Power System Economics
The grid

Master Energy – Master 2

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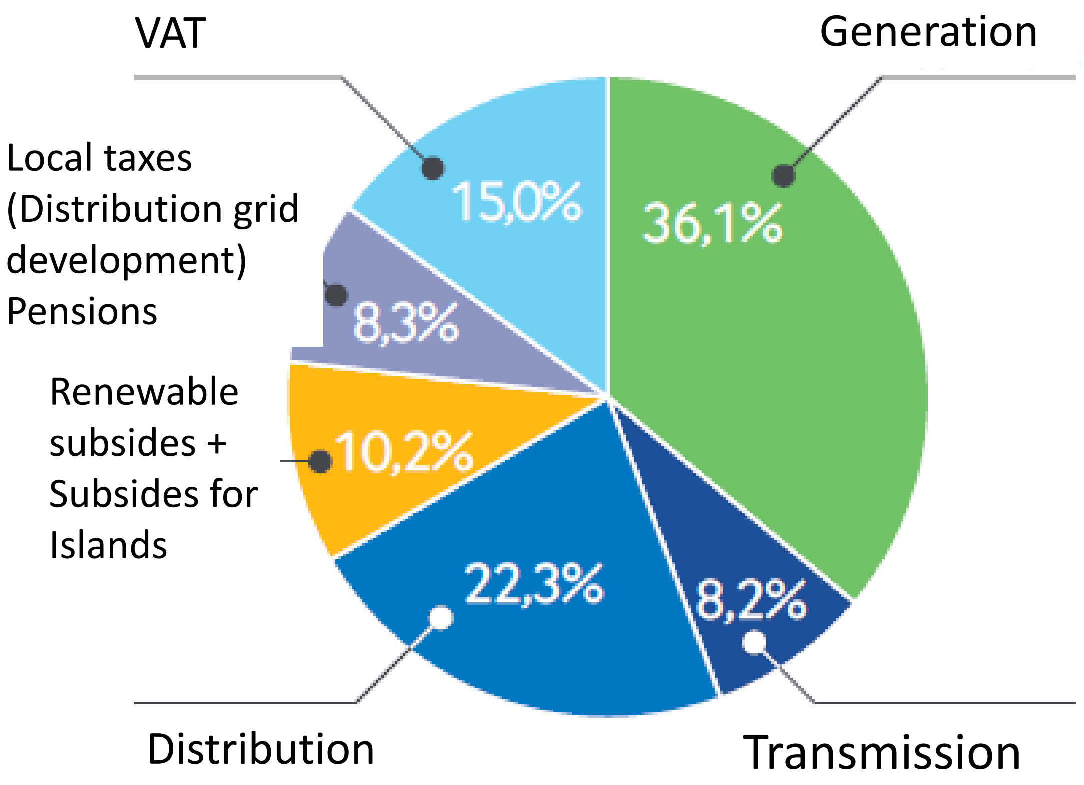
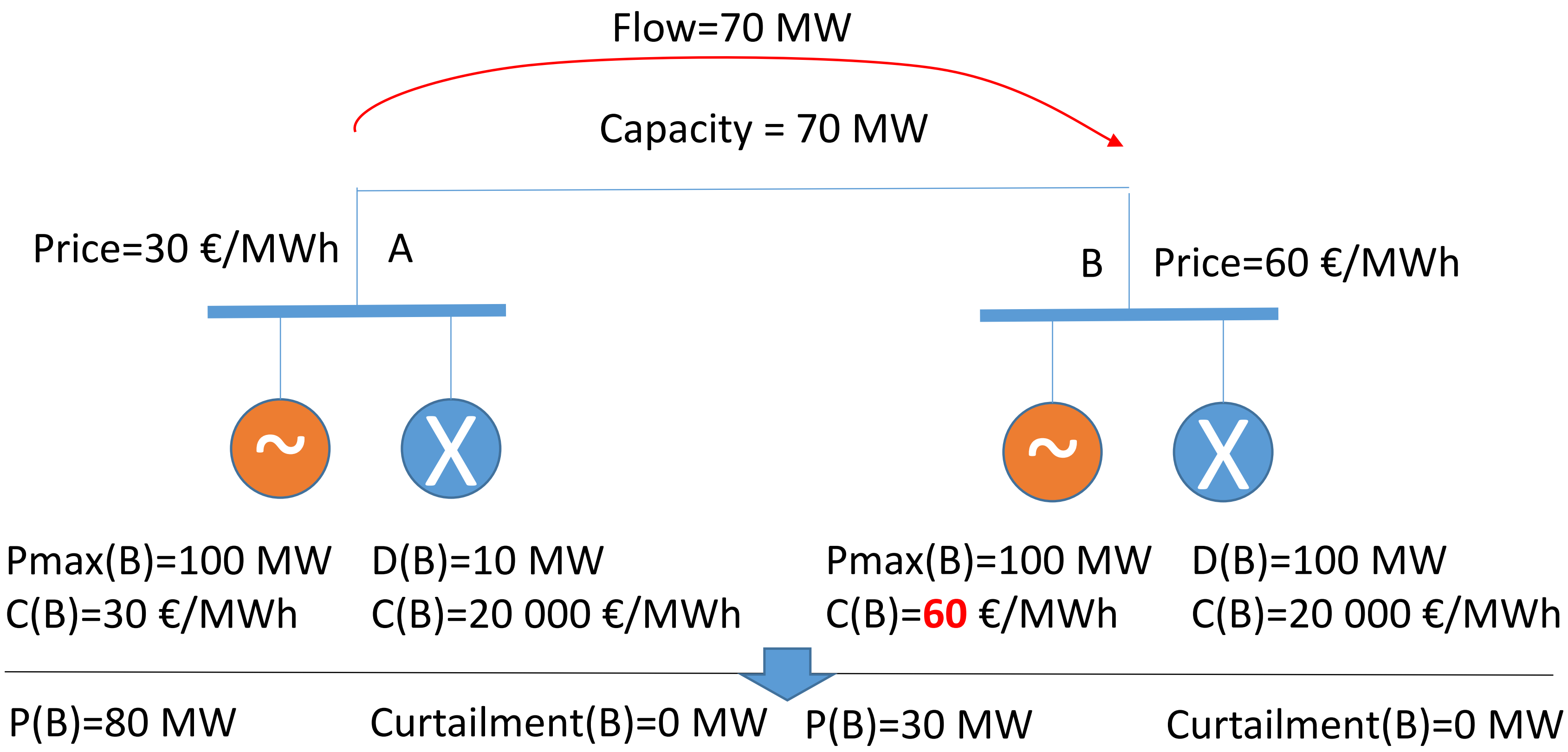
The grid: a significant share of the bill

French household bill decomposition (Jan. 14)



- Household:
  - Generation ~ 60%
  - Grid ~ 40%
- Large industrial:
  - Generation ~ 87%
  - Grid ~ 13%

Short term economics: the congestion



- The flow on the line is limited by its capacity.
- The optimal dispatch uses the expensive generator (2) but less than without the line.
- The price of energy is higher "below" the congestion (at B).

- Gen. cost = 80*30+30*60 = 3 000 €/h < Gen. cost without the line = 100*60 = 6 000 €/h
- Congestion rent = revenue of selling energy in B – cost of buying in A = 70*(60-30) = 900 €/h

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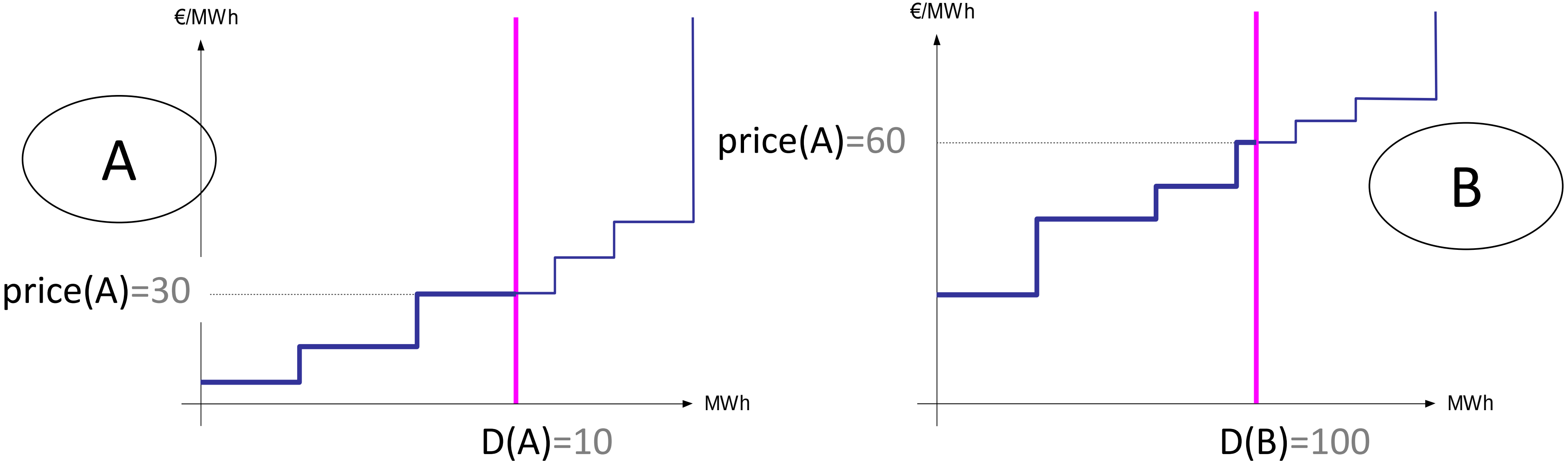
The congestion: graphical example

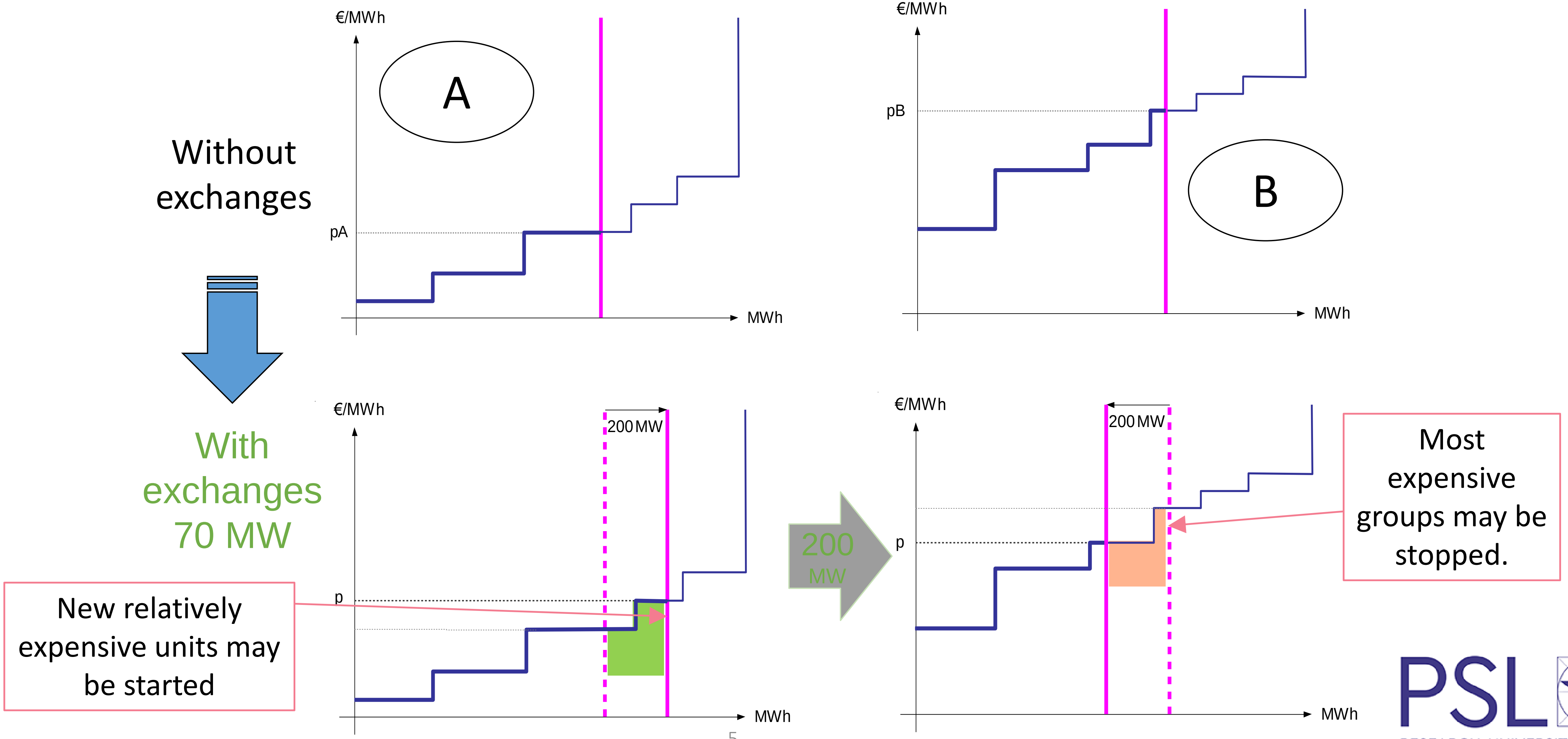
2 zones with inflexible demand D(A) and D(B): price is low in A, high in B.



