E.ON Energy Research Center

Current State of Play

Current state of the power grid and its evolution to deliver clean and cost-effective electricity transmission and distribution

27.08.2019

David Raisz, PhD

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Overview

- History, evolution – origin of the main concepts
- Components of the electricity supply
- Struggles and techno-economic driving forces of the sector
- Evolution towards the “Smart Grid” concept

Basic Concepts

Basic Concepts – Power

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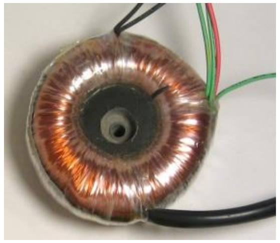
- „Ability”
- kVA, MVA (kW, MW)
- ~ Voltage x Current

- Important i.a. for
  - Peak stress of equipment
  - Equipment rating








Source: Wikipedia

Basic Concepts – Energy

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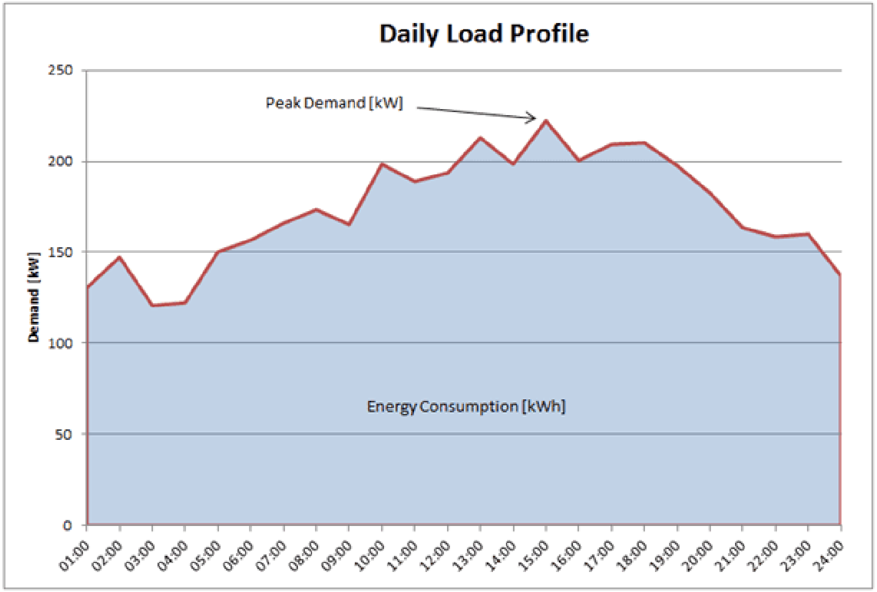
- Consumption, Power x Time
- kWh, MWh (sometimes Joule, BTU, kcal)
- Most consumers pay for energy, not for power

- Load factor: P_{avg} / P_{peak}
  - Measure of utilization



Source: Wikipedia

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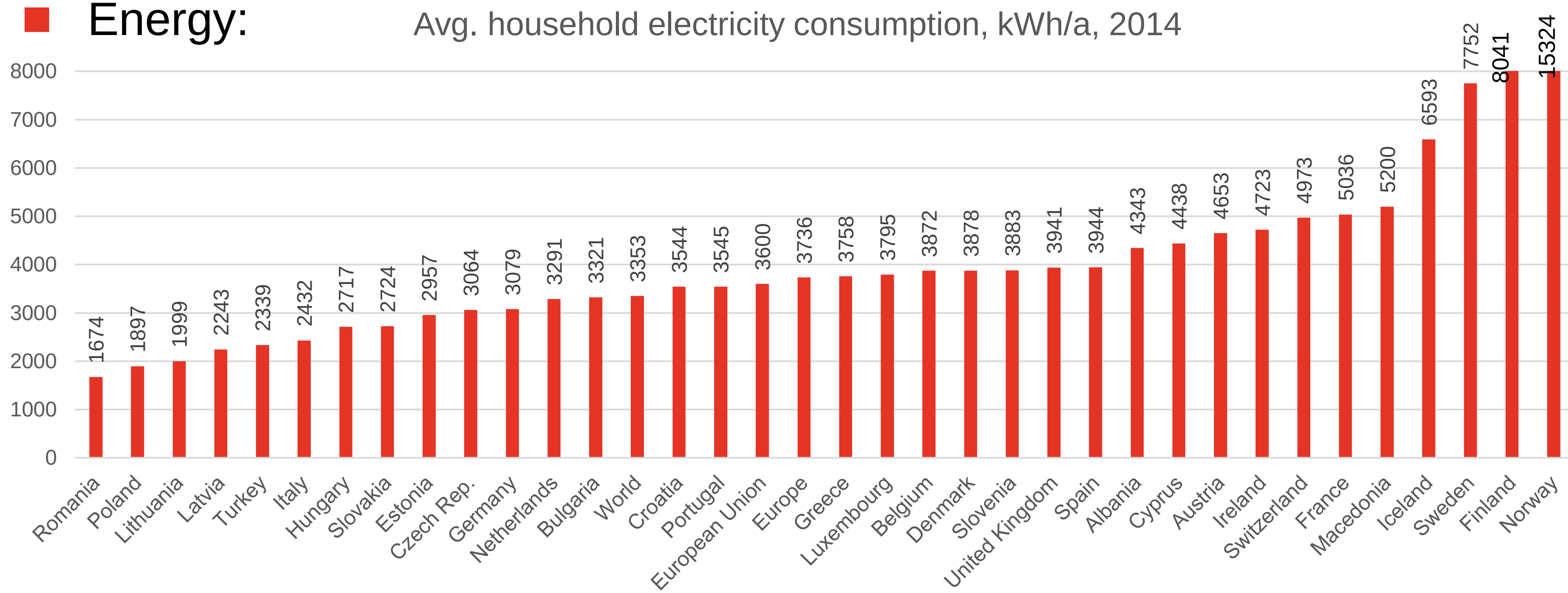
Basic Concepts – Energy

- **Energy:**



- **Power:**
  - Max. possible household peak load @ 3x16A: 11kW
  - Residential transformers have a reated power around 160..630 kVA
    - Rural, low consumption area, 110 consumers incl. school, shop, church, vet: 160 kVA

