Aalto University
School of Electrical
Engineering

Introduction to Electric Energy Conversion and Renewable Energy Sources

ELEC-A8001 Johdatus sähköenergiajärjestelmiin

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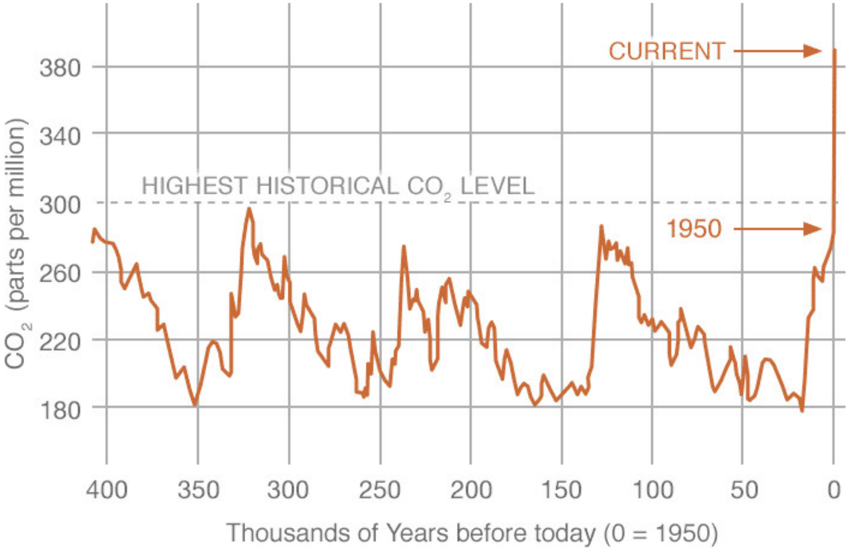
Slides: Marko Hinkkanen

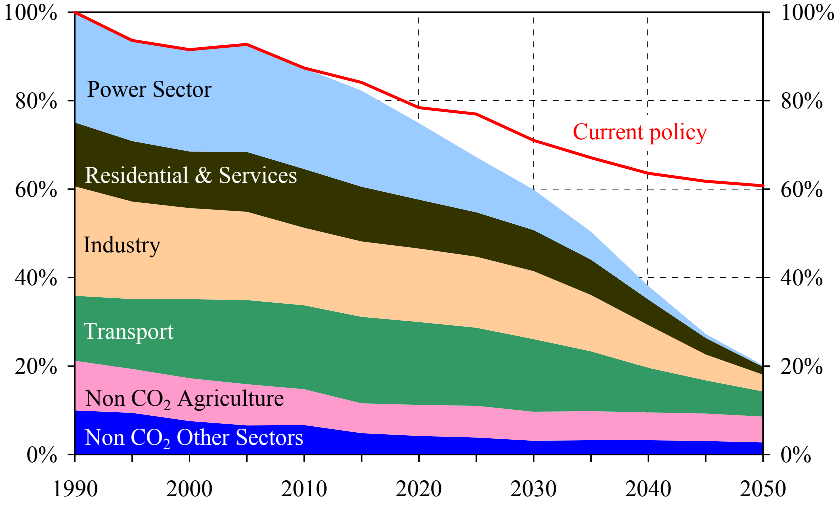
Autumn 2020



http://climate.nasa.gov

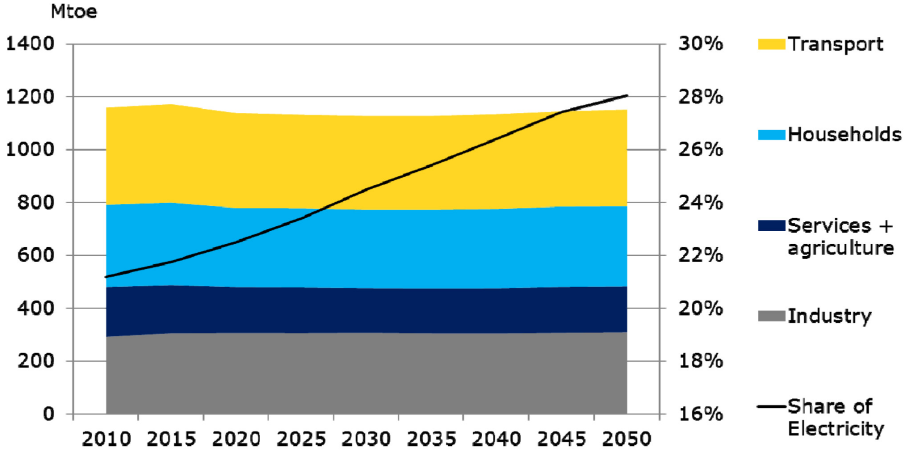
Outline

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

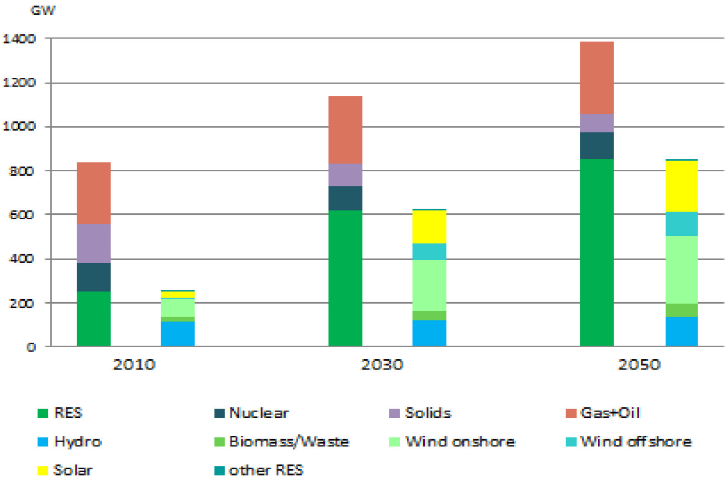
EU Final Energy Consumption by Sector and Share of Electricity