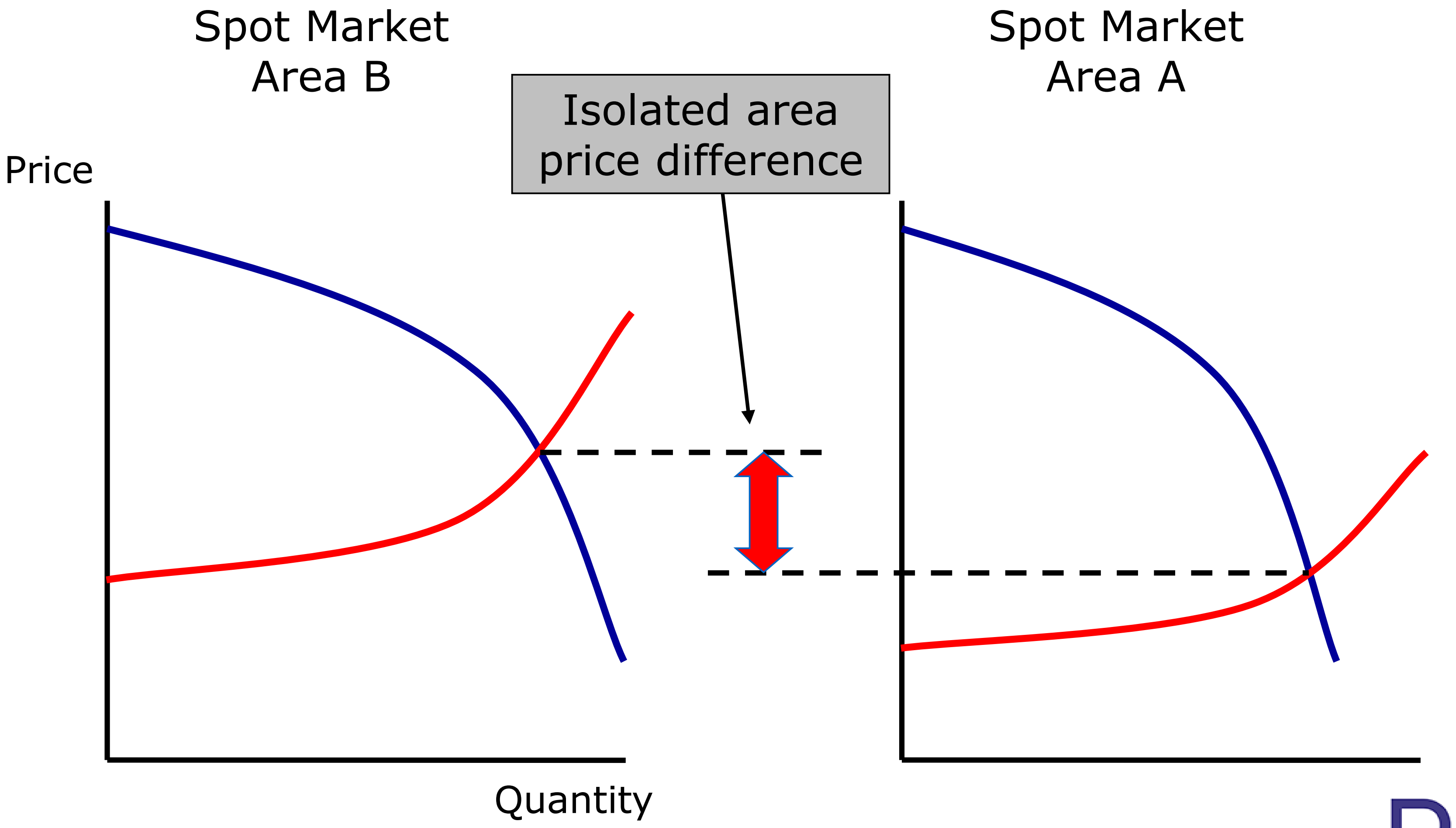
Why exchanging?

An export from A to B decreases the overall generation cost.

