsd.gov.hk based upon original from US Dept. of Energy ]

# How does solar PV work?

- PV panel consists of layers of material that produce electricity when light shines on it
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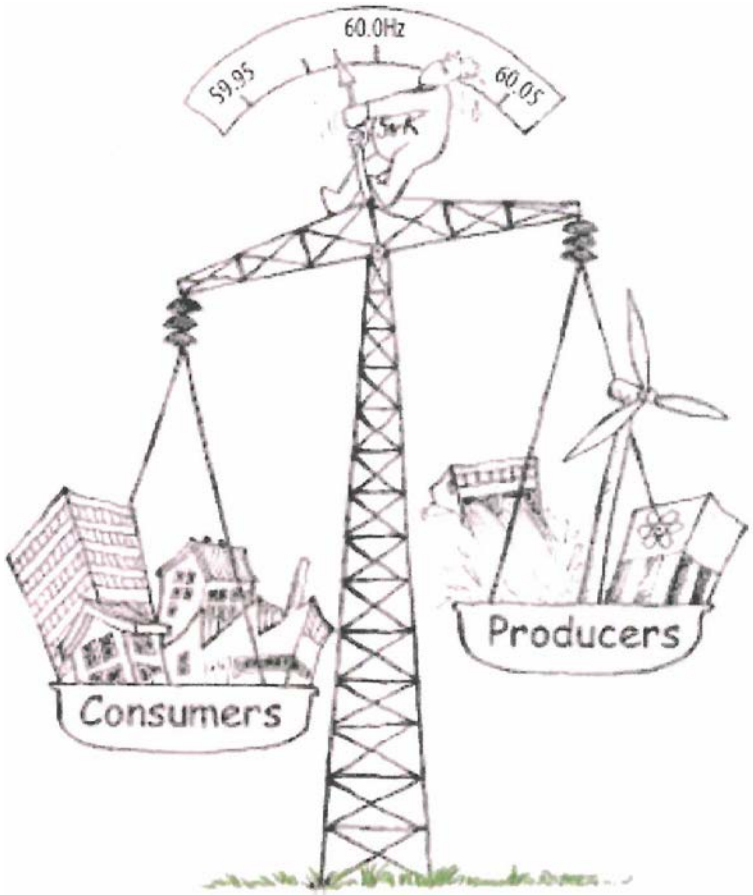
- Higher-end solar cells can achieve about 20-30% efficiency
- Research laboratories have demonstrated > 40%
- Goal is to maximize power generation

[ en.wikipedia.org/wiki/Solar_cell ]