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

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

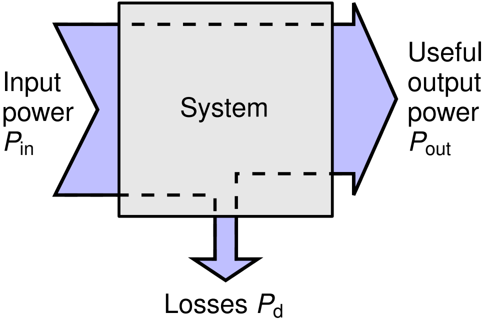
- Power balance

$$P_{\mathrm{in}} = P_{\mathrm{out}} + P_{\mathrm{d}}$$

- Conversion efficiency

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

  is between 0 and 1
- In steady state, $\eta = E_{\mathrm{out}}/E_{\mathrm{in}}$



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

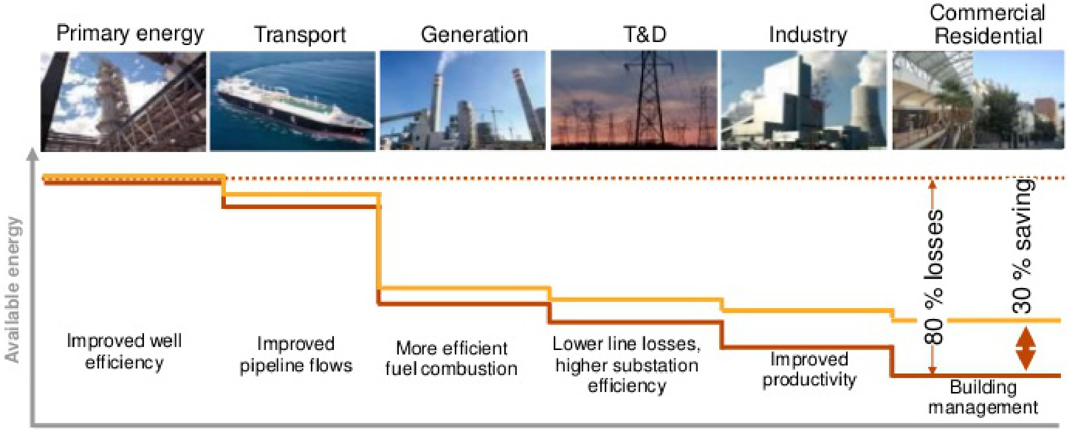
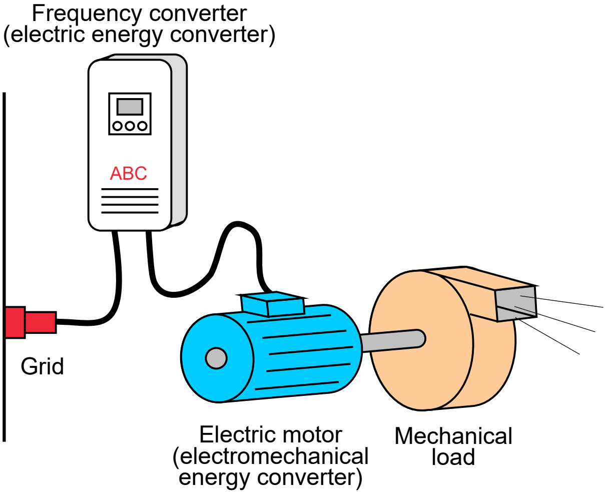


Figure: ABB

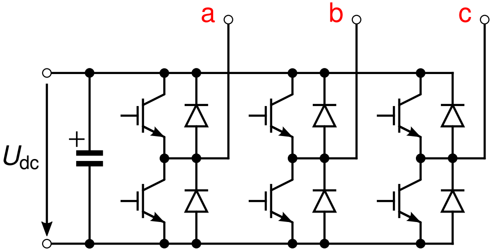
Outline

Electric Drive

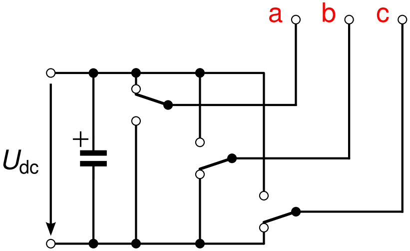
- Electric drive is a system, which converts electric energy into mechanical work
- Direction of the energy flow can also be opposite
- Energy flow can be controlled by means of an electric energy converter



Two-Level Converter



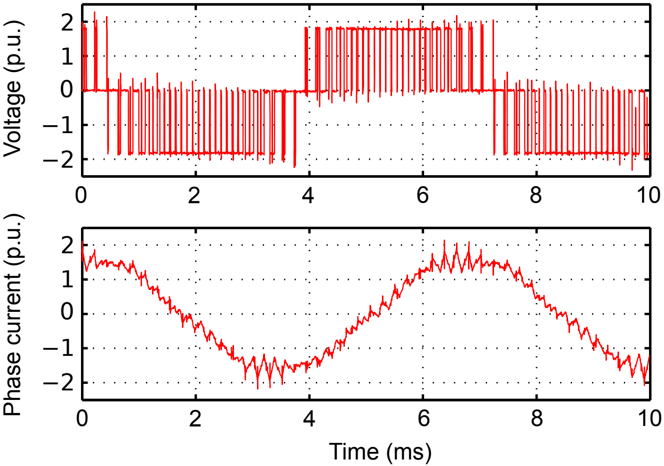
Main circuit



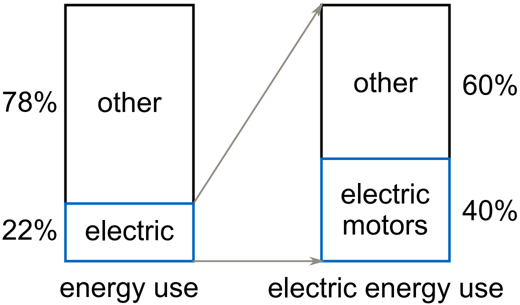
Equivalent circuit

- 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)

