Cyprus University of Technology

EEN320 - Power Systems I (Συστήματα Ισχύος Ι)

Part 1: Introduction

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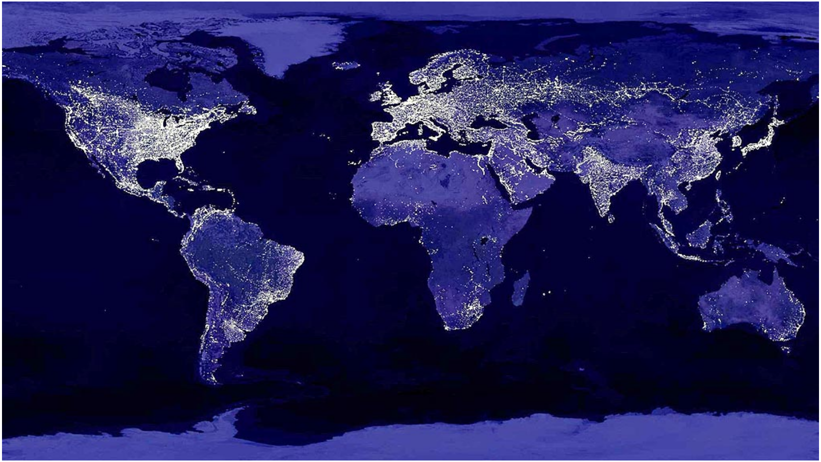
Last updated: January 14, 2020

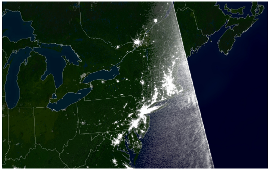
Electric power systems



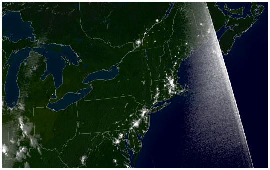
What is their purpose?

1. Transfer electric energy from point A to point B
2. Do it safely (don't kill anyone)
3. Do it reliably (continuous supply, no interruptions)
4. Do it enviromentally friendly
5. Do it at a low cost and accessible to all

(3) - U.S. Northeast Blackout 2003



NYC before blackout, ©Nat. Oceanic and Atmospheric Admin.



NYC after blackout, ©Nat. Oceanic and Atmospheric Admin.

- The outage on Aug, 14 2003 affected about 10 mio. people in Ontario, Canada and 45 mio. in the Northeastern and Midwestern United States
- Estimated cost: US$ 4 to 10 billion
- A power plant in Eastlake, Ohio switched offline during high electrical demand
- This put a strain on high-voltage power lines, which later switched out of service when they came in contact with trees
- The resulting cascading effect ultimately forced the shutdown of more than 100 power plants

(3) - Italy Blackout 2003

Italy and Switzerland after blackout, ©Reuters

- Outage on Sept, 28 2003 struck mainland Italy and parts of Switzerland affecting 56 mio. people
- The power line supplying electricity to Italy from Switzerland was damaged by storms and switched off
- Two 400 kV power lines between France and Italy switched off due to sudden increased demand
- Cascading effect disrupted power supply to Italy from France and Switzerland, control of the grid was lost in the next 4 seconds and lines tripped one by one

(3) - Disruption in European electric grid 2006

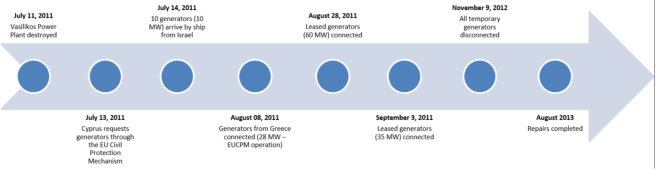
Norwegian Pearl, © Pink Dispatcher

- The outage on Nov, 4 2006 affected 15 mio. households in parts of Germany, France, Italy, Belgium, Spain and Portugal
- Triggered by badly assessed switching off a transmission line over river Ems to allow safe passage of a cruise ship
- Further automatic switching off of transmission lines split the European transmission grid into three independent parts (West, North-East, South-East) leading to power imbalances in each area
- The power imbalance in the Western area lead to a large frequency drop causing outages for consumers

(3) - Disruption in European electric grid 2006

- According to the UCTE report on the disturbance
  - The imbalance between supply and demand as a result of the splitting was further increased in the first moment due to a significant amount of tripped generation connected to the distribution grid
  - Generally, the uncontrolled operation of distributed generation (mainly wind and combined-heat-and-power) during the disturbance complicated the process of re-establishing normal system conditions
- These statements also show that smarter control methods for distributed generation could contribute to system stability

(3) - A bit closer to home

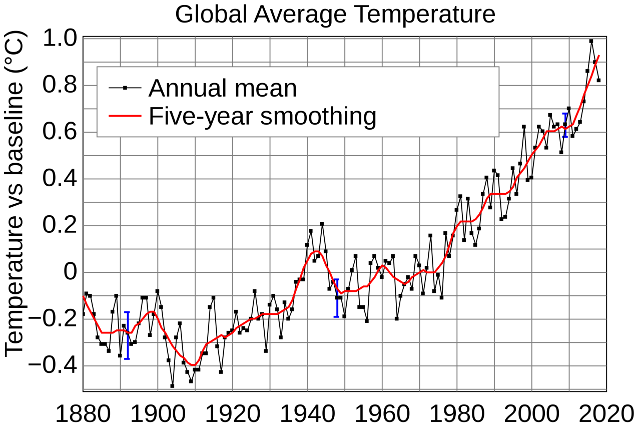


Karagiannis, et al. "Power grid recovery after natural hazard impact", tech. rep., 2017

- The Cyprus outage of 2011 affected all of the population on the island, leading to reduced supply and scheduled outages over a prolonged period of time
- Triggered by an explosion at Evangelos Florakis Naval Base that destroyed the Vasilikos Power Plant
- Almost 60% of the island's power generating capacity was destroyed
- Estimated economic losses from power interruption[1] around 840 million euros per year

[1] T. Zachariadis, A. Poullikkas, The costs of power outages: A case study from Cyprus, Energy Policy, 2012

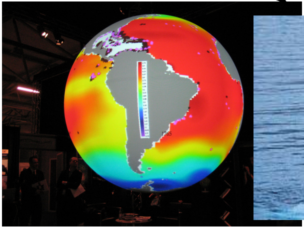
(4) - Environmental aspects



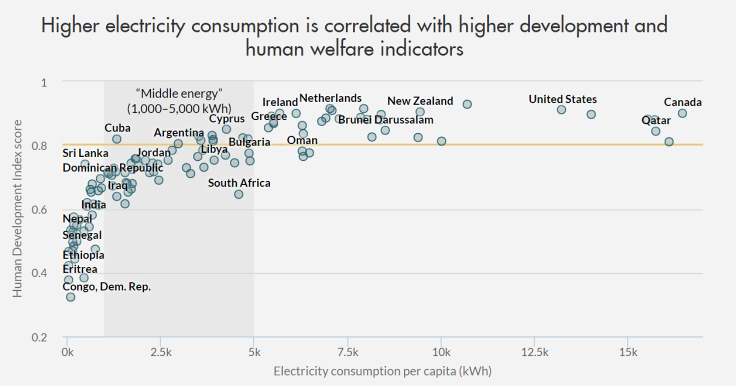
(4) - Two major problems with fossil fuels

1) Energy generation from fossil fuels highly contributes to greenhouse gas emissions & climate change!

2) Fossil fuels are finite!



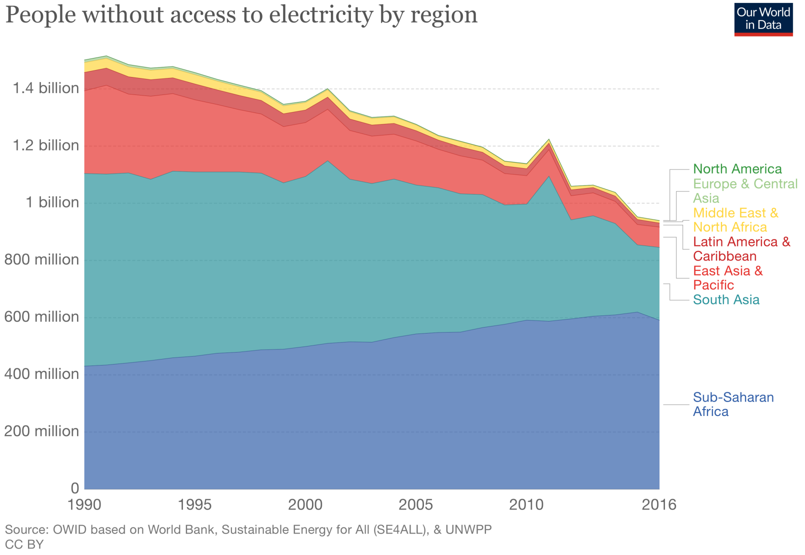
(5) - Cost of energy and development



Source: UNDP Human Development Index (2013); World Bank, World Development Index (2013)

- Human Development Index: statistic composite index of life expectancy, education, and per capita income indicators
- First part of the curve almost linear!