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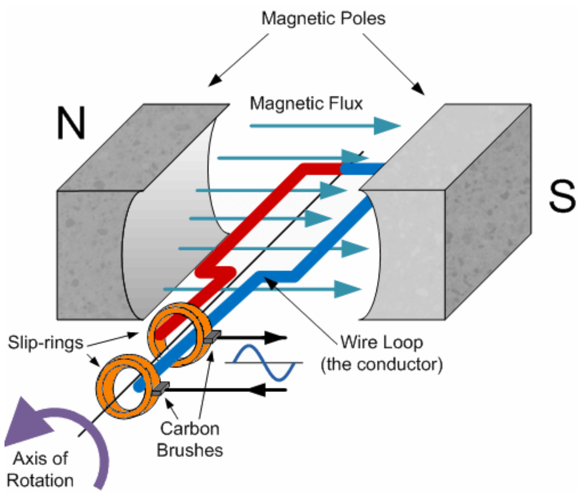
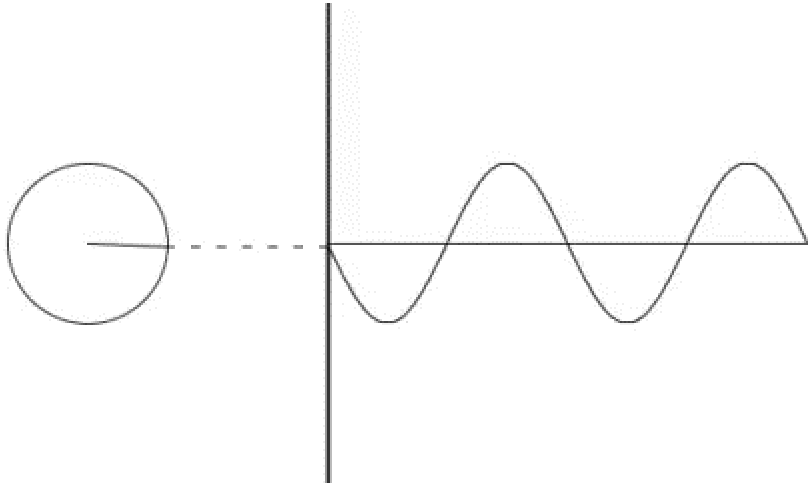
Why does AC have sine waveform?

- Generation: induction principle
  - Movement in a magnetic field generates electricity
- Rotating machines
  - For a simple continuous movement
- Projection of a rotation is a sine



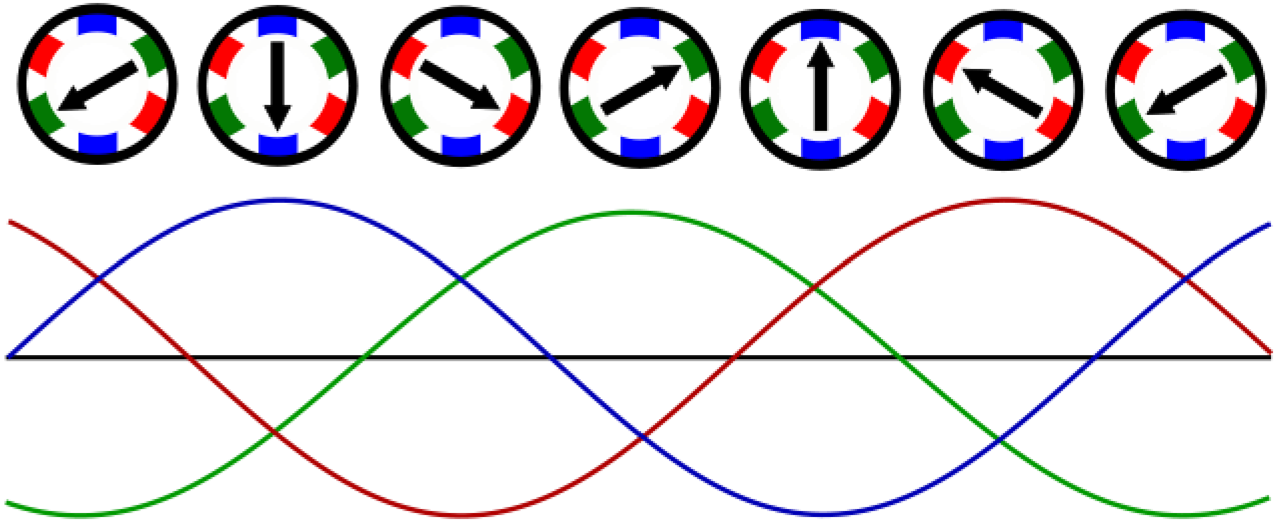
https://www.electronics-tutorials.ws/accircuits/sinusoidal-waveform.html



Easy calculation!

Why do we use three-pase systems?

- Sum of three phase powers is constant
  - Machine power will be constant (not fluctuating)
- A 3-ph system with same voltage and current capacity (per phase) can transmit 3x as much power using just 1.5x as many wires (i.e., 3 instead of 2)
  - The ratio of capacity to conductor material is doubled.



Source: Wikipedia

What are the obstacles for transmitting current?

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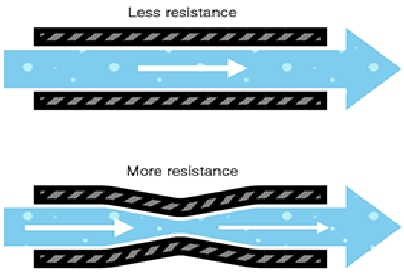
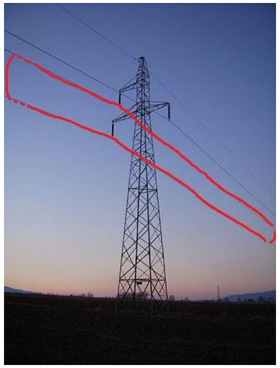
- Resistance
  - both DC and AC
  - Loss of power (heat)
  - Voltage drop



https://learn.sparkfun.com/tutorials/voltage-current-resistance-and-ohms-law/all

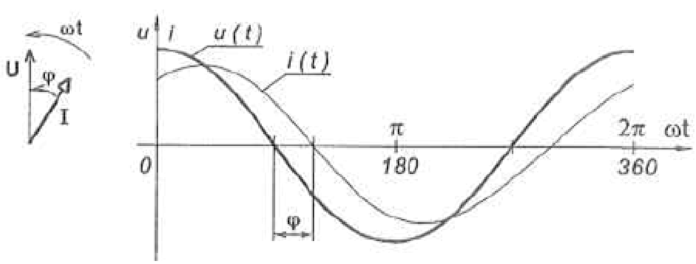
- Reactance
  - only AC, related to loops
  - Voltage drop

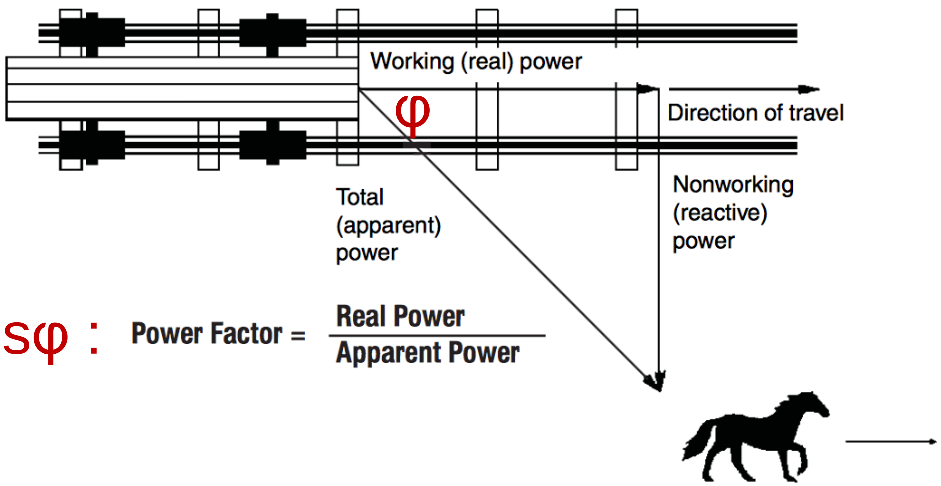


Source: Wikipedia

What is the mysterious „Reactive Power”?