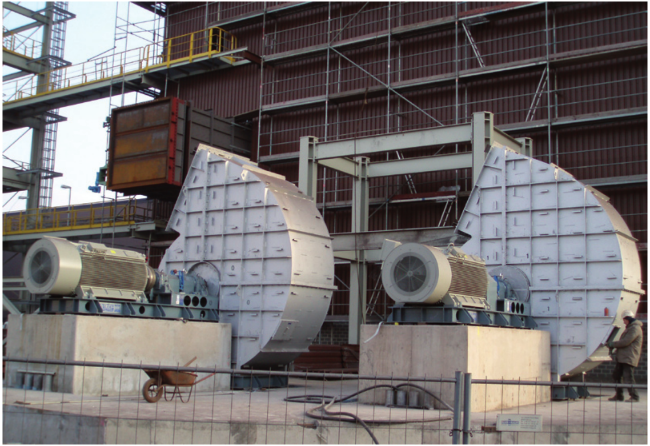
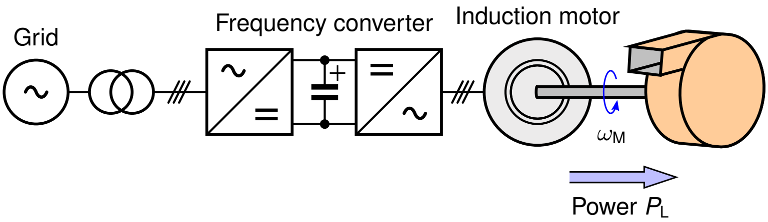
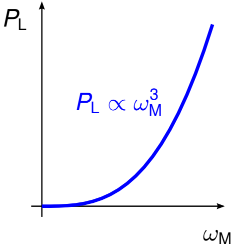


Figure: www.pollrichdlk.com

Pump and Fan Drives

- Fluid flow is controlled by adjusting the speed ω_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

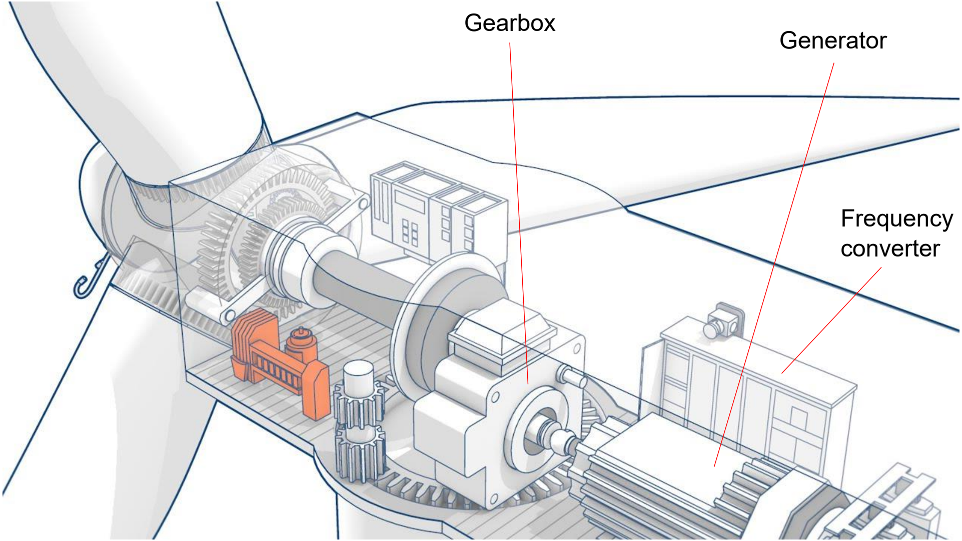
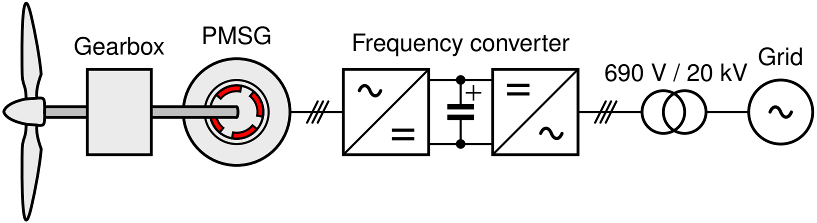


Figure: ABB (modified)

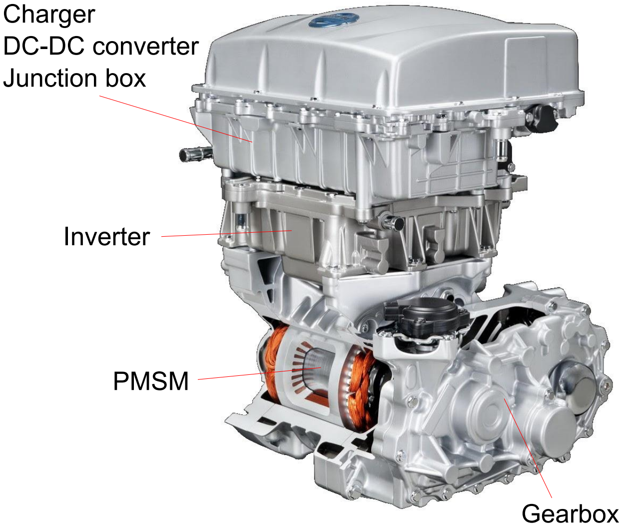
Wind Turbine: Permanent-Magnet Synchronous Generator

- 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

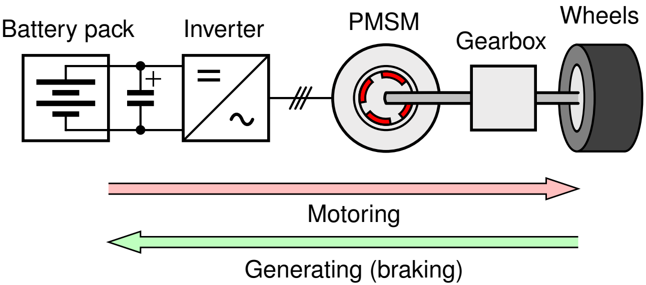
- Nissan Leaf (2014)
- Maximum power 80 kW
- Maximum torque 280 Nm
- Gear ratio 8:1
- Li-ion battery pack 24 kWh



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?