(5) - Cost of energy and development



Why is it hard to do all 5?

- World's largest and most complex engineered systems
- Modern industrialized societies heavily rely on use and steady supply of electric energy
- Power systems are expected to be very reliable
- Even a single failure can have catastrophic consequences for society!
- In addition: power systems continuously subjected to large variety of disturbances and contingencies (lighting, hurricanes, human errors,. . .)

→ Rather complex and sophisticated industrial processes behind electric energy supply!

Solar power

Onshore wind

Offshore wind

Shift energy production from fossil to renewable energy sources

Marine power

Bioenergy

Small hydro power

Motivation - Smart Grid Systems

Production

Markets

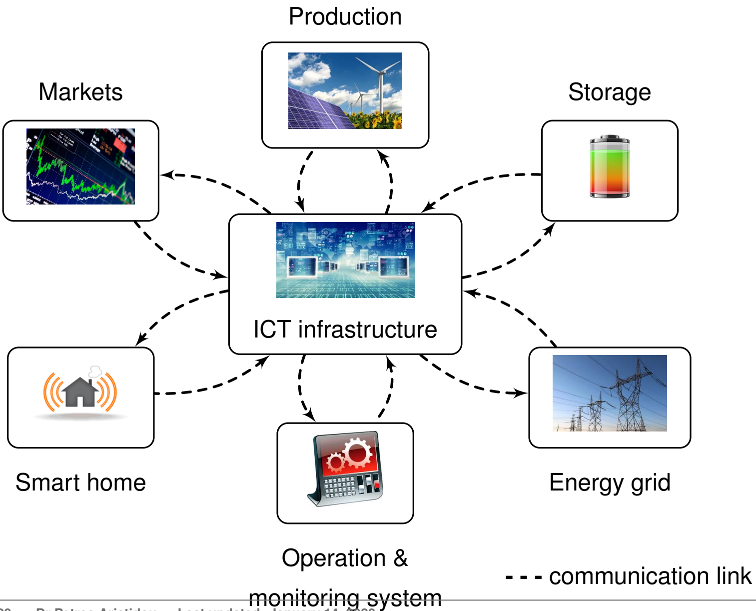
Storage

Smart home

Energy grid

Operation & monitoring system

Motivation - Smart Grid Systems



Motivation - Smart Grid Systems

- Key ingredients: ICT, renewables, flexible operation & consumption
- Many challenging open questions
- Large investments (EU-wide 500 billion euros by around 2020)

$\Rightarrow$ Plenty of exciting & interdisciplinary opportunities

> This course intends to provide you with a fundamental understanding of the key equipment and their functionality in power systems, so that you are well-prepared to further explore these opportunities

1 EEN320 - Power Systems I: Learning objectives

This course intends to provide you with a fundamental understanding of the key equipment and their functionality in electric power systems.

On completion of this course, you should be able to ...

1. ...explain the functioning and modelling of the main components in a power system
2. ...understand the principles of planning and operation of power systems
3. ...be able to solve basic load flow calculations
4. ...have an overview of future trends in power systems and smart grids
5. ...appreciate, through basic case studies, the technical challenges in both the design and the operation of power systems

1 EEN320 - Power Systems I: course overview

1. Introduction
2. Single-phase and three-phase AC systems
3. The power transformer
4. The per-unit system
5. The transmission line
6. Fundamentals of power system operation
7. The synchronous machine (simplified model)
8. Current and future trends in power system operation - the path to the smart grid

1 EEN320 - Power Systems I: course organisation and assessment

- Organisation (subject to changes based on in-semester progress)
  - Monday and Tuesday 08:30-10:30
  - Room B24-L06 (Εργαστήριο Δικτύων και Επιστήμης Δεδομένων)
  - 28h theory, 14h example classes, 8h laboratory, 4h revision[2]
- Assessment
  - Final exam: 60%
  - Mid-term exams: 20% (4 short exams of 5% each, in-class, every 2-3 weeks)
  - Lab report: 20%
- Course site: `https://paristidou.info/courses/een320/`

[2] reserve the right to change based on in-semester progress

1 Acknowledgements and reading material

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This course and its presentation are based on

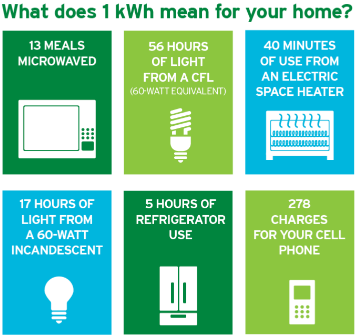
1. J. D. Glover, M. S. Sarma and T. Overbye, ”Power System Analysis & Design”, 6th edition, Cengage Learning, 2017
2. Γ. Γιαννακόπουλος, Ν. Βοβός, ”Εισαγωγή στα συστήματα ηλεκτρικής ενέργειας”, εκδόσεις ΖΗΤΗ, 2017
3. Κ. Βουρνάς, Γ. Κονταξής, ”Εισαγωγή στα συστήματα ηλεκτρικής ενέργειας”, εκδόσεις ΣΥΜΜΕΤΡΙΑ, 2010
4. T. Van Cutsem, ”Introduction to Electric Power and Energy Systems”, Lecture notes, University of Liege, 2018
5. G. Anderson, ”Modelling and analysis of electric power systems”, Lecture notes, ETH Zurich, 2016

Book 1 (available at the library) and the lecture notes are the **official** study material. Book 2 or 3 are alternative in Greek version.

What is a kWh?

$$kWh = \frac{Watt \cdot time(hrs)}{1000}$$

- Unit of measurement of energy
  $1\ kWh = 1000\ W \cdot 3600\ s$
  $1\ kWh = 3600000\ J$
  $1\ kWh = 3.6 \cdot 10^6\ J$



Source: https://www.efficiencyvermont.com/

How much is 1kWh? $\rightarrow$ Try to put in descending order!

1.5V, 2000mAh

Professional cycling athlete

250ml, 100°C

700ml (40%)

10kg, 1m

1t, 100km/h

1kWh electricity

45g, 202kcal

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How much is 1kWh? → Try to put in descending order!