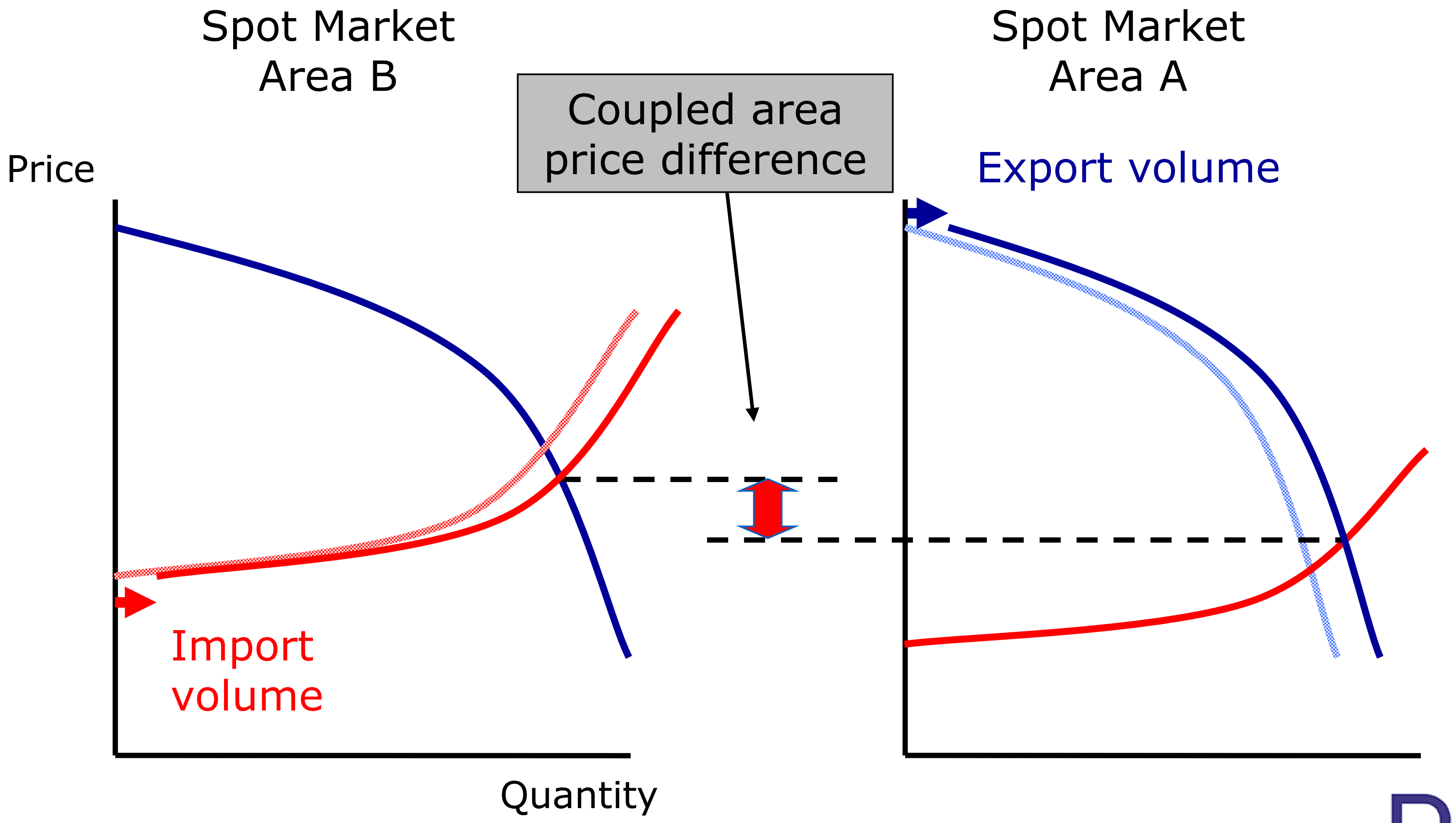
The congestion: graphical example



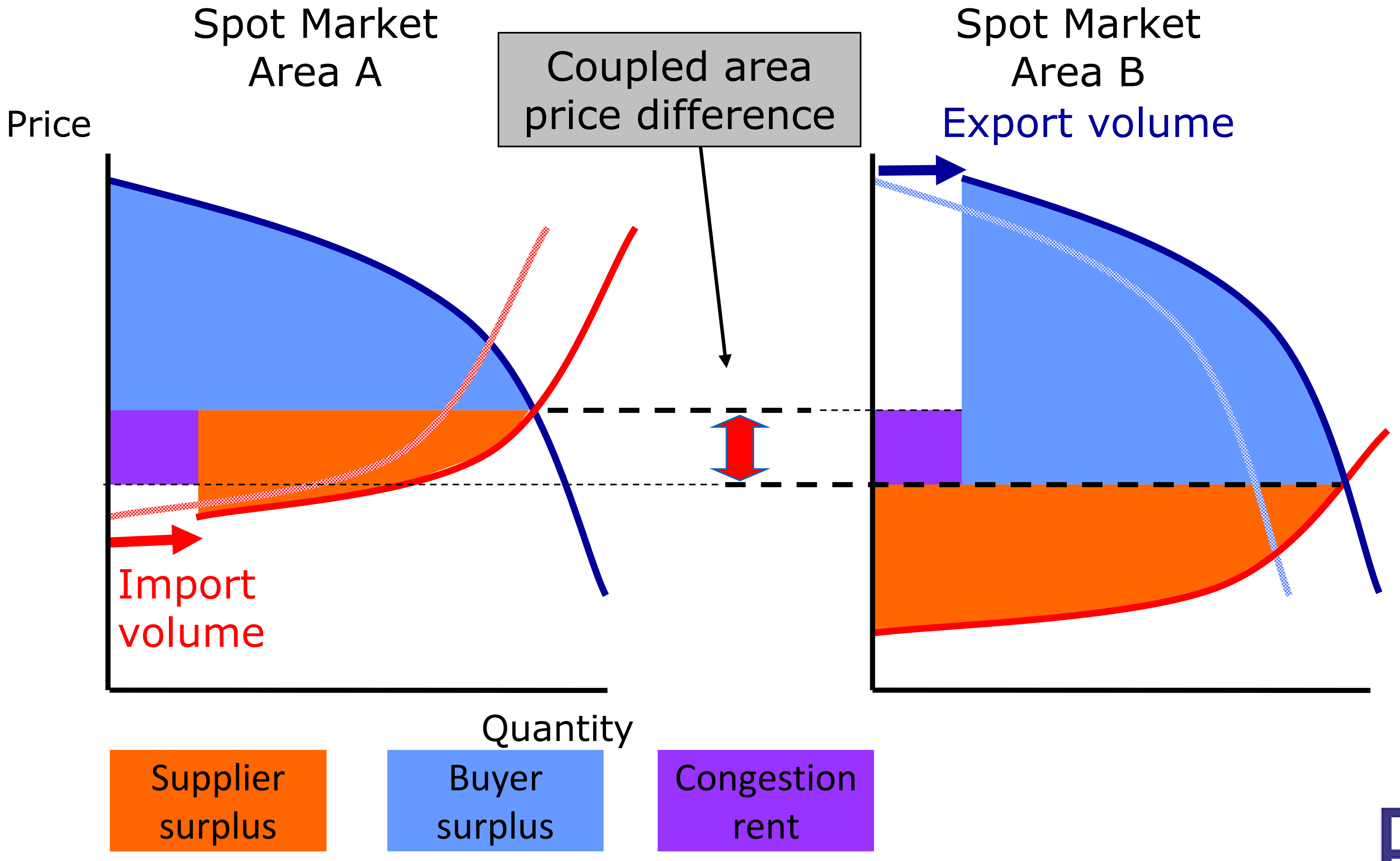
The congestion rent



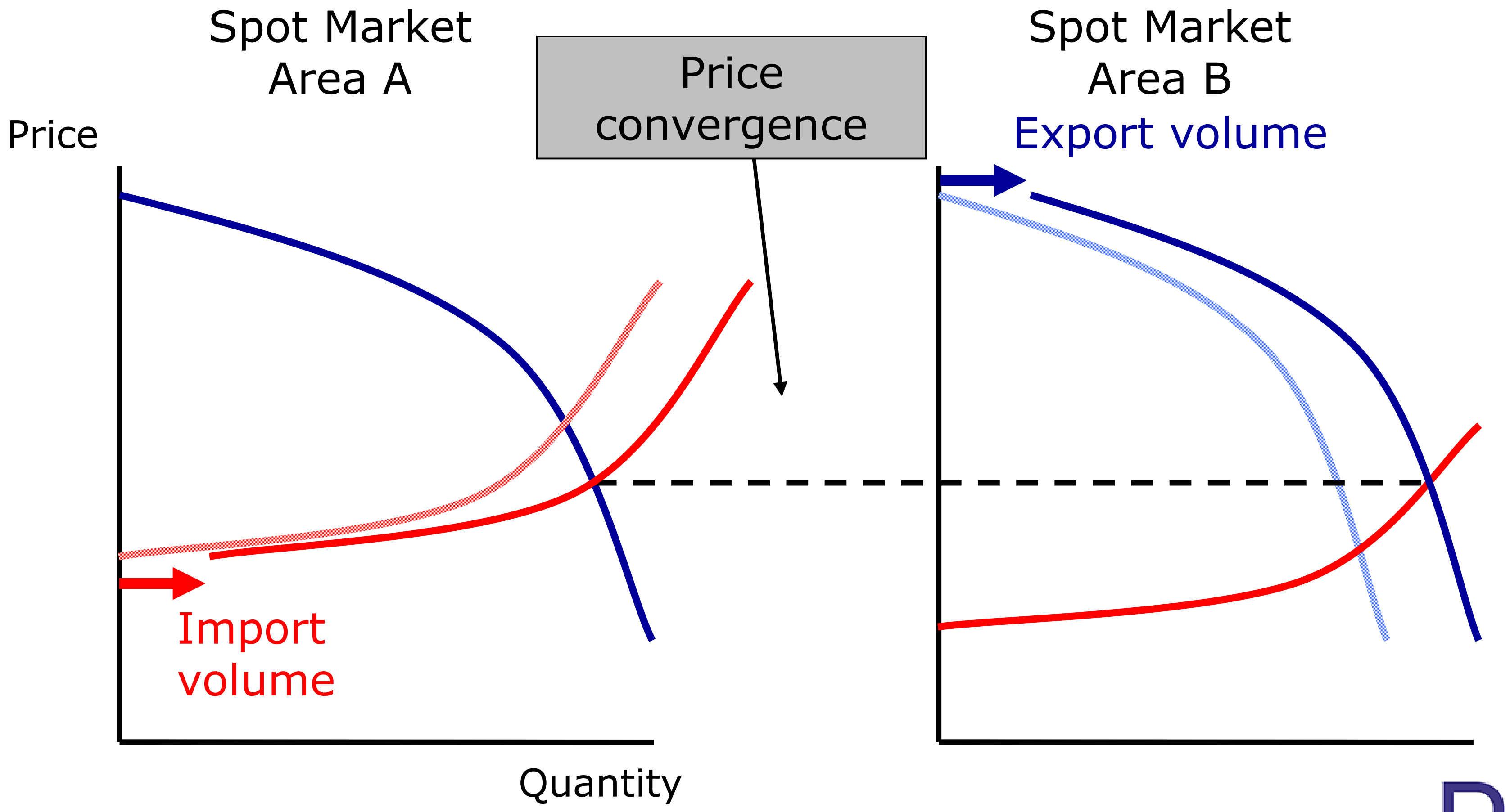
The congestion rent



Interconnections: Influence of exchanges on market prices: price divergence



The congestion and the congestion rent disappear at price convergence



Long term economics: the saturation
The transmission/generation cost trade-off

- Suppose that A has a really cheap energy source that can be used as base generation (run-of-the-river hydro power on a river with a constant flow).
- The marginal value of a line is:

  + Fixed cost of base technology in B *(in €/MW.year)*
  + Variable cost of base technology in B * 1 year

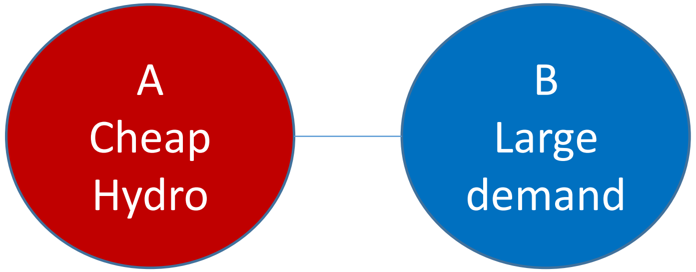
  } Marginal cost decrease in B (in €/MW.year)

  - Fixed c.(hydro in A) *(in €/MW.year)*
  - Var. c.(hydro in A) * 1 year

  } Marginal cost increase in A

  - Fixed cost of line A to B *(in €/MW.year)*
  - Var. c. of line from A to B * 1 year

  } Marginal cost of line from A to B



- The line should be built if the value is negative (the gain is positive).
- It will be saturated (used to full capacity) during all the year.
  - A price difference will appear (= Var. c.(base) – Var. c(hydro))
  - This inframarginal rent allows to pay for the fixed costs of the line.

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Numerical application

Technology	Fixed costs (€/MW.year)	Variable costs (€/MWh)
Hydro	450 000	0
Base technology	400 000	16
Peak technology	80 000	111
Curtailment	0	20 000

- Cost hypothesis for a 400 kV aerial line:
  - Lifetime = 60 years, interest rate 7%
  - Overnight cost = 1 000 €/MW.km.year
  - Variable O&M cost = 1E-3 €/MW.km (1% of losses at 30 €/MWh for a 500 km line)
  - Fixed cost ~ 100 €/MW.km.year (1000 km line: 100 000 €/MW.year)
  - Variable cost ~ 1E-3 €/MWh.km (1000 km line: 0.1 €/MWh)
- Cost hypothesis for hydro: 450 000 €/MW.year
- Numerical application

  400 000 - 450 000 - 100 * length + (16 - 1E-3 * length) * 8760 > 0

  Length < 828 km
- Teaching: if cheap power is available for long duration, long lines can be built.

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Transportation/Transmission costs

- According to Percebois & Hansen (Energies, 2012, p68):

Energy	Oil	Gas	Coal	Uranium	Electricity
Transportation costs (USD/boe.1000 km)	1.7	10	4.3	-	> 10 (~17 USD/MWh.1000 km)
Storage costs (USD/boe.year)	3	6.5 (Storengy: 4-14 €/MWh.year)	0.5	-	- (Annual reservoir water value > 10 €/MWh

- Usually, if produced from oil, gas and coal, electricity is produced near consumption centres.
- Nuclear power requires a lot of cooling water (sea or large river).
- However, even without energy price difference, power grids may be built only for reliability or mutualization (see next example).

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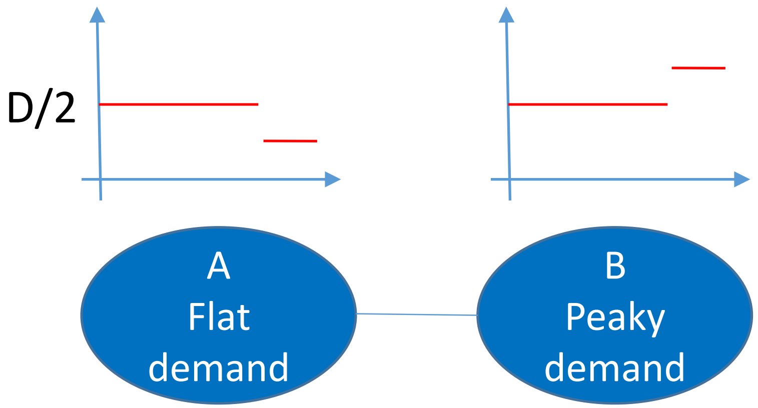
Long term economics: the saturation
A thought example for mutualization

- Suppose 2 areas have inversely correlated demand: D(A,t) + D(B,t) = D
- Suppose that both demands are always equal except for a short period of year f (in %) during which D(B,t)=3*D/4 and D(A,t)=D/4
- Without a line:
  - The base load generator in A will not produce to full power during f
  - An additional peak generator in B is needed to serve the demand during f



- Marginal value of a line:

  Fixed c.(peak) + f * (Var c.(peak)-Var c.(base)) - Fixed c.(line) - f * Var c.(line) (> 0)

- In this case, the line will be **saturated** (used to full capacity) only during the period f.

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Long term economics: the saturation
A thought example for mutualization

Technology	Fixed costs (€/MW.year)	Variable costs (€/MWh)
Base technology	400 000	16
Peak technology	80 000	111
Curtailment	0	20 000
Line	100 000	0.1

- Numerical application ⇒ Build the line if:
  - Fixed c.(line) + f * Var c.(line) < 80 000 + f * (111-16)
  - 100 000 + f * 0.1 < 80 000 + f * 95
  - OK if the duration in year is over 210 hours (2.5% of the time)
- Teachings: lines can be used:
  - To build fewer peak units (to flatten the overall demand curve)
    → fixed cost reduction
  - To avoid curtailment (or to avoid building units to avoid curtailment…)
    - In this case the line is saturated only a very small fraction of the time (difficult to recover fixed costs).
  - To use units with low variable costs
    → variable cost reduction

<u>Even if the long-term marginal costs are identical.</u>

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Long term economics

- Lines are useful:
  - To transmit power from areas with low LTMC to areas with high consumptions and high LTMC.
  - To mutualize assets between areas with equal LTMC.
- The optimal mix theory relying on Long Term Marginal Cost can be extended to the grid:
  - Lines are saturated (used to full capacity) during part of the year
  - The inframarginal rent compensates exactly the fixed cost
  - Lack of lines $\Rightarrow$ congestion appears
  - Excess of lines $\Rightarrow$ cost recovery is impossible (Stranded costs)

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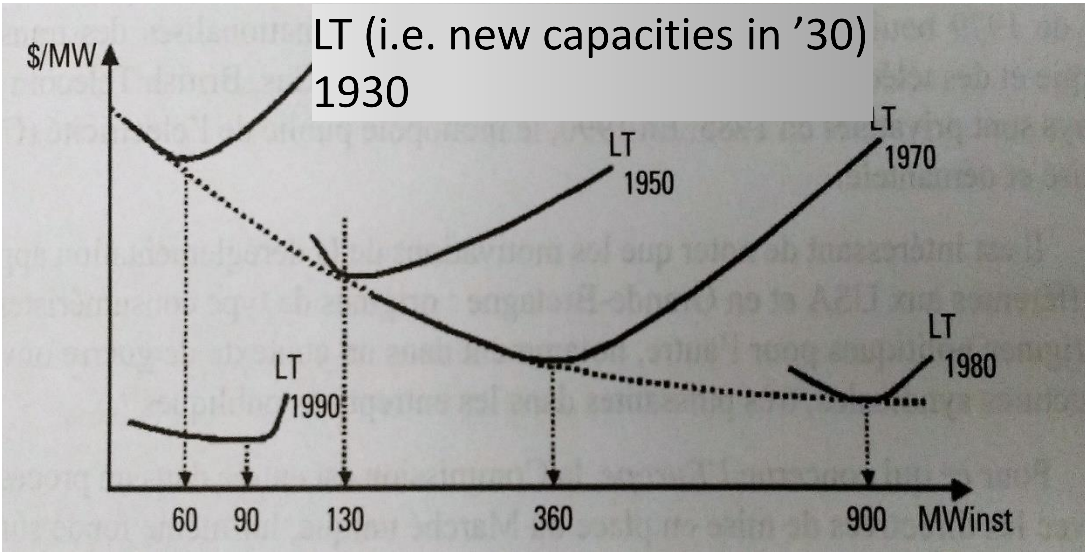
How realistic is the theory?

Long term economics and economies of scale

- According to the theory, anybody could build new lines.
- Practically this is impossible because economies of scale are important.
  - **A significant part of costs is in deciding to build a network**, not to size it.
  - Some costs are **never** proportional to energy, whatever the horizon while the optimal mix theory supposes that all costs are proportional to MWh in the long run.



Generation long-term marginal costs
(from Energies, Percebois & Hansen)

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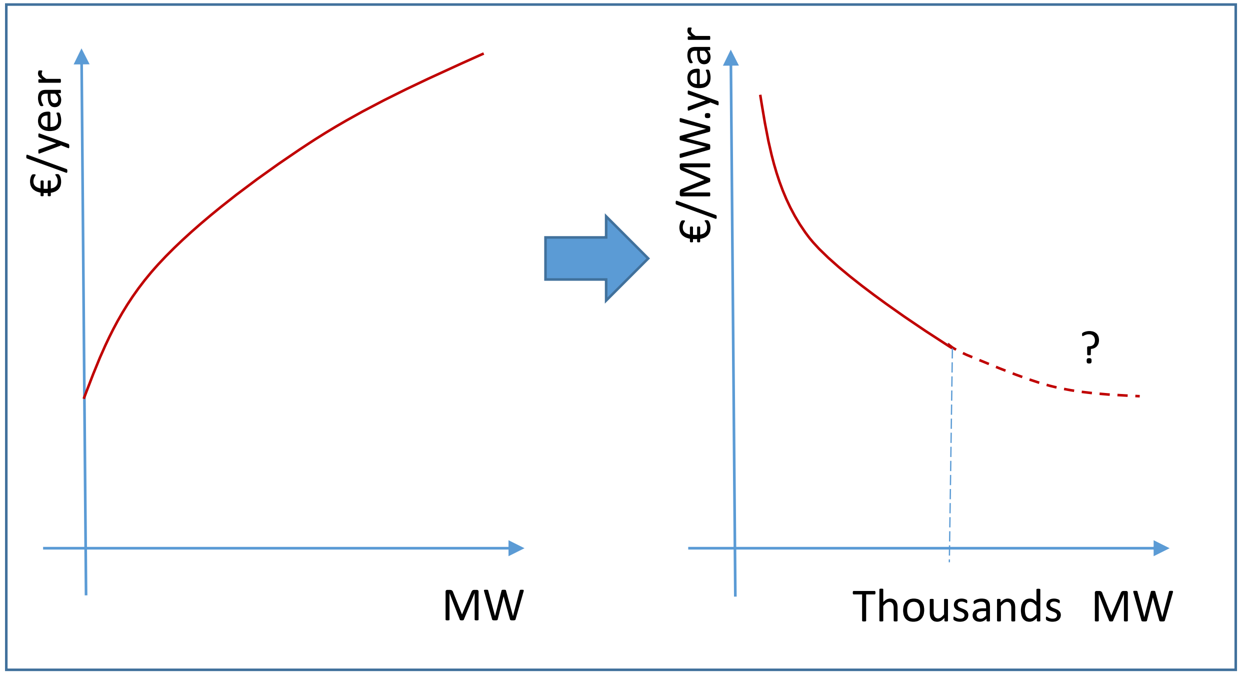

Transmission long-term marginal costs

Long-term marginal costs and monopolies

- The transmission and distribution segment is a natural monopoly because of economies of scales.
- Equivalence between central planning and market is broken: a market would underperform (underinvest).
- While still allowing to reach the lowest cost solution, pricing based long-term marginal cost does not cover the fixed costs.
  - No trivial way to do it (Ramsey-Boiteux…) while not degrading too much the optimum.
  - On solution (among other): the connection fee
    - Fee paid whatever your use of the grid (and whatever the capacity).
    - Implemented in Italy
- Other network monopolies present similar issues:
  - Some manage to recover their costs (gas distribution) or even more (water distribution)
  - Some do not: state subsidies from tax payer (road and railways transportation network) or from another network (wastewater system)
  - The power grid manages to recover its costs because of captive usages resulting in an inelastic demand.