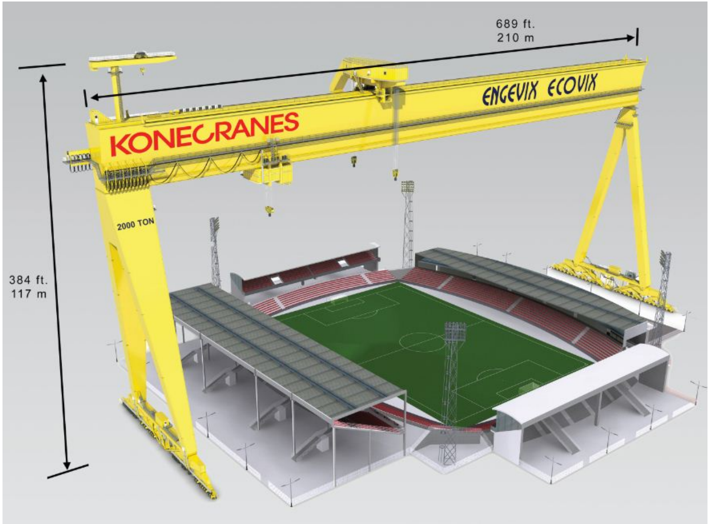


Figure: Konecranes

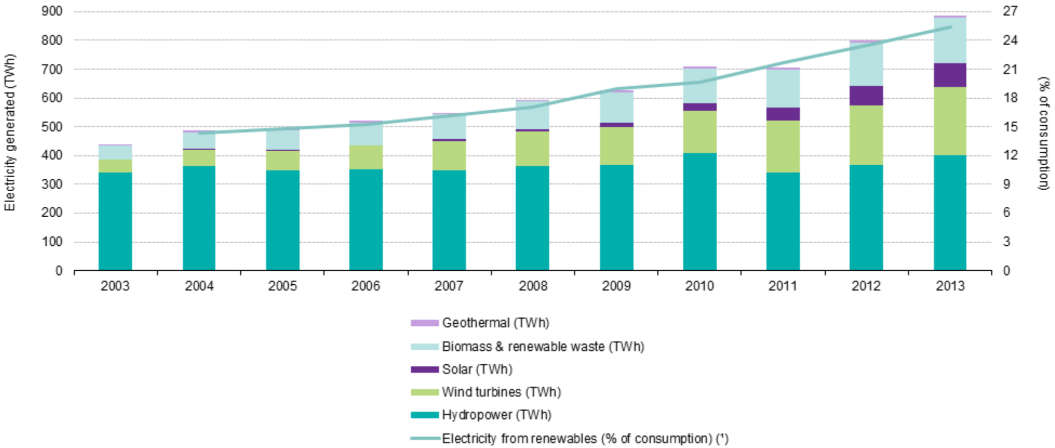
Why Controlled Electric Drives Are Needed?

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.)

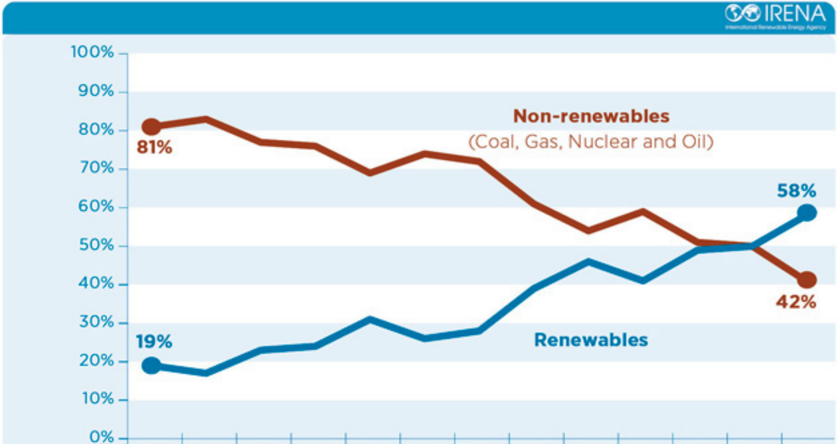
Outline

Electricity From Renewable Sources in EU



(¹) 2003: not available.
Source: Eurostat (online data codes: nrg_105a and tsdcc330)

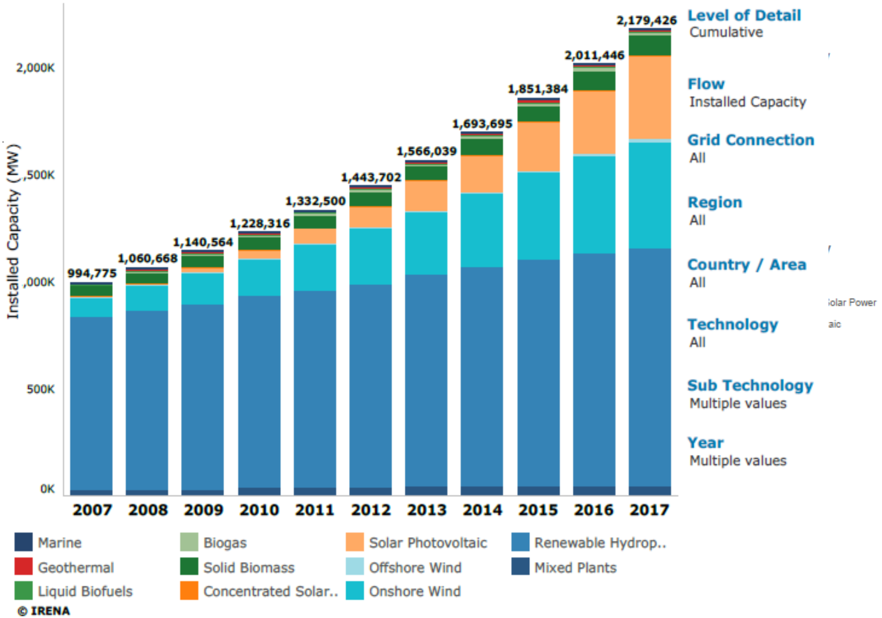
Renewables as a share of global capacity additions (2001-2013)

