**Aalto University**
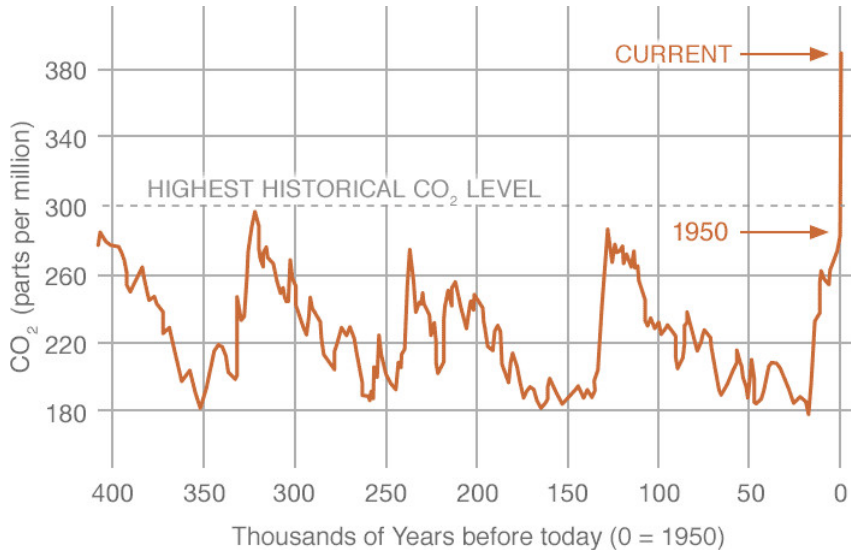**School of Electrical**
**Engineering**

# Introduction to Electric Energy Conversion and Renewable Energy Sources

## ELEC-A8001 Johdatus sähköenergiajärjestelmiin

Lecturer: Jorma Kyyrä (jorma.kyyra@aalto.fi)
Slides: Marko Hinkkanen
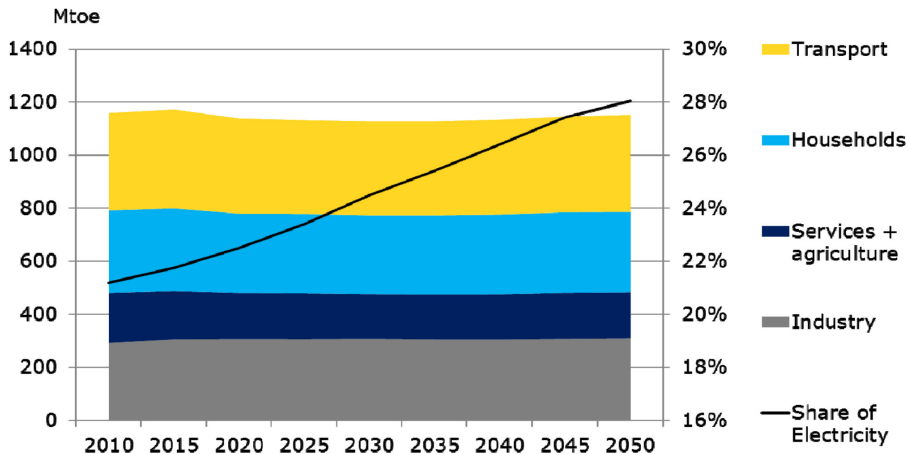
Autumn 2023

http://climate.nasa.gov

# Outline

# EU 2050 Roadmap: Reduction of Green House Gas Emissions
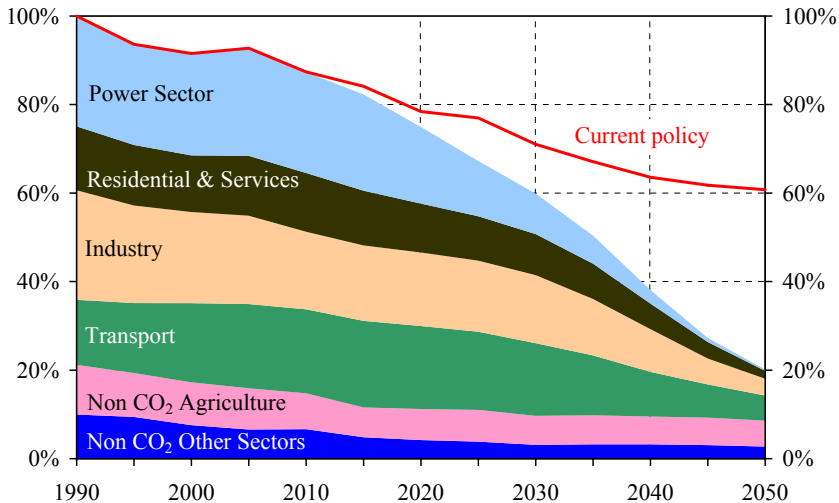


A roadmap for moving to a competitive low carbon economy in 2050, European Commission, COM(2011) 112, 2011

# EU Final Energy Consumption by Sector and Share of Electricity



Impact assessment, European Commission, SWD(2014) 15 final, 2014

# EU Net Power Generation Capacity

With Further Breakdown of Renewable Energy Source Capacities in Right Columns
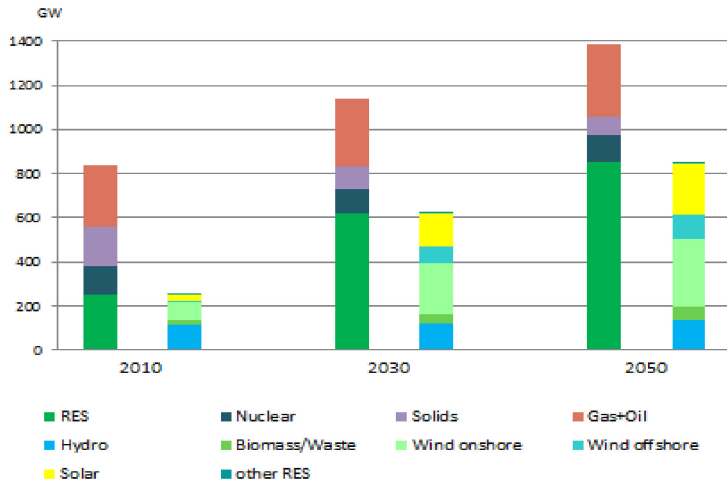


Impact assessment, European Commission, SWD(2014) 15 final, 2014

# Outline

# Electric Energy Is an Energy Carrier

- Examples of energy sources
  Non-renewable: Crude oil, coal, natural gas, natural uranium
  Renewable: Solar, wind, biomass
  Secondary: Hydrogen, electric energy
- Secondary energy sources are also referred to as energy carriers

- Energy has to be converted to a useful form

- Electric energy can be flexibly and efficiently converted to other forms
- But, storing of electric energy is a problem!

