Course ELEC0014

Introduction to Electric Power and Energy Systems

An introductory overview of electric power systems

Thierry Van Cutsem

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Objectives

- 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

Revisit the slides at the end of the course,

in the light of what you will have learnt !

A large-scale system

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

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

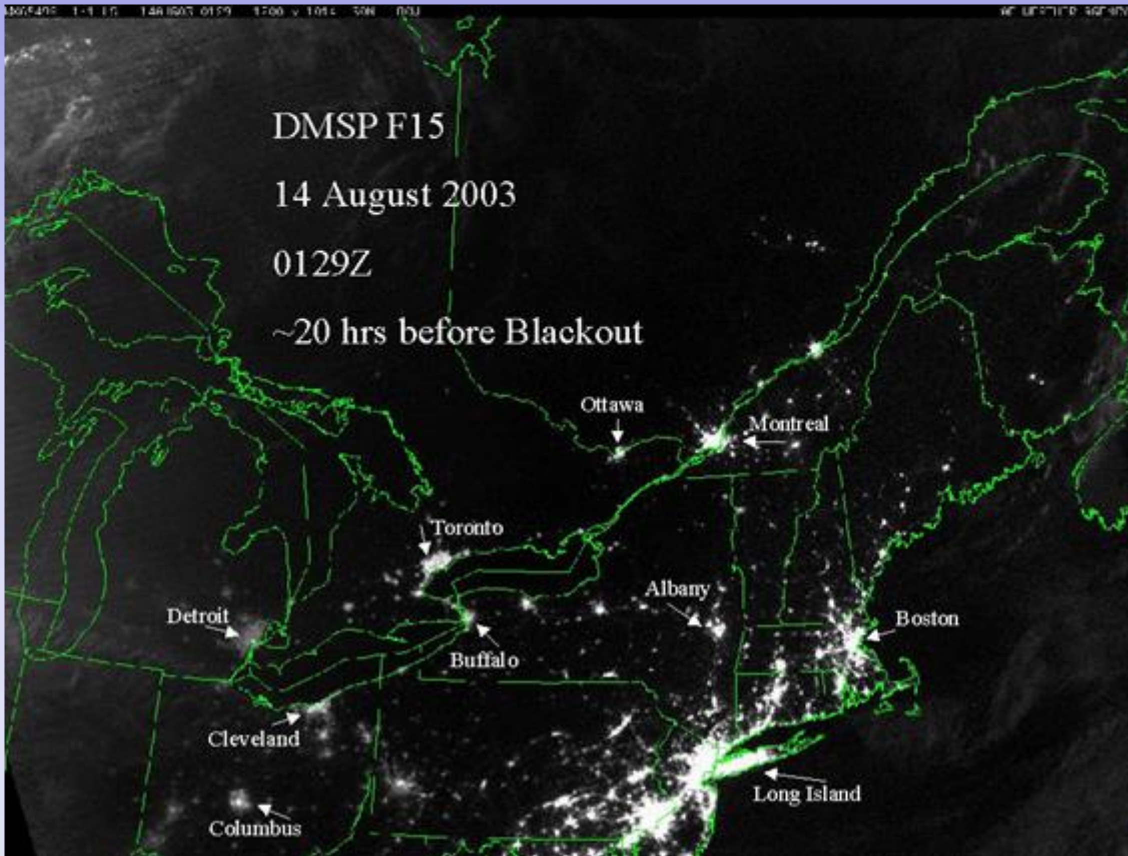
- “behind the power outlet” there is a complex industrial process
- electric energy systems are the largest systems ever built by man
  - thousands of km of overhead lines and underground cables, of transformers
  - tens/hundreds of power plants + a myriad of distributed energy sources
  - devices to (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 counters, 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
  - Example : assume a duration of power supply interruption $\approx$ 0.5 hour / year

$$\text{availability} = \frac{8760 - 0.5}{8760} = 99.994\ \% \quad !$$

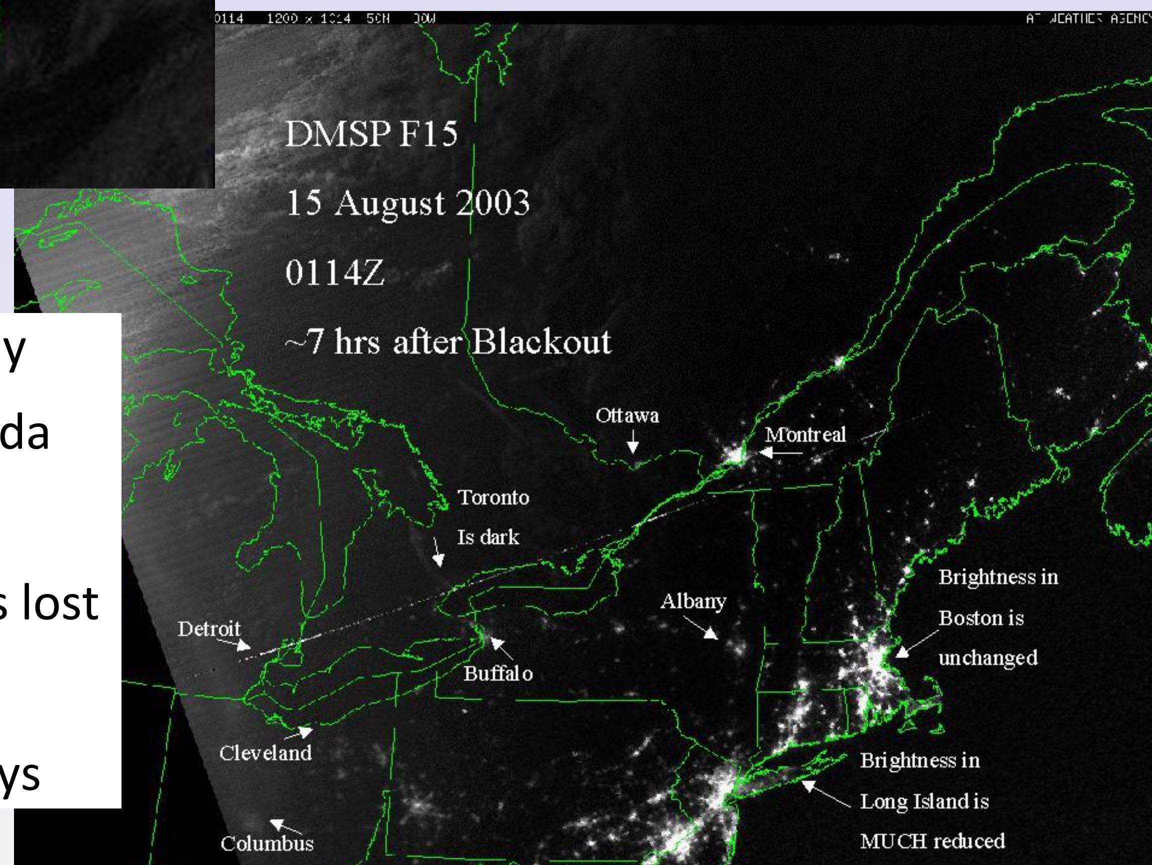
- however, the cost of unserved energy is high
  - average cost used by CREG (Belgian regulator) to estimate the impact of forced load curtailment : 8 300 €/MWh (source: Bureau fédéral du plan)
  - varies with time of the day : between 6 000 and 9 000 €/MWh
  - varies with type of consumer : 2 300 €/MWh for domestic, much higher for industrial
  - even higher average cost considered elsewhere (e.g. 26 000 €/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

source :

North American Electric Reliability Council (NERC)



- 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

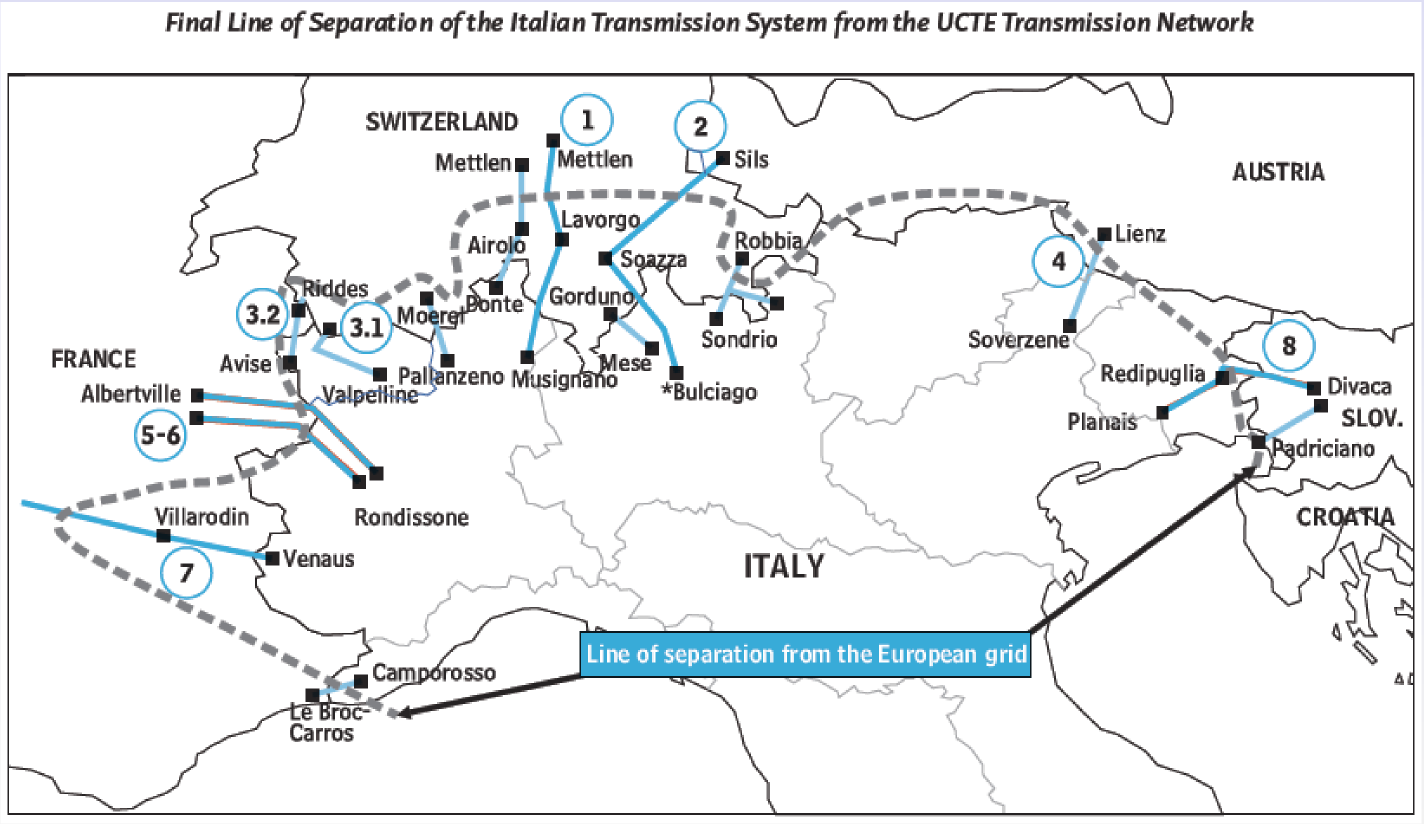
Italian blackout, September 2003

- cascade tripping of interconnection lines → separation of Italy from rest of UCTE system
- deficit of 6 660 MW imported in Italian system, causing frequency to collapse in Italy
- 340 power plants shut down
- 55 million people disconnected initially - 27 000 MW lost (blackout occurred during night)
- estimated cost of disruption ≈ 139 million US $
- restoration time : up to 15 hours

source:

Union for the Co-ordination of Transmission of Electricity (UCTE)

which is now part of ENTSOe



Network : from early DC to present high-voltage AC

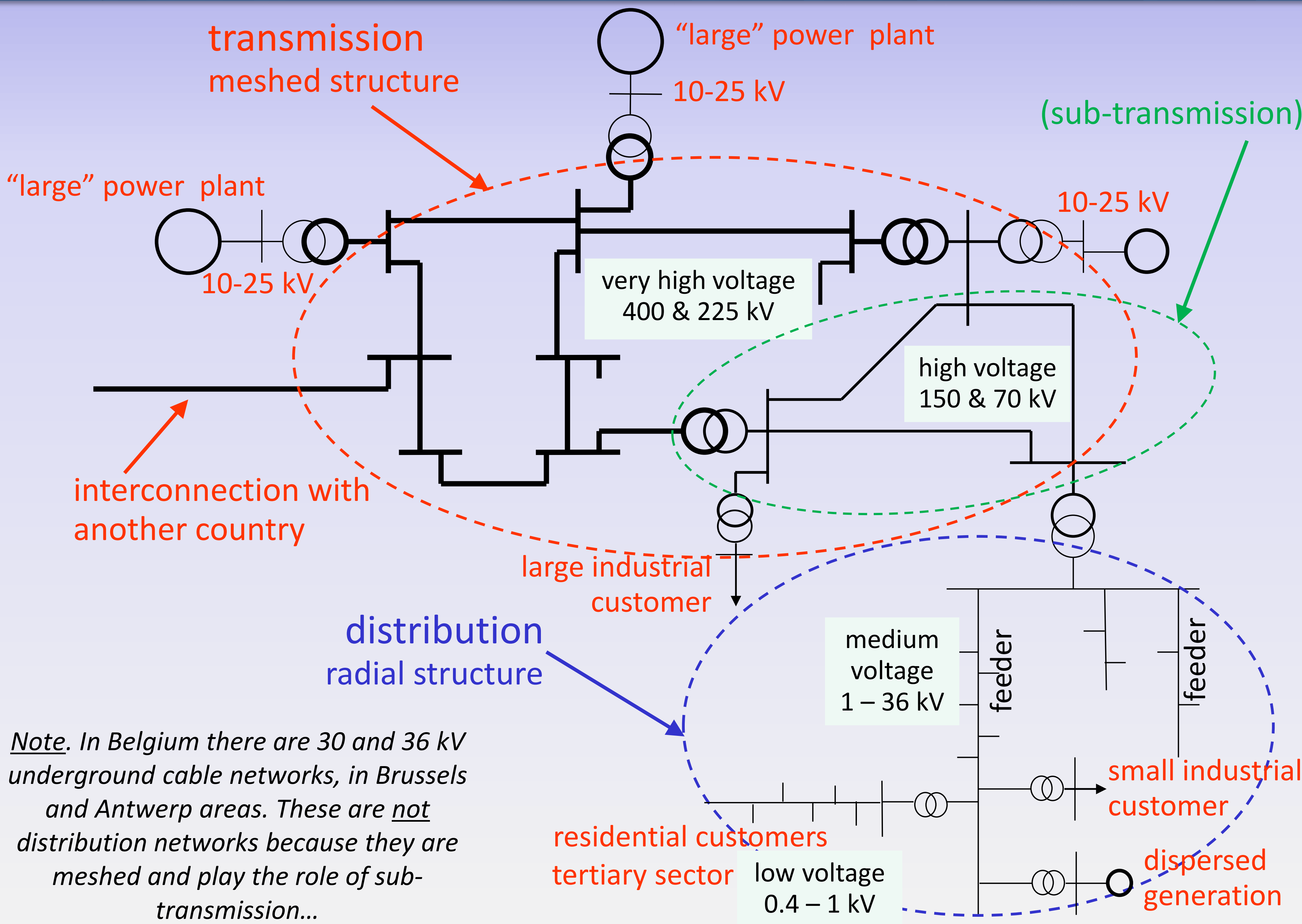
- End of 19th century : Gramme, Edison devised the first generators, which produced Direct Current (DC) under relatively low voltages
- impossibility to transmit large powers with direct current:
  - $power = current \times voltage$

    if voltage cannot be increased, the current must be

    but $power\ lost = resistance \times current^2$ → big waste of energy

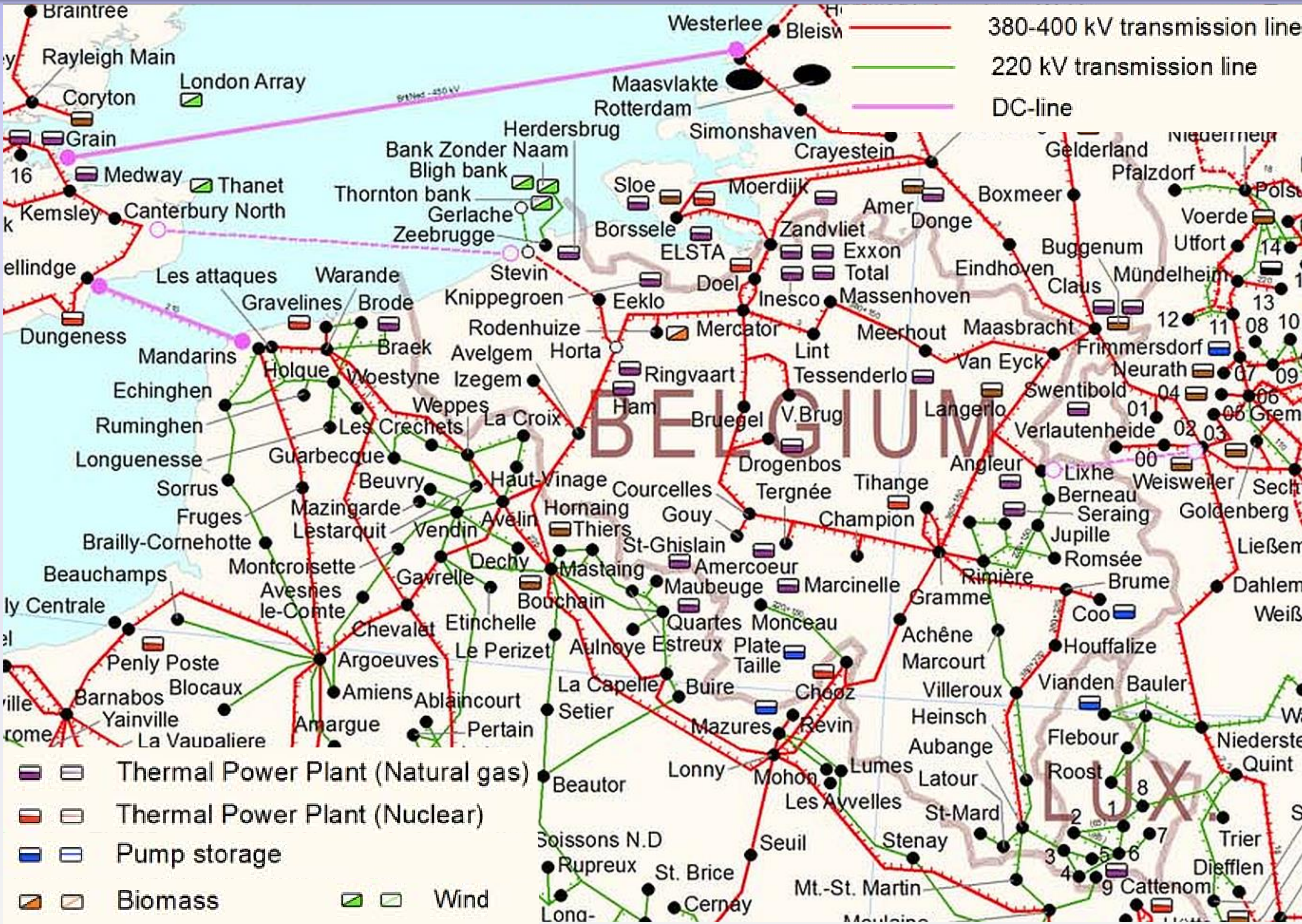
    and large sections of conductors required → expensive and heavy
  - impossible to interrupt a large DC current (no zero crossing), f.i. after a short-circuit
- changing for Alternating Current (AC)
  - voltage increased and lowered thanks to the transformer
  - standardized values of frequency : 50 and 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)