# Possible Solution: APC of Wind and Solar

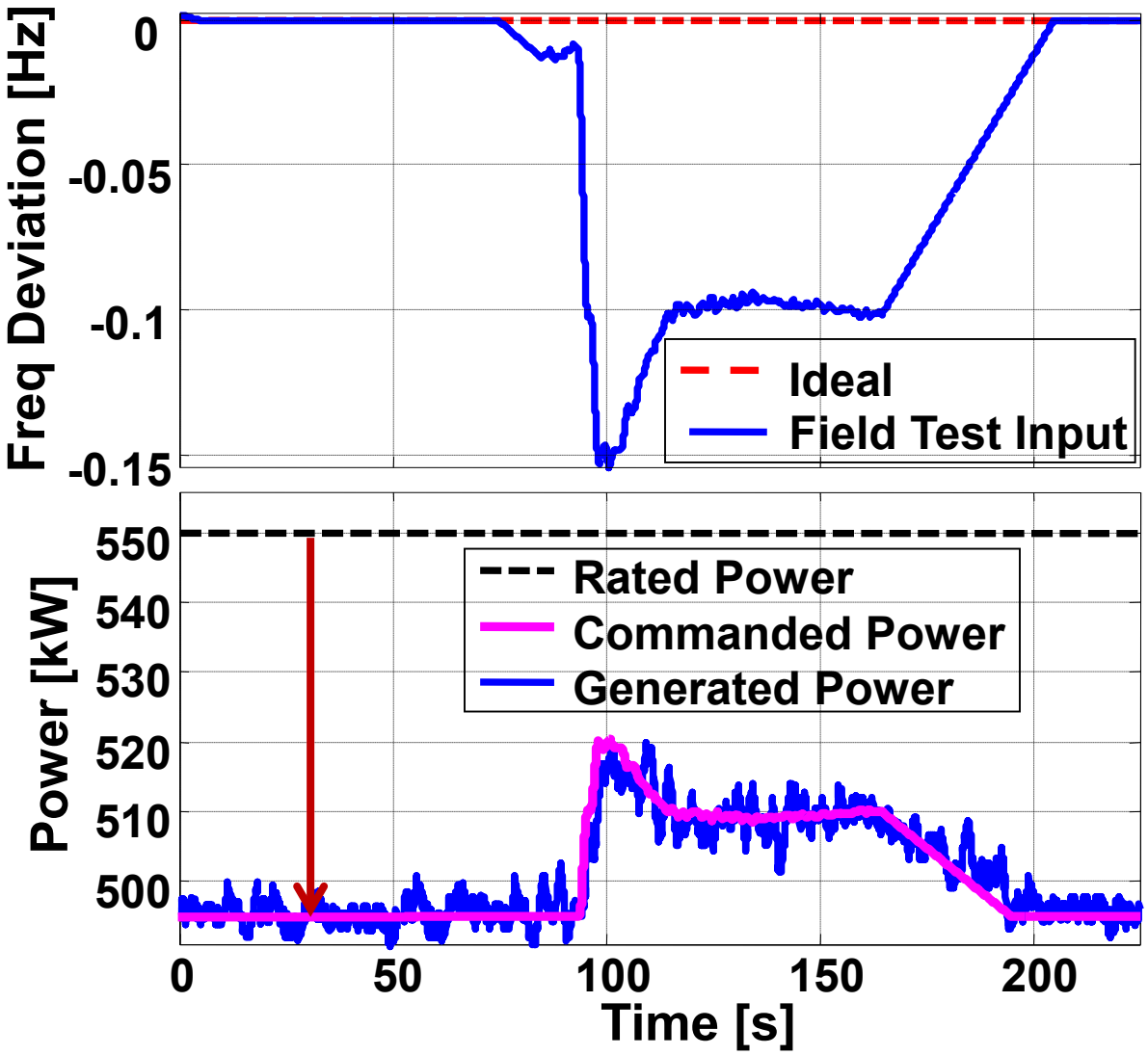
- **Active Power Control of Wind and Solar PV Power Plants**
  - **De-rate wind and solar power plants**
  - **Enable wind turbines and solar photovoltaic panels to follow changing power reference commands**




[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]