# Conversion Efficiency

- Power is the rate at which energy is converted

$$P = \frac{\mathrm{d}E}{\mathrm{d}t}$$

- Power balance
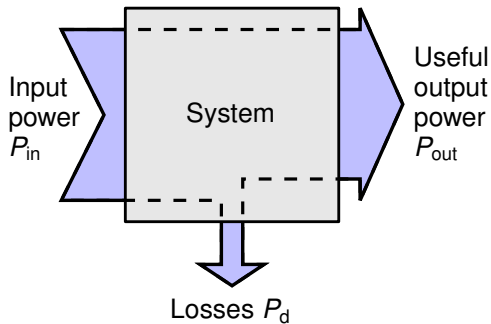
$$P_\text{in} = P_\text{out} + P_\text{d}$$

- Conversion efficiency

$$\eta = \frac{P_\text{out}}{P_\text{in}}$$

  is between 0 and 1

- In steady state, $\eta = E_\text{out}/E_\text{in}$

# Examples of Energy Conversion

| Energy conversion device | Input energy | Useful output energy | Typical efficiency (%) |
|---|---|---|---|
| Automobile engine | Chemical | Mechanical | 25 |
| Power plant boiler | Chemical | Thermal | 85 |
| Steam turbine | Thermal | Mechanical | 45 |
| Electric generator | Mechanical | Electric | 95 |
| Electric motor (large) | Electric | Mechanical | 90 |
| Incandescent lamp | Electric | Light | 5 |
| Electric heater | Electric | Thermal | 100 |
| Silicon solar cell | Solar | Electric | 15 |
| Battery | Chemical | Electric | 90 |

Efficiency values: http://www.ems.psu.edu/~radovic/Chapter4.pdf. Note that these values are just examples and that efficiencies depend also on the operating point.

# Importance of Energy Efficiency



Figure: ABB
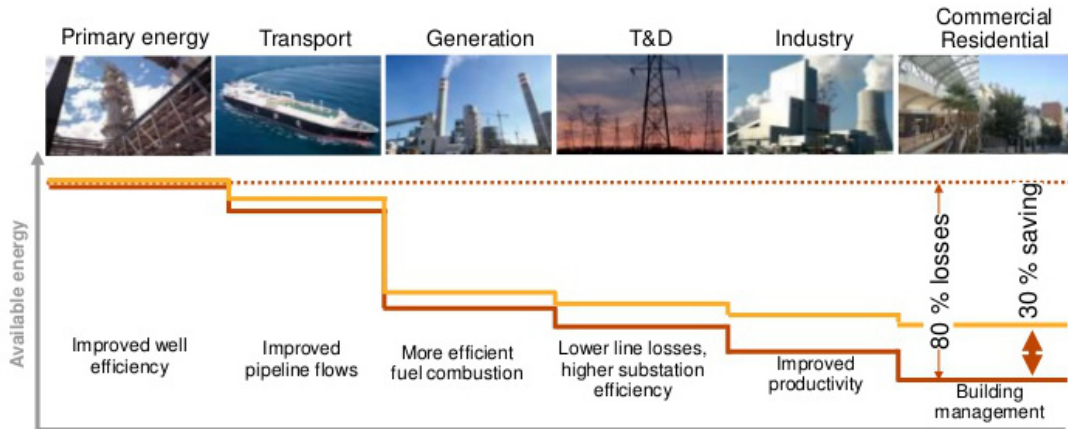
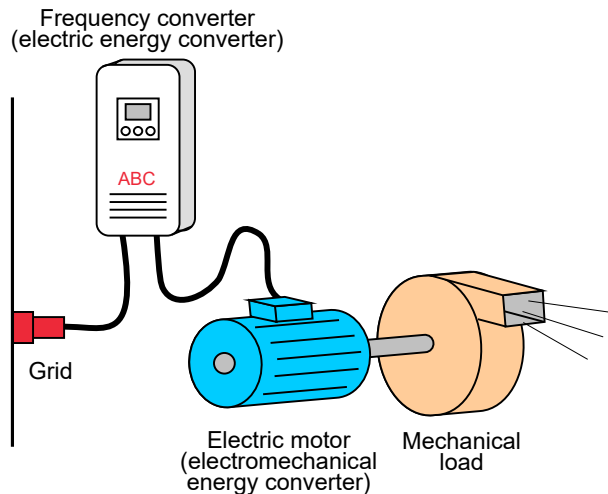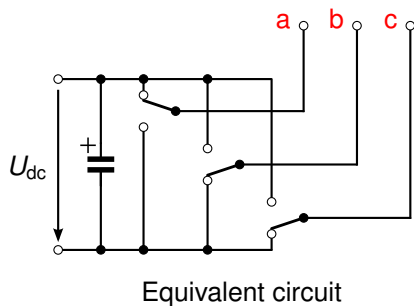# Outline
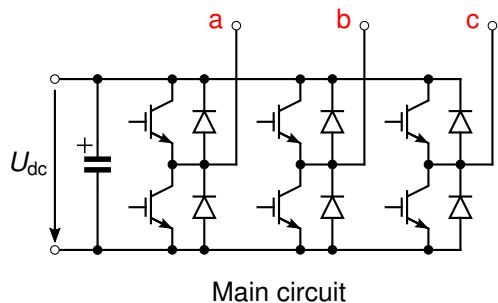
# Electric Drive

- Electric drive is a system, which **converts electric energy into mechanical work**
- Direction of the energy flow can also be opposite
- **Energy flow can be controlled** by means of an electric energy converter



Frequency converter
(electric energy converter)

ABC

Grid

Electric motor
(electromechanical
energy converter)

Mechanical
load

# Two-Level Converter



Main circuit            Equivalent circuit

- ▶ 2-level converters typical in low-voltage drives (below 1 kV)
- ▶ 3-level converters in medium-voltage drives
- ▶ Modular multi-level converters are becoming an interesting option in grid applications ($> 10$ kV)
- ▶ Frequency converter may consist one or two this kind of converters

# Example: AC-Side Waveforms of a Two-Level Converter
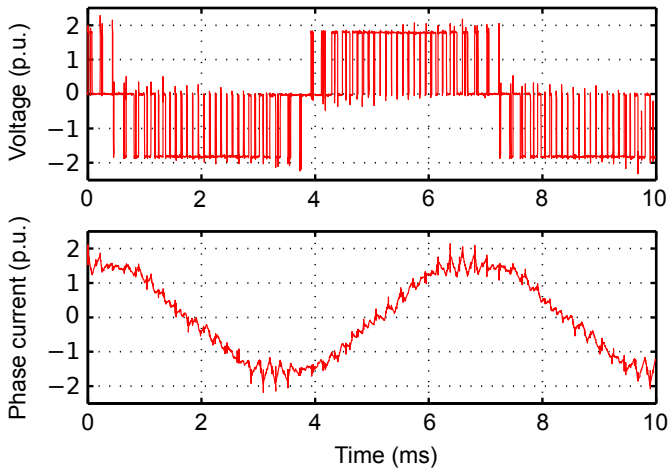
# Energy Consumption of Electric Motors in the EU
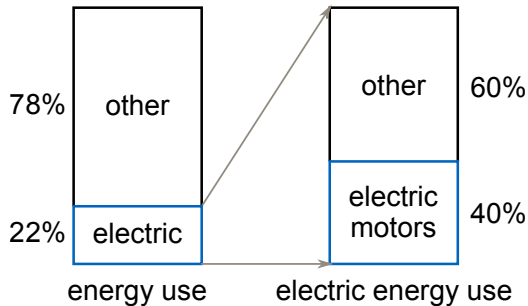


