ELEC0447 - Analysis of electric power and energy systems

Lecture 1: Course organization and introduction

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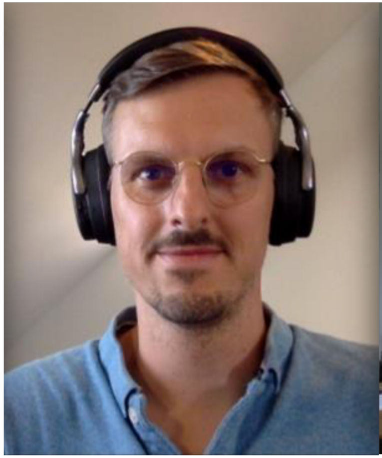
Welcome to ELEC0447

Course organization

- Theory lectures (maximum 2 hours)
- Practice sessions (remainder of the session) $\longrightarrow$ bring your laptop
- Homeworks:
  - Implement a power-flow solver for a particular grid configuration, step by step
- Project:
  - Analyse a system using power flow analyses (power flow solver given)
  - Present your results to the class
- Oral exam in January
  - Theory and exercise

The teaching team


Bertrand Cornélusse


Laurine Duchesne


Selim El Mekki


Louis Wehenkel

References

Main reference book:

- Mohan, Ned. Electric power systems: a first course. John Wiley & Sons, 2012.

Other references:

- Course notes of ELEC0014 by Pr. Thierry Van Cutsem. (In french)
- Weedy, Birron Mathew, et al. Electric power systems. John Wiley & Sons, 2012.

Introduction

Adapted from ELEC0014 introduction by Thierry Van Cutsem

Objectives of this lecture

- Show the overall structure of an electric power system
- Highlight a few important features of power system operation
- Illustrate those on the Belgian and European systems
- Present some orders of magnitude it is important to have in mind
- Introduce some terminology

A large scale system

In modern society, electricity has become a “commodity”:

“marketable good or service whose instances are treated by the market as equivalent with no regard to who produced them”

- “Behind the power outlet” there is a complex industrial process
- Electric energy systems are the largest systems ever built by man
    - thousands of km of overhead lines and underground cables, of transformers
    - tens/hundreds of power plants + a myriad of distributed energy sources
    - devices to (dis)connect elements: substations, circuit breakers, isolators
    - protection systems: to eliminate faults
    - real-time measurements : active and reactive power flows, voltage magnitudes, current magnitudes, energy meters, phasor measurement units
    - controllers: distributed (e.g. in power plant) or centralized (control center)
    - etc.
- Unlike most other complex systems built by man, power systems are exposed to external “aggressions” (rain, wind, ice, storm, lightning, etc.)

Low-probability but high-cost failures

In spite of those disturbances, modern electric power systems are very reliable.
Assume a duration of power supply interruption of 0.5 hour / year

$$\text{availability} = (8760-0.5)/8760 = 99.994\ \% \ !$$

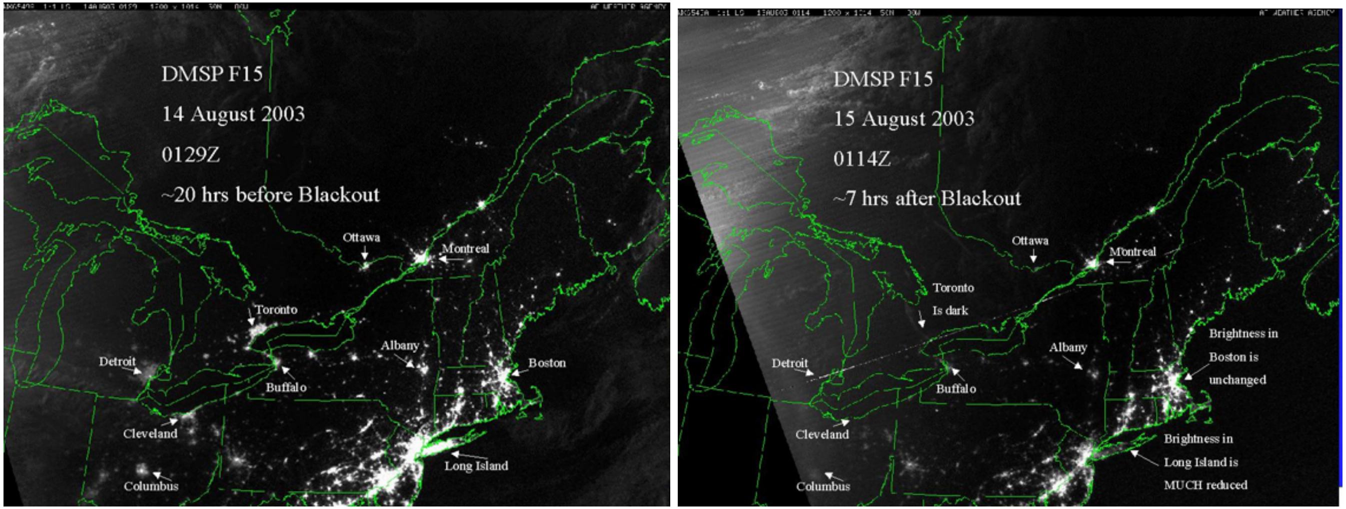
However, the cost of unserved energy is high

- average cost used by CREG (Belgian regulator) to estimate the impact of forced load curtailment: 8.3 k€/MWh (source: Bureau fédéral du plan)
- varies with time of the day : between 6 and 9 k€/MWh
- varies with type of consumer : 2.3 k€/MWh for domestic, much higher for industrial
- even higher average cost considered elsewhere (e.g. 26 k€/MWh in France !)

Large-scale failures (blackouts) have tremendous societal consequences

- next two slides: examples of blackouts and their impacts

USA-Canada blackout, August 2003



- 50 million people disconnected initially
- 61 800 MW of load cut in USA & Canada
- cost in USA : 4 to 10 billion US $
- in Canada : 18.9 million working hours lost
- 265 power plants shut down
- restoration : from a few hours to 4 days

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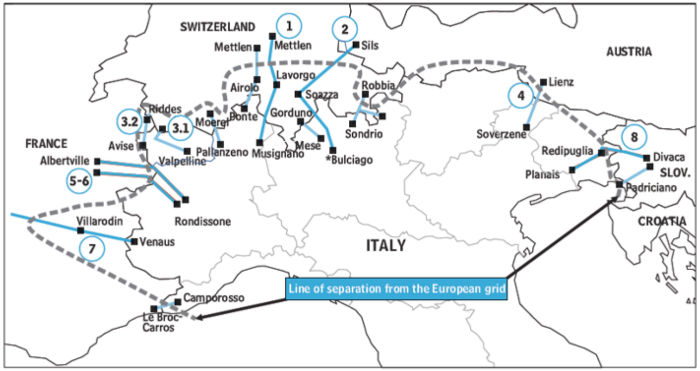
Source : North American Electric Reliability Council (NERC)

Italian blackout, September 2003

- Cascade tripping of interconnection lines $\longrightarrow$ separation of Italy from rest of UCTE system

Final Line of Separation of the Italian Transmission System from the UCTE Transmission Network



- Deficit of 6.7 GW imported in Italian system $\longrightarrow$ frequency to collapse in Italy
- 340 power plants shut down, 55 million people disconnected initially - 27 GW lost (blackout occurred during night)
- Estimated cost of disruption $\approx$ 139 million US $
- Restoration time: 15 hours

Source : Union for the Co-ordination of Transmission of Electricity (UCTE) which is now part of ENTSOe

Network: from early DC ...

