ELEC0080-1 ENERGY NETWORKS
Partim1: Electrical Energy Systems

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An electric power system: the Wikipedia definition

An **electric power system** is a network of electrical components deployed to supply, transfer, and use electric power. An example of an electric power system is *the grid* that provides power to an extended area. An electrical grid power system can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centres to the load centres, and the distribution system that feeds the power to nearby homes and industries. Smaller power systems are also found in industry, hospitals, commercial buildings and homes. The majority of these systems rely upon three-phase AC power—the standard for large-scale power transmission and distribution across the modern world. Specialised power systems that do not always rely upon three-phase AC power are found in aircraft, electric rail systems, ocean liners and automobiles.

Objectives of this first class

- Describe the overall structure of an electric power system.

- Highlight a few important features of power system operation.

- Illustrate those on the Belgian and European system.

- Present some orders of magnitude it is important to have in mind
Introduce some terminology.

- Discuss new (uber-like) models for the electrical power industry.

A large-scale system

- In modern society, electricity has become a “commodity” that is a *“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/thousands/(millions?) 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.
- Like most other complex systems built by man, power systems are exposed to external “aggressions” (rain, wind, ice, storm, lightning, terrorism, etc.)

Several of the next 29 slides are largely inspired from a presentation made by Prof. Thierry Van Cutsem.

Low-probability but high-cost failures

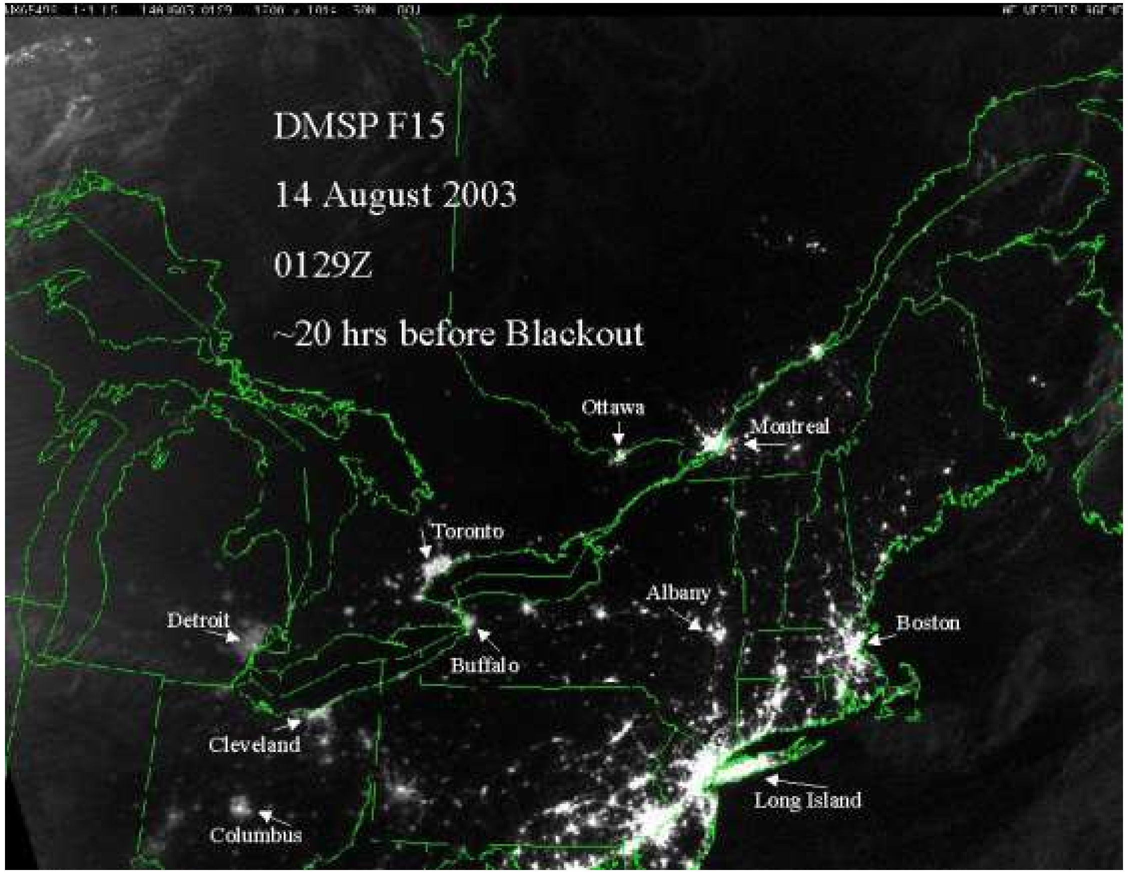
- In spite of those disturbances, modern electric power systems are very reliable

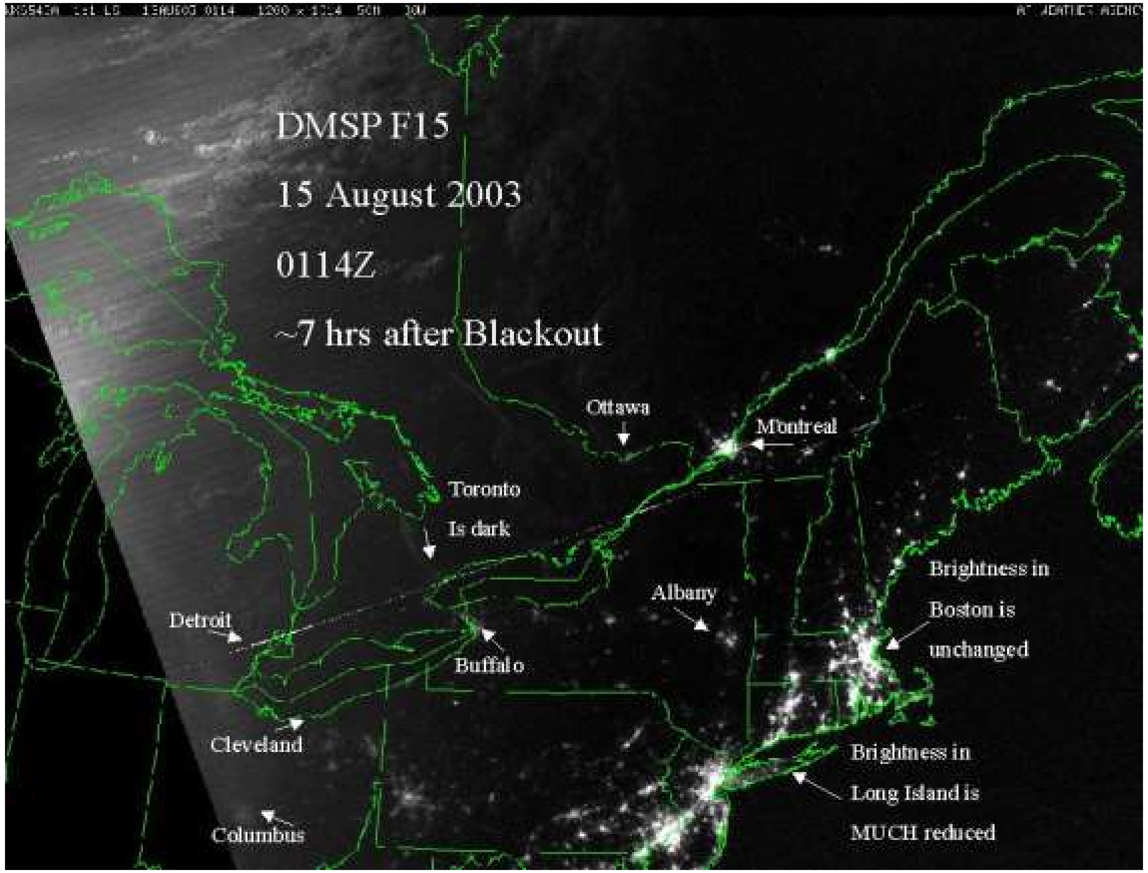
  Example : typical duration of power supply interruption $\approx$ 0.5 hour / year

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

- 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
  - 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





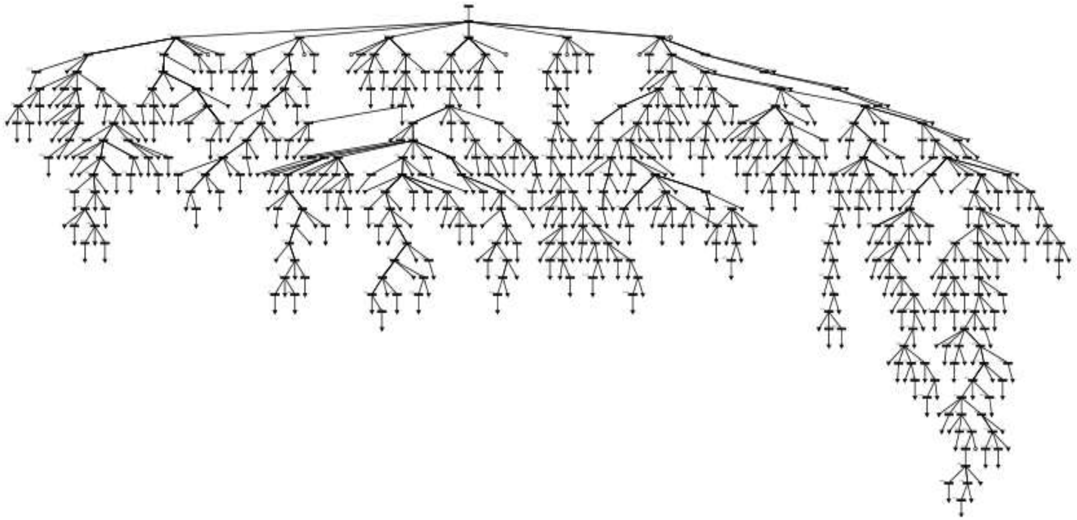
Source : North American Electric Reliability Council (NERC)

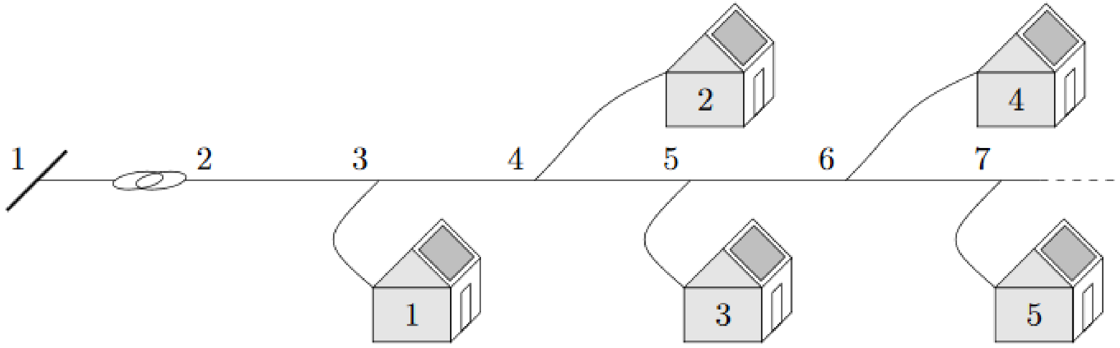
Consequences: 50 million people disconnected initially; 61 800 MW of load cut in USA & Canada; cost in USA : 4 to 10 billion US $; in Canada : 18.9 million working hours lost; 265 power plants shut down; restoration time: few hours up to 4 days

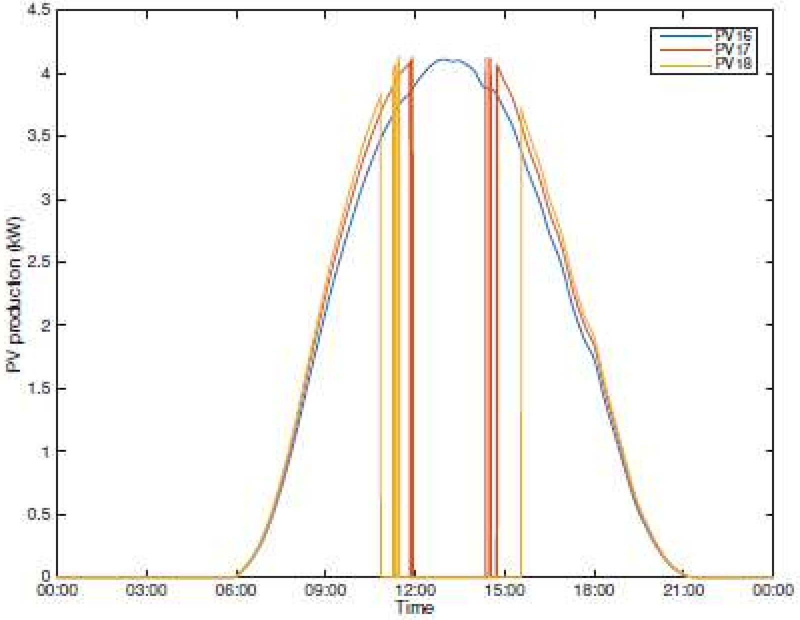
The cause of the 2003 blackout

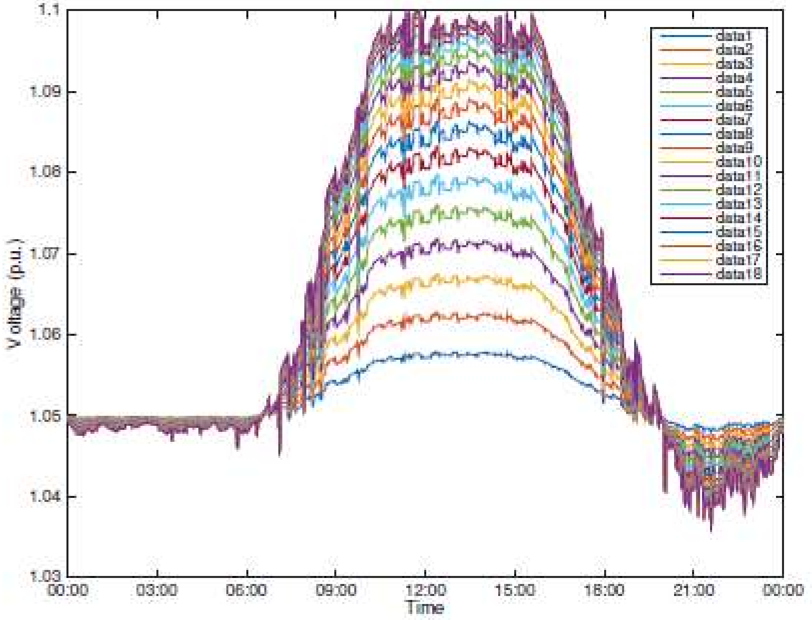
The official report on the blackout states that a generating plant in Eastlake, Ohio, a suburb northeast of Cleveland, went offline amid high electrical demand, putting a strain on high-voltage power lines (located in Walton Hills, Ohio, a southeast suburb of Cleveland) which later went out of service when they came in contact with "overgrown trees". This trip caused load to transfer to other transmission lines, which were not able to bear the load, tripping their breakers. Once these multiple trips occurred, many generators suddenly lost parts of their loads, so they accelerated out of phase with the grid at different rates, and tripped out to prevent damage. The cascading effect that resulted ultimately forced the shutdown of more than 100 power plants.

New vulnerabilities caused by renewables









Photovoltaic panels may cause overvoltages on distribution networks.