- ▶ Share of electricity in final energy use is estimated to rise up to 28% by 2050
- ▶ Electric drives and electric energy converters are important for sustainable use of energy

# Water Pumps at Google Data Center, Hamina, Finland



Figure: Google

# Heavy-Duty Industrial Centrifugal Fan

- 1.35-MW 690-V induction motors (most commonly used machine type)



Figure: www.pollrichdlk.com

# Pump and Fan Drives

- ▶ Fluid flow is controlled by adjusting the speed $\omega_M$ with the frequency converter
- ▶ If the fluid flow reduces to 50%, load power $P_L$ may drop down to ~30%
- ▶ Significant energy savings are possible (in comparison with fixed-speed drives, where the flow is controlled with a valve)

# Wind Turbine



Gearbox
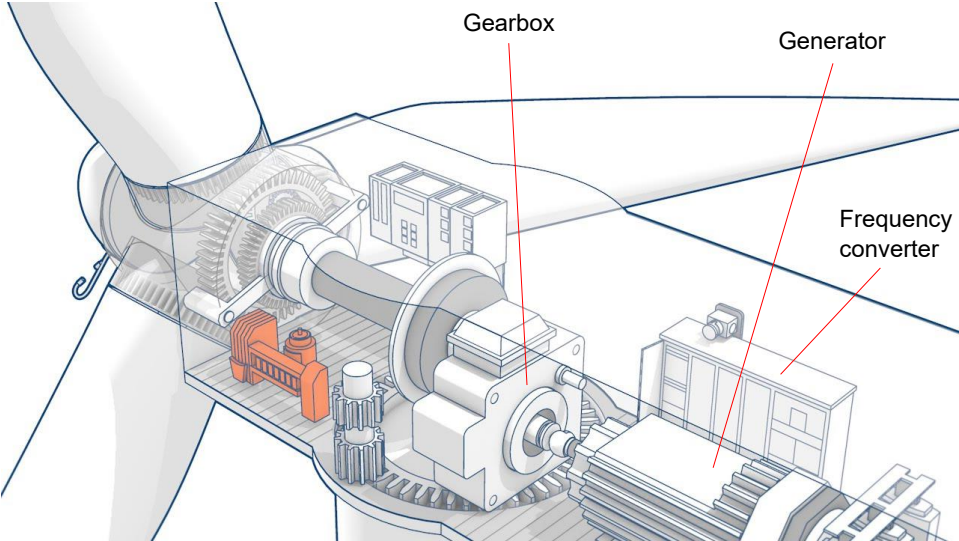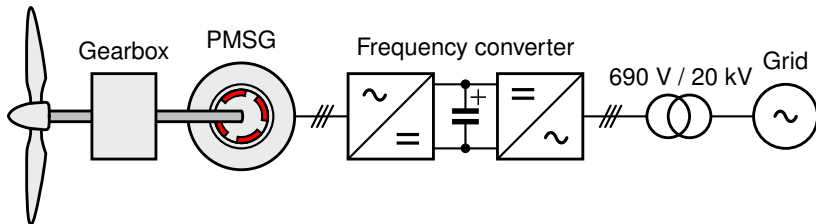
Generator

Frequency converter
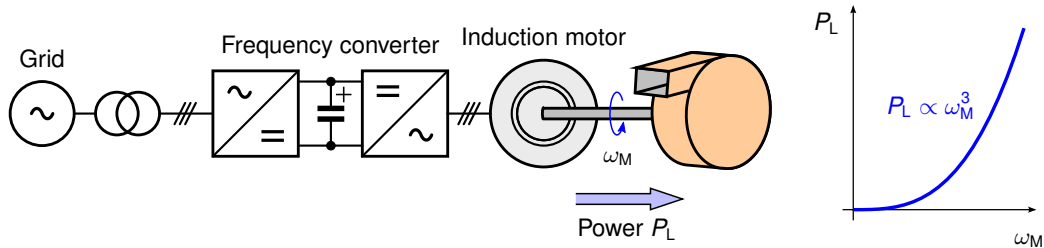
Figure: ABB (modified)

# Wind Turbine: Permanent-Magnet Synchronous Generator

- ▶ Power levels up to 8 MW
- ▶ Typical gear ratios around 100:1 (but direct drives also exist)
- ▶ Optimal blade speed (which yields the maximum power) is controlled by the frequency converter

# Battery Electric Vehicle Powertrain

- Nissan Leaf (2014)
- Maximum power 80 kW
- Maximum torque 280 Nm
- Gear ratio 8:1
- Li-ion battery pack 24 kWh



Charger
DC-DC converter
Junction box

Inverter

PMSM

Gearbox

Figures: Nissan (modified)
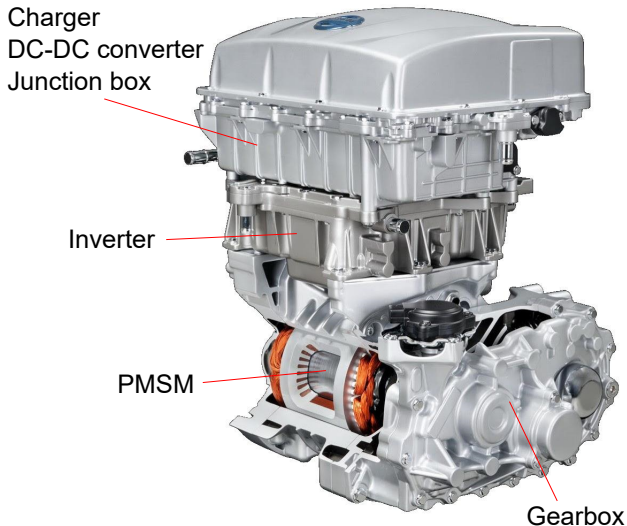
# Battery Electric Vehicle Powertrain

- Most common motor types in electric vehicles
  - Permanent-magnet synchronous motor (PMSM)
  - Induction motor (IM)
  - Permanent-magnet-assisted synchronous reluctance motor (PM-SyRM)
- When braking, the power flows from wheels to the battery pack
- Electric machines are capable to operate both as a motor and a generator
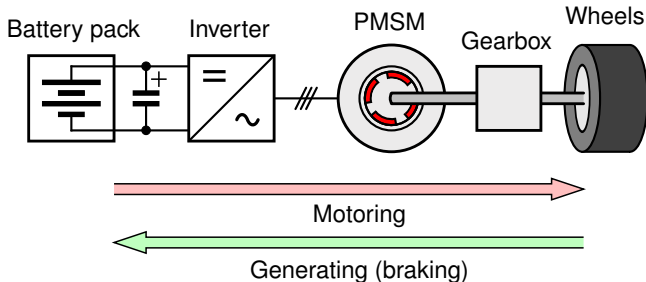
# Goliath Shipyard Crane

