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Swiss Federal Institute of Technology Zurich

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The Global Grid

Spyros Chatzivasileiadis, Damien Ernst and Göran Andersson

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

Gobitec

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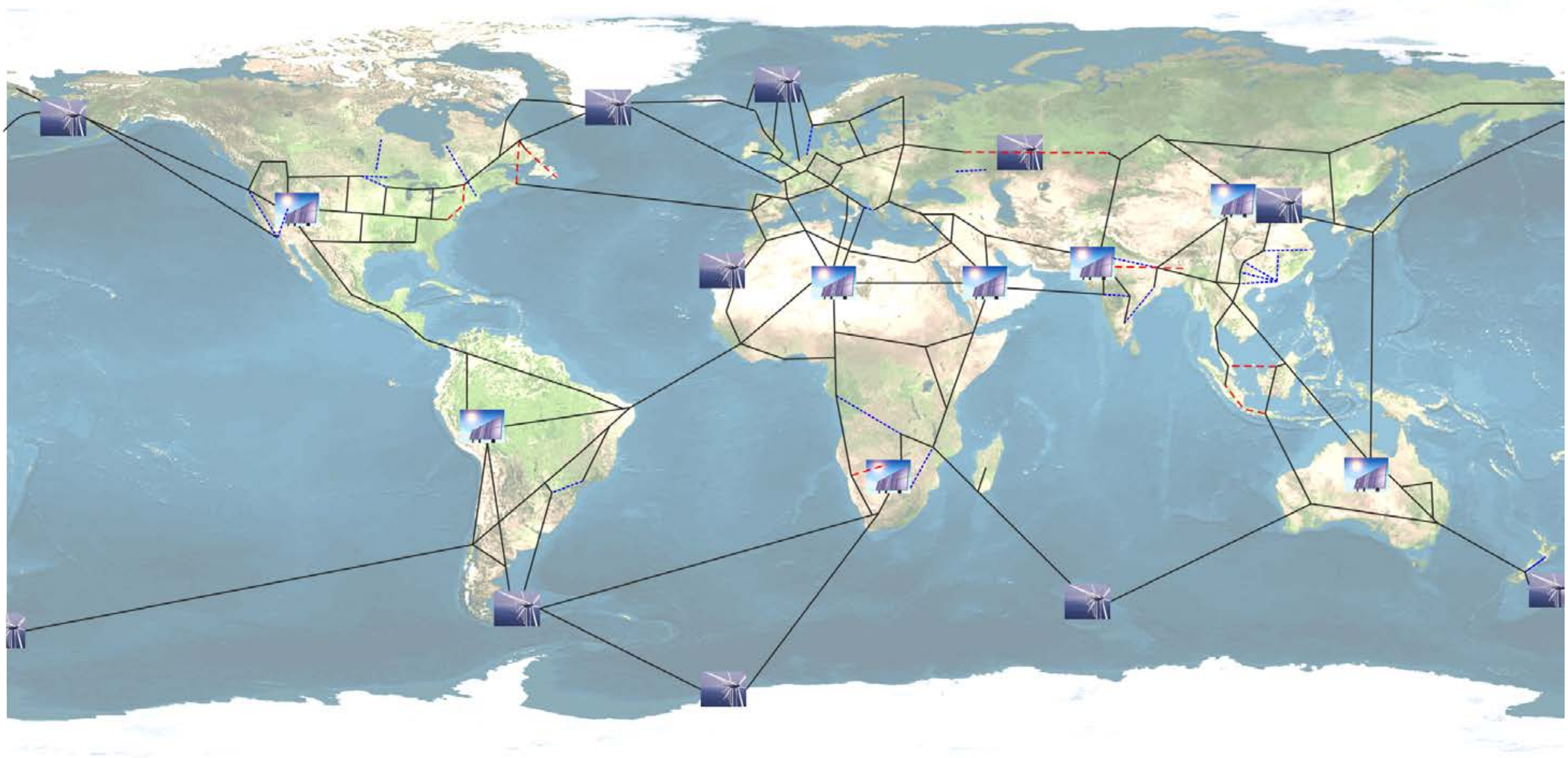
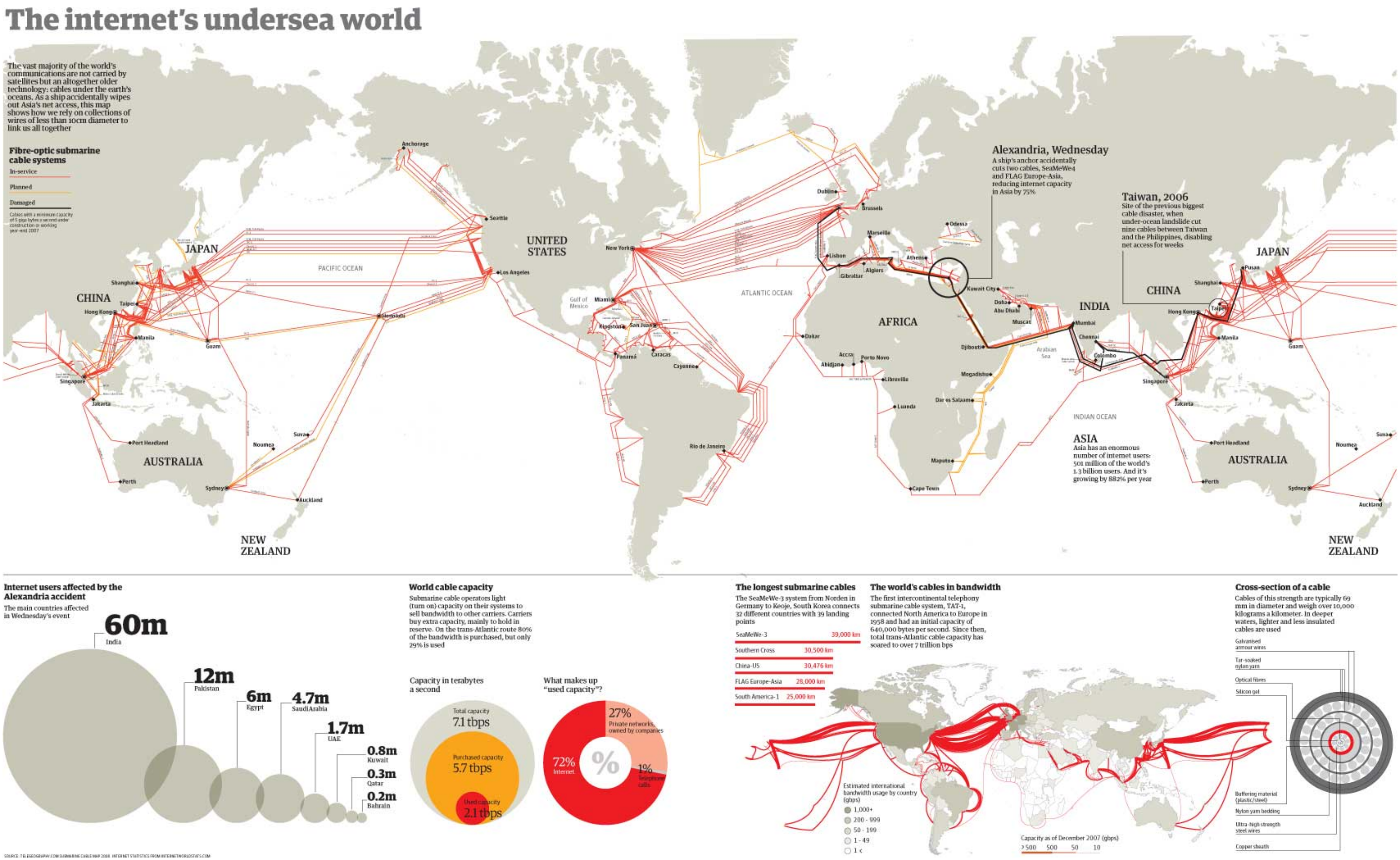
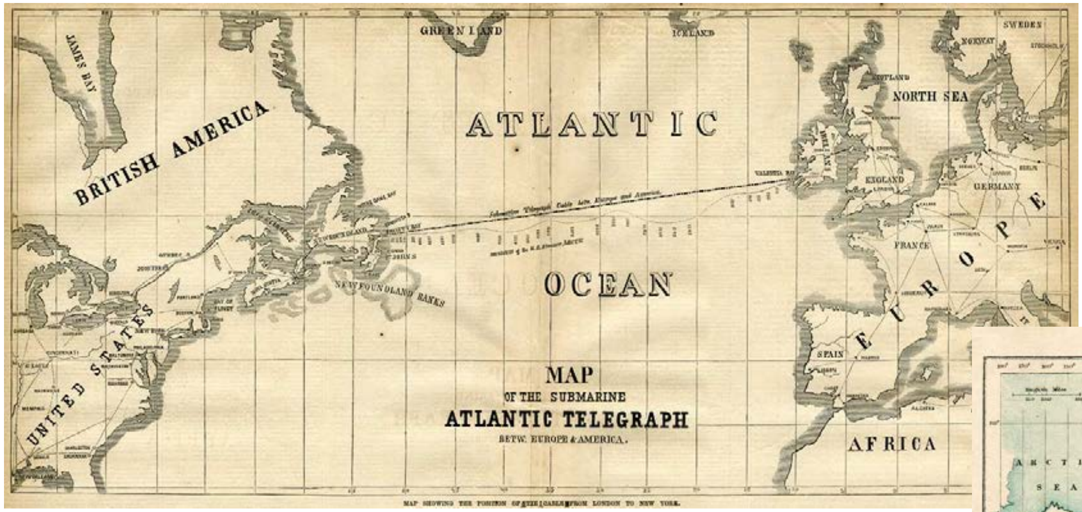
The Global Grid