End of 19th century : Gramme, Edison devised the first generators, that produced Direct Current (DC) under relatively low voltages

Impossibility to transmit large powers with direct current:

- $\text{power} = \text{voltage} \times \text{current}$
  - if the voltage cannot be increased, the current must be
  - but $\text{power lost} = \text{resistance} \times \text{current}^2 \rightarrow$ big waste of energy
  - and large sections of conductors required $\rightarrow$ expensive and heavy
- Hard to interrupt a large DC current (no zero crossing), for instance after a short-circuit

Network: ... to present high-voltage AC

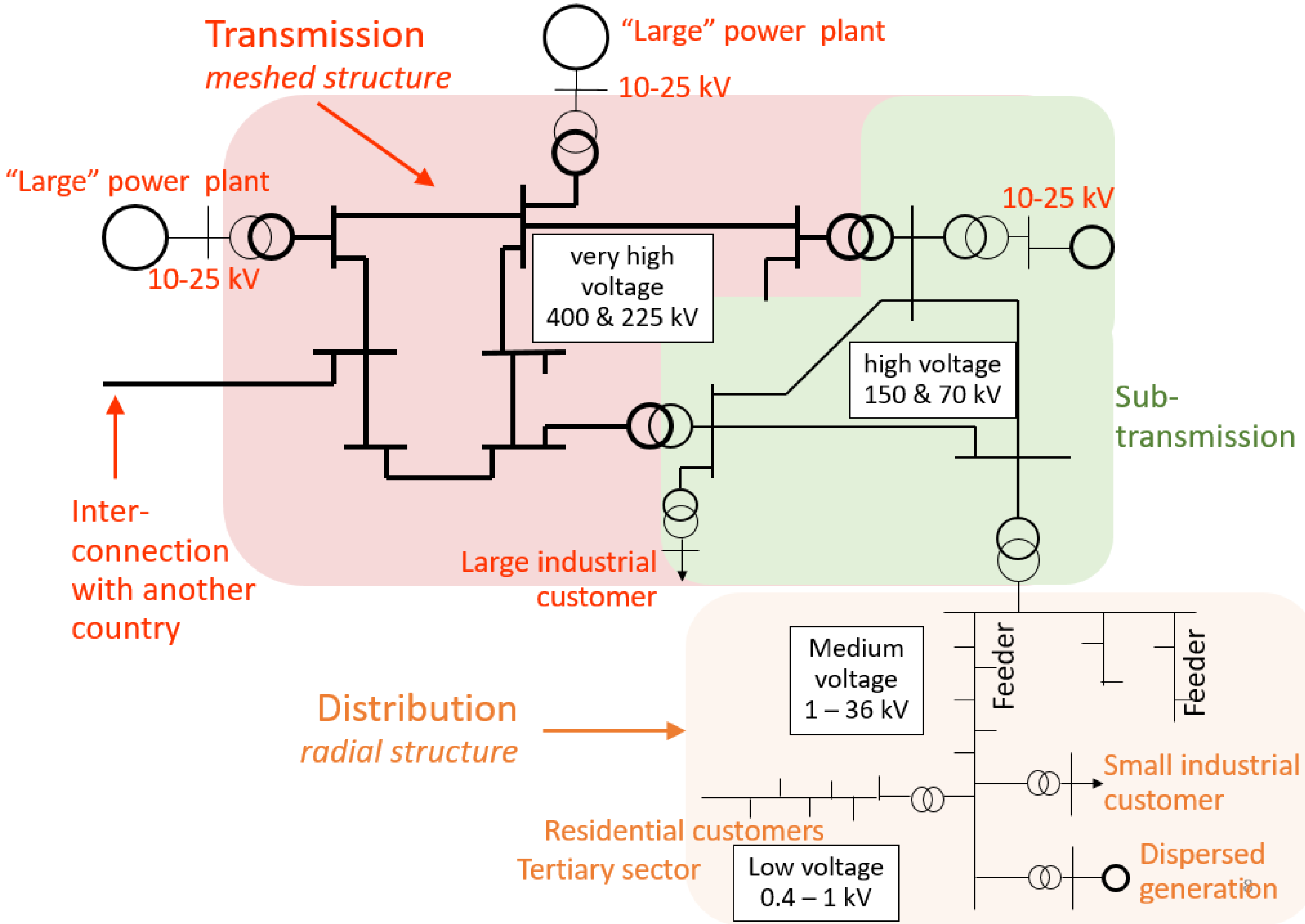
Changing for Alternating Current (AC)

- voltage increased and lowered thanks to the transformer
- standardized values of frequency : 50 and 60 Hz (other values used at a few places)

Larger nominal voltages have been used progressively

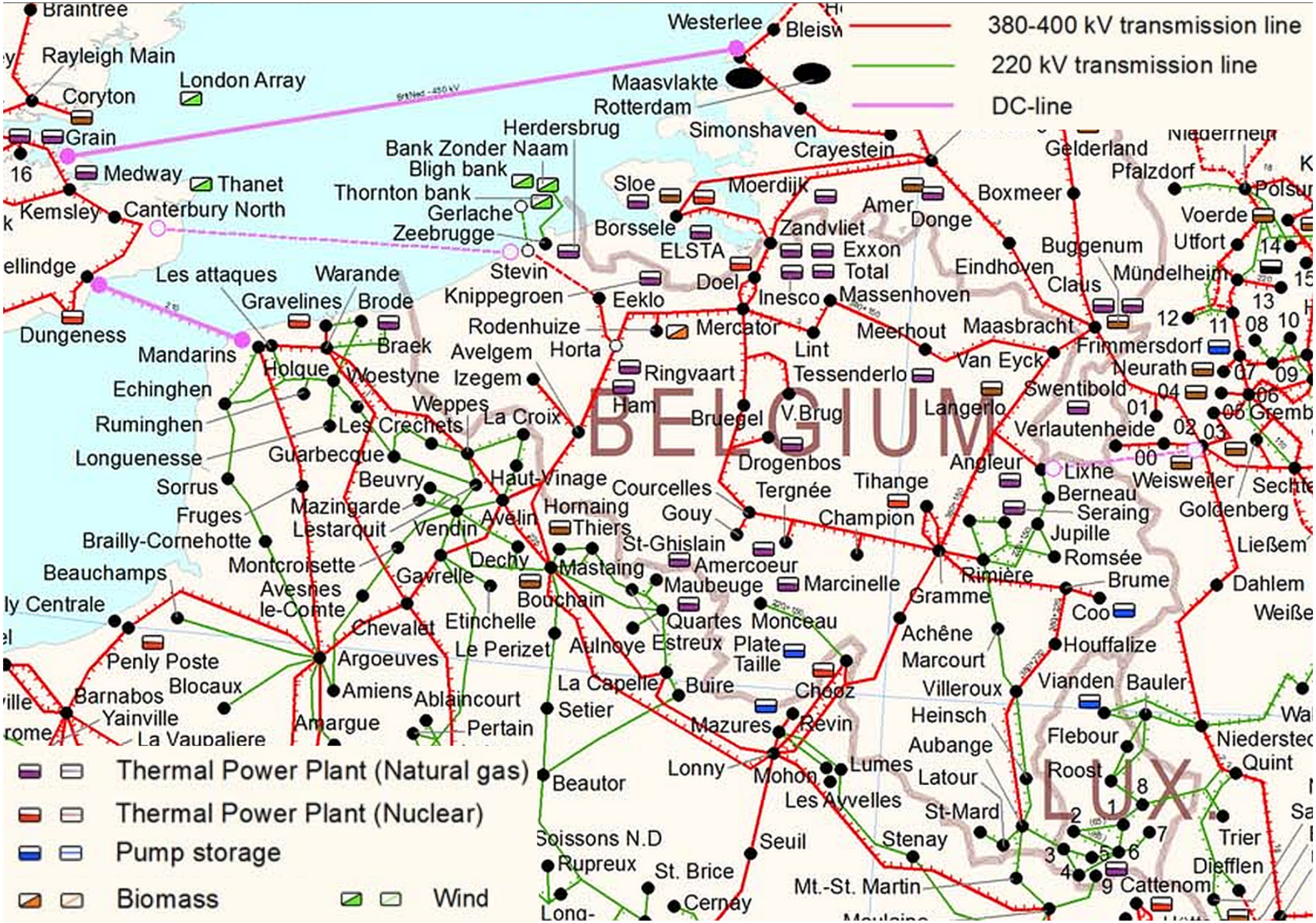
- up to 400 kV in Western Europe
- up to 765 kV in North America
- experimental lines at 1100 kV or 1200 kV (Kazakhstan, Japan, etc.)

Structure of electric network (case of Belgium)



In Belgium there are 30 and 36 kV underground cable networks, in Brussels and Antwerp areas. These are meshed and play the role of sub-transmission.