Grid studies at RTE

- 225 kV – 400 kV grid (“national” grid):
  - Highly meshed, with very variable flow patterns.
  - Are considered:
    - Avoided curtailment costs
    - Avoided congestion costs (reduction of generation costs)
    - Additional losses because of the line

    No explicit trade off to locate generation close to load: **“The grid follows the generation”**
- 63 kV - 90 kV grid (“regional” grid):
  - Mainly radial, with mainly “grid to load” flow patterns.
  - Simplified study, only avoid curtailment costs are considered:
    - Determine the “peak” situation where the grid is heavily loaded.
    - Build the line according to this "peak" situation.
  - A similar method on distribution grids (<20 kV) .
  - But <u>distributed generation is changing flow patterns</u>: new methods needed.

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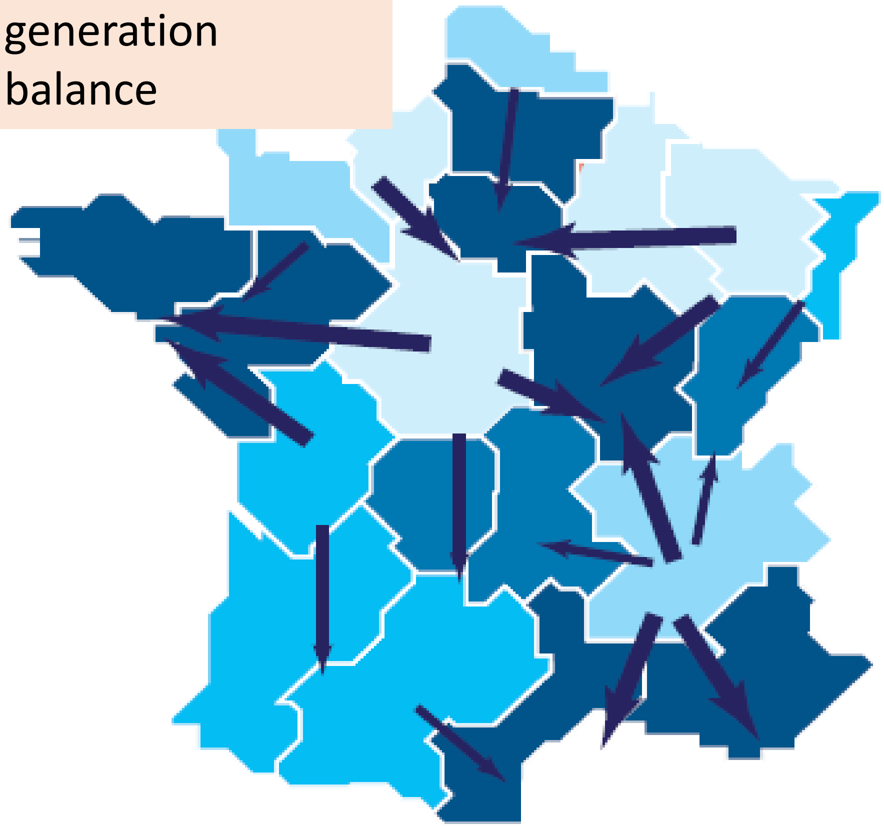
The development of the electricity grid

- The grid evolves constantly in order to adapt to the needs

- The objective is to respond:
  - to demands from new customers (connection)
  - to modifications of energy flows in the grid:
    - increase of local consumption
    - evacuation of decentralized generation
    - evolution of interregional balances (location of groups and consumptions)
  - to the ageing of assets (renewal/restoration)

The transmission grid balances regional disparities

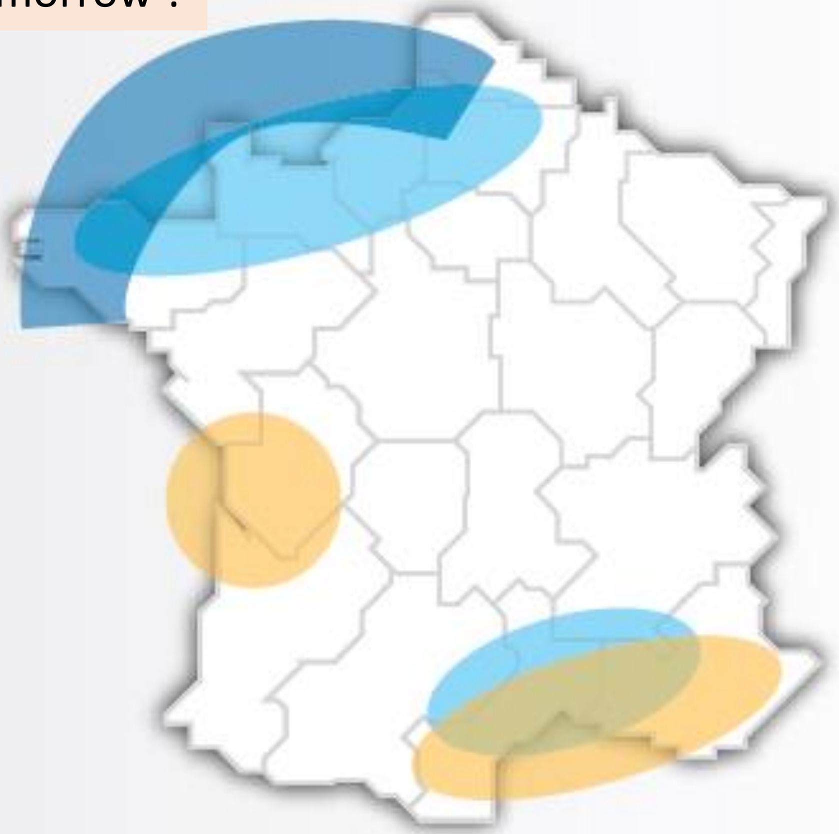
Current generation balance



Region with:

- Large gen. deficit
- Generation deficit
- More or less balanced
- Generation excess
- Large gen. excess

Tomorrow ?



Meteorological conditions well adapted to the development of:

- Onshore wind farm
- Offshore wind farm
- Photovoltaic solar

Specificity of the development of electricity grids

- Grid facilities have long operation duration (> 40 years) with long-term consequences as a result
  - Well define sizing.
- The development process is long (~ 10 years)
  - Occasionally longer than the development time on the customer's side.
  - They must be sufficiently anticipated.
- They can be costly and have an increasingly perceived external impact
  - All developments must be made judiciously.
- They respond to needs which are increasingly difficult to foresee
  - Low underlying growth.
  - “Non-wire” alternatives studies to avoid building new lines.

What are the expectations of the different participants in relation to the grid?

- Technical performance
  - Reliability
  - Continuity of supply
  - Quality of supply
  - Fluidity of the market and exchanges
- Cost
  - Applied directly to the cost of the electricity delivered
- Impact
  - Environment
  - Country planning
  - …

The planning of electricity grids

- The planning of the grids consists in defining, in time, the adaptations of the grids allowing proper, long-term, least cost operation to be ensured
- A long-term vision is required in order to:
  - Ensure our long-term capacity to respond to the needs
  - Measure the robustness of each evolution of the grid and prepare the “next step”
  - Have a “guideline” which goes further than short-term studies
  - Plan for the resources which will be required to build the chosen grid (financing, engineering, suppliers)
- Planning the grid means imagining <u>the most likely future</u> based on credible hypotheses while complying with technical and economical constraints.

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The planning of the electricity grids

- Planning methodologies depend on the grid studied:
  - Distribution grid (out of scope of this presentation)
  - Transmission grid:
    - Regional network (63kV-225kV). Interfaced with the distribution grid, regional control and command
    - National network (400kV, but 225 kV sometimes too): strongly meshed, centralized control and command.

Long Term Marginal Costs: order of magnitude

Illustration with lines

- 400kV aerial (dble circuit) : [700;1000] k€/km - [1000; 3000] MW/circuit → ~ 212 €/MW.km
- 225kV aerial (dble circuit) : [400-600]k€/km - [400; 700] MW/circuit → ~ 454 €/MW.km
- 90kV : [250;450] k€/km - [80; 150] MW/circuit → ~ 3 043 €/MW.km

Strong economies of scale

- Underground cable:
  - Important fixed cost (independent of length)
  - More expensive (1.5-2 for 225 kV and 400 kV, less for 90 kV)

Cotentin-Maine project: 163km 343M€ among which 96M€ of compensation measures (1.5M€/km or 2M€/km with the compensation measures)

Cost vs. acceptability

HVDC project:	(MW)	Distance (km)	Costs (M€)	Costs/km (€/MWkm)
France Spain	2000	65	700	5 385
France Italy	1200	140	1 400 (exp.)	8 333

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Study scheme

- Build up the hypothesis
  - Generation, consumption, exchanges
  - Grid
  - Time slots
- Identify and value the constraints
  - Transit, voltage, short-circuit intensity, power quality, stability, environmental constraints.
- Find and study the solutions
  - Quantitative analysis if possible (explicit in €, or implicit with respect to technical limits)
  - Qualitative analysis if not, but should cover all issues
- Solution comparison and choice of the preferred strategy (technical and economical trade-off)

Quantitative analysis

Three indicators may be used:

- The NPV (Net Present Value)
- The BCR (Expected Benefit Cost Ratio)
- The PEI (Profit per Euro Invested)

Quantitative analysis: the NPV

The difference between the costs and the benefits induced for the society (<u>and not for the owner</u>) by the project during all its life

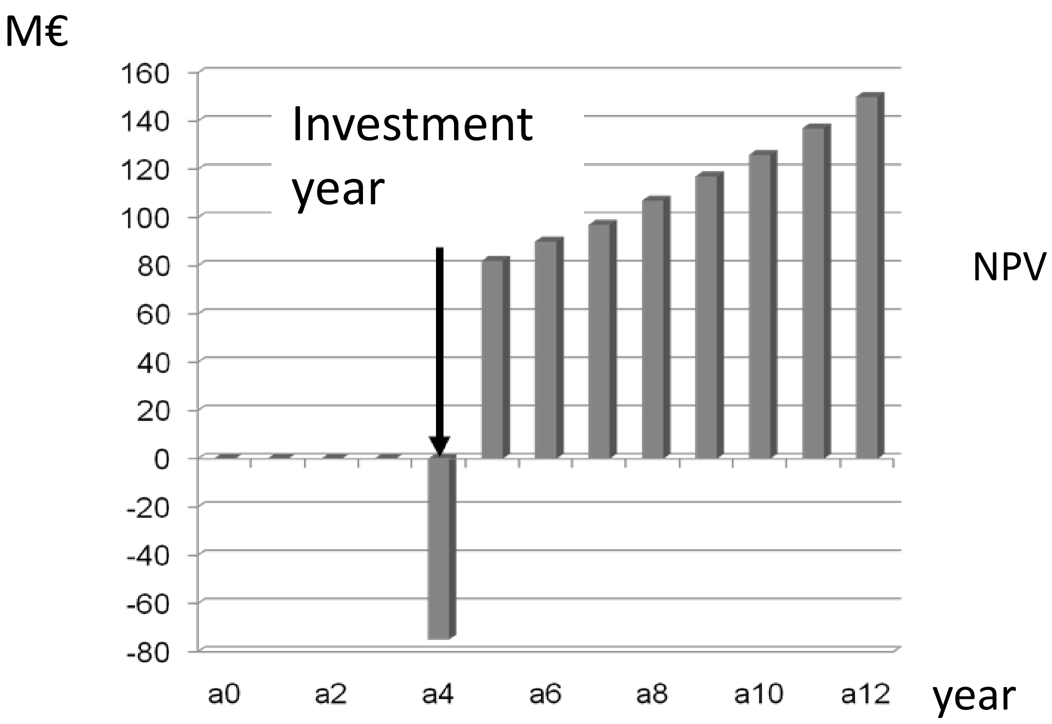
NPV

=

Σ Annual revenues - Σ Annual costs (for the studied reinforcement)

Or (see next slide)

Balance (nothing done) – Balance (studied reinforcement)