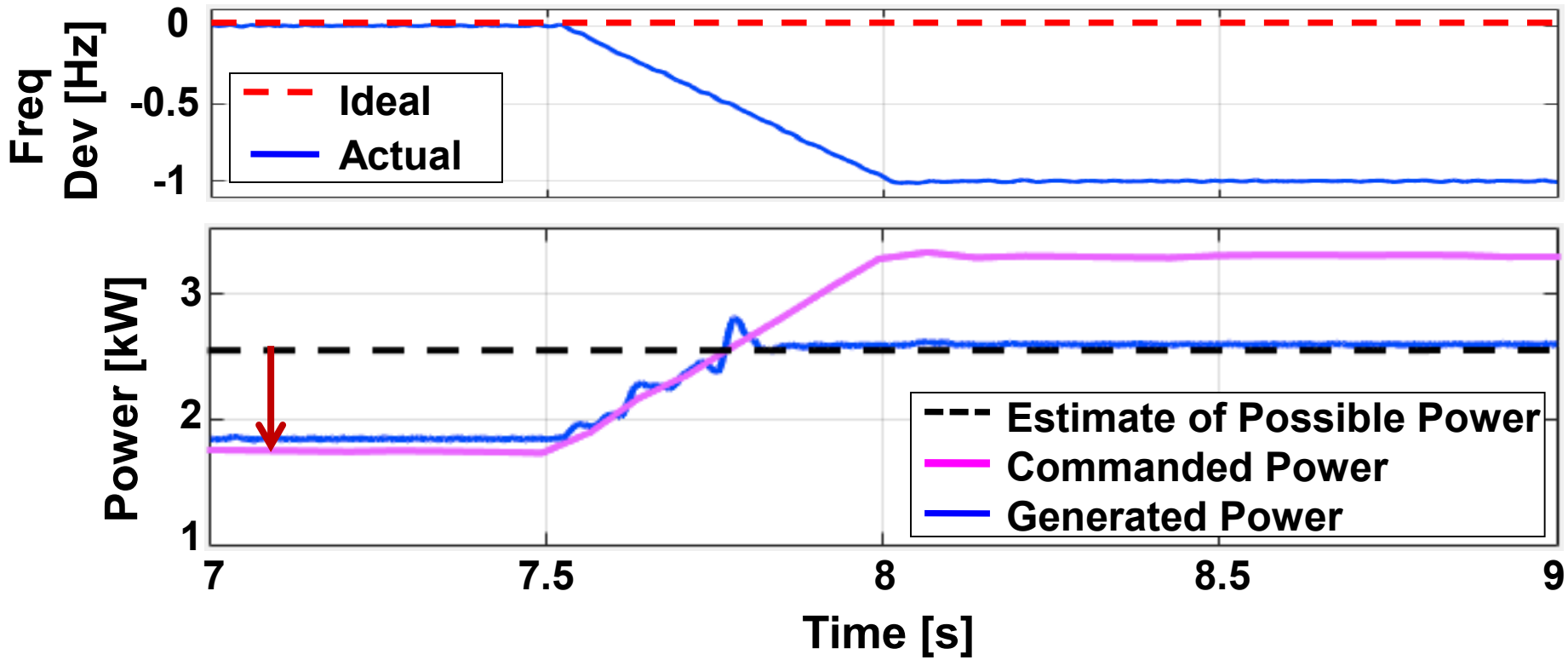
# Wind Turbine Field Test Results

[ 2013 – 2015, Aho, Buckspan, Fleming, Pao ]



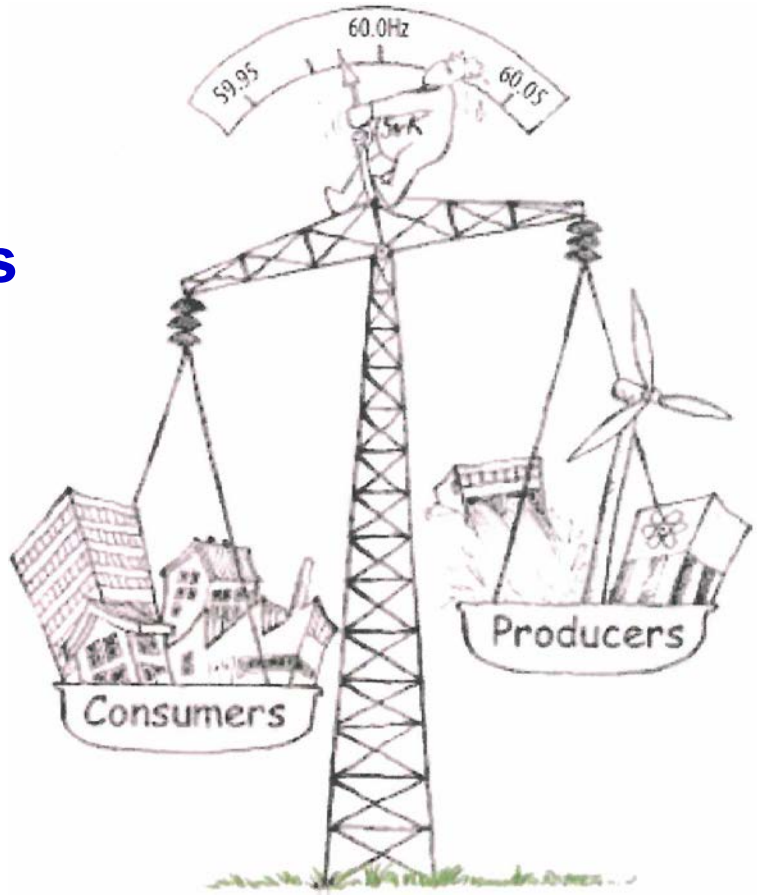

# Solar PV Array Field Test Results

[ 2016 – 2017, Hoke, Shirazi, Chakraborty, Muljadi, Maksimovic ]



