Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Frontiers in Energy Research – 28.02.2012

Université de Liège

The Global Grid

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ETH Zürich and *Université de Liège*

Towards a 100% Renewable Energy Future

- EU target: 20% RES* participation in the energy mix by 2020
- California: 33% RES* participation in the electricity mix by 2020
- EU Roadmap for 80% emissions reduction by 2050
- Studies for 100% RES* energy production

*RES: Renewable Energy Sources

Interconnecting RES increases reliability in supply

- Interconnection of 19 wind farms in Midwest-US
- Area of 850 x 850 km

- “On average, 33% of yearly averaged wind power can be used with the same reliability as a conventional power plant.” (Archer and Jacobson, 2007)

Cheap RES production over long transmission lines and Supergrids

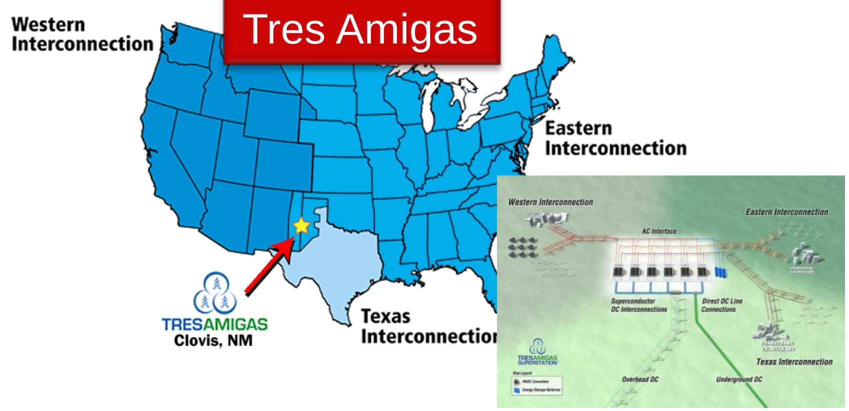
Desertec

North-Sea Grid

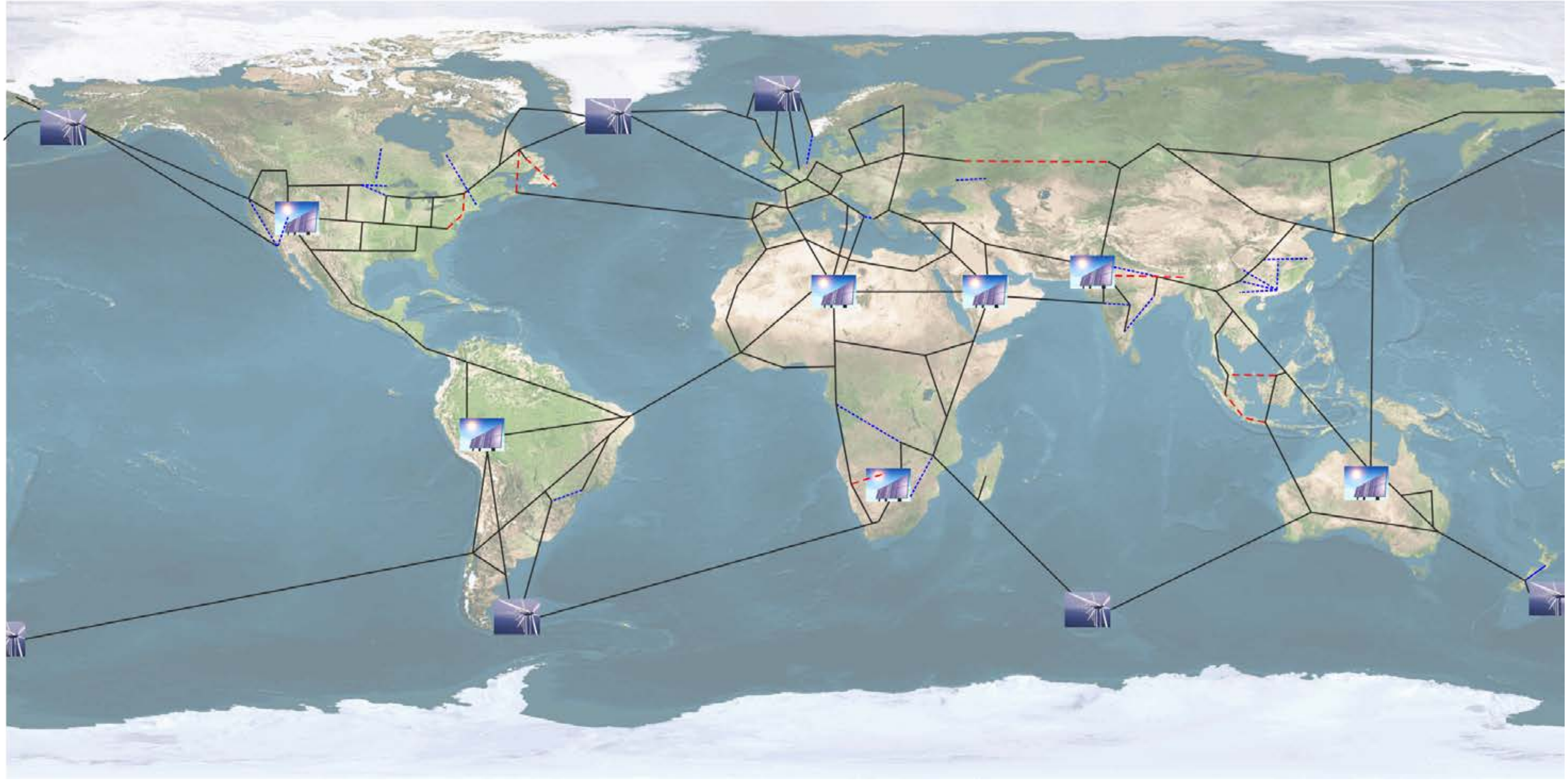
Offshore grid scenario 3: Wind-driven approach (blue = changes to base case, red = existing, pink = under construction, green = planned)