- ▶ Modern cranes can be semi- or fully-automated
- ▶ Constant load torque due to the gravity
- ▶ When lowering the load, the hoist motor operates as a generator
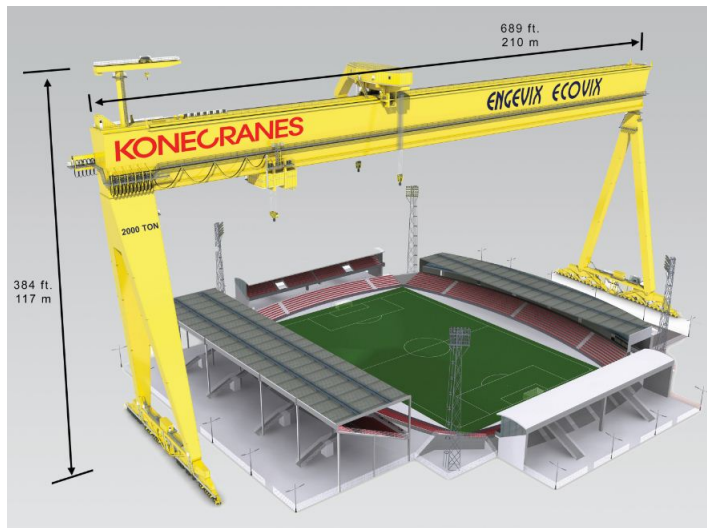- ▶ How much power is needed to hoist mass *m* at speed *v*?



Figure: Konecranes

# Why Controlled Electric Drives Are Needed?

1. Enabling fast and accurate motion control
   - Robotics, elevators, cranes, process automation. . .
2. Improving energy efficiency
   - Process flow is controlled by means of the motor speed
   - Pumps, fans, compressors. . .
3. Conserving braking energy
   - Transportation, cranes. . .

Similar technologies are applied in grid integration of renewable energy sources (wind, solar, etc.)

# Outline

# Electricity From Renewable Sources in EU



Legend:
- Geothermal (TWh)
- Biomass & renewable waste (TWh)
- Solar (TWh)
- Wind turbines (TWh)
- Hydropower (TWh)
- Electricity from renewables (% of consumption) (*)
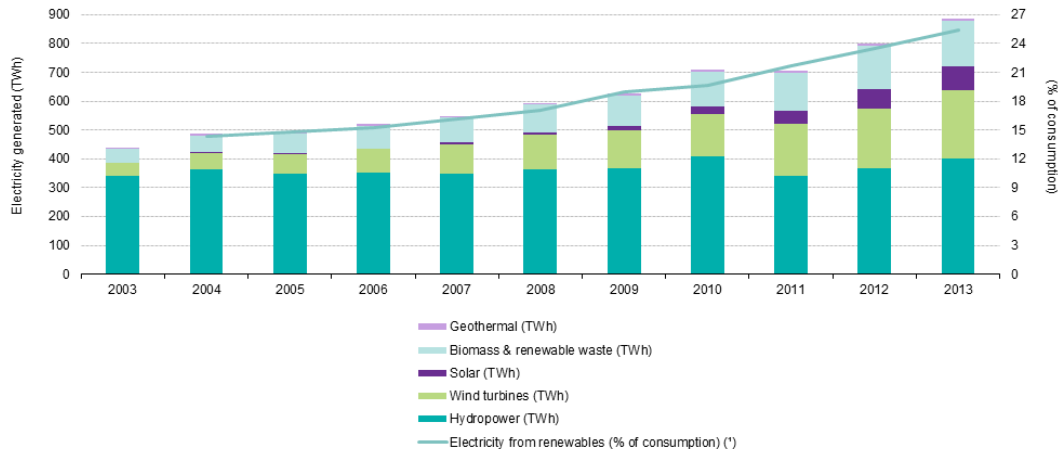
(*) 2003: not available.
*Source:* Eurostat (online data codes: nrg_105a and tsdcc330)

# Since 2011 installed capacity on renewables has been higher than 50 %

Whole World



GW

Share of new electricity generating capacity

Increase in non-renewables (GW)    Increase in renewables (GW)    Renewable share (%)
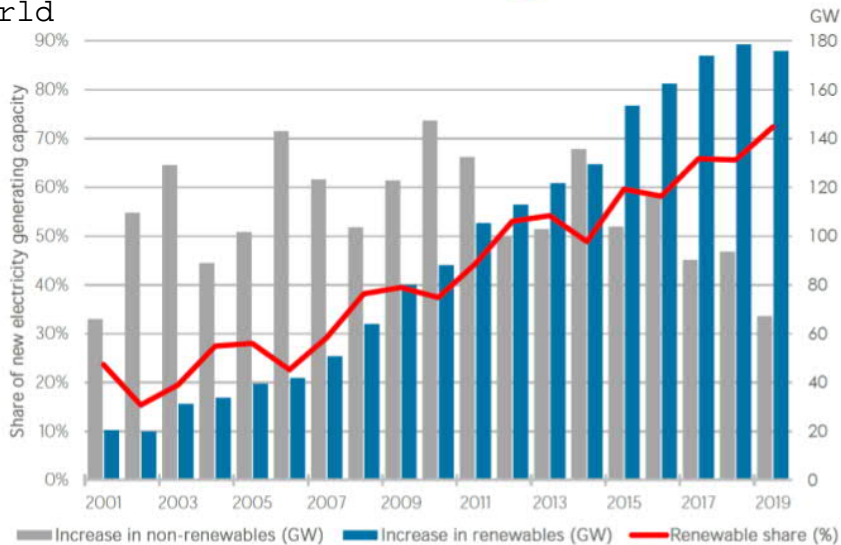
# World Installed Capacity (MW) in Wind and Solar



Installed Capacity (MW)

Legend:
- Solar Thermal
- Solar Photovoltaic
- Offshore Wind
- Onshore Wind

© IRENA
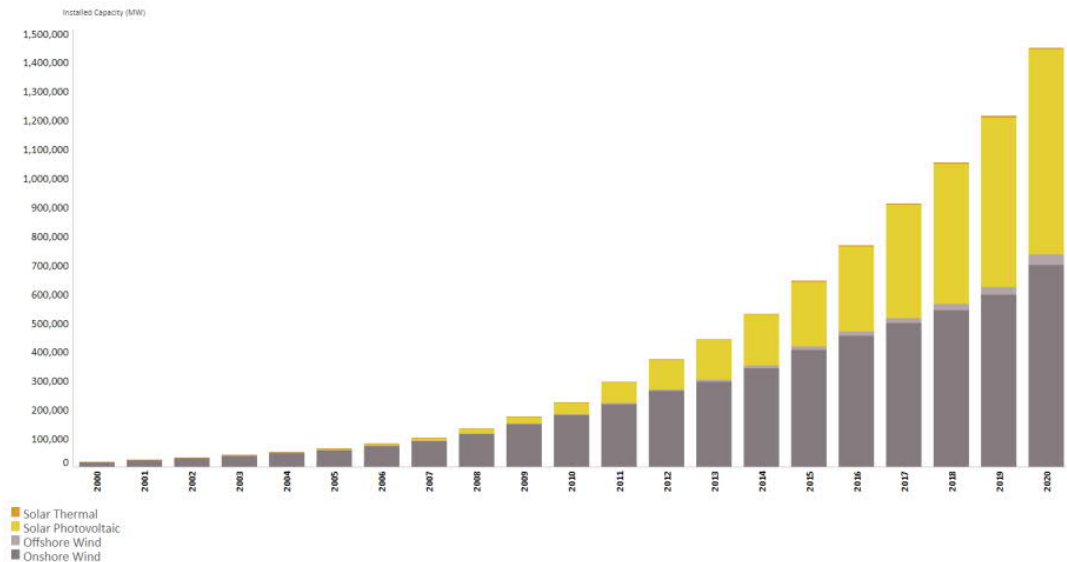
# World Installed capacity in renewables