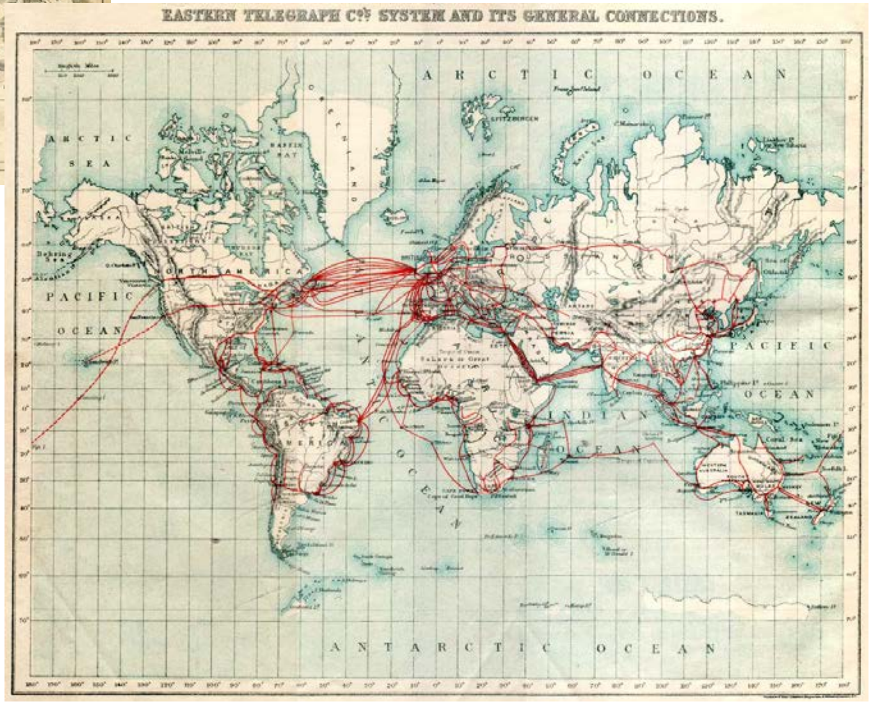

The internet's undersea world
The vast majority of the world's communications are not carried by satellites but an altogether older technology: cables under the earth's oceans. As a ship accidentally wipes out Asia's net access, this map shows how we rely on collections of wires of less than 10cm diameter to link us all together
Fibre-optic submarine cable systems
In-service
Planned
Damaged
Alexandria, Wednesday
A ship's anchor accidentally cuts two cables, SeaMeWe4 and FLAG Europe-Asia, reducing internet capacity in Asia by 75%
Taiwan, 2006
Site of the previous biggest cable disaster, when under-ocean landslide cut nine cables between Taiwan and the Philippines, disabling net access for weeks
JAPAN
CHINA
UNITED STATES
AFRICA
INDIA
AUSTRALIA
NEW ZEALAND
ASIA
Asia has an enormous number of internet users: 501 million of the world's 1.3 billion users. And it's growing by 882% per year
Internet users affected by the Alexandria accident
The main countries affected in Wednesday's event
60m India
12m Pakistan
6m Egypt
4.7m SaudiArabia
1.7m UAE
0.8m Kuwait
0.3m Qatar
0.2m Bahrain
World cable capacity
Submarine cable operators light (turn on) capacity on their systems to sell bandwidth to other carriers. Carriers buy extra capacity, mainly to hold in reserve. On the trans-Atlantic route 80% of the bandwidth is purchased, but only 29% is used
Capacity in terabytes a second
Total capacity 7.1 tbps
Purchased capacity 5.7 tbps
Used capacity 2.1 tbps
What makes up "used capacity"?
27% Private networks owned by companies
72% Internet
1% Telephone calls
The longest submarine cables
The SeaMeWe-3 system from Norden in Germany to Keoje, South Korea connects 32 different countries with 39 landing points
SeaMeWe-3 39,000 km
Southern Cross 30,500 km
China-US 30,476 km
FLAG Europe-Asia 28,000 km
South America-1 25,000 km
The world's cables in bandwidth
The first intercontinental telephony submarine cable system, TAT-1, connected North America to Europe in 1958 and had an initial capacity of 640,000 bytes per second. Since then, total trans-Atlantic cable capacity has soared to over 7 trillion bps
Cross-section of a cable
Cables of this strength are typically 69 mm in diameter and weigh over 10,000 kilograms a kilometer. In deeper waters, lighter and less insulated cables are used
Galvanised armour wires
Tar-soaked nylon yarn
Optical fibres
Silicon gel