«Google» Project

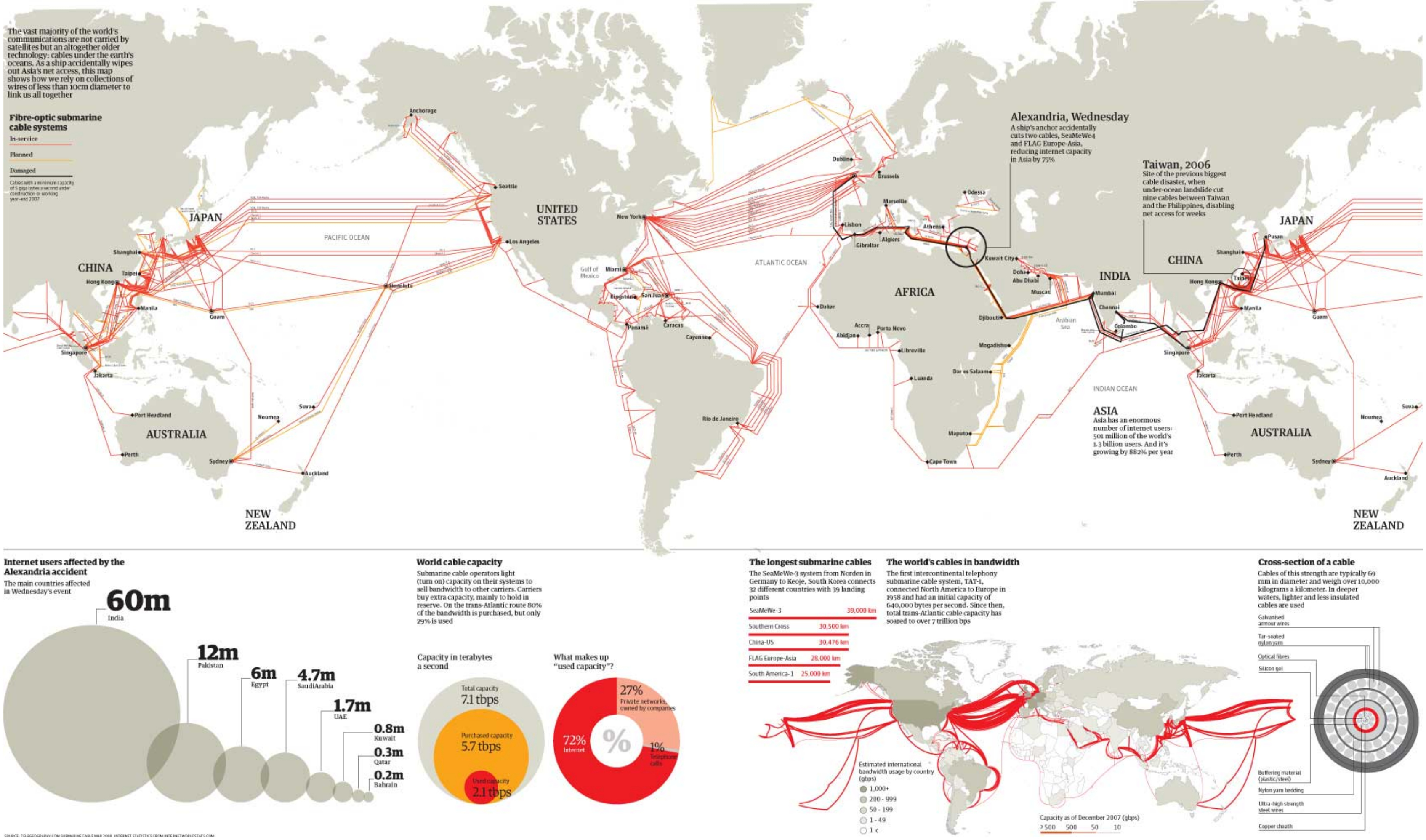
Tres Amigas



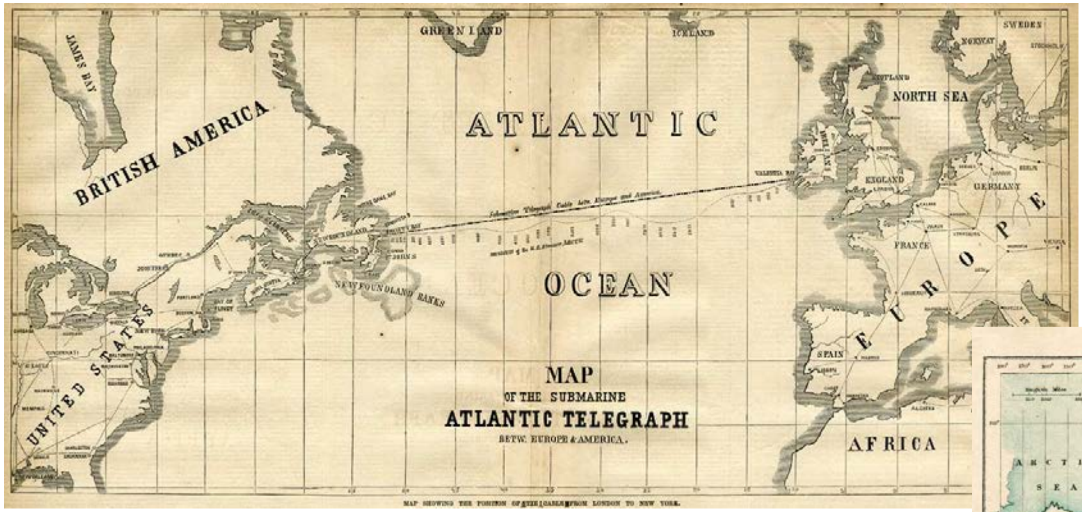
The Global Grid



The internet's undersea world

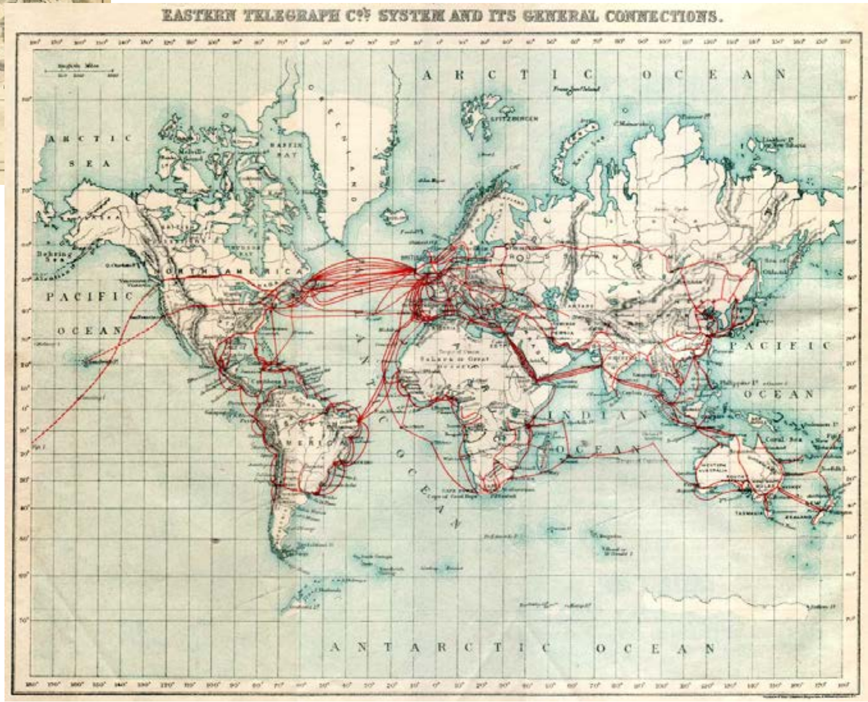


Telegraph 1866-1901



1866: First successful submarine cable

1901: Global Telegraphy Network



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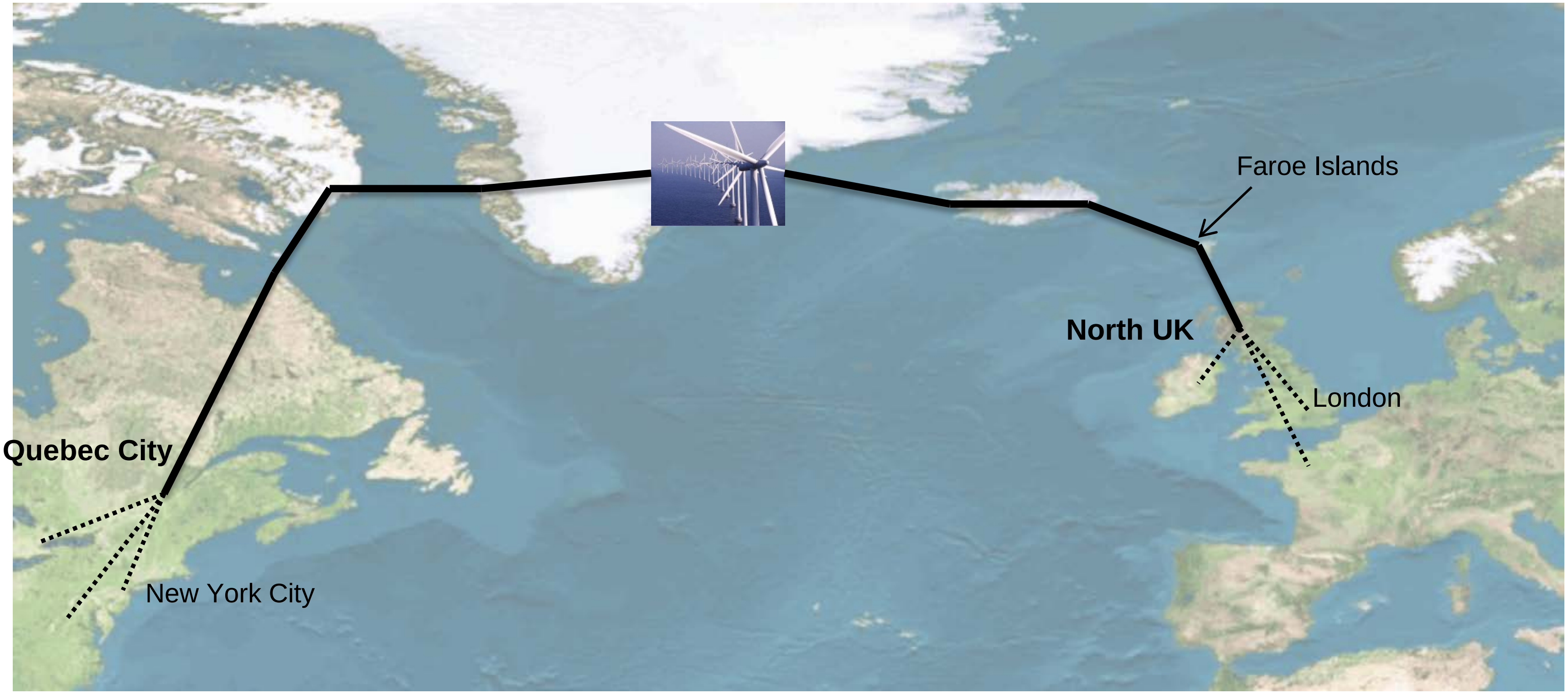
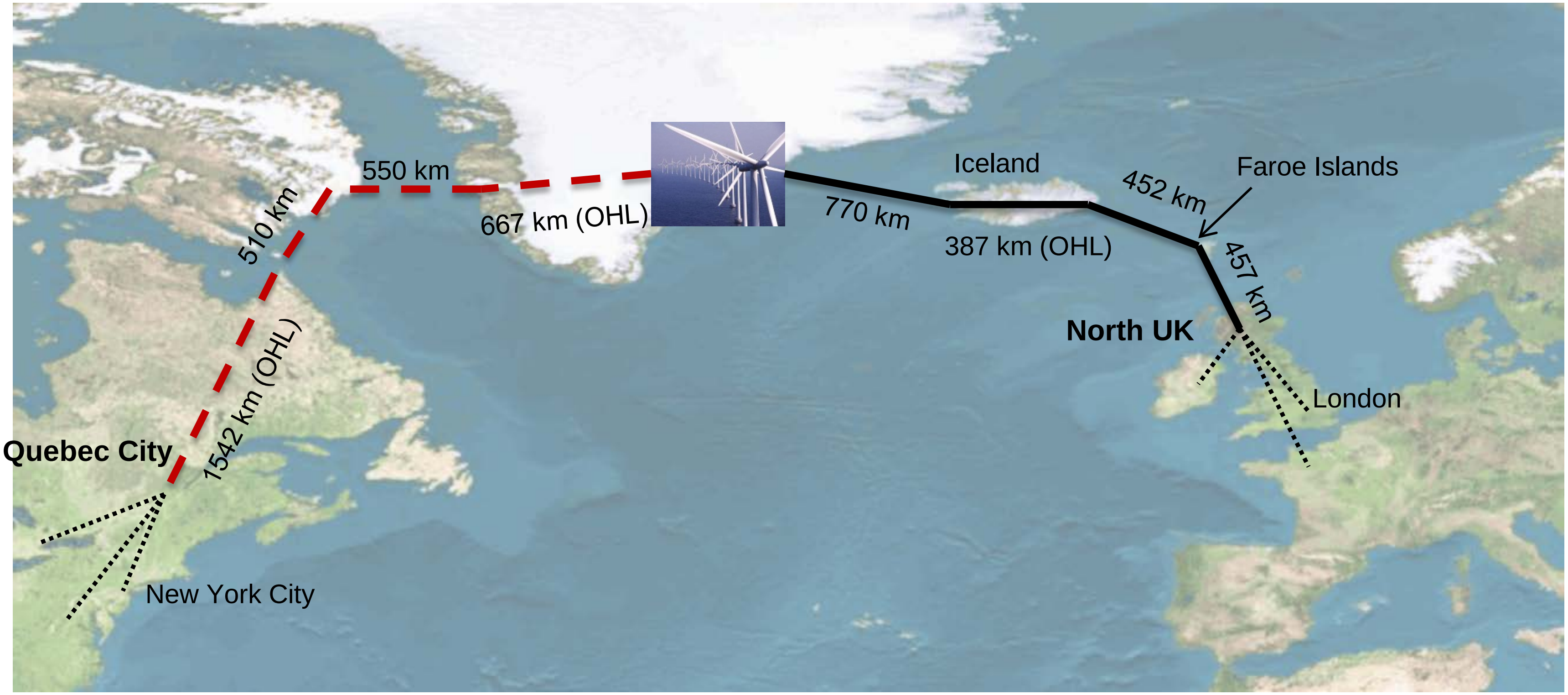
A Possible First Step: Wind Farm in Greenland