1kg → 4kWh

700ml (40%) → 2.26kWh

1kWh electricity

400W, 1h → 0.4kWh

45g, 202kcal → 0.24kWh

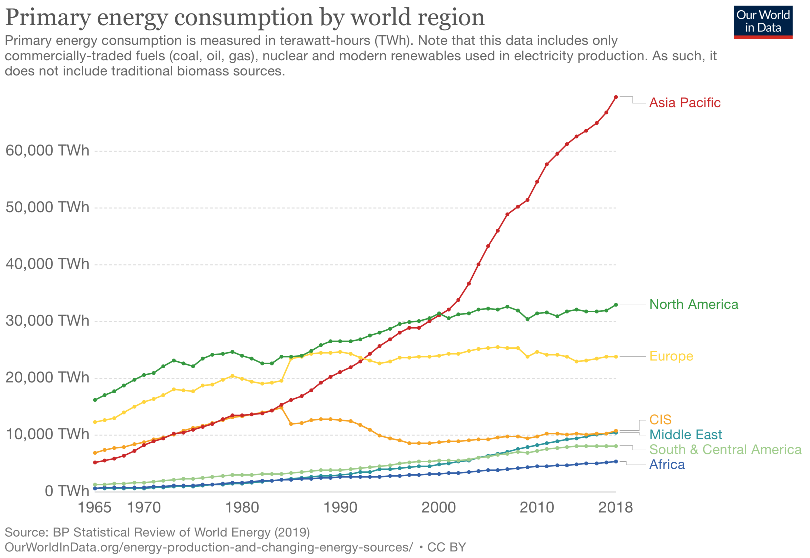
1t, 100km/h → 0.1kWh

250ml, 100°C → 25 Wh

1.5V, 2000mAh → 3 Wh

10kg, 1m → 27 mWh

2 Change in energy demand



2 Energy consumption by fuel

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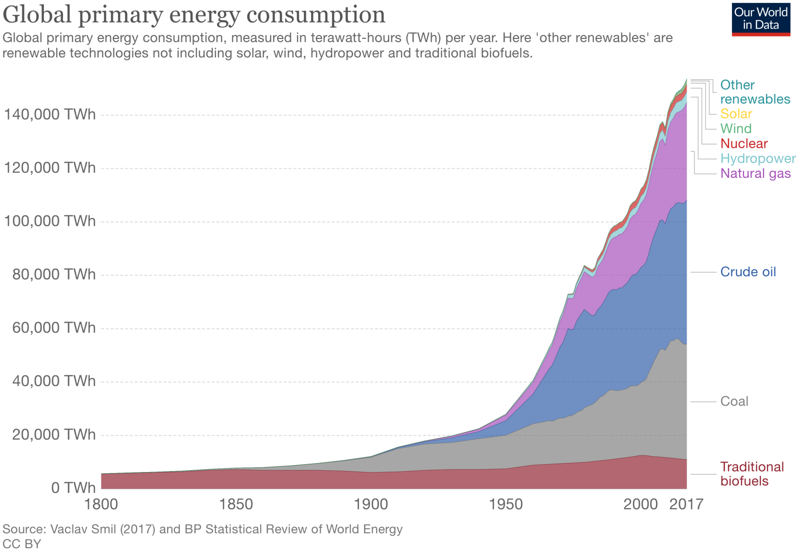
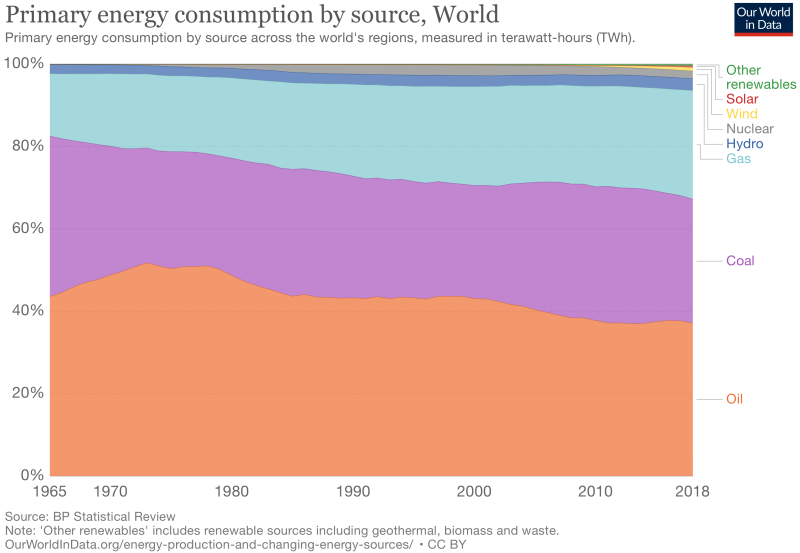
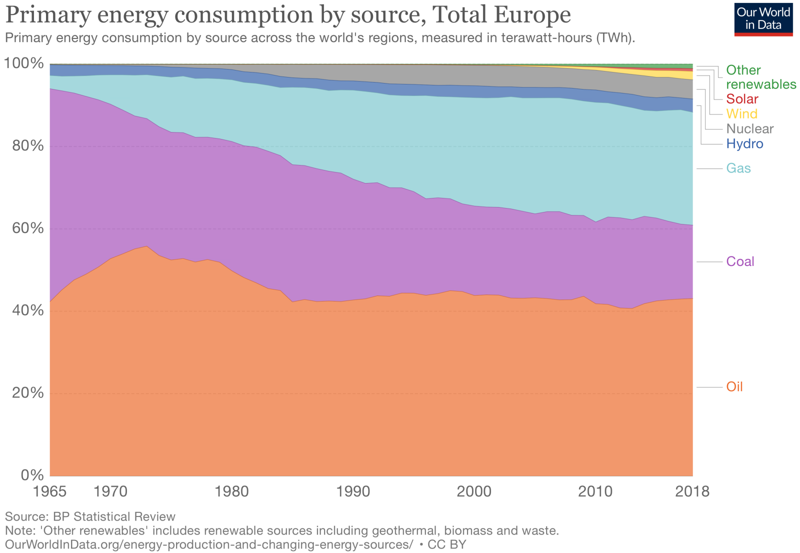


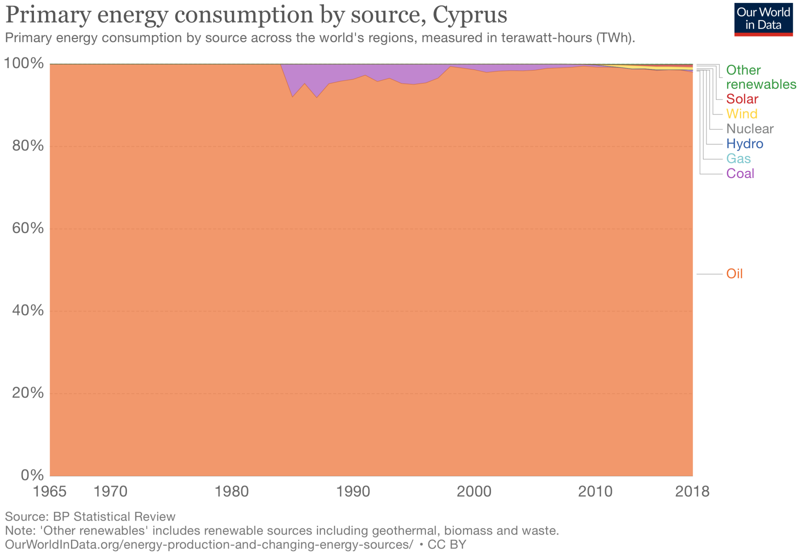
2 Energy consumption by fuel (in %)

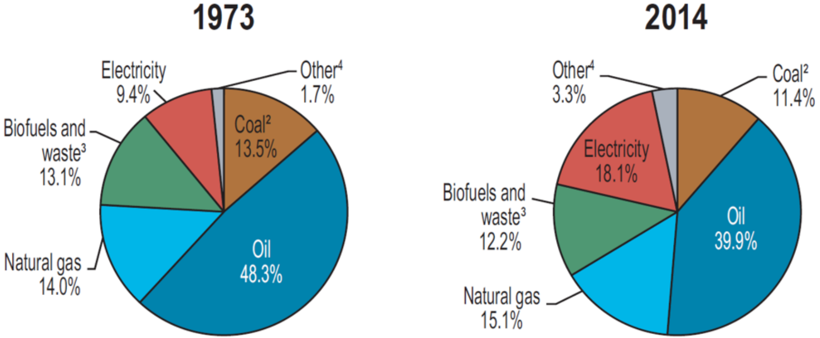


2 Energy consumption by fuel (in %)



2 Energy consumption by fuel (in %)



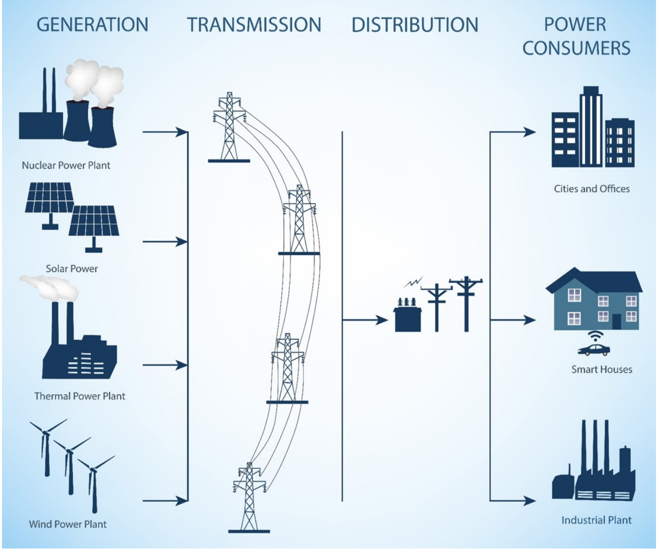


Source: IEA, World Energy Outlook 2015

2 Why electric energy?

- Advantages
  - can be used for a variety of purposes
  - can be converted efficiently from different primary sources
  - can be converted to mechanical or thermal energy with a high efficiency
  - can be transmitted and distributed with reasonably low losses
  - easy to measure and control
- Disadvantages
  - difficult to store
  - danger of handling high-voltages

2 Electric power system overview



3 Generation of electric energy

- Electric energy is obtained by converting primary energy into electric energy
- Strictly speaking, energy can not be generated nor consumed
- Yet we often say that electricity is being ”generated”, meaning that a primary energy source is converted into electric energy
- This process of energy generation (i.e., conversion) takes place in power plants

Fossil (non-renewable) energy sources

- Oil, gas, coal,. . .
- Cannot be replaced on a timespan of human significance
- Limited and can eventually run out

Renewable energy sources

- Sun, wind, biomass, tides,. . .
- Are replaced by natural processes at a rate comparable to their use
- Unlimited

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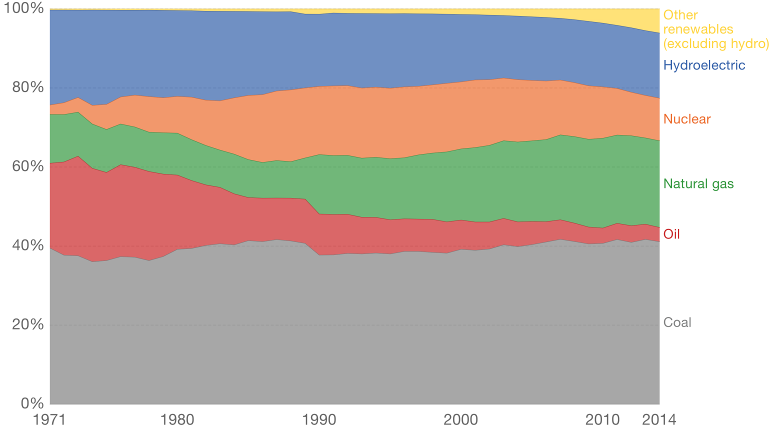
Electricity share by fuel source, World

Electricity production (measured as the percentage of total electricity production) by source (coal, oil, gas, nuclear, hydroelectric power and other renewables). Other renewables in this definition includes biomass, wind, solar, geothermal, and marine power.