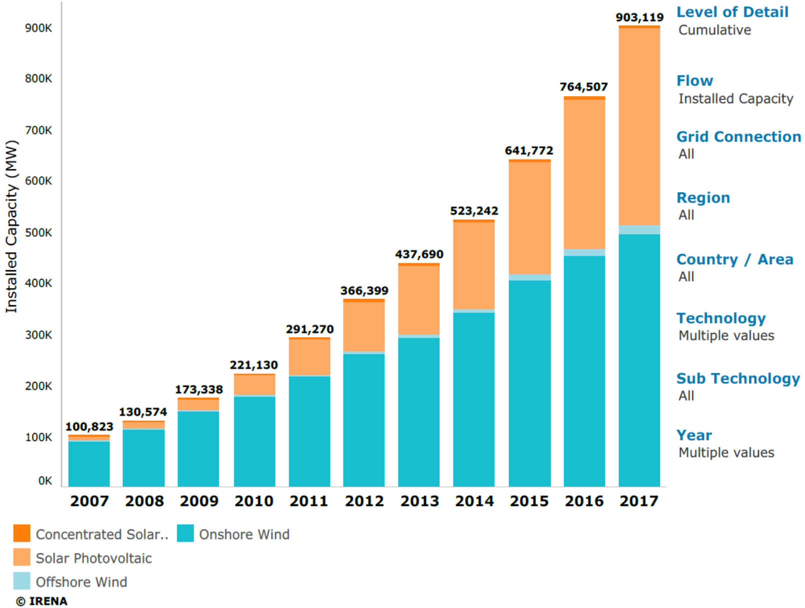


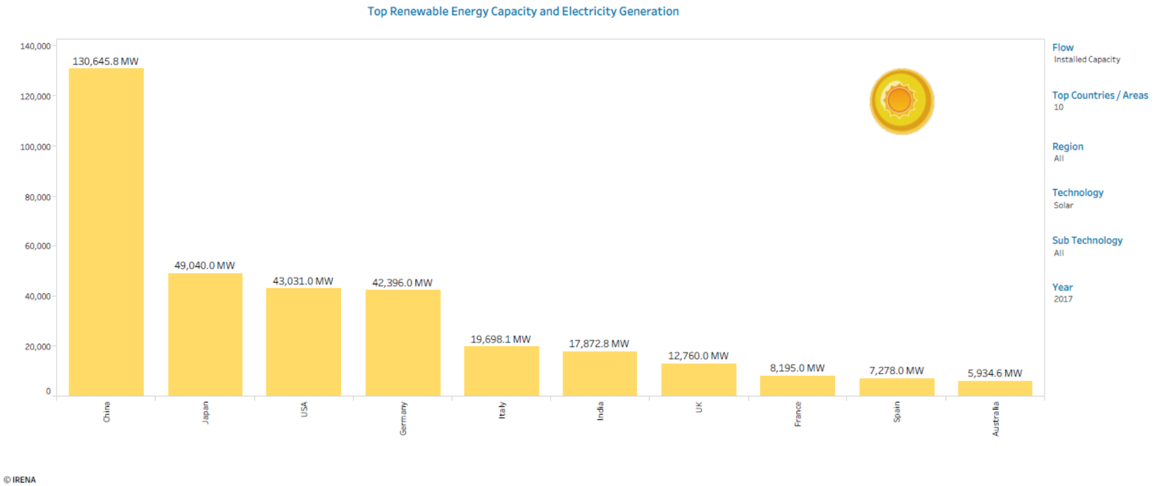
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Total net capacity added per year	**104**	**134**	**150**	**153**	**134**	**180**	**200**	**174**	**185**	**232**	**234**	**233**	**207**
Renewables	20	22	34	36	41	47	56	67	85	94	115	116	120
Non-renewables	84	111	116	116	93	133	145	107	100	138	118	117	87

Source: IRENA database

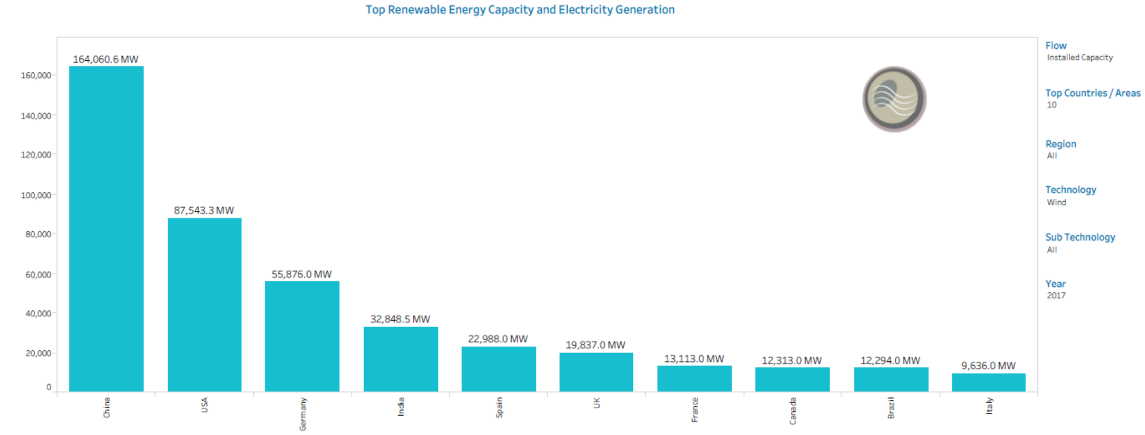
Trends in Renewable Energy (Installed Capacity)




Installed Capacity (MW)
900K
800K
700K
600K
500K
400K
300K
200K
100K
0K
100,823
130,574
173,338
221,130
291,270
366,399
437,690
523,242
641,772
764,507
903,119
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Level of Detail
Cumulative
Flow
Installed Capacity
Grid Connection
All
Region
All
Country / Area
All
Technology
Multiple values
Sub Technology
All
Year
Multiple values
Concentrated Solar..
Onshore Wind
Solar Photovoltaic
Offshore Wind
© IRENA