- High winds ~9.0 m/s
- Shallow waters



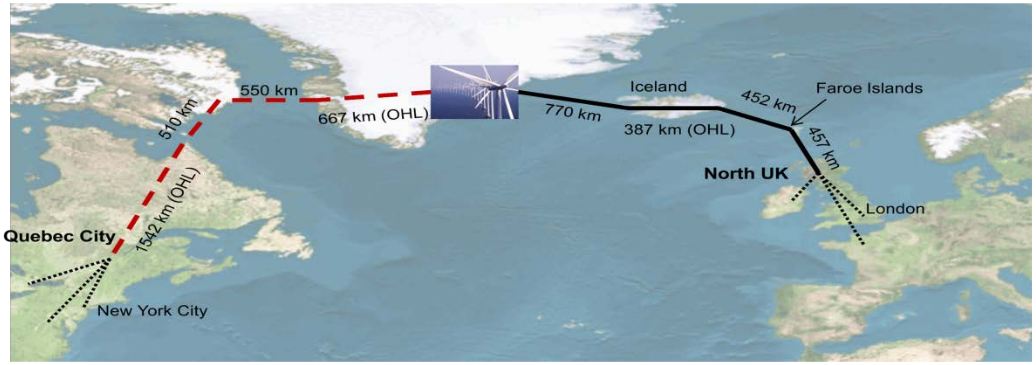
- Sell wind power always at peak prices
- Trade electricity with the remaining line capacity

Wind Farm in Greenland



- Greenland – North UK: 2066 km (81% Cable)
- Greenland – Quebec: 3269 km (32% Cable)

Wind Farm in Greenland (3 GW)

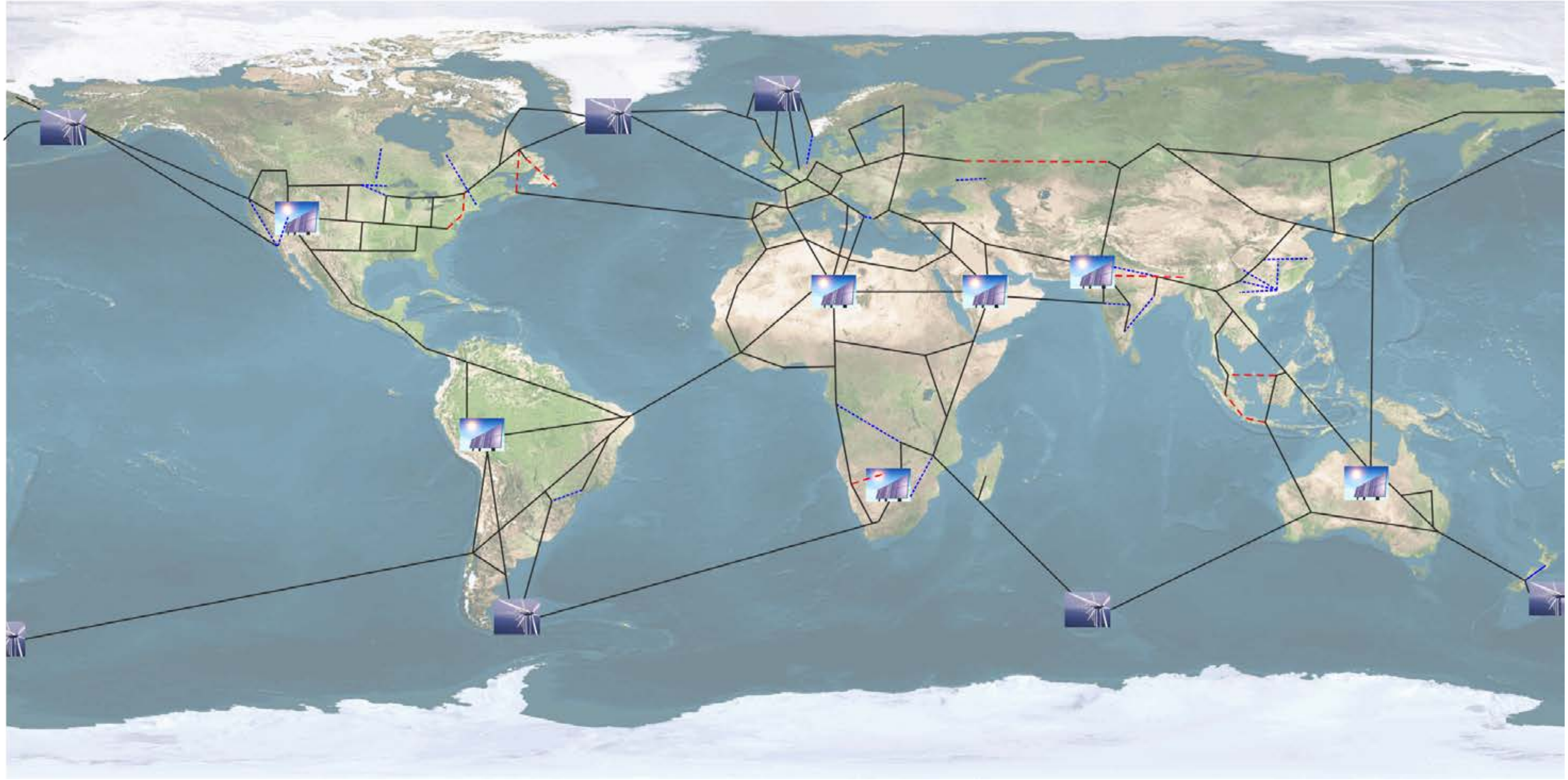


	Greenland-UK	Both to North America and the UK	
		Greenland-UK	Greenland-North America
Line Energy Capacity		~20'000 GWh/year	
Delivered Energy	9'600 GWh/year	4'800 GWh/year	4'600 GWh/year
Transmission Cost	1.3-1.9 cent €/kWh	2.9-3.8 cent €/kWh (if only wind)	
Wind Farm Cost (2020)	6.0 cent €/kWh		
Cost Increase		21-24%	
Revenues Increase	***Sell at peak price****	31-33%	
	Electricity Trade	~10'000 GWh/year available	