400 (and 220 kV) grid in Belgium and interconnections



Length of network by voltage level and type in Belgium

	Nominal voltage (kV)	Underground cables (km)	Overhead lines (km)	Total (km)
	Transmission and sub-transmission			
Very High Voltage	400	49	919	968
	225	47	301	348
High Voltage	150	573	1 981	2 554
	70	301	2 404	2 705
Medium Voltage	30 & 36	2 022	60	2 082
	Total	2 990	5 665	8 657
	Distribution (1)			
	1 ≤ < 30	71 804	5 069	76 873
Low Voltage	< 1 (2)	80 480	47 360	127 840
	Total	152 284	52 429	204 713

(1) 552 connection points between T & D
(2) does not include public lighting

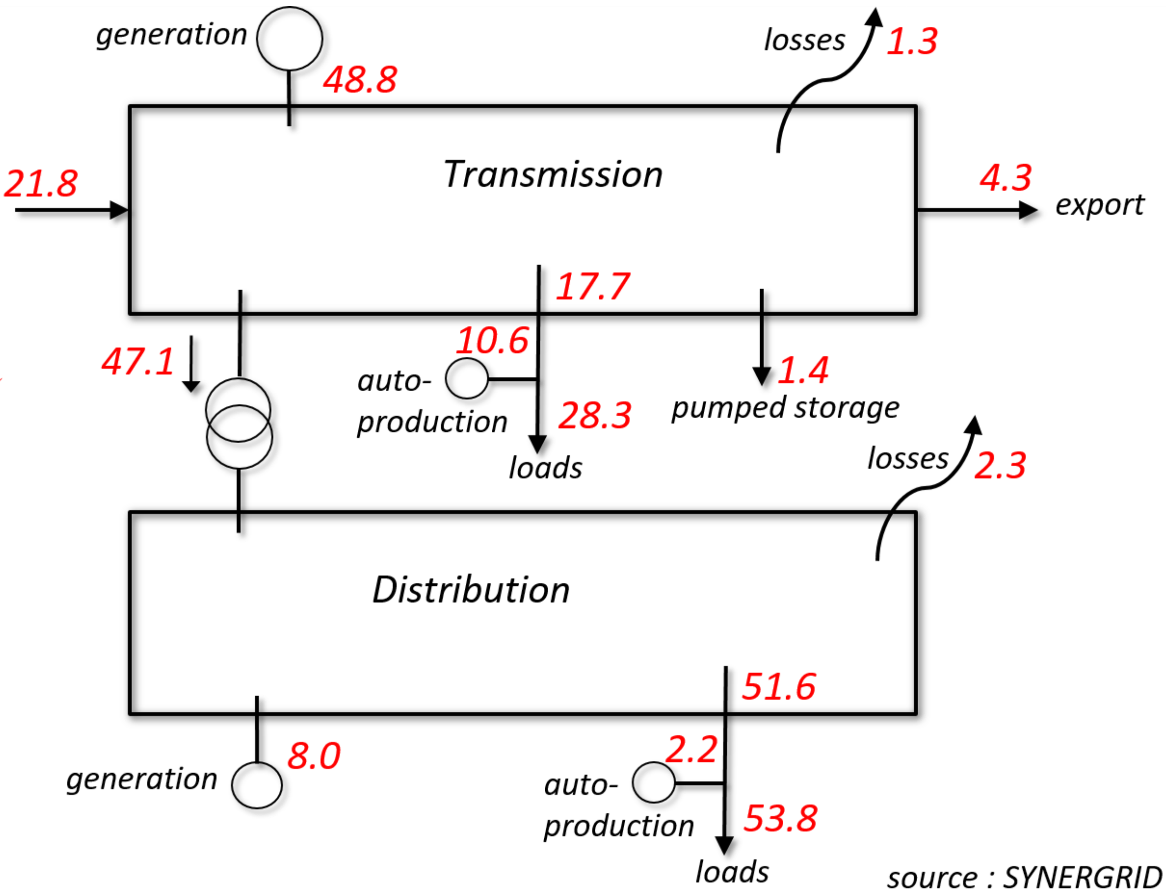
Total number of transformers : 74 990

source : SYNERGRID, as of December 2008

Electrical energy balance over the year 2018 in Belgium

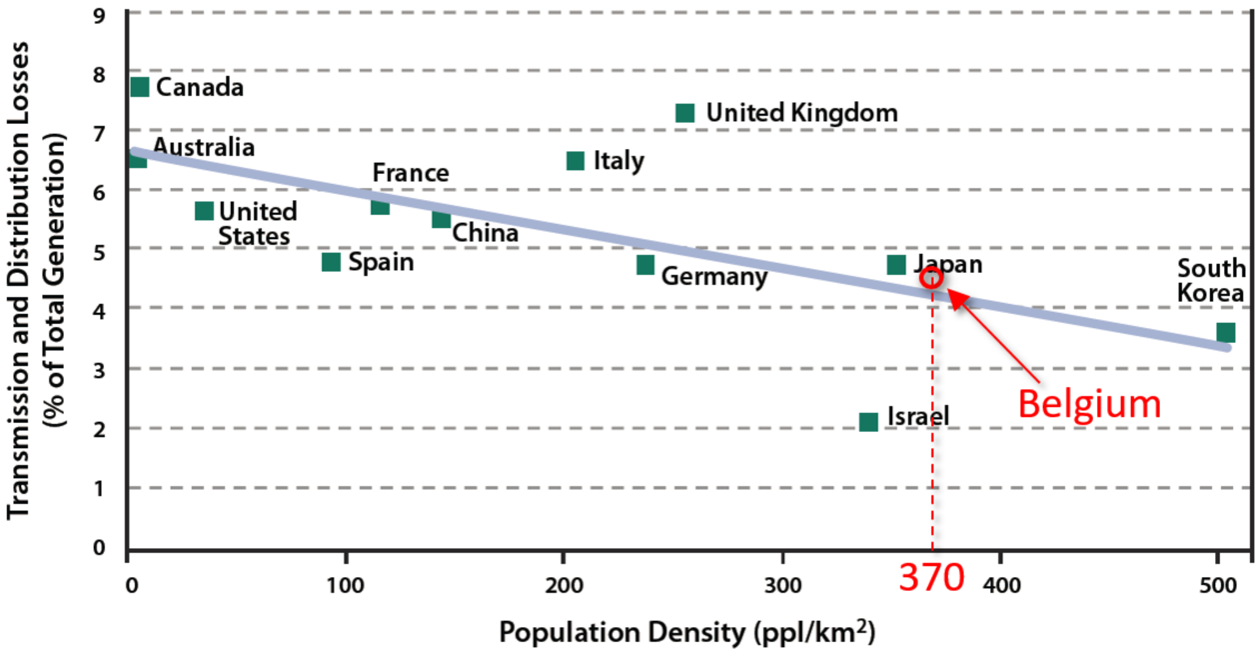
All values in TWh

1 TWh
= 10^3 GWh