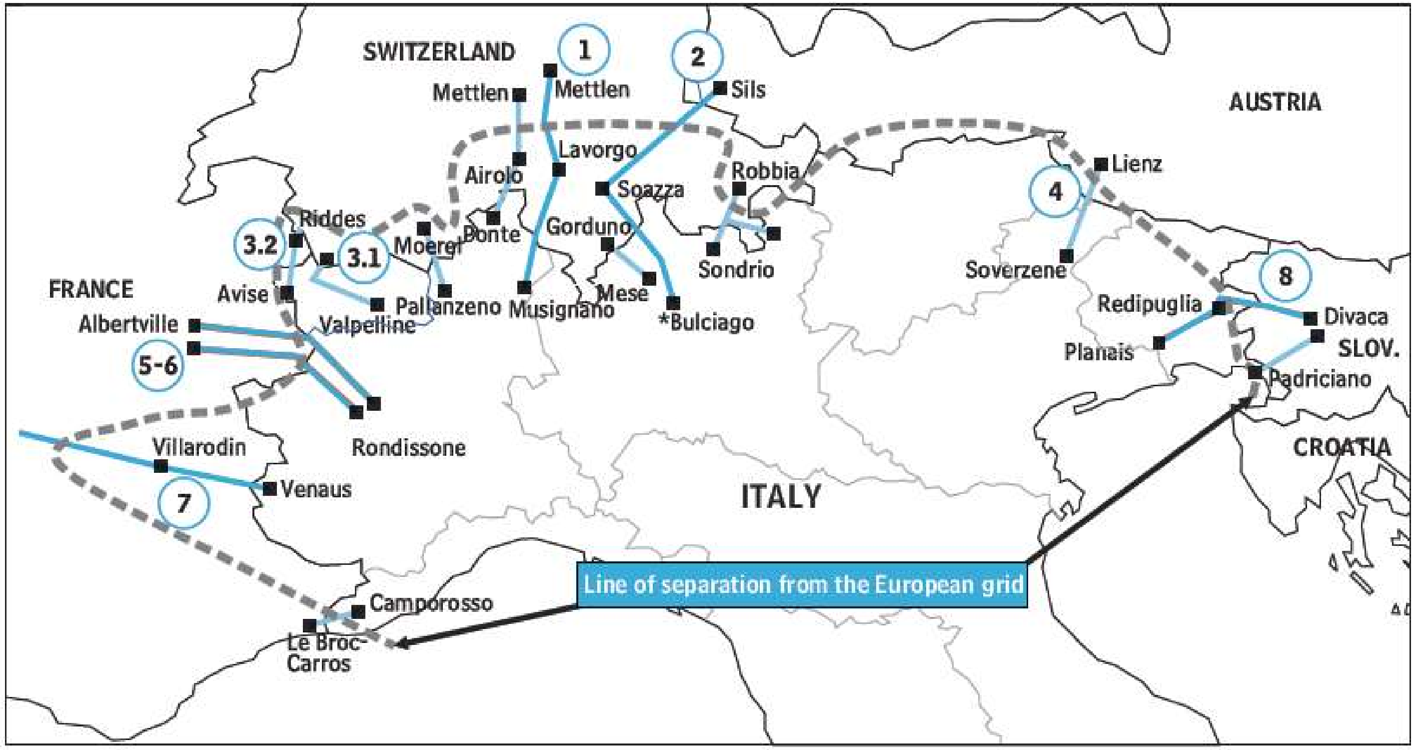
Inverters disconnect the PV panels when average voltage above 253 V during 10 mins.

Immediate disconnection when voltage above 264.5 V.

Italian blackout, September 2003

- Cascade tripping of interconnection lines $\rightarrow$ 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 - 26 000 MW lost (blackout occurred during night)
- Estimated cost of disruption $\approx$ 139 million US \$
- Restoration time: up to 15 hours

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



source:

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

Operational tasks of UCTE transferred to ENTSO-E, the European Network of Transmission System Operators (TSOs) for Electricity in 2009.

What are TSOs? What is ENTSO-E?

Transmission System Operators are are responsible for the bulk transmission of electric power on the main high voltage electric networks. TSOs provide grid access to the electricity market players (i.e., generating companies, traders, suppliers, distributors, and directly connected customers) according to non-discriminatory and transparent rules. In many countries, TSOs are in charge of the development of the grid infrastructure, too. TSOs in the European Union internal electricity market are entities operating independently from the other electricity market players (unbundling).

According to its website, "ENTSO-E promotes closer cooperation across Europe's TSOs to support the implementation of EU energy policy and achieve Europe's energy & climate policy objectives, which are changing the very nature of the power system. The main objectives of ENTSO-E centre on the integration of renewable energy sources (RES) such as wind and solar power into the power system, and the completion of the internal energy market, which is central to meeting the European Union's energy policy objectives of affordability, sustainability and security of supply. [...] ENTSO-E aims to be the focal point for all technical, market and policy issues relating to TSOs and the European network, interfacing with power system users, EU institutions, regulators and national governments."

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

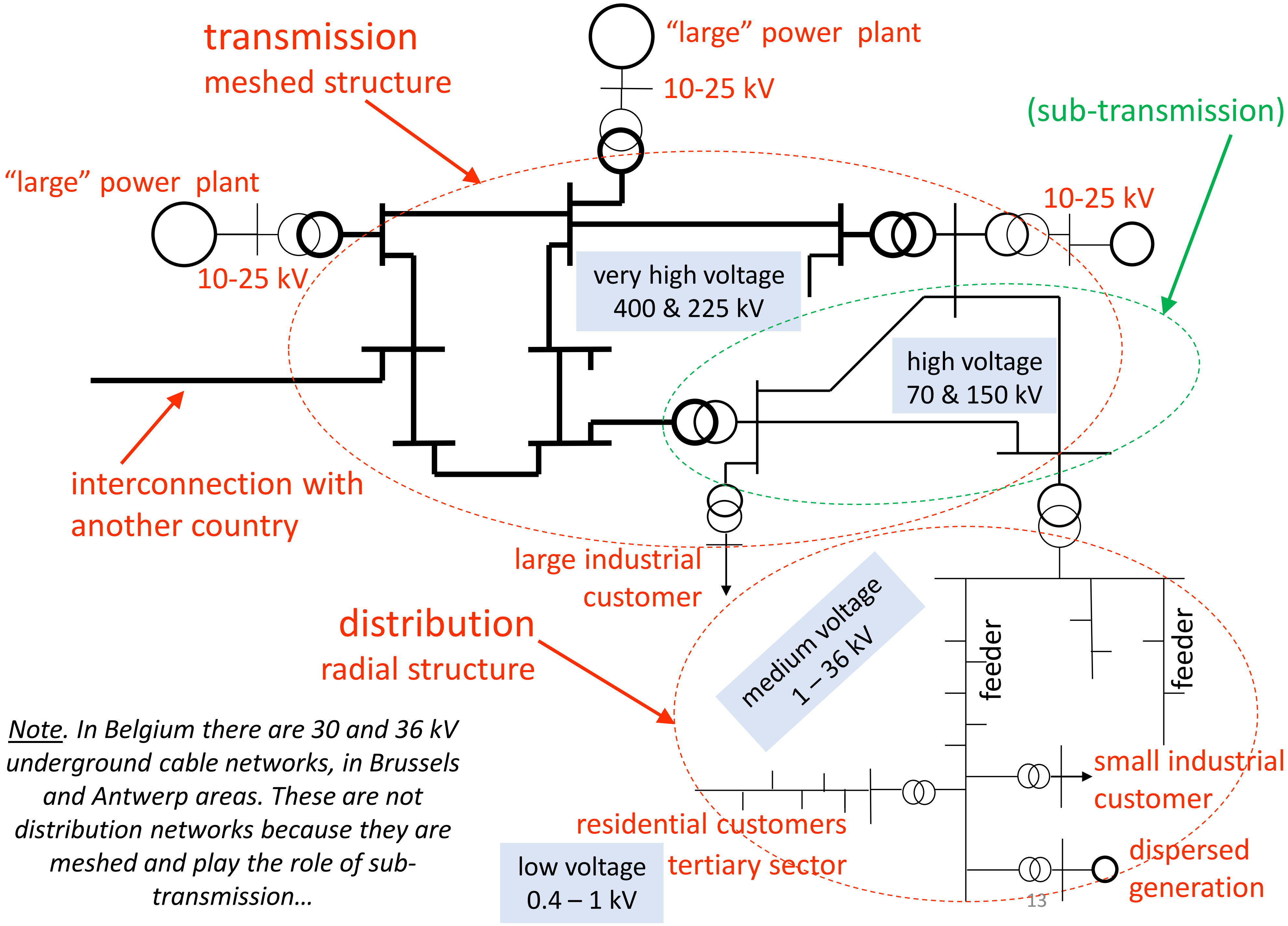
  but $$power\ lost = resistance \times current^2$$

  increasing the current wastes energy and requires large sections of conductors
- impossible to interrupt a large DC (no zero crossing), e.g. after a short-circuit
- changing for Alternating Current (AC) (thanks to the work of Lucian Gaulard and Nikolas Tesla, inventors of the transformer (1882) and of the synchronous machine (1888), respectively)
  - 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.)

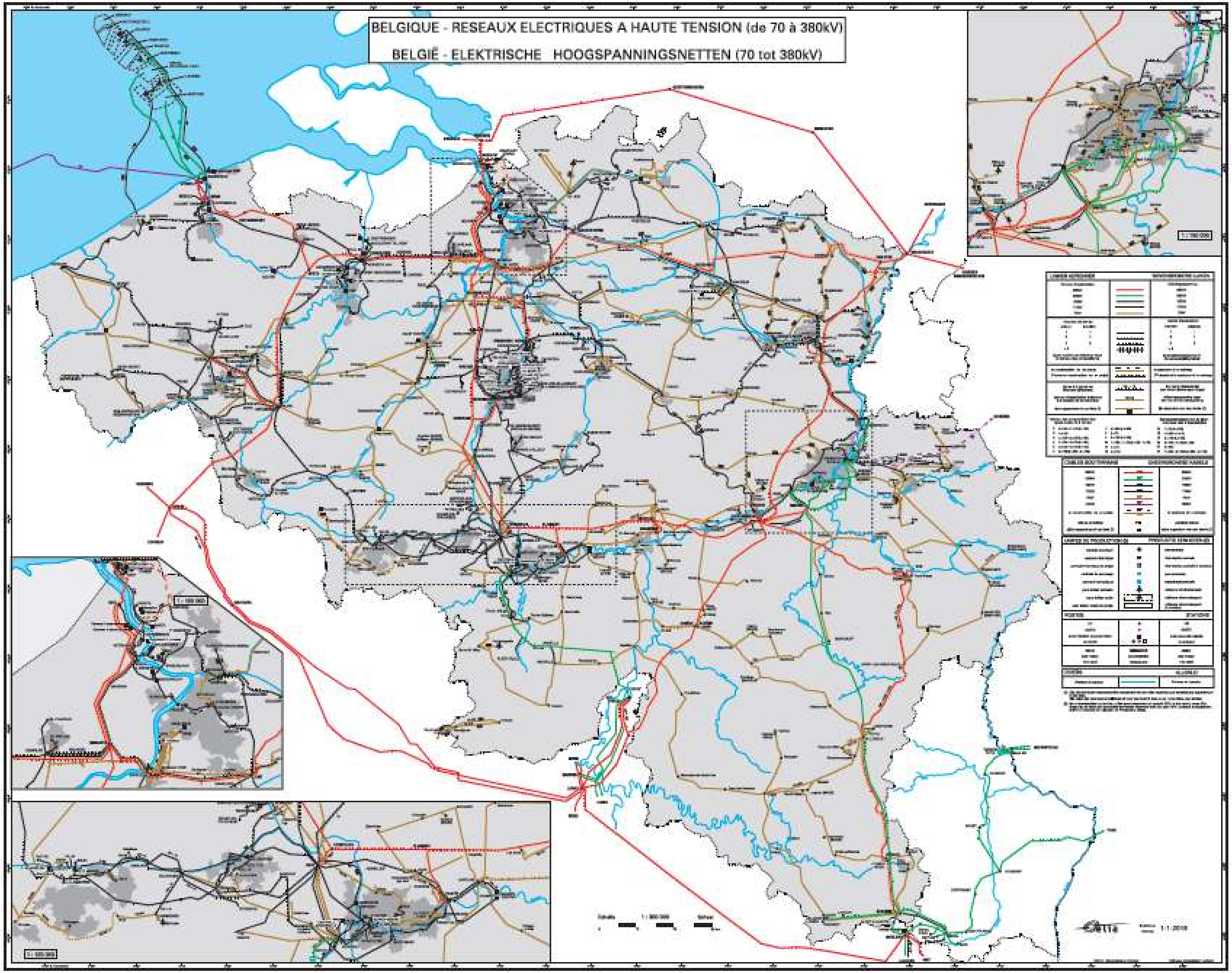
Pearl Street station: the ‘true’ first power system

In 1881, two electricians built the world's first power system at Godalming in England. It was powered by two waterwheels and produced an alternating current that in turn supplied seven Siemens arc lamps at 250 volts and 34 incandescent lamps at 40 volts. However, supply to the lamps was intermittent and in 1882 Thomas Edison and his company, The Edison Electric Light Company, developed the first steam-powered electric power station on Pearl Street in New York City. The Pearl Street Station initially powered around 3,000 lamps for 59 customers. The power station generated direct current and operated at a single voltage. Direct current power could not be transformed easily or efficiently to the higher voltages necessary to minimise power loss during long-distance transmission, so the maximum economic distance between the generators and load was limited to around half a mile (800 m).

Structure of Belgian electric network

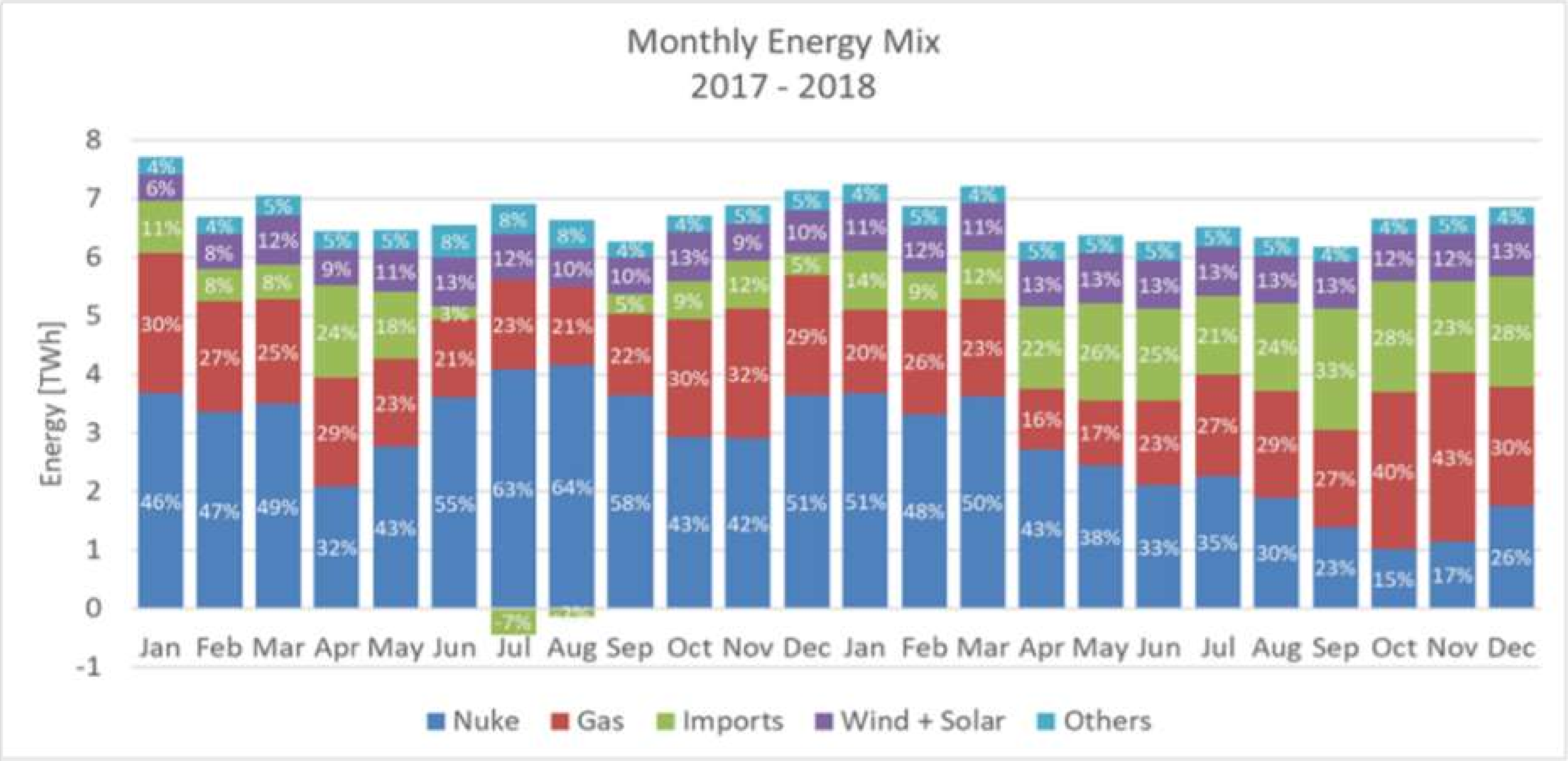


<u>Note</u>. In Belgium there are 30 and 36 kV underground cable networks, in Brussels and Antwerp areas. These are not distribution networks because they are meshed and play the role of sub-transmission…



