

ET3035TU Sustainable Electrical Power Engineering

January 2011 – Carsten Broich



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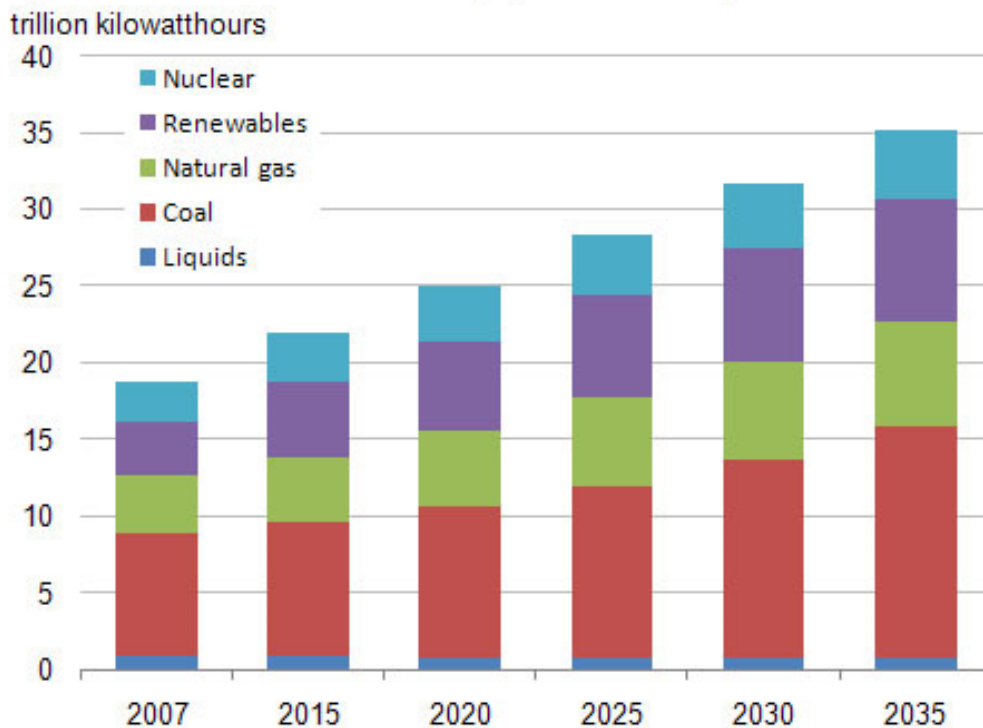
Emerging technologies in future power system

The goal of the first chapter is to know some figures about the world electricity production, changing paradigms, to get a feeling about challenges, vision of the 2020 Cigre report and science and technology priorities.

World electricity production

The us energy information administration had an international outlook from 2010:

Figure 6. World net electricity generation by fuel

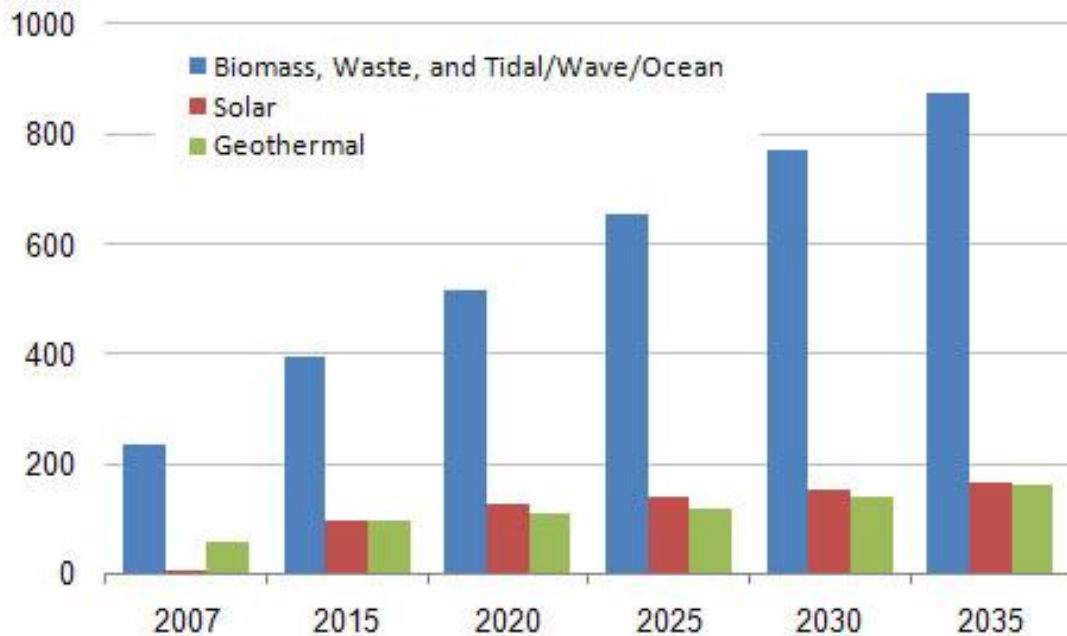


From the it can be seen that the world net electricity generation increases by 87 percent in the Reference case, from 18.8 trillion kilowatthours in 2007 to 25.0 trillion kilowatthours in 2020 and 35.2 trillion kilowatthours in 2035.

Furthermore it gives an indication about the various energy forms that are used:

Figure 7. World renewable electricity generation by energy source, excluding wind and hydropower

billion kilowatthours



From 2007 to 2035, world renewable energy use for electricity generation grows by an average of 3.0 percent per year (Figure 6), and the renewable share of world electricity generation increases from 18 percent in 2007 to 23 percent in 2035.

Also there are still 16 % of the earths population without access to electricity in 2030.

Changing paradigms

The main drivers for the change are:

1. Environmental pressures
2. Customer pressures
3. Financial pressures
4. Technology developments

As an example for the changing paradigms one can see that during the early electrification age there was first an engineering idea, then it was put into reality to check its economic potential and lastly the environment was considered. Later one considered first the economic situation then though about the environment and lastly the engineering point is regarded. In the future one will first consider the environmental aspect, check for its economics and lastly put it into reality through engineering.

As a comparison of the “old” and “new” economies of the world one can investigate different aspects:

| | Old economies | New economies |
|-------------|---|-----------------------------|
| Finance | Moderate growth Quality / price rate | Fast growth |
| Customer | Environmental concerns | Increased power demands |
| Tech policy | Asset management Aged infrastructure | Building new infrastructure |

As a result of that the “old” economies will have to replace their existing infrastructure (eg. Electricity network)

The trends for that can be summarized:

- Intelligence in hybrid Networks 2020 → Smart Grid
- Automatic decentralized functionalities in networks 2050
- Existing infrastructure replacement wave
- New Technologies: reliability & environment requirements
- Integration of utilities, e.g. GIL tunnel through urbanised areas

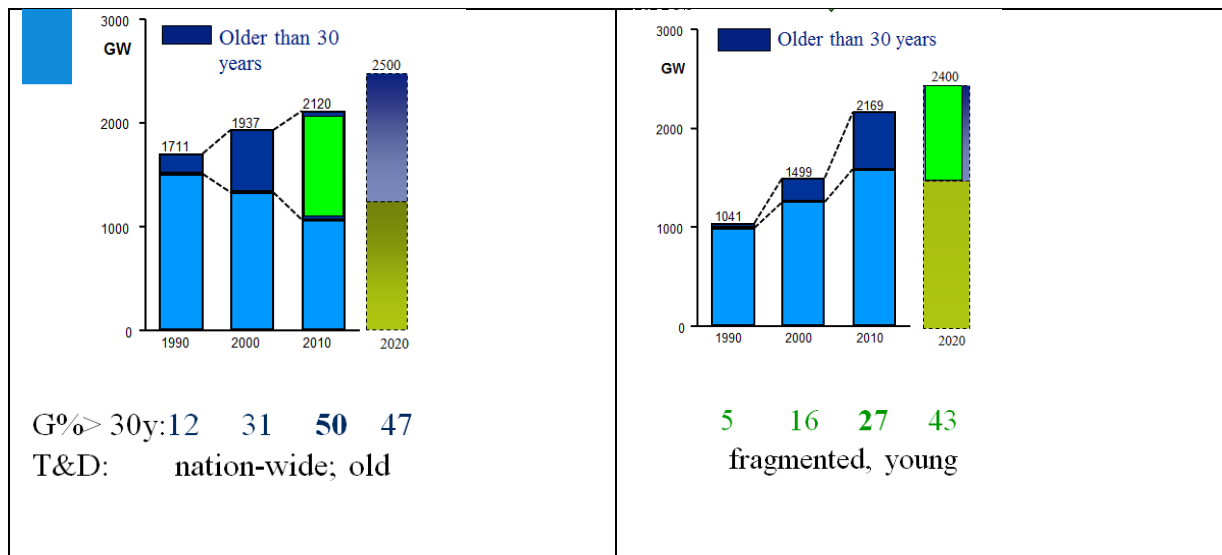
The new network will have a greater efficiency leading to higher profitability, availability, reliability, revenue and customer satisfaction.

Cigre vision on electric power systems 2020

CIGRE (International Council on Large Electric Systems) is one of the leading worldwide Organizations on Electric Power Systems, covering their technical, economic, environmental, organizational and regulatory aspects.

More specifically, issues related to planning and operation of power systems, as well as design, construction, maintenance and disposal of HV equipment and plants are at the core of CIGRE's mission. Problems related to protection of power systems, telecontrol, telecommunication equipment and information systems are also part of CIGRE's area of concern.

The figures below show on the left the OECD countries and on the right the developing countries. The green area shows when there will be a need for upgrading the infrastructure since it is older than 30 years.



There are several reasons why the traditional technologies are not appropriate anymore for current usage:

- Do not meet current environmental pressures
- Cannot readily meet customer pressures
- Are no longer the most appropriate solutions for developing countries
- Have long term paybacks which do not meet current financial restraints
- Do not allow for innovative solutions

The new electricity production technologies consist of:

- Development of gas infrastructures
- Application of gas fired generation closer to loads
- Combined heat and power
- Embedded generation
- Development of microturbines
- Advancement of fuel cell technologies
- Development of renewable sources
- Development of energy storage technologies
- Development of photovoltaic technologies
- Nuclear generation?

When setting up scenarios about an electric power system in 2020 there are two options. The first option is the distribution scenario which consists of a mainly centralized generation:

Generation → Transmission → Distribution → End use

The second option is a mixdistribution scenario which consists of various sub transmission and distribution levels.

Also there will be a big change in terms of **electrical delivery technologies**: For transmission systems it means that there will be a reduced use of fossil fuelled generation units but a generation closer to

loads (solar panels wind etc). This also means rapid changing load patterns due to the development of large renewable sites. Therefore the transmission system needs to be adaptable.

For a technological point of view it means that a **user centric approach** is needed (smart grid). Furthermore to enable secure and sustainable solutions integration of utility infrastructures and supergrids are needed. For the next decades a detailed asset management needs to be done in order to determine the efficient investments, sustainable utilization and precise removal to have an effective hybrid network consisting of old and new technologies.

Another aspect that needs to be discussed is **energy conservation** which refers to the preservation of fossil energy sources (oil and gas). For that restrictions need to be imposed. Also it needs to be pointed out that we are trying to conserve raw materials and the environment. Saving of energy will only assist but will not be part of energy conservation.

From a material point of view it will require a greater cooperation between technology equipment and material developers, identification of idealized material requirement for new technologies and a decrease of development periods. The following aspects for material developments need to be considered:

- High temperature superconducting compounds
- Polymers
- Ceramics
- Semiconductors
- Liquid insulation
- Gas insulation etc

The new material technologies are needed to cope with customer reliance on power, to meet environmental pressures, to comply with decentralization trends, to enable innovative solutions and to develop energy storage technologies.

From an end customers point of view one can state for the developing countries that there need to be supplies for remote villages, hospitals, schools, industries and communication. Therefore technologies like microturbines, fuel cells, solar / wind energy and biomass need to be established.

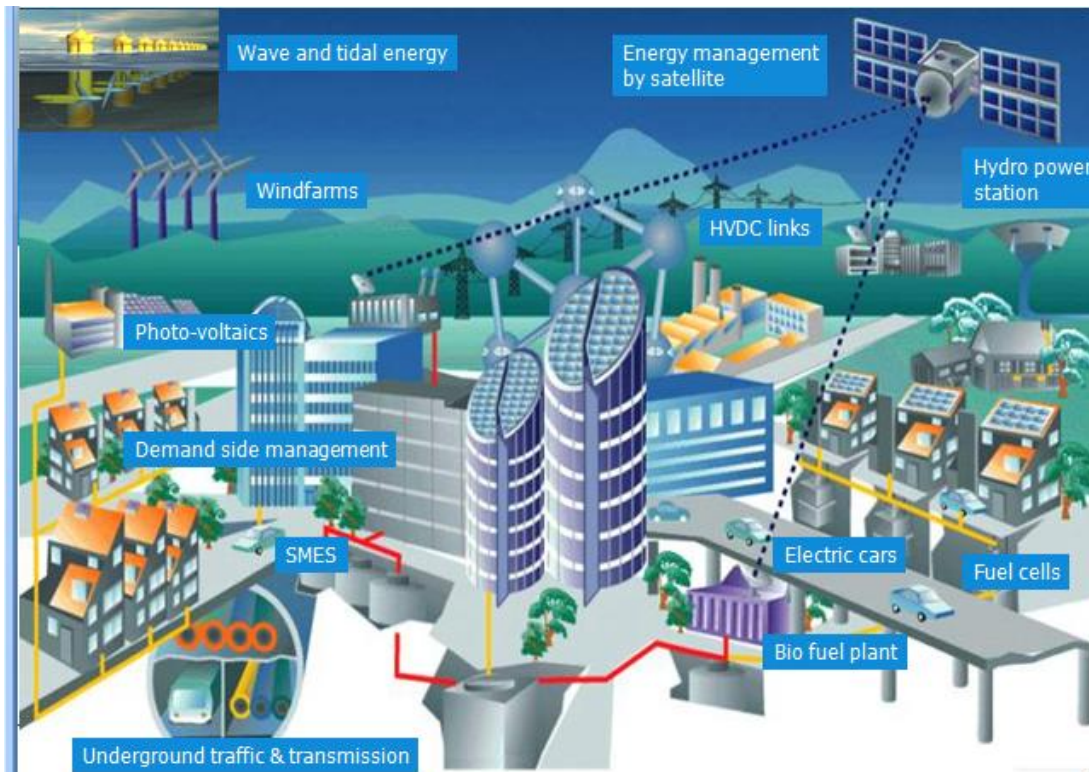
For the developed countries a continuous and high quality supply needs to be ensured and furthermore environmentally friendly supply while holding reasonable costs.