= 10^6 MWh
= 10^9 kWh



source : SYNERGRID

Network losses

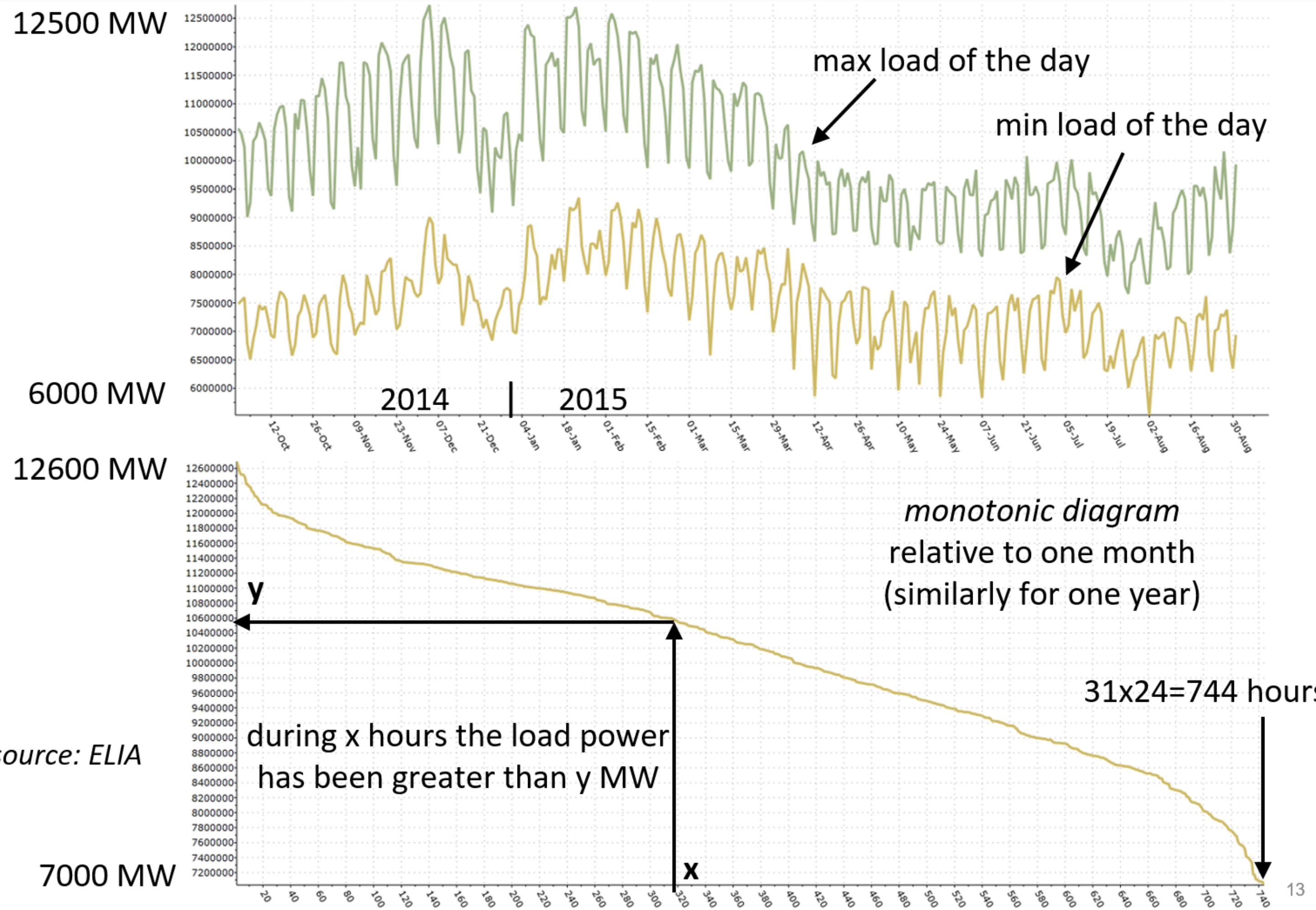


Source: World Bank Development Indicators, http://data.worldbank.org/indicator.

$$\frac{Transmission\ \&\ Distribution\ losses}{Production\ injected\ in\ network + import} = \frac{1.3 + 2.3}{48.8 + 21.8 + 8.0} = 4.6\ \%$$

Transporting and distributing electrical energy is an industrial process with a relatively high efficiency

Consumption outlook

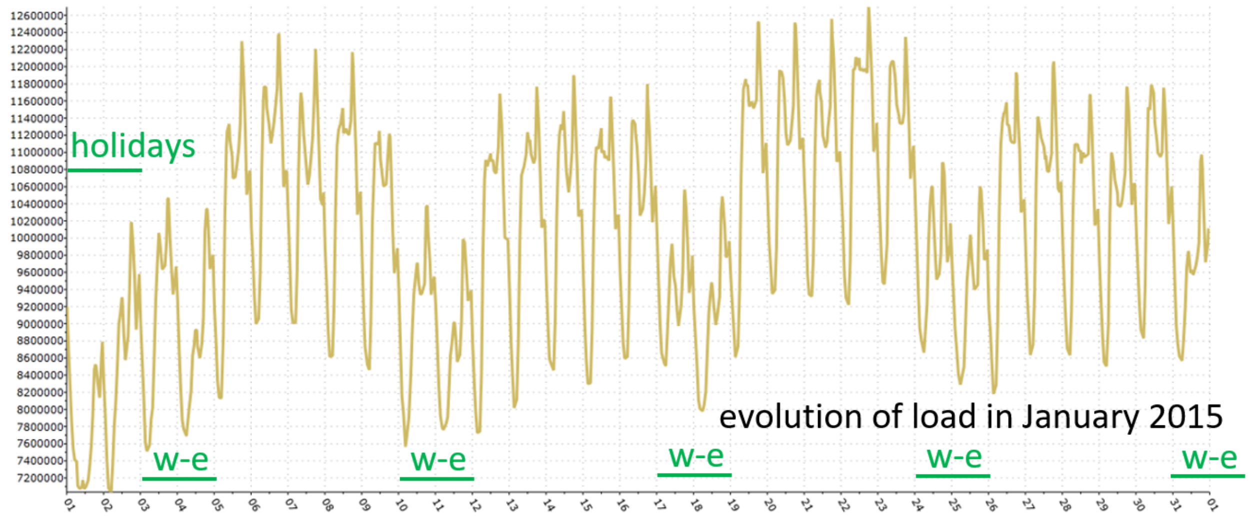


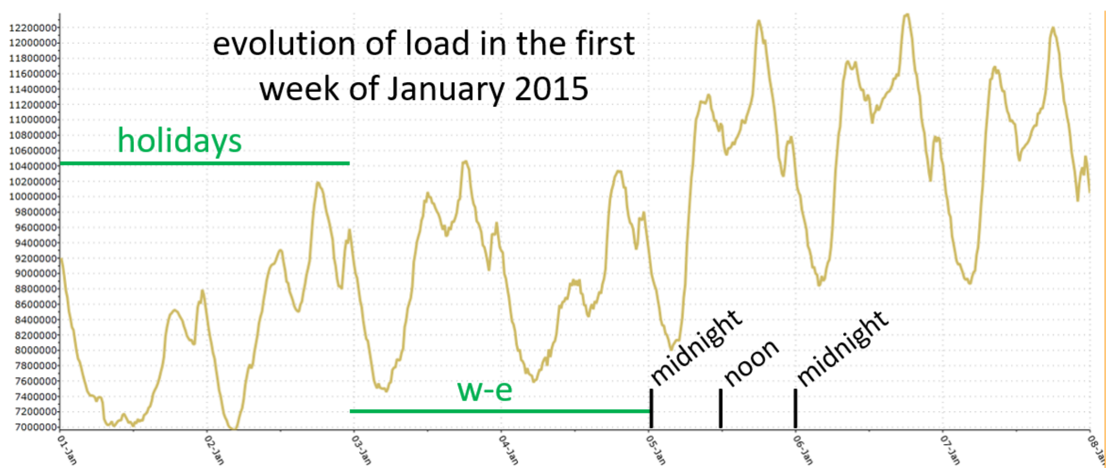
source: ELIA

12600 MW

source: ELIA

7100 MW





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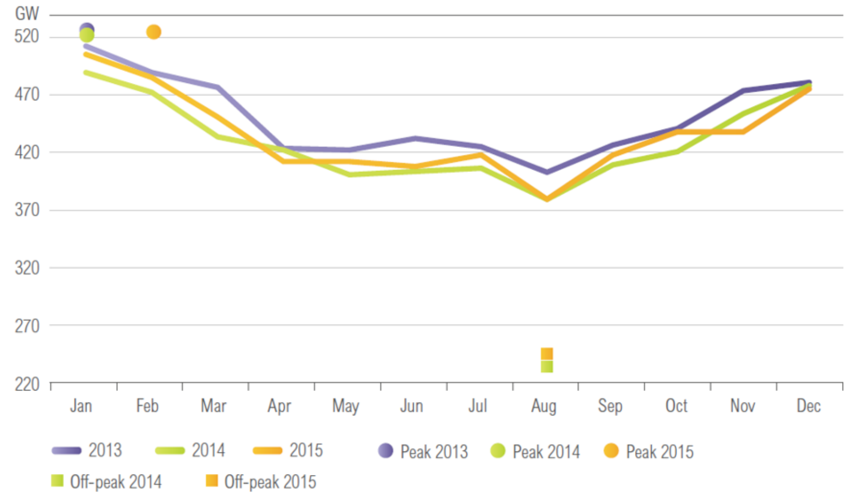
Peak load on some grids

$$\text{Monthly power in ENTSOe networks} = \frac{energy\ consumed\ in\ the\ month\ (GWh)}{nb\ days\ in\ the\ month\ \times\ 24}$$