- Apparent power (rating): $S = U \cdot I$ (kVA, MVA)
- Active (real, useful) power: $P = U \cdot I \cdot \cos\varphi$ (kW, MW)
- Reactive (nonactive) power: $Q = U \cdot I \cdot \sin\varphi$ (kvar, Mvar)
  - Generators, lines, loads can produce or consume it
  - Motors need (consume) it
  - Capacitors produce it
  - Important for voltage control
  - in AC systems only





cosφ : Power Factor = $\frac{\text{Real Power}}{\text{Apparent Power}}$

http://energyinnovationproject.com/understanding-the-basics-of-reactive-power/

So how can we transmit power over long distances?

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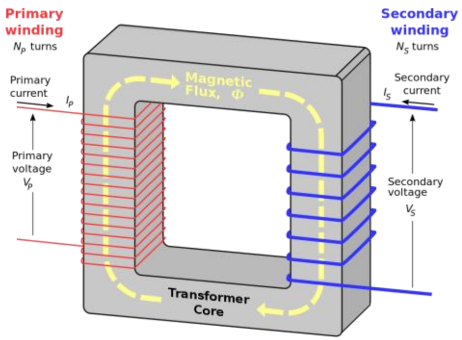
- Voltage drop ~ Current
- Power loss ~ Current^2

➔ Want to use smaller current

- Transmitted power ~ Current x Voltage

➔ Have to use higher voltage

- Transformer:



Source: Wikipedia

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How did 50 (60) Hz evolve?

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Why not DC? Why not higher frequencies?

	DC	25 Hz	50/60 Hz	400 Hz
Early rotating machines	👎	👍	👍	👎
Transformation	👎	🤚	👍	👍
Transmission	🤚	👍	👍	👎
Lighting	👍	👎	👍	👍
System interconnection	Frequencies must be the same			

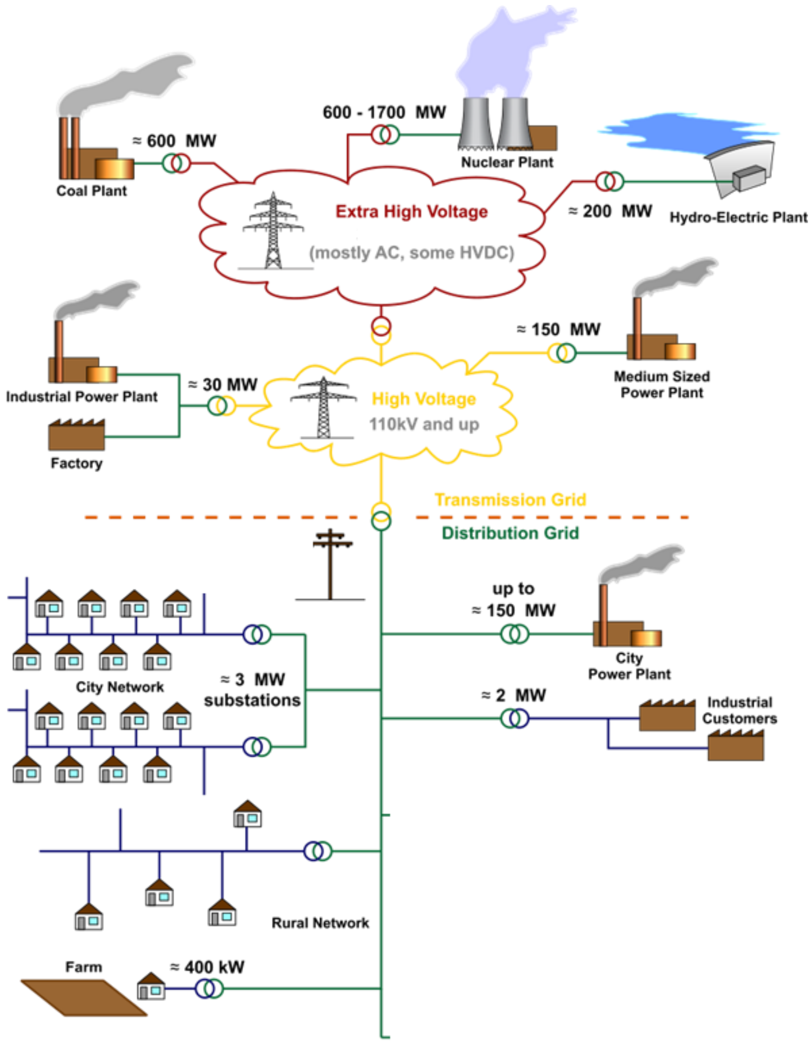
Traditional Power System:
Structure, Elements and Tradeoffs

Voltage Levels

Example:

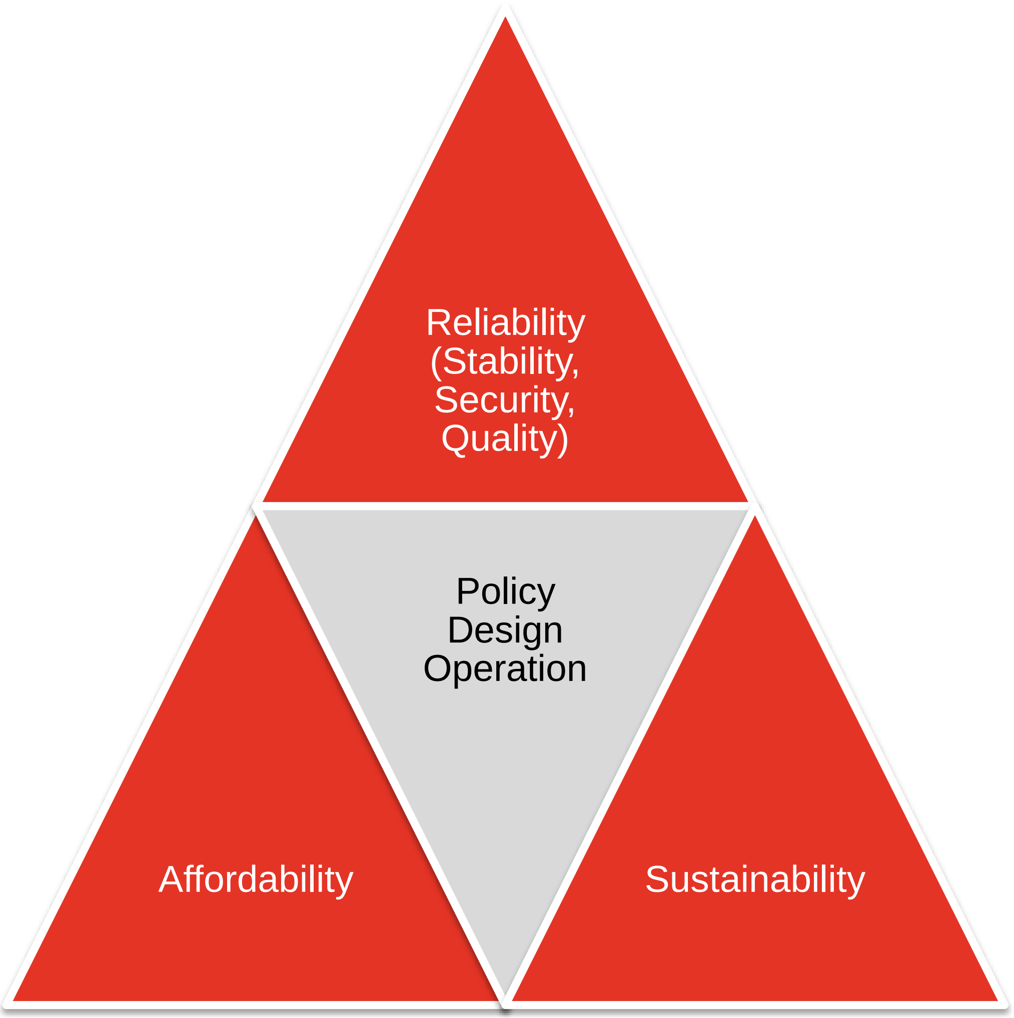
- Germany:

LV	MV	HV	EHV
distribution	distribution	subtransmission	transmission
1 123 000 km	479 000 km	77 000 km	35 000 km
radial	radial	radial / meshed	meshed
400 V (230 V)	6 kV **10 kV** 15 kV **20 kV** 30 kV	60 kV **110 kV**	**220 kV** **400 kV**



Source: Wikipedia

Main Aspects for Design and Operation

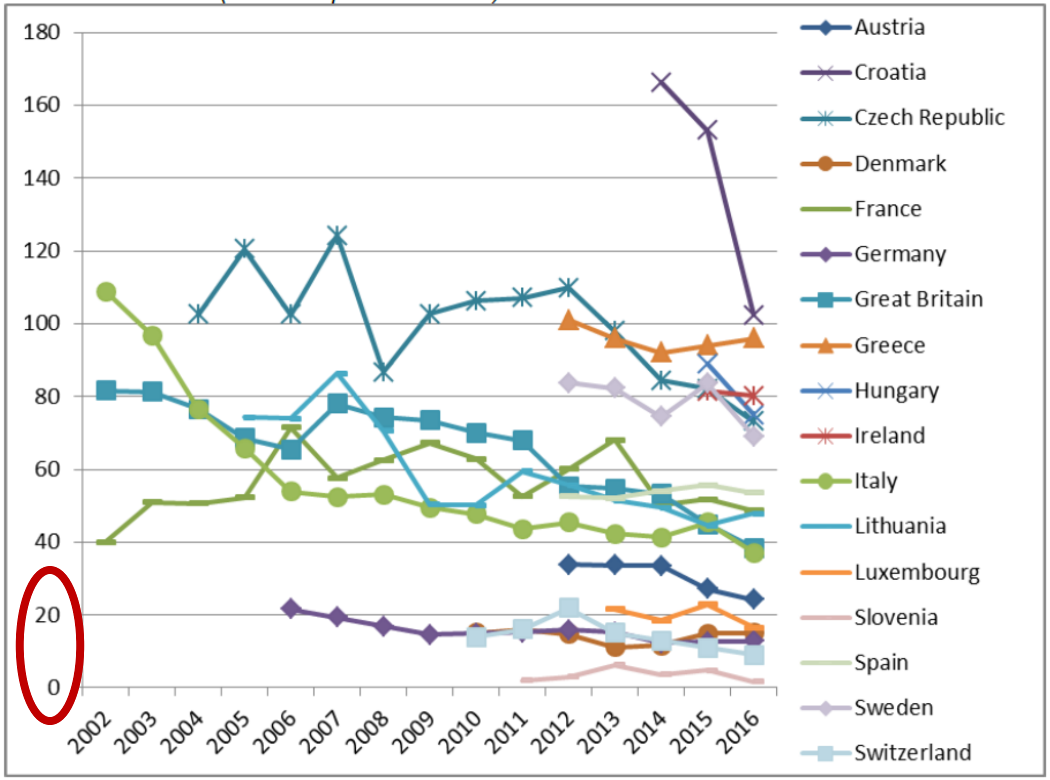


Reliability

CEER Benchmarking Report 6.1 – Continuity of Electricity and Gas supply

- SAIDI – System Average Interruption Duration Index (minutes/customer/year)

Figure 4 – Electricity: unplanned SAIDI, without exceptional events, only countries not exceeding 200 minutes (minutes per customer) – time series and min-max



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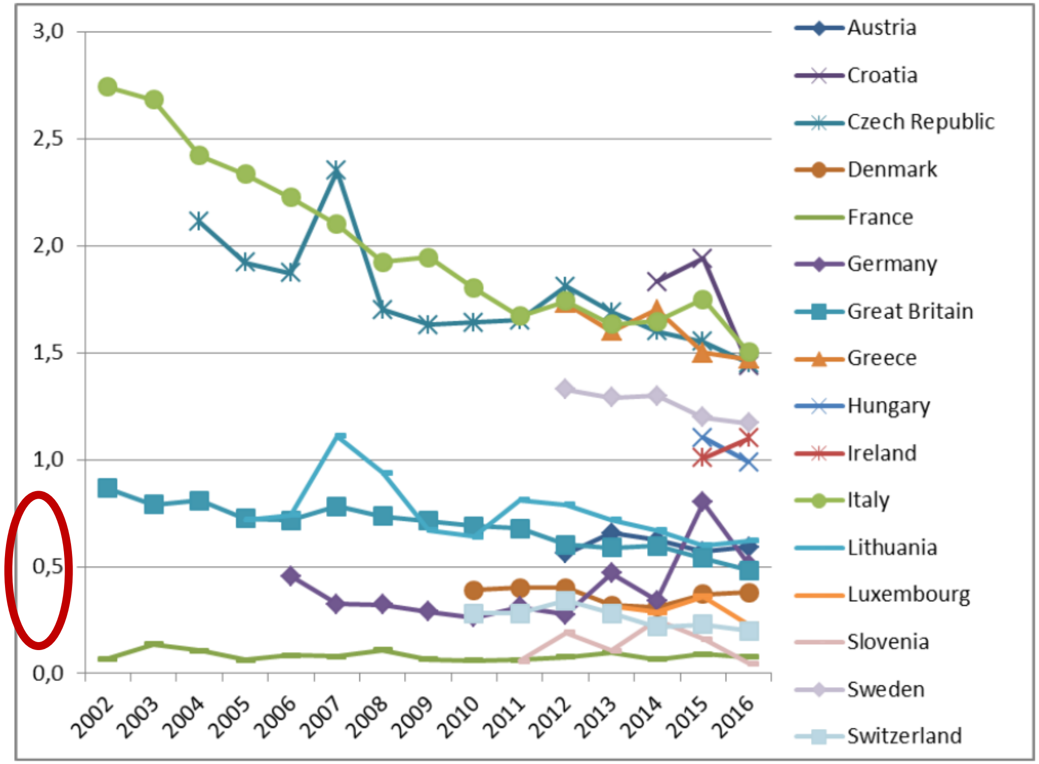
CEER Benchmarking Report 6.1 – Continuity of Electricity and Gas supply

- SAIFI – System Average Interruption Frequency Index (event/customer/year)

Figure 12 – Electricity: unplanned SAIFI, without exceptional events, only countries not exceeding 3 interruptions (interruptions per customer) – time series and min-max