© IRENA
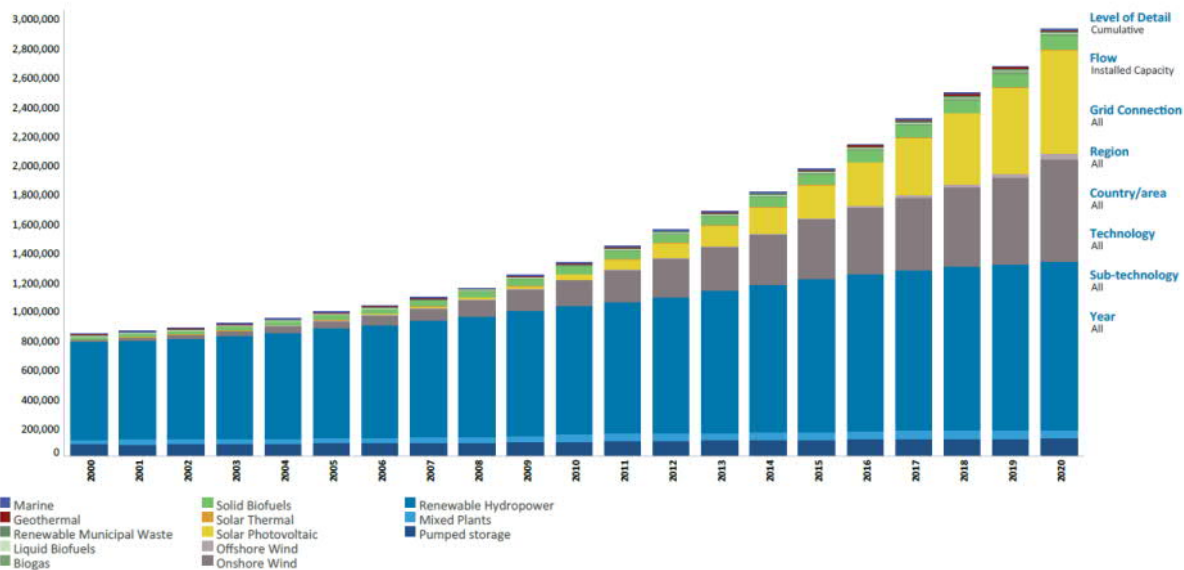
# Top 10 Countries/areas



**SHOW BY**
Electricity Generation

**TECHNOLOGY**
Solar energy

**SUB-TECHNOLOGY**
All

**YEAR**
2020

GWh

Bar chart showing values for China (~260,000), United States of America (~120,000), Japan (~82,000), India (~57,000), Germany (~50,000), Italy (~25,000), Australia (~20,000), Spain (~20,000), Republic of Korea (~16,000), Viet Nam (~15,000).

© IRENA

Last update: 20 July, 2022

# Top 10 Countries/areas

| SHOW BY | TECHNOLOGY | SUB-TECHNOLOGY | YEAR |
|---|---|---|---|
| Electricity Generation | Wind energy | All | 2020 |

GWh



© IRENA

Last update: 20 July, 2022

# Photovoltaic Solar Electricity Potential in European Countries



Global irradiation*
[kWh/m²]

Solar electricity**
[kWh/kW_peak]
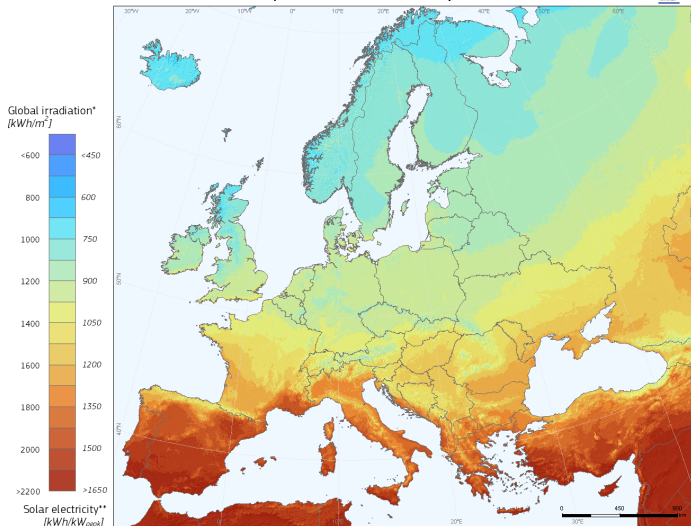
* Yearly sum of global irradiation incident on optimally-inclined
south-oriented photovoltaic modules

**Yearly sum of solar electricity generated by optimally-inclined
1kW_p system with a performance ratio of 0.75

© European Union, 2012
PVGIS http://re.jrc.ec.europa.eu/pvgis/

Authors: Thomas Huld, Irene Pinedo-Pascua
EC • Joint Research Centre
In collaboration with: CM SAF, www.cmsaf.eu

Legal notice: Neither the European Commission nor any person acting on behalf of the
Commission is responsible for the use which might be made of this publication

# Outline

# Power From the Wind

- Wind energy $E_w$ and power $P_w$ flowing through an area $A$

$$E_w = \frac{1}{2} \underbrace{\rho A v_w t}_{m} v_w^2 \quad \Rightarrow \quad P_w = \frac{1}{2} \rho A v_w^3$$

where $\rho$ is the air density and $v_w$ is the wind speed

- Power extracted by the turbine

$$P = C_p \cdot \frac{1}{2} \rho A_b v_w^3$$

where $A_b = \pi r_b^2$ is the area swept by the blades, $r_b$ is the blade length, and $C_p$ is the power coefficient

# Power Coefficient $C_p$

- Power coefficient depends on
  - Blade design
  - Pitch angle
  - Tip speed ratio $\lambda = r_b \Omega_b / v_w$, where $\Omega_b$ is the angular speed of the rotor blades
- Theoretical limit: $C_p < 59\%$
- In variable speed turbines, $C_p$ can be kept at its maximum (if the power and rotor speed are below their rated values)
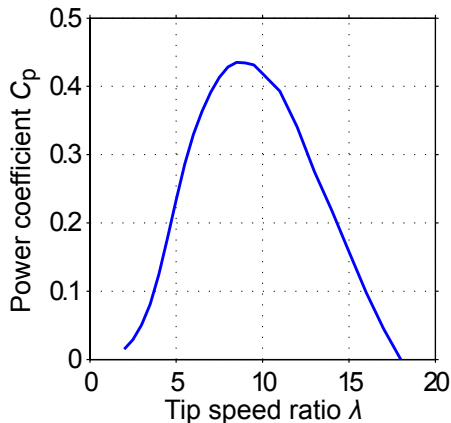