source: ENTSOe



Peak loads recorded on the Belgian transmission system

Year	Date	Time	Day	Power (MW)
2010	Dec 14	18:00	Tue	14 390
2013	Jan 17	18:00	Tue	13 255
2014	Dec 4	18:00	Thu	12 736
2015	Jan 22	18:00	Thu	12 696
2016	Jan 19	18:00	Thu	12 679
2017	Jan 18	18:00	Thu	13 270
2018	Nov 19	18:00	Mon	13 453

source: ENTSOe

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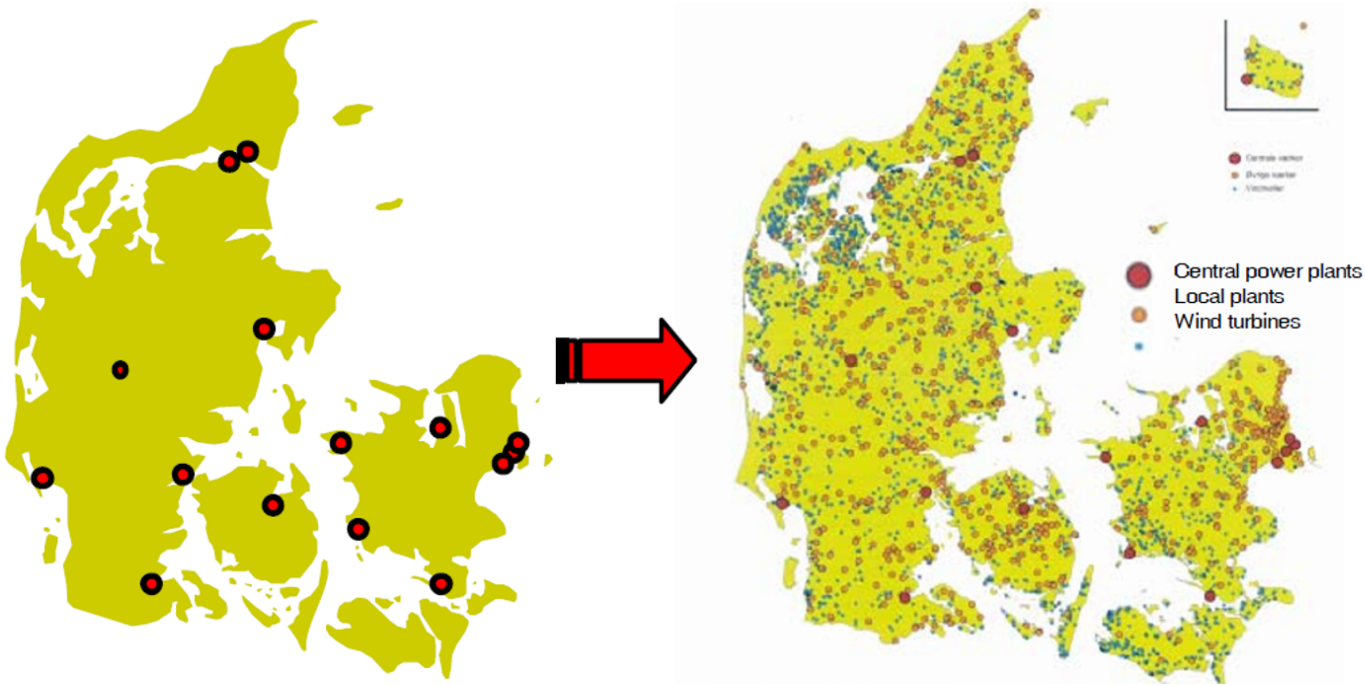
From large centralized to small dispersed power plants

Denmark : a country with huge penetration of renewable energy sources



16 central power plants

16 central power plants + 1000 local CHPs
+ 6000 wind turbines

Evolution of Danish power system over the period 1980-2005

(Z. Xu, M. Gordon, M. Lind, J. Østergaard, “Towards a Danish Power System with 50% Wind - Smart Grids Activities in Denmark”, IEEEXplore, 2009)

Energy outlook for Belgium

Sources of electrical energy in Belgium in 2018

Category	Energy source	Generation capacity Dec 2018		Energy produced in 2018		Capacity factor
		MW	% total	TWh	% total	%
Nuclear	total	5 919	26.0	27.0	39.0	52
Non renewable non nuclear	gas			22.1		
	others			3.4		
	total	7 680	33.7	25.5	36.9	38
Hydro	pumping stations	1 308		1.0		9
	run-of-river	125		0.3		27
	total	1 433	6.3	1.3	1.9	
Renewable non hydro	wind	3 247		7.1		25
	solar (PV)	3 581		3.5		11
	biomass-biogas	811		3.5		49
	wastes			1.2		
	total	7 764	34.1	15.3	22.1	
TOTAL		22 796	100	69.1	100	

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source : ENTSOE

Comments

- “Nuclear generation capacity” involves all units, even those temporarily shut down for technical reasons, or waiting for the decision to extend their lifetime
- Gas power plants includes small CHP (Combined Heat Power) units
- Same for biomass plants
- Purposes of pumping storage :
  - pumping : convert electrical energy into mechanical (potential) energy when demand is low compared to available generation (e.g. during night)
  - turbining : reverse operation when demand is high (e.g. at day peak) $\longrightarrow$ “peak shaving” and “valley filling” of daily load curve
  - efficiency of whole cycle $\approx$ 85 %
  - usually profitable since cost of electricity higher when demand is high
  - fast reserve : a hydro unit can be started (resp. pumping stopped) quickly to replace a generation unit that is taken out of service
  - allows keeping base units (e.g. nuclear) in operation when load is very low

Comments: capacity factor

- Capacity Factor: $\frac{\text{energy produced in 1 year (MWh)}}{\text{generation capacity (MW)}\times 365\times 24(h)}$
  - usually close to 90 % for nuclear, but some Belgian units have high unavailability
  - note the low value for solar energy!

Some trends in Belgium

- Early retirement of gas power plants not enough competitive on electricity market, too expensive to maintain
    - political decision to keep a “strategic reserve” !
    - Angleur
- Biomass plant of "Les Awirs" just decommissioned.
- Natural hydro resources saturated in Belgium
    - there are plans to expand the pumping storage
    - Coo power plant : currently $(3 \times 158 + 3 \times 230 =)$ 1164 MW installed capacity
- Wind energy :
    - public opposition to new on-shore wind farms (densely populated country !)
    - NIMBY attitude : Not In My BackYard