Source: International Energy Agency (IEA) via The World Bank

3 Sources of electric energy - Fossils and renewables

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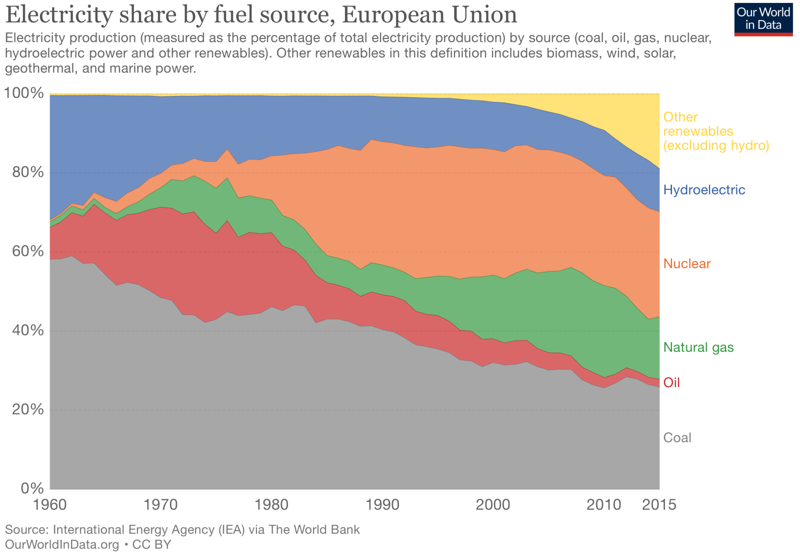

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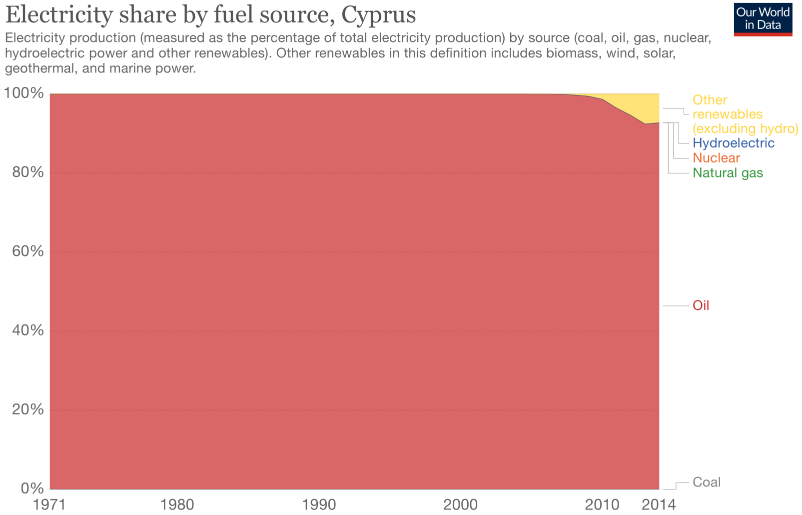
Electricity share by fuel source, Cyprus

Electricity production (measured as the percentage of total electricity production) by source (coal, oil, gas, nuclear, hydroelectric power and other renewables). Other renewables in this definition includes biomass, wind, solar, geothermal, and marine power.

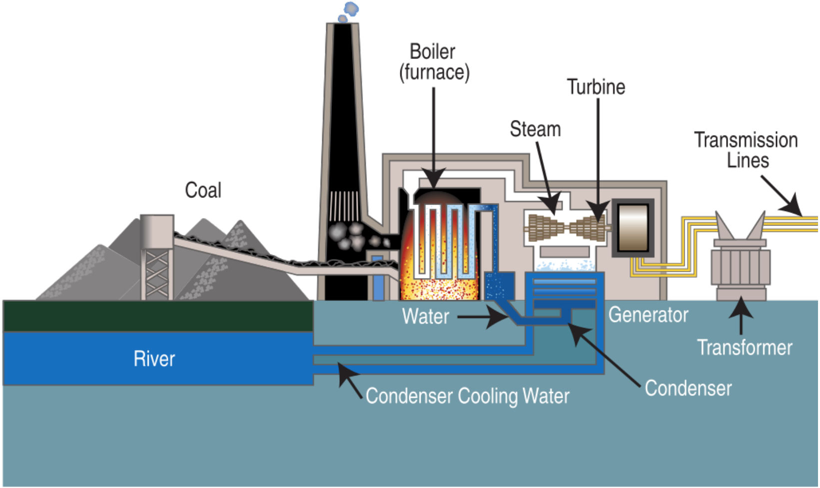


Source: International Energy Agency (IEA) via The World Bank

3.1 Power plant technologies

- Traditional technologies
  - **Steam power plant**: thermal energy of steam expanded in steam turbine; steam production mainly via fossil (coal, oil) or nuclear (uranium) primary sources
  - **Gas turbine generation**: kinetic energy obtained from burning fuel directly to create high-pressure gas used to drive turbine; mostly natural gas (methane) used as primary energy source; turbines similar to those used in aircraft
  - Steam and gas turbine generation jointly referred to as thermal generation
  - **Hydro power plant**: potential and kinetic energy of water is used to generate electricity via turbines
- **Renewable energy technologies**
  - Wind power plants
  - Solar power plants
  - Biomass-based power plants
  - . . .

3.1 Power plant technologies - Steam power plant (1)



©Tennessee Valley Authority

3.1 Power plant technologies - Steam power plant (2)

- Combustion of coal or gas creates high-temperature (up to 600°) and high-pressure (up to 280 bar) steam based on Rankine cycle
- In nuclear power stations, nuclear fission used to create heat
- That steam is passed through steam turbines; usually turbines with several nozzles at different pressure levels (high, medium, low) $\rightarrow$ pressure-compounded turbine
- Exhaust steam cooled down in condenser
- Turbine shaft connected to synchronous generator to convert mechanical energy into electric energy
- Efficiency 38-47%
- Efficiency can be increased up to 60% through combined-heat-and-power (CHP) plants
- Very high power rating up to several 1000 MW

- Steam power plants are less flexible, compared to hydro power plants
- Need to operate within certain maximum temperature gradients

→ Large time constants for variation in power output

- Also, operation mostly economic within certain operating regions

→ Steam power plants usually used as *base load*

3.1 Power plant technologies - Drax steam power plant

© Dave Pickersgill

- Coal-fired power station in North Yorkshire (also capable of co-firing biomass and petcoke)
- Generating capacity of 3,960 MW (highest in UK)

3.1 Power plant technologies - Steam turbine rotor

©Siemens

3.1 Power plant technologies - Gas power plant

- Based on gas turbine cycle: burn fuel (natural gas) in compressed air, similarly to aircraft engines
- Comparable efficiency to steam power plants
- Advantage: can use gas-turbine exhaust to produce steam in conventional boiler to drive additional steam turbine

→ Combined-cycle-gas turbine (CCGT) with improved efficiency around 60%

- Fast start-up and shut-down (2-3min for gas turbine)

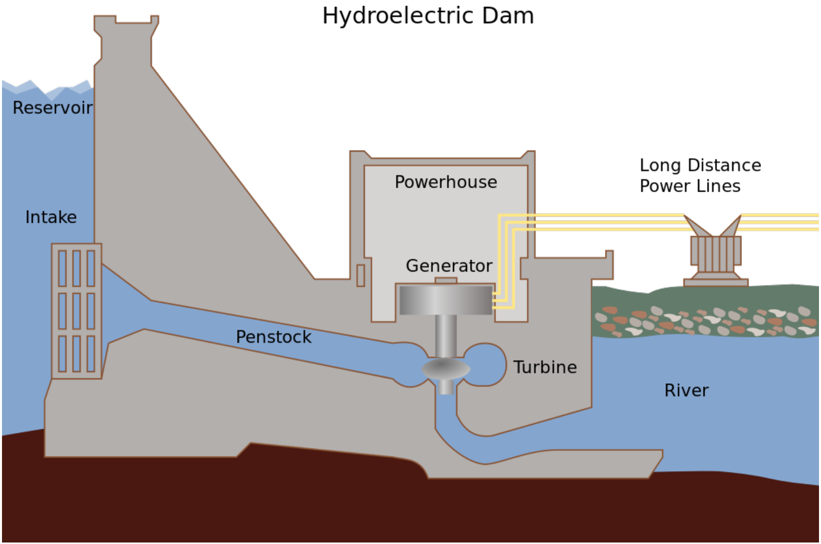
→ Often used for peak load supply

ΣΥΝΟΛΙΚΗ ΕΓΚΑΤΕΣΤΗΜΕΝΗ ΚΑΙ ΑΝΑΜΕΝΟΜΕΝΗ ΔΙΑΘΕΣΙΜΗ ΣΥΜΒΑΤΙΚΗ ΙΣΧΥΣ (MW) ΙΑΝΟΥΑΡΙΟΣ 2020						
Ηλεκτροπαραγωγός Σταθμός	Εγκαταστάσεις Συνδυασμένου Κύκλου	Ατμοστρόβιλοι	Αεριοστρόβιλοι	Μονάδες Εσωτερικής Καύσης	Ολική Ικανότητα Παραγωγής Ισχύος	
					Συνολική Εγκατεστημένη Ισχύς Ηλεκτρ. Σταθμών	Αναμενόμενη Διαθέσιμη Ισχύς Ηλεκτρ. Σταθμών
Μονής	-	-	4 x 37,5 = 150		**150**	**150**
Δεκέλειας	-	6 x 60 = 360	-	100	**460**	**367**
Βασιλικού	2 x 220 = 440	3 x 130 = 390	1 x 37,5 = 37,5	-	**868**	**608**
Ολική Ικανότητα Παραγωγής Ισχύος	**440**	**750**	**187,5**	**100**	**1478**	**1125**