Telegraph 1866-1901

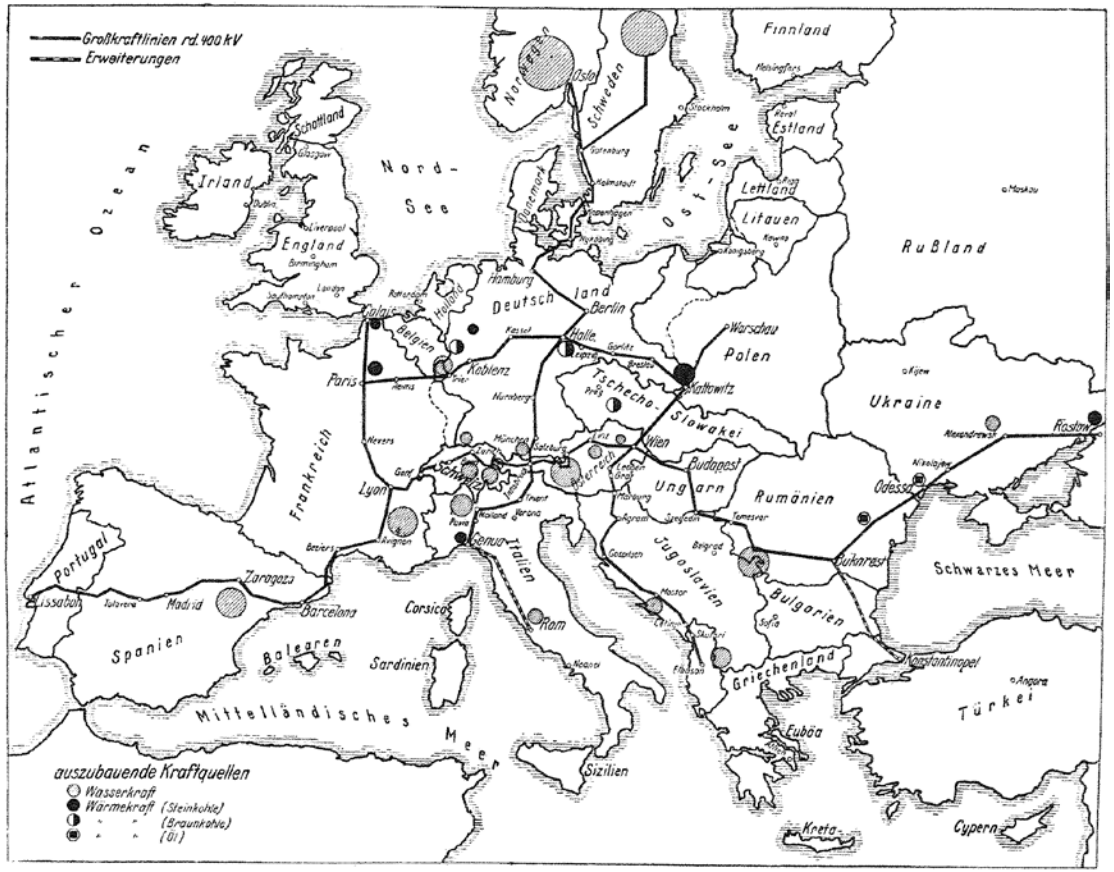


1866: First successful submarine cable

1901: Global Telegraphy Network



European Supergrid: A plan from the 1930s



Oskar Olivens Plan for a pan-European Supergrid

[Teknisk Tidskrift (1930), p. 438]

Cited in:
Mats Fridlund. “Den gemensamma utvecklingen; Staten, storföretaget och samarbetet kring den svenska elkrafttekniken.” *PhD Thesis. KTH Stockholm*. Symposion, 1999