In order to reach all those goals a coordination of R&D needs to be established. This requires a rethink to coordinate efforts and reduce development times. Fundings can be done by regulatory policies, corporate investment, state sponsored and through venture capitalists. Furthermore education is needed in order to increase the knowledge.

Science and technology direction

European Technology Platform:

A “Smart Grid” is an electricity network that can intelligently integrate the behavior and actions of all users connected to it –generators, consumers and those that do both –in order to efficiently deliver sustainable, economic and secure electricity supplies.



To enable all this projects like DESERTEC need to be set up:

- DESERTEC aims to harness the largest source of energy on earth: solar power from deserts
- More than 90% of the world's population live within 3,000 km of a desert and may receive clean power from there

Roadmap 2050: The mission of Roadmap 2050 is to provide a practical, independent and objective analysis of pathways to achieve a low-carbon economy in Europe, in line with the energy security, environmental and economic goals of the European Union. The Roadmap 2050 project is an initiative of the European Climate Foundation (ECF) and has been developed by a consortium of experts funded by the ECF

Conclusion

A challenging time faces us over the next decades R&D should reverse to 80% on sustainable technology heading for complete solutions incorporating environmental and social concerns

Primary sources potential and electromechanical conversion

This chapter will give an overview about various conventional and renewable sources of energy followed by an overview about electromechanical conversions which start with the basics, then talk about generator systems and lastly deals with the size and efficiency of those systems.

Sources of energy

Within the Netherlands roughly 100GW is used per year, however on 15 % from that is electrical energy. This chapter will deal with the electric energy only.

Conventional

When considering conventional sources of energy one can list the following:

- Coal (200 years)
- Oil (50 years)
- Gas (100 years)
- Nuclear fission (100 year)

One can see that those sources will not last forever, rather they will be completely exploited within the next 50 – 200 years. This means that it is needed to find new sustainable sources. This also means that less CO₂ is used and lastly when using sustainable sources, it often comes directly or indirectly from the sun which means that it is abundantly available.

Renewable

Renewable sources can be listed as follows:

- Wind energy
- Hydro power (rivers)
- Tidal
- Ocean currents
- Ocean wave energy
- Geothermal
- Solar - thermal
- Solar - chemical (to hydrogen)
- Photovoltaic (solar – electrical)
- Blue energy (salinity gradient)
- Biomass
- Nuclear fusion

Wind energy

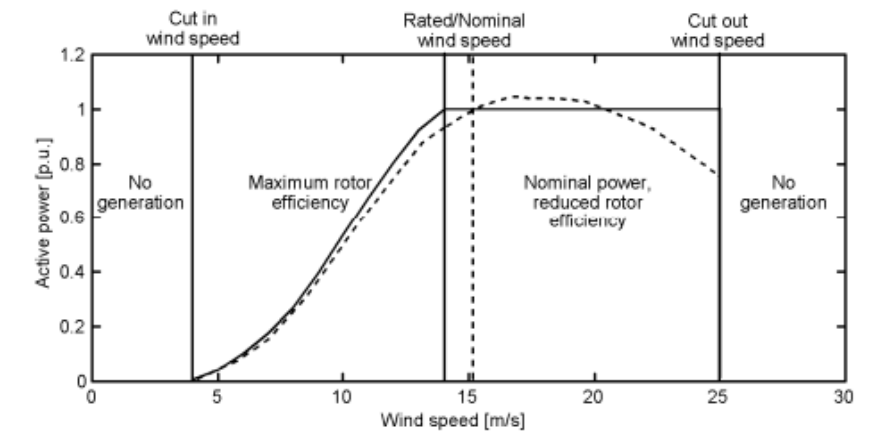
Lets have a look at the market developments and basic relation and requirements for wind energy. During the last years small wind turbines came into existence because they give a “green image” and they can be used for developing countries. For large turbines they developed from 30 kW and 15 m rotor diameter in 1980 to 6000kW and 125 m rotor diameter by 2008. The market for wind energy grows by roughly 30% per year and within the EU there is a plan to install 6 GW offshore in the Netherlands and 15GW offshore for the UK.

The wind power station consists of project developers, offshore companies and wind turbine manufactures. They sell the energy rather than the turbines. Huge efforts are placed in offshore infrastructure and placing it offshore. Wind turbines are used which consist of track record, proven technology and guaranteed performance which means for the wind turbine industry that there are technical evolutions instead of revolutions.

For the basic relation for wind energy one can start with the power coefficient C_p given by:

$$P = \frac{1}{2} \rho_{air} C_p A_r v_w^3 = \frac{1}{2} \rho_{air} C_p (\lambda, \theta) \pi r^2 v_w^3$$

Another important characteristic for wind energy are the power curves which determine how much active power can be drawn for a specific wind speed. Above rated wind speed the power has to be limited by pitching the blades or stall effect to prevent damage to the turbine.



The rated wind speed is limited because of noise production by blade tip speed v_{rated}

$$N_{rated} = \frac{60}{2\pi} \frac{v_{rated}}{r_r} \propto \frac{1}{\sqrt{P_{rated}}}$$

r_r : rotor radius

P_{rated} : rated power

For offshore platforms there are different conditions than onshore. There is an aggressive environments which means enclosed equipment and conditioned air. A strong focus needs to be on reliability and maintenance. Condition based maintenance and control are also necessary.

Hydro and tidal power / ocean currents

Hydropower is a combination of a river and a dam. Mostly it is used in large scale (up to 50 GW) and consists of a reservoir with a constant speed generator. Hydropower can also be used without a dam for example in rovers or in the sea using currents. For that a variable speed is used for optimum performance.

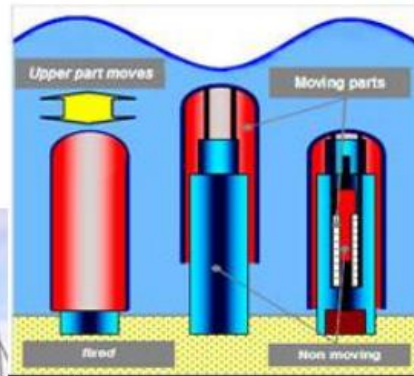
Ocean wave energy

Ocean wave energy has a potential of 290 GW in western Europe and 1 TW worldwide. To harvest that energy there are various systems. One can classify those in:

- Position: shoreline / near shore / off shore
- Power take off system: air turbine / water turbines / hydraulic systems / direct drive
- Principle: oscillating water column / overtopping / hinged contoured/ buoyant moored device

As an example for ocean wave energy is the **Archimedes Wave Swing (AWS)**:

Archimedes Wave Swing (AWS)



Air filled cylinder works as air spring:
 -Wave crest pushes floater down
 -Wave trough: air pressure pushes floater up

It uses a linear permanent magnet generator. Due to the pulsing nature the power quality is rather low.

Geothermal

Geothermal energy is directly used for heating. It uses steam turbines for electricity generation.

Solar

Solar energy can be used for water heating, steam production for electricity generation and photovoltaic systems.

Electromechanical conversions

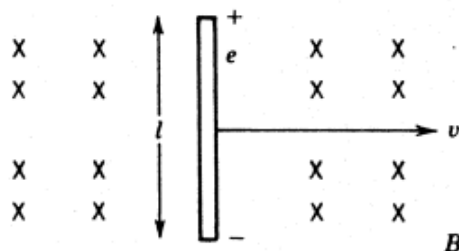
Principles

Induced Voltage e

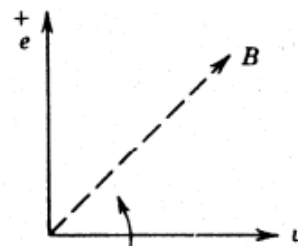
$$e = Blv$$

$$p = ei = Blvi$$

e : voltage
 B : magnetic flux density
 l : length of the conductor
 v : speed of the conductor
 p : converted power
 i : current



X indicates B into the paper

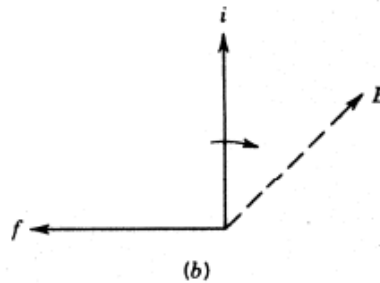
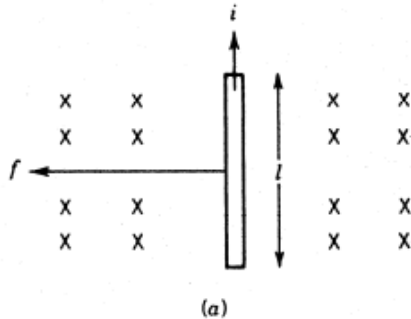


Lorenz Force

$$F = Bli$$

$$p = Fv = Bliv$$

F : force
 B : magnetic flux density
 l : length of the conductor
 v : speed of the conductor
 p : converted power
 i : current



Generator types

Synchronous generators with electrical excitation

Synchronous generators consist of a rotor and stator. They have a magnetic circuit and teeth. The electro magnets produce a magnetic field. When it rotates a voltage is induced in the windings. When a current flows in the windings there is a force (torque).

For maximum power at a given maximum current, the currents should be in phase with the no load voltage

The advantages of electrical excitation are a controllable field, with high speed and low wind speed and there is no risk of demagnetization. .

Permanent magnet generators

The advantages of PM excitation is a higher efficiency, significant reduction in mass of active materials and cheaper.

Induction generators

Generator construction

Geared or direct drive

For generator system with gearboxes the advantage is the the generator will be cheaper, however extra maintenance is required. For direct drive generators it is reversed.

Linear generators

Linear generators such as used for the AWS have no gears but are rather expensive.

Generator system types

Generator systems

Nearly constant speed (CS)

- Squirrel cage induction generator

Partial variable speed with gear (DFIG)

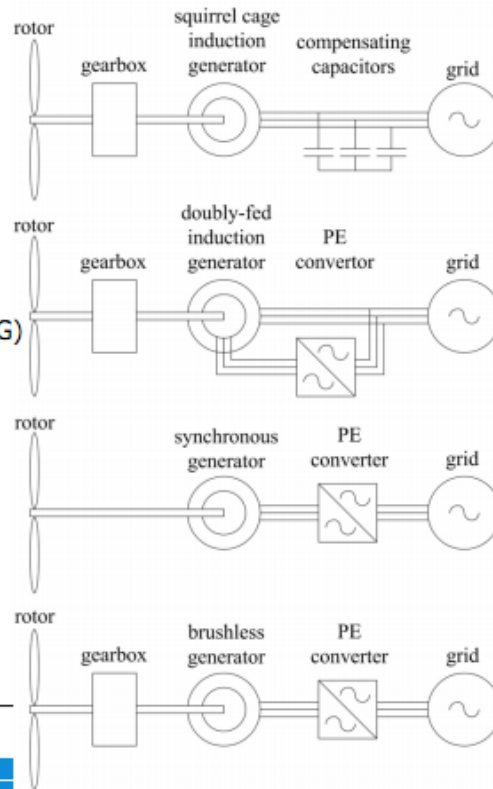
- Doubly-fed induction generator (DFIG)
- Partly rated converter

Full variable speed direct drive (DD)

- Synchronous generator
- Fully rated converter

Full variable speed with gear (GFC)

- Brushless generator
- Fully rated converter



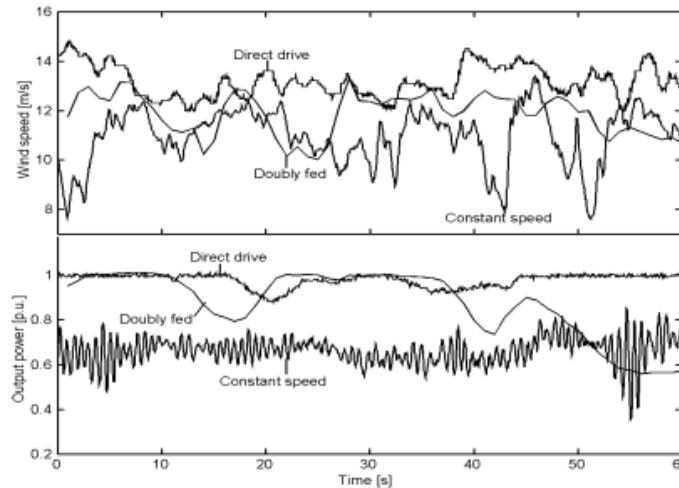
Comparison of generator systems

| | | CS | DFIG | DD | GFC |
|-----------------------------|-------------------|----|------|----|-----|
| Cost, size and weight | | + | 0 | - | 0 |
| 50/60 Hz grid frequency | | - | - | + | + |
| Audible noise of blades | | - | + | + | + |
| Energy yield | Variable speed | - | + | + | + |
| | Gearbox | - | - | + | - |
| | Generator | + | + | - | + |
| | Converter | + | 0 | - | - |
| Reliability and maintenance | Brushes | + | - | 0 | + |
| | Gearbox | - | - | + | - |
| | Mechanical loads | - | + | + | + |
| | Complexity | + | - | - | - |
| Power Quality | 'Flicker' | - | + | + | + |
| | V&f control | - | + | + | + |
| | Harmonics | + | - | - | - |
| Grid faults | Fault currents | + | 0 | 0 | 0 |
| | Restoring voltage | 0 | 0 | + | + |

Dip in power when blade passes tower

Visible in constant speed: no use of energy storage

Not visible in variable speed: uses energy storage in inertia



Constant speed: SM, field control

Constant speed synchronous generators are directly grid-connected and in case of a controllable source or reservoir it can contribute to frequency control. It can contribute to voltage control because the field current can be controlled.