NPV = revenues - costs

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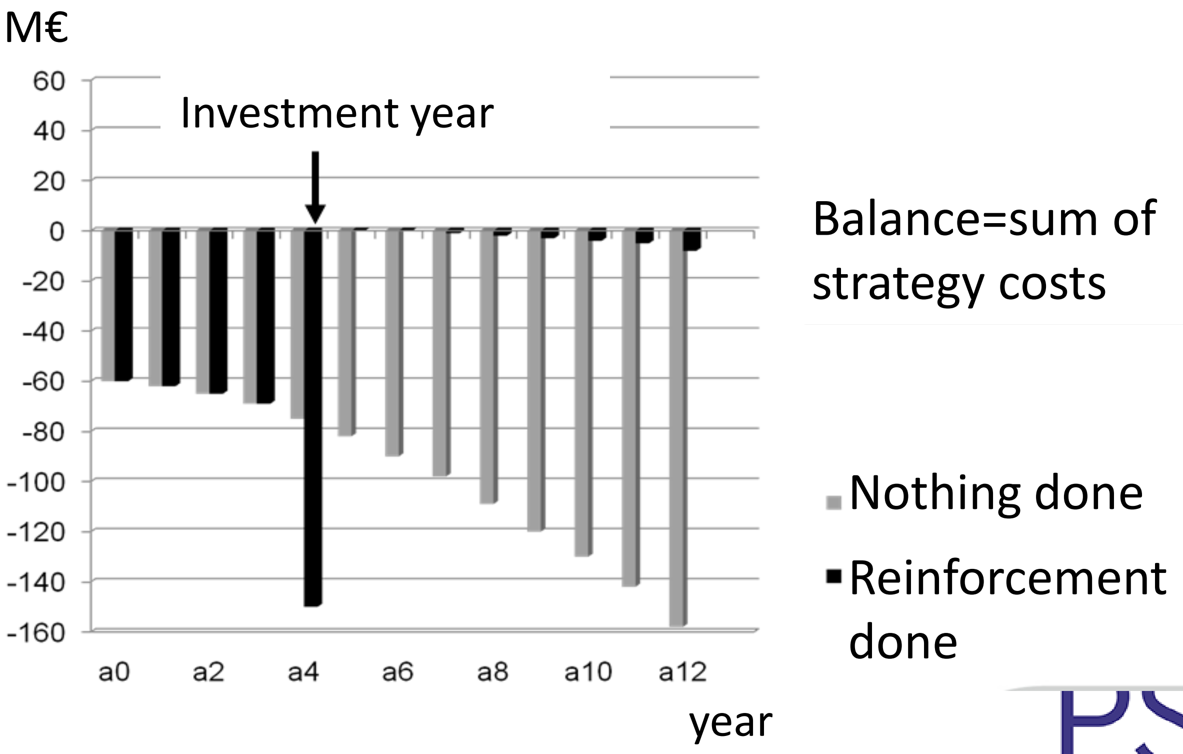
Quantitative analysis

$$\text{Balance}(S) = \sum_{t=1}^{T} \frac{UD(t) + Cong(t) + Losses(t) + Expl(t) + Inv(t)}{(1+i)^t}$$

- UD(t) = "Cost" of Unserved Demand for year t (Value of Lost Load)
- Cong(t) = Congestion cost for year t
- Losses(t) = Cost of losses for year t
- Expl(t) = Exploitation costs for year t
- Inv(t) = Investment for year t
- i = Discount rate
- T = End of study year



Balance=sum of strategy costs

The NPV: an optimization tool

It represents the main indicator for the criteria that are convertible to money.

- Allows to rank strategies

- Computed on 15-20 years. If evolutions are uncertains, also computed on 10 years.

- A reinforcement is deemed useful if NPV is positive

  Avoiding low performance or too early reinforcement that costs a lot to the society.

- **The highest the NPV, the more useful the reinforcement.**

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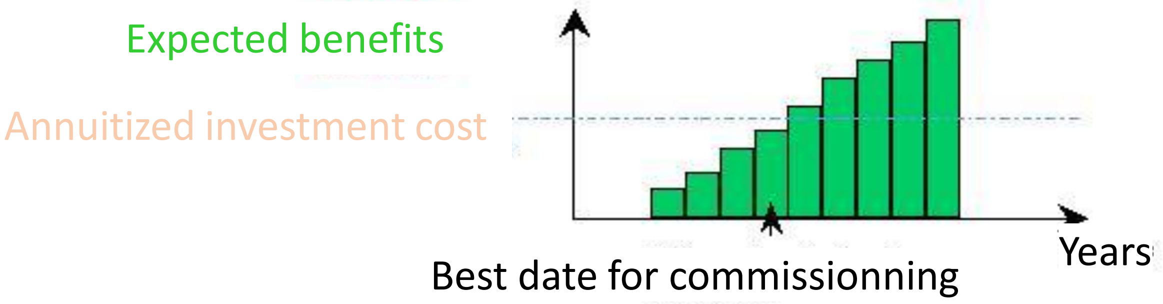
Other indicator: the BCR

- In theory, the best date for an investment is the first year for which the benefits are higher than the costs:

$$BCR(N) = \frac{\text{Benefit(N)}}{\text{Investment}} > \text{discount rate}$$



- Limit of method: OK for regional studies
  - BCR > 5,5% involves increasing profits (constant growth) and that the investment will always be usefull
  - If evolutions are more complex, BCR is useless.

Risk analysis

- Under uncertain future, it is not enough to determine the optimal strategy with fixed hypothesis
- It is needed to identify the most robust strategy with respect to the various hypothesis made from available information
- 2 methods are used:
  - Worst-case regret minimization (to perform as close to optimum in each scen.)

	Benefits			Regret	
Scenario	**Inv. 1**	**Inv. 2**	***Max***	**Inv. 1**	**Inv. 2**
No new generating unit	1850	1900	*1900*	50	0
2 new generating units	2000	1750	*2000*	0	250
			Worst regret:	**50**	250

  - Real options
    - Strategy and hypothesis are represented as a tree
    - For each branch, the NPV is computed.
    - At each node, select the strategy with the highest NPV

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Some real-world examples

The building of the European network

- In 1929, George Viel, at the “Compagnie électrique de la Loire et du Centre”, proposed:
  - to build a 400 kV network in France because losses are reduced at such a voltage level
  - “To be able to exchange electricity on a seasonal basis with neighbours, and to provide emergency assistance”.
  - It was not practical at the time (the technology did not exist).
- It really started after World War II. In 1951, UCPTE was founded to optimize operation of power plants:
  - The problem of spilled water: if hydro generation is too high in a given country, export to another country can be made at no cost.

French 400 kV network, 1962

The building of the European network

- In the 50s: due to political conditions, Eastern and Western Europe are not connected…
- In the 60s: shared primary control / decentralized secondary control.
- In the 90s: connection of Eastern Europe (thus disconnected from Russia).
- But disconnection during more than 10 years of South Eastern Europe due to the destruction key substations in Croatia and Bosnia during the former Yugoslavia war…
- In the 00s: from UCTE (“Keep the lights on”) to ETSO (“Let the market happen”).
- 2003: blackout in Italy (At least people 4 died*).
- 2006: Major disturbance down to Tunis due to an incident in Northern Germany.

*Electrifying Europe. The power of Europe in the construction of electricity networks, Vincent Lagendijk

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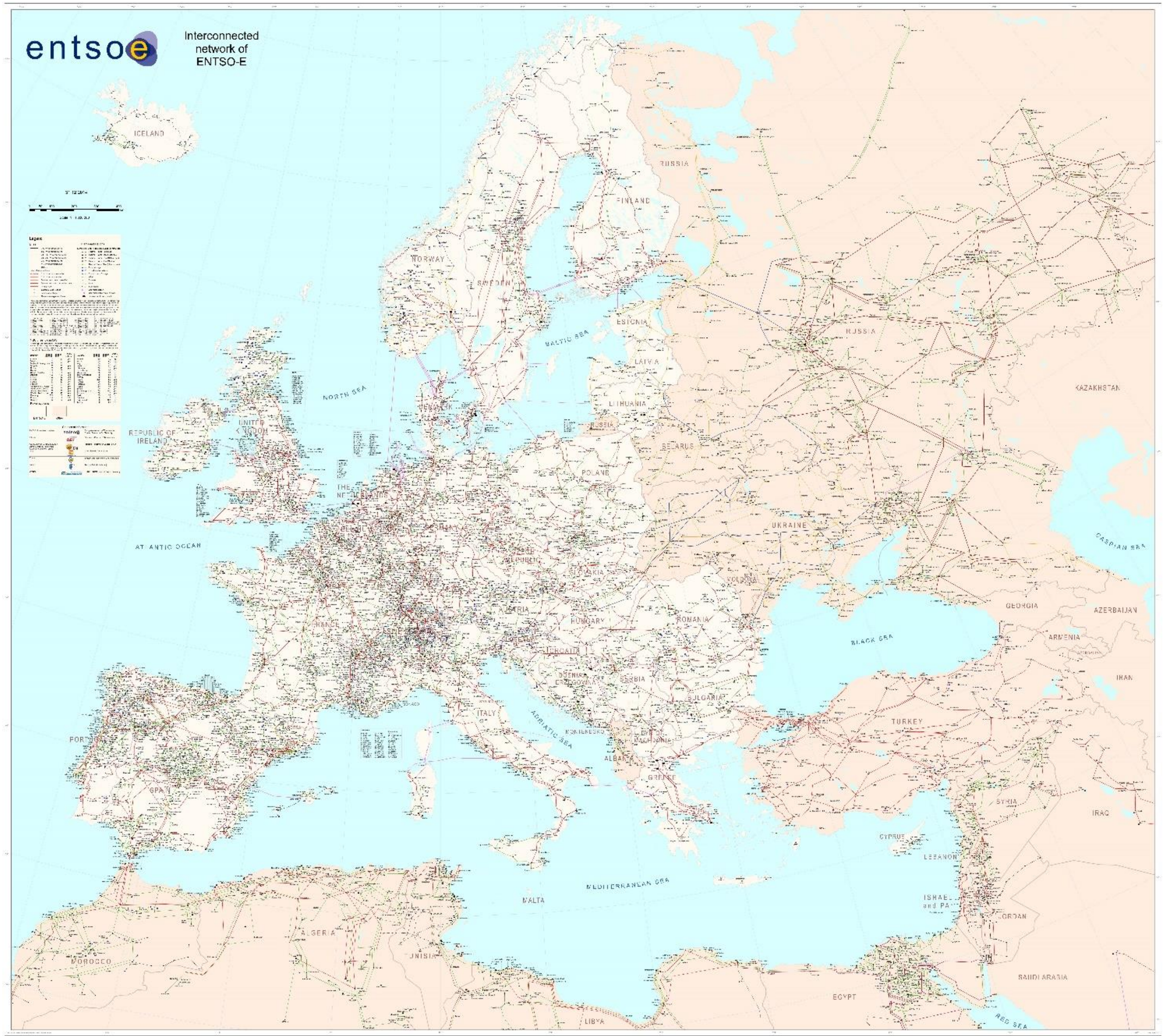
European transmission network



Average distance on the transmission grid: **~ 200 km**

https://www.entsoe.eu/publications/order-maps-and-publications/electronic-grid-maps/Pages/default.aspx

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European scale analysis: security

- Balancing at the European level:
  - Sharing the same frequency allows to share the Frequency Containment Reserve (primary reserve).

	UK	Continental Europe	*French share*
Primary Reserve	2.25 GW	3 GW	*565 MW (19%)*

  - "Netting" of the automatic Frequency Restoration Reserve (secondary reserve) through IGCC (International Grid Control Cooperation), i.e. avoid the activation of secondary reserve in opposite directions.
- Overall, hundreds of millions of Euros spared.

https://www.energy-community.org/portal/page/portal/ENC_HOME/DOCS/2856182/Grid_Control_CooperationGermany_-_Mr_Walzuch.pdf

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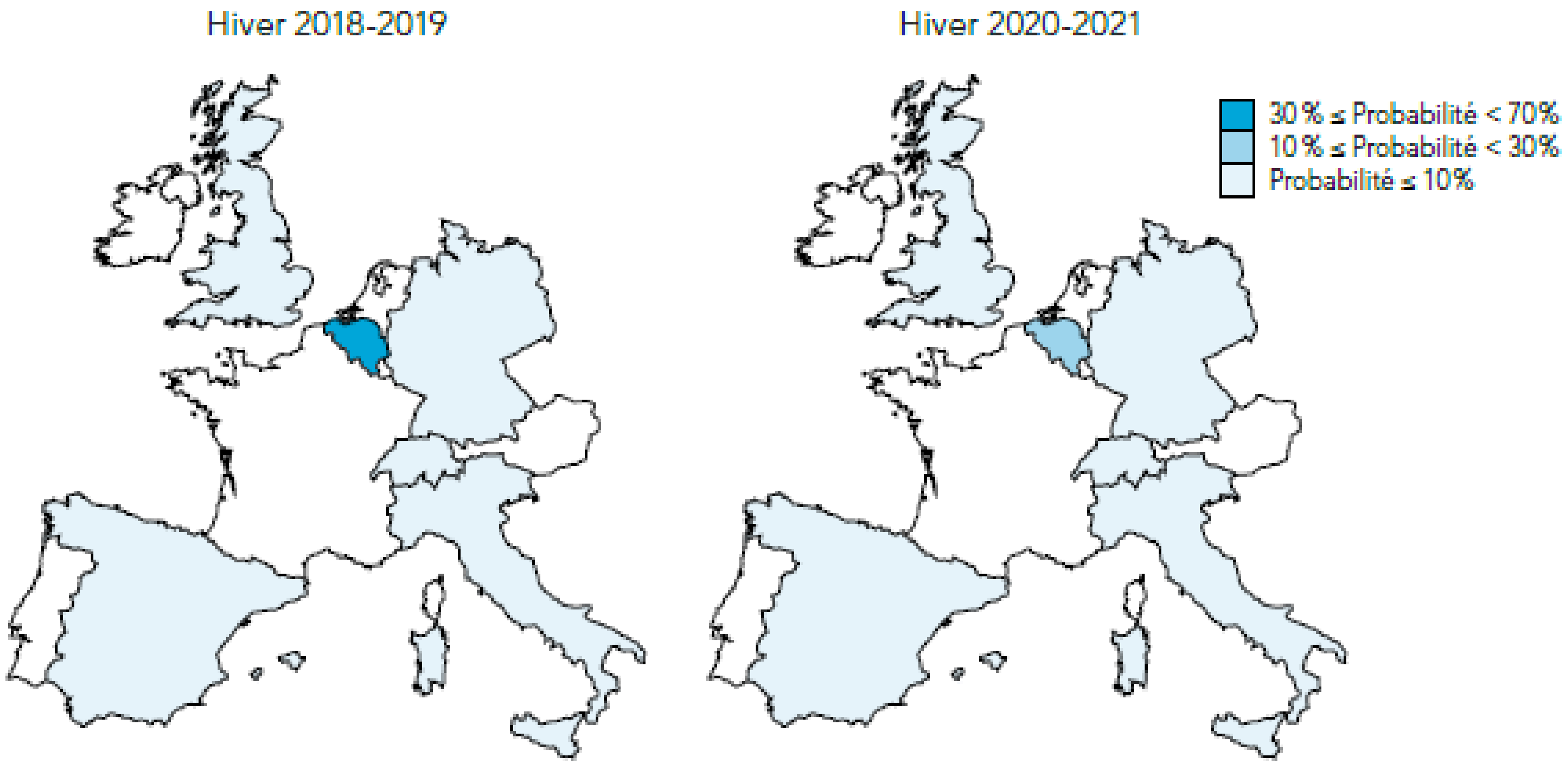
European scale analysis: adequacy

- Adequacy issues at the European level:
  - France cannot ensure adequacy without imports.
  - Impact of the German shutdown of nuclear power plant on their neighbours.
  - The lack of generation capacity in Belgium for the winter 2014-2015.
- ENTSO-E (European Network of Transmission System Operators for Electricity) produces an adequacy report in the TYNDP (Ten Year Network Development Plan).

https://www.entsoe.eu/publications/system-development-reports/adequacy-forecasts/Pages/default.aspx

Adequacy: who can "help" France in case of curtailment?