>31-33%

*Assumption: off-peak-price/peak-price = 50%

The Global Grid



“Extreme RES”

- Equivalent to “Extreme Oil” = extraction of oil through unconventional oil fields or processes

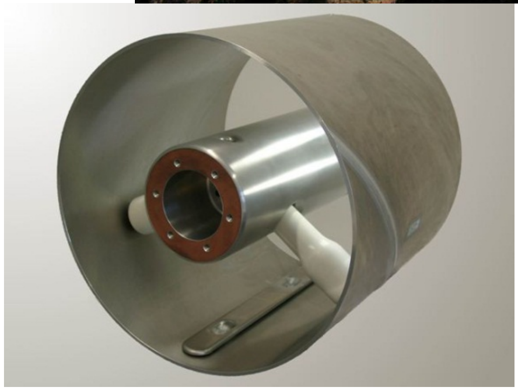
- RES power plants where the installation is more difficult than in current locations or the technology is not yet mature

  - E.g. Hywind:
    floating wind turbine for deeper sea levels

Global Grid Transmission

- Ultra High Voltage AC
- High Voltage Direct Current (HVDC)
- Gas-Insulated Lines

- Most Probable: HVDC
  - Less thermal losses
  - No need for reactive compensation
  - Can connect asynchronous networks



OUTLINE

1. Concept
2. **Opportunities**
3. Investments
4. Operation
5. Challenges
6. Alternatives to the Global Grid
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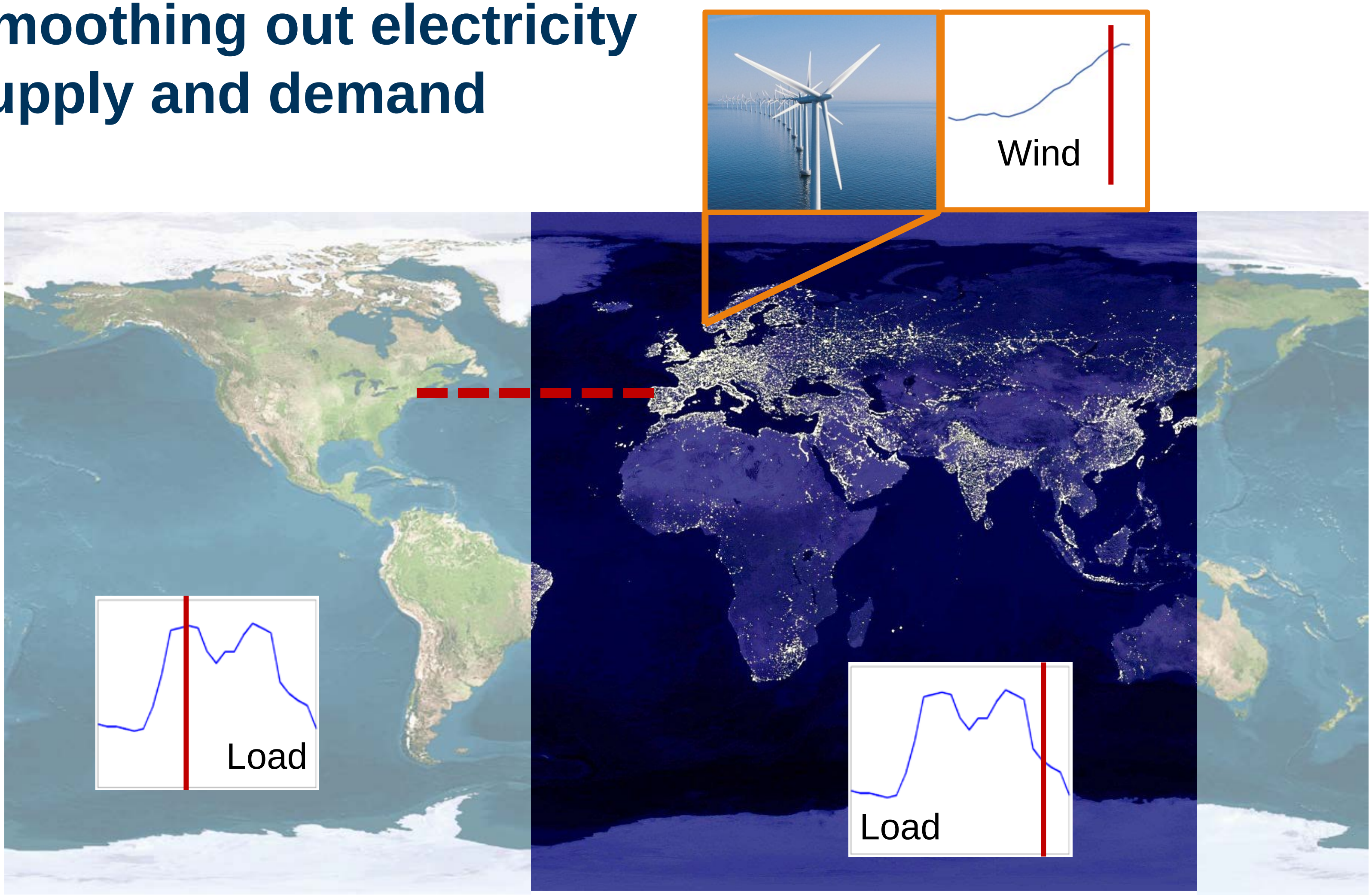
Smoothing out electricity supply and demand



- Oporto → New York : 5334 km
- Oporto → Halifax : 4338 km

- 5’500 km , 3 GW submarine cable
  - Low Cost: $0.023 per delivered kWh
  - High Cost: $0.035 per delivered kWh

- RES Cost in 2020*
  - below $0.04 up to $0.13 per delivered KWh

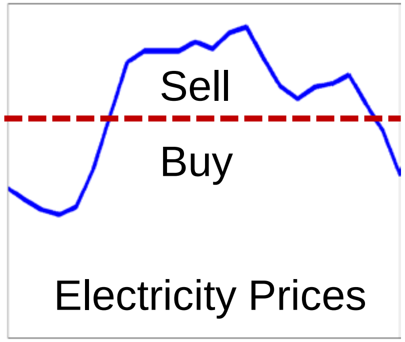
- Conventional plant cost in 2020 in the US*
  - $0.08/kWh, with the social costs: $0.14/kWh

- Except for the most expensive RES generators, it is more economical for the US to import RES power from Europe that operate its own conventional power plants

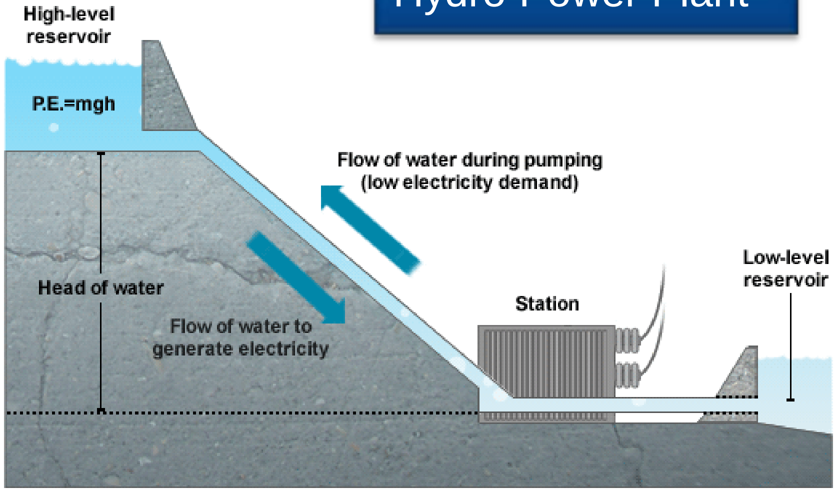
*Delucchi and Jacobson, 2010

Alleviate the need for bulk storage

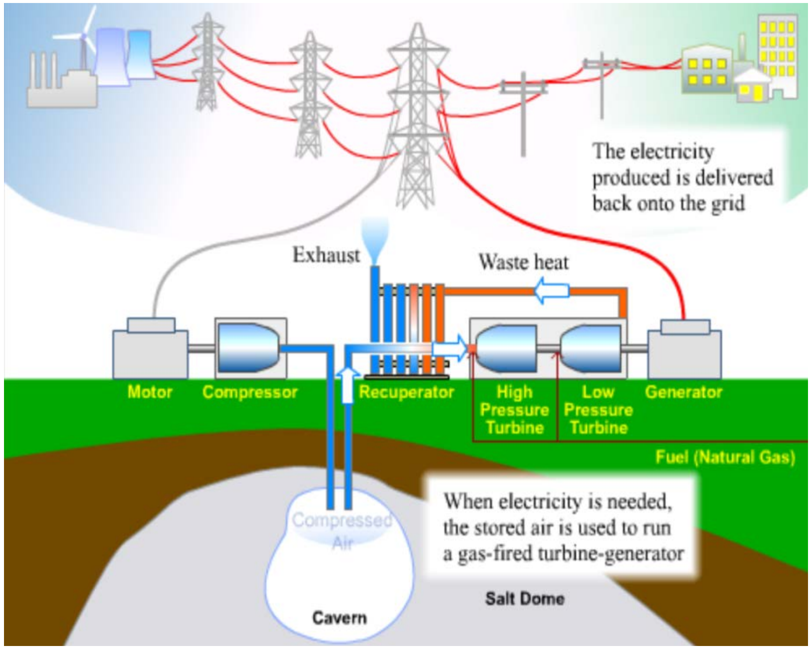
- Storage necessary to absorb non-transmissible power and relieve congestion
- HVDC interconnections can serve equally well such purposes and may further allow the exploitation of untapped storage potential in remote locations
- Bulk storage: Pump-storage power plants, Compressed-Air Energy Storage
- [Redox-Flow Batteries], [Hydrogen]
  - High costs
  - Hydrogen – Fuel Cell: limited efficiency at the moment