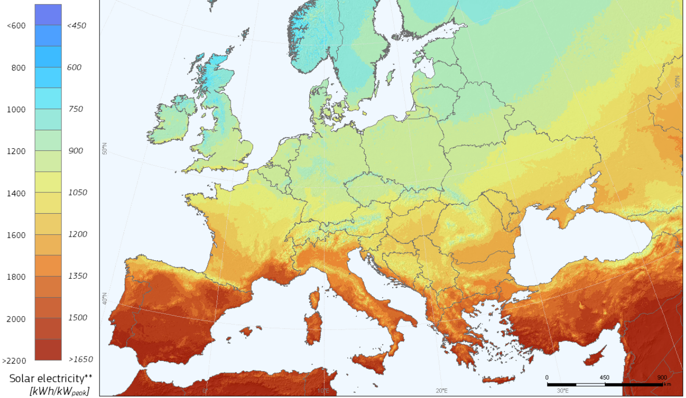


Top Renewable Energy Capacity and Electricity Generation
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
130,645.8 MW
49,040.0 MW
43,031.0 MW
42,396.0 MW
19,698.1 MW
17,872.8 MW
12,760.0 MW
8,195.0 MW
7,278.0 MW
5,934.6 MW
China
Japan
USA
Germany
Italy
India
UK
France
Spain
Australia
Flow
Installed Capacity
Top Countries / Areas
10
Region
All
Technology
Solar
Sub Technology
All
Year
2017
© IRENA


Top Renewable Energy Capacity and Electricity Generation
164,060.6 MW
87,543.3 MW
55,876.0 MW
32,848.5 MW
22,988.0 MW
19,837.0 MW
13,113.0 MW
12,313.0 MW
12,294.0 MW
9,636.0 MW
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
China
USA
Germany
India
Spain
UK
France
Canada
Brazil
Italy
Flow
Installed Capacity
Top Countries / Areas
10
Region
All
Technology
Wind
Sub Technology
All
Year
2017

Photovoltaic Solar Electricity Potential in European Countries

Global irradiation*
[kWh/m²]



Solar electricity**
[kWh/kWpeak]

* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

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

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*

Outline

Power From the Wind

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

$$E_\mathrm{w} = \frac{1}{2} \underbrace{\rho A v_\mathrm{w} t}_{m} v_\mathrm{w}^2 \quad \Rightarrow \quad P_\mathrm{w} = \frac{1}{2} \rho A v_\mathrm{w}^3$$

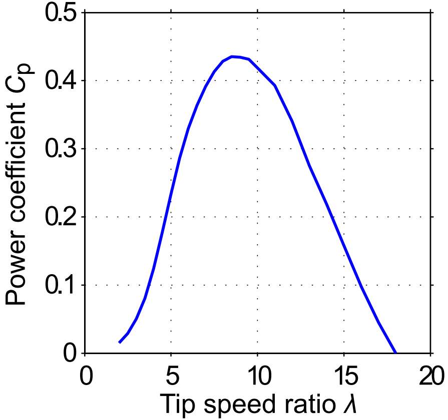
  where ρ is the air density and v_w is the wind speed
- Power extracted by the turbine

$$P = C_\mathrm{p} \cdot \frac{1}{2} \rho A_\mathrm{b} v_\mathrm{w}^3$$

  where $A_\mathrm{b} = \pi r_\mathrm{b}^2$ 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 Ω_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

Figure (modified): Petersson, "Analysis, modeling and control of doubly-fed induction generators for wind turbines," Ph.D. dissertation, KTH, Stockholm, Sweden, 2005

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

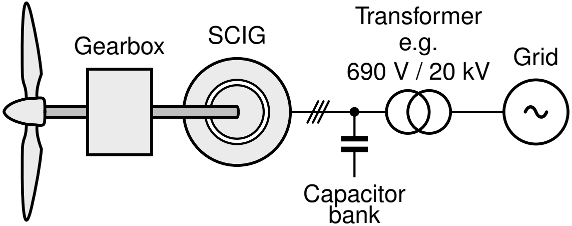
$$T_\mathrm{b} = \frac{P}{\Omega_\mathrm{b}} = \frac{r_\mathrm{b}P}{v_\mathrm{b}} = \left(\frac{2}{C_\mathrm{p}\rho\pi v_\mathrm{w}^3 v_\mathrm{b}^2}\right)^{\frac{1}{2}} P^{\frac{3}{2}}$$

- 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

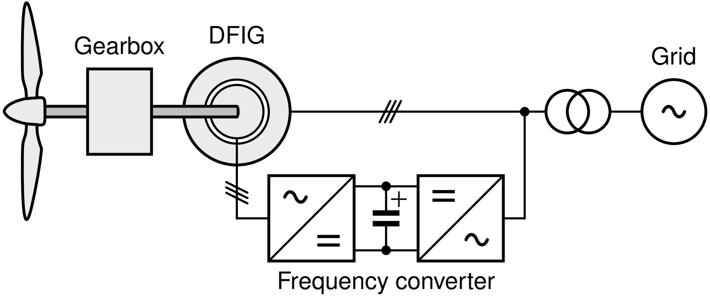
Squirrel-Cage Induction Generator (SCIG)

- 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



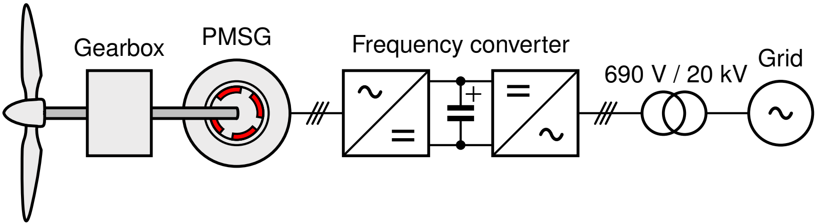
Doubly-Fed Induction Generator (DFIG)

- 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



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 $\Rightarrow$ less maintenance
- Is the gearbox necessary?