[Access a detailed version of this map]

Monthly energy mix



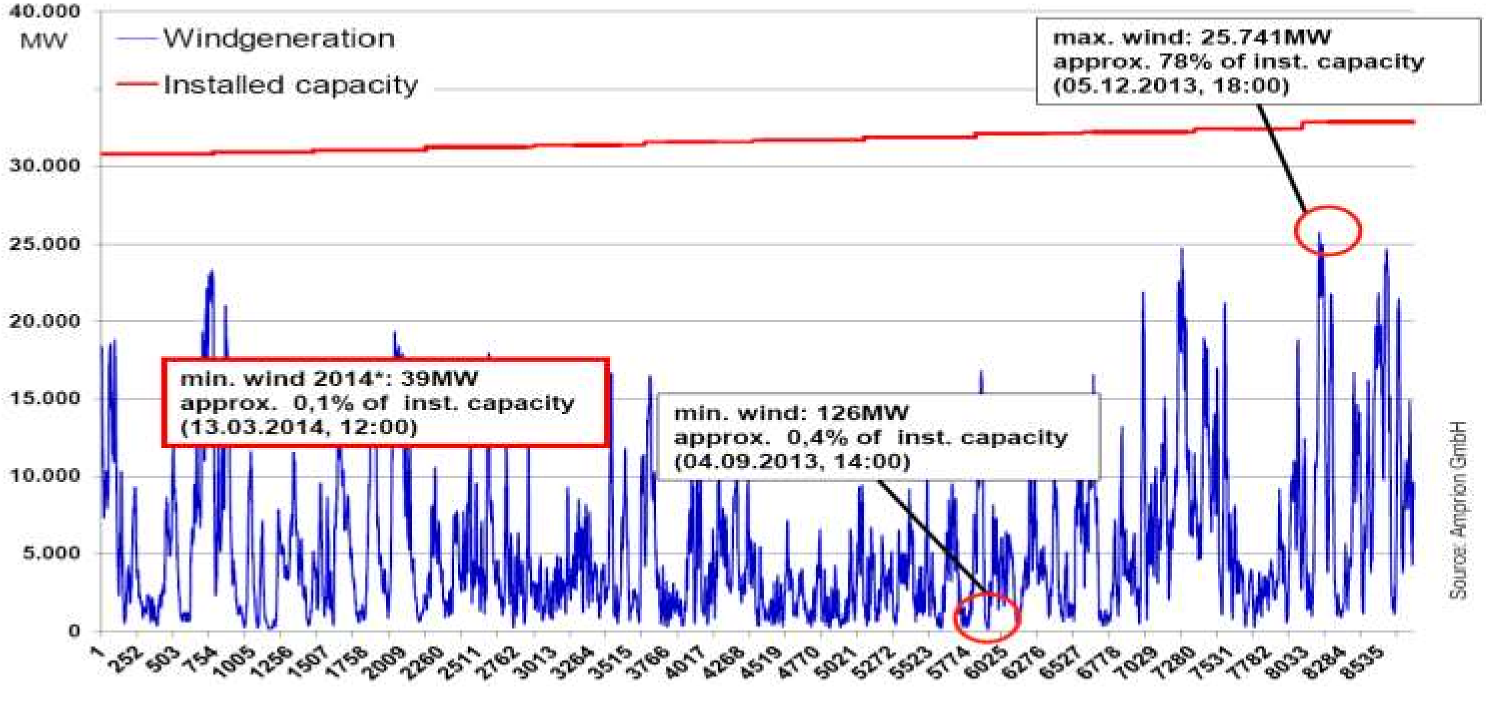
[Data about the energy mix available on ELIA website]

[Data about renewable energy in Belgium available on the APERE website]

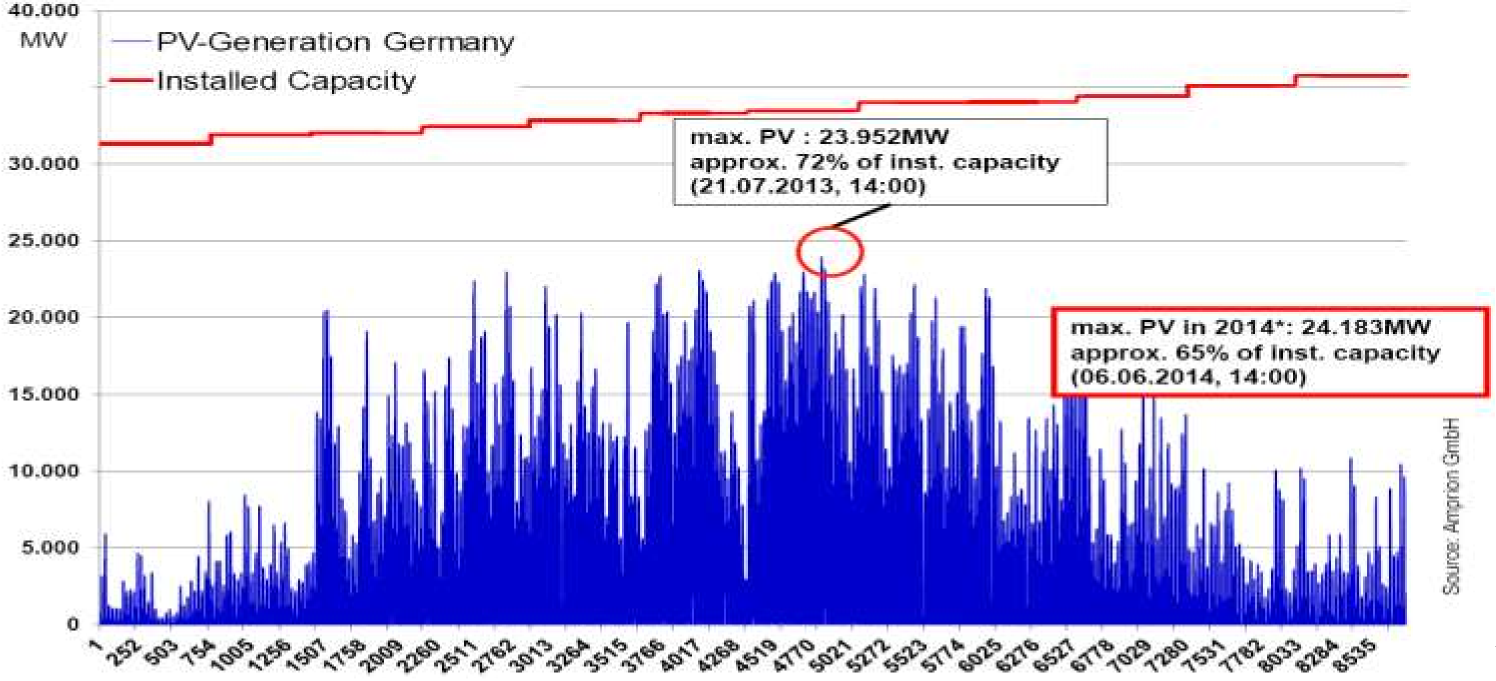
Type of power plant	Efficiency wrt primary energy source	Cost of fuel + operation & maintenance €/MWh	Cost of installed power (construction) €/kW	Average starting time
Classic thermal (coal, gas, oil)	≈ 40 %	45	1 500	1 h if unit is warm 8 h if unit is cold
Combined-cycle gas unit	Up to 60 %	40	750	2 to 6 h
Nuclear	≈ 33 %	10	2 900 (without waste treatment)	24 h
Hydro	≈ 90 %	0 (water) + 15	Depends a lot on the type of plant	5 min
Pumped storage	≈ 85 %	0 (water) + 15	900	2 to 4 min
Gas turbine (peaking unit)	≈ 40 %	65	500	Less than 10 min
Wind	≈ 50 %	0 (wind) + 15 (on-shore) / 30 (off-shore)	1 500 (on-shore) 4 000 (off-shore)	A few min
photovoltaic	≈ 20 %	0 (sun) + 5	2 000	negligible

Energy mix: remarks

- *Capacity Factor* = $\frac{energy\ produced\ in\ 1\ year\ (MWh)}{installed\ power\ (MW) \times 8760\ h}$. Usually close to 90 % for nuclear. For solar energy, it is around 10%. So around 54000 MW of PV is necessary to produce the same amount of electrical energy as the 6000 MW Belgian nuclear fleet.
- Off-shore wind farms have a higher capacity factor than on-shore ones: wind is more steady in the sea; great potential available (up to 8 GW of installed capacity). Public opposition to construction of on-shore wind farms (in densely populated areas): “Not In My BackYard” (NIMBY)
- Solar PV with a significant level of auto-consumption is competitive without subsidies.
- Gas units are not competitive but a Capacity Remuneration Mechanism (CRM) will be put in place to support them and support the construction of new gas-fired power plants. Those are necessary if we indeed phase out nuclear in 2025 (according the a law voted in 2003).



hour of the year 2013

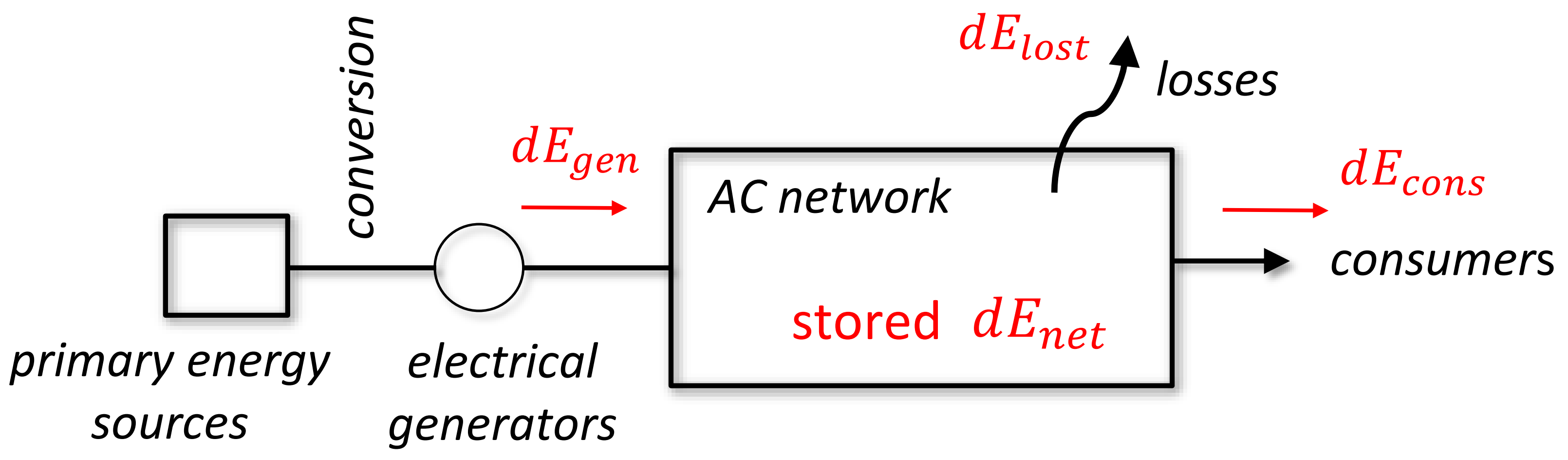


hour of the year 2013

Examples of variability of wind and photovoltaic generation

(Germany)

The power balance



Conservation of Energy over an infinitesimal time dt:

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

Introducing the corresponding powers at time t:

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

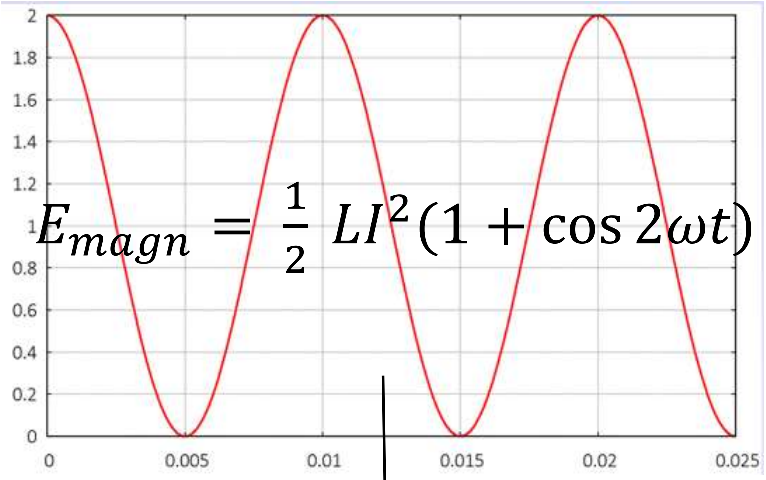
$$\Leftrightarrow \quad p_{gen}(t) = p_{cons}(t) + p_{lost}(t) + p_{net}(t)$$

About $\boldsymbol{p_{cons}(t)}$: The consumers decide how much power they want to consume! This demand fluctuates at any time.

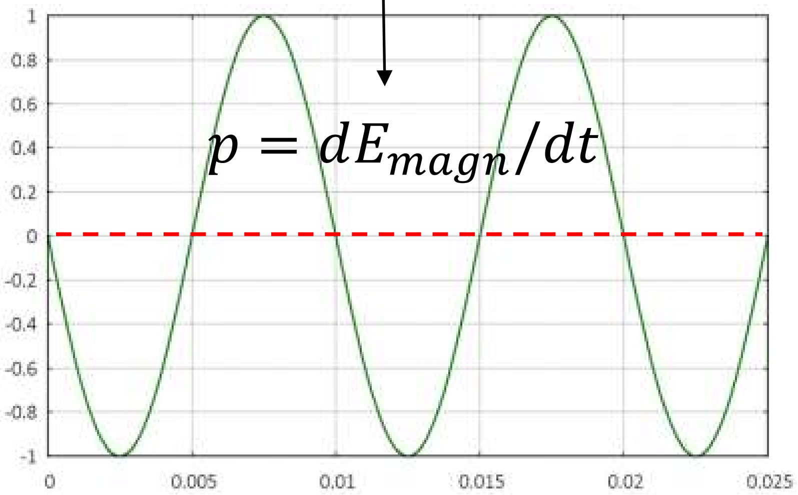
About $p_{net}(t)$:

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 (potential energy (e.g., hydro-pumped station), kinetic (e.g., flywheels), chemical (e.g., batteries)).