Nearly constant speed: IM

Partial variable speed: DFIG + partial PE

Full variable speed: SM, IM, PM + full PE

Size and efficiency

Sizing equations: generator dimensions

$$F_d \approx 25 - 50 \text{ kN/m}^2$$

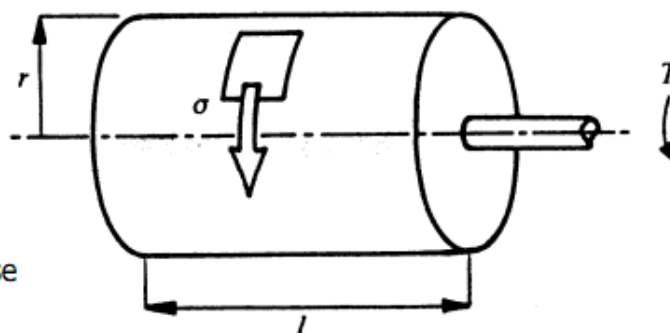
$$F_d = \sum B_g i$$

Rather constant because

- Saturation limits B
- Losses limit i

$$T = r_s F = 2\pi r_s^2 l_s F_d = 2V_r F_d$$

$$P = \omega_m T = \omega_m r_s F = 2\omega_m \pi r_s^2 l_s F_d = 2\omega_m V_r F_d$$



Generator efficiency

Depends on speed

- low speed - high torque
- limited efficiency
 - Induced voltage
 - Resistive voltage drop

$$\vec{E}_{ind} = \vec{B} \times \vec{v} \approx 4\text{V/m}$$

$$\vec{E}_R = \rho_{Cu} \vec{J} \approx 0.1\text{V/m}$$

INTEGRATION ISSUES WITH DISTRIBUTED GENERATION

The goal of this chapter is to give an overview of some important aspects of the future of power systems. This includes voltage changes, increase in fault current level, power quality, protection, stability and islanding operations.

The conventional power systems are designed to accommodate power flow from the transmission system to various users connected to the distribution system, as shown in Figure 1. The power flow (both active and reactive) is always from the higher voltage level to the lower voltage level. Since embedded generators are connected to the distribution system they supply power from the distribution side and the power flow may be reversed. The distribution network is no longer passive network but it has energy sources and can in some cases supply power to the high-voltage transmission system. The distributed generators are not under the direct control of distribution network operators. The network operators therefore must always assume the worst possible generation case in the calculations in their network. This may lead to overly conservative requirements and limitations for the distributed generators.

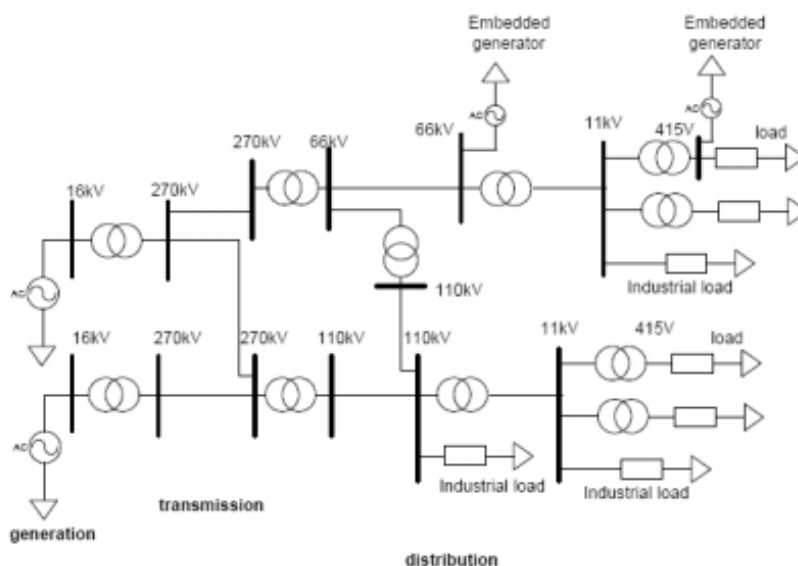


Figure 1. Simplified single-line diagram of an electrical power system with embedded generator

As already stated in chapter 1, there will be a change from a vertical transformation of energy to a horizontal transformation. This means that there are various stations for power generations which use energy but also deliver energy to the grid.

Voltage changes

Distribution companies have the obligation to supply power at a voltage level within a specified range. There are various components that contribute voltage control in order to compensate for the changes in the system loading. These are typically on-load tap changers on transformers and various reactive power compensating equipment, like shunt capacitors or static Var compensators. In case of distributed generation, the voltage profile will change and the mechanisms for voltage control must be redesigned. However in some cases the presence of distributed generator may improve voltage control.

Due to that change there will be big change in the network for **the voltage**. Voltage however must not vary a lot because loads are specified for particular nominal voltage. By changing the load the voltage will change accordingly. Depending on the supply network this will lead to a more inductively or more capacitive network. The voltage can be regulated by the transformer tap change, reactive compensation and static VAR compensators.

Increase in fault current levels

Fault level is a very important indicator of the strength of the power grid. The maximum fault current influences rating of all concerned electrical equipment. The fault level also indicates the maximum power rating for the distribution generation, and typically weak systems (low fault level) will be able to accommodate very limited amount of embedded generation. The embedded generators which use rotating machinery (both synchronous and induction) will increase fault level. If the fault level increases beyond the rating of grid switchgear, traditionally the operators of embedded generators have been asked to fund switchgear upgrade (which may be a considerable amount). In addition, the direction of fault current may change. This might have negative consequence on the operation of protection relays.

The most important issues when a new network is built is the load flow and short circuit levels. According to the short circuit current level protections need to be adjusted and switchgears need to be coordinated. Furthermore protective relays need to be adjusted according to fault current level and $1.3 \times I_n$ value depending on the degree of relay operation. Lastly switchgears are rated according to their ability to interrupt short-circuit currents. This depends on the generated transient recovery voltage.

Power quality

The most important aspects of power quality that will be considered here are: transient voltage variations and harmonics. The embedded generation can have varying effect on power quality. Some embedded generators (like fixed speed wind generators) will have negative effect on voltage control, since induction generators consume reactive power in proportion to the loading. The distributed generators that are interfaced through converter systems will typically have the ability of fast voltage control. The converter systems however in general inject harmonic currents, although

some advanced concepts can actively control low order harmonics on the grid. In most cases harmonics and transient voltages are factors that influence power quality. Some embedded generation units affect the power quality. Fixed speed generators have negative effect on the voltage control because induction generators consume reactive power in proportion to the load. Newly embedded generators are converter based and the voltage control is efficient.

Protection

Embedded generators complicate distribution system protection arrangements. The new generator should be protected by a range of protection circuits and these must be coordinated with the distribution system protection installations. Also distributed generators increase fault levels and this implies redesign of the existing protection installations.

New power system will be horizontally operated therefore at all distribution levels there will be no longer radial networks. Some generators sometimes can operate and sometimes can be disconnected. Hence protection issues are a problem because the short circuit currents can change depending on the number of DG included.

Important issues for the protection are the critical clearing time (CCT) calculation, fault ride-through capability of DG units and operation of DG protection.

Critical Clearing time

The protection needs to operate within 200-300ms from the fault occurrence. CCT means how long the fault current can exist without having any impact on the system stability.

When doing a transient stability analysis three-phase faults at different locations are considered. DGs CCT and critical generators are determined. The fault time duration is varied. The most critical element is the microturbine and the most critical fault location is the high voltage side of the substation. DG transient stability is not endangered.

The parameters which influence the network transient stability can be listed as follows:

- The behavior of the microturbine following a three-phase fault with duration of 612 ms is examined
- A fault at the terminals of the most critical element is less critical than a fault at the common busbar
- The restoration of the post-fault voltage profile on the common busbar is even more crucial than the transient behaviour of the DG during a fault
- Microturbine terminal voltage is lower during the disturbance for fault location #8 than for location #1, after the fault the situation is vice versa
- For a fault clearing time larger than the CCT, the microturbine cannot retain stable
- Induction generator is delivering power during the disturbance, after the fault clearance the active power becomes zero

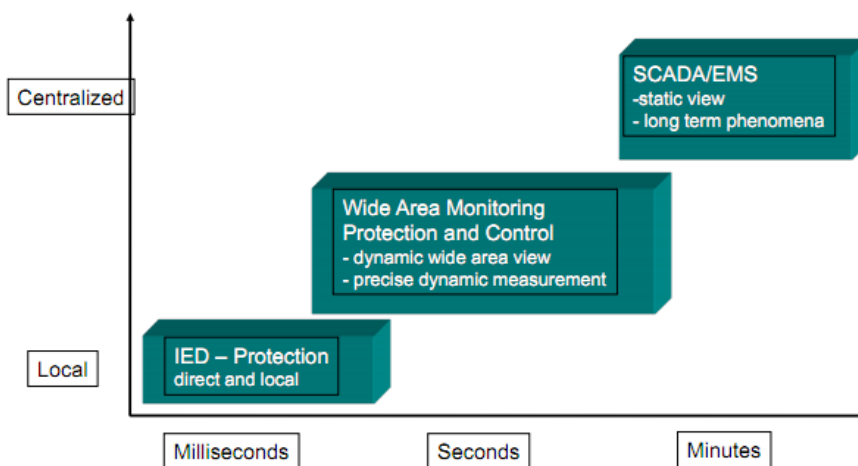
Fault ride-through capability of DG units.

The CCTs of the micro turbine for different external faults and at its terminal are determined. The magnitude of voltage dips corresponds to the distance of the fault in the external grid.

Stability failure – leads to blackout

The primary aim of the traditional embedded generators has been generation of kWh of electricity and the impact on the host grid has not been of great concern. However as the share of power generated from embedded generators is increasing it is important that these generators undertake some (if not all) of the control and regulation functions required from the central generators, which they are replacing. Network operators worldwide, have issued a set of requirements for the connection of large (typically over 30MVA) distributed plants. They are now required to provide a number of functions (like reactive power support, voltage regulation, frequency response, spinning reserve sharing, controllable power ramp rates and others) which contribute overall system stability and integrity

Measures how to protect the system



Islanded Operation

Islanded operation may occur if a generator with some local loads becomes disconnected from the rest of the network. This may happen in case of faults which lead to permanent opening of some distribution lines. With conventional, central power systems, islanding is a very rare event since it may happen only if a large geographical area (with a number of generators and load centers) becomes completely disconnected from the national grid. Many transmission lines should be opened for such event and these events have been recorded only for very short time during blackouts and widespread outages. With distributed generation, tripping of a single distribution feeder may result in a small electrical island with a generator and the feeder load. Islanded electrical system is a highly undesirable situation. If the load is larger than the generator capacity the system will gradually collapse. If the load is below generator rating the generator may accelerate. The AC voltage may also reach very high levels depending on the nature of the generator. Modern embedded generators will typically have protection to detect islanded operation and trip the unit

Utilities and existing standards currently do not allow the islanding operation of micro grids. Also there are technical problems with electromagnetic transients during switching from the grid-connected to the island mode of operation.

Conclusion

- Future PSs differ significantly from the PSs of the 20th century
- There is more power electronics and some issues like protection, stability etc. must be considered to insure correct operation

- Efforts are made to insure safety operation of autonomous networks regarding stability and new protection schemes during fault currents
- Power Quality issues – should also be taken into account considering the large number of AC – DC converters taking place in the Past

Offshore Wind Integration

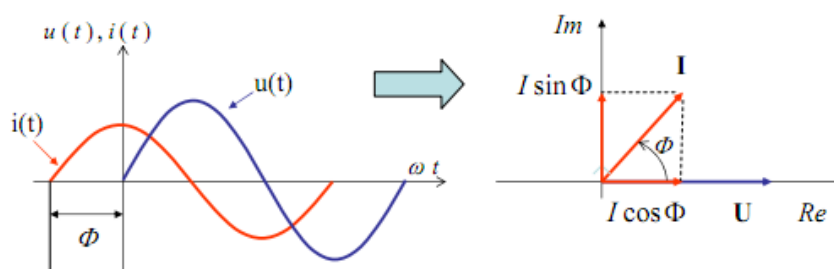
Vision for wind power developments in the North Sea

Challenges for offshore wind power integration

The main challenges for offshore wind power integration are:

- designing a reliable offshore (super)grid
 - reliability and redundancy
 - flexibility, standardization and modularity
 - multi-terminal HVDC converter operation
- interaction between offshore and onshore grids
 - stability following a disturbance event
 - controllability of power flows to avoid congestion
 - compensating for the variability in wind power by ramping up/down the conventional power plants
 - coordinated planning of the capacity in the two grids

When talking about the challenges one need to consider some AC transmission basics:

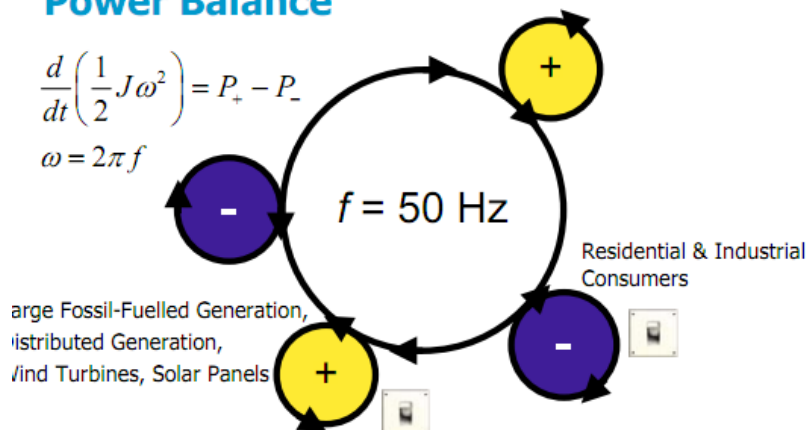


$$\text{Transmitted 3-phase AC power: } P = \sqrt{3}UI \cos \Phi$$

$$\text{Reactive power: } Q = \sqrt{3}UI \sin \Phi$$

$$\text{Power losses: } P_{loss} = 3I^2R$$

Power System Basics: Instantaneous Power Balance



Wind as Power Plant

The main challenge for wind as a power plant is the fact that the wind is uncontrollable.