Note. In Belgium there are 30 and 36 kV underground cable networks, in Brussels and Antwerp areas. These are not distribution networks because they 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

source : SYNERGRID

as of December 2018

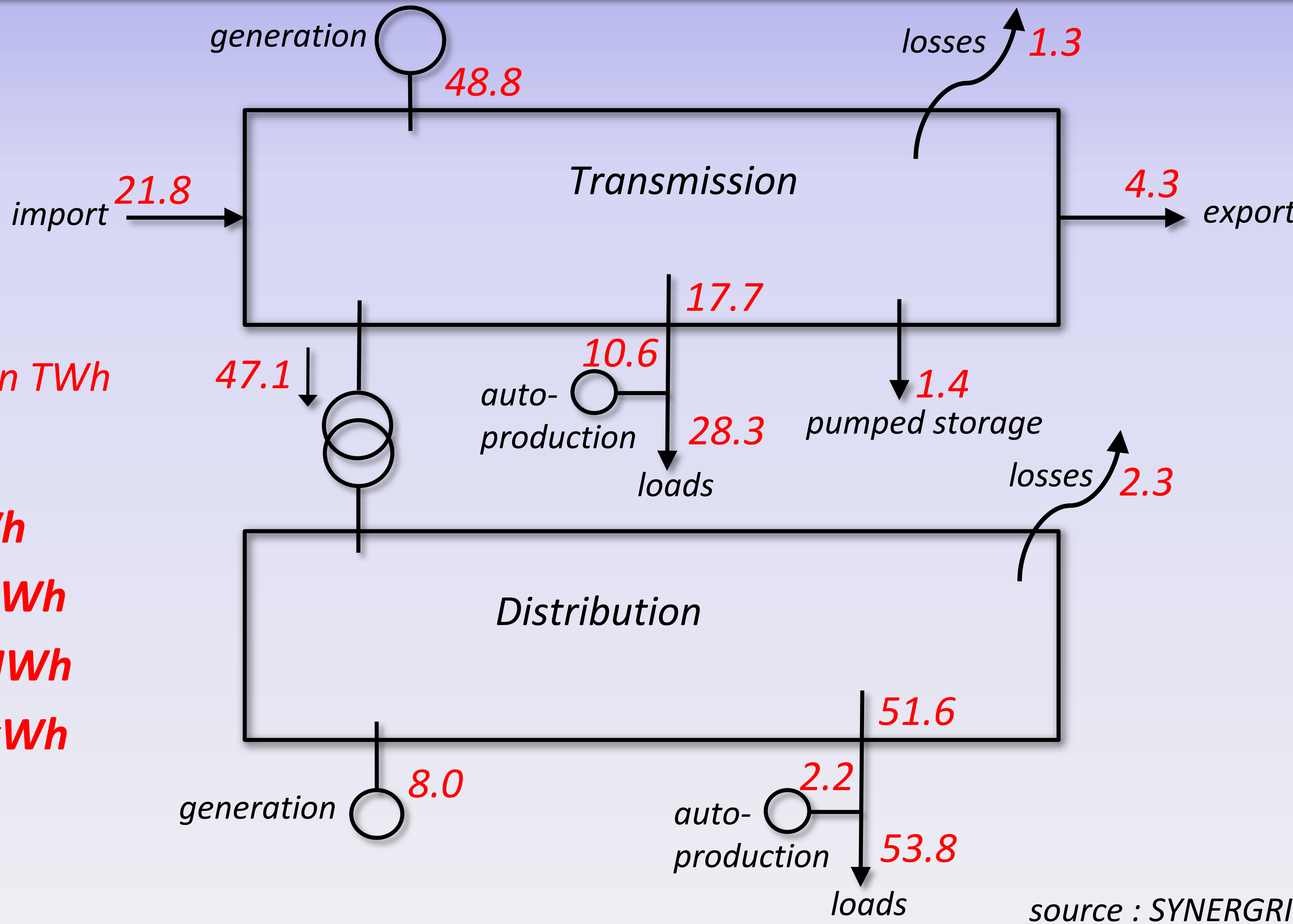
	Nominal voltage (kV)	Underground cables (km)	Overhead lines (km)	Total (km)
	Transmission and sub-transmission			
Very High Voltage	400	49	919	968
Very High Voltage	225	47	301	348
High Voltage	150	573	1 981	2 554
High Voltage	70	301	2 404	2 705
Medium Voltage	30 & 36	2 022	60	2 082
	Total	2 990	5 665	8 657
	Distribution (1)			
Medium Voltage	$1 \leq \ < 30$	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

Electrical energy balance over the year 2018 in Belgium



1 TWh

= 10^3 GWh

= 10^6 MWh

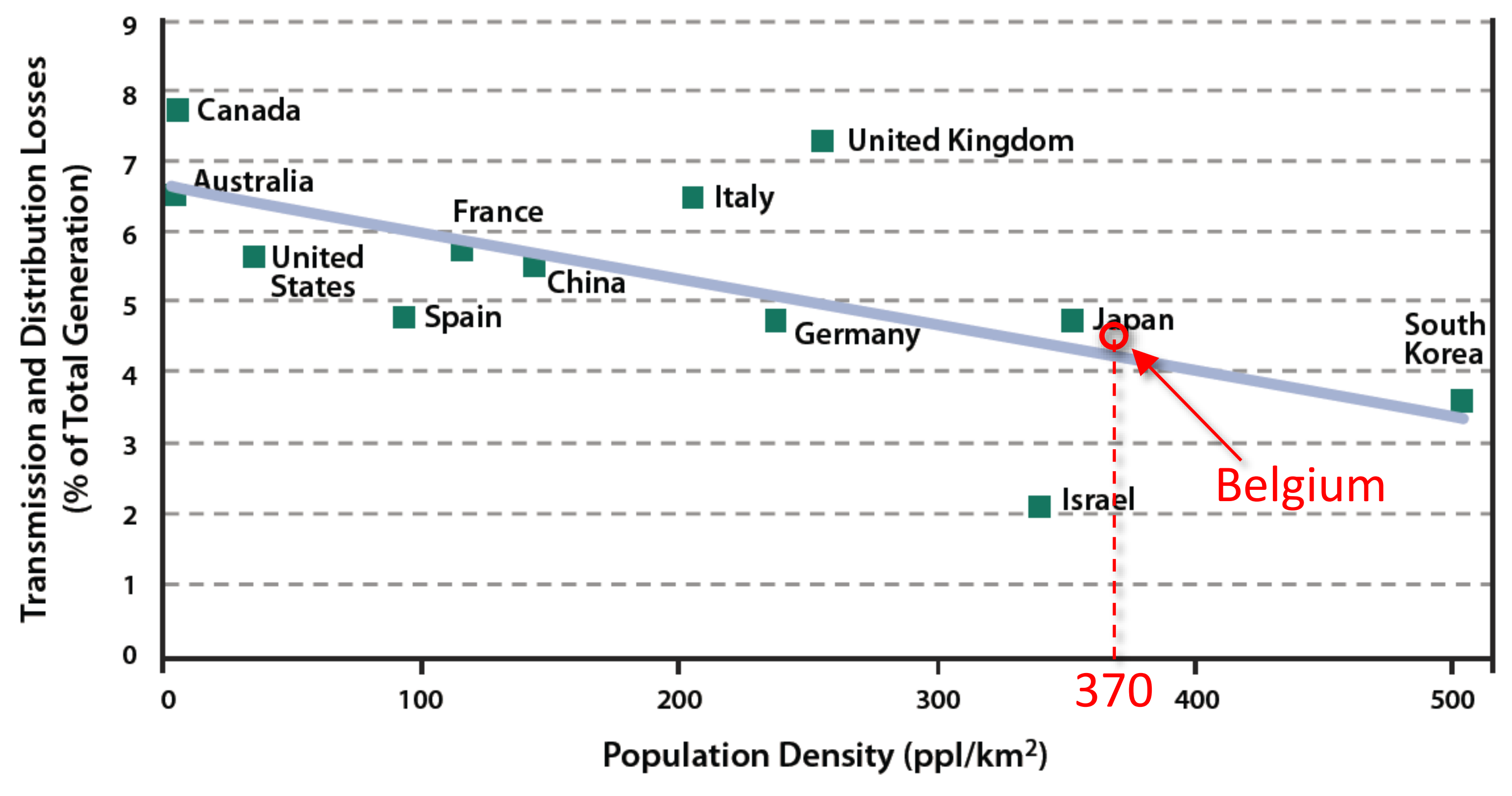
= 10^9 kWh

source : SYNERGRID

Total consumption = 28.3 + 1.3 + 2.3 + 53.8 = 85.7 TWh

Yearly average consumption of a family (4 persons) ≈ 3500 – 4000 kWh

Network losses



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

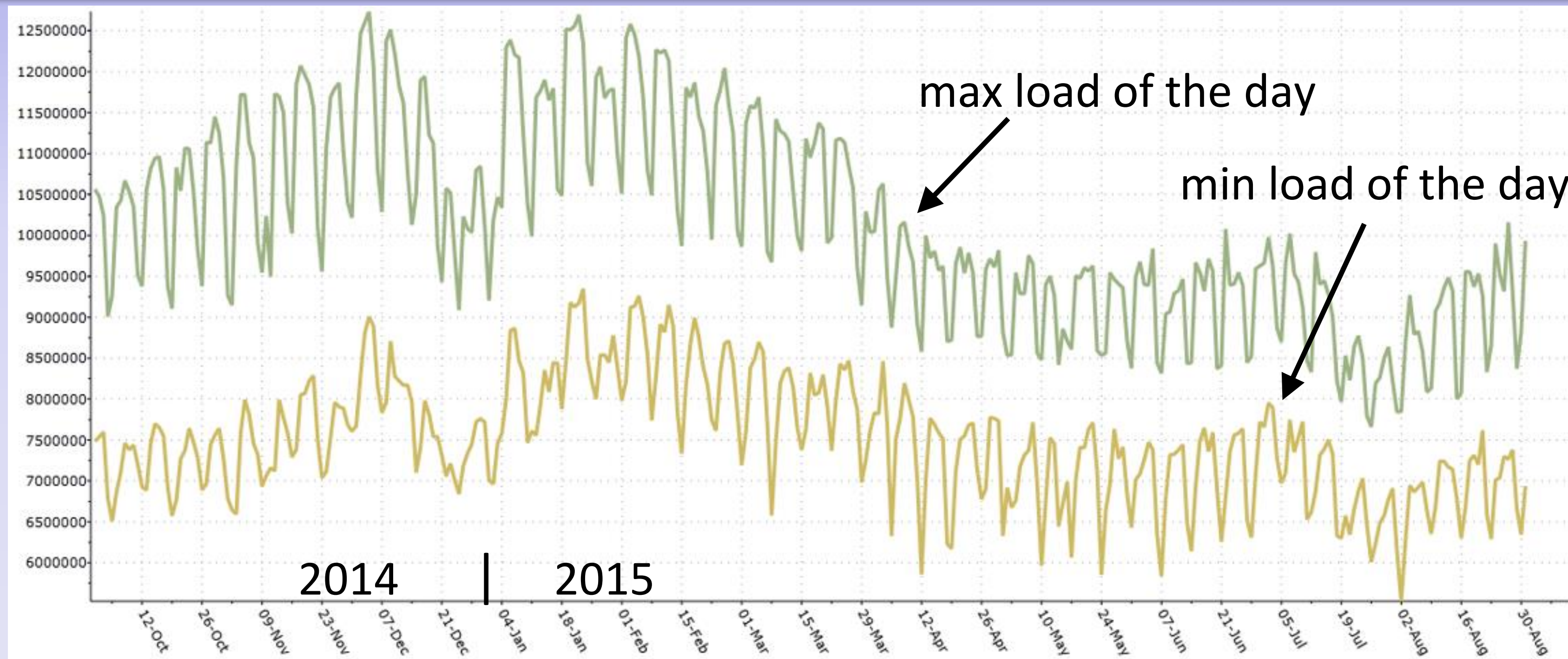
$$\frac{Transmission\ \&\ Distribution\ losses}{Production\ injected\ in\ network + import} = \frac{1.3 + 2.3}{48.8 + 21.8 + 8.0} = 4.6\ \%$$