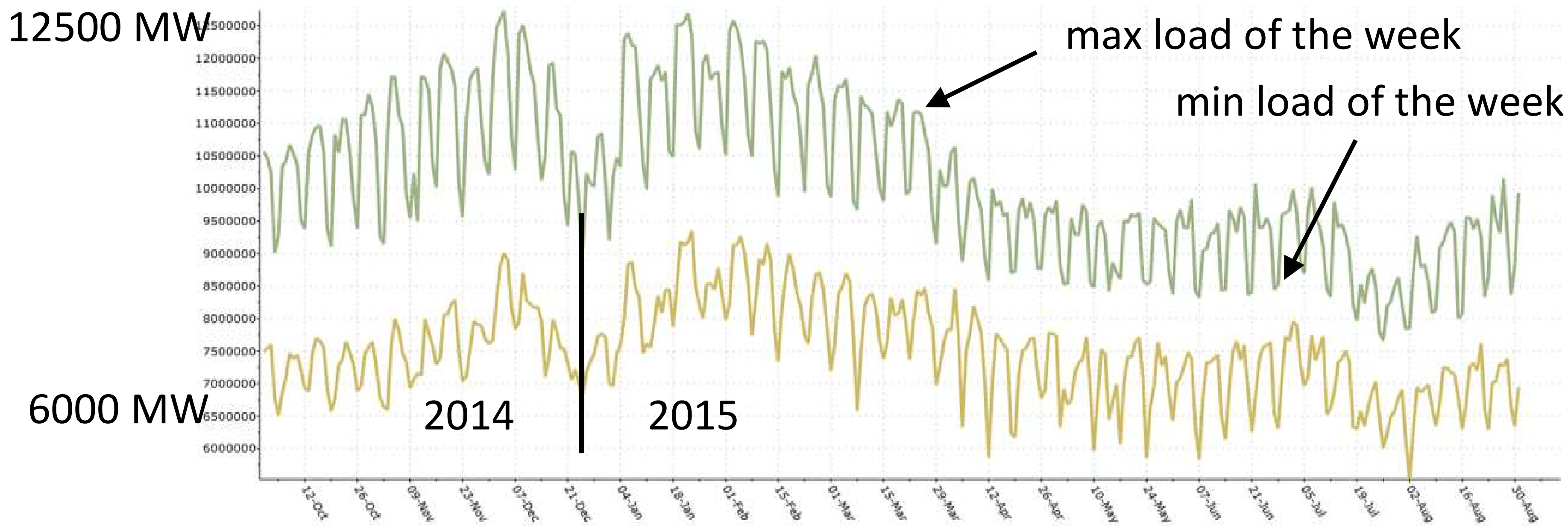
About $p_{loss}(t)$:

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

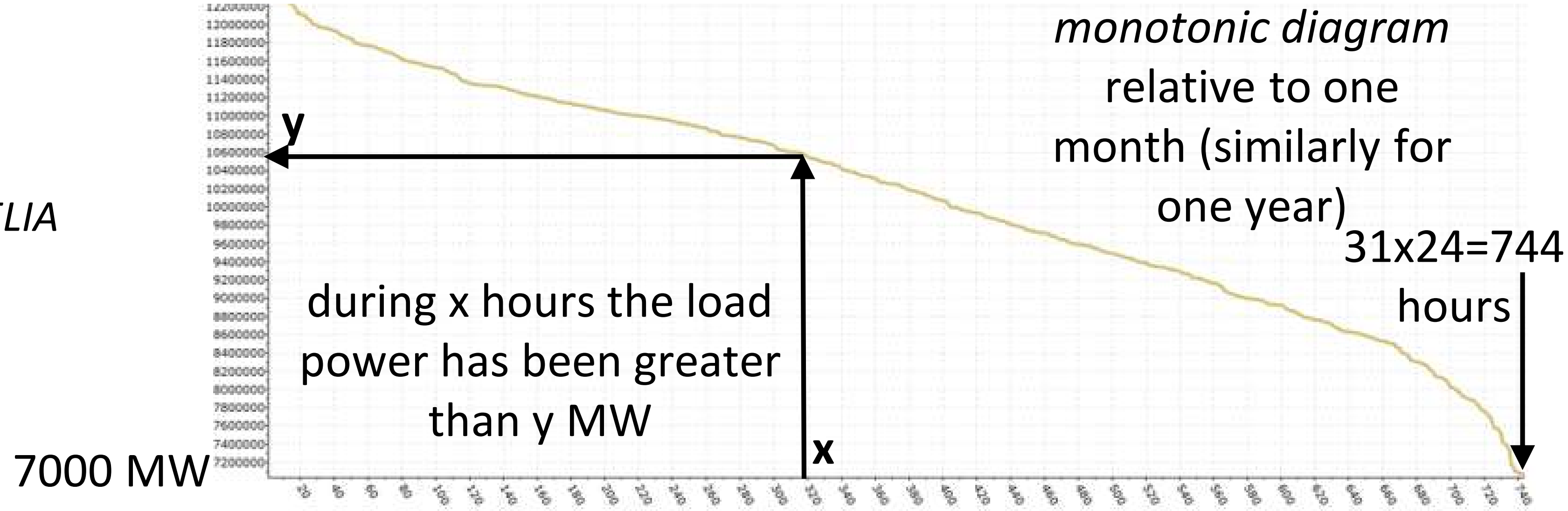
Remarks on the power balance:

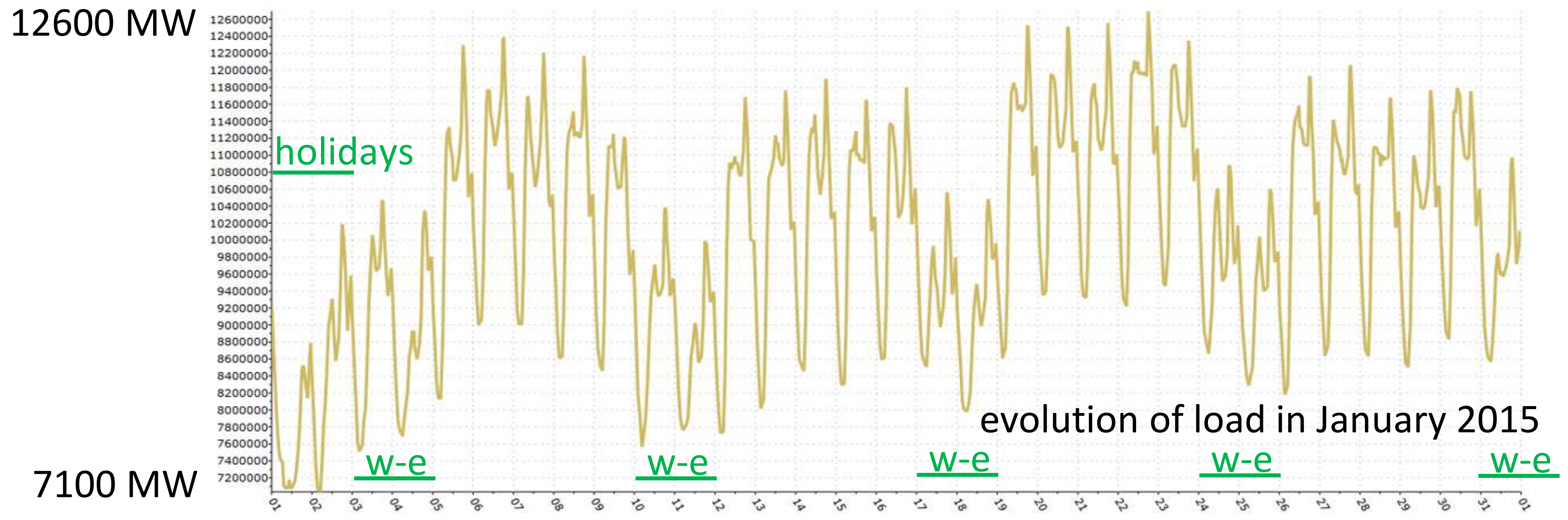
- The variations of load power have to be compensated by the generators
- However, the conversion primary $\rightarrow$ electrical energy is not instantaneous: example: changing the flow of steam or water in a turbine takes a few seconds
- An "energy buffer" is needed to quickly compensate power imbalances
- 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 = maximum 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.

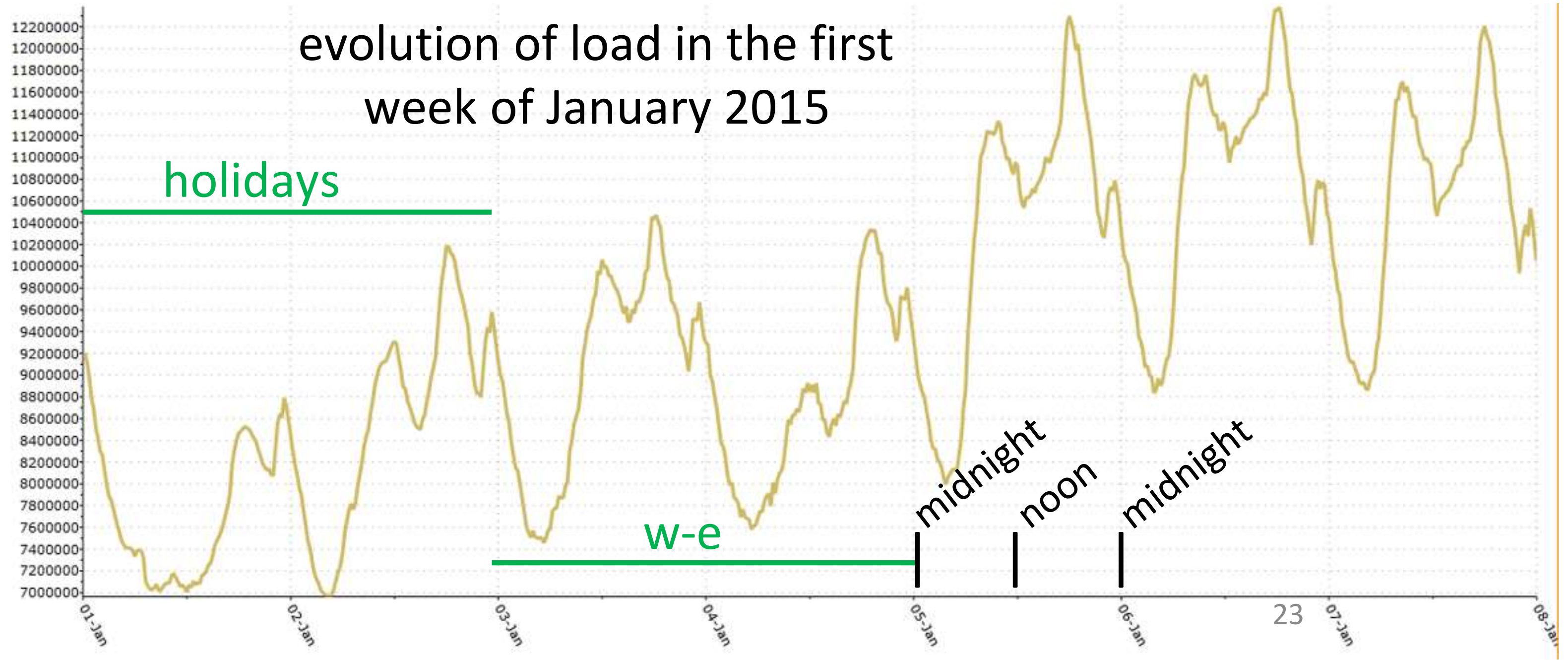
Consumed power in Belgium



source: ELIA




12600 MW
7100 MW
holidays
w-e
w-e
w-e
w-e
w-e
evolution of load in January 2015

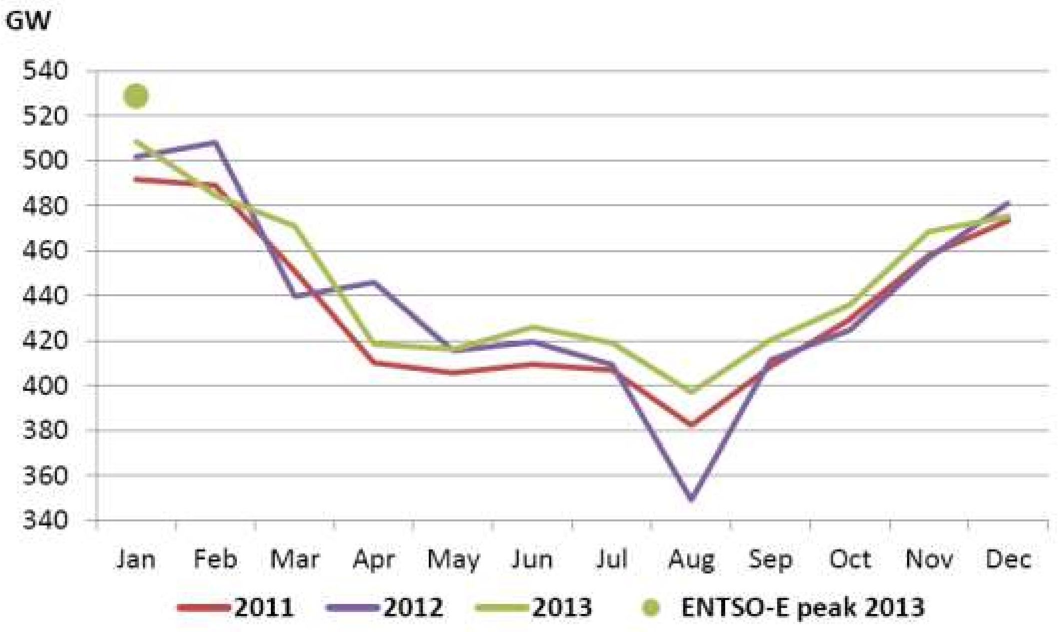

evolution of load in the first
week of January 2015
holidays
w-e
midnight
noon
midnight
01-Jan
02-Jan
03-Jan
04-Jan
05-Jan
06-Jan
07-Jan
08-Jan

source: ELIA

Consumed power in Europe and Belgium

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

source: ENTSO-E



Peak loads recorded on the Belgian transmission system

source: SYNERGRID

Year	Date	Time	Day	Power (MW)
2010	Dec 14	18:00	Tue	14 200
2011	Feb 1	18:15	Tue	13 000
2012	Feb 7	18:30	Tue	13 144
2013	Jan 17	18:00	Thu	13 255
2014	Dec 4	18:00	Thu	12 692

Large AC interconnections

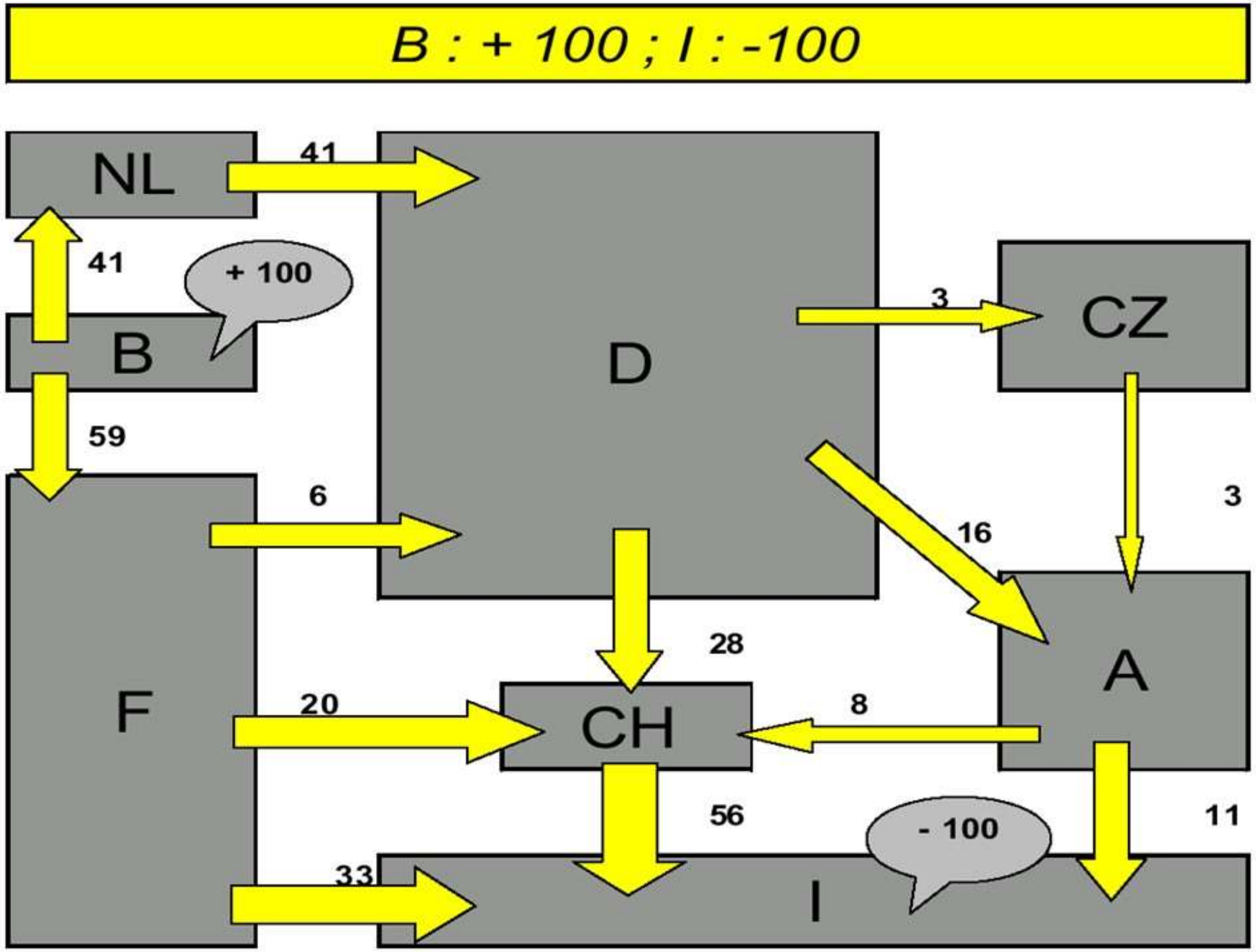
Motivations:

- 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, wind power and PV plants.
- Smoothing out fluctuations of renewable energy sources by collecting them over larger zones.
- Allows partners to sell/buy energy, to create a large electricity market.