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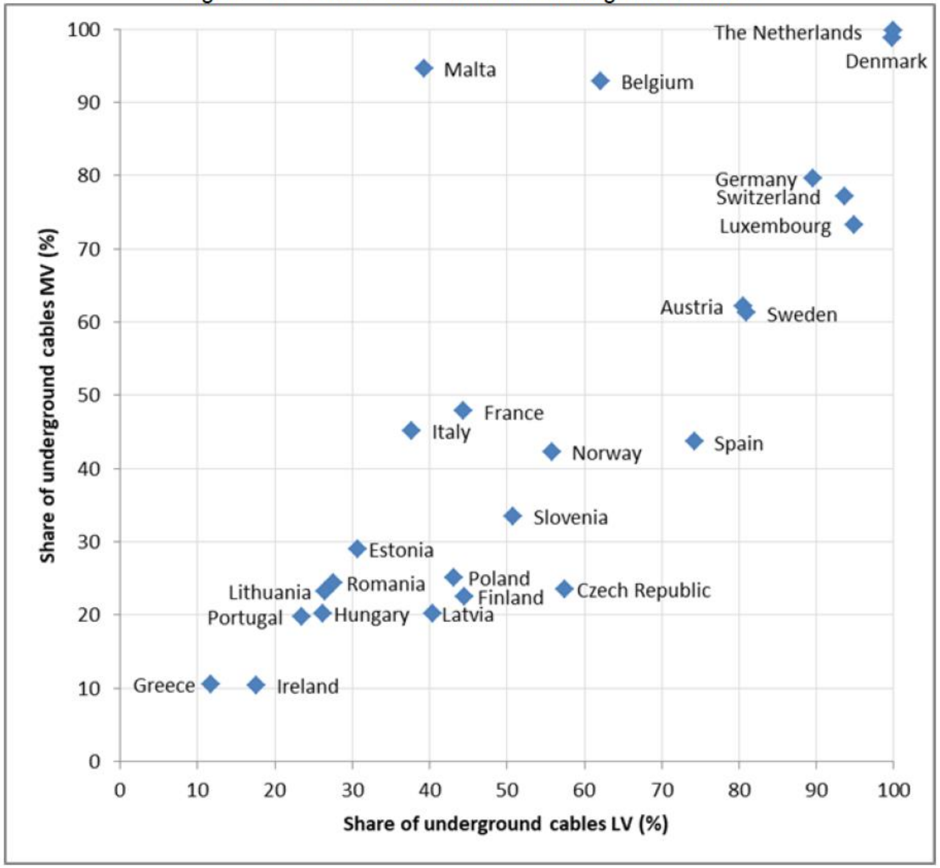
Reliability

Figure 21 – Share of LV and MV underground cables



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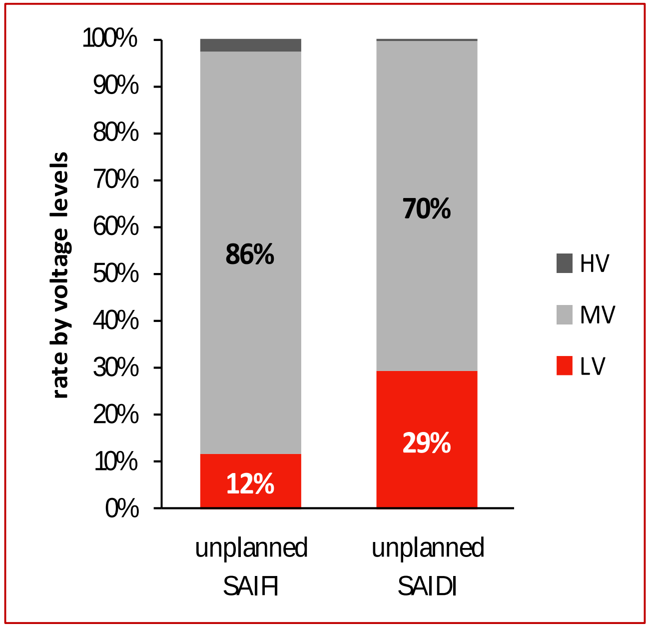

Data from one specific DSO with 80% OHL share

Affordability / Reliability: Outage costs

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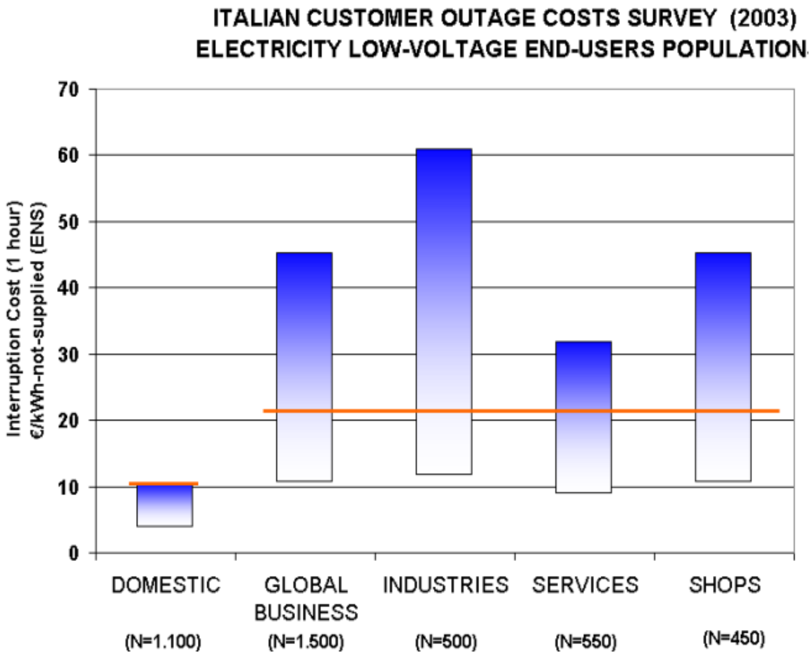
- Many studies exist, each comes to different conclusions ☺



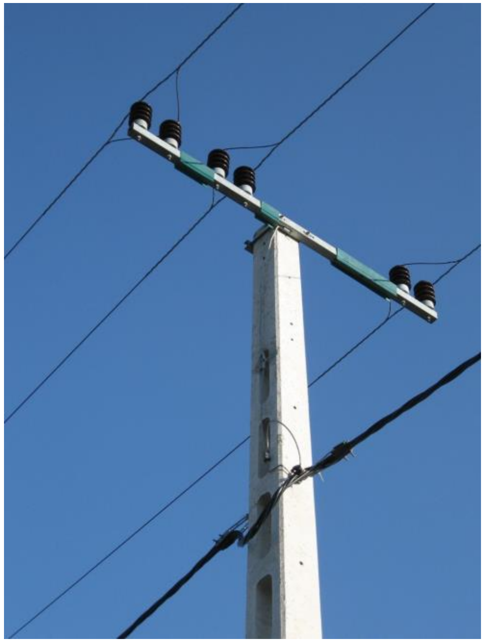
CEER: Guidelines of Good Practice on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances, Ref: C10-EQS-41-03

- US: **100 billion USD/year**

Lines

- Overhead Lines (OHL)
  - Weather, trees
  - Visual impact, birds
  - Right-of-way

- Cables (underground)
  - Price



Source: Wikipedia

Affordability – Investment costs

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Figure 1: Overhead lines by circuit route length (km) by box-plot