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

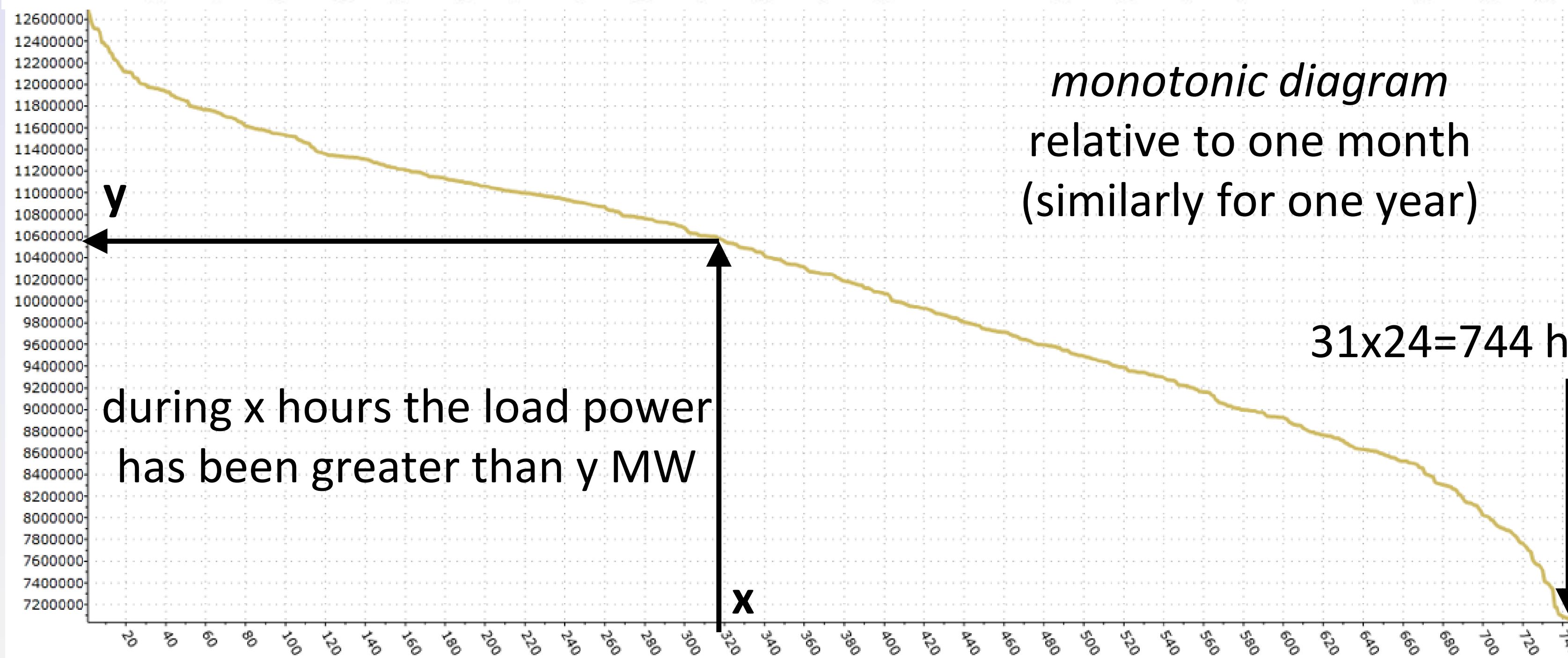
Consumption

12500 MW

6000 MW



12600 MW



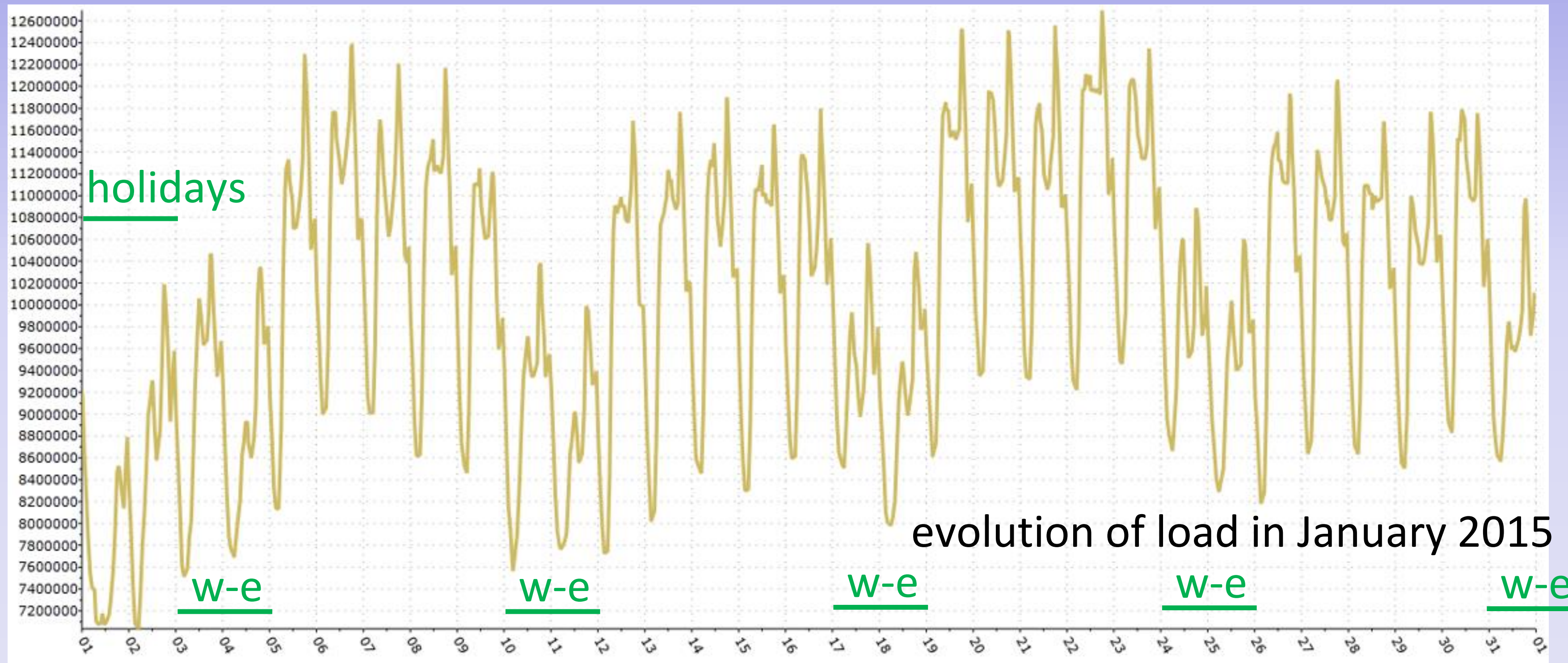
source: ELIA

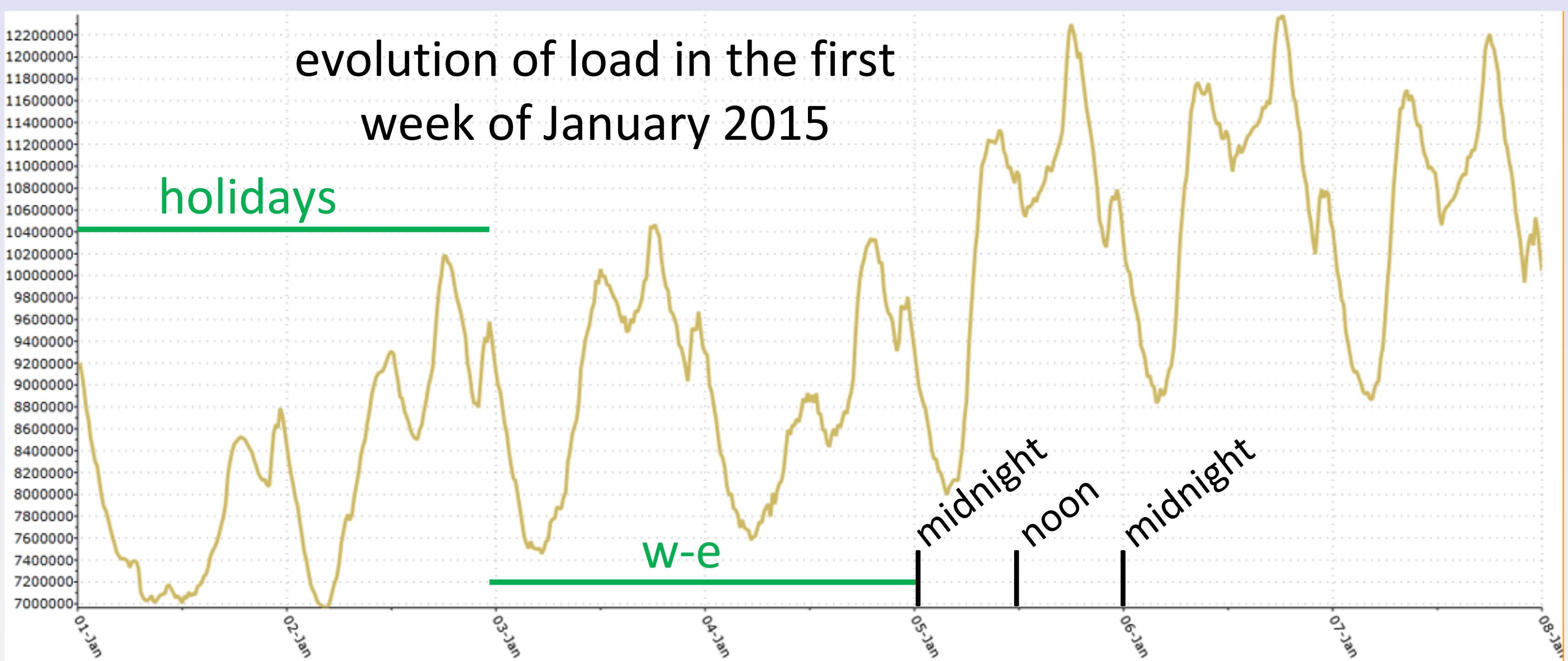
7000 MW

12600 MW

7100 MW

source: ELIA

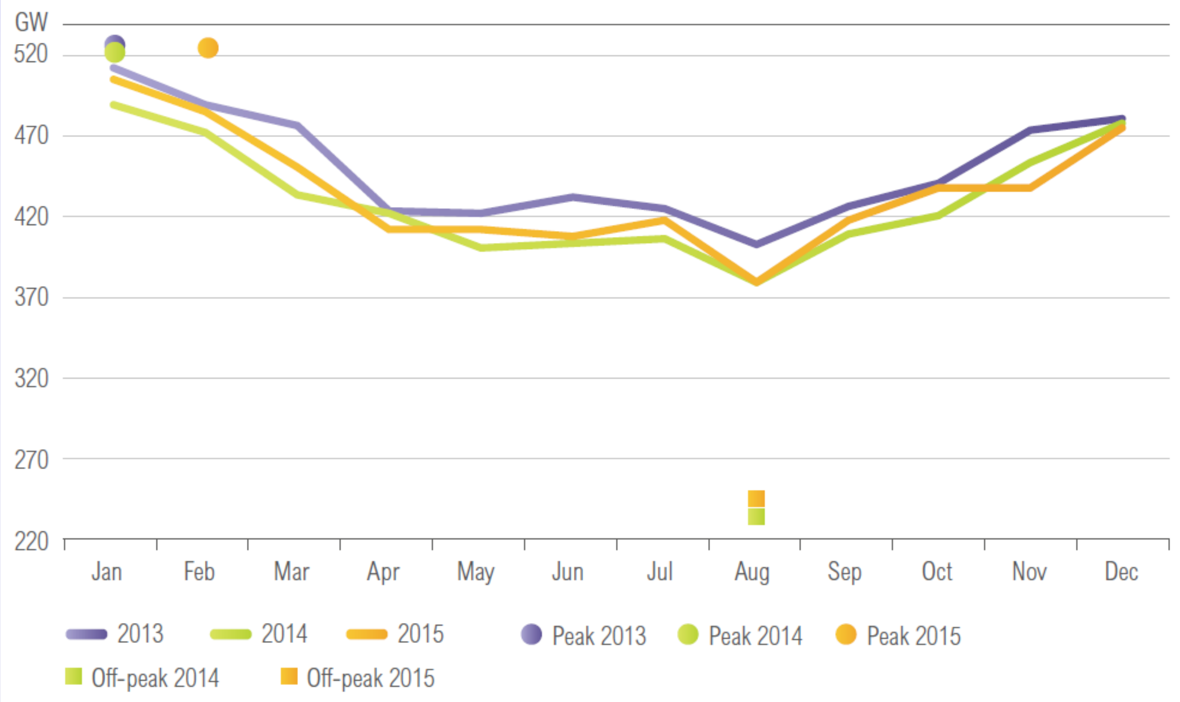




Power consumed in Europe and in Belgium

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

source: ENTSOe



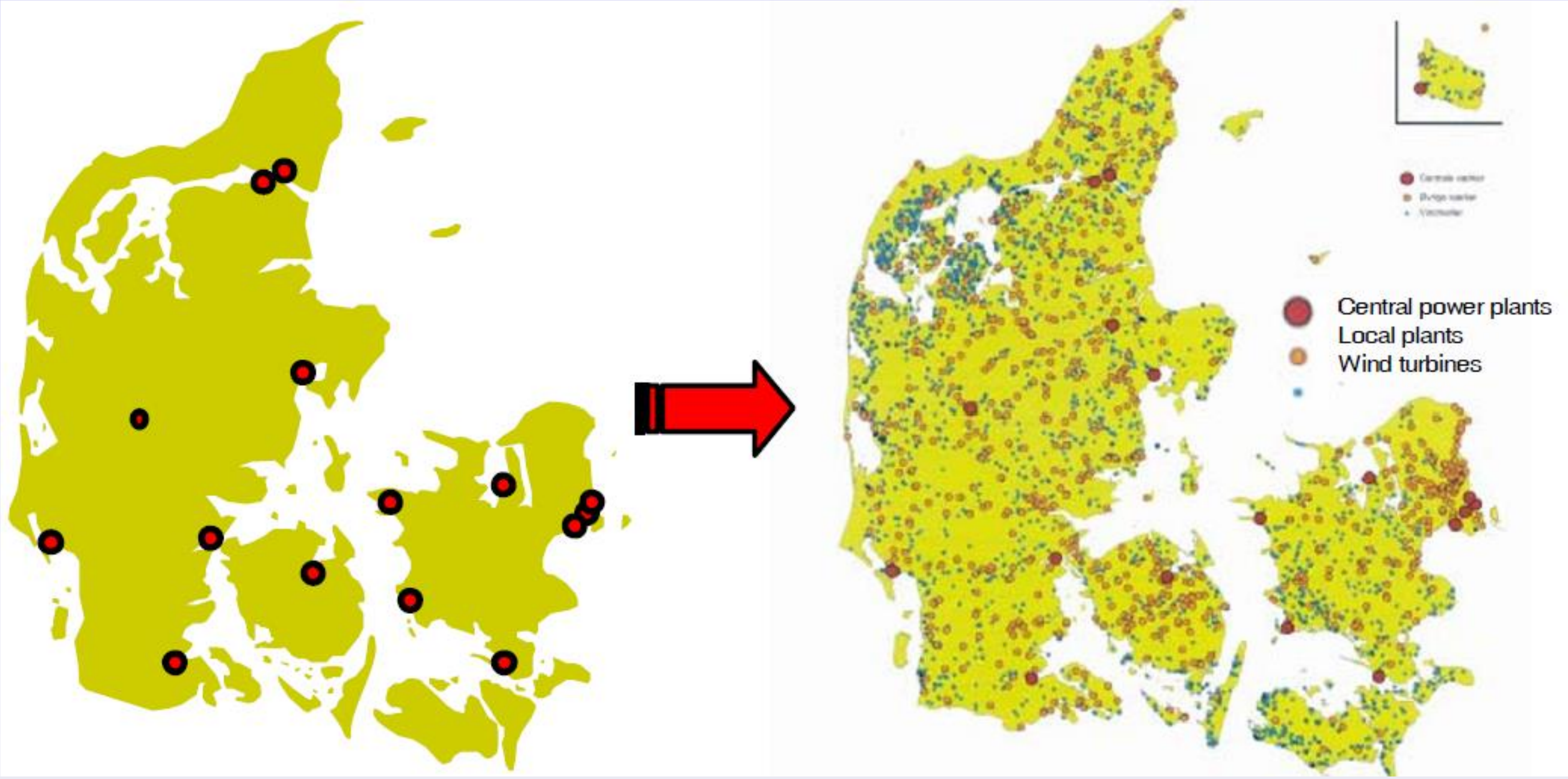
Peak loads recorded on the Belgian transmission system

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

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)

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	

source : ENTSOe

Comments on previous slide

- "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 :
  1. *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)