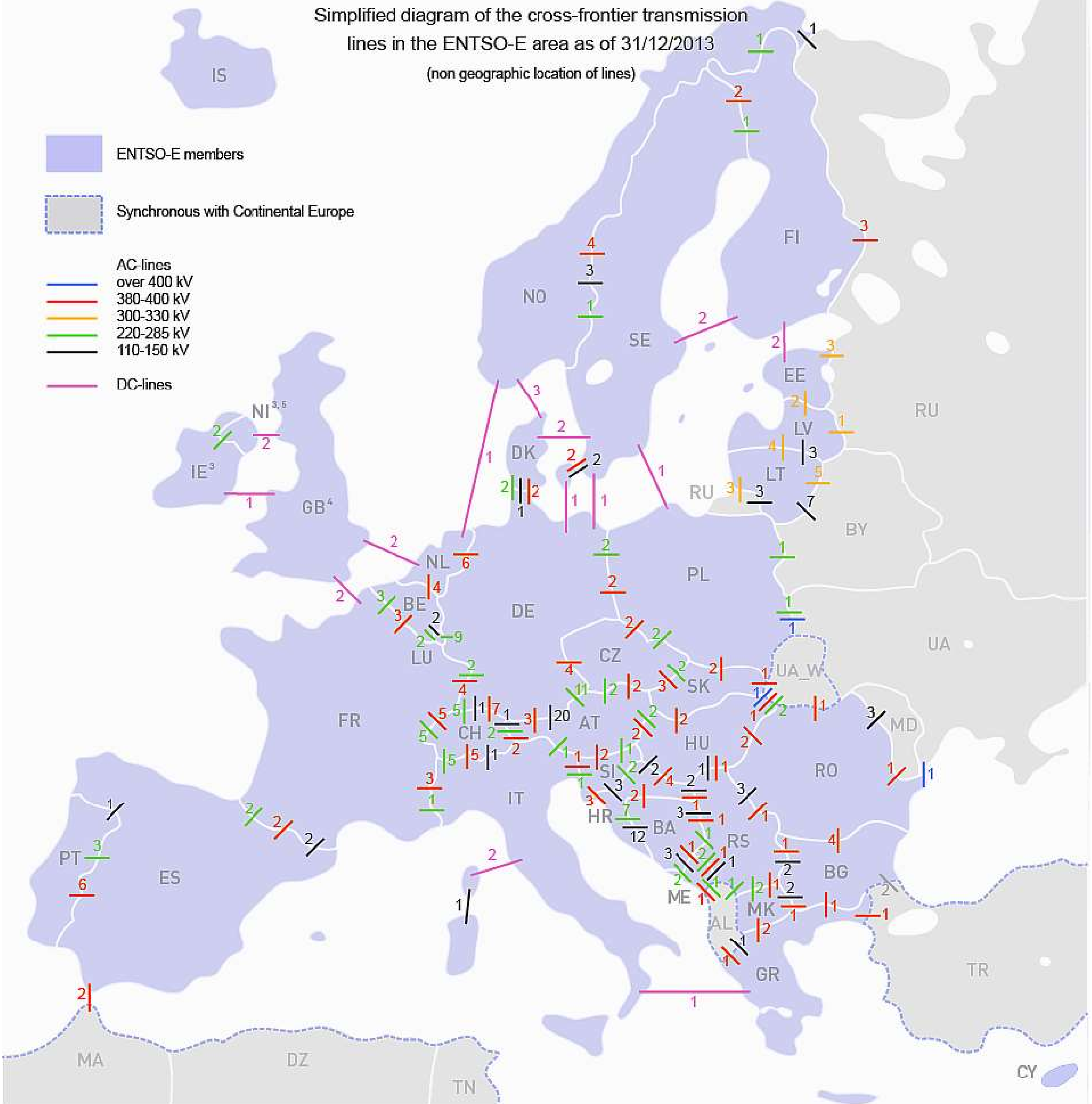
Constraints:

- 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. Partners not involved in the transaction undergo the effects of the power flow
- In large AC interconnections, there may be emergence of badly damped, slow (0.1 to 0.5 Hz frequency) interarea oscillations. 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.

Example of paths followed by 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)



European network

ENTSO-E :

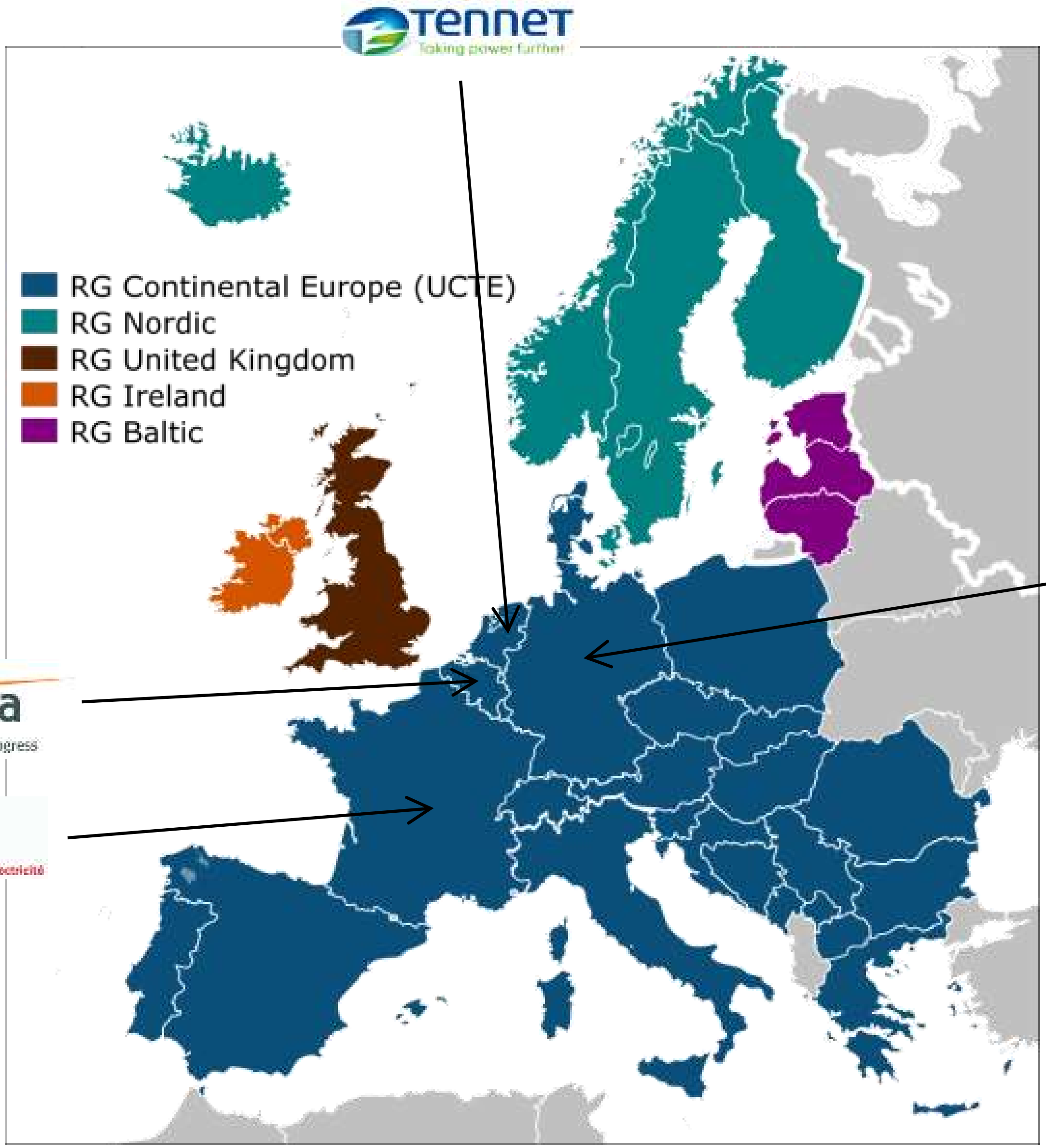
European Network of Transmission System Operators (TSO) for Electricity

41 TSOs from 34 countries

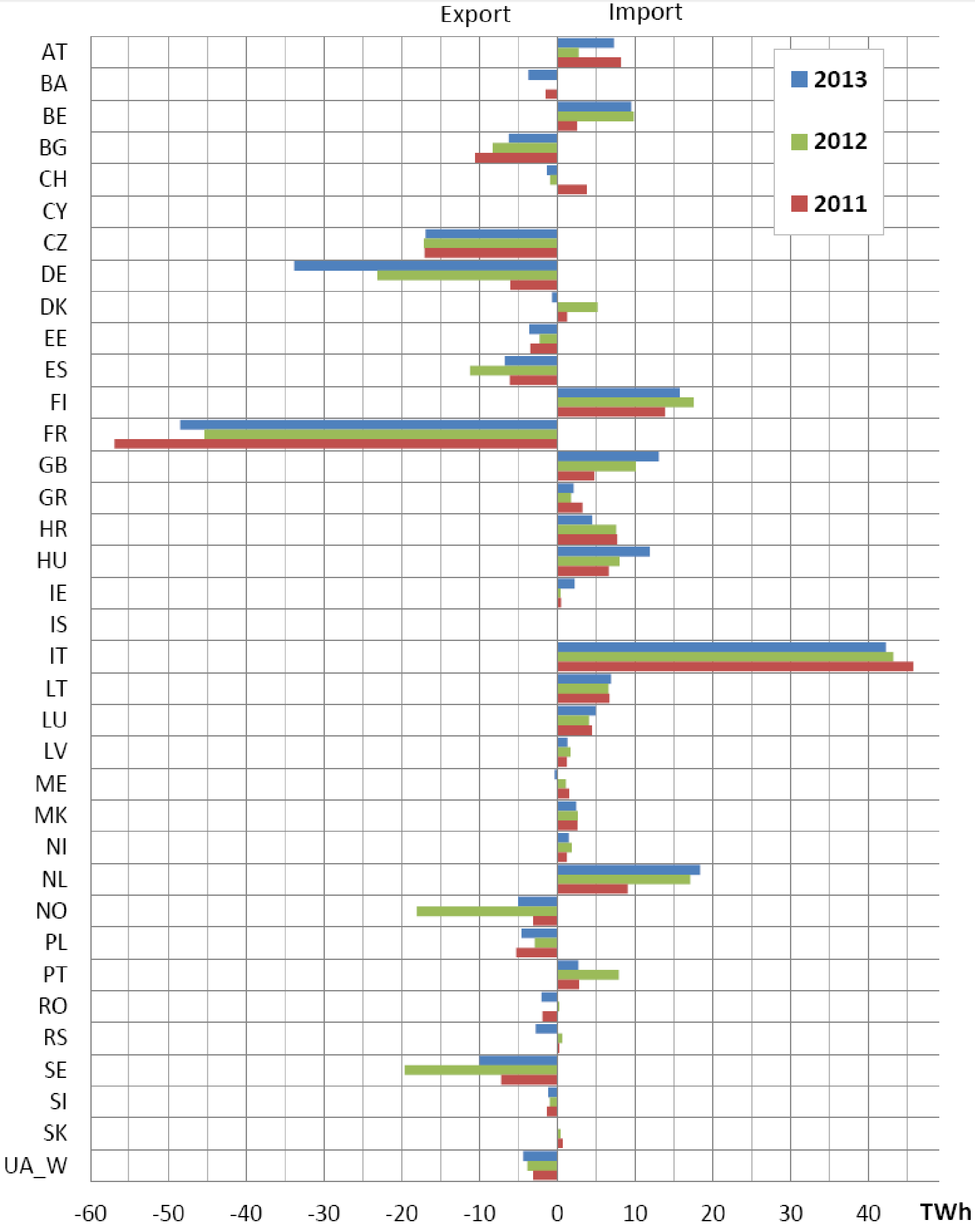
Website: www.entsoe.eu

The synchronous grids of Europe

RG = Regional Group



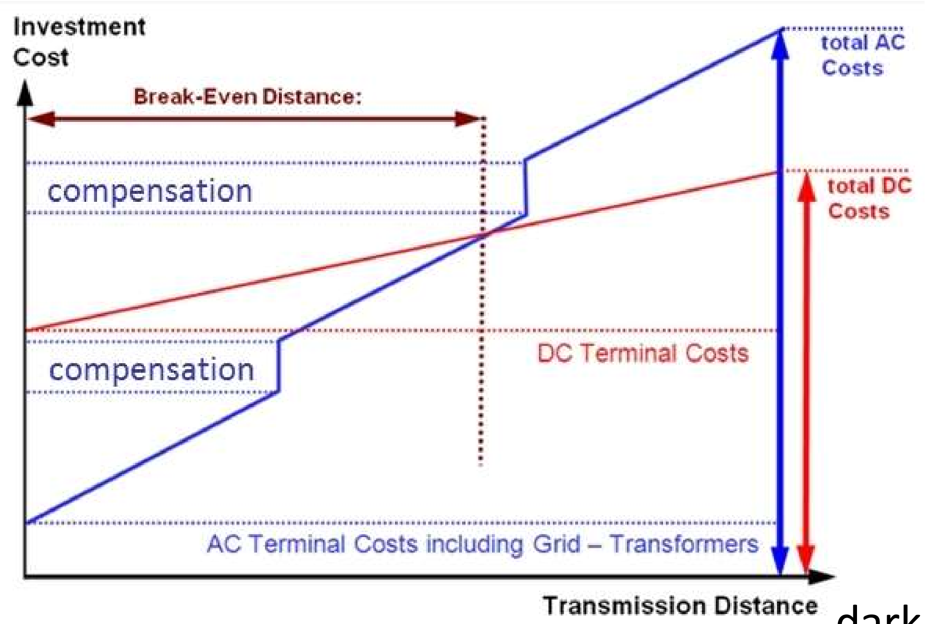
source: ENTSO-E



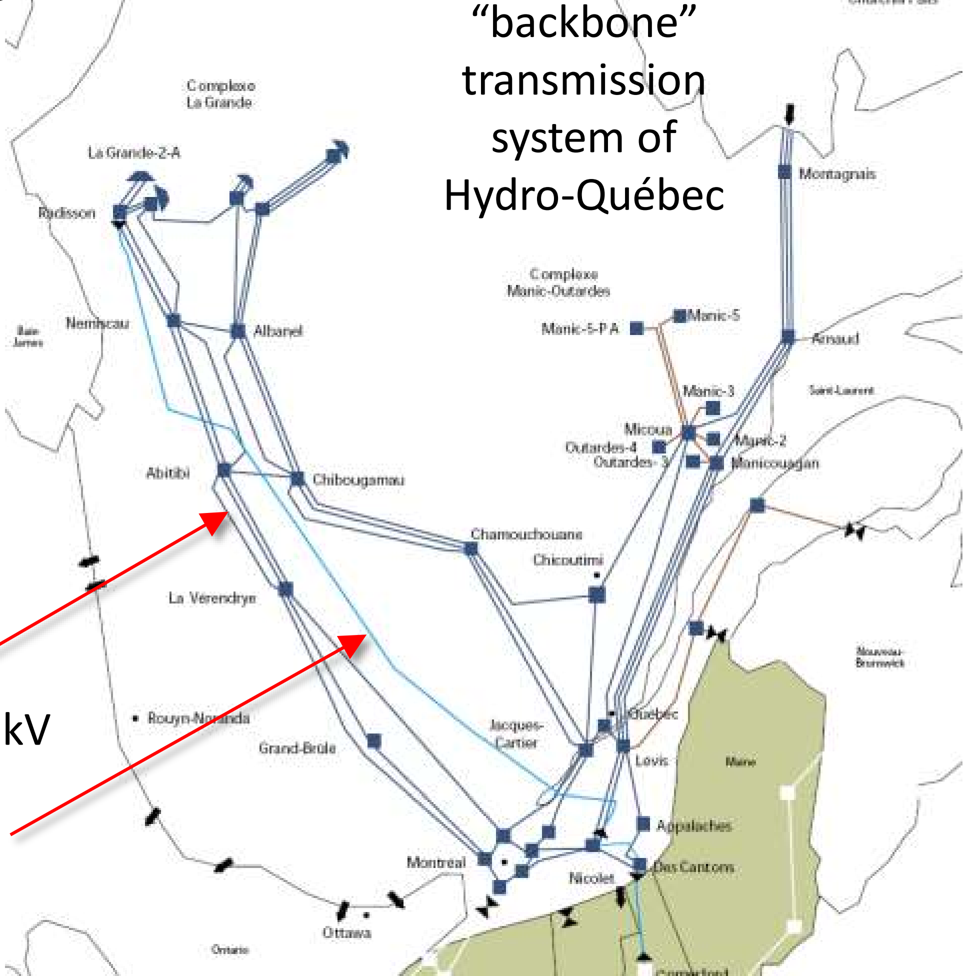
Yearly energy exchange of the countries members of ENTSO-E.