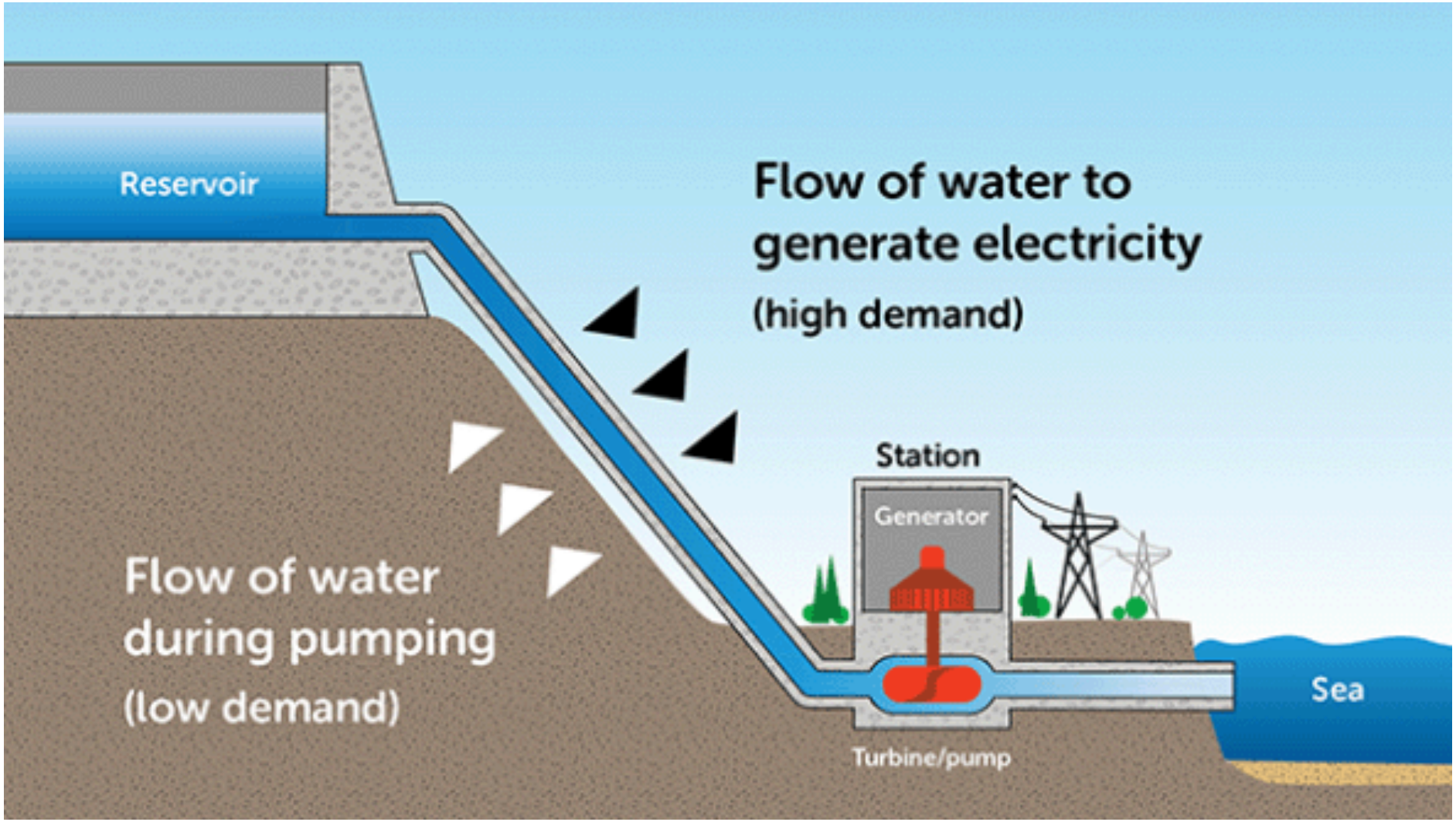
# Other Possible Solutions

- Curtail wind and solar as needed
- More transmission lines
- Improved wind and solar forecasts
- Demand-side management
  - Thermal storage
  - Time-of-use pricing and "optimal" pricing strategies
- Storage (at GWh scale)
  - Expensive
  - Effect of millions of electric vehicles, whose batteries can be either a load or a supply




[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]

# Pumped Hydro as a Means of Storage




[ image from antinuclear.net ]

# Summary

Hydro

Solar PV

Wind

Grid Integration

**While there are many challenges, there are many solution possibilities.**

# Acknowledgments

## Research supported by:

arpa·e

NSF

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

ENVISION

Hanse-Wissenschaftskolleg
Institute for Advanced Study

as well as other industry (who wish to remain anonymous)

# Acknowledgments

**Current students, recent postdoc:**

David Pasley joined in August 2018


Lucy Pao

Christopher Bay (2017-2018)

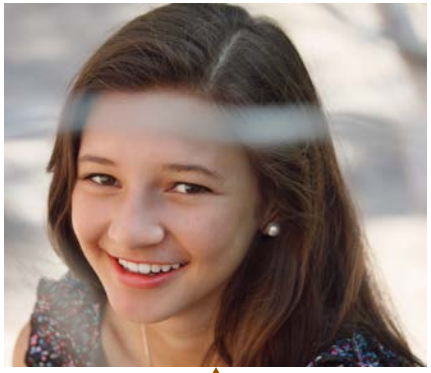
Michael Sinner

Daniel Zalkind

R. Arnold Braker

Nikhar Abbas

**Daughter:**



Sarah Pao Radzihovsky

# *Vielen Dank!*

University of Colorado **Boulder**

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CREW Center for Research and Education in Wind