     $\rightarrow$ "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
  2. fast reserve : a hydro unit can be started (resp. pumping stopped) quickly to replace a generation unit that is taken out of service
  3. allows keeping base units (e.g. nuclear) in operation when load is very low

- *Capacity Factor* = $\dfrac{energy\ produced\ in\ 1\ year\ (MWh)}{generation\ capacity\ (MW) \times 365 \times 24\ (h)}$
  - 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
  - $\Rightarrow$ political decision to keep a "strategic reserve" !
- 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 : ***N**ot **I**n **M**y **B**ack**Y**ard*
  - 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 :

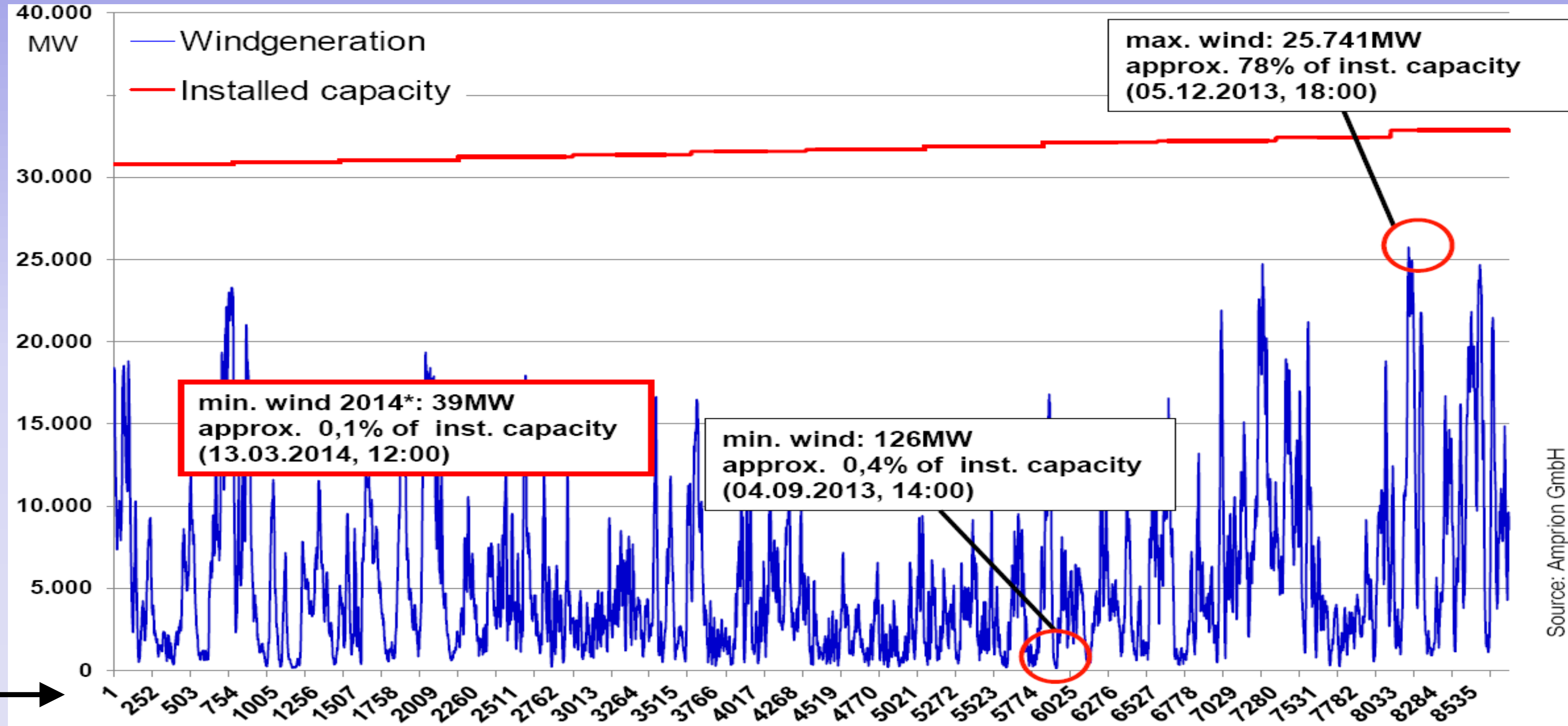
    5 wind parks with an installed capacity of 1186 MW have produced 3,408 TWh