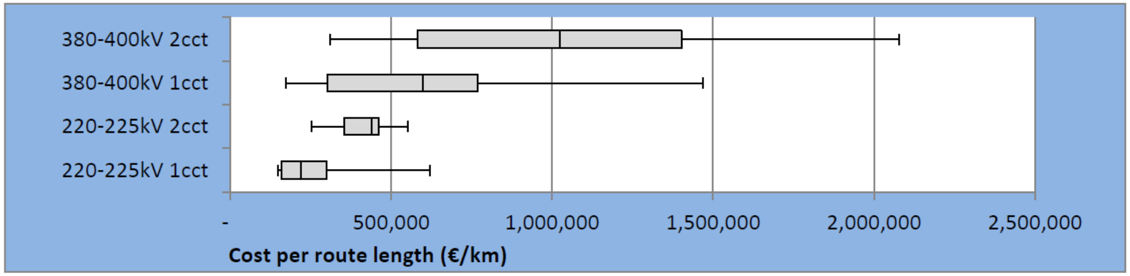


Figure 3: Underground cables by route length (km) by quartile box-plots

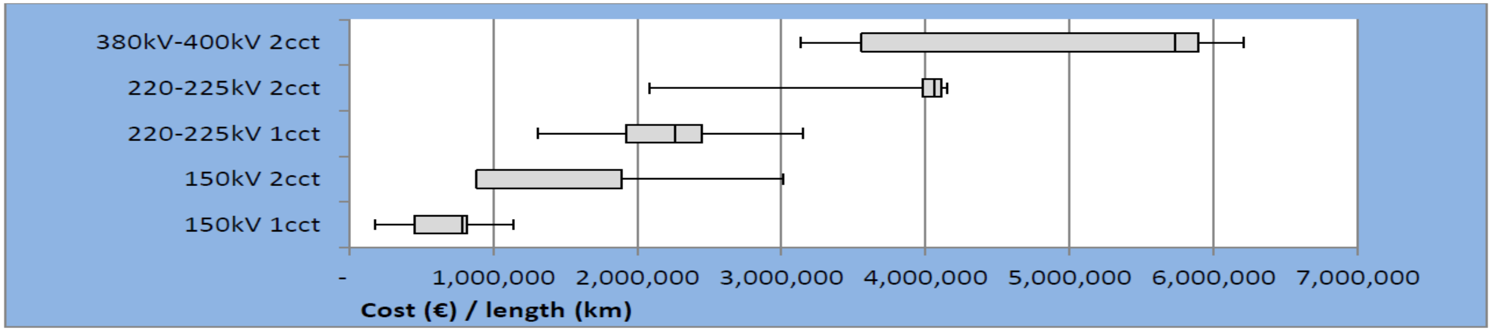
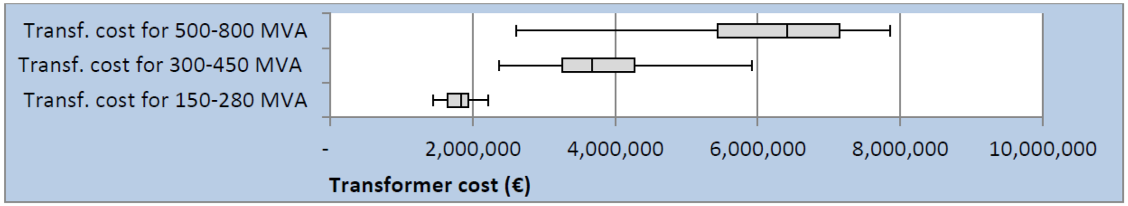


Figure 10: Transformer cost (€s) split into rating ranges by quartile box-plots



ACER Ref: 15 - Infrastructure Unit Investment Costs - ELEC-2015

Generation

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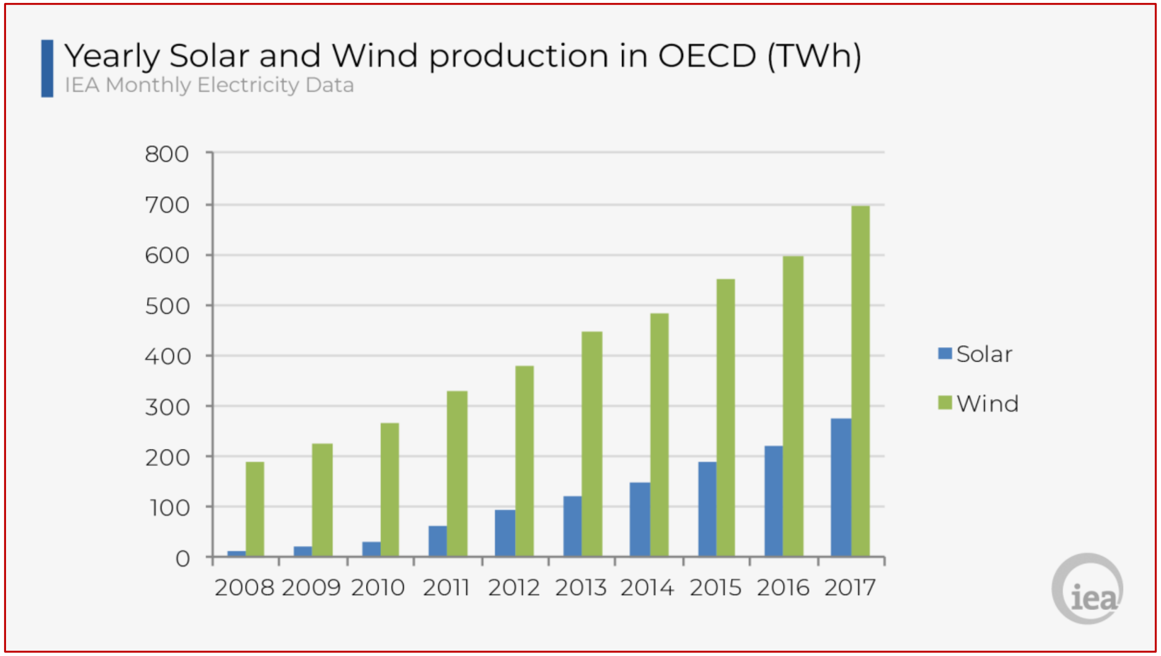
- Thermal power stations dominate the traditional power system

Source: Wikipedia

  - **Flexible!**
- Recent trends:
  - Some power plants lose business ➔ high „reserve” prices (see freq.control)
  - „Energiewende” in Germany – away from nuclear

Generation

- Recent trends:



Source: IEA

- Consumers become producers
  - **Voltage rise problem**
  - **Weather dependent – balancing problem**

Substations

- Node = „Bus“ or „Busbar“
- Different voltage levels meet – transformers
- Network topology can be arranged