However power electronic interfaces make wind power to a large extent controllable:

- Voltage - Reactive power control
- Primary and secondary response (Real power)
- => Requirements laid down in grid code

Some functions require communication between TSO or wind farm operator and wind farm controllers. This means a challenge for installation and control of offshore wind. In order to avoid communication delays it is preferred to design controllers that rely on local signals.

Connection solutions for large offshore wind farms

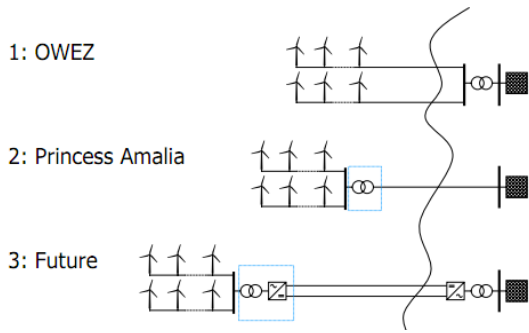
Features of HVAC transmission

- existing onshore grids are large, AC, meshed
- HVAC onshore transmission uses overhead lines
- for offshore, submarine cables are needed
- XLPE insulation, currently $\sim 170 \text{ kV}$, foreseen 245-400 kV
- AC cables produce reactive current => as length increases, capacity for transporting "real" MW diminishes
- inductive compensation requirements difficult to fulfill in an offshore environment => distances $< 100\text{-}120 \text{ km}$

Features of HVDC transmission

- Transmission distance not limited by charging current (as the case with HVAC cable)
- IGBT-based VSC most promising choice for offshore applications (ratings up to $\sim 1200 \text{ MW}$, $\pm 320 \text{ kV}$)
- VSC allows for multi-terminal applications through easy control of current direction
- VSC can operate in weak and dead networks => black-start capability
- But: compliance with grid connection requirements (e.g. low voltage ride-through) for VSC-HVDC challenging due to limited overload capability

One can also compare HVAC with HVDC:



Synergies with other offshore applications

Besides offshore wind energy there are other sources of renewable energy, offshore consumers (oil and gas sector) and interconnectors between power systems. When finding synergies between those parties it could be an improvement to the entire transmission system.



150 MW wind (30 REpower 5 MW turbines)
 90 MW gas turbines
 ~40 km AC cable, 132 kV
 operational ~2011

Connection Concepts: Kriegers Flak, 1600 MW

| Separate, national | Combined AC-based | Combined, hybrid AC – HVDC multiterm. | Combined HVDC-based. KF1 separate |
|--|--------------------|---------------------------------------|-----------------------------------|
| A | B | C | D |
| | | | |
| Rough cost estimate: | | | |
| Sep. solution... | + 130 mio.€ | + 300 mio.€ | + 245 mio.€ |
| Capacity for North-South intra-day trading: | | | |
| No exchange | ≤ 400 MW | ≤ 1000 MW | ≤ 600 MW |

Variability and Predictability of Wind: NL example

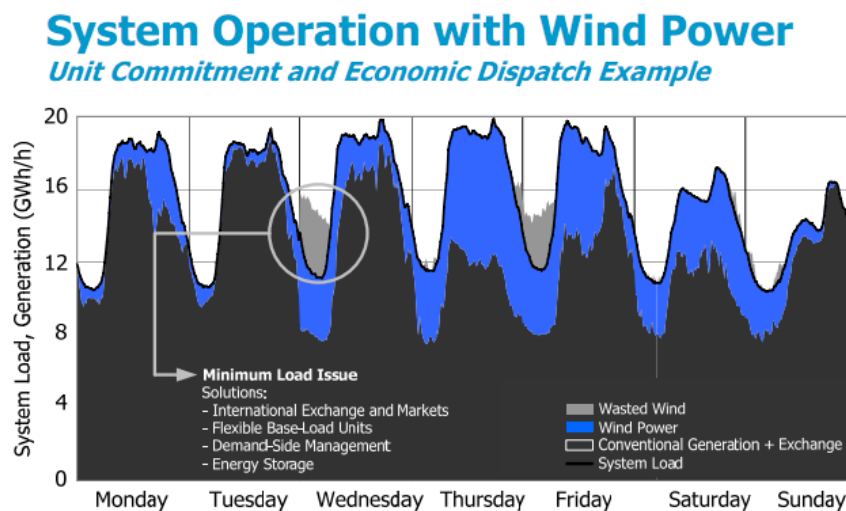
Due to the variability and limited predictability of wind power there is a need for regulation and reserve power. For that the minimum load consequences for the production need to be considered.

In order to enhance the prediction a time series has been created for 4 GW onshore and 8 GW offshore. For a period of one year, every 10 minutes the speed data was taken. There were 22 measurement station and 7 forecast stations. Interpolation was used to foresee wind farm locations. The speed power conversion was done by multi turbine curves. The result was a 14% variability across 15 minute intervals, 55% unpredictability for 12-36 hours prediction.

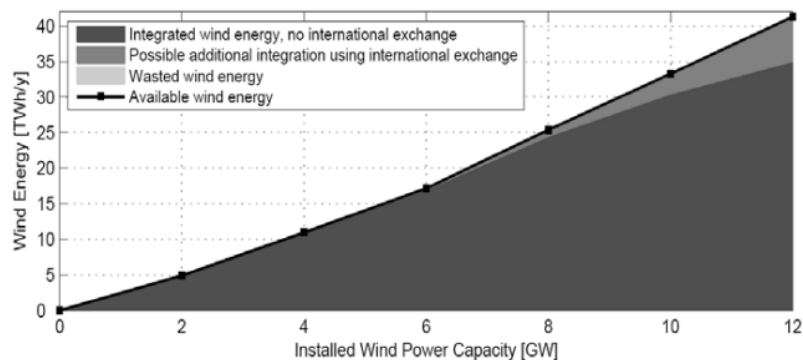
Estimating balancing requirements for Dutch wind power

To give an overview about the Dutch generation park year 2014 excluding wind power:

- Thermal generation system ~30 GW installed capacity
- Large share of CHP (~55%)
- No hydro plants
- Consumption ~130 TWh
- Peak ~21 GW
- Netherlands is net importer
- ~7350 MW interchange capacity



Integrated and Wasted Wind in the Netherlands, 32 GW Wind in Germany



Impacts on unit commitment and economic dispatch

Wind power does not replace conventional generation. The unit commitment is continuously optimized based on an hourly update of wind power forecasts. Wasted wind due to minimum load constraints appears around 4 GW installed wind power. The wind power results in a more dynamic operation of conventional units. The conventional units able to follow aggregated load and wind power variations.

Role of power electronics to achieve energy savings

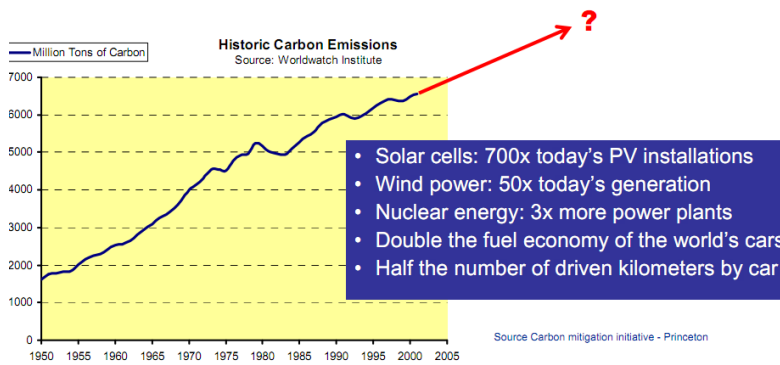
Trends and examples

Introduction

The big challenge for this century is to find a sustainable equilibrium for our technology driven society. The main question is how power electronics can be applied and which new technologies should be developed so that homo sapiens makes a smaller imprint on the earth.

In the 2007 EPRI Summer Seminar an electricity solution was suggested for a carbon-reduced electricity network which introduces a mix of different technologies. The main question is always whether predictions can be put into reality.

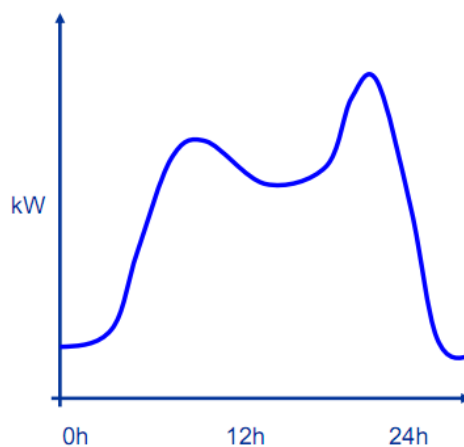
The graph bellows shows how much world investment is needed to save 1000 millions tons of carbon per year:



A saving approach could be the 1kW society in which the imbalance between biological and technology PER CAPITA energy requirement is addressed. At the moment in the US 8kW are used per person, in the future this should go down to 1kW.

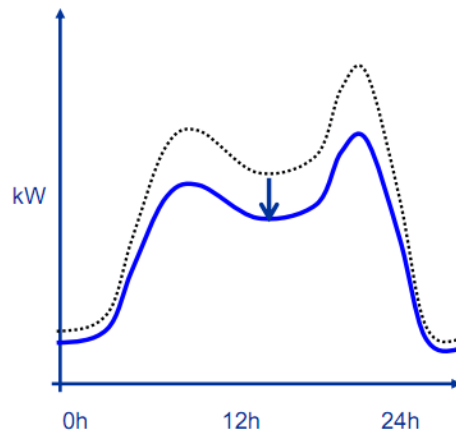
Examples

As an example for that we will have a look at the current situation of the energy consumption of home appliance.



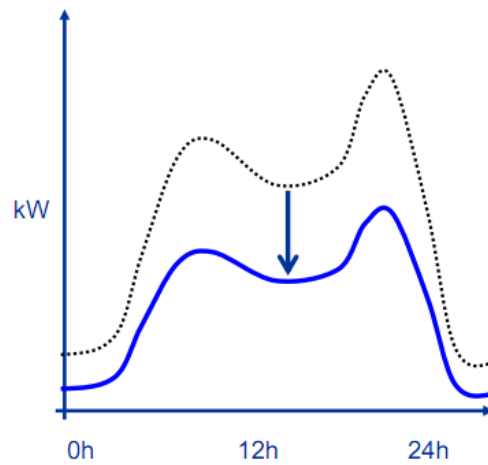
By 2020 we can reach 20% improvement with new motor drive systems leading to the following graph:

**20% improvement with
new motor drive systems**



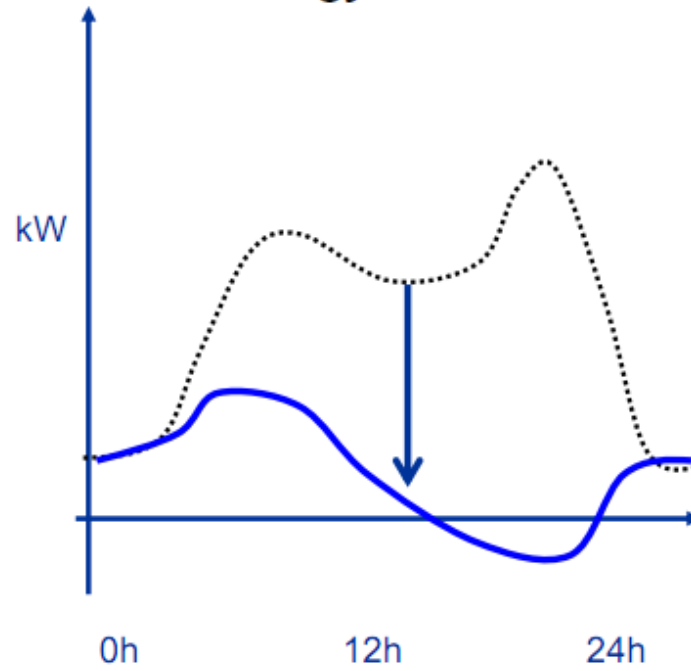
By 2030 a 40% improvement can be done by new science and new conversion efficiency leading to:

**40% improvement with
new science &
new conversion technology**



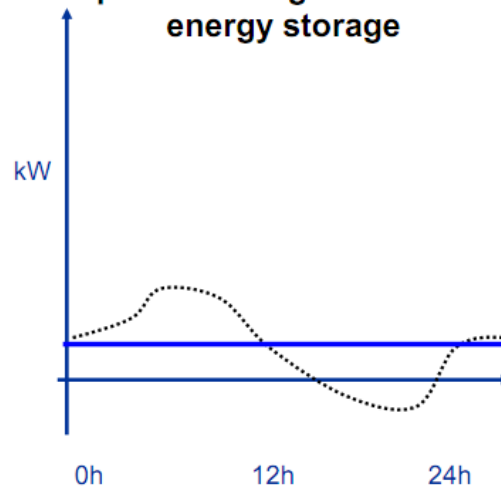
If we now consider the usage of new appliances using renewable energy sources like photovoltaics which can be mounted on a roof of a house this can lead to:

New appliances: renewable energy sources



Additionally when a smart energy storage management is introduced, for example using electric cars as battery storage one can end up:

Control consumption profile with power management and energy storage



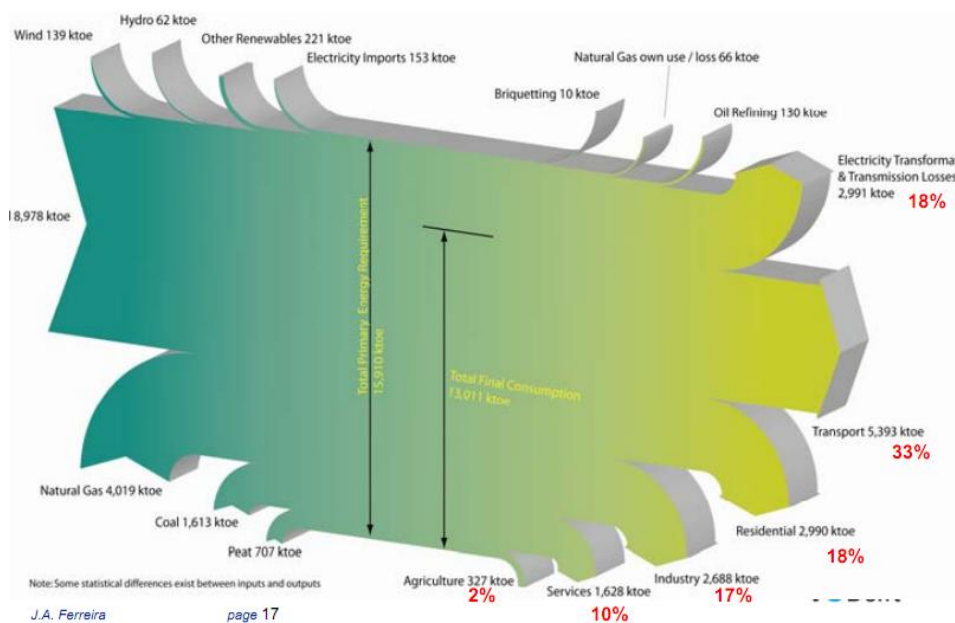
Scope

Now lets have a look at the usage of energy. The applications for energy can be summarized as follows:

- Energy
- Industry
- Transport
- Tertiary sector
(Commercial buildings, ...)
- Lighting
- Home/domestic appliances
(Energy management on the home)
- Others
- Mobile (e.g. medical implants)

For Ireland the energy flow can be listed as follows:

Energy Flow for example in Ireland 2006



Energy Saving Potential – Moter Drives

- f Motor drives use 55% of consumed electrical energy.
- f Power electronic drives can control the motor speed to match output with the needs.
- f By using variable speed drives (VSDs) a potential reduction in energy consumption of 20-30% is achievable.
- f 200TWh savings in the EU-25, equivalent to 130 fossil fuel 350MW power plants (enough energy to supply a country the size of Spain).
- f 12% of motors in Germany is operated with electronic speed controls, from the energy viewpoint
it would make sense to install them with 50% of all drives

Energy Saving Potential – Home Appliances

- f Home appliances use 30% of all generated electricity (second largest consumer).
- 1. f This consumption will grow by 13% from 2000 to 2010 and by 25% by 2020
- 2. f By 2020, 10% of total appliance consumption could be for stand-by
- f Electronic thermostats for refrigerators and freezers can yield 23% energy saving and additional 20% by using power electronics to control compressor motors.
- f Appliance market trends:
 1. f New products based on ICT
 2. f Networking all appliances (white goods, brown goods, heat ventilating/AC systems)

Energy Saving Potential – Lighting

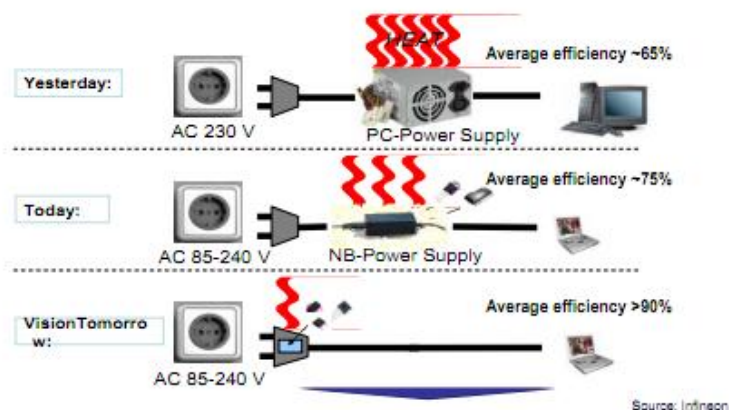
- f Lighting uses ~21% of consumed electrical energy.
- f Power electronics can improve the efficiency of fluorescent and HID ballasts by minimum of 20%, advanced power electronics for dimming, light and occupancy sensing can save an additional 30%.
- f Efficiency improvement
 1. f 15% to 25% from magnetic to electronic ballasts
 2. f 80% from incandescent to fluorescent energy saving lamp

10 ways to save energy

1. Efficiency improvement of power electronic interfaces

Power electronic interfaces are present between the grid and most electrical load. A 1% improvement is more than doubled if the efficiency of electricity generation and transport is considered. For R&D there is an opportunity: New power electronic solutions with higher efficiency and the potential of market acceptance.

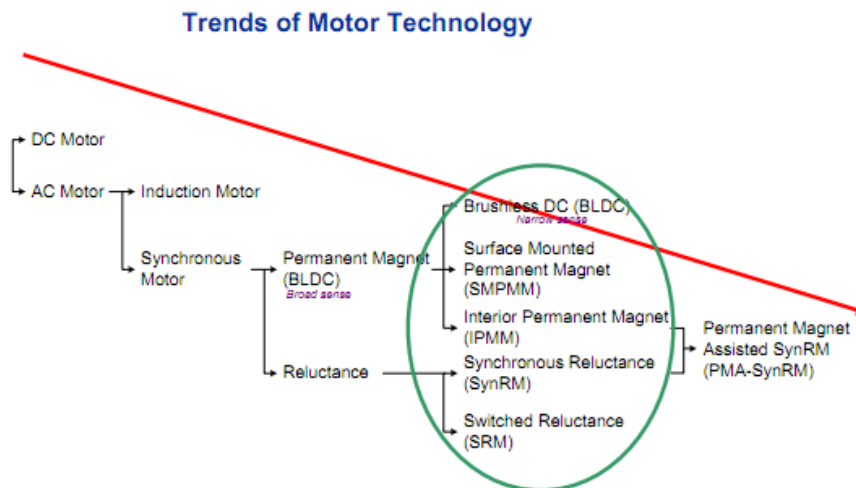
As an example there is the supply efficiency of a pc / laptop adapter:



2. Efficiency improvement with better machines

The second option is the combination of machines and power electronics which makes it possible to have high efficiencies over the full range. For example new permanent magnets materials make substantially high efficiencies possible. As a R&D opportunity:

New electromechanical solutions with higher efficiencies and the potential of market acceptance.

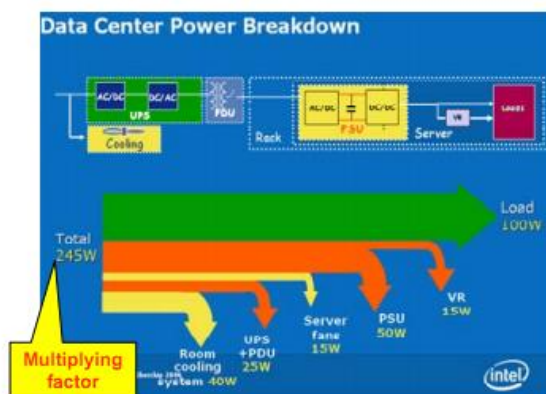


3. Efficiency improvement with better software

Additionally improvement can be done by improving the software. This means that algorithms and software routines can be designed to maximize the computing power for their execution. For example the clock speed and processor voltage should be controlled to reduce the energy consumption.

As a R&D challenge there will be new software solutions that in combination with new computer architecture will use less energy.

More power efficient software benefits from the multiplication factor of the power conversion chain.



4. Efficiency improvement with power management

Integration of power electronics and ICT in systems makes it possible to apply energy where and when it is needed in space and time. As an example one can take a lighting system that uses power electronic energy saving lamps and ICT to the light on and off and control its intensity.

R&D Opportunity: System level research, exploiting the potential of the synergy of ICT and power electronics in energy saving.

The steps for that would be as follows:

1. Apply energy only when needed in the exact amount.
2. Apply energy only where it is needed.
3. Do the power conversion at the highest efficiency.
4. Use the highest power density converters because they reduce weight and require less energy to manufacture

5. Improved energy balance in renewable energy systems

One of the main factors that counts for the energy balance is the **energy payback time**. For wind turbines that is around 6 – 12 months and for solar panels 1.5 – 4 years. The efficiency of renewable energy improves the energy balance. Another important factor is the **leverage factor** which consists of system costs divided by costs for the conversion system.

As a R&D opportunity: Sophisticated and complex solutions that may cost more but which give a substantial efficiency improvement. For example wind turbines have a leverage factor of 2.5

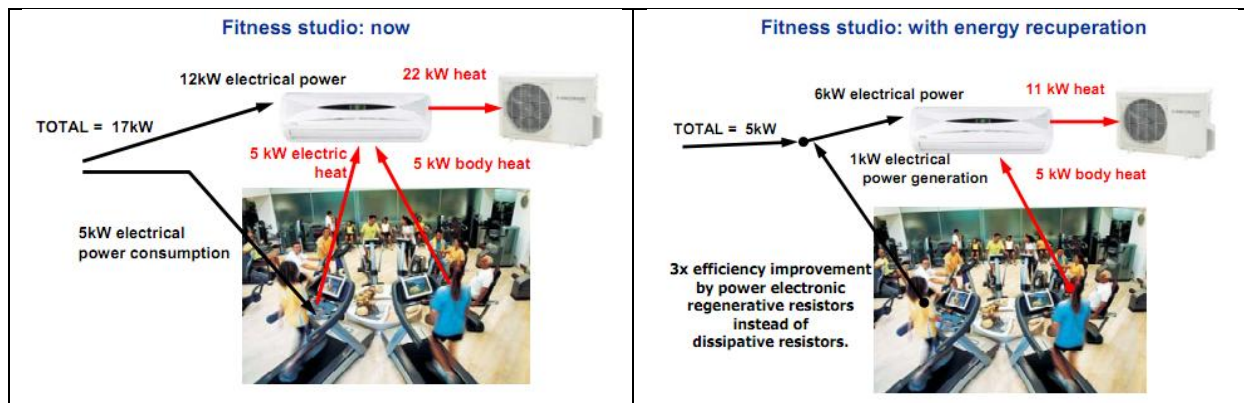
6. Grid efficiency improvement by better voltage regulation

- Dissipation in resistive loads proportional to the square of the voltage.
- All harmonic power is dissipated.
- Narrow voltage band power electronic converters are more efficient.
- R&D opportunity: Power Electronics solutions to regulate the voltage and filter the harmonics

7. System efficiency improvement by energy recovery

System efficiency improvement by energy recovery can be used when energy that would be wasted as heat is recovered by converting it to electricity. For example: electronic resistors, brakes, heat exchangers etc. As a R&D opportunity: Numerous potential applications exist that have not been investigated.

As an example a fitness studio:



8. More efficient combustion

At the moment the light load efficiency of combustion engines are low, they are only efficient if they work on their limit. Energy storage and power electronics combined allows the combustion engine to be operated at its point of maximum efficiency. The fuel efficiency of a diesel engine with variable load can be doubled. R&D opportunity: Develop hybrid and energy storage technology further to improve fuel consumption and reduce CO₂

9. Energy harvesting

Energy harvesting (also known as Power harvesting or energy scavenging) is the process by which energy is captured and stored. A variety of different sources exist for harvesting energy, such as solar power, thermal energy, wind energy, salinity gradients and kinetic energy. Energy harvesting is renewable energy at low and very low power levels. R&D opportunity: It is a new application field with much growth potential. Examples are watches which create energy through the temperature difference of skin and material.

10. Miniaturization

- Smaller systems, lower recycling cost and a reduced impact on the environment.
- Examples: Less material is used and systems like PDA's and computers can become smaller with more computing power. Trains, trams and battery vehicles can be made lighter.
- R&D opportunity: Higher energy density passive components, low loss switching devices and integration technologies

Hybrid Dynamic Systems with Energy Storage

An inconvenient truth

The film "An inconvenient truth" makes it clear that the earth is small compared to the number of citizens. Therefore the film asks for the following improvements:

- making the end-use electrical systems more efficient

- making other end-use systems more efficient
- making passenger vehicles more efficient
- making other transport systems more efficient
- using renewable energy sources and making energy supply more efficient and store carbon dioxide.

The energy storage market segments consist of 3 parts:

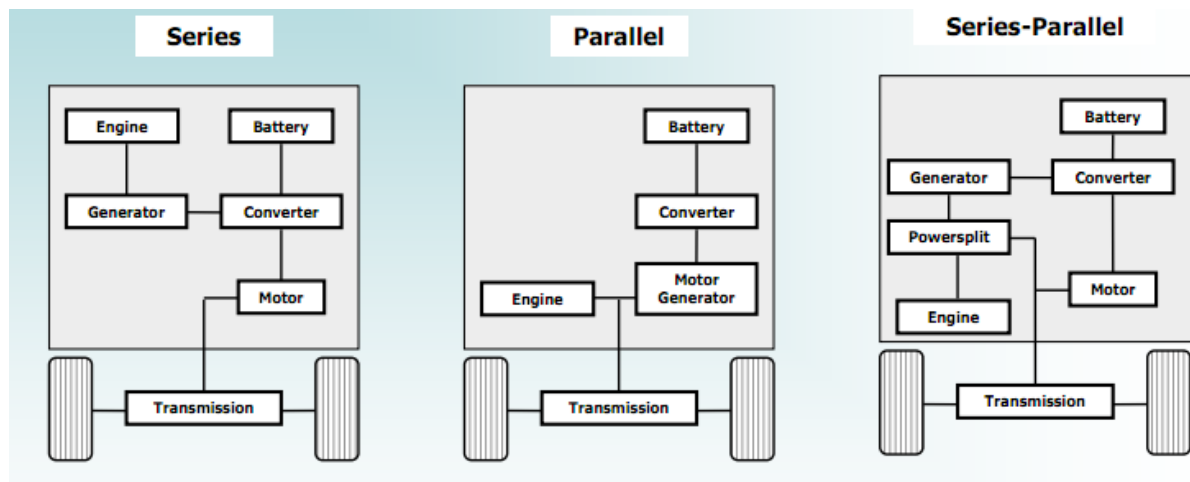
1. Utility / industrial applications including: grid reinforcement, renewables integration and uninterruptible power supply (UPS) applications
2. Transport / mobile applications including: on-board power for vehicles, new drive trains (electric and hybrid electric vehicles) and leisure applications (caravanning)
3. Portable applications including: computing, cell-phones and cameras (the 3 'C's')

We will focus on the second part in this chapter and deal with hybrid electric, plug-in hybrid electric and all-electric vehicles.