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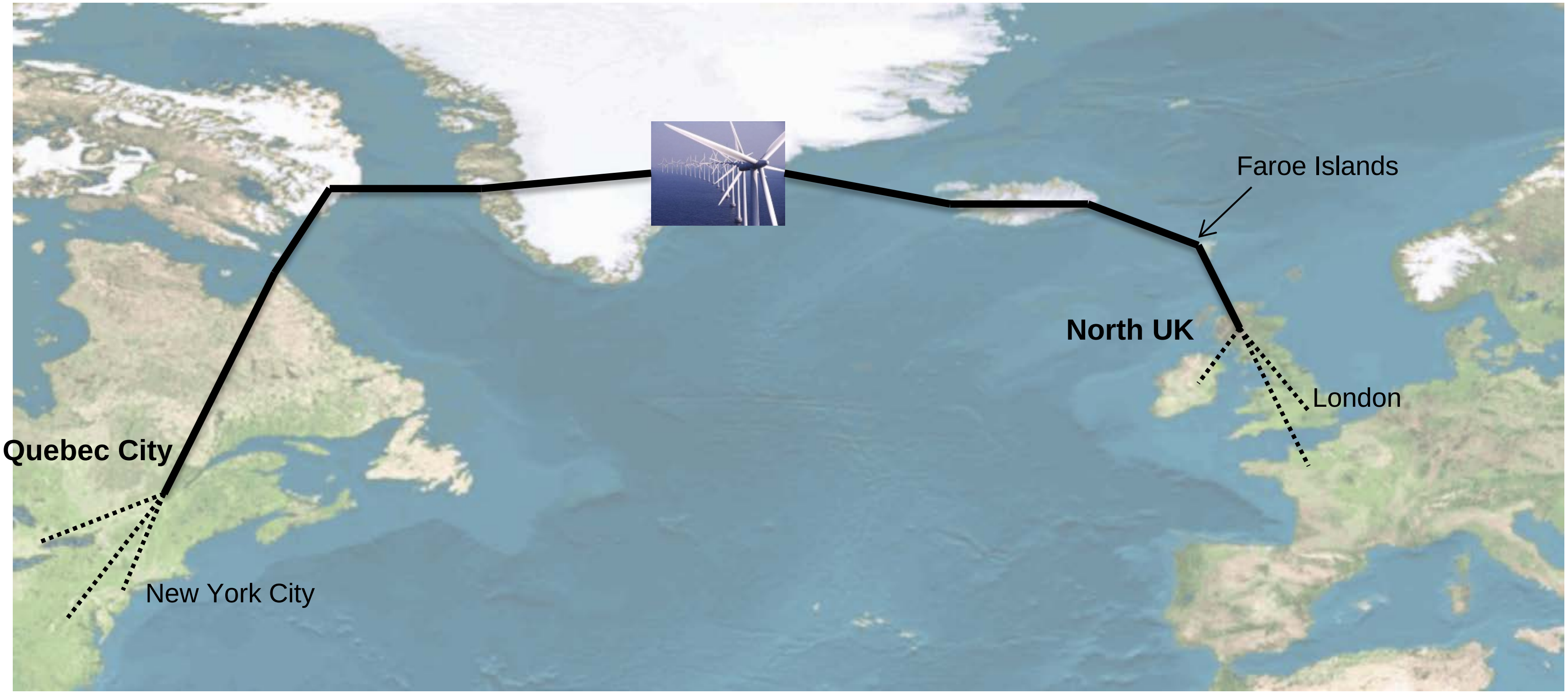
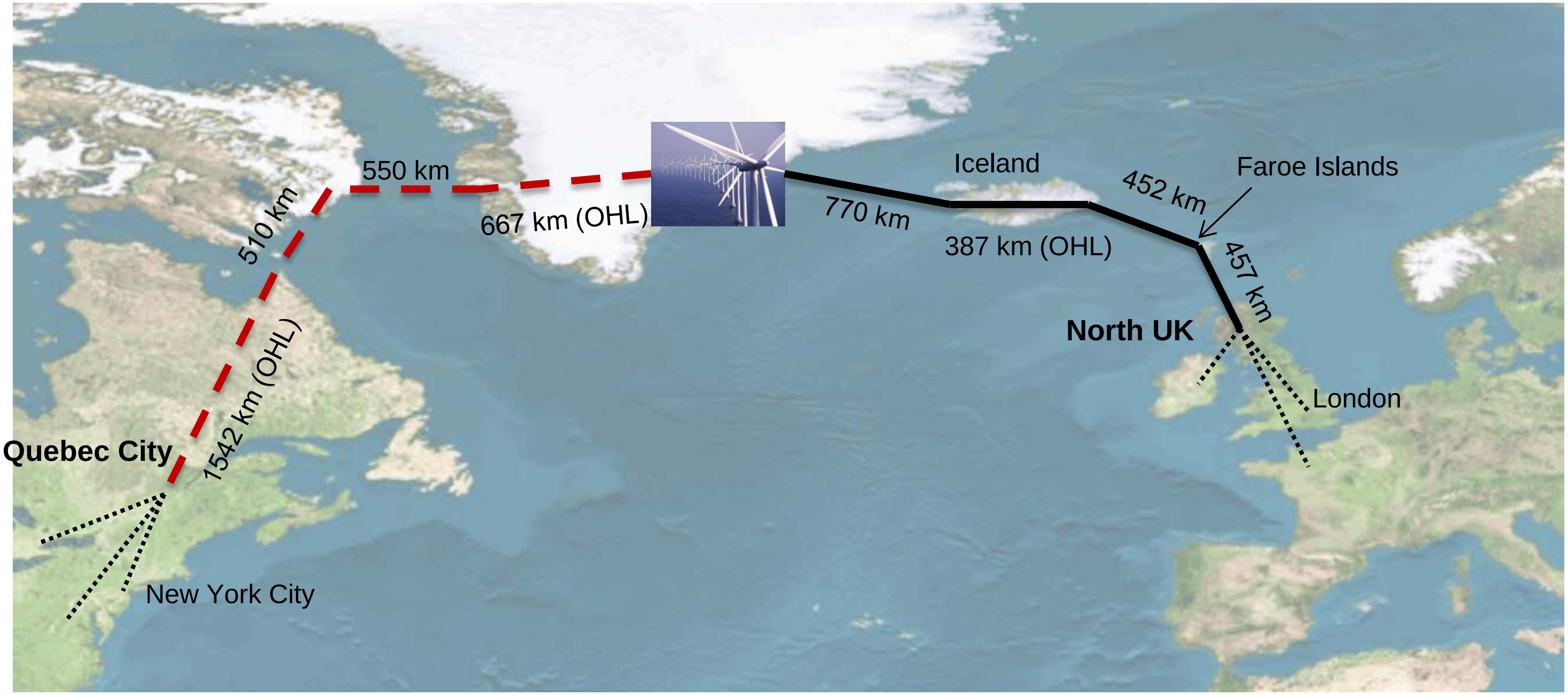
A Possible First Step: Wind Farm in Greenland

- 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)

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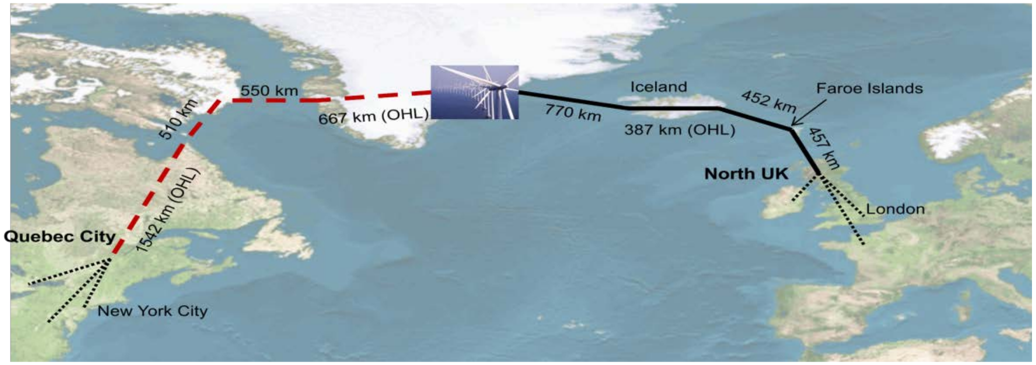
Wind Farm in Greenland (3 GW)