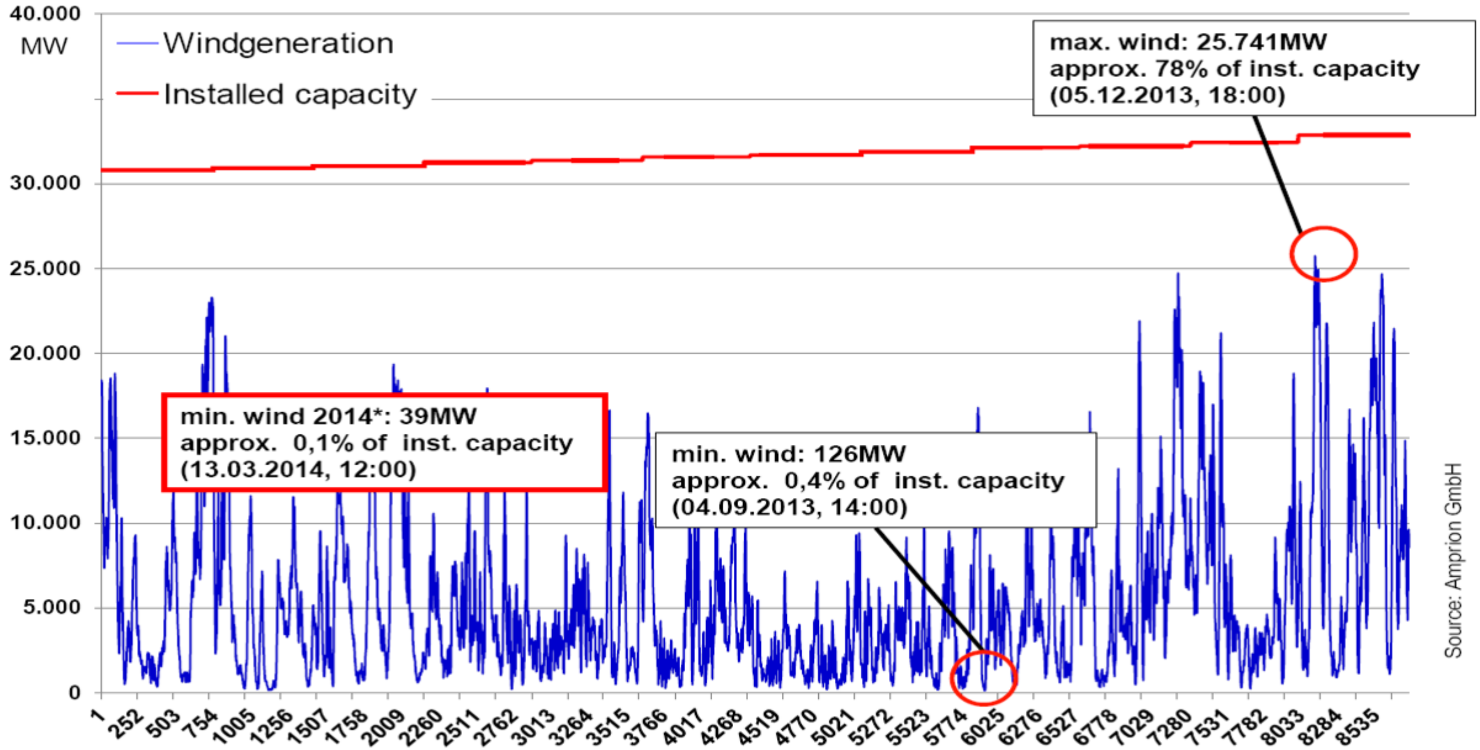
Some trends in Belgium (...)

- off-shore wind farms have a higher capacity factor than on-shore ones: wind is more steady in the sea
- Belgian off-shore wind farms in 2018 :
  - 5 wind parks with an installed capacity of 1186 MW have produced 3,408 TWh
  - Capacity Factor = $(3,408 \times 10^6)/(1186 \times 365 \times 24)$ = 32 %
- still a great potential for new off-shore wind farms :
  - 3 under construction (+ 1076 MW) $\rightarrow$ 8 TWh production expected in 2020

Renewable generation

Wind generation potential

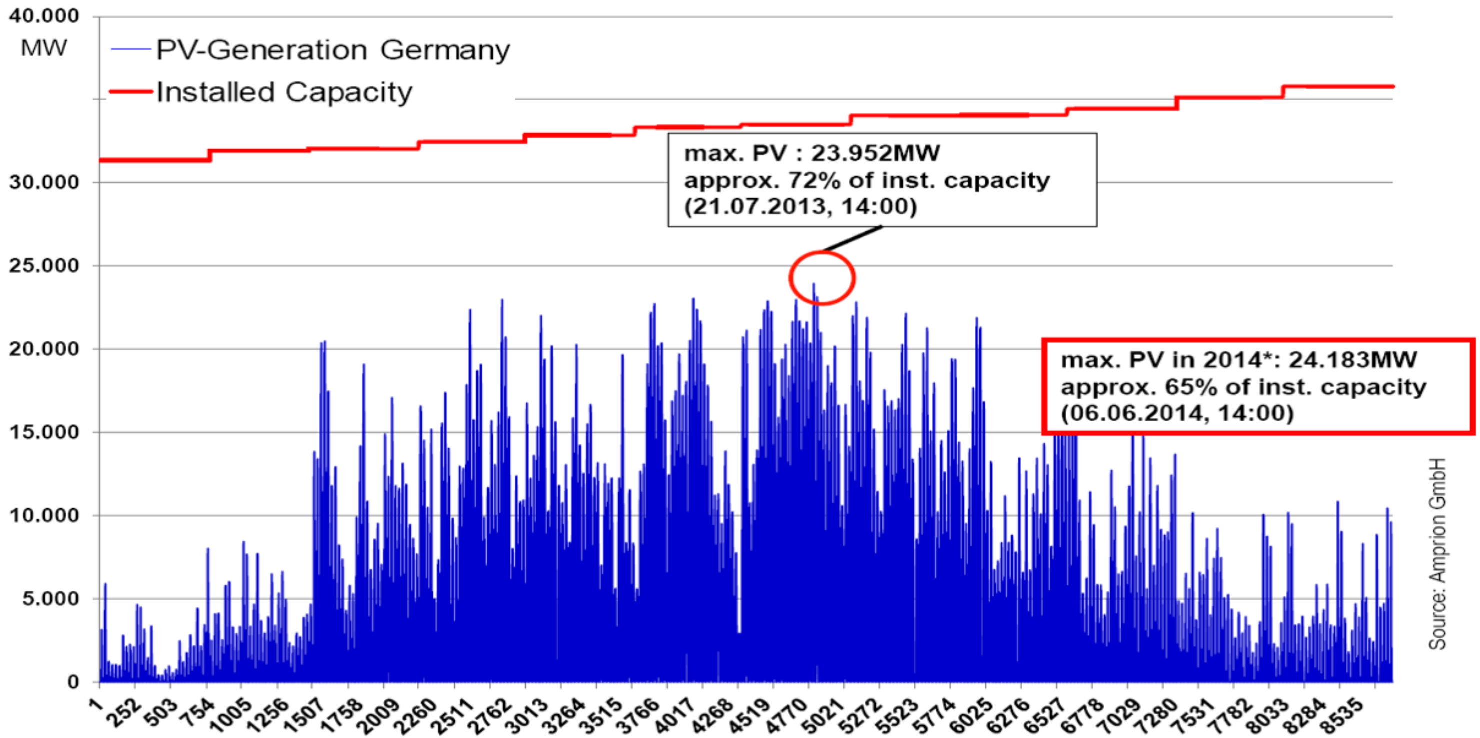
https://globalwindatlas.info/



Hour of the year 2013

PV generation potential

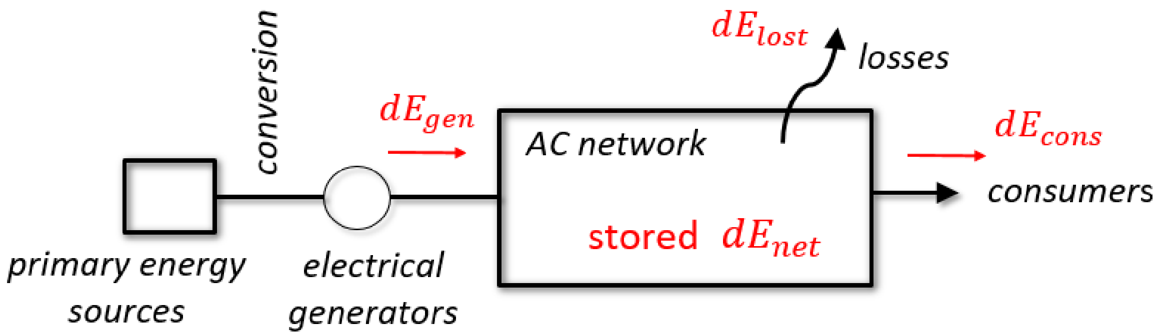
https://re.jrc.ec.europa.eu/pvg_download/map_index_c.html#!



Hour of the year 2013

Power balance

The power balance issue



Conservation of Energy over an infinitesimal time dt:

$$dE_{gen} = dE_{cons} + dE_{lost} + dE_{net}$$

Introducing the corresponding powers at time t:

$$p_{gen}(t).dt = p_{cons}(t).dt + p_{lost}(t).dt + p_{net}(t).dt$$

Hence

$$p_{gen}(t) = p_{cons}(t) + p_{lost}(t) + p_{net}(t)$$

$p_{cons}(t)$: The consumers decide how much power they want to consume !