When comparing conventional with BEV one can state the grid efficiency from a conventional car is 15% and for BEV 65%.

This change in efficiency is due to the recover energy through regeneratives, braking and store, batteries and selective shut off.

Powertrain architecture:

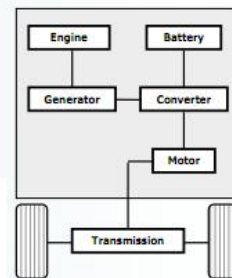
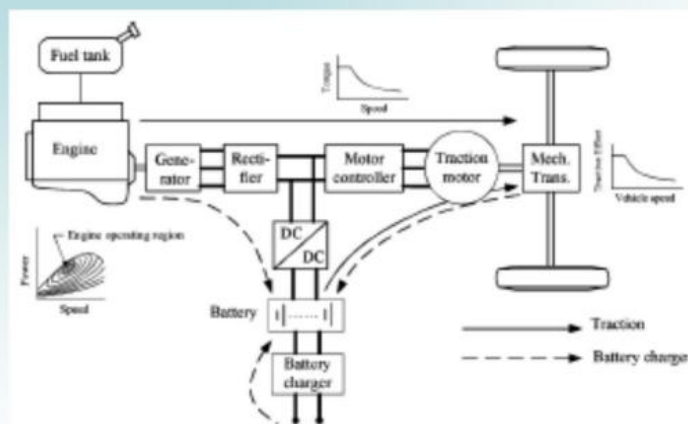


The **series** architecture: The use of an internal combustion engine to drive a generator and provide electrical power for one or more traction motors is a common propulsion method which has been used in locomotives for many years. This is the technology that series hybrid is based on with the addition of some form of energy storage. The traction motor is the only power supply unit with a direct connection to the road wheels. The advantage is that the internal combustion engine can be operated at its most efficient point to generate the necessary current for driving the traction motor or charging the battery. This type of configuration is most advantageous for start-stop style driving, such as public urban transport.

The **parallel** hybrid architecture can simultaneously transmit power to the drive wheels from both internal combustion engine and the battery powered electric drive. Although most parallel hybrids have a traction motor between the vehicles engine and transmission a parallel hybrid can also use its engine to drive one of the vehicles axles while the electric motor drives the other axles.

The series-parallel or dual mode hybrid has the flexibility to operate in either series or parallel. These types of hybrid power trains are currently used by Ford, Nissan and Toyota and the advantage is that both series and parallel hybrid modes are possible. Since 2007 most plug in hybrid conversions have used this architecture. Although this type of architecture is more flexible in terms of driving modes it is also more complex and costly.

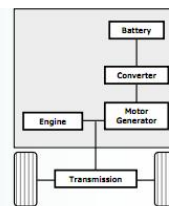
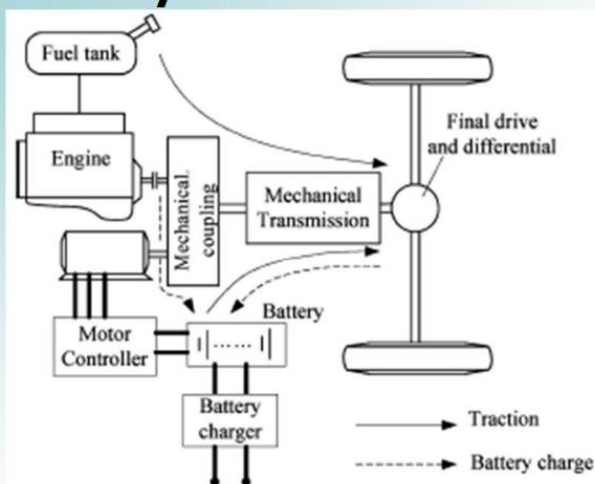
Series hybrid drivetrain



The use of an internal combustion engine to drive a generator and provide electrical power for one or more traction motors is a common propulsion method which has been used in locomotives for many years [80]. This is the technology that the series hybrid is based on, with the addition of some form of energy storage. The traction motor is the only power supply unit with a direct connection to the road wheels. The advantage is that the internal combustion engine can be operated at its most efficient point to generate the necessary current for driving the traction motor or charging the battery. This type of configuration is most advantageous for start-stop style driving, such as public urban transport.

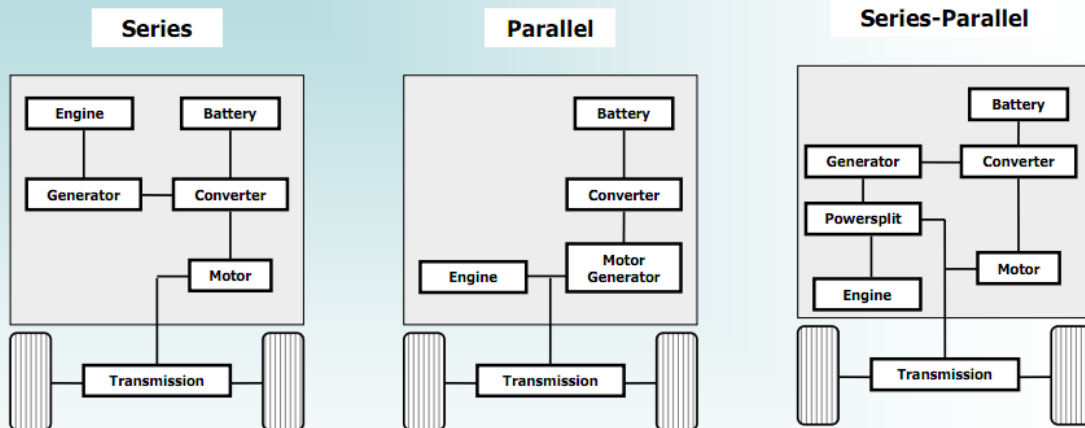
P Bauer: 5-1-2010

Parallel hybrid drivetrain



The parallel hybrid architecture can simultaneously transmit power to the drive wheels from both internal combustion engine and the battery-powered electric drive. Although most parallel hybrids have a traction motor between the vehicle's engine and transmission, a parallel hybrid can also use its engine to drive one of the vehicle's axles while the electric motor drives the other axle and/or a generator used for recharging the batteries.

Powertrain architecture



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pbauer; 5-1-2010

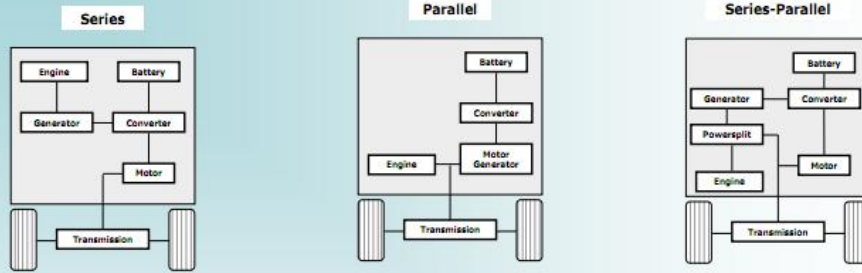
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pbauer; 5-1-2010

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pbauer; 5-1-2010

Powertrain architecture comparison



| | Fuel economy improvement | | | | Driving performance | |
|-----------------|--------------------------|-----------------|-------------------------|------------------|---------------------|------------------------|
| | Idling stop | Energy recovery | High efficiency control | Total efficiency | Acceleration | Continuous high output |
| Series | Good | Excellent | Good | Good | Poor | Poor |
| Parallel | Good | Good | Poor | Good | Good | Poor |
| Series-Parallel | Excellent | Excellent | Excellent | Excellent | Good | Good |

Energy storage

Energy storage can be classified as mechanical energy storage, magnetic energy storage, thermal energy storage or chemical energy storage.

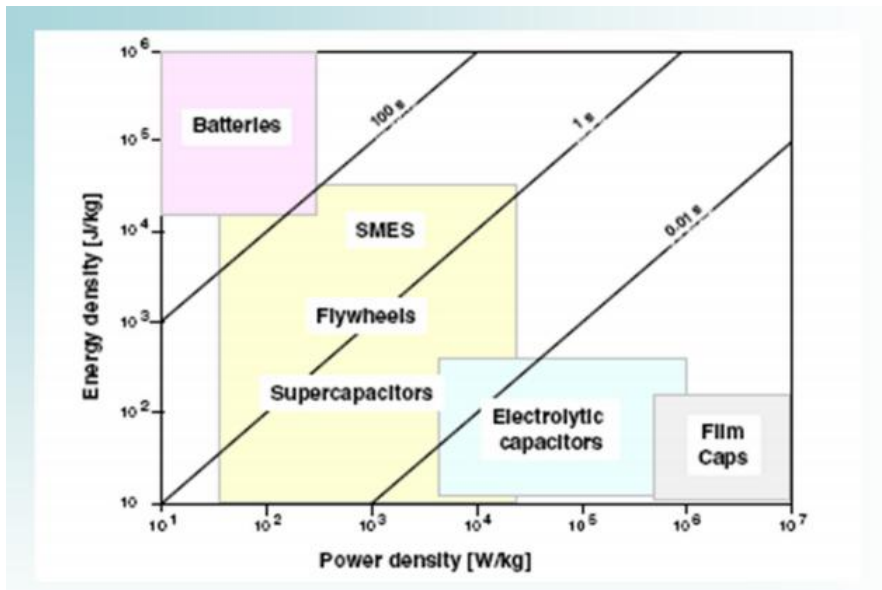
Fundamental properties:

- the **energy** that can be stored in the element;
- the **power** that can be drawn from/charged in the storage element;
- the **specific energy** (energy per unit weight);
- the **specific power** (power per unit weight);
- the **energy density** (energy per unit volume);
- the **power density** (power per unit volume)

Technology and economy

The technology and economy of an energy storage are determined by the cycle life, self-discharge, costs, fast charge time, cell voltage, load current, maintenance and energy efficiency.

The figure bellows shows the energy density and power density of various storage devices:



Now let's have a look at various types of storage:

Flywheels: Mechanical energy storage

The principle of fly wheels is simple: Energy is stored in the form of mechanical energy. Light weight fiber composites are used to increase efficiency. Energy density is 0.05MJ/kh considering an efficiency of 0.8

Energy density is defined as: $\frac{E}{m} = \frac{1}{2}V^2 = \frac{\sigma}{\rho}$

In which V is the circular velocity of the flywheel, σ the specific strength of a material and ρ is the density of the material.

The advantages are that it is a very compact system when compared to other energy storage systems, they are used for starting and braking locomotives. They are preferred due to light weight and high energy capacity. However it is not economical as it had a limited amount of discharge / charge cycle.

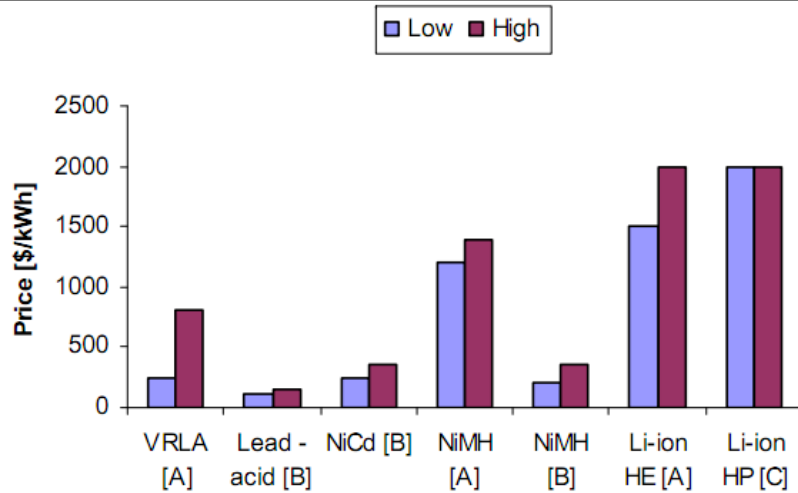
Batteries

There are various type of batteries: lead-acid, nickel cadmium (NiCd), nickel metal hydride battery (NiMH) and the Lithium ion battery. The peak storage of a battery is define as

$$P_{peak} = \frac{E^2}{4(R_{int} + R_{ohm})}$$

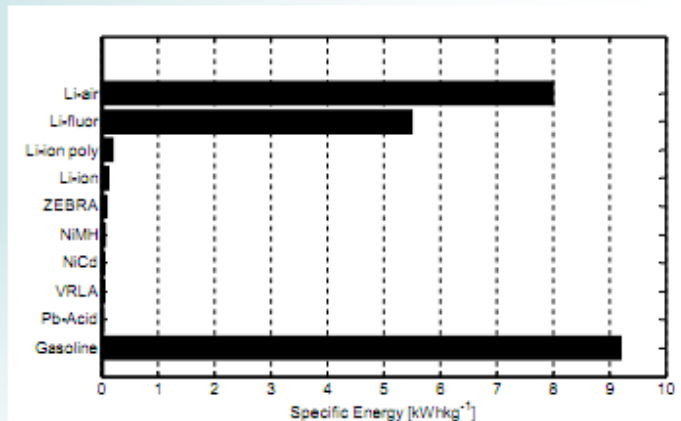
In which R_{int} represents the internal resistance and R_{ohm} the conductor resistance.