Τελευταία Αναθεώρηση: **02 Ιανουαρίου 2020**

Source: https://www.dsm.org.cy/

3.1 Power plant technologies - Hydro power plant (1)



©Tomia

- Potential and kinetic energy of water in rivers and water reservoirs is converted to electric energy by using turbines
- Head = difference in height between upper reservoir and outflow level of turbine
- Different turbines used for different heads: Pelton (heads of 150 - 1500m), Francis (50 - 500m), Kaplan (run-of-river stations, heads up to 60m)
- Rule-of-thumb for generated active power

$$P \approx 8QH \quad \text{[kW]}$$

- Q: flow rate through turbine [m^3/s]
- H: head [m]
- Above expression includes efficiencies of hydraulic system, turbine and generator $\eta \approx 0.82$ [10^3 kg /(m^2s^2)]

3.1 Power plant technologies - Hydro power plant (3)

- Perhaps oldest form of energy conversion
- Have ability to start up quickly (as little as 3 min.)
- Have no energy losses when stand still

→ Often used to supply (fast-varying) peak demand

- Challenge: need appropriate geographical conditions (that are difficult to find in Cyprus)
- Low running costs (water is free), but rather high capital cost of construction

3.1 Power plant technologies - Hydro power plant (4)

©Le Grand Portage

- Three Gorges Dam on the Yangtze River, China
- Largest hydro power plant in the world with rated power of 22,500 MW

3.1 Power plant technologies - Wind power plants (1)

- Use kinetic energy of wind to produce electricity
- Maximum theoretically achievable active power

$$P_{\text{Betz}} = \eta_{\text{Betz}} \frac{1}{2} A \rho v^3$$

- Active power proportional to third power of wind speed v^3 [m/s]
- A: imaginary rotor surface [m^2]
- ρ: air density [kg/m^3]
- $\eta_{\text{Betz}} = 0.593$: Betz constant
- Practically achievable active power lower; modern plants achieve 70-80% of P_{Betz} at rated wind speed
- Often several wind turbines gathered in a wind park

Enercon E70, ©Hadhuey

3.1 Power plant technologies - Wind power plants (2)

- Wind power generation fluctuates with wind speed variation
- Often, on-shore higher fluctuations than off-shore; also, typically higher wind speeds off-shore

→ (Fairly) recent trend: off-shore wind farms

- Typical power rating: on-shore 2-5 MW, off-shore 4.6 - 8 MW per turbine

©Ad Meskens

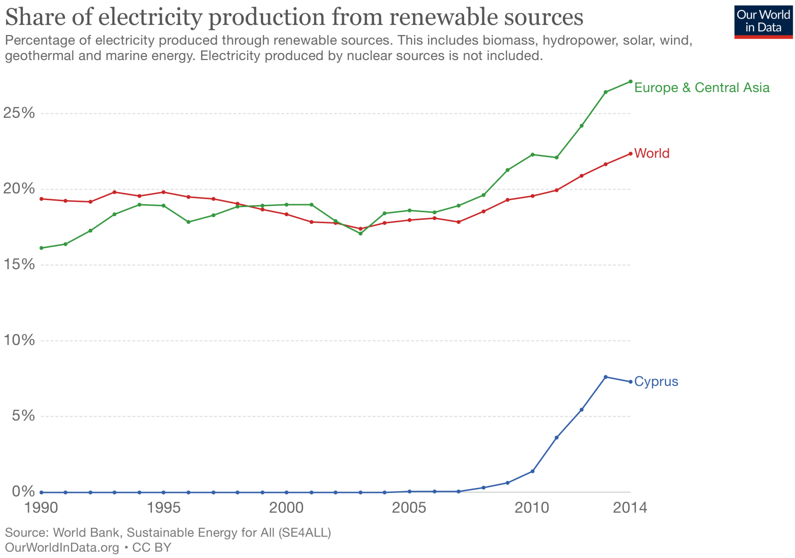
3.1 Power plant technologies - Solar power plants

- Solar energy can be either used directly or indirectly to generate electricity
  - Direct approach: Photovoltaics; conversion of solar energy into DC current; efficiency approx. 12-20%
  - Indirect approach: Concentrated solar power power plants; use solar energy to generate heat or steam to drive a turbine; efficiencies of up to 42%

©Koza1983

©Andrewglaser

3.1 Power plant technologies - Renewables Cyprus



3.1 Power plant technologies - Renewables Cyprus

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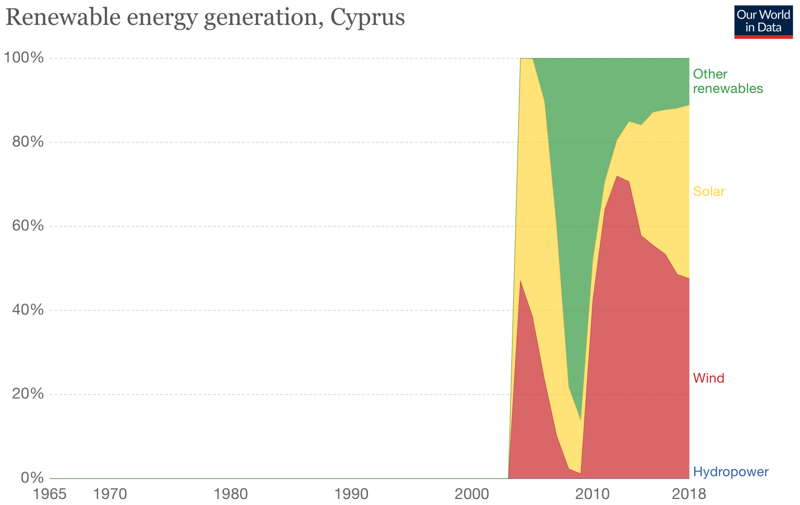


Source: BP Statistical Review of Global Energy (2019)
Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not inclu
OurWorldInData.org/renewable-energy • CC BY

3.1 Power plant technologies - Further technologies

- Fuel cells
- Geothermal power
- Wave power
- Tidal power
- ...

3.2 Generation mix and capacity - Planning

- Generation costs are composed of
  - Investment costs (e.g. plant construction)
  - Operating costs (e.g. for fuel)

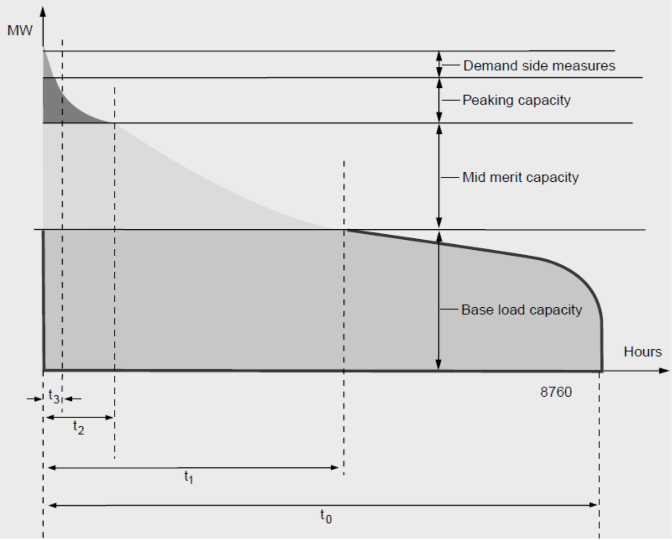
$\Rightarrow$ Optimal technology depends on its specific purpose(s)

- Usual differentiation of generation technologies
  - Base-generation
  - Mid-merit generation
  - Peak-load generation

3.2 Generation mix and capacity - Operation

- Base-generation
  - High capital and low per unit operating costs
  - Run-time $>$ 5000 h/y
  - Example: nuclear, hydro, lignite
- Mid-merit generation
  - Medium capital and medium per unit operating costs
  - Run-time $>$ 4000 h/y
  - Example: coal
- Peak-load generation
  - Low capital and high per unit operating costs
  - Run-time $<$ 1000 h/y
  - Example: gas, pump storage