Pumped-Storage Hydro Power Plant



Compressed-Air Energy Storage

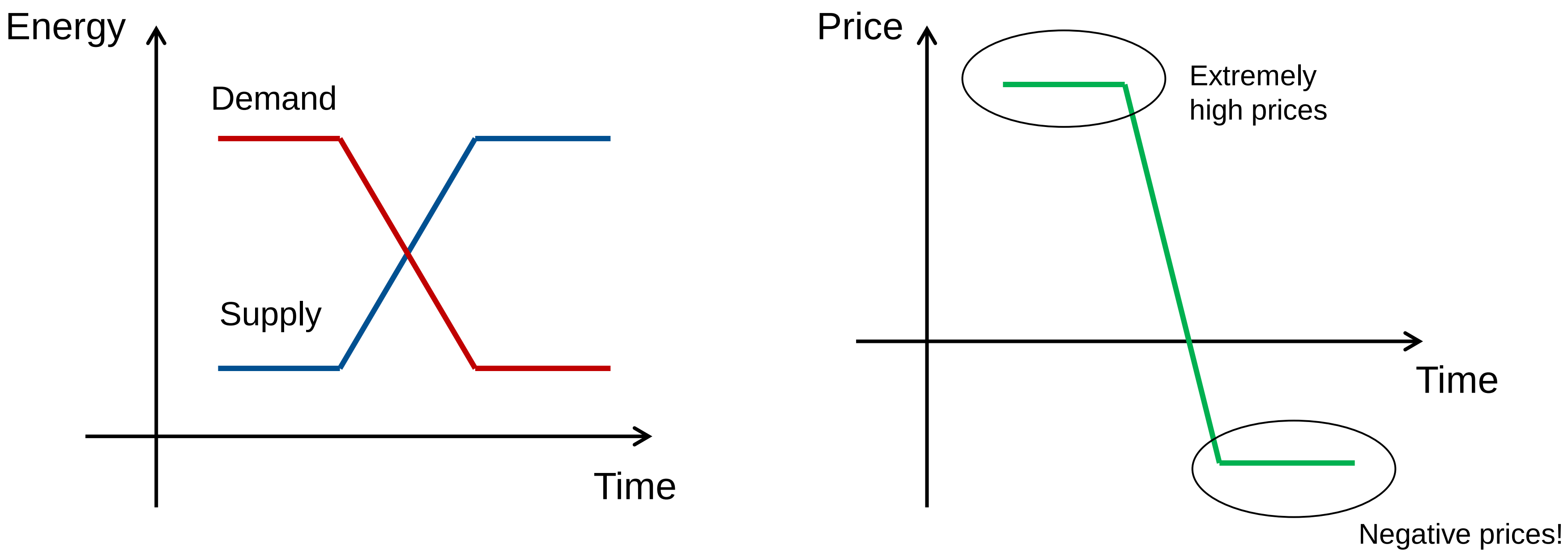


Alleviate the need for bulk storage

- Pump-storage hydro power plants (PHP), Compressed-Air Energy Storage (CAES)
  - Limited availability of appropriate locations
  - PHP: ~76%, CAES: ~50-70%
  - Very long HVDC lines have better efficiency (e.g. 6'000 km ~81%)
  - *But, PHP and CAES cost less*

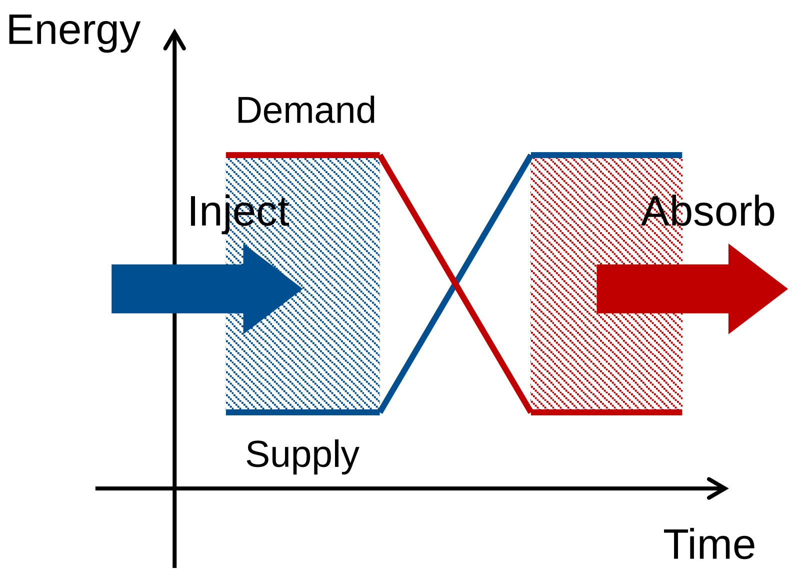
- For cost comparisons, need to consider:
  - HVDC does not need to replenish energy → "unlimited" capacity
  - HVDC can offer energy in both directions
  - Studies show that even with storage, network reinforcements are necessary → synergies can arise

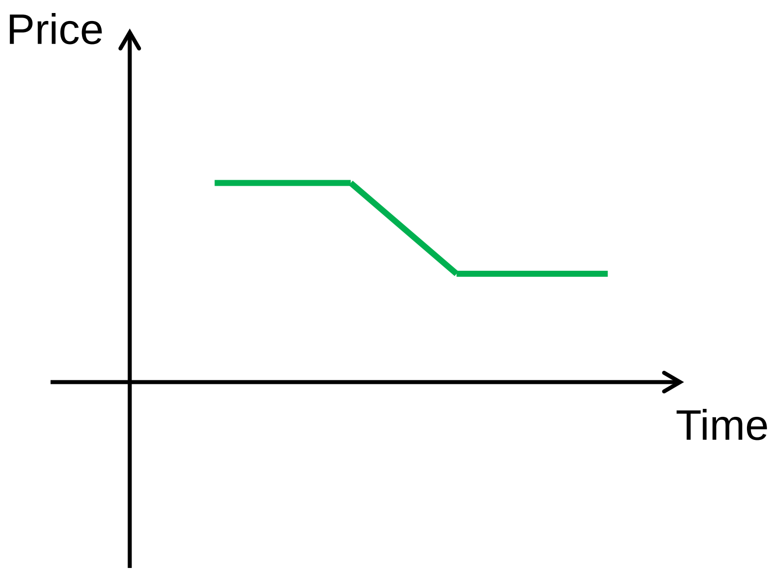
Reduce the volatility of the electricity prices



- RES integration increases the uncertainty in the supply curve → increase in price volatility

Reduce the volatility of the electricity prices

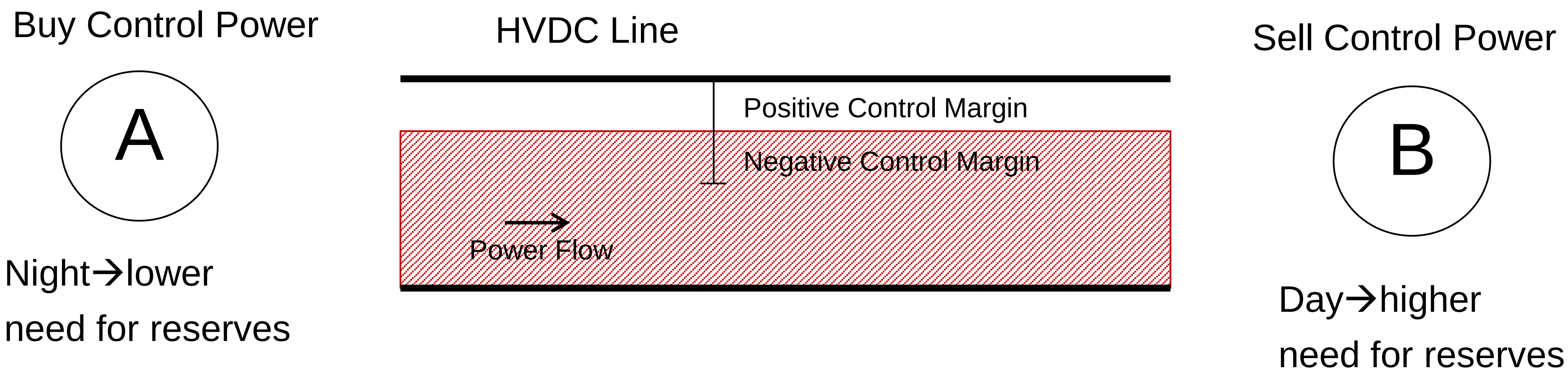




- Global interconnections can mitigate price volatility by injecting or absorbing power, when necessary