To give an overview of the various prices:



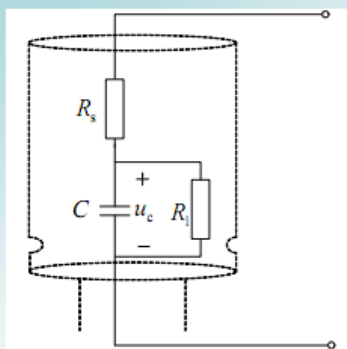
Battery technology and efficiency

- Gasoline 9000/ 3000Wh/kg
- Li-ion 600 Wh/kg
- Li-Fluor 6000 Wh/kg
- Li-Air 8000 Wh/kg
- Efficiency 15% vs 65%



Super capacitor

Supercapacitor



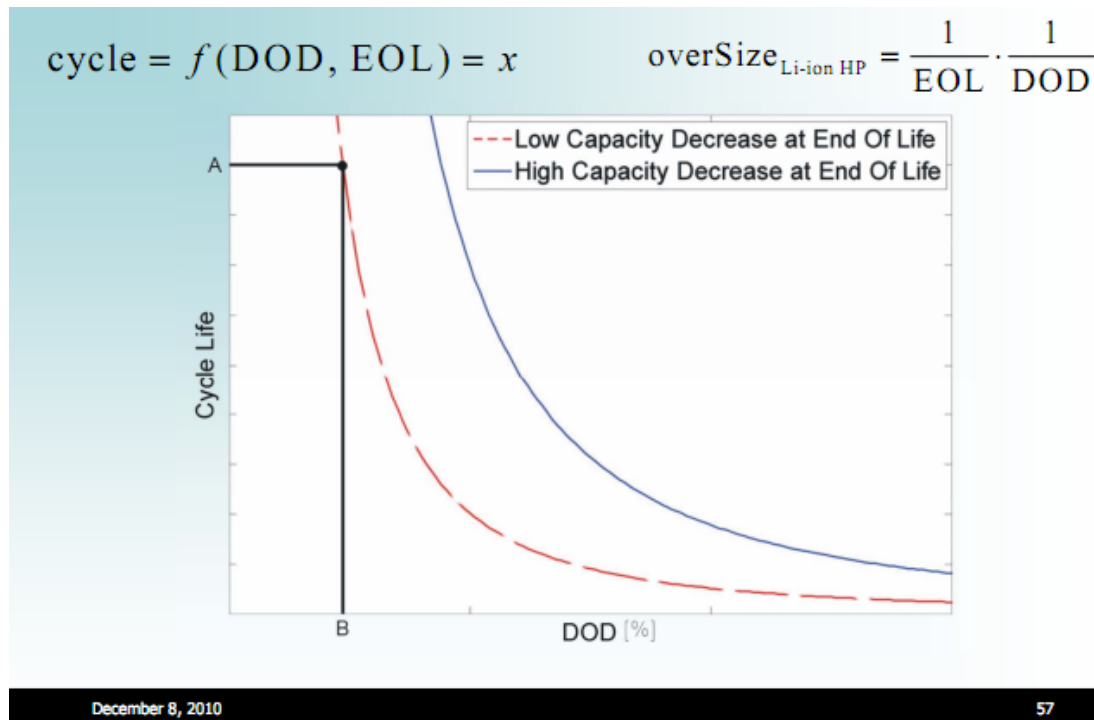
$$E = \frac{1}{2} C u_c^2$$

$$P_{\text{peak,storage}} = \frac{u_c^2}{4(R_s)}$$

Case study

Energy recovery factor: $REC = \frac{E_{recovered}}{E_{regenerated}}$

Dissipation factor: $DIS = \frac{E_{dissipated}}{E_{regenerated}}$



The lifetime of a battery is depended on the depth of discharge (DOD), number of cycles and the age. A lower DOD means a much larger cycle life.

Superconducting materials

Introduction

The biggest challenge we are facing right now is the increasing energy consumption. To overcome that challenge one can introduce electric however to fully use them the grid needs to be improved. One part of that is a connection within Amsterdam using a “super cable” and since then their importance increased steadily.

From invention to product

Superconducting materials were discovered in 1913

A superconductor has zero electrical resistance below a critical temperature. Once set in motion, a persistent electric current will flow in the superconducting loop forever without any power loss. A superconductor excludes external magnetic fields by means of induced currents.

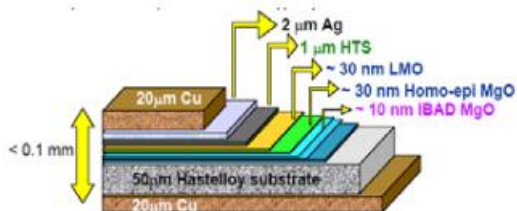
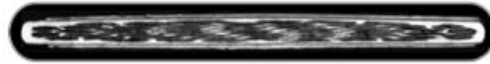
State of art

Lets have a look at the tapes used:

Bi-2223/Ag tape YBCO coated tape



Source: American Superconductor



Source: Superpower



Source: American Superconductor

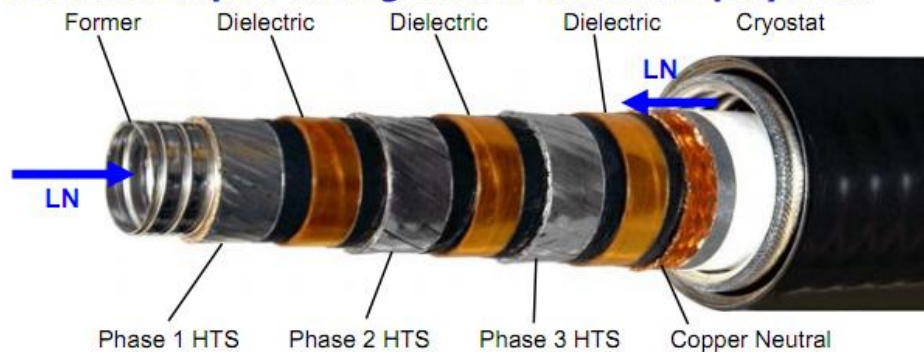
What are the large scale application of HTS:

| Application | Technical Points |
|-------------------|--|
| Power cable | High current power densities, More efficient use of existing right of way |
| Current Limiter | Low loss at rated current and high resistance to fault current. |
| Transformer | Low losses |
| Motors/generators | Smaller weight and size |
| Various magnets | High magnetic field, low losses |
| Magnetic bearing | Low losses, self controlled levitation |
| Energy storage | Large scale only designs. |

Amsterdam project

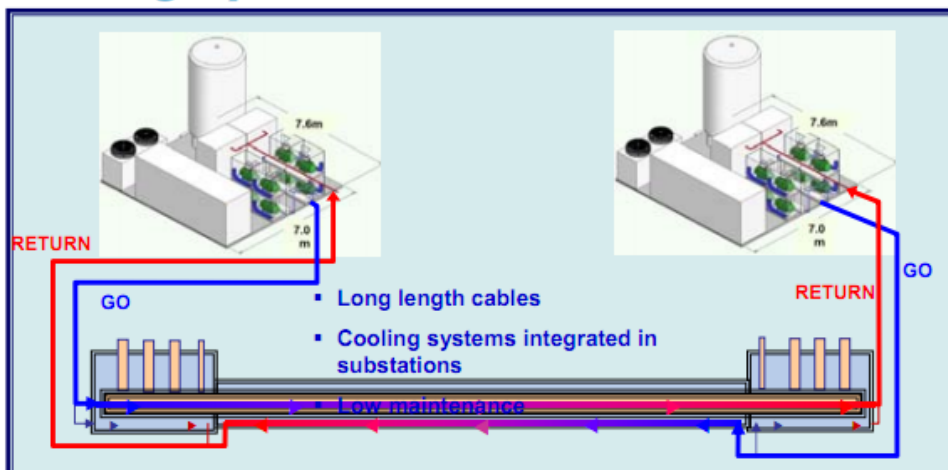
Amsterdam HTS Triax[®] Development project

- Triax cable design is very efficient
- Suitable for medium voltage (10 – 70 kV)
- Coolant: Liquid Nitrogen in a closed loop system



Amsterdam HTS Triax[®] Development project

Cooling System: cooling units only at the cable ends



The two major issues where the cryostat heat leak in the middle of the cable and the AC loss.

Sustainability aspects

The worldwide trends can be summarized as follows:

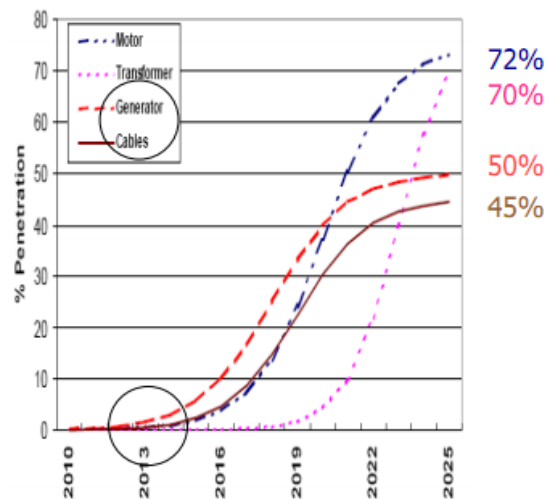
- Dependence on electrical power
- Decentralized power generation
- Urbanization
- Aging infrastructure

Sustainable power generation: A form of power generation, which can be maintained economically without depleting or damaging the resource

Renewable power generation: A form of power generation, in which the required resources are normally replenished through natural processes

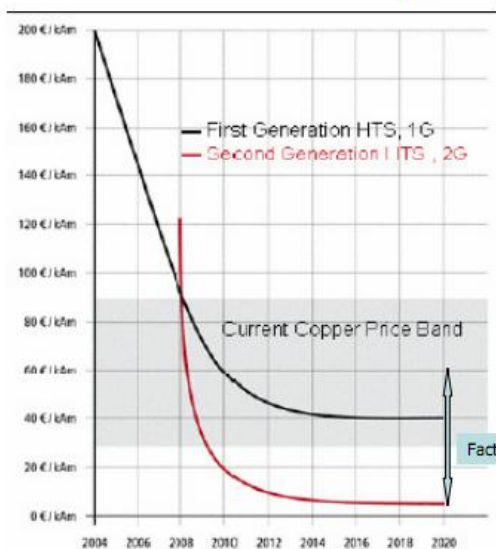
Sustainable power transmission: A form of power transmission, which can be maintained economically without depleting or damaging the resource

During the next 20 years a penetration of HTS devices into the power market is estimated for:



Source: Mulholland 2003

Price of HTSC vs copper, rare earth metals



In 2000 the electricity consumption in the Netherlands was 100 TWh which will reach 200 TWh by 2030. The electricity losses are around 10 TW each year or all offshore wind produced. Conventional upgrading would consist of higher grid voltages and introduction of power electronics. The bottlenecks are however: more energy losses and more environmental damage. Therefore one needs to look for HTSC sustainable options:

In terms of energy technology these are: Green materials, higher energy density, lower losses and electromagnetic compatibility. For economy and society: urbanized area: retrofitting of cables.

Energy savings

1) Conventional grid solution in 2030: HTSC 0% effective

- T&D losses= -10 TWh= -5% of total energy delivered
- offshore wind= 9% sustainable energy
- offshore + Grid net sustainable delivery= 9%-5%= 4 %

2) HTSC grid solution in 2030: 100% effective

- net loss saving 50%: T&D losses= -5 TWh= -2,5%
- extra energy delivered= +2,5%
- offshore wind= 9% sustainable energy
- off shore + Grid net sustainable delivery= 9%-2,5%+2,5%= 9 %

case 2-1 advantage = 5% of total energy delivery

Roadmap study

- 1) Evolution trajectory towards a future sustainable grid with integrated HTSC components
- 2) HTSC cable for AC, DC and offshore applications
- 3) HTSC components resolving bottlenecks . 5 MVA (wind)generator is 2-3X lighter, smaller
- 4) Enabling technologies and materials for HTS

DC-HTSC to long distance renewables

1. Transmission capacity
2. Efficient due to less losses
3. Reduced RoW
4. Other

Clean, high performance materials

The building blocks of electrical power components are metals and dielectrics. The challenges that need to overcome during the next decades are:

- Environment friendly during entire life cycle
- High efficiency/Low losses
- Long life
- Smart, self-healing
- High energy density
- Non-flammable
- High operating temperature
- In case of fire, low smoke production and non toxicity

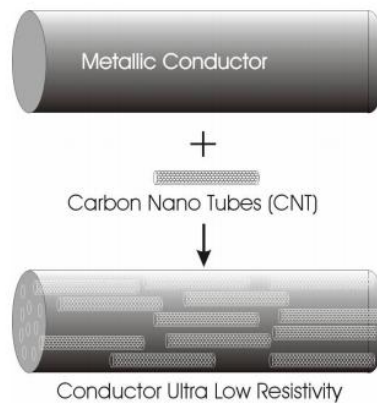
Metals

Reduction of losses using carbon nanotubes

Carbon nanotubes have a length to diameter ratio of $> 10^7$

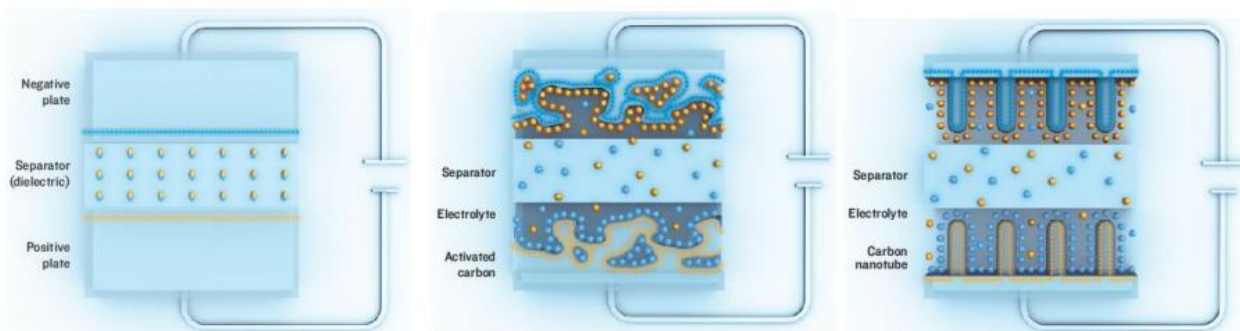
Ballistic conduction

As the length of a conductor approaches zero, the conductance approaches a finite value and not infinity. This conductance is determined by the interface between conductor and contact pads. If the length of the conductor is much smaller than the mean free path all resistance occurs at the interfaces. For a carbon nanotube: 6454 Ohm per tube. Their resistivity is only half of the resistivity of copper. Ultra low resistivity in practice would look like:



Ultracapacitors

Ultracapacitors can store only a fraction (5%) of the energy of an equivalent size lead-acid or lithium battery. Therefore more surface area is needed. By using tightly bunched nanotubes, the surface area can be increased drastically. MIT believes that storage capacity can be increased to between 25 and 50 percent of a battery's energy. At that point it becomes a compelling device for many applications. Now let's have a look how we can increase the active surface area:



Plain Old Plates: In a typical capacitor, electrons are removed from one plate and deposited on the other. Polarized molecules in the dielectric concentrate the electric field. One major factor determining capacitance is the surface area of the plates.