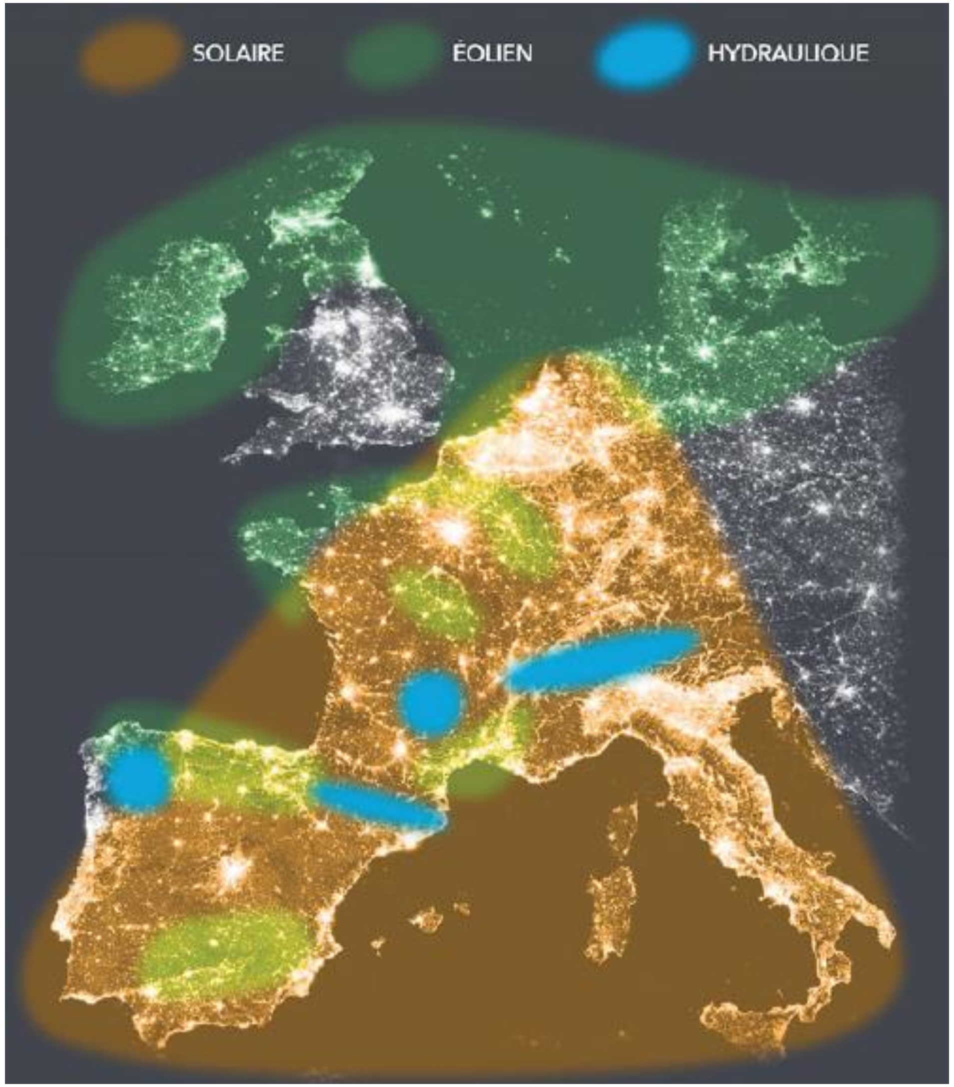
Probability of simultaneous curtailement (BP 2016)

European scale analysis

Today:

Tomorrow:

Complementary generation mixes



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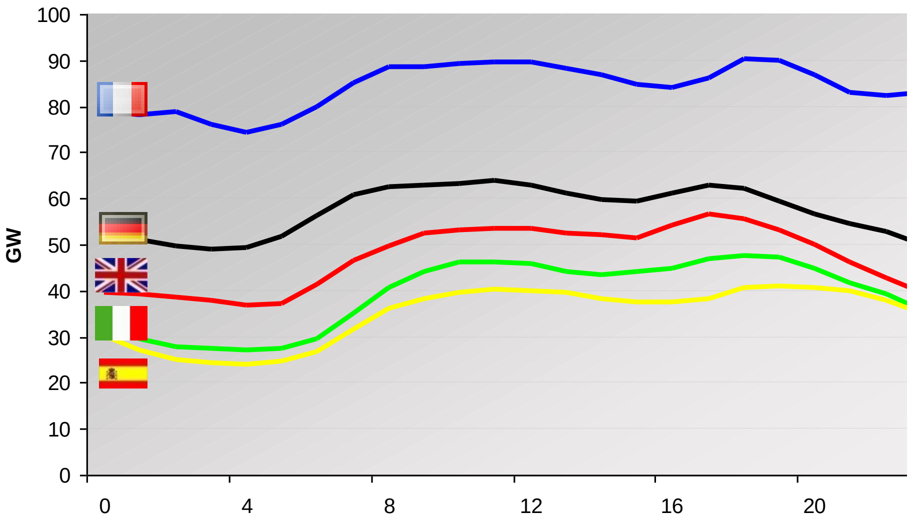
European scale analysis: economics

Heterogeneous consumption curves

- Daily winter day variation



- Annual variation

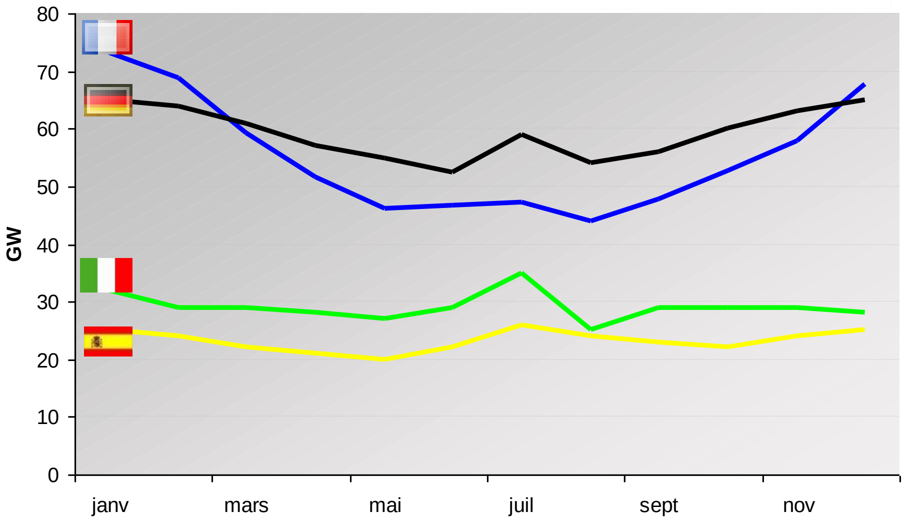


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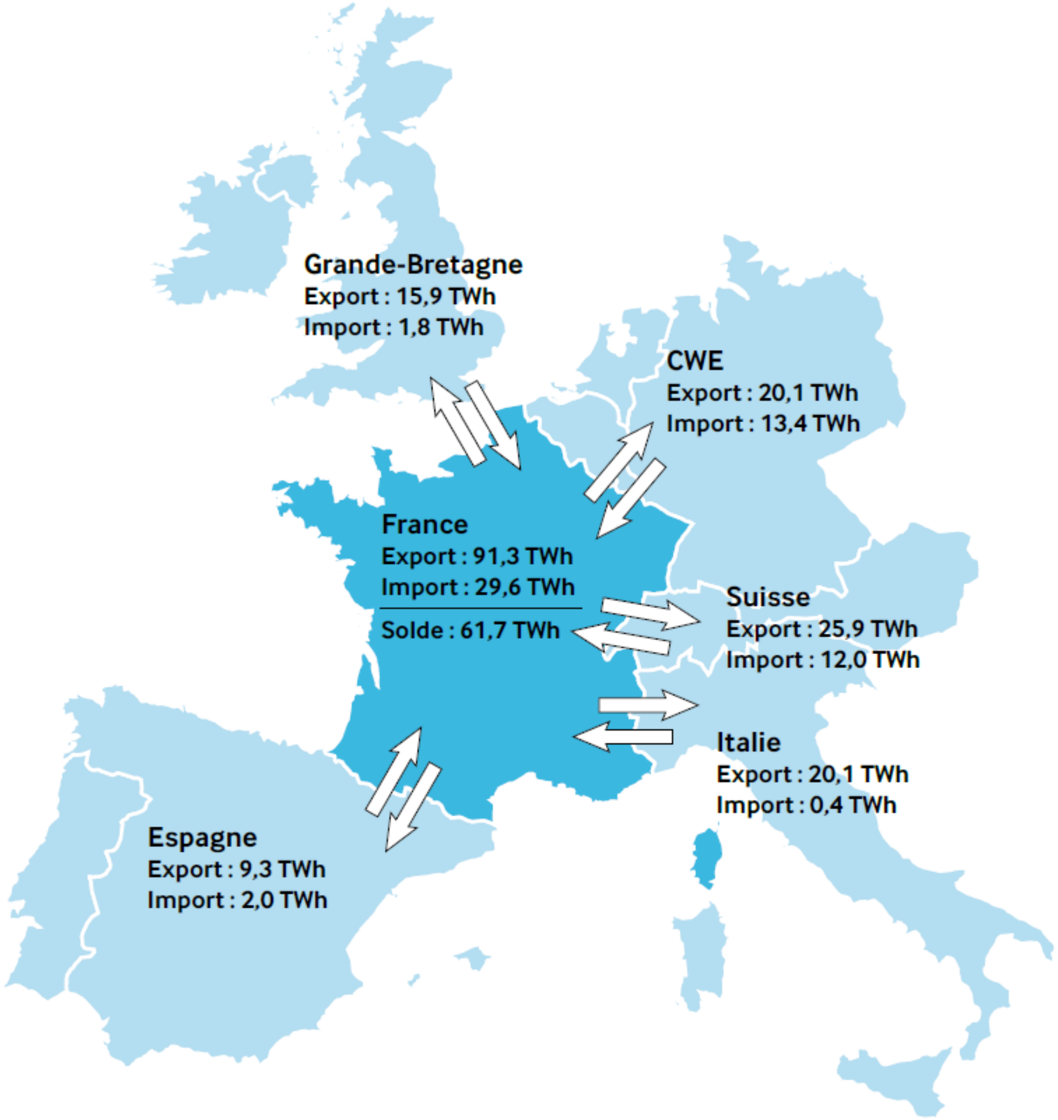
Illustration with France



(RTE BP 2015)

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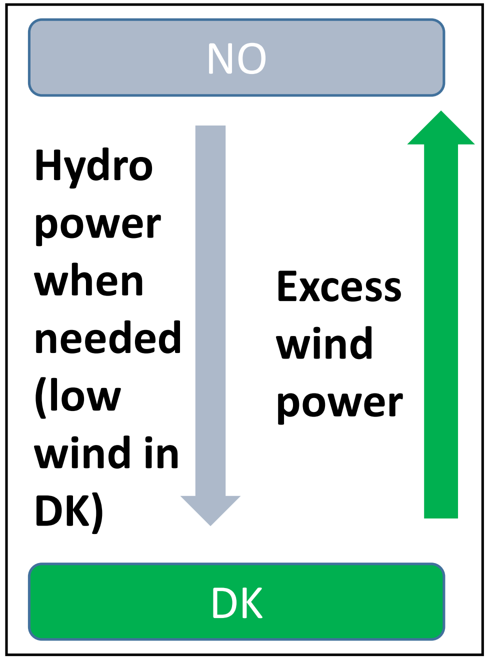
Interconnections: use cases
Exchanging power between DK and NO