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> : Power transmission over longer distances through overhead lines



“backbone” transmission system of Hydro-Québec



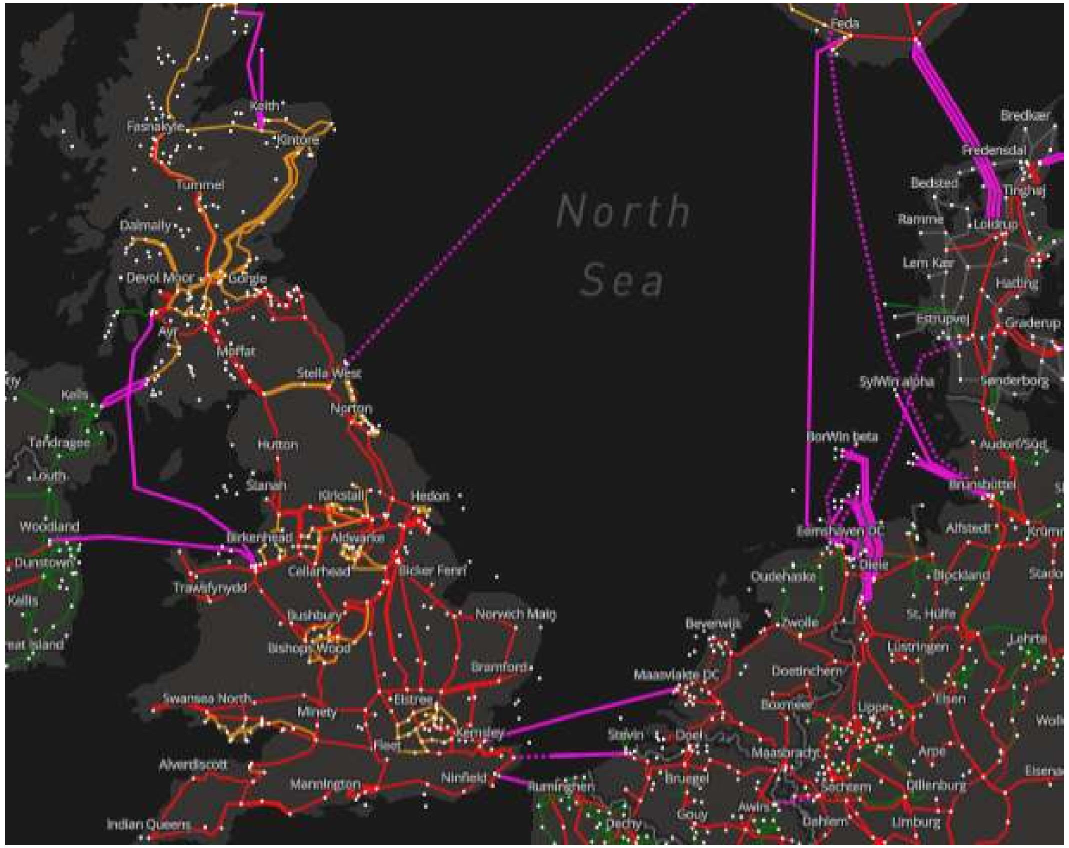
dark blue: AC transmission at 735 kV

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

The come-back of Direct Current

- <u>2nd use</u> : power transmission in submarine cables
  - DC more attractive than AC for distances above ≈ 50 km : owing to capacitive effects of AC cables
  - Existing links in Europe
  - Two newly completed projects involving
  - Belgium: *Nemo* with England, *Alegro* with

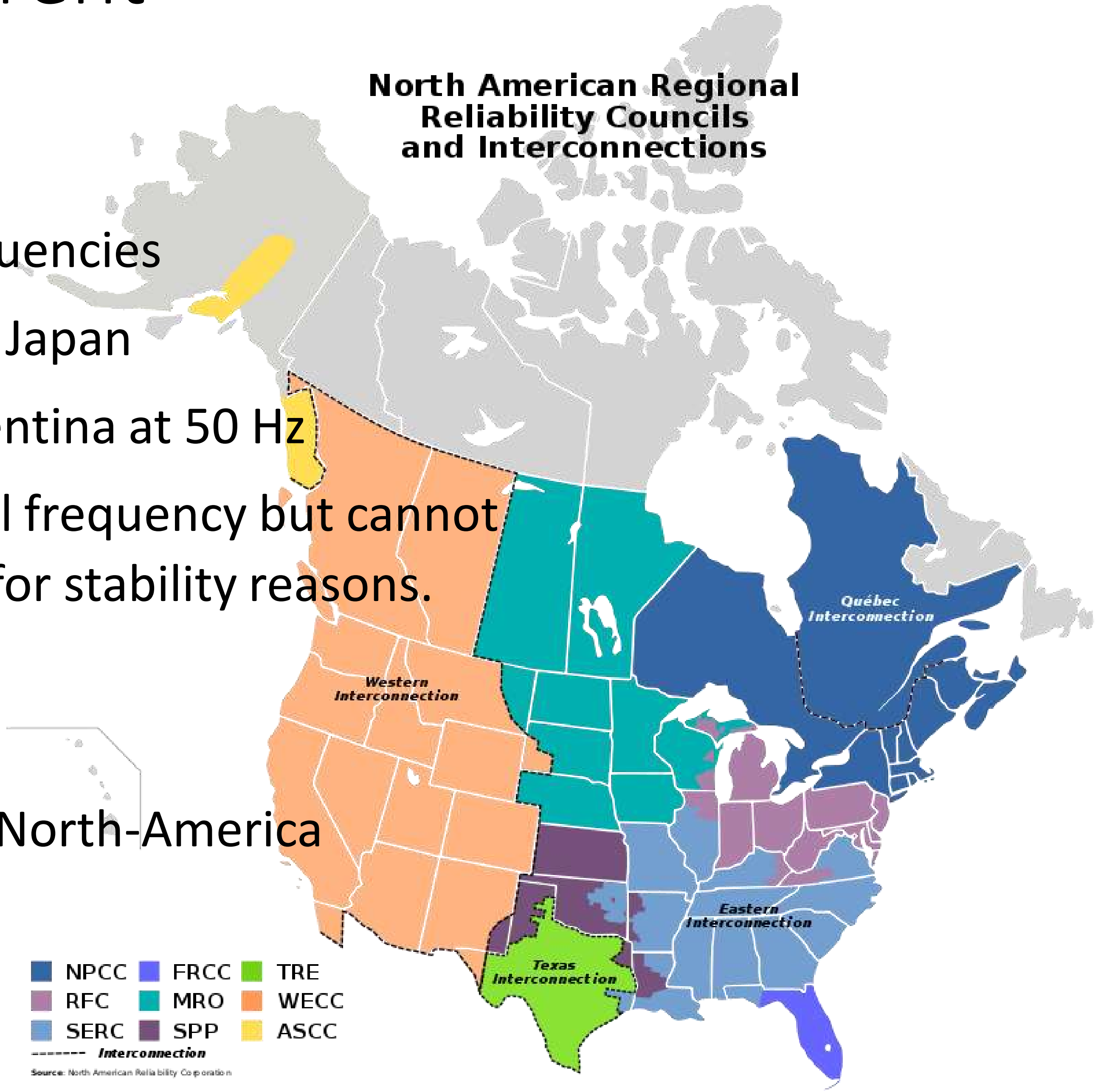
  Germany
  - Connection of off-shore wind parks

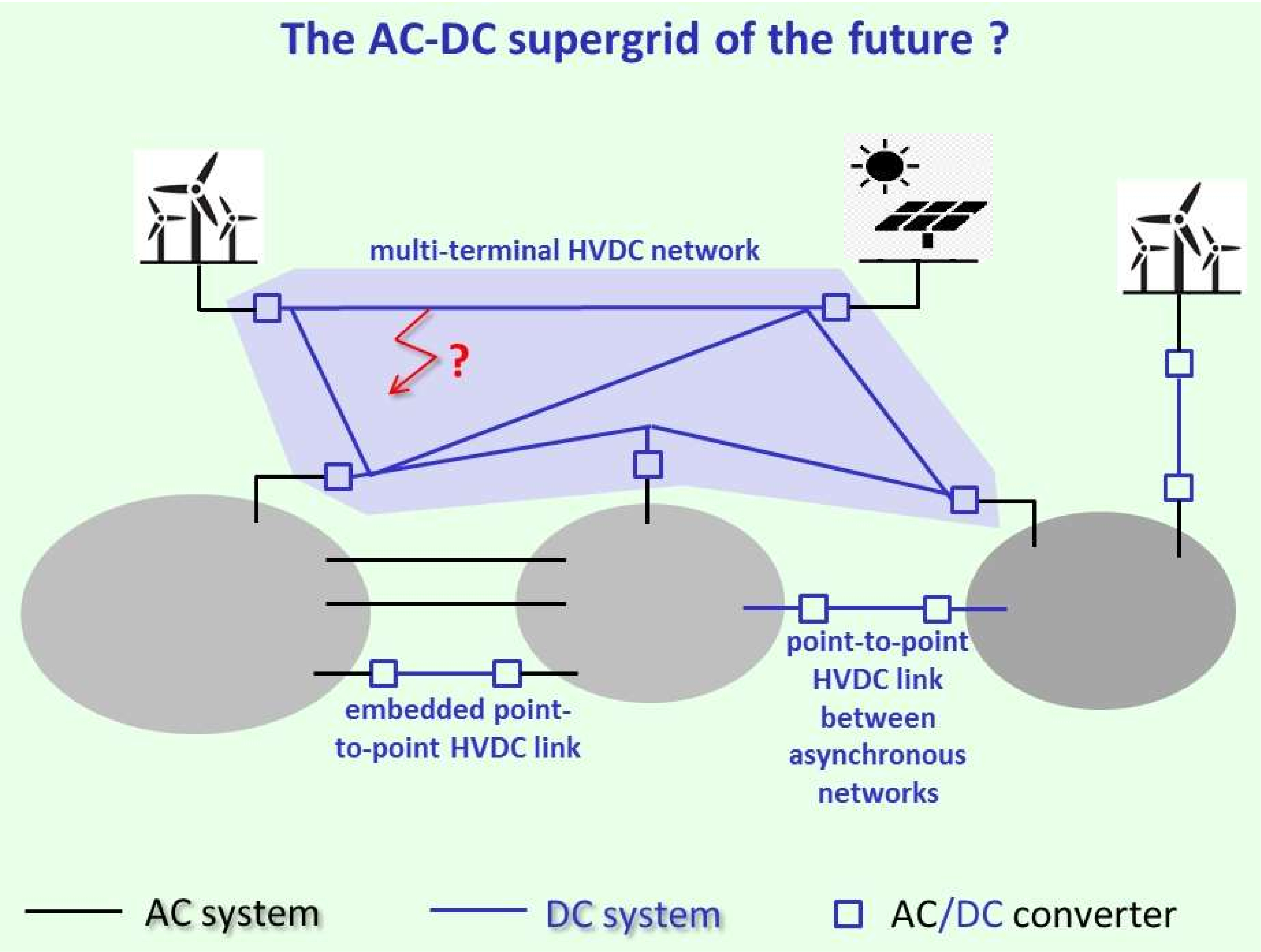


In pink: HVDC links. Soure ENTSOE-E

The come-back of Direct Current

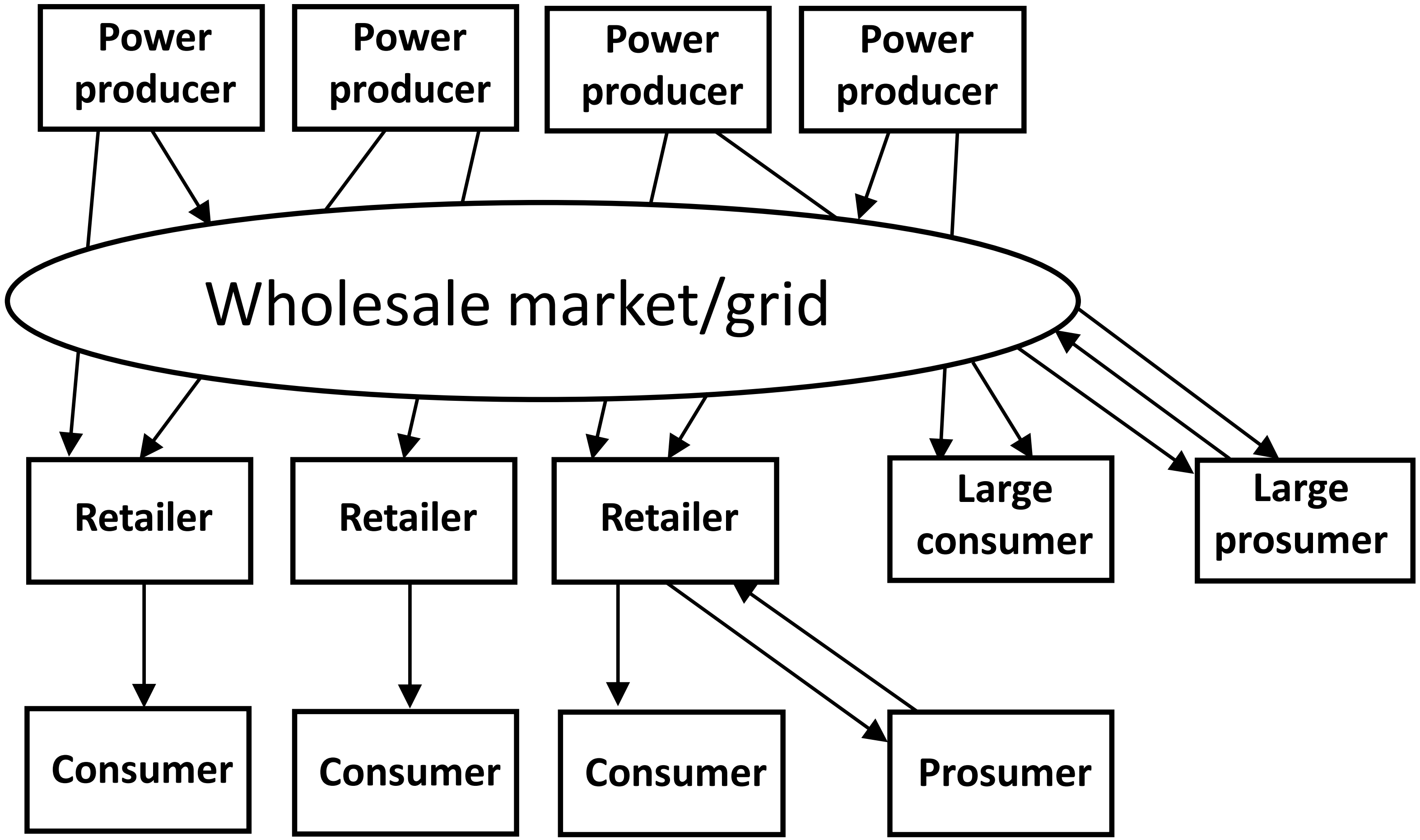
- 3rd use : “back-to-back” connection of :
  - two networks with different nominal frequencies
    - connection of 50 and 60 Hz systems in Japan
    - connection of Brazil at 60 Hz with Argentina at 50 Hz
  - two networks that have the same nominal frequency but cannot be merged into a single AC network, e.g. for stability reasons. Example:
    - UCTE and Russian (IPS/UPS) system
    - Eastern - Western interconnections in North-America





Main technological challenges : (i) Direct Current circuit breaker (to clear short-circuits in DC grid without shutting down the whole grid) (ii) Adequate control of the active and reactive power of the converters.