	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%	
>31-33%	***Electricity Trade***	~10’000 GWh/year available	

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

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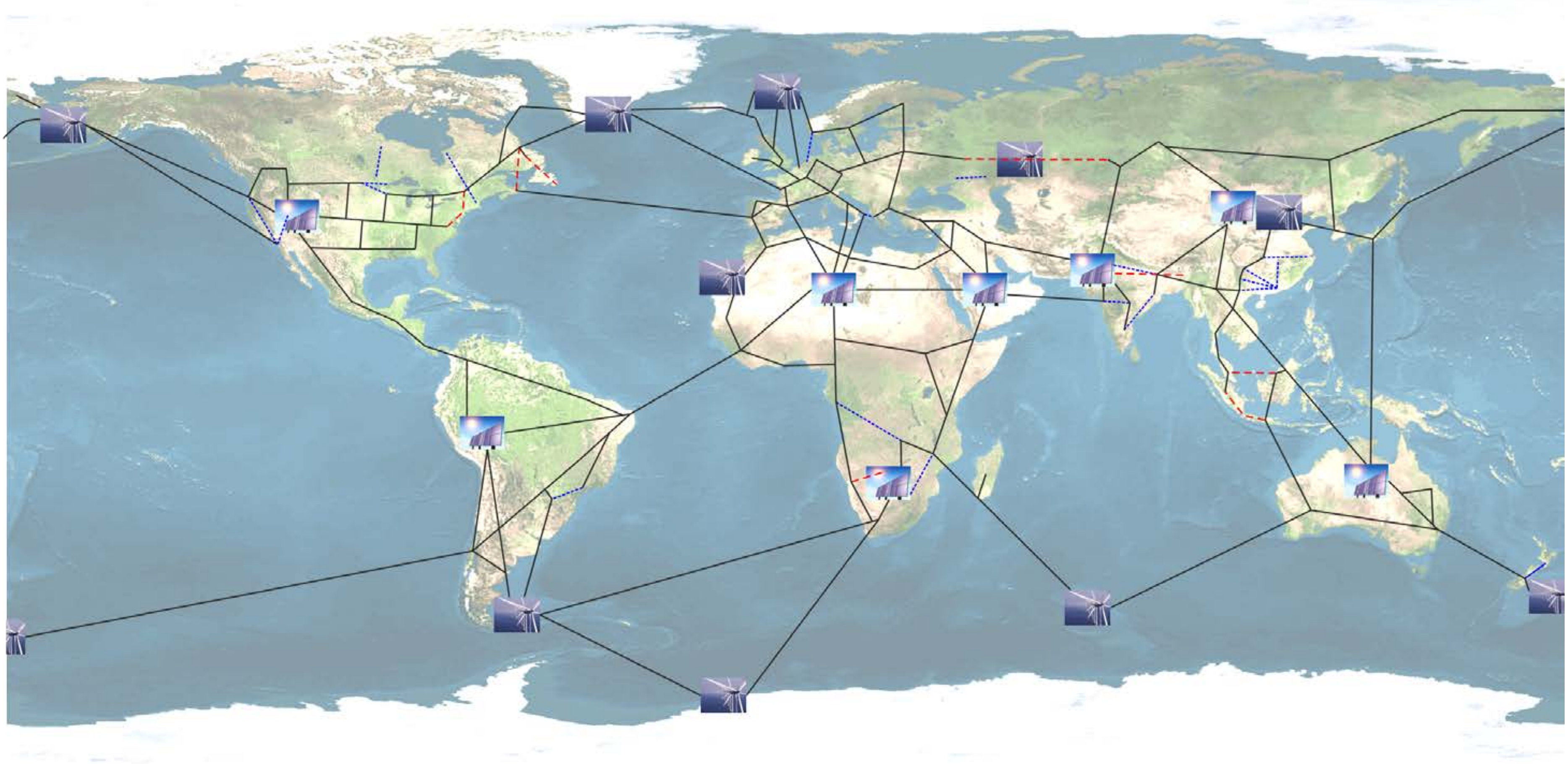
The Global Grid



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"Extreme RES"

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

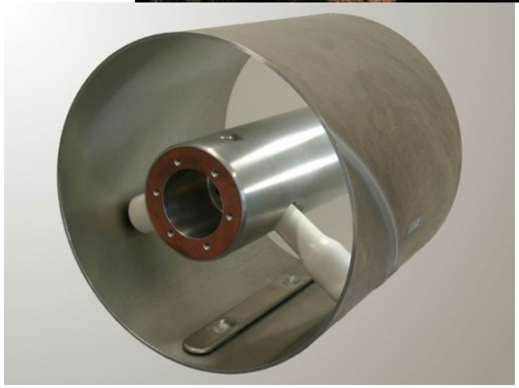
- RES power plants where the installation is more difficult than in current locations or the technology is not yet mature