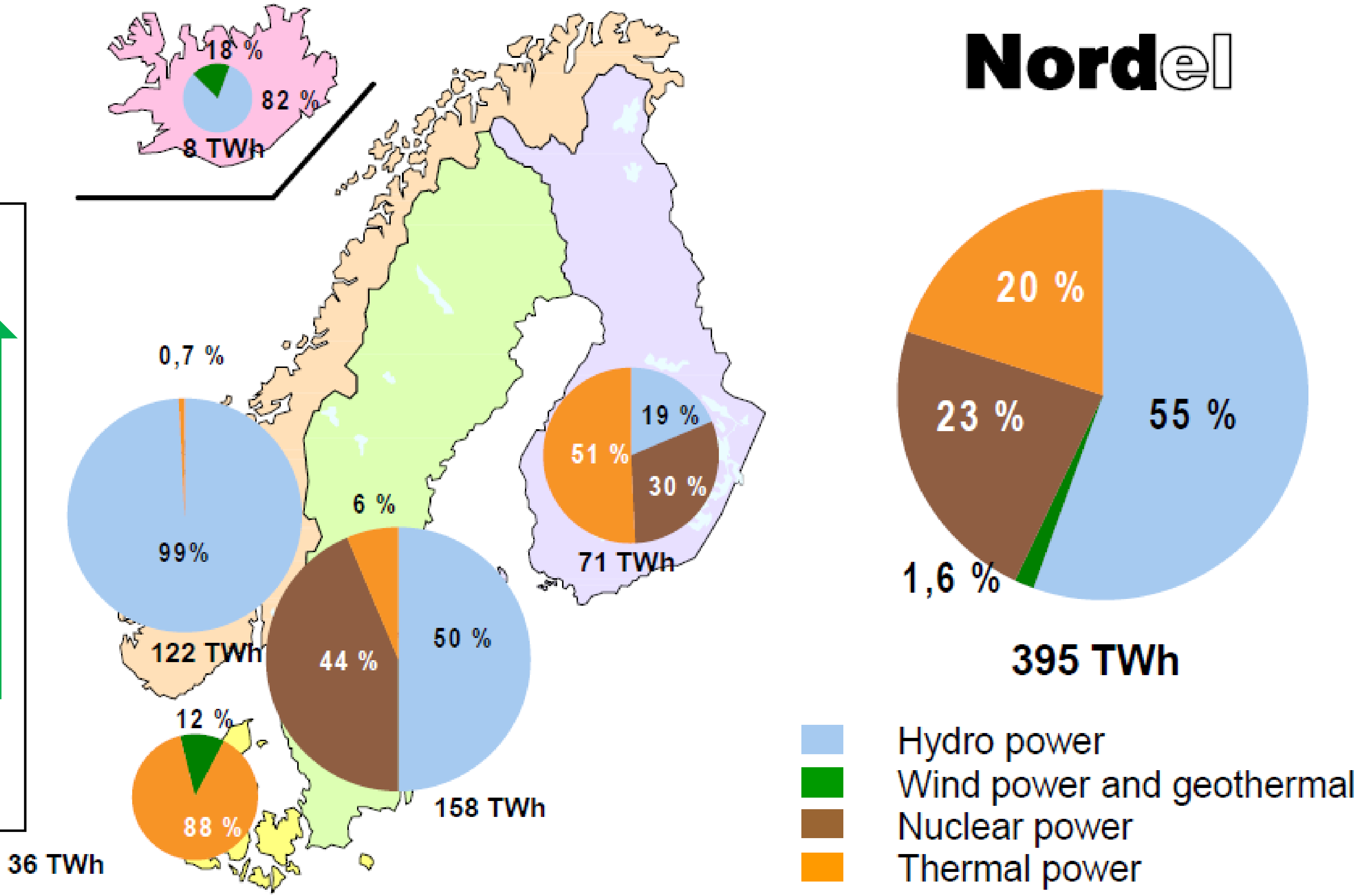
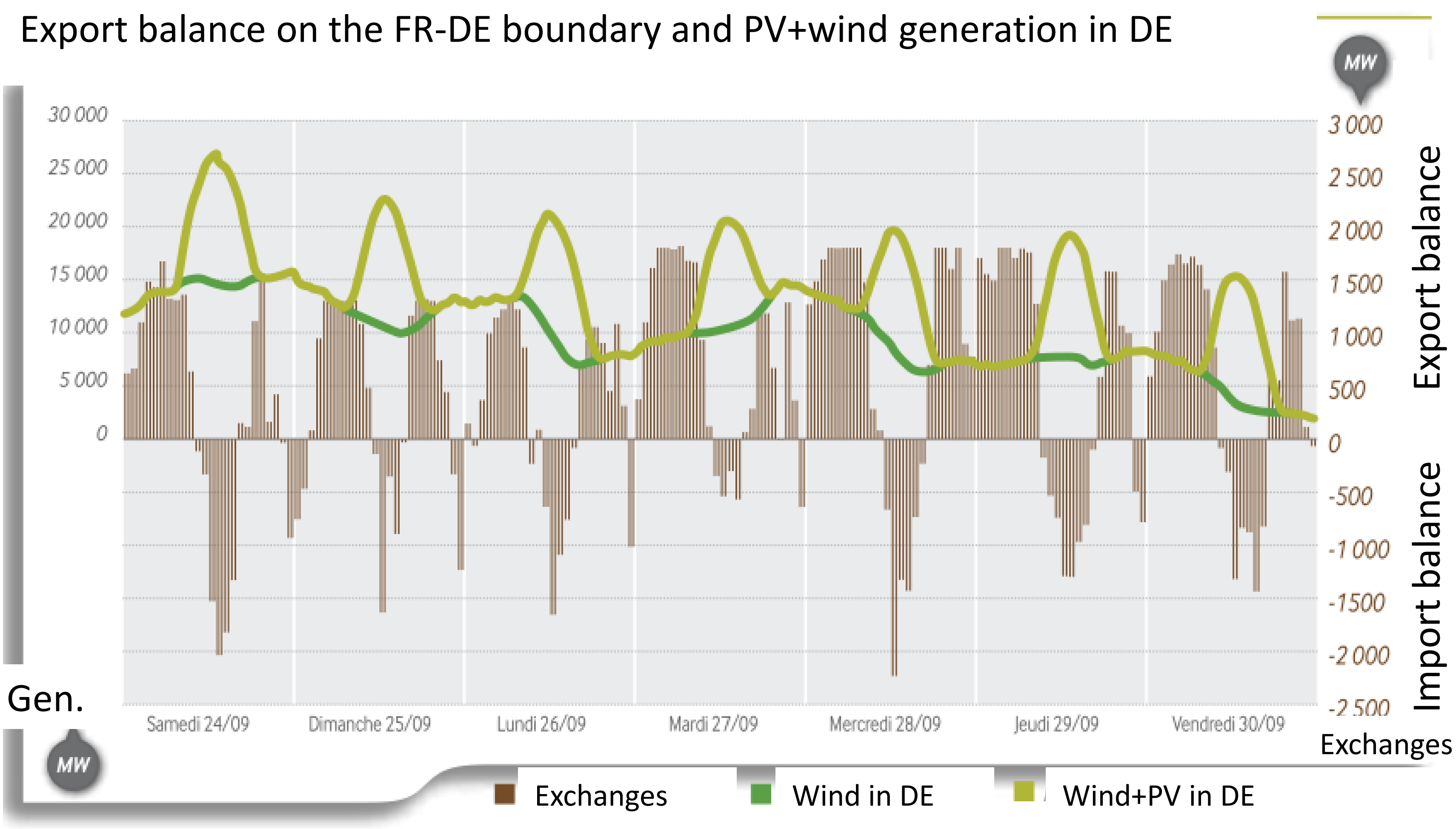


Figure 2. Electricity production in the Nordic countries in 2001. Installed power plant capacity is about 90 GW. (Source: Nordel/Finergy.)

Source: Holttinen 2004

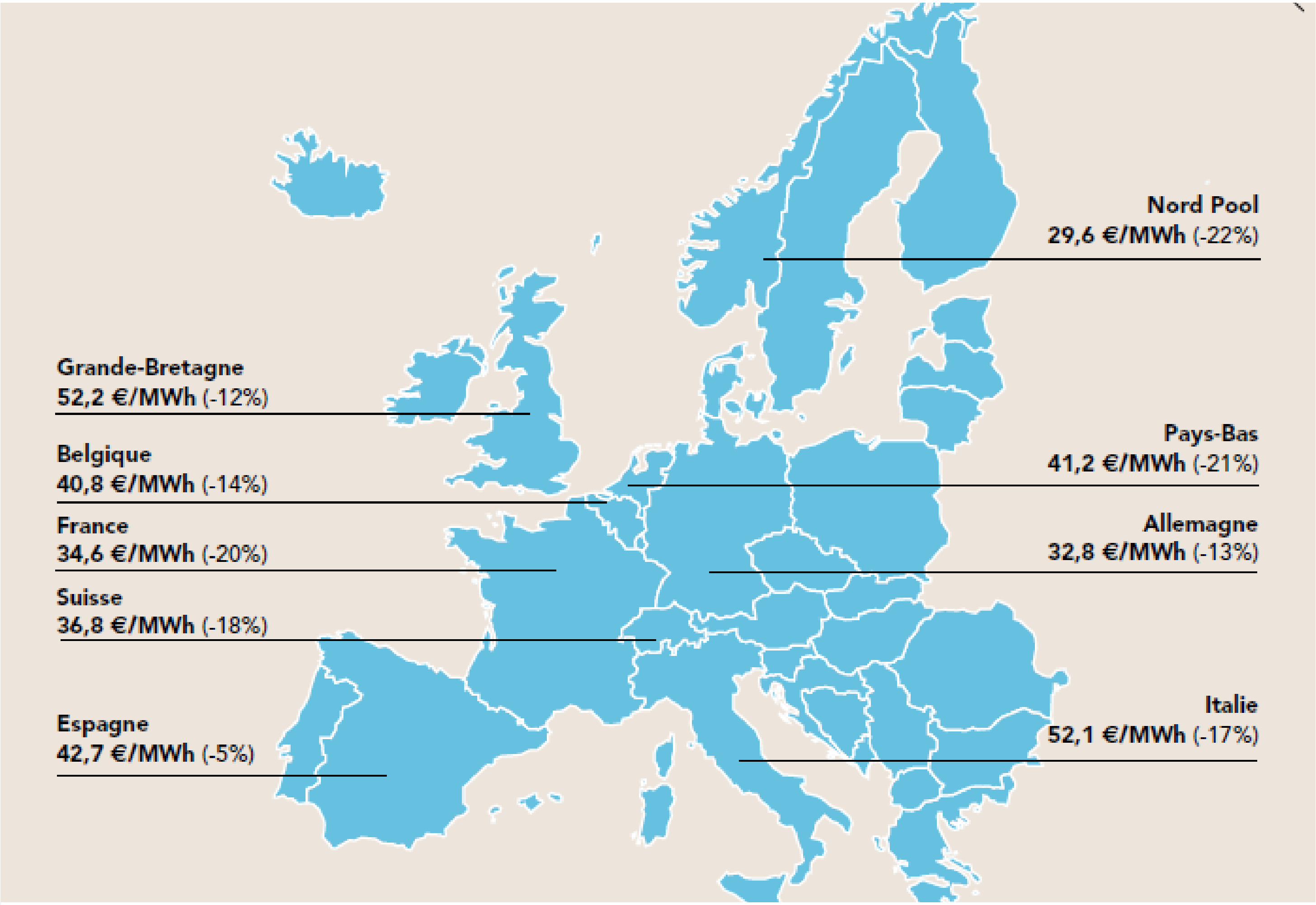
French absorption of German renewable energy



Source: RTE BP 2011

Some convergence on average prices.