Uber-like models for the electrical industry



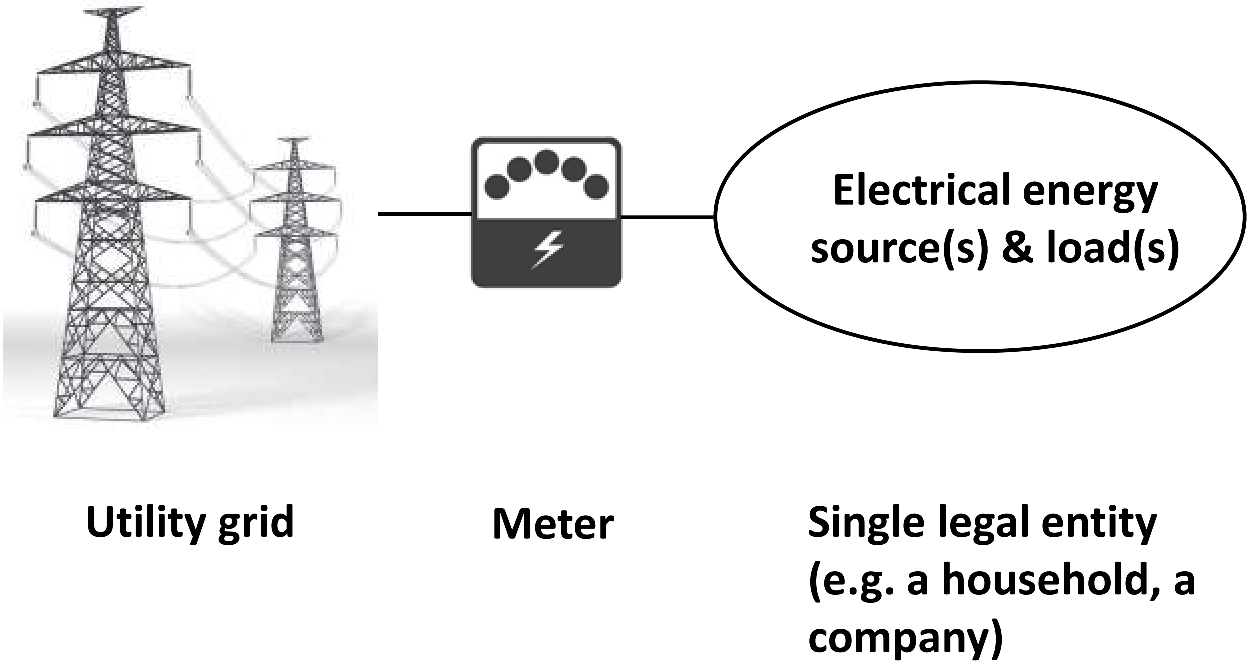
→ Electrical energy sales

<u>Uber-like models for electricity: a definition</u>

Electrical energy consumed by loads that does not go (only) through the electrical energy sale channels defined by →

Microgrids: the most popular uber-like model

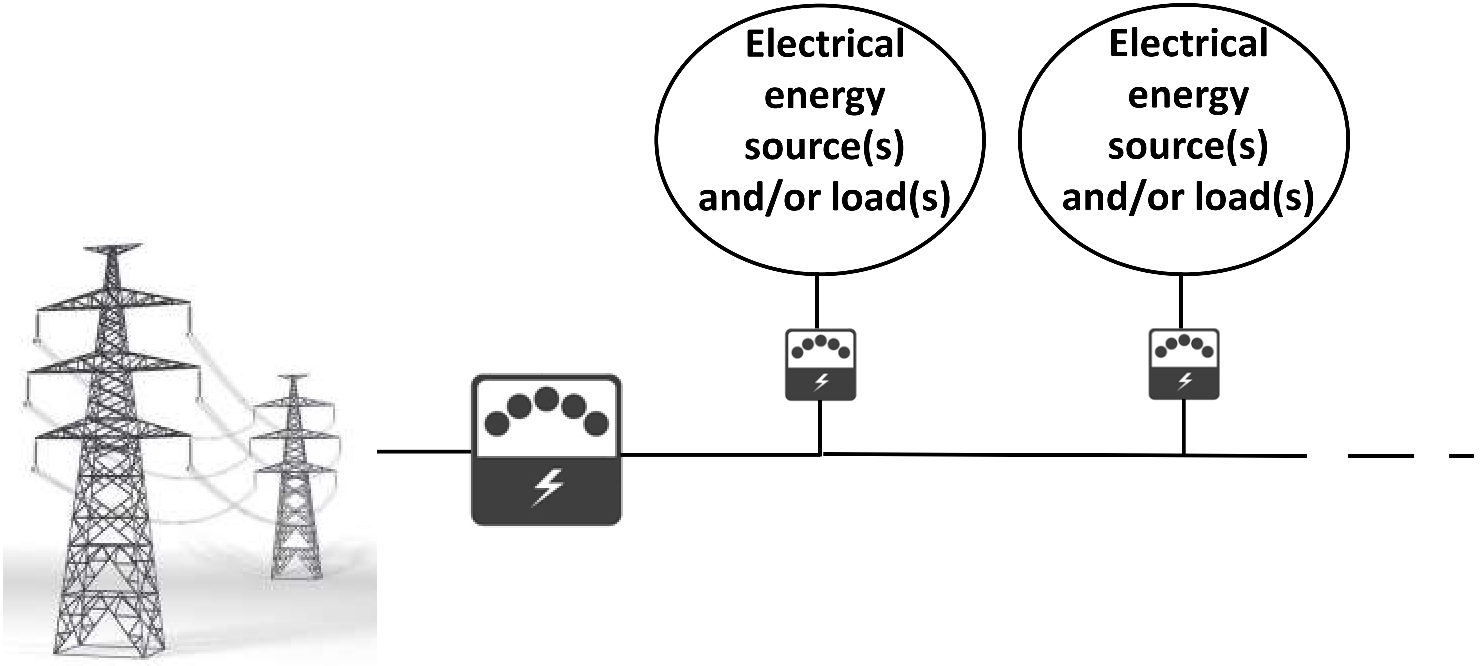
A **microgrid** is an electrical system that includes one or multiple loads, as well as one or several distributed energy sources, that are operated in parallel with the broader utility grid.



The single-user microgrid

1. Legal.
2. Popularised by PV panels and batteries.
3. Possibility to have a microgrid fully disconnected from the utility grid.

The multi-user microgrid



Utility grid

Money paid for energy and transmission/ distribution and tariffs only based on this meter

Several legal entities. Submetering

1. Regulatory framework may not allow for the creation of multi-user microgrids.
2. Often more cost-efficient than the single-user microgrid (e.g. economy of scale in generation and storage, easier to get higher self-consumption at the multi-user level).

Why microgrids?

1. Financial reasons: (i) Price paid for generating electricity locally is lower than price paid for buying electricity from the utility grid (ii) Hedging against high electricity prices.

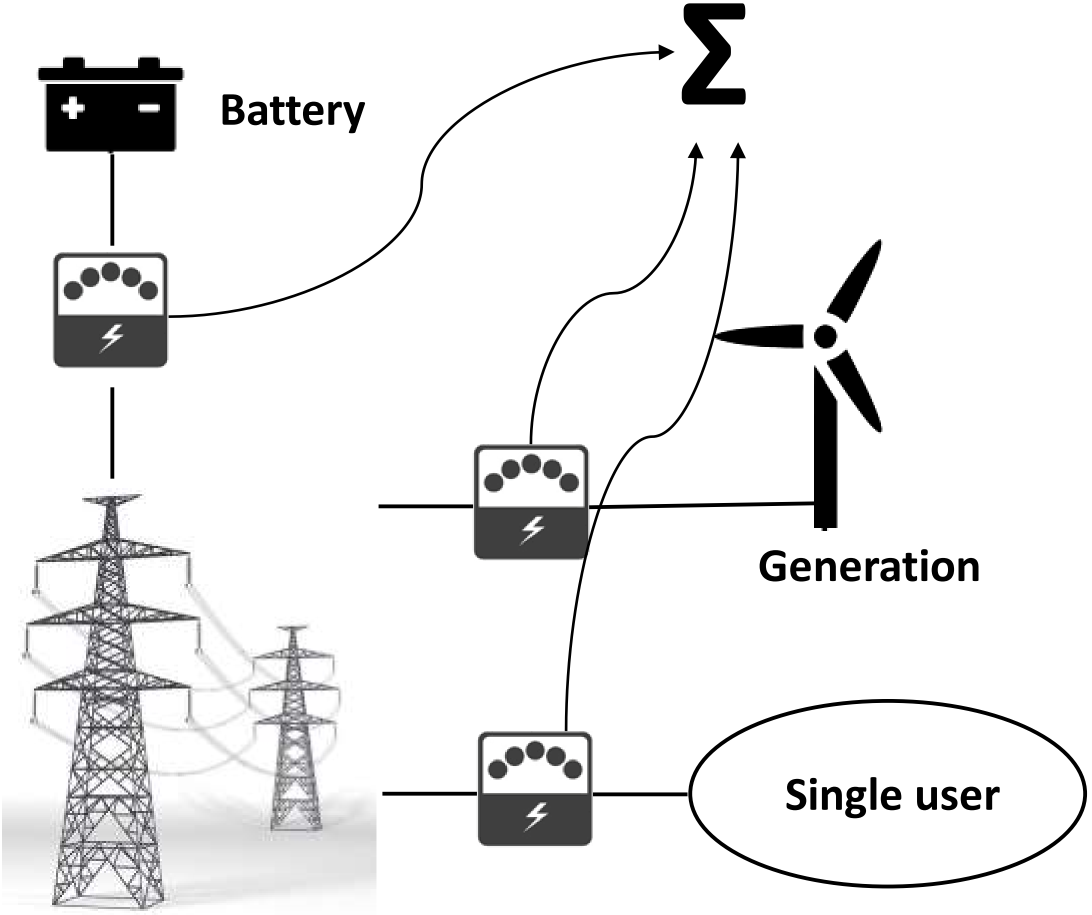
2. Technical reasons: (i) Microgrids – especially multi-user ones – are a great way for integrating renewables into the grid and developing active network management schemes (ii) Security of supply, especially if the microgrids can be operated in an autonomous way.

3. Societal reasons: (i) Local jobs (ii) Energy that belongs to the people.

A taxonomy for uber-like models for electricity

- Microgrid
  - 1. Single-user
  - 2. Multi-user
- Virtual microgrid
  - Single-user
    - 3. Power generation and/or storage close to the user
    - 4. Power generation and/or storage anywhere
  - Multi-user
    - 5. Users close to each other
    - 6. Users located anywhere
- Mobile storage device
  - Electric Vehicles (EVs)
    - Not V2G
      - 7. Car not always charged at home
    - Vehicules to Grid (V2G)
      - 8. Car discharging only at home
      - 9. Car as a substitute for the utility grid
  - No Electric Vehicle Battery
    - 10. Delivery of electricity with storage devices
    - 11. Storage devices as a substitute for the transmission grid

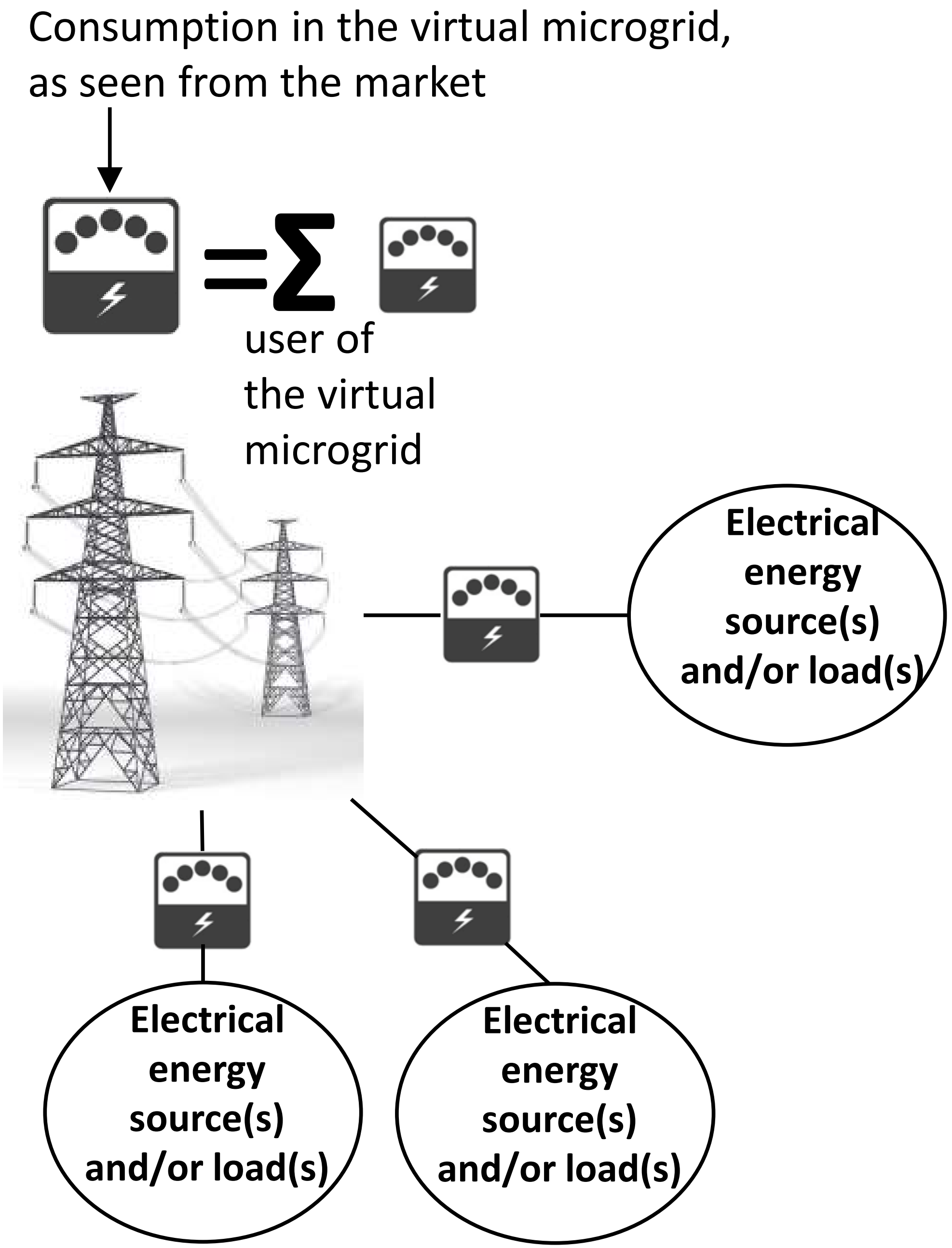
From the market point of view, the consumption of the ‘single user’ is equal to the sum of the consumption measured by the three meters, for every market period.



Model 3 and 4: The single-user virtual microgrid

1. If the user is located close to generation/storage (Model 3), it may have beneficial effects on the network to increase self-consumption in the virtual microgrid.
2. Model 3 tested in Belgium. Known as E-Cloud. Big storage generation/storage devices in an E-Cloud but they are divided up among several single users.
3. Standard regulations do not allow for the creation of virtual microgrids.

Model 5 and 6:The multi-user virtual microgrid



1. May be very helpful to integrate renewables if users are located close to each other (Model 5).
2. Difficult to have multi-user virtual microgrids that can operate in an autonomous way.
3. Easier to create a multi-user virtual microgrid in one area of a network than a multi-user microgrid. In a multi-user microgrid, one single potential user may block the creation of the microgrid.

Model 5 (not 6) authorized soon in Wallonia

A piece of regulation in Wallonia « authorizing » the creation of multi-user virtual microgrids (Model 5):

Les communautés d'énergie renouvelable, pour une meilleure consommation de l'énergie

Publié le 15/03/2019

Ce jeudi 14 mars 2019, le Gouvernement wallon a adopté en troisième lecture le projet de décret présentant l'instauration d'un cadre décrétal favorisant le développement des communautés d'énergie renouvelable (l'autoconsommation collective d'électricité).