Minimize power reserves

- Power reserves: necessary to balance supply and demand and deal with contingencies
- With increased RES integration, the amount of necessary power reserves will increase



- Global interconnections can offer such services
  - Additional benefit: more efficient use of the available capacity in the regional system

Additional Benefits

- Enhance power systems security
- Deliver the power directly to the load centers (less losses)
- Enhance security of supply
- Boost developing economies and reduce their GHG emissions

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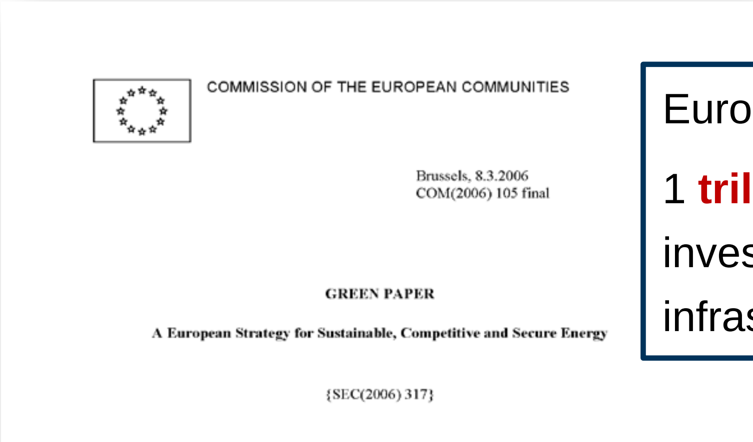
Investments

- Costs are the biggest concern for the Global Grid
- Investment costs are estimated in the range of billions of dollars for each interconnection
- *However:* this is in line with the costs of other energy infrastructure projects


COMMISSION OF THE EUROPEAN COMMUNITIES

Brussels, 8.3.2006
COM(2006) 105 final

GREEN PAPER

A European Strategy for Sustainable, Competitive and Secure Energy

{SEC(2006) 317}

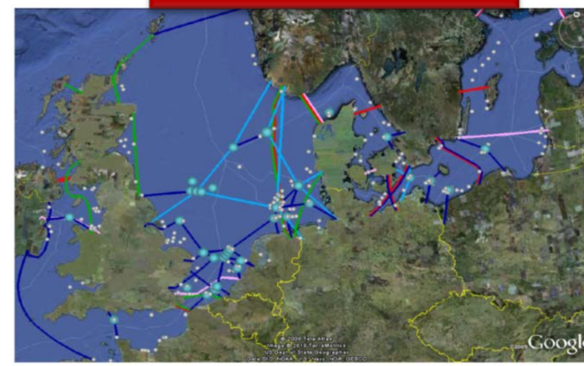
Europe:

1 **trillion** Euros in investments for energy infrastructure necessary

Google Project:
~ $5 US billion

Olkiluoto, Finland: 4th Gen. Nuclear Power Plant; *Cost: $4.1 US billion*

North-Sea Grid



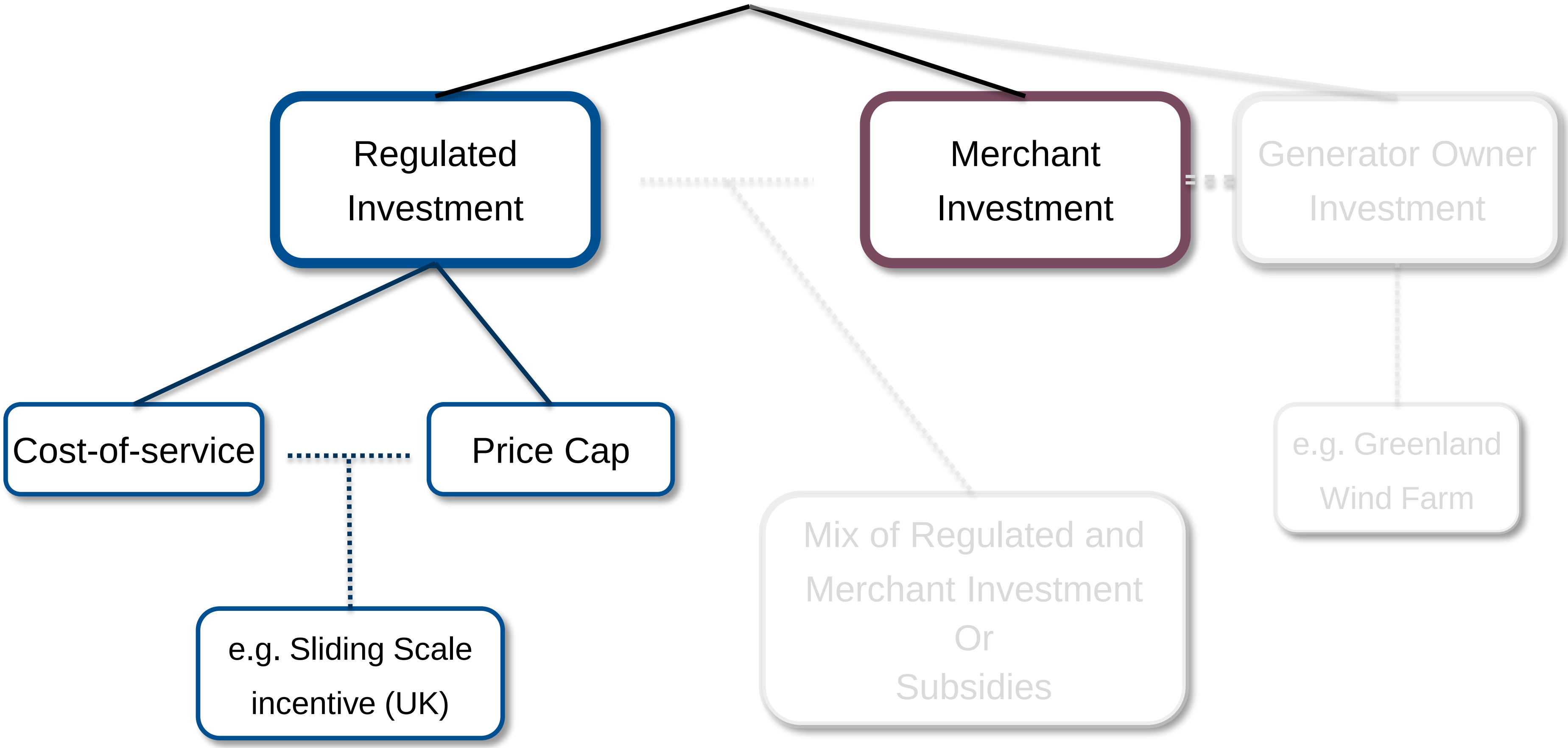
Offshore grid scenario 3: Wind-driven approach (blue = changes to base case, red = existing, pink = under construction, green = planned)

Estimated Costs:
~ €70-90 billion until 2030

NorNed Operation

- Revenues of €50 million in 2 months
- 8% of investment costs
- Equivalent to an income of
  5.6 €cent per delivered kWh
- A 5’500 km sea cable has transmission costs of 1.6-2.5 €cent per delivered kWh
- Under these conditions, income exceeds 2 to 4 times the cost

Investment Mechanisms



Regulated Investment

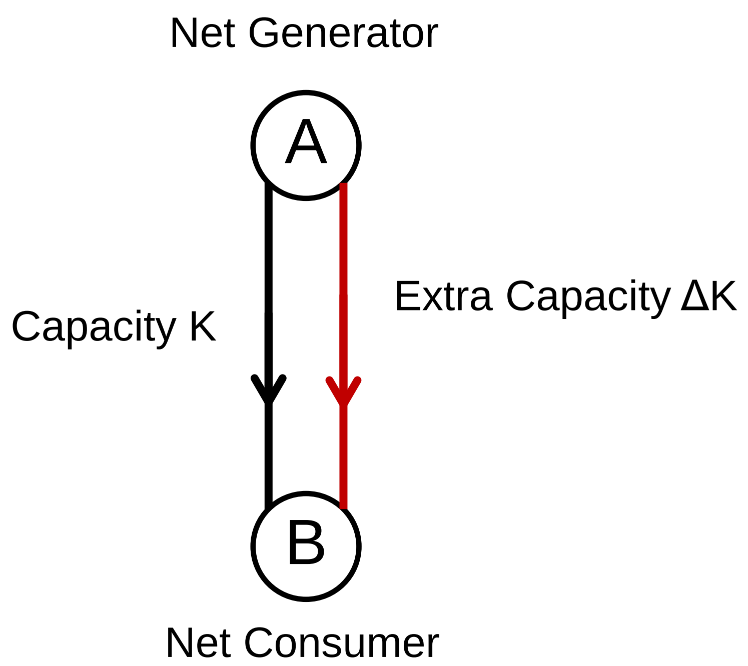
- Most common type of investment
- Until recently only TSOs and transmission owners
- EU, 2009: also third parties