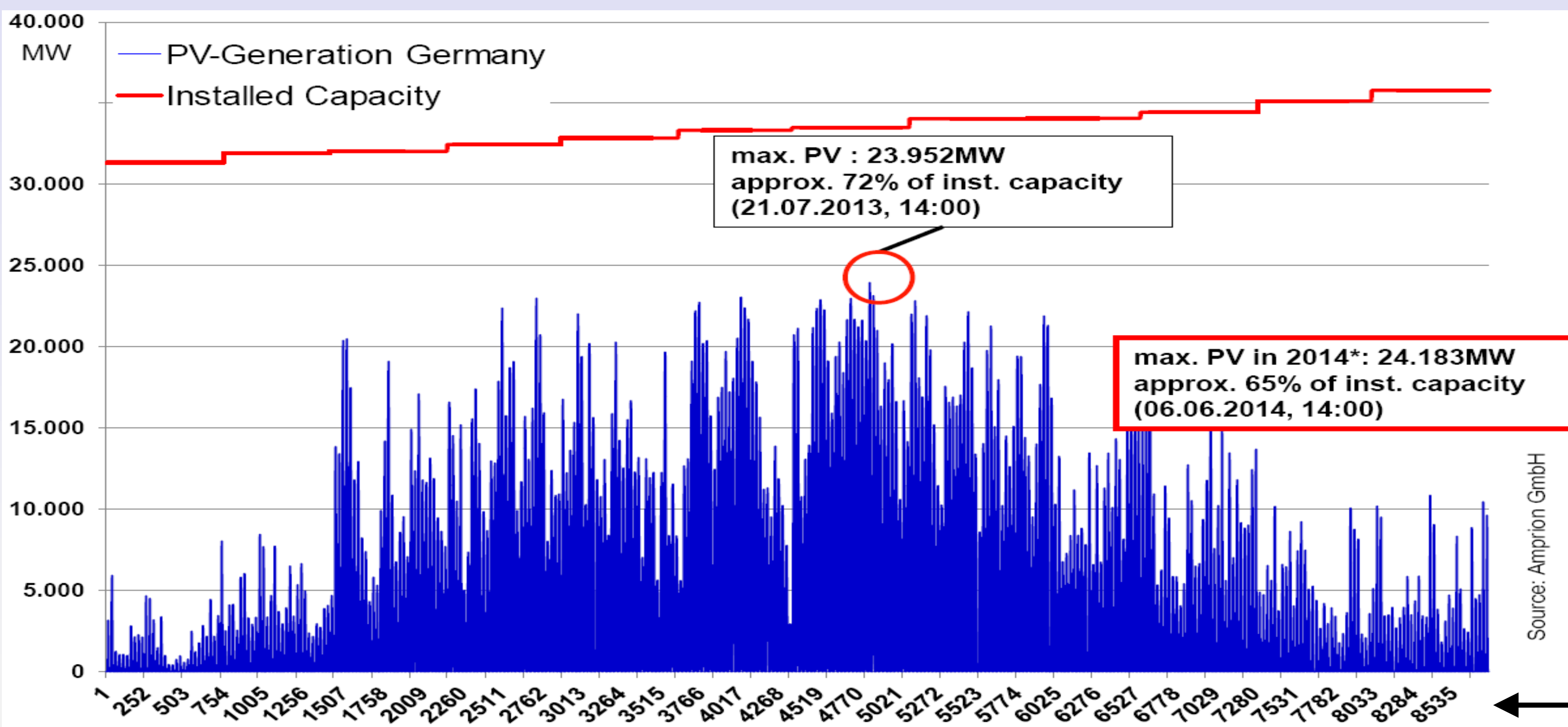
    $\Rightarrow$ Capacity Factor = $\dfrac{3{,}408\ 10^6}{1186 \times 365 \times 24}$ = 32 %
  - still a great potential for new off-shore wind farms :

    3 under construction (+ 1076 MW) $\rightarrow$ 8 TWh production expected in 2020

Examples of variability of wind and photovoltaic generation (Germany)

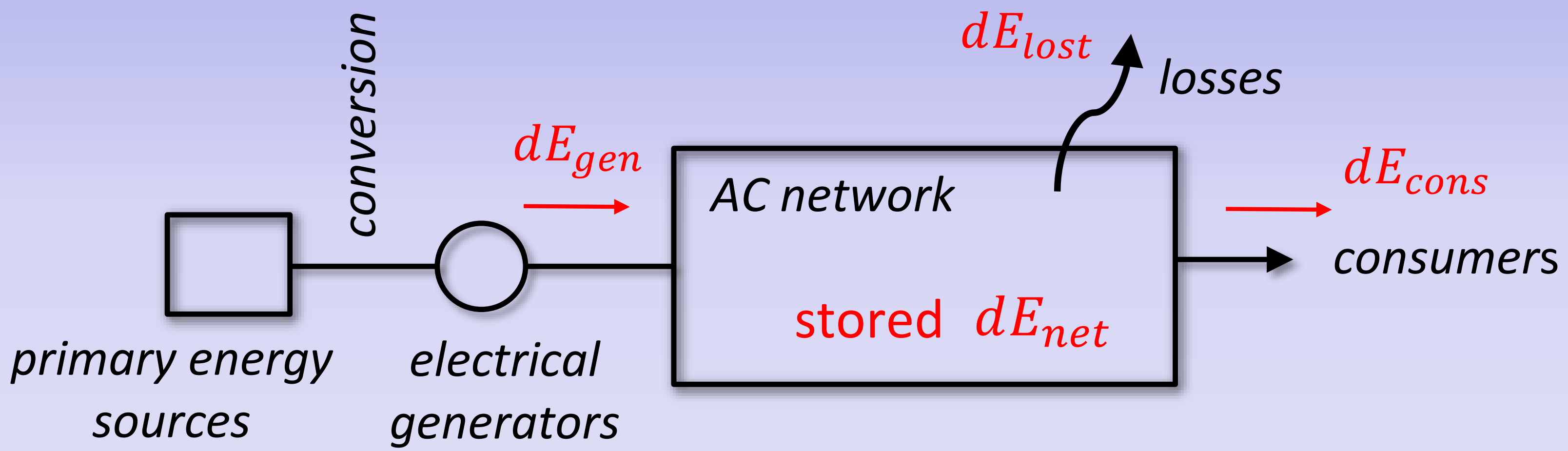
hour of the year 2013





hour of the year 2013

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

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

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

$p_{cons}(t)$

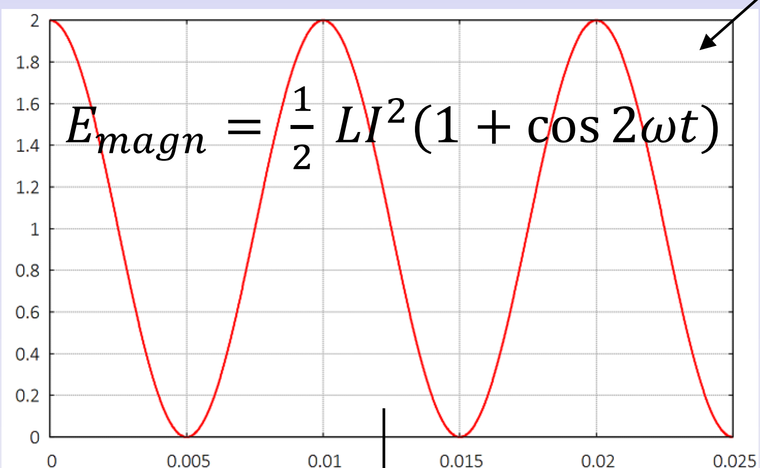
- The consumers decide how much power they want to consume !
- this demand fluctuates at any time

$p_{net}(t)$

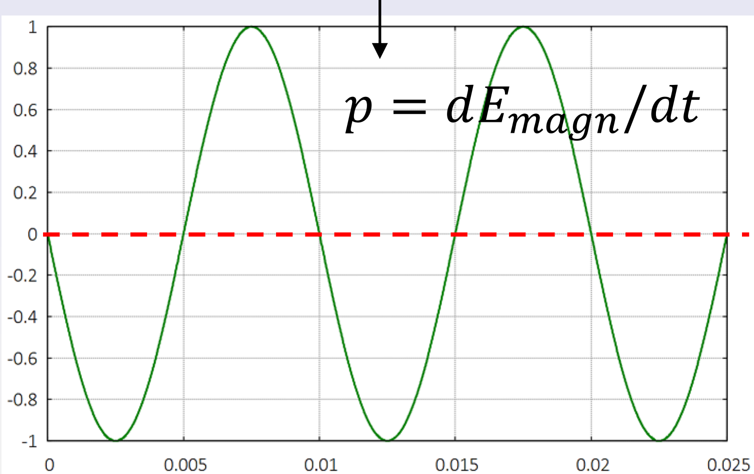
- Network elements which store electrical energy : inductors and capacitors

Example of inductor

$$i(t) = \sqrt{2}\, I \cos \omega t$$



$$E_{magn} = \frac{1}{2} L I^2 (1 + \cos 2\omega t)$$



$$p = dE_{magn}/dt$$

- 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 !!*)

$p_{lost}(t)$

- Losses mainly due to Joule effects $\Rightarrow$ depend on currents in components
- kept as small as possible, not really controllable

Conclusion

- The variations of load power have to be compensated by the generators
- but the conversion (primary energy $\rightarrow$ 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 :