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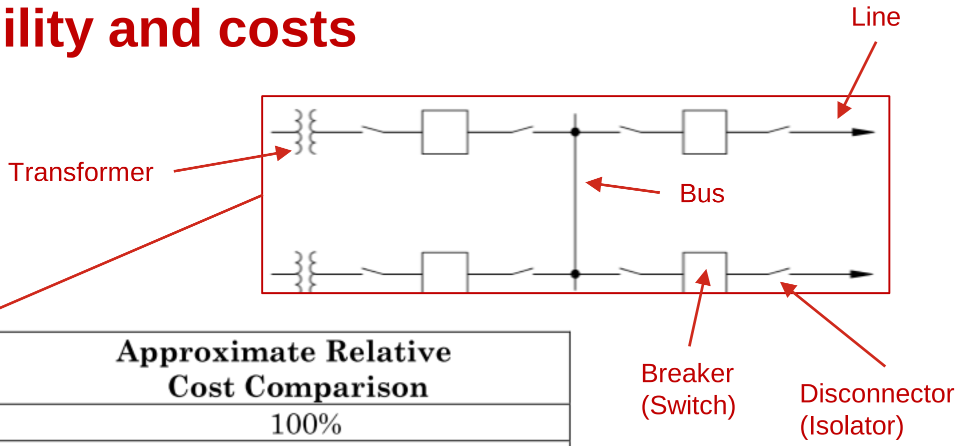
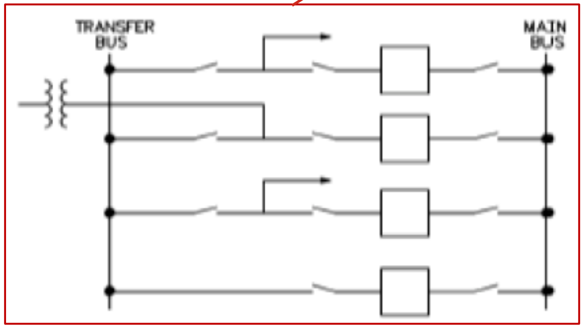
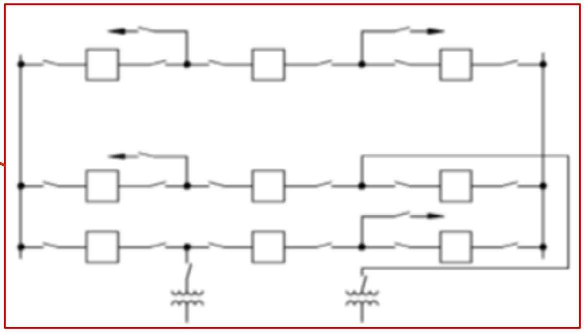
Substations

- Different topologies affect **reliability and costs**
  - Circuit breakers are expensive



Bus Arrangement	Approximate Relative Cost Comparison
Single Bus	100%
Sectionalized Bus	122%
Main and Transfer Bus	176%
Ring Bus	156%
Breaker-and-a-half	158%
Double Bus - Double Breaker	214%





Source: CIGRÉ

Protection, ITC

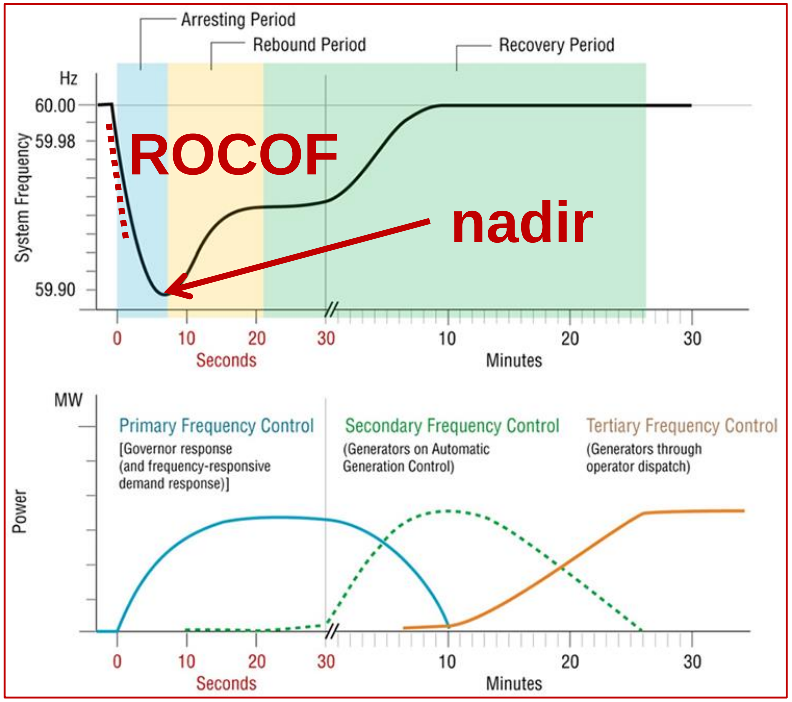
- Simple protection schemes
  - Short circuits and earth faults are the greatest danger to equipment
  - Overcurrent, distance (impedance), differential protections well established
- Recent challenges with high RES share:
  - **Short circuit current?**
  - **Impedance?**
  - **Reverse flows**
  - **Reconfigurations (microgrids)**
- SCADA (Supervisory Control and Data Acquisition)
  - The neural system of the electricity infrastructure
  - Development towards few control centres, remotely managed substations
    - EHV / HV levels only
  - Recent years:
    - Smart meters (first @ industry/commercial, then residential) – 15min values offline
    - PMUs

Frequency control

Principle:

https://learn.pjm.com

Types of reserve:



https://www.e-education.psu.edu/ebf483/node/705

No storage.

Power Electronics based Generation

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- Challenges
  - ROCOF, nadir (inertia problem)
  - Stability problems at higher frequencies
  - Synchronization:

https://www.youtube.com/watch?v=Aaxw4zbULMs

- Opportunities
  - Faster control
  - Decentralized / distributed control (resilience)
  - Microgrids

Schedules – market contracts – balancing

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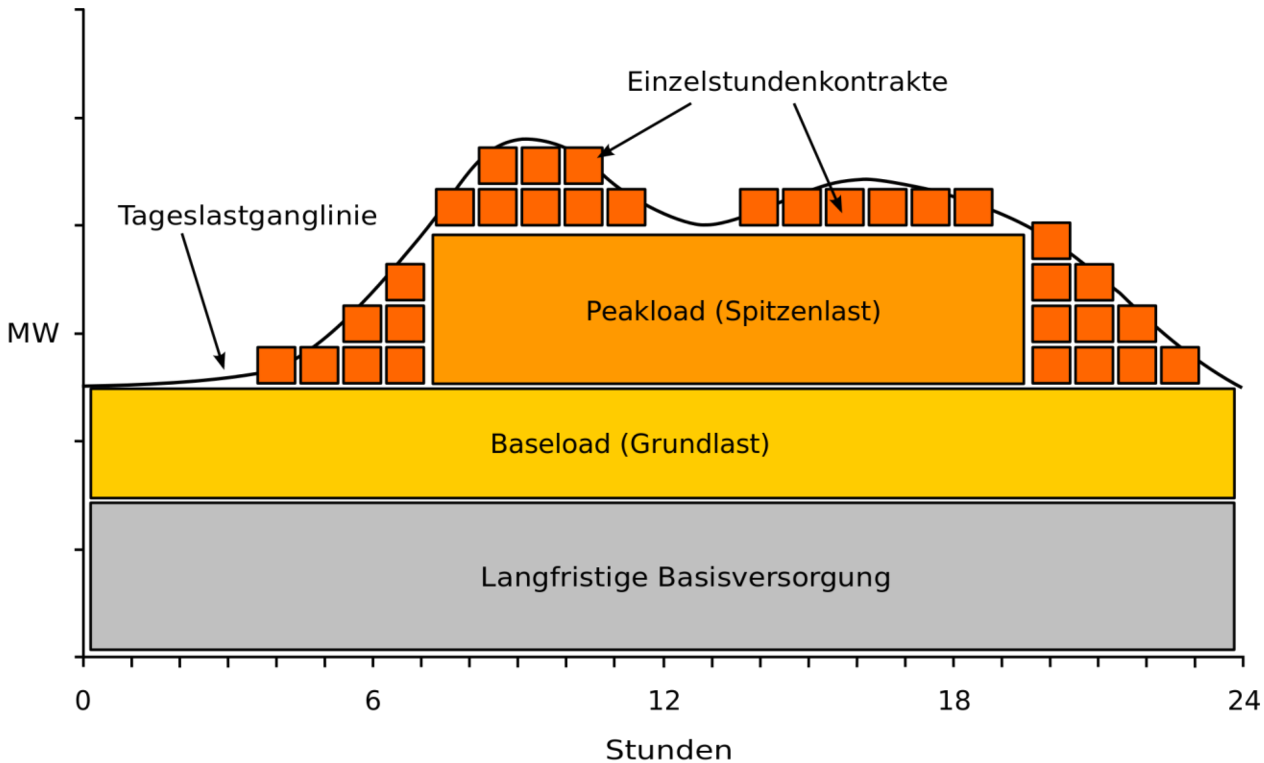
- Consumer's daily load profile has to be covered with various **products** from the market, over various time horizons (risk hedging)