- Subject to a cost-benefit analysis
- Supervised from the regulator (or ISO)

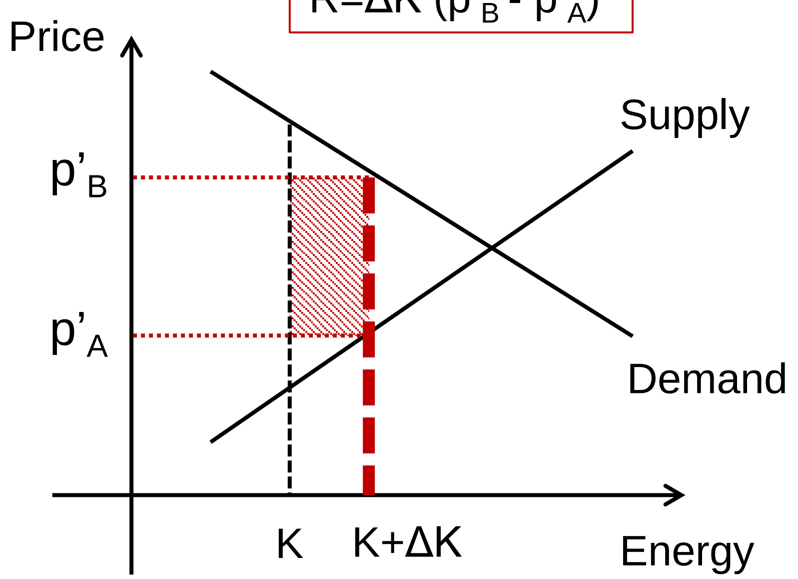
- Cost-of-service: inefficient operation, overinvestments
- Price cap: efficient operation but reduced service quality

Merchant Investment

- Not coordinated from a central authority
- Not subject to regulation
- Profits derive from electricity trade between two areas



$R=\Delta K \cdot (p'_B - p'_A)$

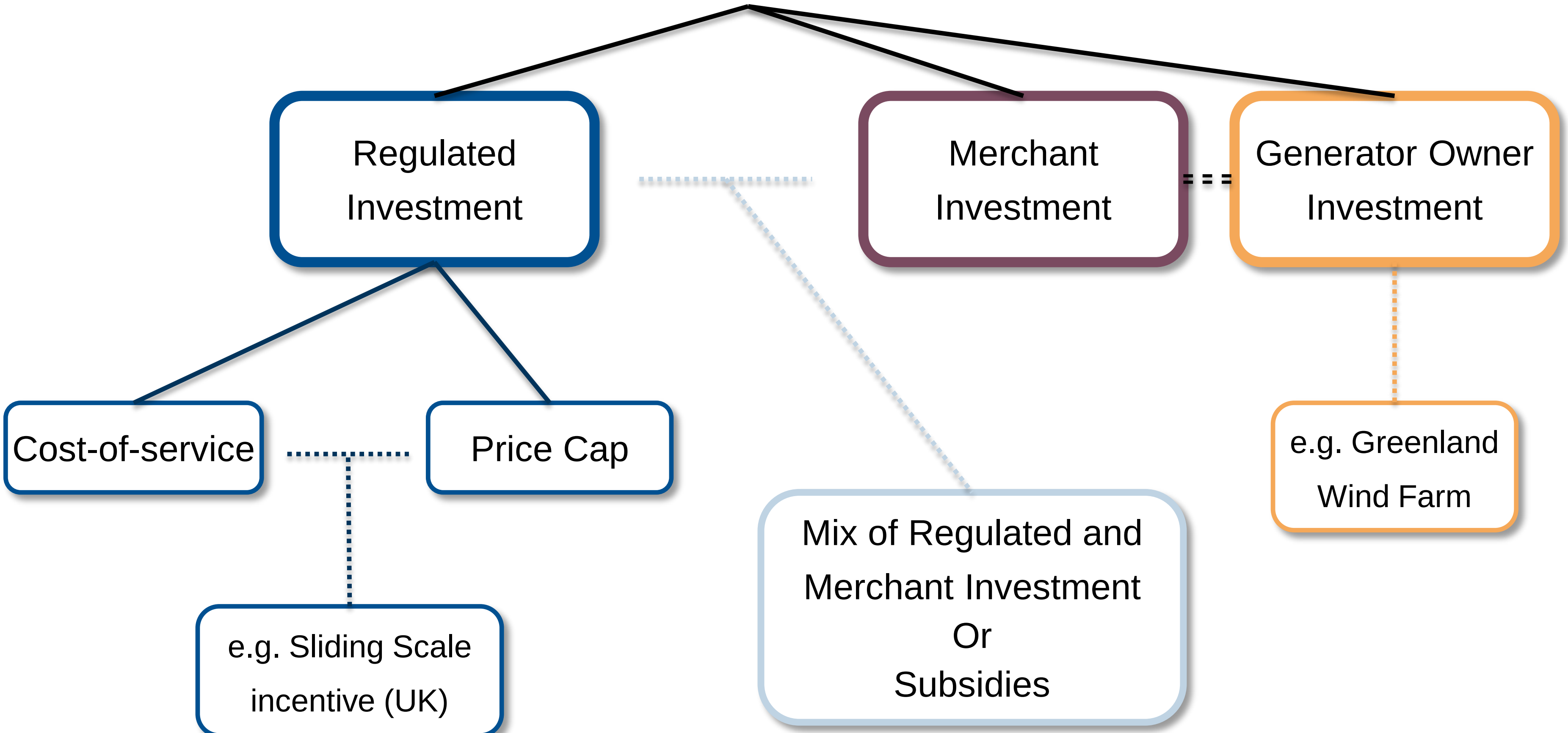


Regulated vs. Merchant Investment

- Controversy
- Both mechanisms have certain advantages and exhibit different inefficiencies

- HVDC interconnections can be eligible for both regulated and merchant investments (Brunekreeft, 2004)

Investment Mechanisms



Investments in the Global Grid

- Very long submarine cables → Regulated investment
  - Could pass the cost-benefit analysis tests
- Why not merchant investment for the very long cables?
  - Capital intensive: high risk for private investors
  - Possibly small profit margin: unattractive investment
  - In a second phase, with decreasing HVDC costs, also merchant investments
- Interconnections up to 2'000 km → Merchant investment
  - Benefit from the global interconnections
  - Facilitate the expansion of the global grid
- Generator-owner investments or subsidized investments also possible

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Operation

- Interconnections can increase competition within each region
- Establish competition among the lines
- Couple the regional markets into a global market
- e.g. NorNed and NordBalt: coupled Norwegian and Baltic Markets to the Central European Market

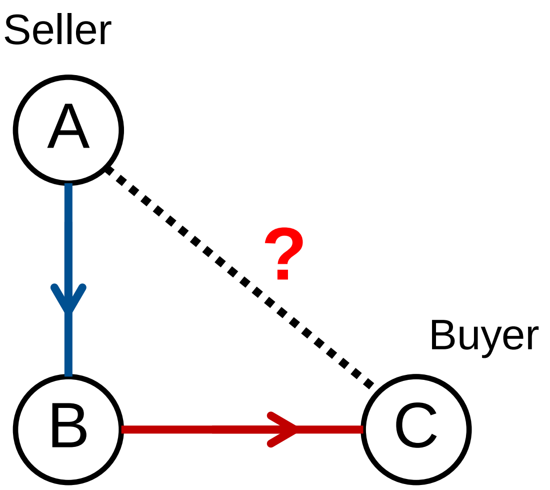
Regulation and Operation

- The “Global Regulator”
  - Supervisory role
  - Coordinate the regulated investments
  - Ensure a competitive market environment

- The “Global System Operator”
  - Global Market
  - Explicit Auction
  - Flow-Based Allocation
  - Global Power Exchange