- this demand fluctuates at any time

$p_{lost}(t)$: Losses mainly due to Joule effects $\longrightarrow$ depend on currents in components

- kept as small as possible, not really controllable

$p_{net}(t)$: Network elements which store electrical energy : inductors and capacitors

- In sinusoidal steady state, the power in an inductor (or a capacitor) reverts every quarter of a period, and is zero on the average
  - in balanced three-phase operation, the sum of the powers in the inductors/capacitors of the three phases is zero at any time !
  - hence, electrical energy cannot be stored in the AC network
- to be stored, electrical energy has to be converted into another form of energy
  - mechanical: e.g. potential energy of water in the upper reservoir of a pumping station, flywheels, etc.
  - chemical: batteries, but amounts of stored energy are still very small !! Really?
  - Hornsdale Power Reserve
  - NGK's batteries

Conclusion

The variations of load power have to be compensated by the generators but the conversion (primary energy $\longrightarrow$ electrical energy) is not instantaneous

- example: changing the flow of steam or water in a turbine takes a few seconds
  Hence, an "energy buffer" is needed to quickly compensate power imbalances
    - this is provided by the rotating masses of synchronous generators
    - a deficit (resp. excess) of generation wrt load results in a decrease (resp. increase) of speed of rotation speeds (and hence, frequency)
    - in a synchronous generator and its turbine, kinetic energy $\approx$ nominal power of the generator produced during 2 to 5 seconds
    - controlling the power balance in a power system without rotating machines (only power electronic interfaces) would be a challenge (still at research level) ! Larger variations in load (e.g. during the day) require starting up/shutting down power plants ahead of time

Large AC interconnections

Motivations:

- Mutual support between partners to face the loss of generation units
- Each partner would have to set up a larger "reserve" if it would operate isolated
- Larger diversity of energy sources available within the interconnection
- Allows exploiting complementarity of nuclear, hydro and wind power plants
- Allows partners to sell/buy energy, to create a large electricity market.

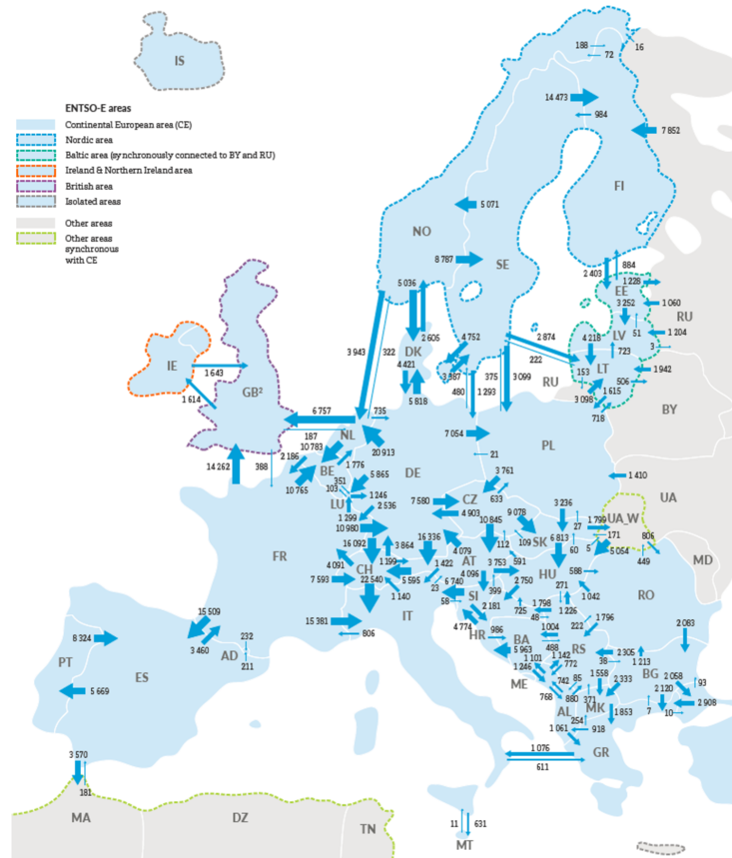
Constraints:

- If one partner is unable to properly “contain” a major incident, the effects may propagate to the other partners’ networks
- A transaction from one point to another cannot be forced to follow a “contractual” path; it distributes over parallel paths (“wheeling”) : see example on another slide.
    - Partners not involved in the transaction undergo the effects of the power flow.
- In large AC interconnections, there may be emergence of badly damped interarea electromechanical oscillations (frequency in the range 0.1 - 0.5 Hz)
    - Rotors of synchronous generators in one area oscillate against the rotors of generators located in another area
    - It may not be possible to connect two networks with different power quality standards

European networks

ENTSOe : European Network of Transmission System Operators for electricity

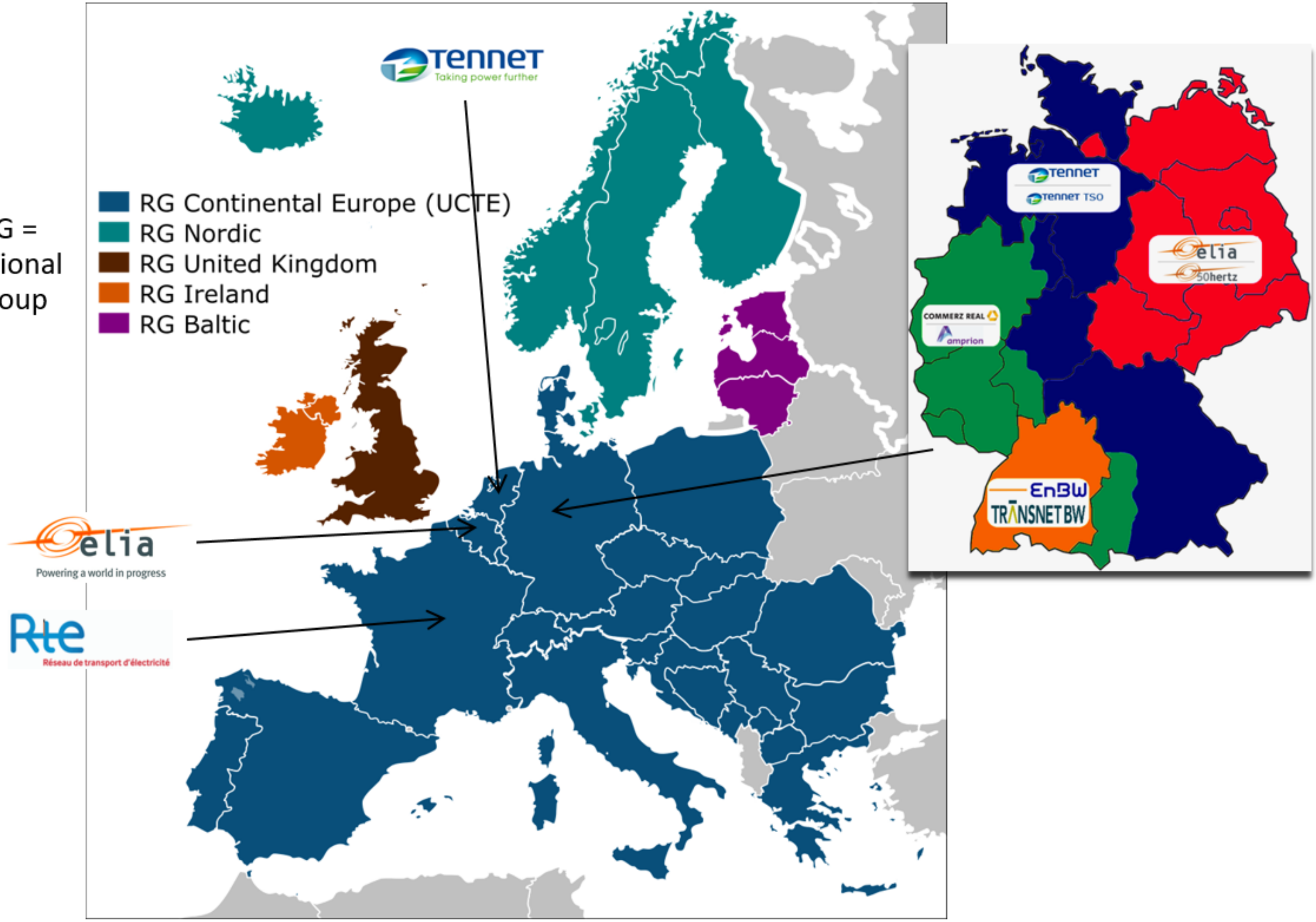
41 Transmission System Operators (TSOs) from 34 countries