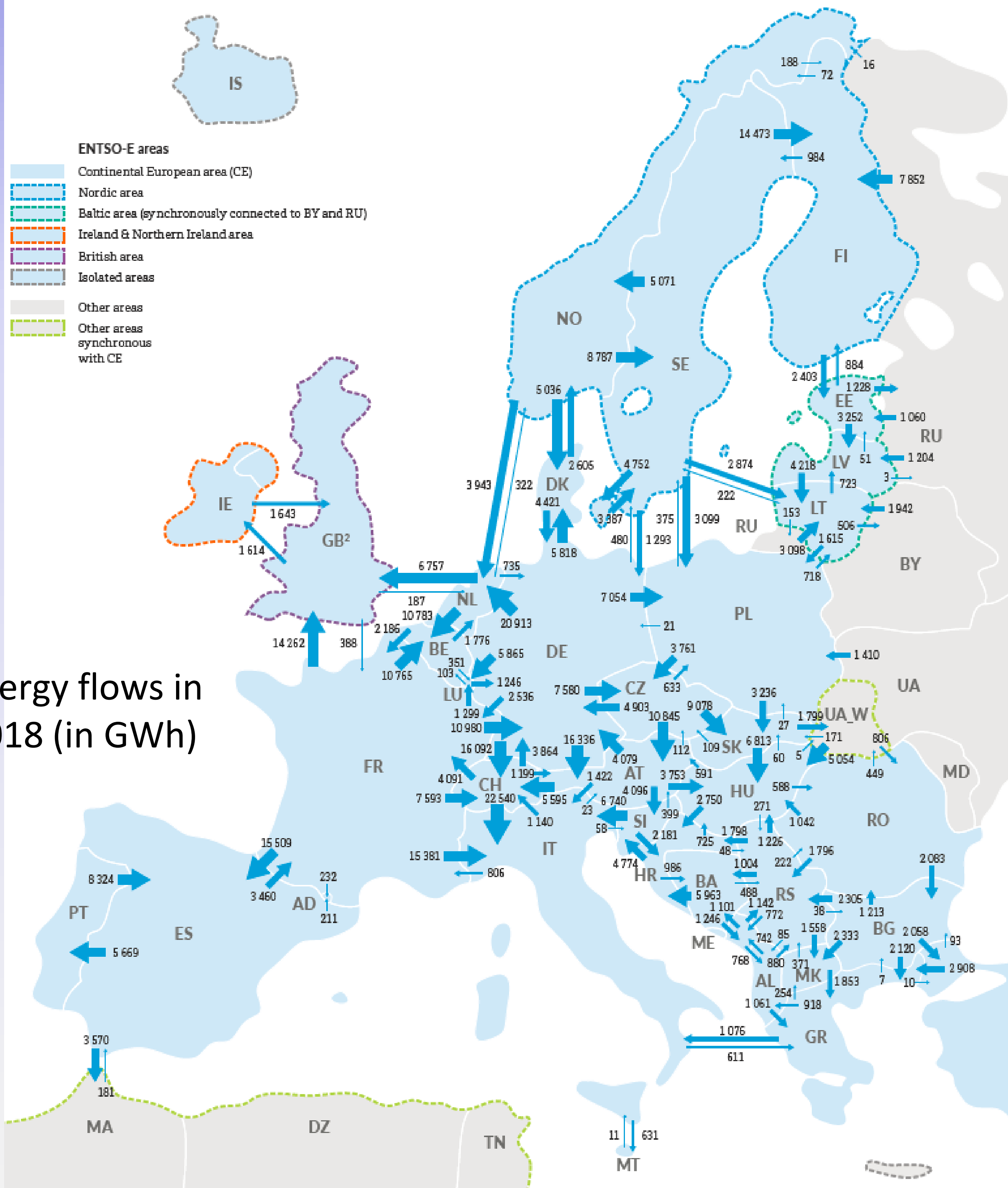
- mutual support between partners to face the loss of generation units
  - each partner would have to set up a larger "reserve" if it would operate isolated
- larger diversity of energy sources available within the interconnection
  - allows exploiting complementarity of nuclear, hydro and wind power 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 in slide # 27.

  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



energy flows in 2018 (in GWh)

ENTSOe :

European **N**etwork of **T**ransmission **S**ystem **O**perators for **e**lectricity