Example power coefficient curve

# Torque of the Blade Rotor

▶ Blade length for a given rated power

$$P = C_{\mathrm{p}} \cdot \frac{1}{2} \rho \pi r_{\mathrm{b}}^2 v_{\mathrm{w}}^3 \quad \Rightarrow \quad r_{\mathrm{b}} = \left( \frac{2P}{C_{\mathrm{p}} \rho \pi v_{\mathrm{w}}^3} \right)^{\frac{1}{2}}$$

▶ Blade tip speed $v_{\mathrm{b}} = r_{\mathrm{b}} \Omega_{\mathrm{b}}$ limited to avoid excessive mechanical forces, wear, and audible noise

$$T_{\mathrm{b}} = \frac{P}{\Omega_{\mathrm{b}}} = \frac{r_{\mathrm{b}} P}{v_{\mathrm{b}}} = \left( \frac{2}{C_{\mathrm{p}} \rho \pi v_{\mathrm{w}}^3 v_{\mathrm{b}}^2} \right)^{\frac{1}{2}} P^{\frac{3}{2}}$$

▶ Rated torque $T_{\mathrm{b}} \propto P^{3/2}$ increases more than proportional to the power level

---

More information: Polinder et al., "Trends in wind turbine generator systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, 2013

# Squirrel-Cage Induction Generator (SCIG)

- Old concept, manufactured mainly during the last century
- Operates at (almost) constant speed
- Simple, robust, and cheap
- Power levels up to 1.5 MW
- Typically three-stage gearbox
- Power above the rated wind speed limited using the stall principle
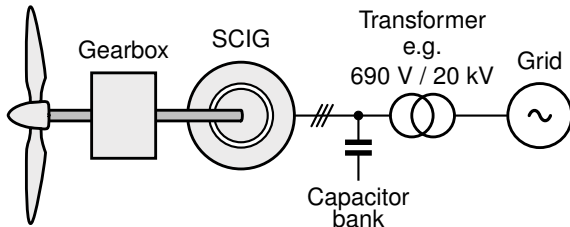
# Doubly-Fed Induction Generator (DFIG)

- ▶ Most popular concept nowadays (power levels up to 5 MW)
- ▶ Rotor winding is connected via slip rings to a converter
- ▶ Power rating of the converter is about 25% of the rated power (corresponds to the speed range 60%. . . 110%)
- ▶ Optimised tip speed ratio $\lambda \Rightarrow$ improved energy yield
- ▶ Less power fluctuations and audible noise



Frequency converter
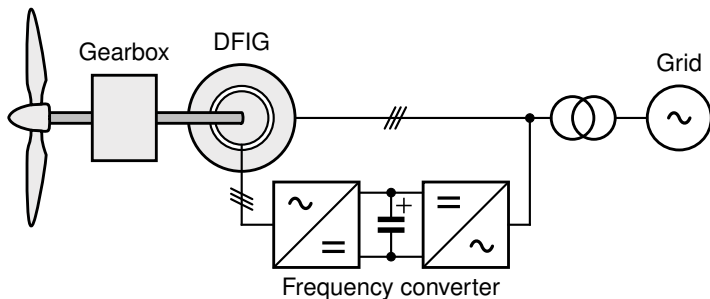
# Permanent-Magnet Synchronous Generator (PMSG)

- ▶ Power levels up to 8 MW
- ▶ Fully rated frequency converter (expensive, more losses)
- ▶ Better grid-fault ride-through capability
- ▶ No brushes ⇒ less maintenance
- ▶ Is the gearbox necessary?
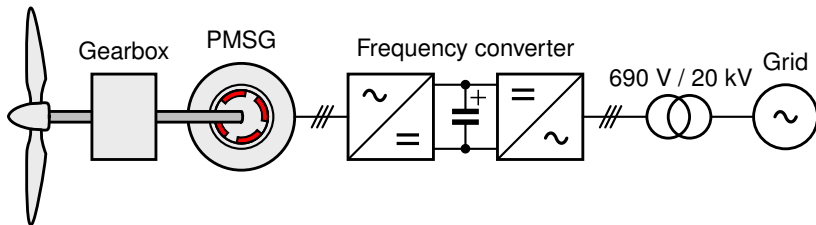
# 4-MW 690-V Frequency Converter

Grid-Side Converter Unit is Visible in the Figure



Auxiliary control
unit

Grid-side
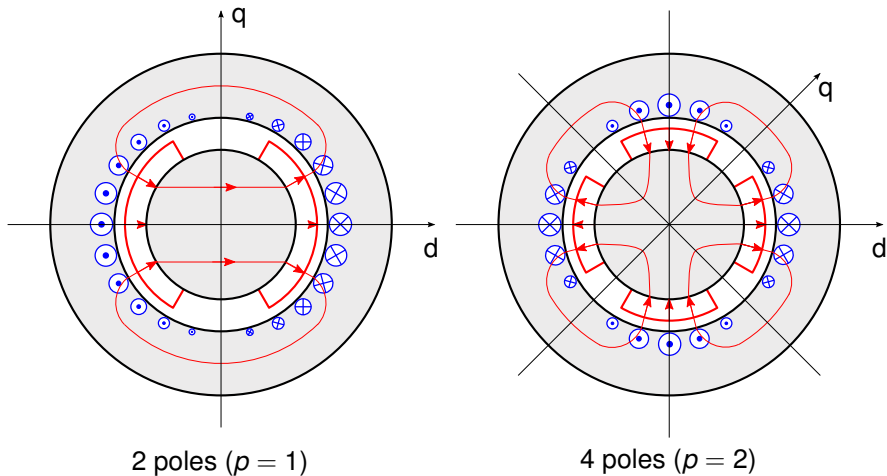filter unit

Grid-side converter unit
with power modules

Figure: ABB

# Conceptual PMSG: Operating Principle

- Three-phase stator winding
- Permanent magnets (e.g. NdFeB or SmCo) in the rotor
- Very high efficiency
- No magnetizing supply needed
- Equal (but opposite) reaction forces affect the rotor

# Number of Poles



2 poles ($p = 1$)

4 poles ($p = 2$)
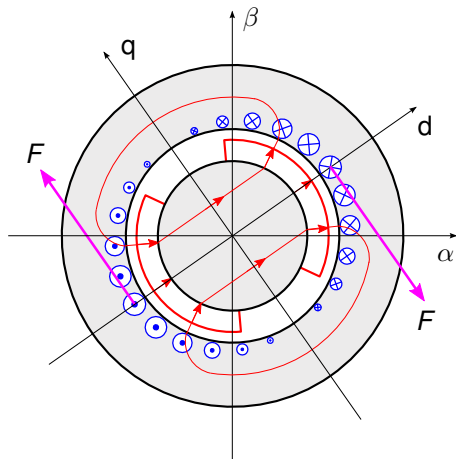
► Angular rotor speed $\Omega = \omega/p$, where $\omega$ is the angular supply frequency