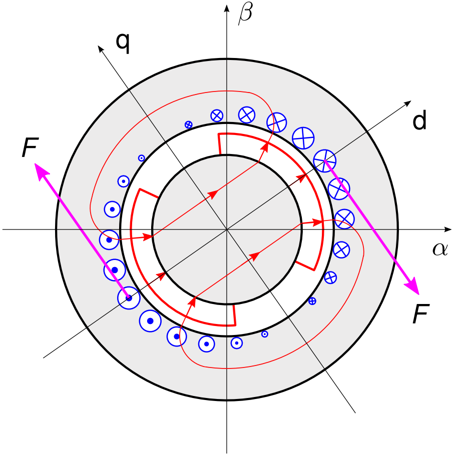
4-MW 690-V Frequency Converter

Grid-Side Converter Unit is Visible in the Figure

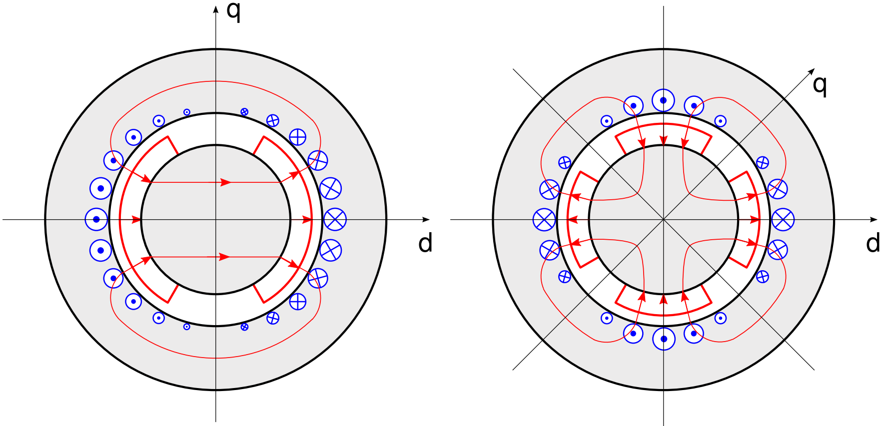
Figure: ABB

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 ω is the angular supply frequency

Generator Scaling

- Shear stress of active air-gap surface area

$$\tau = \frac{1}{2}\hat{B}_{\mathrm{g}}\hat{A}_{\mathrm{s}}\cos\gamma \qquad [\mathrm{N/m^2}]$$

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

$$T = r_{\mathrm{r}}\,(2\pi r_{\mathrm{r}}\ell\,\tau) = 2\tau V_{\mathrm{r}}$$

  since $V_{\mathrm{r}} = \pi r_{\mathrm{r}}^2\ell$ is the rotor volume
- Price of the generator depends on its size and materials

Generator Scaling: Effect of the Gear Ratio

- Rated mechanical power

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

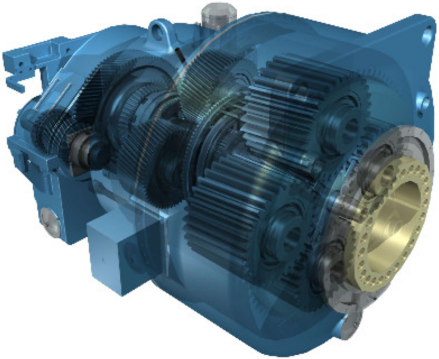
where Ω is the generator speed

- Assumption: lossless gearbox

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

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

$$T = T_b/R$$

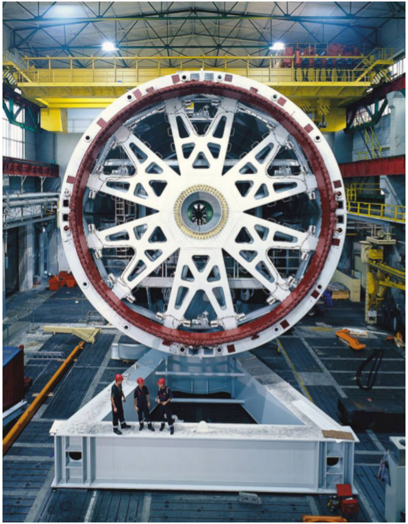


Wind-turbine gearbox ($R = 78 \ldots 136$)

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

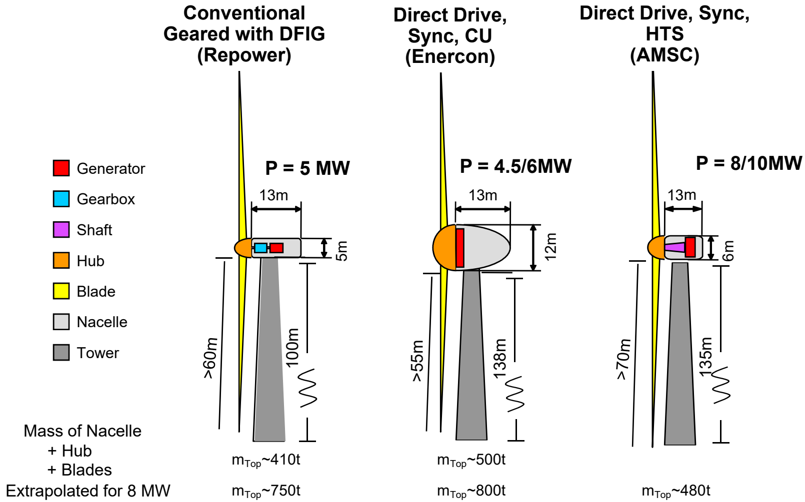
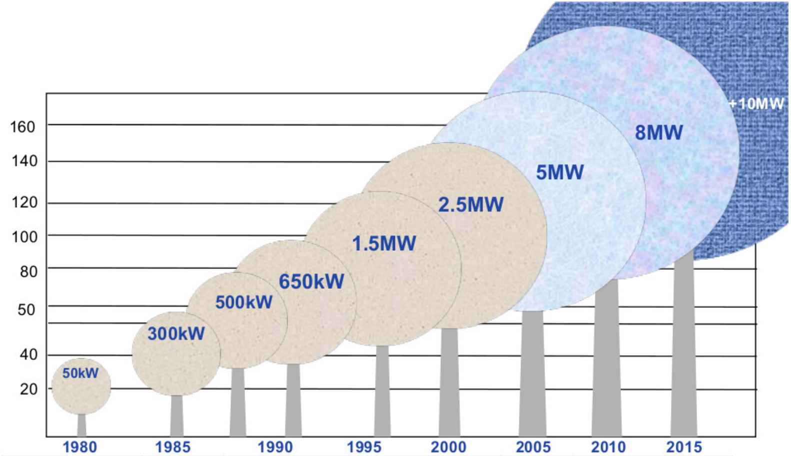