41 Transmission System Operators (TSOs) from 34 countries

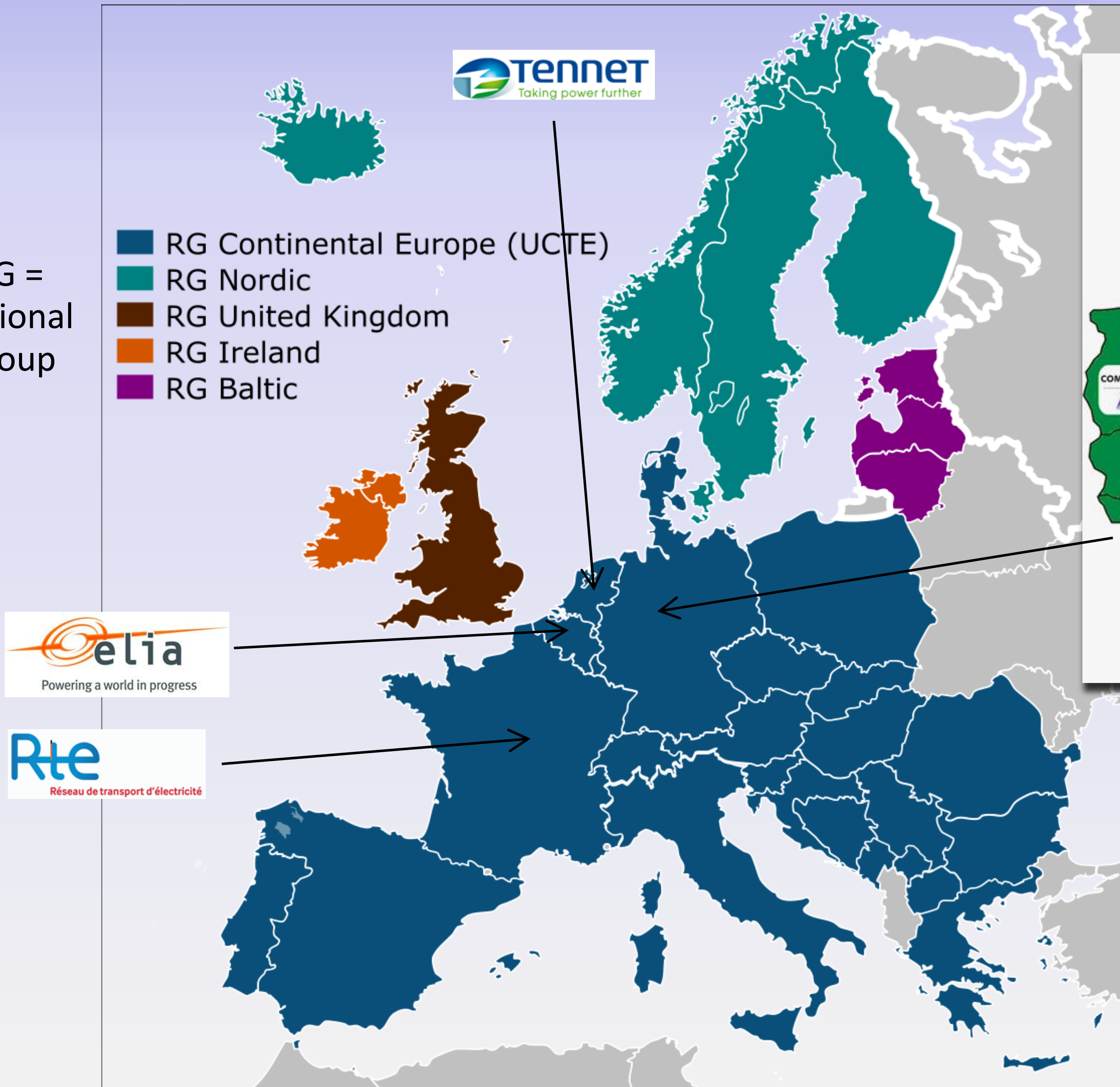
www.entsoe.eu

entsoe

Reliable Sustainable Connected

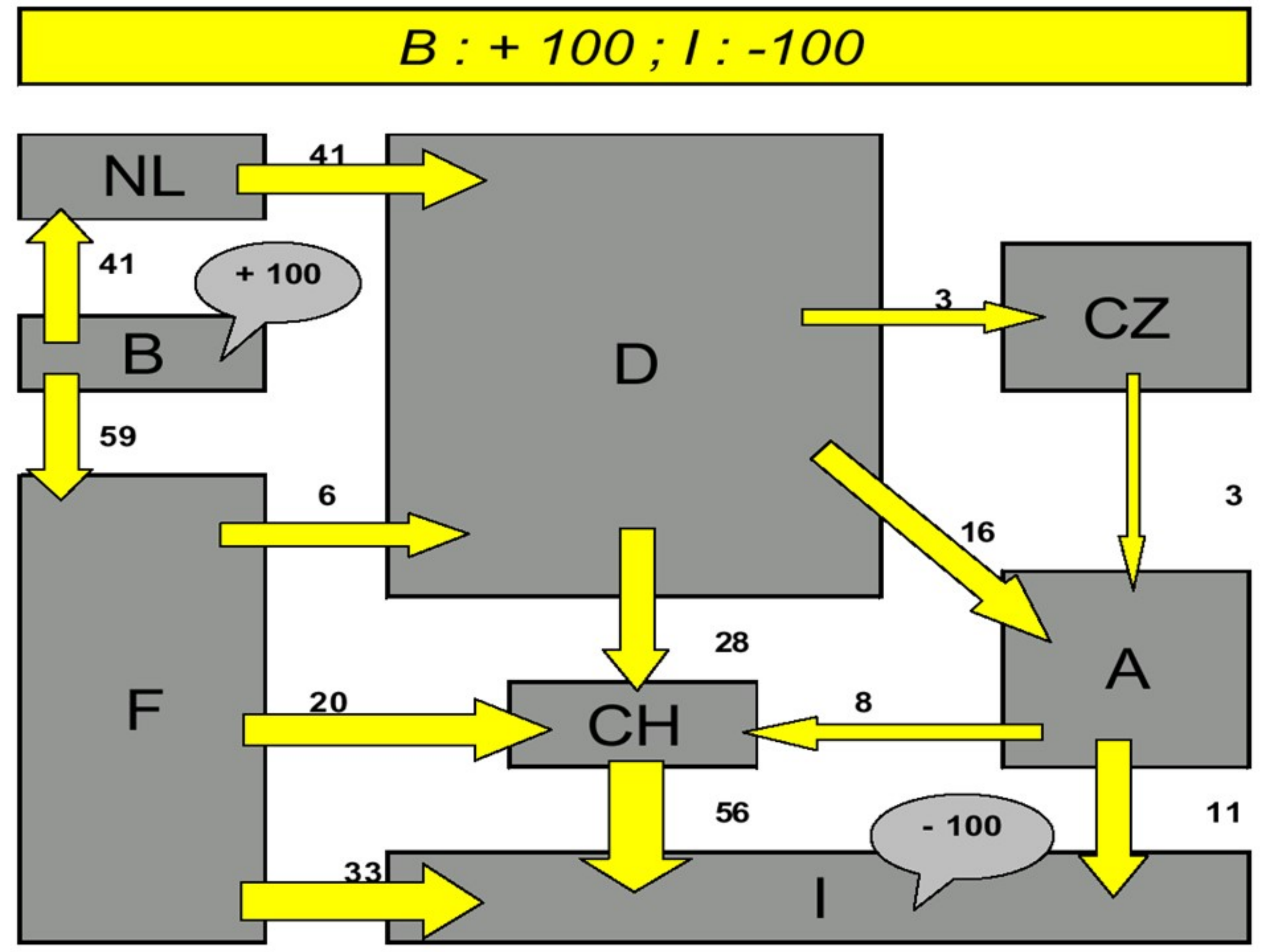
The synchronous grids of Europe

RG = Regional Group



source : ENTSOe

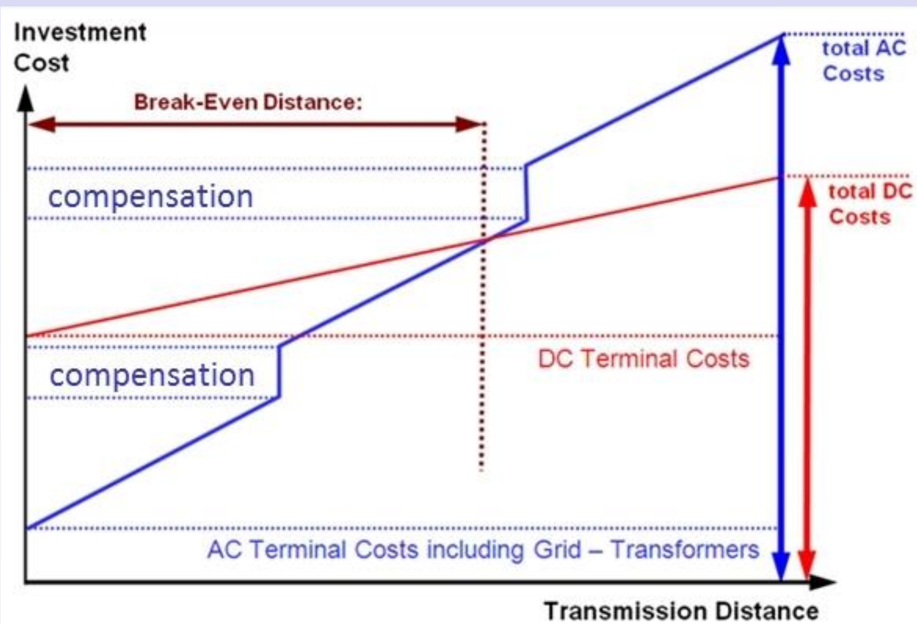
Example of paths followed by power due to a transaction

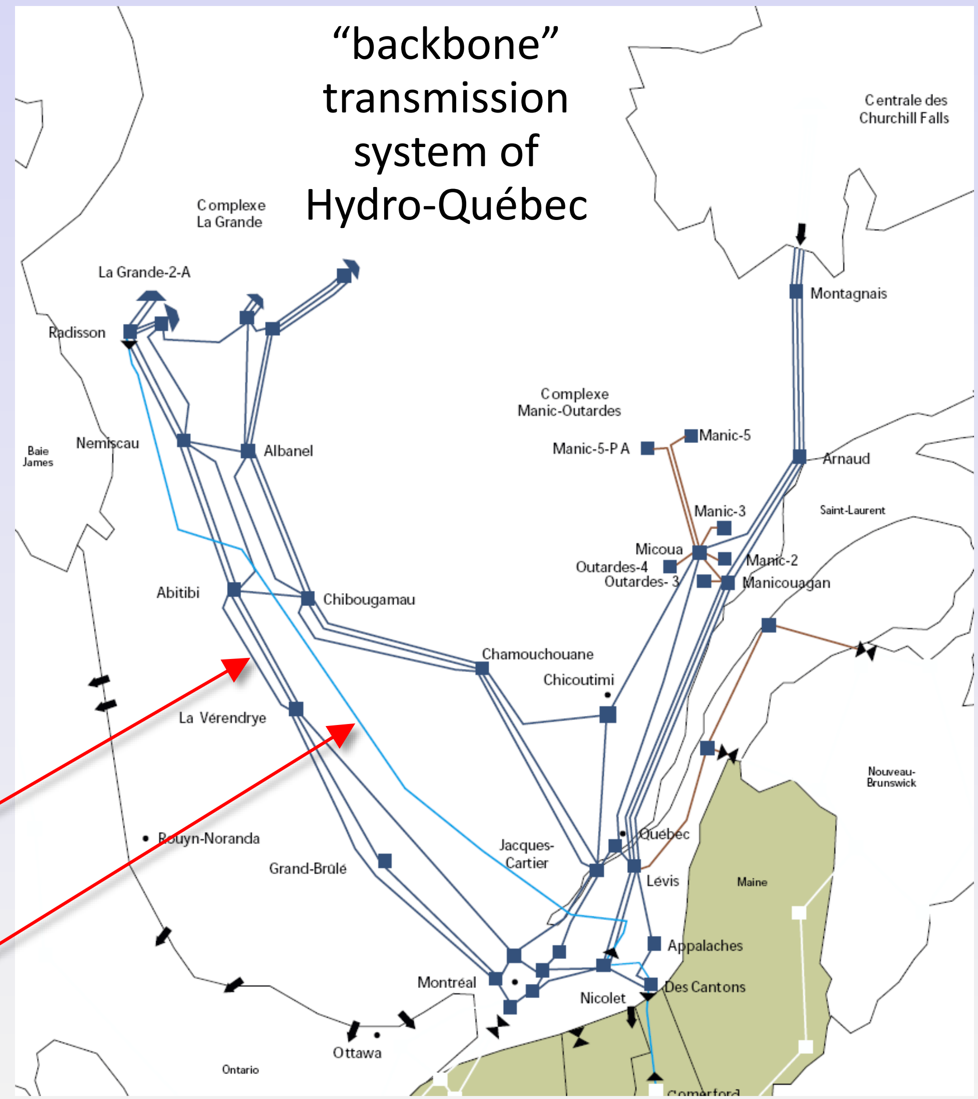


Paths taken by a production increment of 100 MW in Belgium
covered by a load increase of 100 MW in Italy (variation of losses neglected)

The come-back of Direct Current

- Advances in power electronics $\rightarrow$ rectifiers and inverters able to carry larger currents through higher voltages $\rightarrow$ transmission applications made possible
- <u>1st use</u> : <u>transmission over longer distances</u> through overhead lines





dark blue: AC transmission at 735 kV

light blue: HVDC link :
1018 km $\pm$ 450 kV 2000 MW

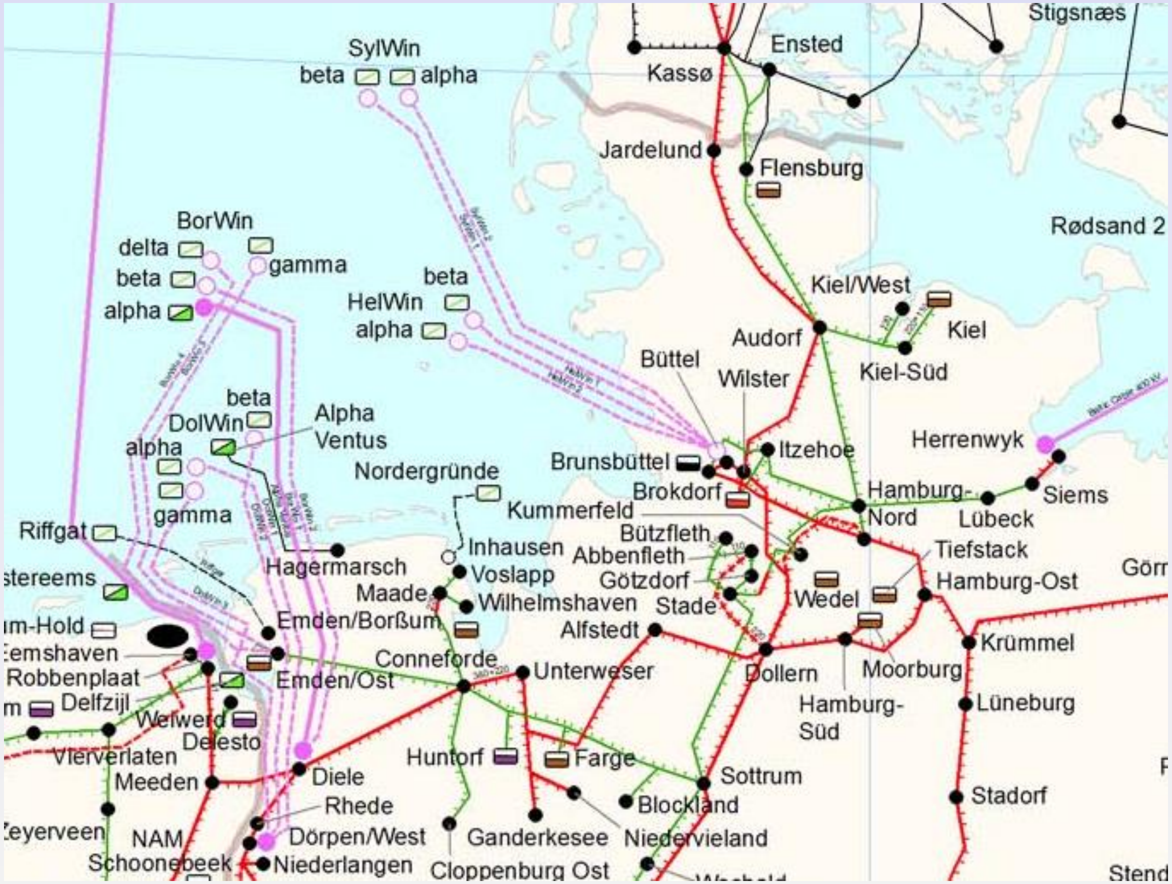
The come-back of Direct Current

- 2nd use : 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 slide # 25
  - projects involving Belgium: *Nemo* with England, *Alegro* with Germany : see slide # 9
  - connection of off-shore wind parks :

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)

source : ENTSOe



The come-back of Direct Current

- <u>3rd use</u> : <u>connection of AC networks with different frequencies</u>
  - 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 AC network, e.g. for stability reasons
    - UCTE and Russian (IPS/UPS) system
    - Eastern - Western interconnections in North-America
    - Western Europe : see slides #25 and 26.