Average spot prices on power exchanges in 2014 and evolution with respect to 2013



Source: european power exchanges. For NordPool: system price

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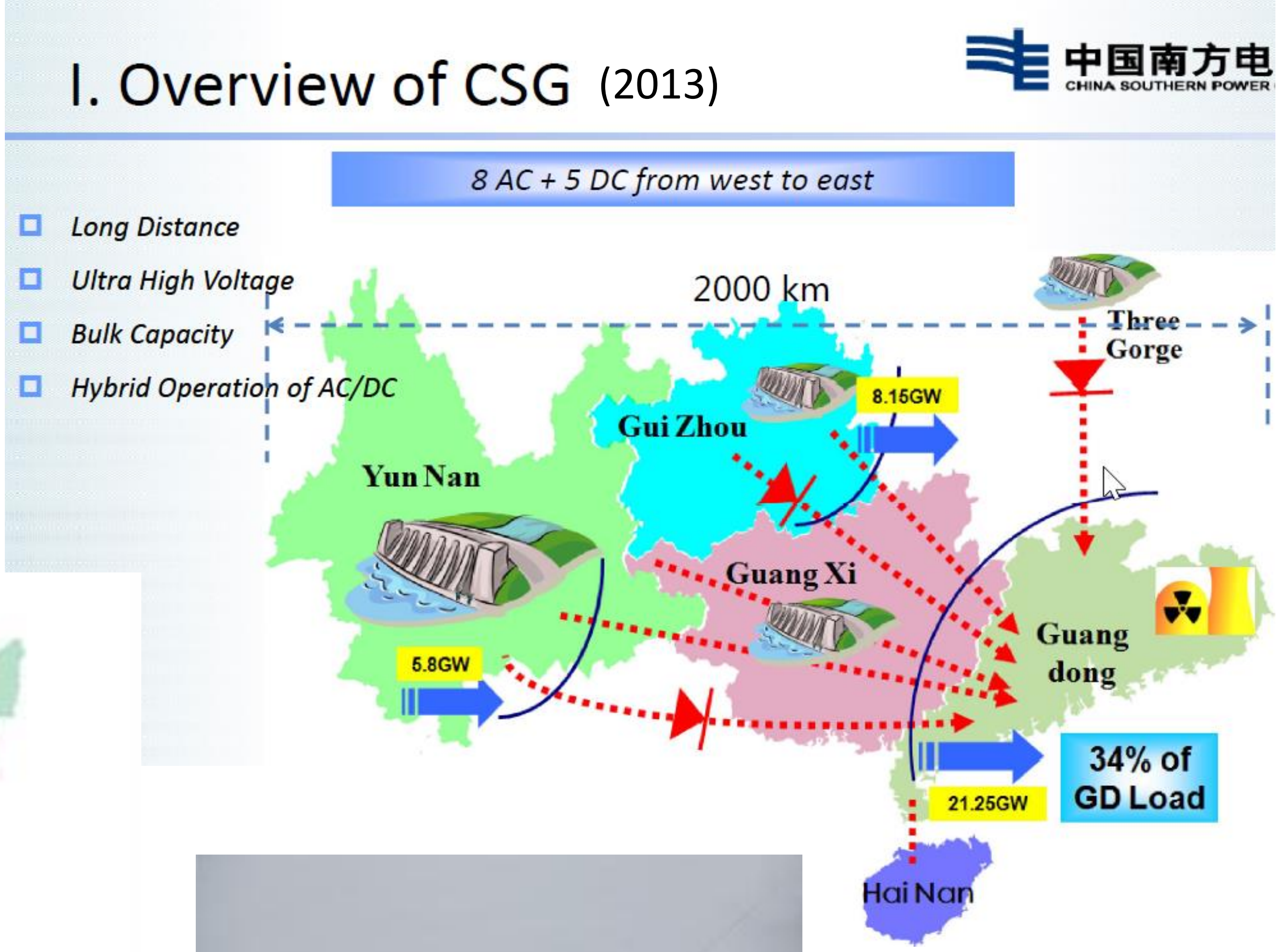
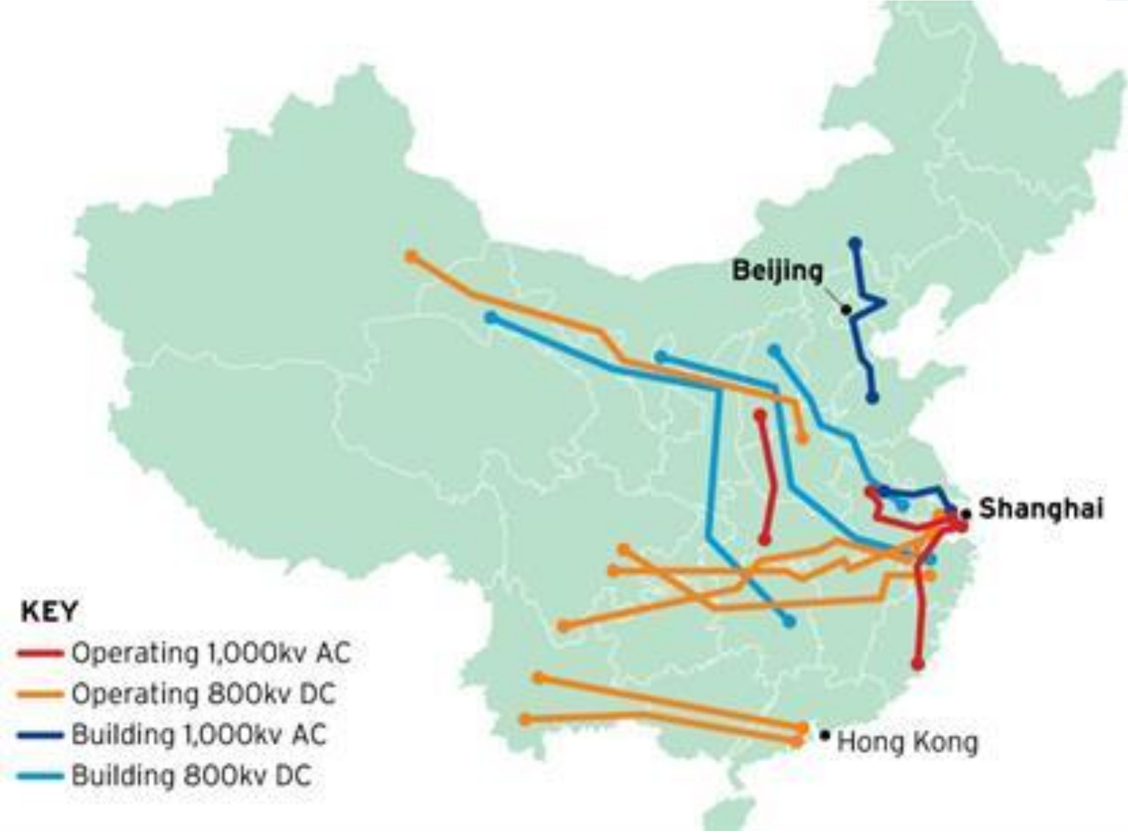
China's fast developping grid.
Where do economies of scale stop?





China’s global grid: the ultimate economies of scale?

Global Energy Interconnection
Development and Cooperation Organization
全球能源互联网发展合作组织

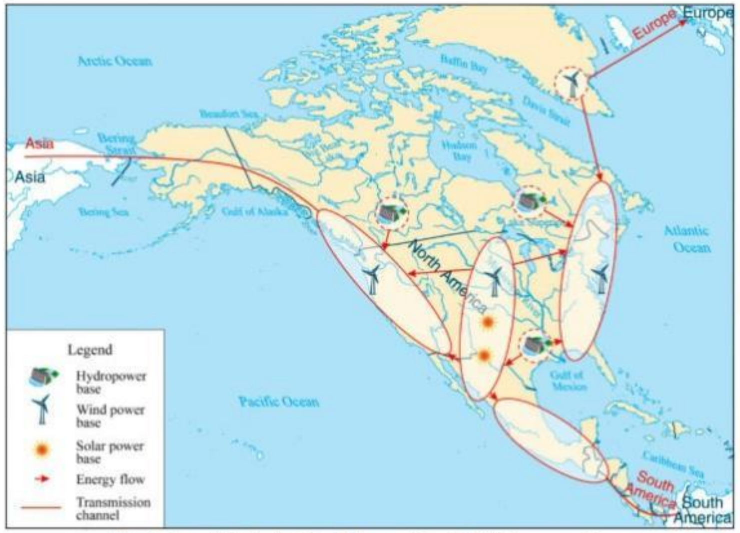


Illustration of North America's Transnational Grid Interconnections

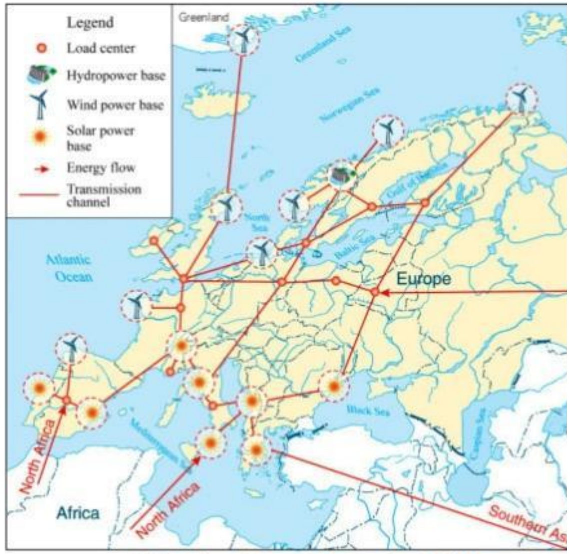


Illustration of Europe's Transnational Grid Interconnect

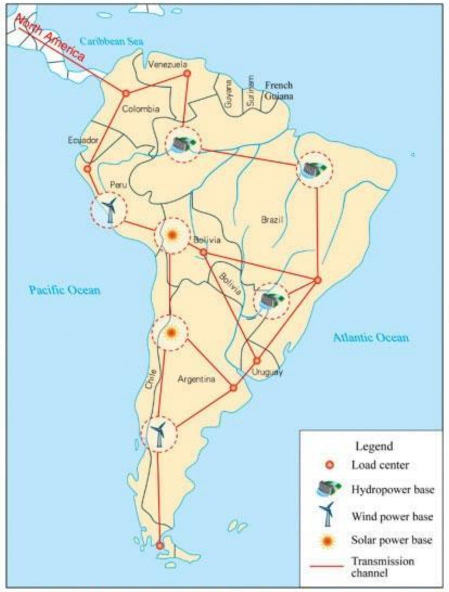


Illustration of South America's Transnational Grid Interconnections

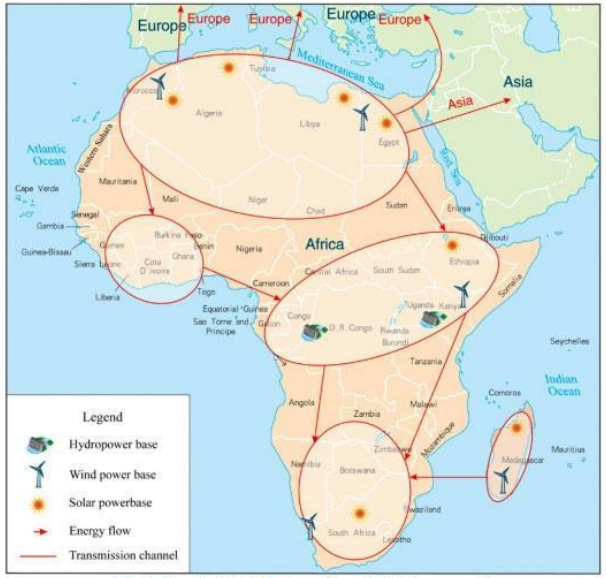


Illustration of Africa's Transnational Grid Interconnection

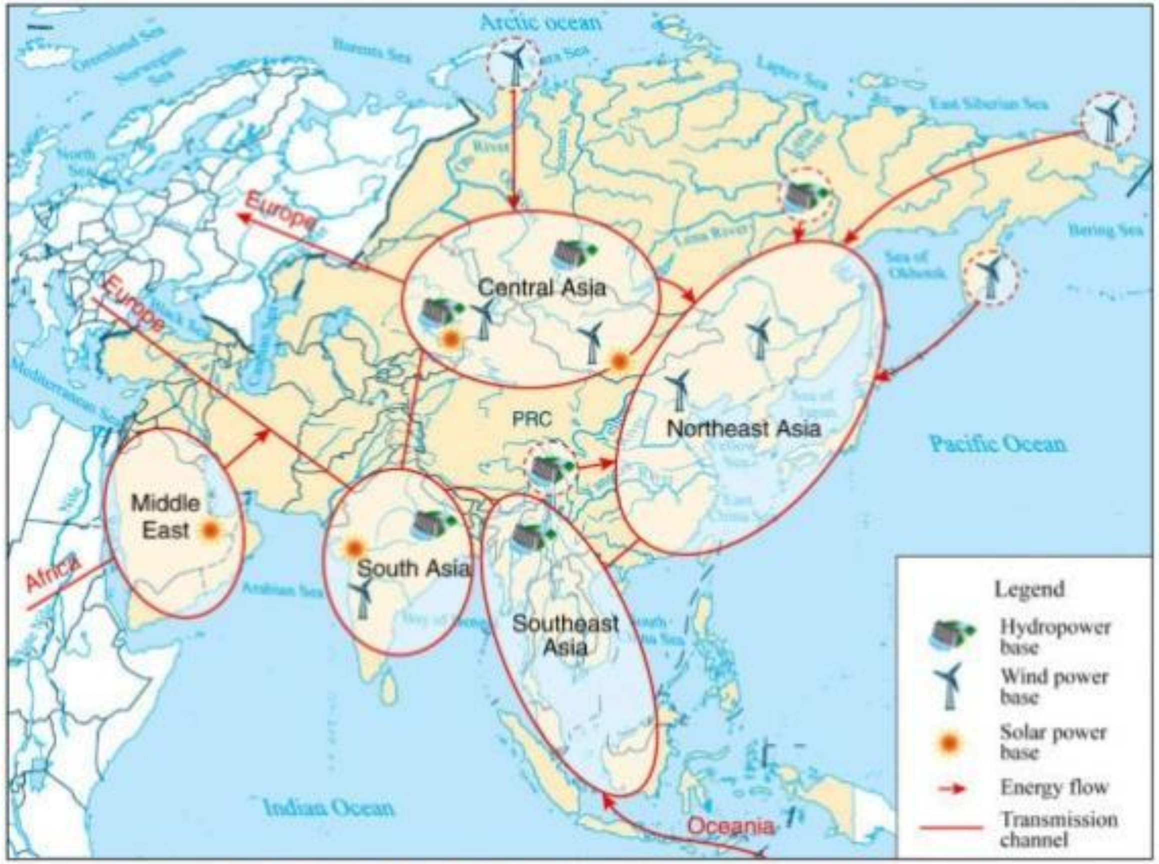


Illustration of Asia's Transnational Grid Interconnections

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