Source: Wikipedia

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Stages of Power System Development

Early 1900's – 80's

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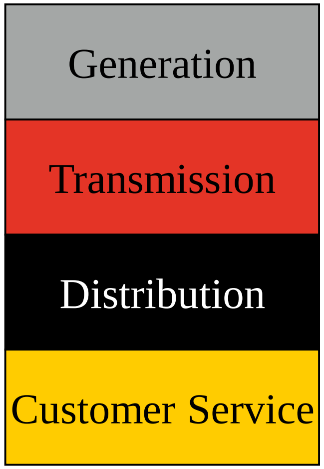
- Transmission technology development
  - Increasing voltage levels
  - Increasing coverage of supply
- Reliability – interconnector lines at higher voltage levels
  - Standardization of voltage levels, frequencies
- Development towards centralized, large power stations
  - Better economies of scale than decentralized small units
  - Decreasing electricity prices
- Vertical monopolies: service area = state/country
  - Cooperation: accidental … national institutions
  - HVDC links between Eastern and Western Europe



80’s – early 2000’s

- Increasing fuel prices, inflation, environmental concerns:
  - First acts that introduce competition: utilities to purchase power from independent generators located in their service area
- Major opening of industry to true competition in generation
  - “nondiscriminatory” access to transmission
  - Dramatic restructuring of electric utility industry
- Cooperation: increasing levels of harmonization in
  - operation (incl. East-West connection in the 90’s)
  - planning
  - market development (way paved by some blackouts…)

Development in the last decade

- Transmission
  - Already smart (observed, controllable)
  - Meshed
  - High investment costs (HVDC, FACTS already there)
  - ➔ Not the focus of „Smart Grid“

- Distribution
  - Most prone to faults
  - Unusual situations due to renewables
  - Low level of observability and controllability
  - Radial (in some cases a mesh can be created)
  - Lower investment costs
  - ➔ „Smart Grid“ playing field
  - Investments in measurement and automation (FLISR)

Summary

Characteristics of traditional and evolving power systems

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Traditional

- Large-scale, centralized, fully controlled generation, no small-scale or decentralized
- Unidirectional power flow
- Voltage control: few devices, simple planning and coordination
- Observability / controllability at EHV/HV level only
- Negligible storage
- Few power electronic elements in the system (except consumers)

Transforming

- Increasing levels of small-scale, decentralized, less predictable generation
- Bidirectional power flow
- Voltage control requires new devices and sophisticated coordination
- Observability / controllability penetrates to MV and LV
- Storage is becoming available
- Power electronics dominate generation – new control opportunities

Characteristics of traditional and evolving power systems

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Traditional	Transforming
Frequency control: fully controlled generation follows load variation	Frequency control: less predictable generation ➔ more coordination between consumers – producers – storage, flexibility gains value
Simple protection schemes	Complex protection schemes, automatic reconfiguration (self-healing, microgrid-based)
Big players dominate the market	Small players are entering the market. Active consumers.

Further Aspects

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Challenges:

- Environmental concerns increase – 100% RES vision
- Aging asset
- Increasing risk at investments (40+ years lifetime!) – regulatory challenges

Opportunities:

- ICT development (5G, cloud…)
  - Higher observability (measurements and data transfer from distribution levels, metering at residential level, PMUs)
  - Development in automation technology (distributed/decentralized)
- Sector coupling (EV – V2G, P2G)
- MVDC, LVDC (**household AC-DC-AC conversion losses: 15%+**)

Our contributions – a sample…

- Substation Automation Unit – **new devices & concept for decentralized DS automation** – more resiliency and flexibility (H2020 IDE4L)
- Advanced platform for the **coordination of local energy storage**, focus on the multi-physics aspect: thermal and electrical (H2020 ELSA)
- Fully virtualized substation, **5G based edge computing** to support IoT connection at MV and LV (H2020 SOGNO)
- VILLAS & Global RT SuperLab: interconnection of physically remote **HiL** infrastructure
- Linear Swing Dynamics – a new approach to use inverter dof for improved **virtual inertia** with 100% RES (H2020 RESERVE)
- Development of practical Virtual Oscillator Control based solutions for a **island and grid connected** operation of inverters (BMBF ENSURE)
- **MVDC** system-level control and automation development (FEN)

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Thank you for your attention

27.08.2019

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Interactive session

- Quiz
  - Socrative.com
  - ➔ Login
  - ➔ Student Login
  - ➔ Room name: „SMARTGRID”
- Game
  - Google „Power the Grid 2020”
  - Online: https://www.crazygames.com/game/power-the-grid-2020
  - Download: https://gamejolt.com/games/powerthegrid2/286451
- Q&A

Quiz

Quiz

- Which is an SI unit of active power?
  A. kVA
  B. kW
  C. kWh
  D. kvar
  E. kvarh

- Which of the below statements are TRUE?
  A. Power is proportional to energy times time
  B. Energy is proportional to power times time
  C. Power is proportional to voltage times current
  D. Equipment peak stress is expressed in terms of energy
  E. Equipment peak stress is expressed in terms of power

Quiz

- Which of the below statements are TRUE?
  A. Load factor = P_{avg} / P_{peak}
  B. Load factor = P_{peak} / P_{avg}
  C. Load factor is a measure of equipment utilization
  D. Load factor is a measure of reactive power
  E. Load factor is a measure of the load curve shape

Quiz

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- TRUE or FALSE?
  - Resistance is defined in AC systems only
  - Reactance is defined in AC systems only
  - Both resistance and reactance cause voltage drop
  - Transformers are used to change the voltage in order to transport electricity to large distances
  - Transmission systems are operated mainly in a radial way
  - Cables are less exposed to faults than overhead lines
  - SAIDI in most well developed countries is around 200 minutes/customer/year
  - SAIFI in several well developed countries is below 1 outage/customer/year
  - Most distribution systems were designed for bidirectional power flows
  - System-wide balance of active power generation and consumption can be judged by looking at the frequency
  - Rotational inertia in the power system is decreasing due to the increasing share of RES

Quiz Solutions

Quiz

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