Figure (modified): D. McGahn, "Drivetrains: direct drive generators and high temperature superconductor based machines," MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

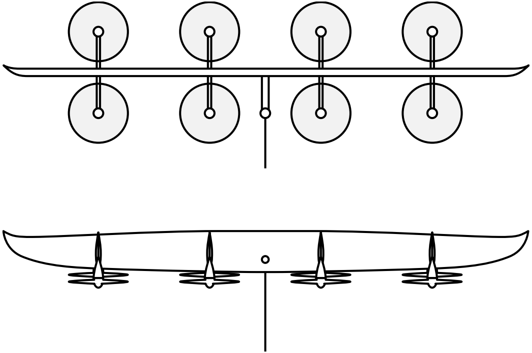
Growth in Turbine Size



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

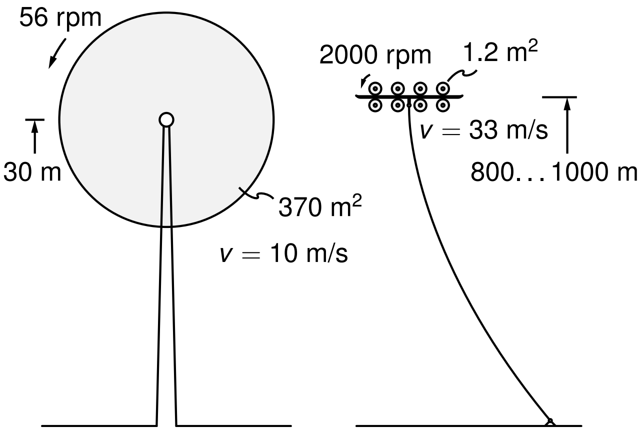
Figure (modified): D. McGahn, “Drivetrains: direct drive generators and high temperature superconductor based machines,” MIT Windweek, 2009, http://web.mit.edu/windenergy/windweek/Presentations/P7%20-%20McGahn.pdf

Airborne Wind Turbine: Power Kite by Joby Energy



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

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*

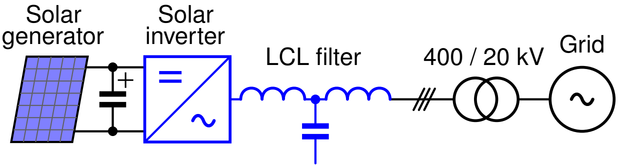
30-kW Buoyant Airborne Turbine

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

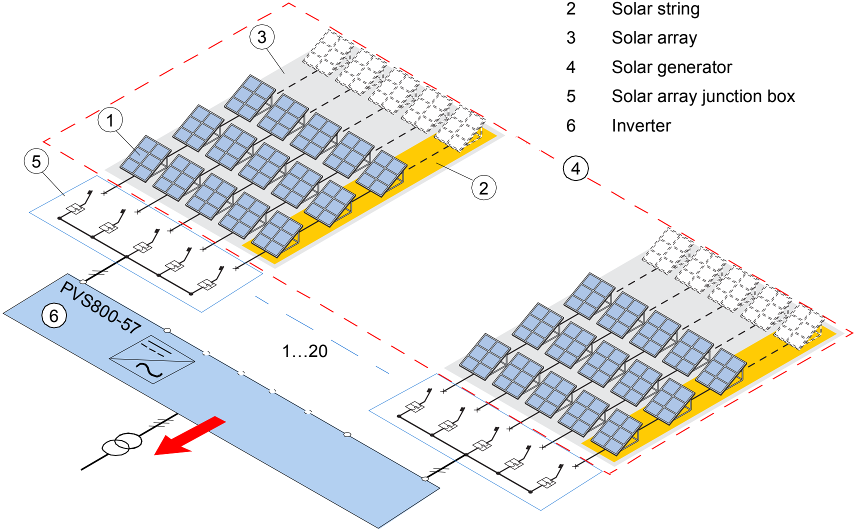
Finsterwalde I-III Solar Power Plant Cluster (Peak Capacity 83 MW)

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

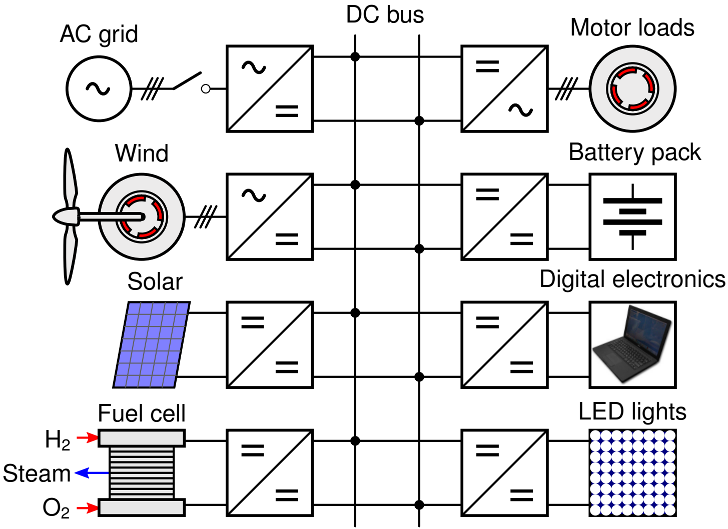
Outline

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)

Source: Bose, "Global energy scenario and impact of power electronics in 21st century," *IEEE Trans. Ind. Electron.*, 2013