Energy flows in 2018 (in GWh)

The synchronous grids of Europe

RG = Regional Group



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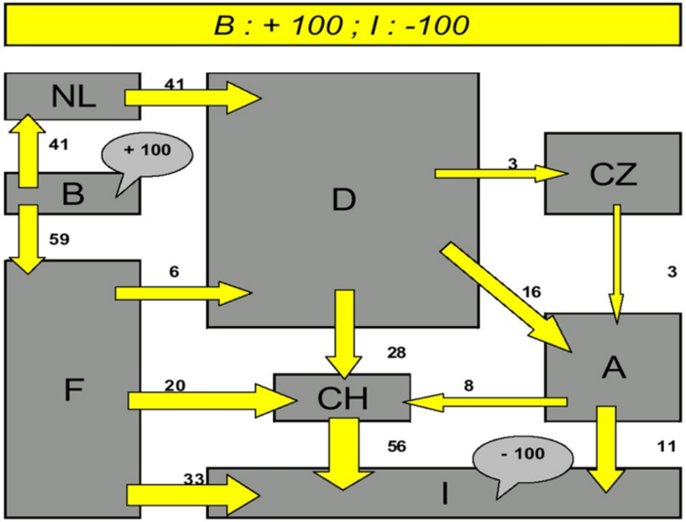
Source: ENTSOE

Example of paths followed by power due to a transaction

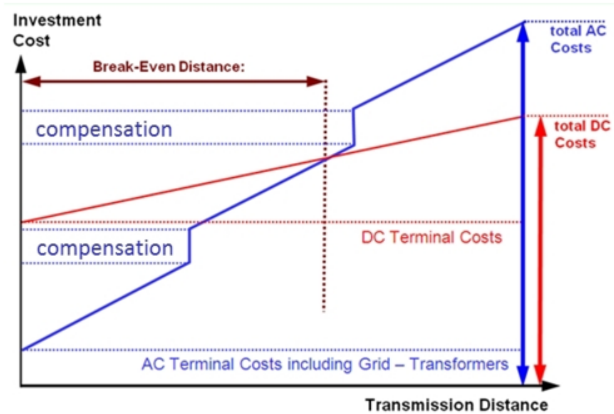
Paths taken by a production increment of 100 MW in Belgium covered by a load increase of 100 MW in Italy (variation of losses neglected):

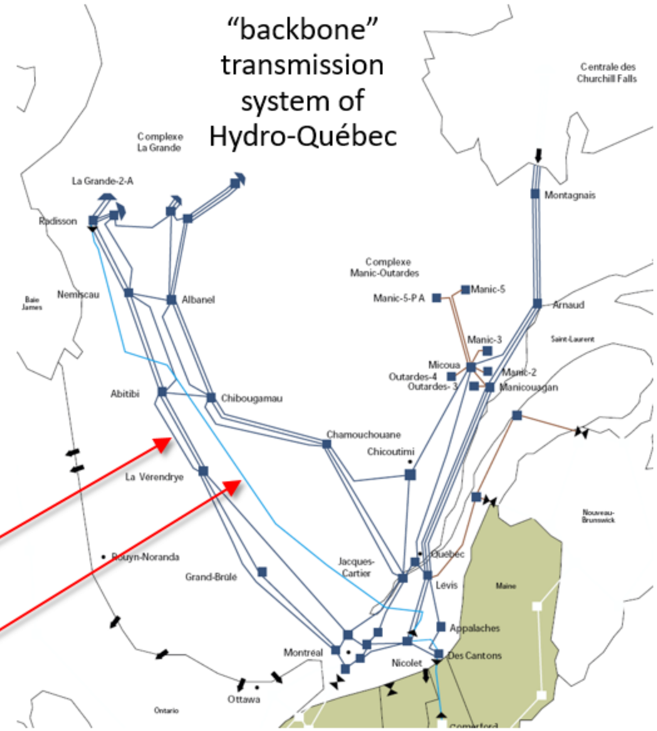


The come-back of Direct Current

Advances in power electronics $\longrightarrow$ rectifiers and inverters able to carry larger currents through higher voltages $\longrightarrow$ transmission applications made possible

Transmission over longer distances through overhead lines





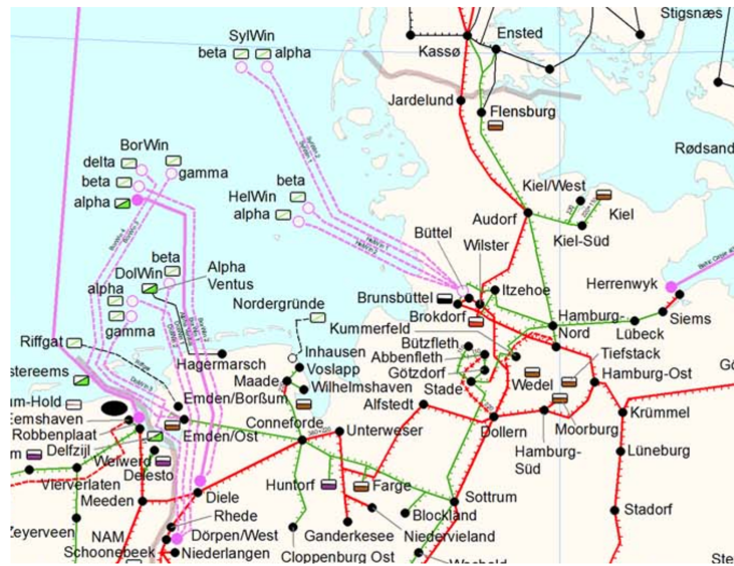
dark blue: AC transmission at 735 kV

light blue: HVDC link :
1018 km ± 450 kV 2000 MW

Transmission through submarine cables

- DC more attractive than AC for distances above >= 50 km : owing to capacitive effects of AC cables
- Existing links in Europe : see a previous slide
- Projects involving Belgium: Nemo with England, Alegro with Germany : see a previous slide

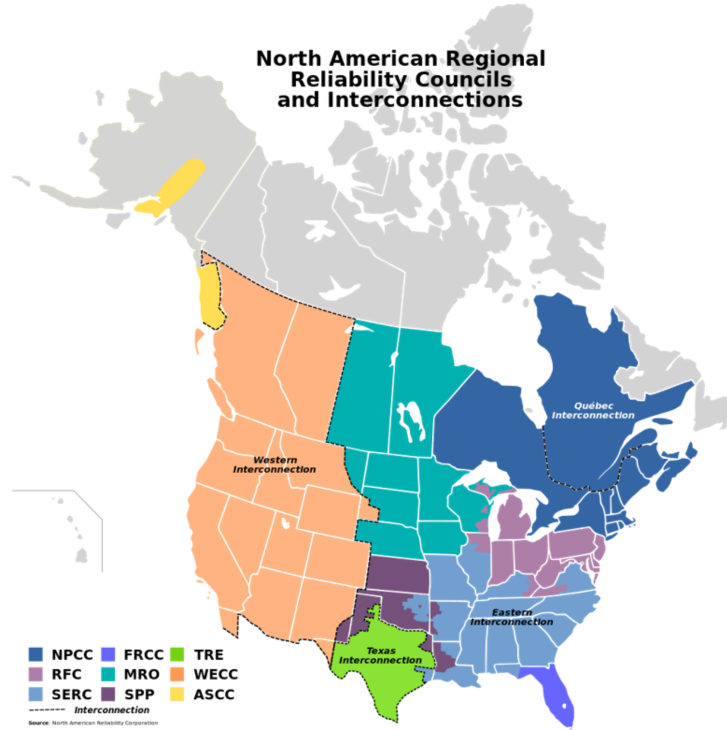
Connection of off-shore wind parks (source: ENTSOE, AC and DC connections of off-shore wind parks in North Sea to the grid of the Tennet German TSO, links under construction shown with dotted lines):



Connection of AC networks with different frequencies or ...

Two networks with different nominal frequencies

- connection of 50 and 60 Hz systems in Japan
- connection of Brazil at 60 Hz with Argentina at 50 Hz
- two networks that have the same nominal frequency but cannot be merged into a single C network, e.g. for stability reasons
  - UCTE and Russian (IPS/UPS) system
  - Eastern - Western interconnections in North-America
  - Western Europe (see previous slides)



The end.