  - 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
7. Conclusions

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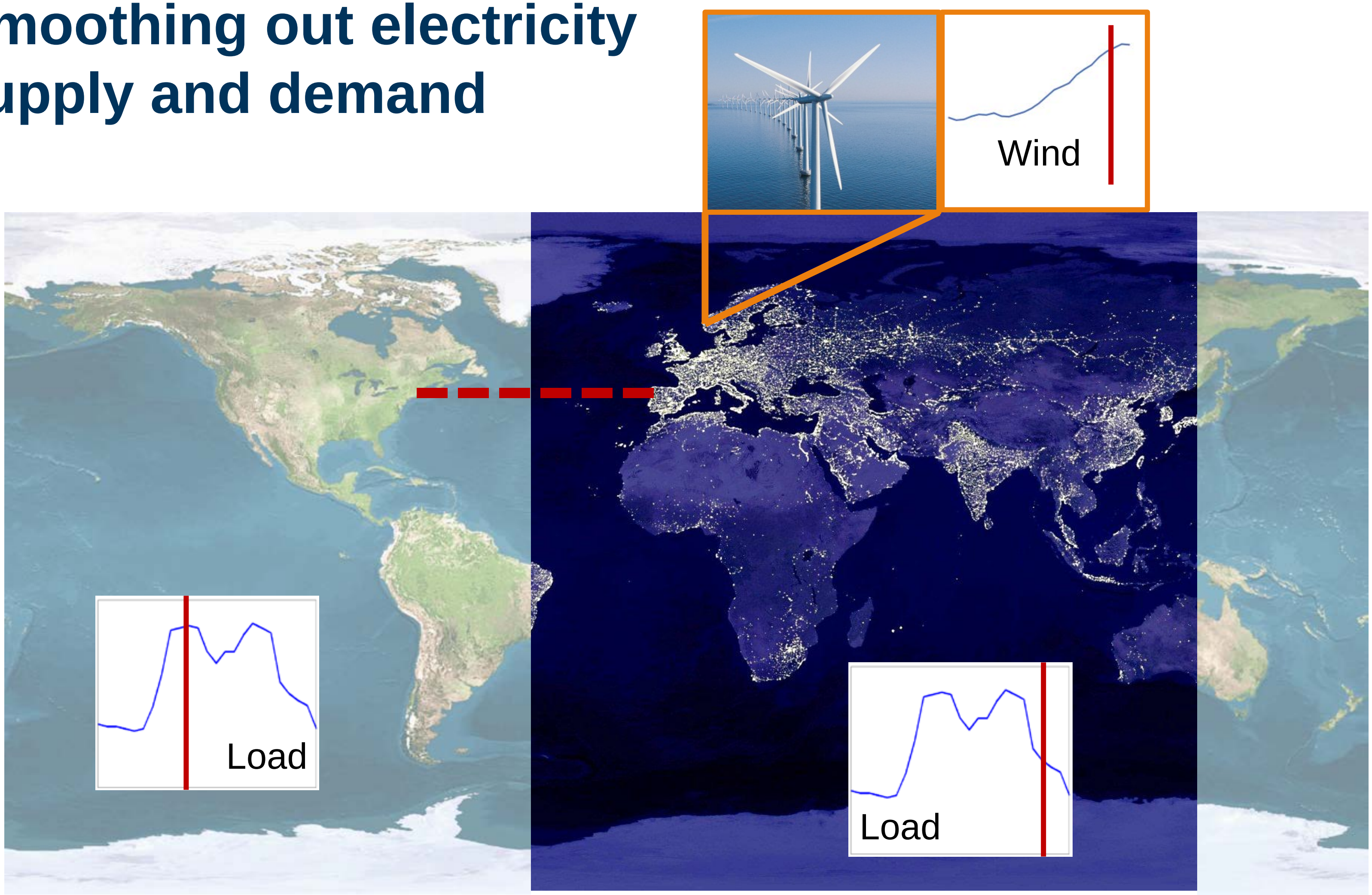
Smoothing out electricity supply and demand



- 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

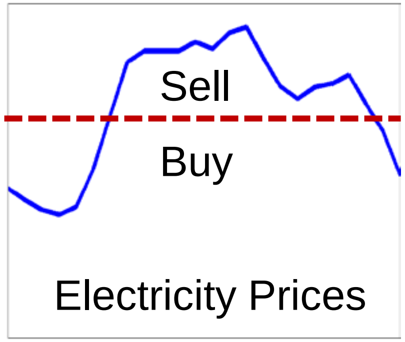
- Conventional plant cost in 2020 in the US*
  - $0.08/kWh, with the social costs: $0.14/kWh