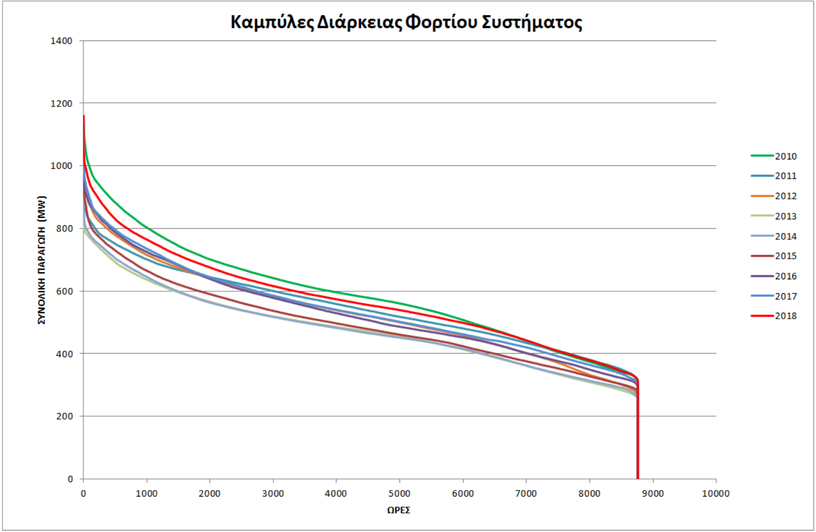
3.2 Generation mix and capacity - Example



Source: Weedy et al., Electric Power Systems

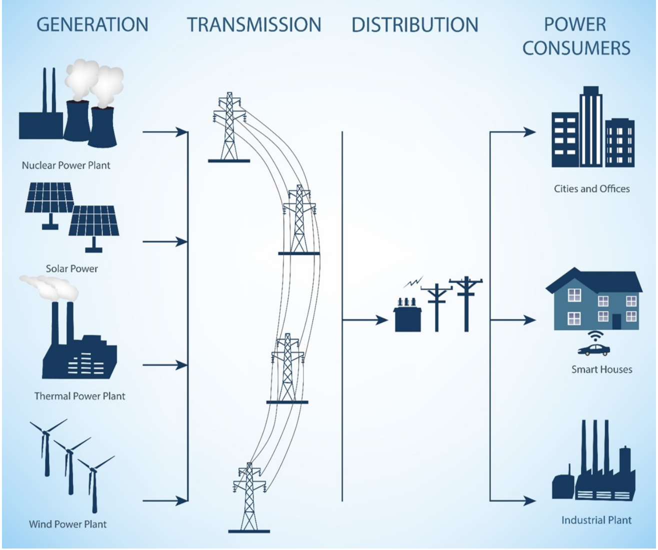
- t_0 base load run-time
- t_1 mid-merit run-time
- t_2 peak-load run-time
- t_3 time period of load curtailment

3.2 Generation mix and capacity - Cyprus



Source: https://www.dsm.org.cy/

4 Electric power system overview



- Often, economic, geographic, environmental or technological reasons impede generation of *all* demand closed to load centres (cities, industrial sites)
- Therefore, large share of electric power is generated far away from load centres

$\rightarrow$ Need (electric) infrastructure to transport electricity from generators to loads

- This infrastructure is called a power network

4.1 Voltage levels and network types

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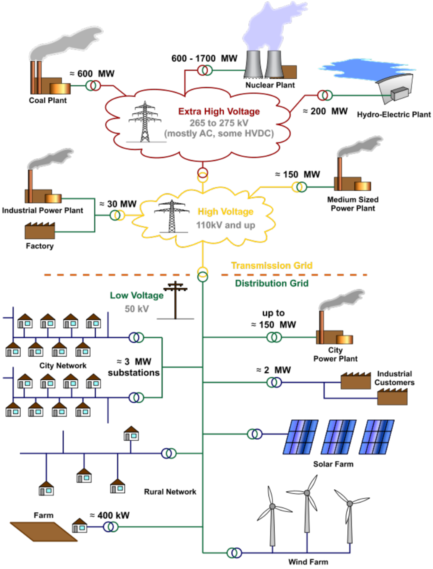
- Optimal economic interconnection of different generators / end-users / networks mainly depends on
  - Distance
  - Amount of power to be transmitted
- Consequently, most power systems worldwide consist of
  - **Transmission network**: *global* power network over large distances; works at high voltages
  - **Distribution network**: *local* electricity network to deliver power to end-users; works at medium and low voltage
  - Voltage usually transformed several times to lower values the closer to end-user
  - These voltage transformations are performed in **substations**
  - Above low voltage (LV) level, power transfer is usually three-phase

4.1 Electric power systems - Standard structure (1)



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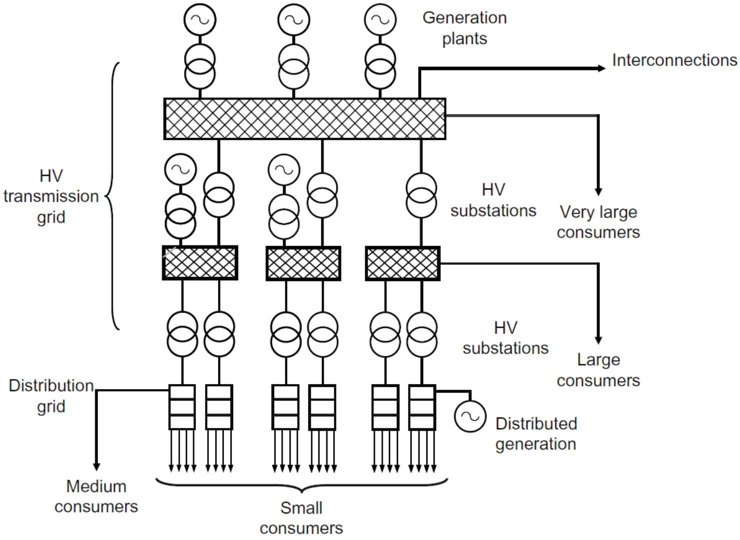
4.1 Electric power systems - Standard structure (2)



Source: J. Machowski et al, "Power system dynamics: stability and control", John Wiley & Sons, 2011

- **1882** — T. Edison develops first DC steam powered electric station, New York, USA
- **1884** — F. J. Spague produces DC motor for Edison Systems
- **1886** — W. Stanley develops commercially practical transformer
- **1888** — N. Tesla presents paper on two-phase AC induction and synchronous motors
- **1889** — First single-phase AC transmission line (4 kV, 21 km) Oregon, USA
- **1891** — First three-phase AC transmission line (12 kV, 179 km) Germany
- **1893** — First three-phase AC transmission line in USA (2.3 kV, 12 km) California, USA

- 1878: T. Edison began work on electric light and designed concept of central power station serving lighting in its neighbourhood
- Opening of Pearl Street Station (DC, 30 kW, 110 V, lighting for 59 customers, 2.5 m^2 area) marks beginning of electric utility industry
- Beginning of fast growth of electric utility industry until today
- Development of transformer alleviated voltage issues encountered with longer transmission lines
- War of currents: Edison promoted direct current (DC), while Westinghouse (US entrepreneur and engineer) promoted alternating current (AC)
- Change of voltage levels via transformers and circuit breakers exploiting zero-crossings, along with Tesla's AC motors pushed AC systems

4.1 Early history of electric power systems: Cyprus

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- 1903: First generators to serve the needs of the Commission and the general hospital in Lefkosia
- 1912: First generation company in Lemesos – Electrofotistiki Eteria Lemesou (The Limassol Electric Light Company)
- 1913: Nicosia Electricity Company
- 1922: Municipal Electricity Authorities of Ammochostos, Larnaka and Pafos
- 1927: Municipal Electricity Authority of Kyrenia
- 1952: Electricity Authority of Cyprus merged 28 companies serving 6 major towns and 22 smaller townships and villages (total 28)
- 1972: Full electrification of the island (527 towns and villages). From 20,000 consumers in 1952 to 180,000 in 1973 and 576,000 in 2018

Source: https://www.eac.com.cy/

4.1 Development of demand & generation

Globally:

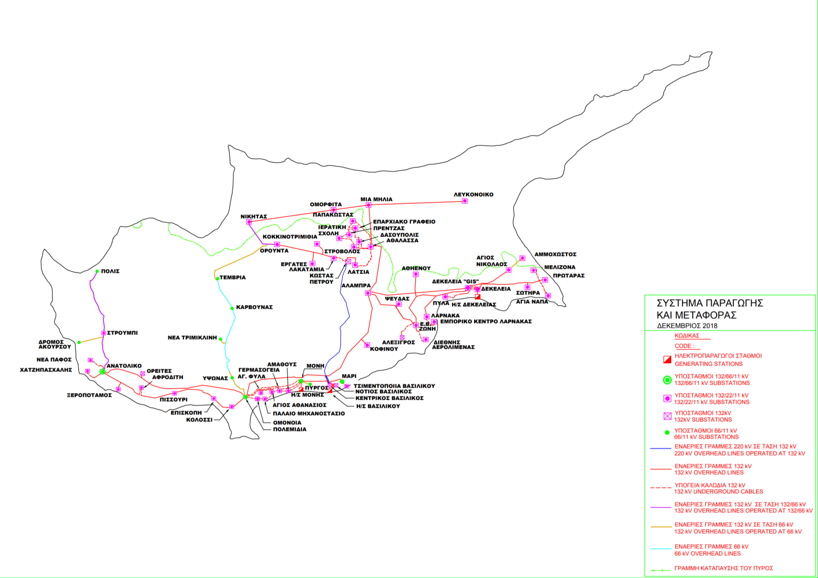
- From 1890 to 1975 electric energy consumption raised in average 7% in industrialised nations
- This is equivalent to doubling the energy demand every 10 years!
- Likewise, size of generation units increased
- Main incentive: *economy of scale*
  - Lower installation costs per kW
  - Lower operating costs per kWh