Contexte

Actuellement, un cadre légal existe déjà pour le *prosumer* qui est le client résidentiel qui autoconsomme son électricité (photovoltaïque). Pour rappel, la déclaration de politique régionale du 25 juillet 2017 énonce que : *« En s'appuyant sur l'expertise du régulateur, le décret et les arrêtés seront modifiés en vue d'établir un cadre de développement approprié des réseaux alternatifs et micro-réseaux, y compris citoyens, sous leurs différentes formes. L'émergence de ces réseaux se réalisera en étant attentif à une contribution équitable de l'ensemble des utilisateurs du réseau public ».*

La nouvelle réforme, portée par le projet de décret favoriser donc la création de communautés d'énergie renouvelable autorisant l'autoconsommation collective *d'électricité*, ce qui permet de s'affranchir de la dimension physique du réseau. Ainsi, tout en mobilisant le réseau public, plusieurs entités (personnes physiques ou morales), au sein d'un périmètre, pourront s'entendre pour mutualiser et synchroniser leur production et consommation électrique.

Model 7: EV – Car not always charged at home

A few comments on how this model could affect the electrical industry:

1. May help domestic microgrids with PV and batteries to go fully off grid. How? During a sunny period the owner of the (good-sized) domestic microgrid would charge its EV at home. Otherwise, he would charge it at another location. This would help the fully off-grid microgrid to handle the inter-seasonal fluctuations of PV energy.

2. The EVs could be charged immediately adjacent to renewable generation units where electricity costs may be much lower than retailing cost for electricity. Two numbers: retail price for electricity in Belgium: 250 €/MWh. Cost of PV energy in Belgium: less than 100 €/MWh.
May also help to avoid problems on distribution networks caused by renewables.

An App-based Algorithmic Approach for Harvesting Local and Renewable Energy Using Electric Vehicles

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Keywords: Multi-agent System, Electric Vehicles, Renewable Energy

Abstract: The emergence of electric vehicles (EVs), combined with the rise of renewable energy production capacities, will strongly impact the way electricity is produced, distributed and consumed in the very near future. This position paper focuses on the problem of optimizing charging strategies for a fleet of EVs in the context where a significant amount of electricity is generated by (distributed) renewable energy. It exposes how a mobile application may offer an efficient solution for addressing this problem. This app can play two main roles. Firstly, it would incite and help people to play a more active role in the energy sector by allowing photovoltaic (PV) panel owners to sell their electrical production directly to consumers, here the EVs' agents. Secondly, it would help distribution system operators (DSOs) or transmission system operators (TSOs) to modulate more efficiently the load by allowing them to influence EV charging behaviour in real time. Finally, the present paper advocates for the introduction of a two-sided market-type model between EV drivers and electricity producers.

Download the reference: An App-based Algorithmic Approach for Harvesting Local and Renewable Energy Using Electric Vehicles.

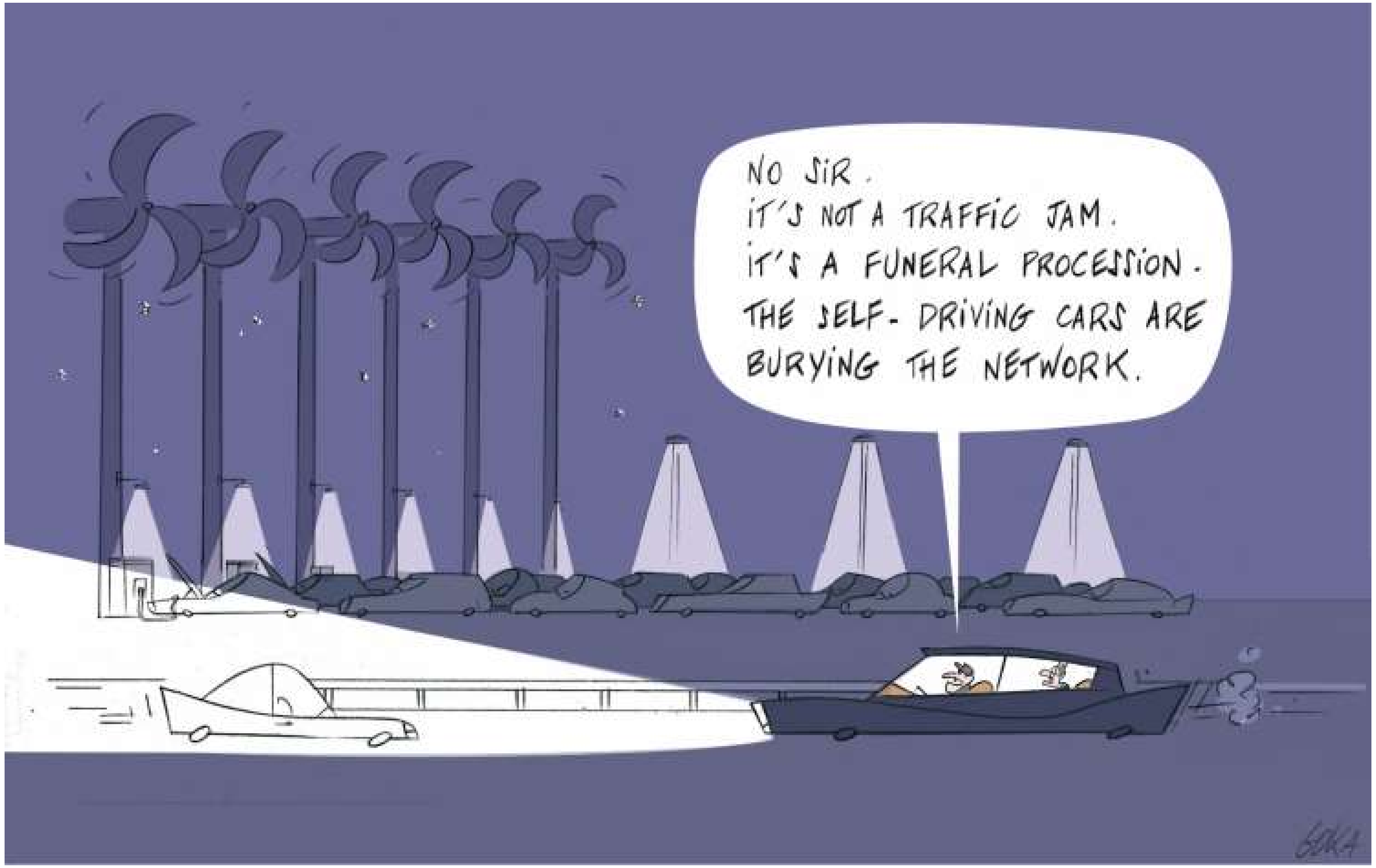
Model 8: V2G – Vehicle discharging only at home

1. Could allow for the creation of fully off-grid microgrids that do not have their own generation capacities.

2. Self-driving EVs could, during the night, autonomously bring back electricity to the house. This electricity could be stored in the batteries of the house.

Model 9: V2G – Car as a substitute for the utility grid

EV charging could be carried out next to electricity sources at a cheap price. Afterwards, EVs could directly sell their electricity (without using the grid) to any electricity consumer at a higher price. As such, they will act as a true competitor for the utility grid.



Model 9 may become very successful with the rise of self-driving cars for two main reasons:

1. No one will be needed to drive the car to collect electricity and deliver it to the electricity consumer.

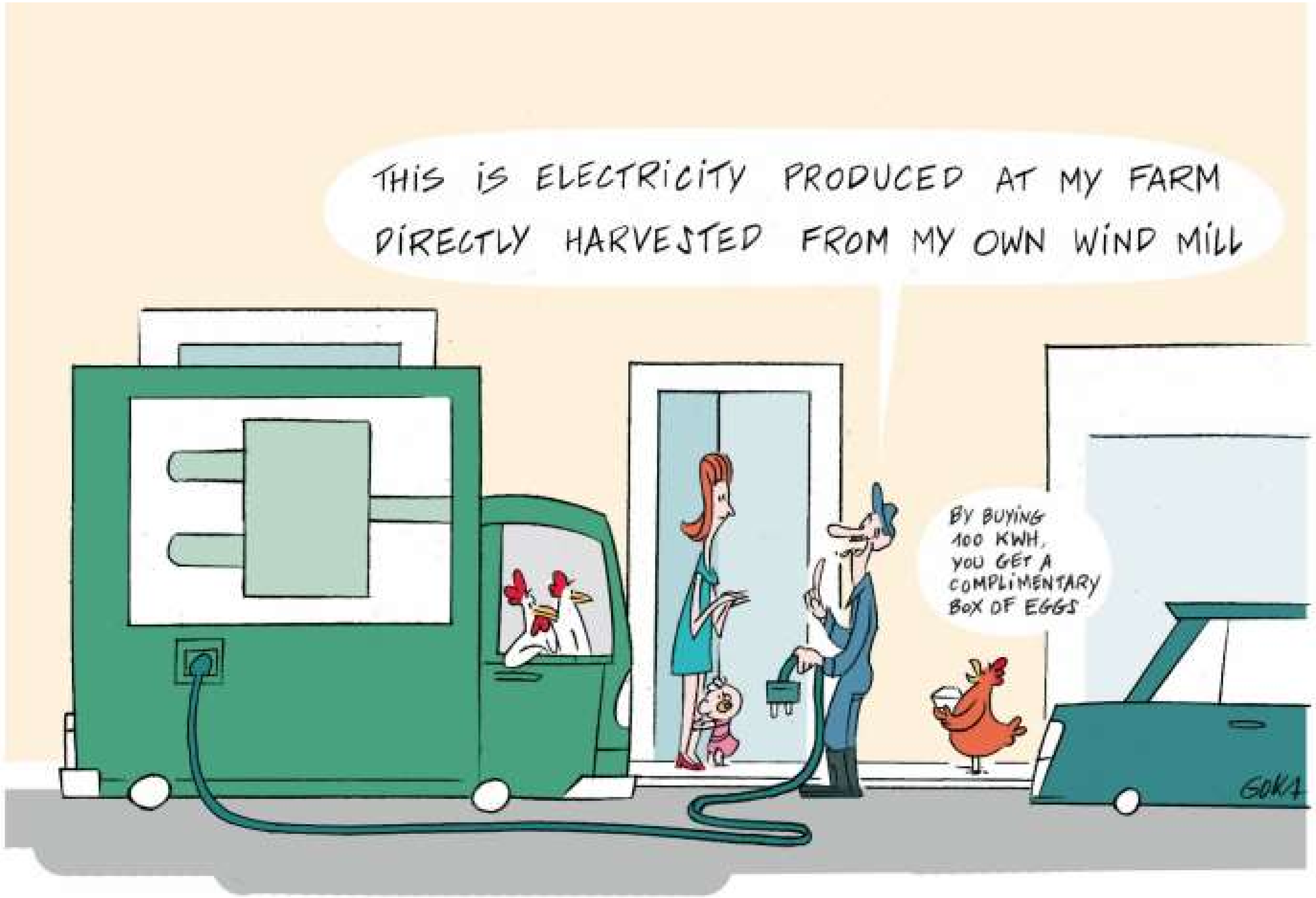
2. Fleets of self-driving cars will not be used during the night to transport passengers. Using them during the night as a substitute for the electrical network will therefore accrue very little additional capital costs.

Model 10: No EV battery. Delivery of electricity using storage devices

1. Many producers of electrical energy could start delivering electricity directly to home batteries through the use of mobile batteries.

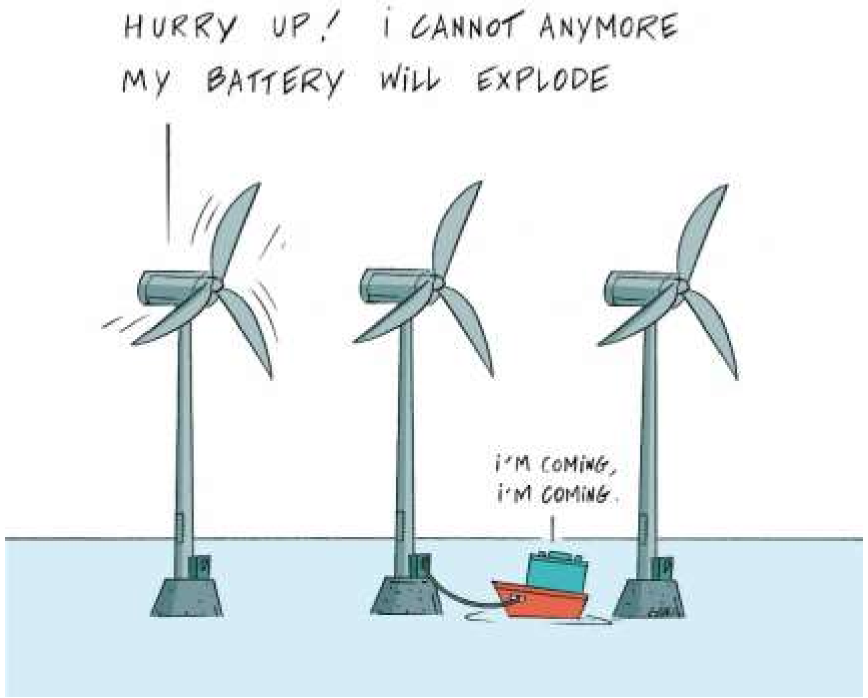
2. Delivery system may be significantly cheaper than the cost of running distribution networks in rural areas.

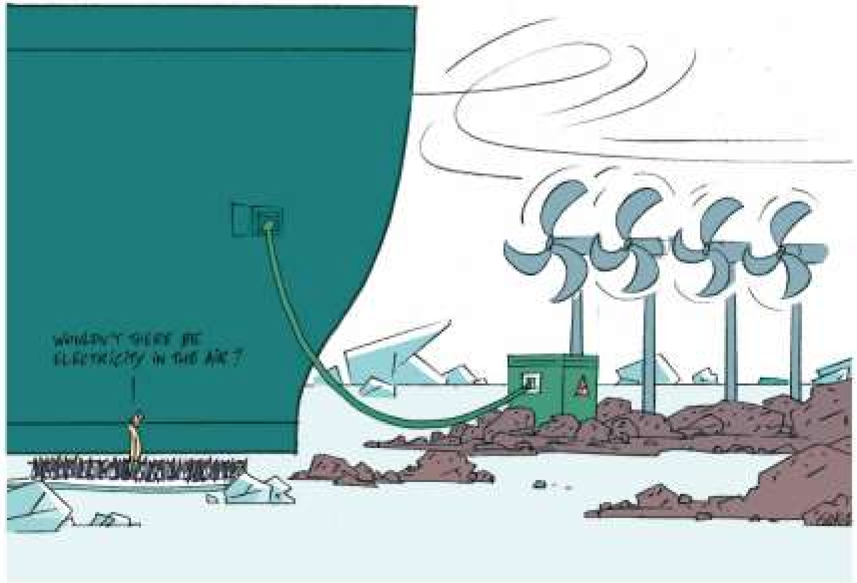
3. Biggest competitor of Model 10: Model 9.



Model 11: No EV battery. Storage devices as a substitute for the transmission grid

1. The off-shore grid could be replaced by a system of boats with batteries.
2. Renewable energy collected at remote locations, such as the East coast of Greenland for example, where there is ample wind, could be brought back to consumption centres with using large ships full of batteries. Model is competitive with undersea cables once cost of batteries drops below 50 €/kWh.
3. Model 11 could be combined with a model based on electricity distribution with batteries.





Organisation of the class

Lesson 2. Basic electricity notions (direct current, alternating current, three-phase current).

Lesson 3. Basic elements of the electricity network (cables, transformers, lines, generators, loads). Concept of primary reserve to ensure the balance between production and consumption.

Lesson 4. Electricity markets: liberalization, actors, operation.

Lesson 5. Integrating Renewables, Flexible Loads and Electric Vehicles into the Electricity Market.

Lesson 6. The Global Grid. Technology for Building Global Grid (HVDC, converters, undersea cables).

Lesson 7. Microgrids and Energy Communities.

Lesson 8. Coupling between different energy sectors (electricity and gas).

Lesson 9. The major environmental problems related to the construction and operation of electrical networks (electro-magnetic and electric fields, SF6, NIMBY issues, mineral resources).

Reading after every class

- One scientific paper or technical document given on the class website and a list of associated questions.
- A written exam at the next class during which you will have to answer these questions.
- A group that will have to present this paper/document.
- An open discussion after the presentation.