Plated Packed with Ions: An ultracapacitor can store more charge than a capacitor can, because the activated carbon has a pocked interior, much like a sponge. This means that ions in the electrolyte can cling to more surface area.

Enter the Nano-World: With finer dimensions and more uniform distribution, carbon nanotubes enable greater energy storage in ultracapacitors than activated carbon does.

Electrical insulation

Development of green and high performance alternatives

Gases – SF₆ (sulphur hexafluoride)

SF₆ is used world-wide in electric power industry for electrical insulation, for interruption and cooling as a few examples it is used for gas insulation system, switchgears, transformers, capacitors and cables. The advantages are that it has a **high dielectric strength** and **thermal stability** however it is **harmful for the environment** and decompose into **toxic substances**.

Further according to the intergovernmental panel on climate change, SF₆ is the most potent greenhouse gas that is evaluated with a global warming potential of 22.200 times that of CO₂ when compared to a period of 100 year. However due to its density relative to air SF₆ flows to the bottom of the atmosphere which limits its ability to heat the atmosphere. Its mixing ratio in the atmosphere is lower than that of CO₂ about 6.5 parts per trillion in 2008 but has steadily increased. Its atmospheric lifetime is 3200 years.

Alternatives for SF₆ are SF₆-N₂ mixtures, high pressure air insulation, vacuum insulation, solid dielectric insulation and fluid insulation.

Liquids

Insulation systems consisting of a solid and a liquid are the most frequently used systems in high voltage apparatus, where components have to be insulated and loss heat has to be dissipated. The requirements on the liquid part of the insulating system are not only the electric and dielectric performance but also the performance regarding requirements concerning the environment and low flammability.

Mineral oil

Mineral oil is used worldwide in electric power industry for electric insulation and cooling, The advantages are its high dielectric strength in combination with solids, high thermal conductivity and that is it's a proven technology. However the disadvantages are that it is harmful for the environment, toxic and has a low fire point.

As an alternative one could use ester liquids from vegetable oil instead of mineral oil. Esters are a class of chemical compounds and functional groups. Examples are rapeseed, sunflower or biodiesel oil.

When comparing liquids with mineral oil one can see that mineral oil is slightly toxic whereas liquids are non toxic. Also fluids are highly biodegradable whereas mineral oil is only high biodegradable. When comparing ester liquid with mineral oil one can see that the flash point and flame point of mineral is a lot lower which bares quite some risks.

Nanofluids

The thermal and electrical properties of liquids can be further improved by adding small fractions of nanoparticles.

Solids

Oil-impregnated paper is used worldwide as insulation in transformers, high voltage cables and capacitors. Epoxy resin is used in Insulators, cable accessories and switchgears. Polyethylene is used in high voltage cables.

The challenges of solids are to design clean insulation materials to replace oil insulated systems, allow the construction of compact and light weight insulation systems, increase efficiency and create self-healing properties.

Polymer insulation

The advantages of polymer insulation are its high dielectric strength, low losses and the fact that it is clean, however the disadvantages are that it has a bad heat conductivity and is susceptible to electrical degradation.

In order to design better properties we can add fillers to existing materials to affect properties but we have reached limits of what can be achieved on microscopic to macroscopic levels therefore it is necessary to move to nano-scale.

Nano dielectrics

When we shrink the dimension of a material we notice a change in material properties. In dielectric systems in which one of the length scales is below 200 nm (nanodielectrics), the surfaces and interfaces between dielectric elements become increasingly important.

Importance of the interfacial zone

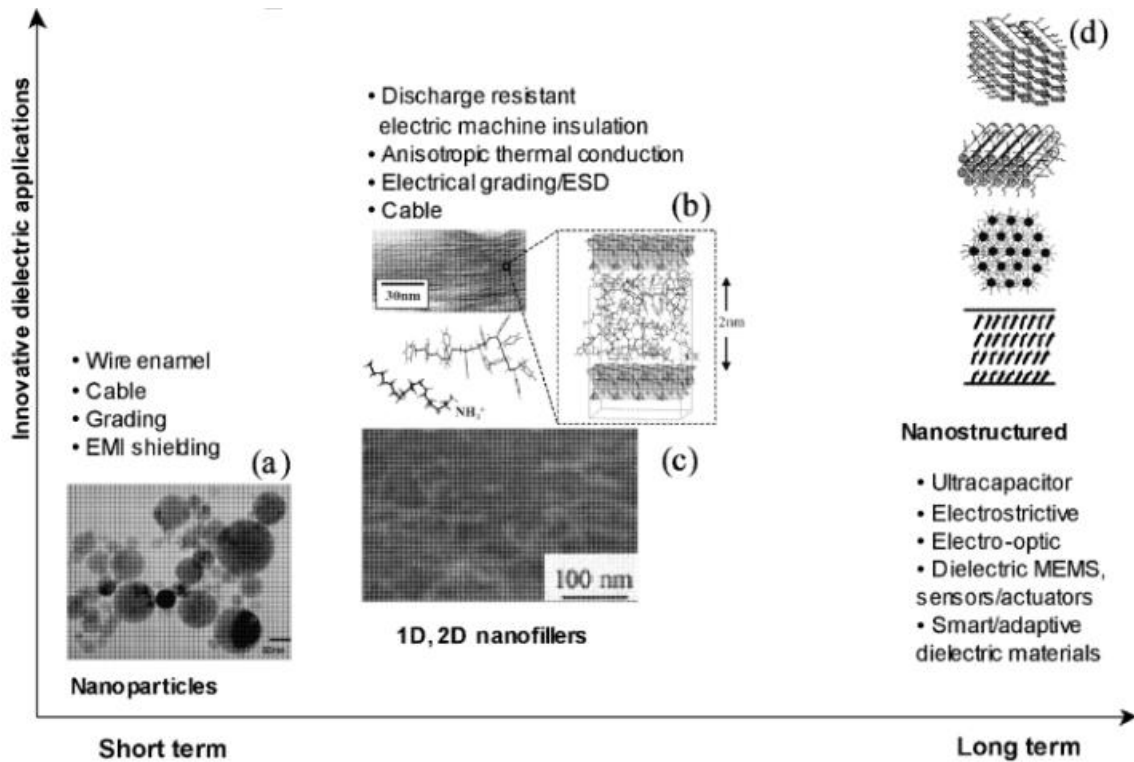
Material properties may change drastically within the interfacial zone which may even become more important than the bulk dielectrics.

Nano composites consist of a dielectric matrix (host) and a disperse phase (nano-scale filler). A very large surface area means much more interaction between filler and host. This creates new mesoscopic properties between atomic and macroscopic scale.

This results in a higher mechanical strength, better thermal properties, higher electrical breakdown strength, decreased flammability, better adhesion and smart behavior.

Developments

Building macroscopic structure with nanosized bricks.



Summary

Conductors

- Prospect of lower losses using carbon nanotubes
- Ultra capacitors using large surface areas

Insulating systems

- Alternatives for greenhouse gases such as SF6
- Alternatives for mineral

oil and insulation polymeric using materials "performance high, clean" creating of Prospects • nanotechnology

- Sensors and smart material

Offshore Wind & Large-Scale Storage Solutions

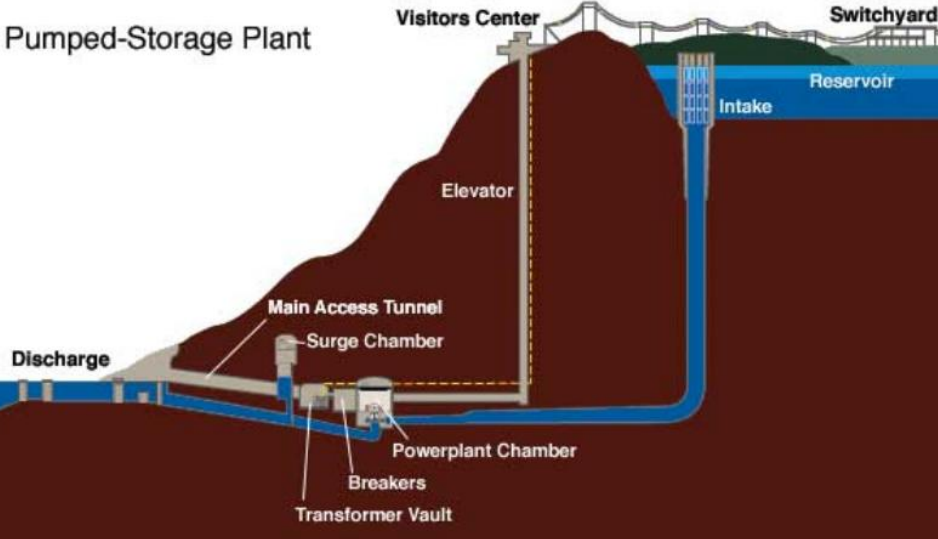
This chapter follows up the chapter "Offshore Wind Integration". In this chapter the effects of large-scale wind on the operation conventional units will be outlined. Then a review of large scale storage techniques will be given, followed by operating strategies for storage (wind power output smoothing, reserve related to forecast errors, day night price arbitrage, wasted wind reduction). Lastly a conclusion will be given.

When using large scale wind energy production there question arises how to use energy storage. The storage is used to smooth out the variability. Tis requires efficient use of infrastructure and efficient operation of conventional units. Furthermore the energy storage is needed to cancel out forecast errors and to make money.

One method is **compressed air energy storage**:



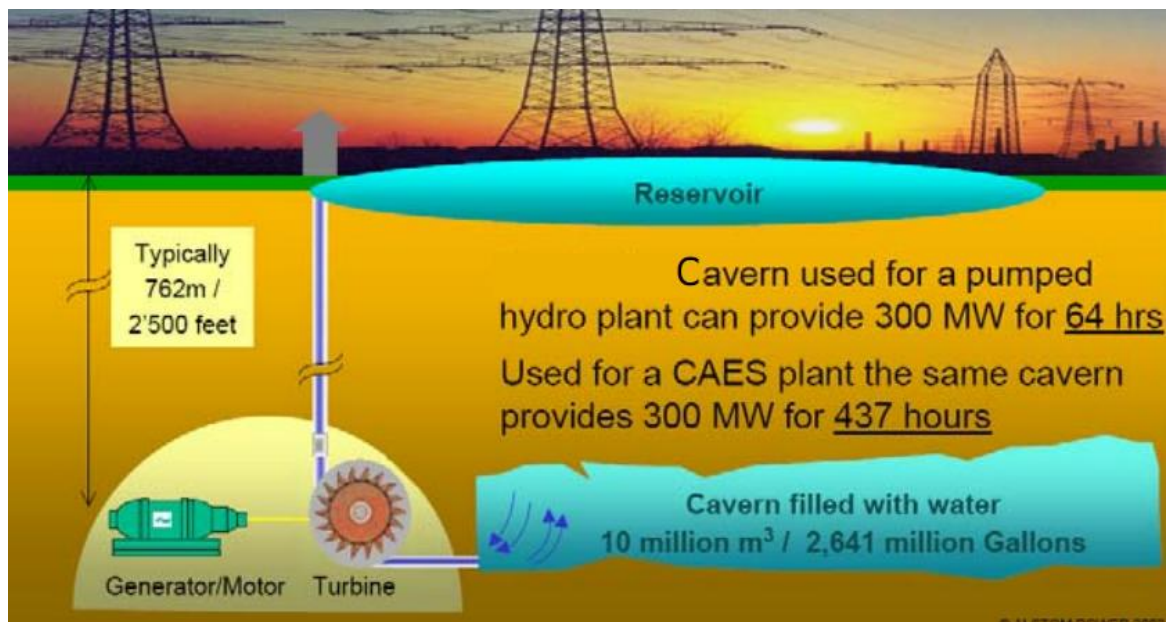
Secondly pumped accumulation can be used:



Furthermore Inverse Offshore PAC (Energy Island)



Underground PAC (versus CAES)



Storage Sizing

The problem with large scale storage is that it will be under-utilized most of the time. In contrast small amount of storage can lead to insufficient capacity to compensate for longer periods of low wind. Storage will not be the only major component to reduce impacts of wind intermittency. Conventional units are able to follow wind power variations in the Netherlands. Storage may be added at sending end for efficient utilization of transmission infrastructure.

Storage Alternatives

Energy storage can be operated based on prices: During low prices there will be storage and high prices will lead to generation. Value of energy storage depends on price differences between peak and off-peak hours and conversion efficiency.

Conclusion

Energy storage is not a must for integration of wind power, provided that exports to non-correlated areas are possible. Energy storage can prevent wind to be wasted. Energy storage can therefore lead to big revenues. The use of energy storage increases total CO₂ emission due to energy conversion losses, substitution of peak load gas by base load coal units.