4.1 Voltage levels today

Country	high voltage (HV)	medium voltage (MV)	low voltage (LV)
UK	400 kV (275 kV)	132 kV - 11 kV	400 / 230 V
Germany	380 kV	110 - 10 kV	400 / 230 V
US	765 - 345 kV	230 - 4 kV	480 / 120 V
Nigeria	330 - 132 kV	33-10 kV	415/240 V
Cyprus	132 - 66 kV	22-11 kV	400/230 V

- The above voltage magnitudes refer to the line-to-line voltage V_{LL} of the corresponding three-phase system
- The line-to-ground voltage V_{LG} is given by $V_{LL} = \sqrt{3}V_{LG}$

4.1 Example of Cyprus

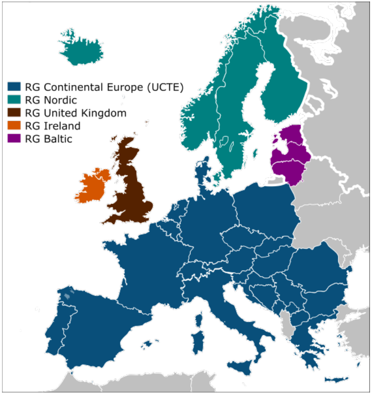


Source: https://www.dsm.org.cy/

- Interconnection of power systems has advantages in reliability and economy
  - Power support in emergencies
  - Cross-border power transfers and trading

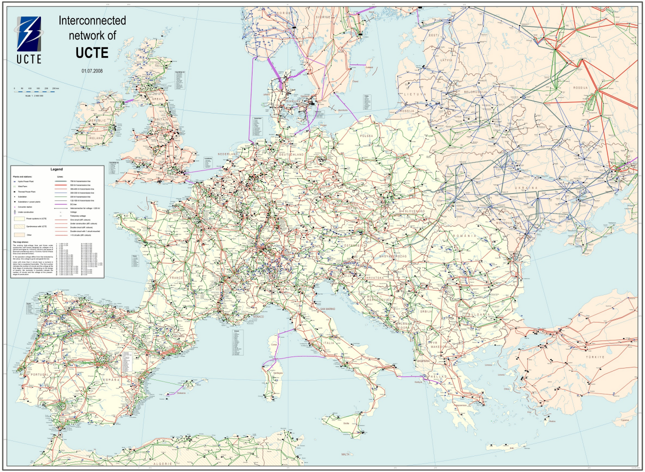
  → Fundamental prerequisite for international electricity market

- Two power systems can be coupled via
  - Synchronously = AC connection (e.g., continental Europe)
  - Asynchronously = DC connection (e.g., UK)



Synchronous grids in Europe, ©Kimdime

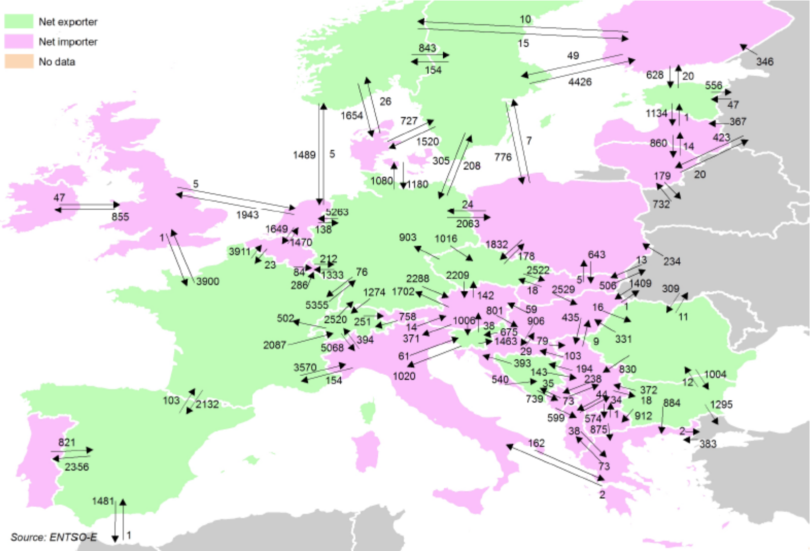
4.2 Interconnected power systems - ENTSO-E



Source: ENTSO-E

- European Network of Transmission System Operators for Electricity (ENTSO-E)
- 41 transmission system operators
- 34 countries, 450 mio. people
- 1,000 GW generation capacity

4.2 Commercial electricity flows in Europe May-July 2014 [GWh]



Source: European Commission, Quarterly Report on European Electricity Markets

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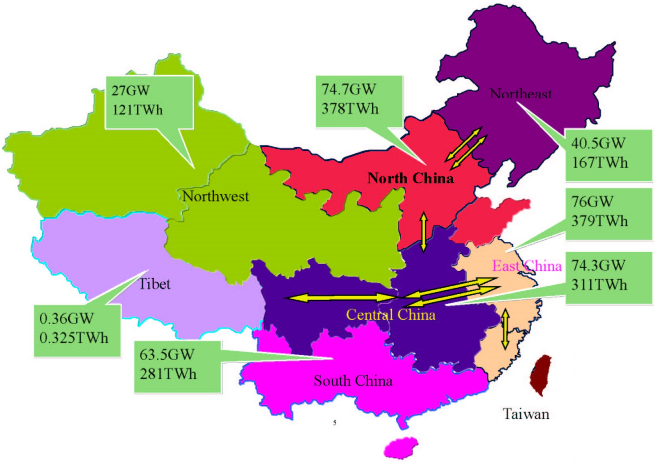
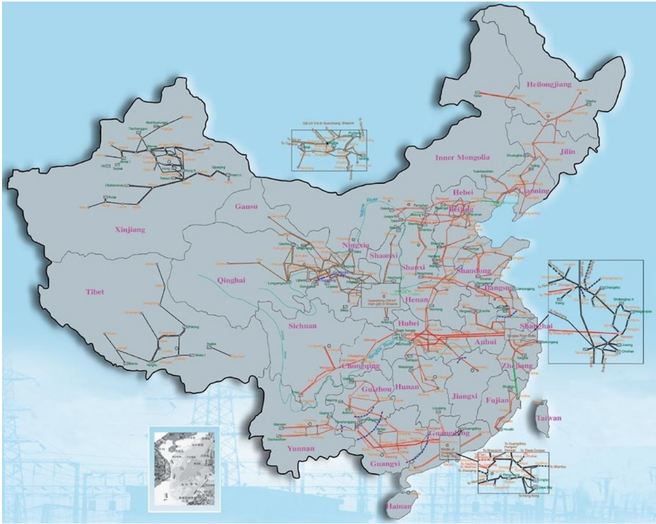


Source: www.geni.org

- 2 transmission system operators: State Grid Corporation & China Southern Power Grid
- ¿360 GW generation capacity

4.2 Interconnected power systems - China



Source: www.geni.org

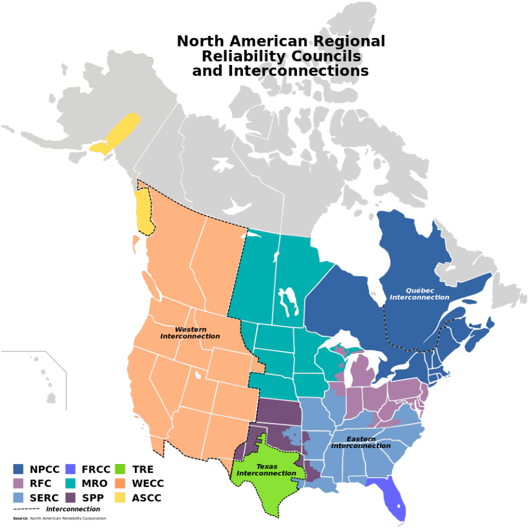
- 2 transmission system operators: State Grid Corporation & China Southern Power Grid
- ¿360 GW generation capacity

4.2 Interconnected power systems - WAPP

Source: www.ecowapp.org

- West African Power Pool (WAPP)
- 14 countries

4.2 Interconnected power systems - NERC



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- North American Electric Reliability Corporation (NERC)
- 8 regional reliability entities
- ¿ 1,000 GW installed capacity

4.3 Network topologies - Some key facts

- Simple point-to-point connections are not suitable to provide *reliable* power supply, as a single line failure leads to blackout

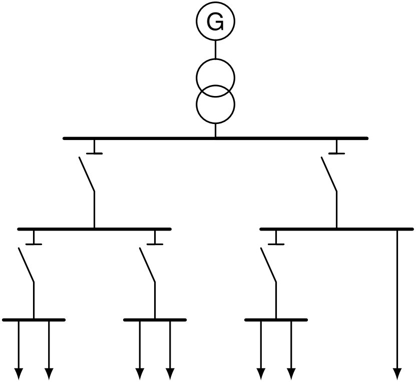
→ Need network topology, where power can be transmitted over alternative path if a power line fails

- This creates redundancy and, hence, increases reliability
- Most common criterion to define redundancy of a power network is *(N-1) criterion*

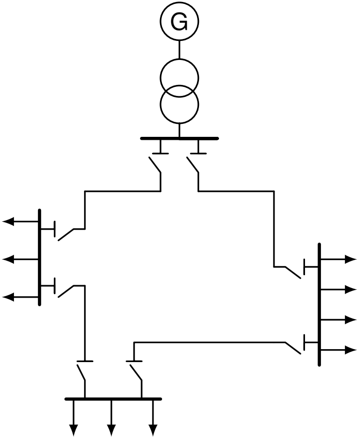
4.3 Network topologies - (N-1) criterion

- After loss of one single element (e.g. line, transformer, power station)
  1. Network must be able to continue service
  2. No network element is overloaded
- (N-1) criterion is standard security criterion worldwide for power system planning and operation
- Defines network redundancy with respect to equipment outages
- Higher security indices: (N-2), (N-3),...