# Generator Scaling

- Shear stress of active air-gap surface area

$$\tau = \frac{1}{2}\hat{B}_g\hat{A}_s \cos\gamma \qquad [\text{N/m}^2]$$

- Air-gap flux density $\hat{B}_g$ is limited due to saturation
- Stator current loading $\hat{A}_s$ is limited due to dissipation
- Generator size roughly proportional to the (rated) torque

$$T = r_r\left(2\pi r_r \ell\,\tau\right) = 2\tau\,V_r$$

since $V_r = \pi r_r^2 \ell$ is the rotor volume

- Price of the generator depends on its size and materials

# Generator Scaling: Effect of the Gear Ratio

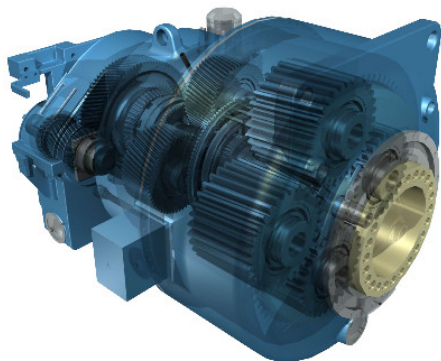- Rated mechanical power

$$P = T\Omega = 2\tau V_r \Omega$$

  where $\Omega$ is the generator speed

- Assumption: lossless gearbox

$$P = T_b \Omega_b = T\Omega$$

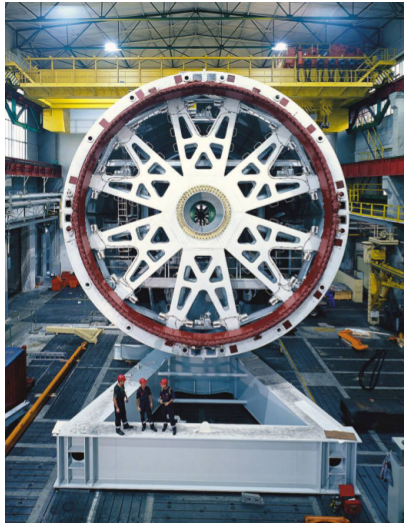- Generator size depends on the gear ratio $R = \Omega/\Omega_b$

$$T = T_b/R$$



Wind-turbine gearbox ($R = 78 \ldots 136$)

Figure: GE

# 4-MW 10-rpm Direct-Drive PMSG

Rated Speed Around 10 rpm, Very High Number of Poles



Figures: http://www.eal.ei.tum.de/fileadmin/tueieal/www/courses/EAGUA/lecture/2013-S/x_Handout_Alan_Jack_new_developments.pdf

# Future Concepts: Superconducting Direct-Drive Generators
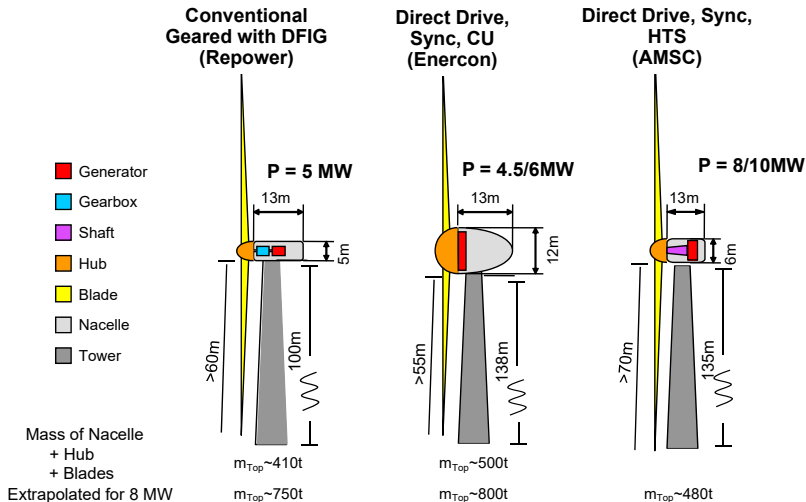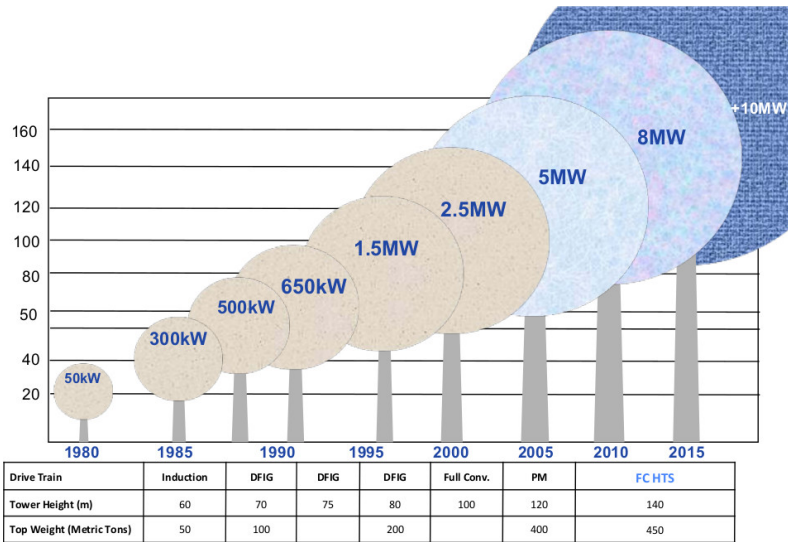
High Temperature Superconductor (HTS), Operated at 30...50 K
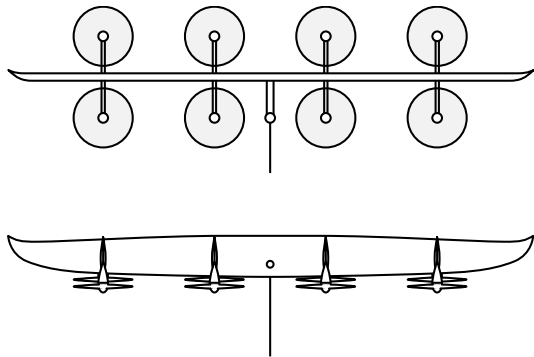


Figure (modified): D. McGahn, "Drivetrains: direct drive generators and high temperature superconductor based machines," MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

# Growth in Turbine Size



| Drive Train | Induction | DFIG | DFIG | DFIG | Full Conv. | PM | FC HTS |
|---|---|---|---|---|---|---|---|
| Tower Height (m) | 60 | 70 | 75 | 80 | 100 | 120 | 140 |
| Top Weight (Metric Tons) | 50 | 100 | | 200 | | 400 | 450 |

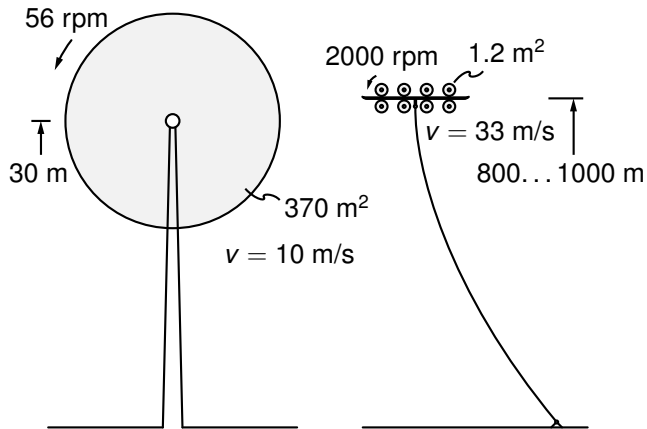Figure (modified): D. McGahn, "Drivetrains: direct drive generators and high temperature superconductor based machines," MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