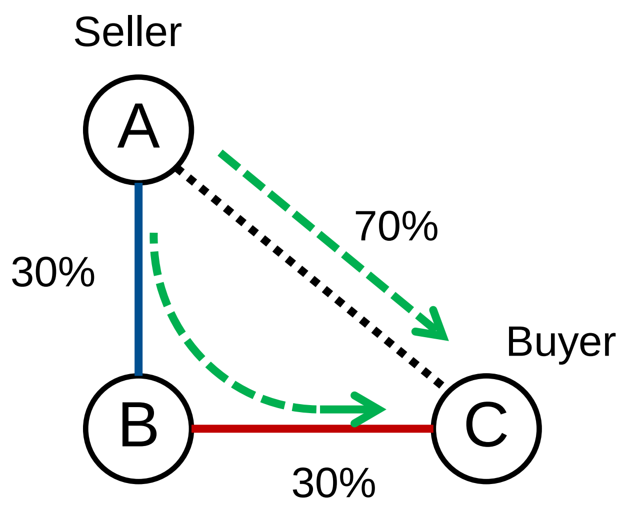
Capacity Allocation

- Explicit Auction



- Two Stages:
  - Reserve Capacity A→B *and* B→C
  - Trade electricity A→C

- Flow-Based Allocation (Implicit Auction)



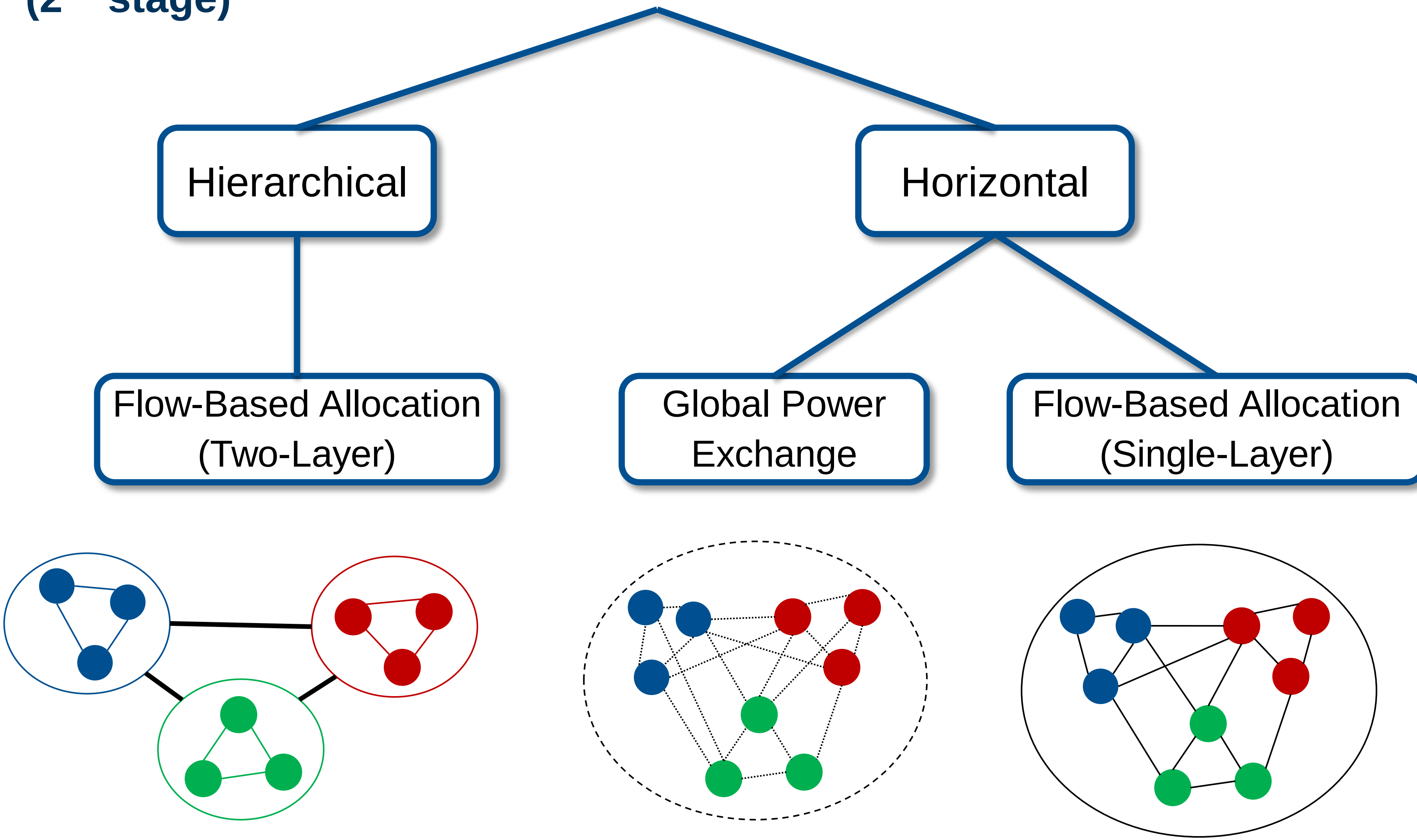
- Trade electricity A→C
  - Internal network model
  - Calculate flows
  - Allocate capacity implicitly

Global Grid Operation

- 1st stage: individual interconnections
  - Long-term contracts between RES producers and consumers
  - Explicit capacity auction
  - Market coupling of neighboring systems with flow-based allocation

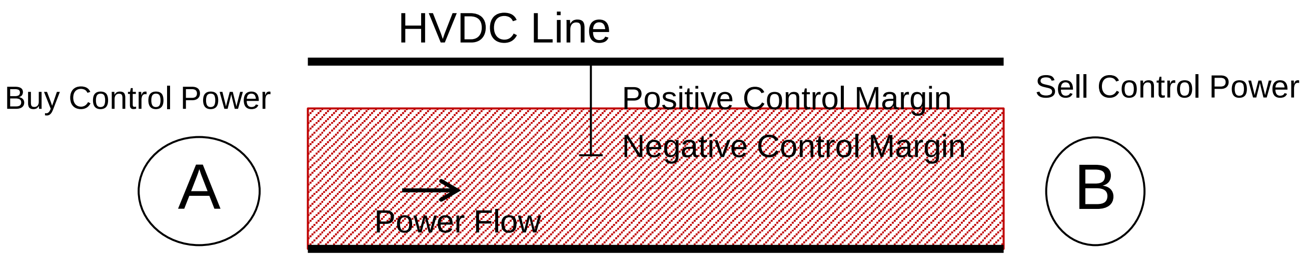
- 2nd Stage: meshed Structure of Global Grid

Possible Operational Schemes of the Global Grid
(2nd stage)



Ancillary Services

- Global Ancillary Services Market
- HVDC line can “emulate” a generator
- HVDC-Voltage Source Converters offer independent control of active and reactive power



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Challenges

- Operation of multiple HVDC lines in a flow-based allocation method
- Appropriate model for market coupling
- Pricing of the HVDC nodes
- Power Systems Security → Global Blackouts?

Alternatives to the Global Grid

- Business as Usual: Electricity production based on coal, gas and nuclear
  - Increased environmental awareness will probably lead to a paradigm change
- Smartgrids
  - Despite the economies of scale, decrease of wind/solar resource quality may lead to a flattening out or a U-shape cost curve *(Dinica,2011)*
  - In the future, break-even point between local and remote energy sources can be expected
  - Smartgrids and Global Grid can act complementary
- Hydrogen Production and Transport
  - Low round-trip efficiency at the moment (~32%)

Conclusions

- The Global Grid can be technologically feasible

- The Global Grid can be economically competitive for a 100% RES future

- New opportunities emerge
  - Smoothing out of RES electricity supply and demand
  - Decrease of price volatility
  - Alleviate the need for bulk storage
  - and more...

Conclusions

- Working groups can be established
- Need to examine in detail several different aspects of the Global Grid
- Studies in order to substantiate the benefits and the challenges
- Open questions that need to be addressed from the research community

Thank you!

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Appendix

Table A.1: Costs of HVDC submarine projects

NorNed	SAPEI	BritNed	NorGer	NordBalt	
±450	±500	±450	450-500	±300	Voltage (in kV, DC side)
700	1000	1000	1400	700	Capacity (MW)
580	435	260	570	450	Length (km)
410	1600	n/a	410	n/a	Maximum Sea Depth (m)
€ 600[a]	€ 750[b]	€ 600[c]	€ 1400 (±30%)[d]	€ 550[e]	Cost (in millions)
€ 300[g]	€ 450[g]	€ 300[g]	€ 680-1520[g]	€ 270[f]	Cost without converters[h] (in millions)
€ 0.52	€ 1.03	€ 1.15	€ 1.19-2.67	€ 0.6	Cost/km (in millions)

[a] (NorNed, 2008a) [b] `www.sapei.it` [c] (TenneT, 2011) [d] planning phase; `www.norger.biz` [e] planning/construction phase; (Mullett, 2010) [f] both for cable supply and installation; (Jäderberg, 2010a) [g] The cost of each terminal converter was *assumed* equal to € 150 million, based on the lower limit of the mentioned studies, although one would expect that the cost of the NorGer terminal stations could be somewhat higher. [h] We assume that these costs correspond to the manufacturing and *installation* of the cable.