4.3 Network topologies - 1) Radial network



- Several independent network branches
- Often used in rural areas
- Overhead lines or cables (depends on country and load density)
- Advantages
  - Simple operation
  - Low investment costs
  - Easy to analyse and predict
- Disadvantages
  - Voltage sags at branch ends by high loading
  - Simple failures can lead to blackouts for end-users (not N-1 secure)



- Equipment rated such that operation can be maintained also if fault on ring occurs
- Often has circuit breaker in middle of ring
- Advantages
  - Higher reliability against failures (”quasi” N-1 security)
- Disadvantages
  - Higher costs: larger conductor, such that all loads can be fed from one end
  - Slightly higher complexity

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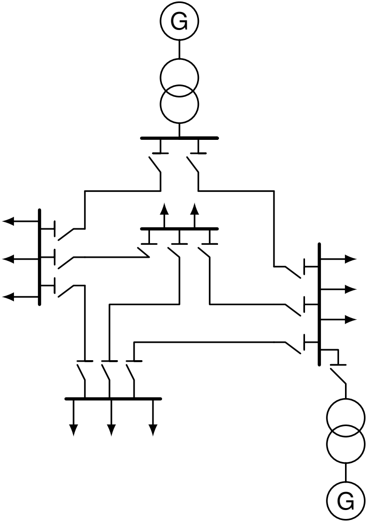

- Multiple (redundant) conductors
- Used in areas with high load density
- Often underground cables used
- Advantages
  - Very reliable (N-1 secure)
  - Outage/failure of one line
  - Even voltage profile
  - Low losses
- Disadvantages
  - Network analysis and design more complex
  - Too large meshed networks can be difficult to re-start after blackout

4.4 Substations

- Substations connect different voltage levels in a power system
- Main tasks
  - Nodes of power network that connect different voltage levels with each other via power transformers
  - Switching station at which different lines leaving or entering substations can be connected and disconnected
  - Measuring, monitoring and control of local variables (e.g., voltage, current, protection, meters)
  - Separation of distribution from transmission network

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4.5 System operation and monitoring - Control center

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- System monitoring and operation takes place in *control centers*
- Depending on size of network, there may be one or more control centers
- Control centers obtain data from several measuring points (e.g., substations) in network via supervisory-and-data-aquisition (SCADA) system

Source: https://www.dsm.org.cy/

4.5 System operation and monitoring - Power quality

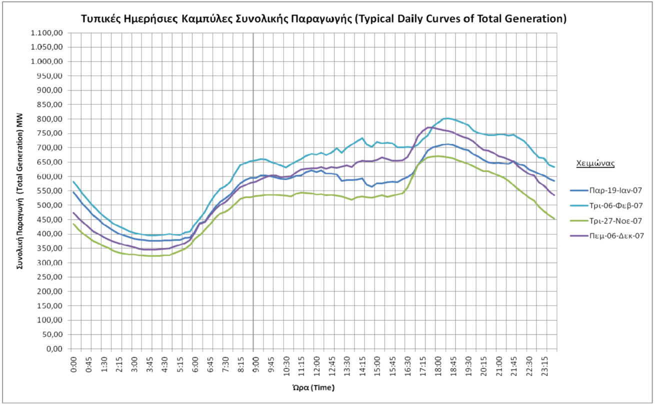
- For proper functioning of many appliances, it is essential that not only required amount of power is supplied, but also that it is provided with a certain *power quality*
- Power quality is measure for ”fitness” of electrical power delivered to consumers
- It comprises the following criteria
  - Continuity of service
  - Variation in voltage magnitude
  - Frequency stability
  - Unbalances and harmonic content
- Control and compensation equipment ensures that (usually) deviations from nominal voltage amplitude and frequency remain within $\pm$10% of their respective nominal values at customer’s point of connection

5 Typical load composition

Typical load sectors

- Industrial
- Commercial
  - Offices
  - Schools
  - Shops etc.
- Residential (domestic)
  - Refrigerators
  - Freezers
  - Heating
  - Air condition etc.

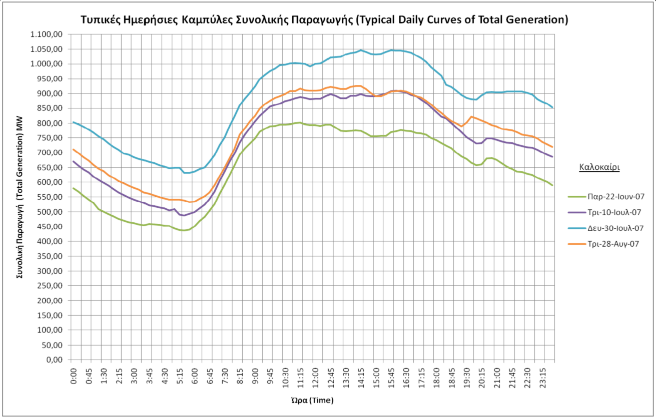
5 Cyprus winter 2007 representative daily load curve



Source: https://www.dsm.org.cy/

- Base load: approx. 350 MW / Daily fluctuation: approx. 350 MW (December curve)
- Peak occurs in the evening (18:30), high lighting and heating demand

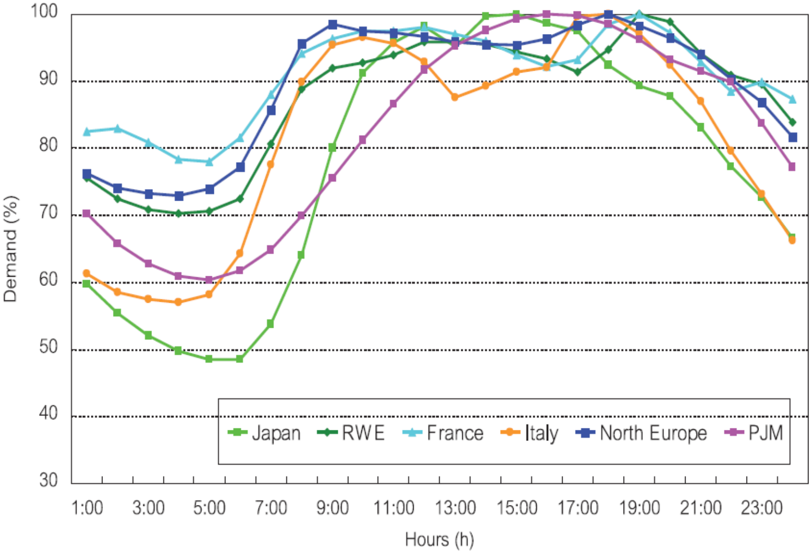
5 Cyprus summer 2007 representative daily load curve



Source: https://www.dsm.org.cy/

- Base load: approx. 600 MW / Daily fluctuation: approx. 400 MW (July curve)
- Peak occurs at noon, high air-conditioning demand
- On average 40% higher demand in summer

5 Comparison of daily load curves



Source: IEC, Electrical Energy Storage

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On demand-side...

- Load demand exhibits long-term (e.g. seasonaly) and short-term variations (e.g. daily)
- Irregular events: extreme weather, special events (e.g. World Cup final)
- Exact load demand never known beforehand

5 Some more...

On generation- and infrastructure-side...

- Up to today, electric energy can not be stored in significant quantities (e.g. GWh)
- Electric equipment (generation plants, substations, power lines, ...) is often used for decades
- Planning, construction and commissioning of new equipment also often takes decades
- Investment costs are fairly high
- Starting-up large power stations can take up to several days

5 ...and their consequences for power system operation

- (Most) Energy has to be produced at the moment it is demanded
- Need to estimate load demand in advance (load forecast)
- Need to plan power generation based on demand forecast
- Need of real-time adjustments (controls)
- Installation of new equipment requires careful technical and economic planning

5 Summary

- Electric power systems highly complex and nonlinear
- Electric power can *not* be stored

→ Generation needs to match load in real time!

- Key infrastructure
  - Power generators
  - Loads
  - Transmission network
  - Distribution network
  - Substations with power transformers to connect networks at different voltage levels
  - System operator