# Airborne Wind Turbine: Power Kite by Joby Energy

# Size Comparison: 100-kW Conventional and Airborne Wind Turbines



Figures (modified): Kolar et al., "Conceptualization and multiobjective optimization of the electric system of an airborne wind turbine," *IEEE J. Emerg. Sel. Topics Power Electron., 2013*

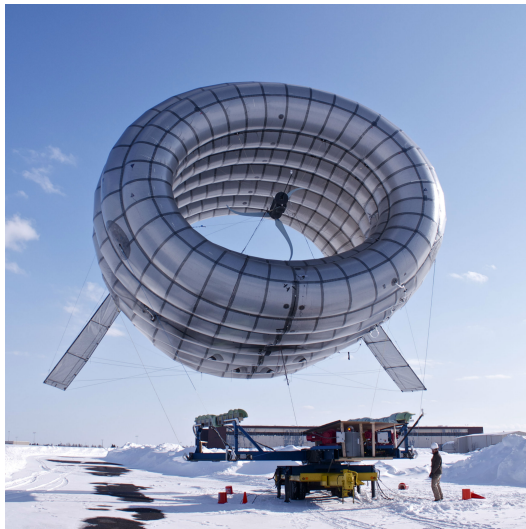# 30-kW Buoyant Airborne Turbine



Figure: http://www.altaerosenergies.com/

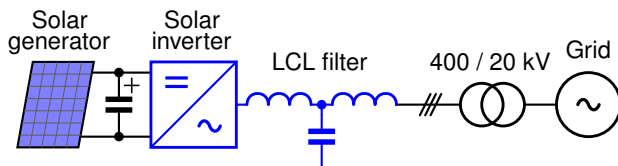# Outline

# Utility-Scale Solar

- ▶ Solar generator produces the DC voltage
- ▶ DC-bus voltage is adjusted for maximum power-point tracking (600. . . 850 V)
- ▶ Additional DC/DC converter between the generator and the inverter is often used in residential-scale solar (for better maximum power-point tracking)

# Utility-Scale Solar Plant

Finsterwalde I-III Solar Power Plant Cluster (Peak Capacity 83 MW)



Inverter stations

Figure: http://www.q-cells.com/consumer/power-plants/references.html

# 2-MW Inverter Station With Two 1-MW Central Inverters



Figure: ABB

# Central Inverter and Solar Generator
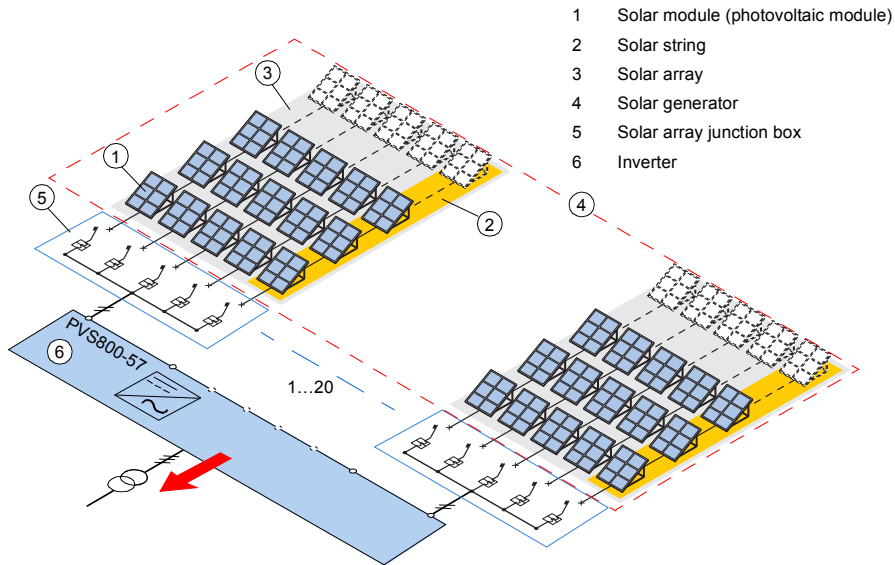


1    Solar module (photovoltaic module)
2    Solar string
3    Solar array
4    Solar generator
5    Solar array junction box
6    Inverter

Figure: ABB

# Outline

# Electrification Is a Key Trend
Just a Few Selected Examples Were Considered in This Lecture

- ▶ Electrified transport sector
- ▶ Renewable and distributed energy production
- ▶ Smart grids
  - ▶ DC grids (buildings, communities, HVDC)
  - ▶ Energy storages (batteries, pumped hydro)
  - ▶ Electricity, heat, transport, water, gas
- ▶ Energy and resource efficiency
  - ▶ Everywhere (from devices to systems)
  - ▶ Wide-bandgap power semiconductors (SiC, GaN)
  - ▶ Internet of things, industrial internet

# Concept of a DC Grid: Less Conversion Stages ⇒ Less Losses
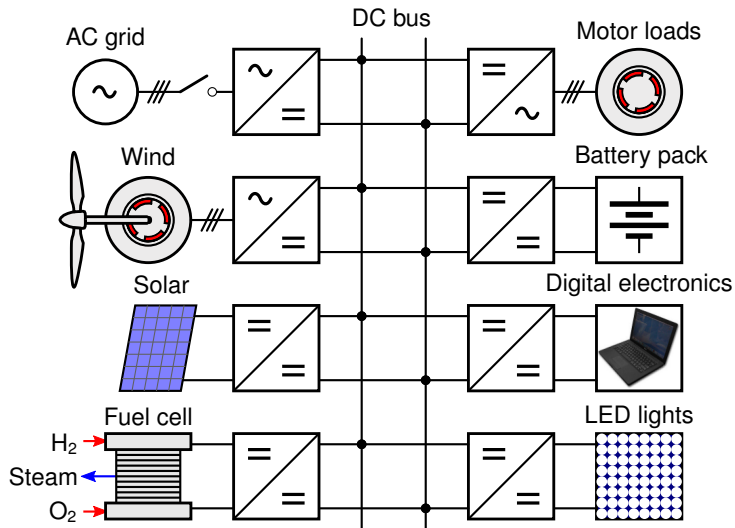
# Methods for Mitigating the Climate Change Problems

- ▶ Eliminate coal-fired power generation (or develop CCS)
- ▶ Increase nuclear power?
- ▶ Generation of environmentally clean energy
- ▶ Electrified (mass) transport
- ▶ Smart grids (efficient generation, transmission, distribution, and utilization of electricity)
- ▶ Preserve rain forests and promote forestation
- ▶ Control human and animal population?
- ▶ Simpler lifestyle (33% of energy in the world can be saved)