- 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

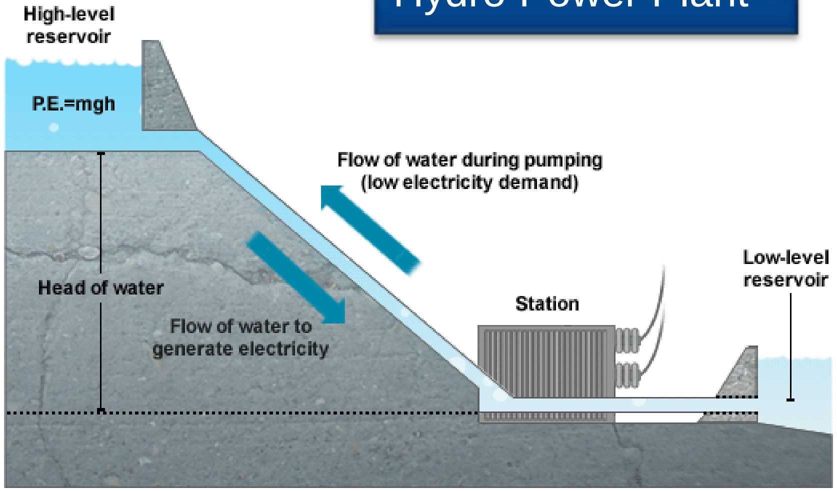
*Delucchi and Jacobson, 2010

Alleviate the need for bulk storage

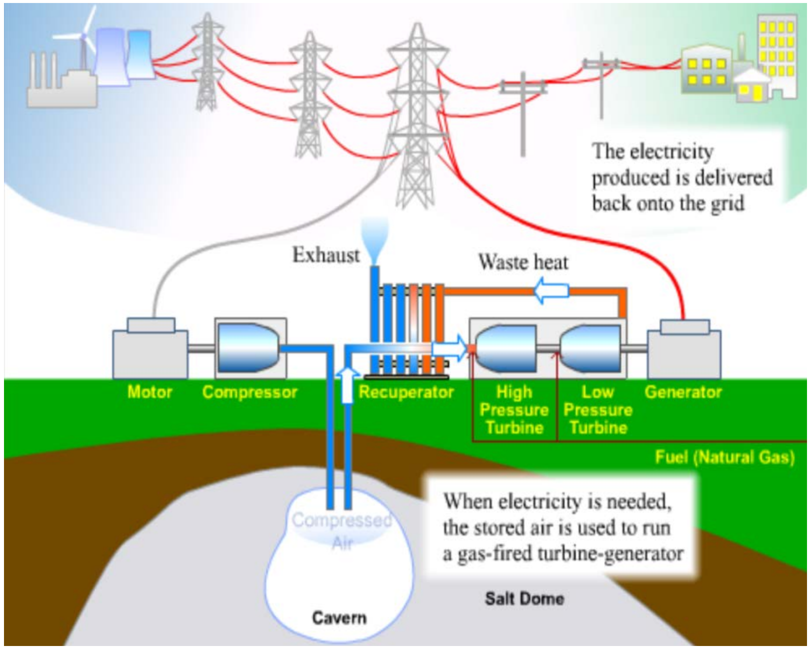
- Storage necessary to absorb non-transmissible power and relieve congestion
- HVDC interconnections can serve equally well such purposes and may further allow the exploitation or untapped storage potential in remote locations
- Bulk storage: Pump-storage power plants, Compressed-Air Energy Storage
-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



Pumped-Storage Hydro Power Plant



Compressed-Air Energy Storage

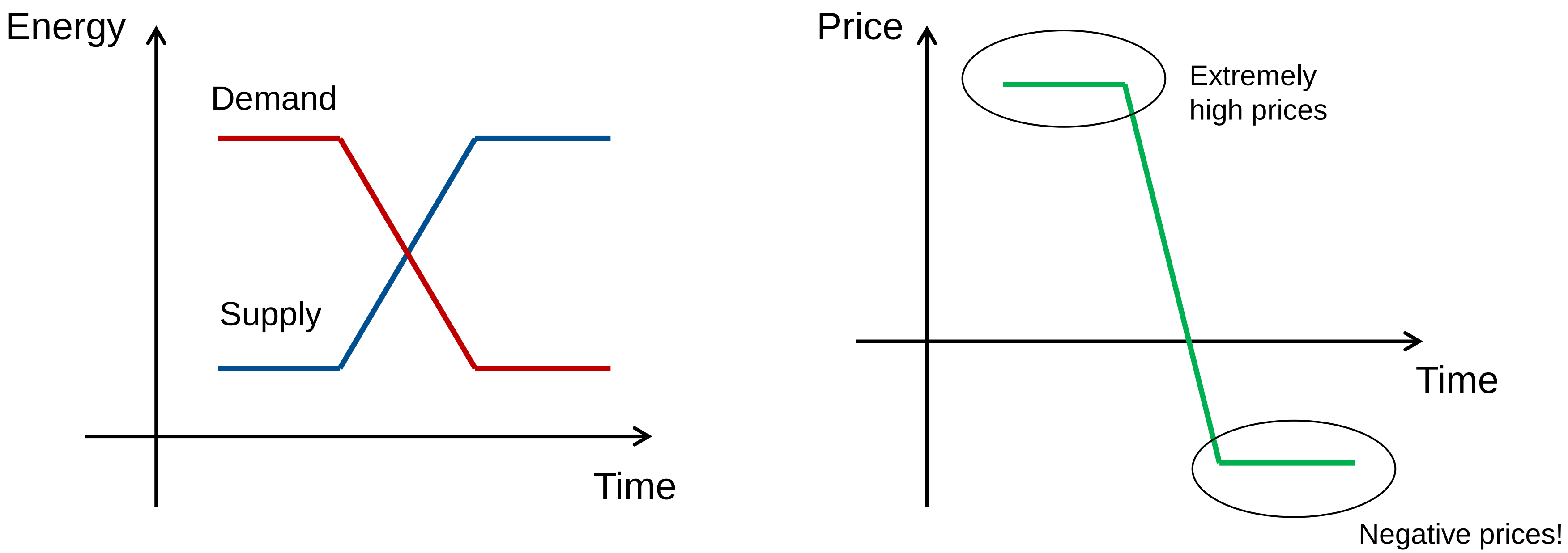


Alleviate the need for bulk storage

- 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*

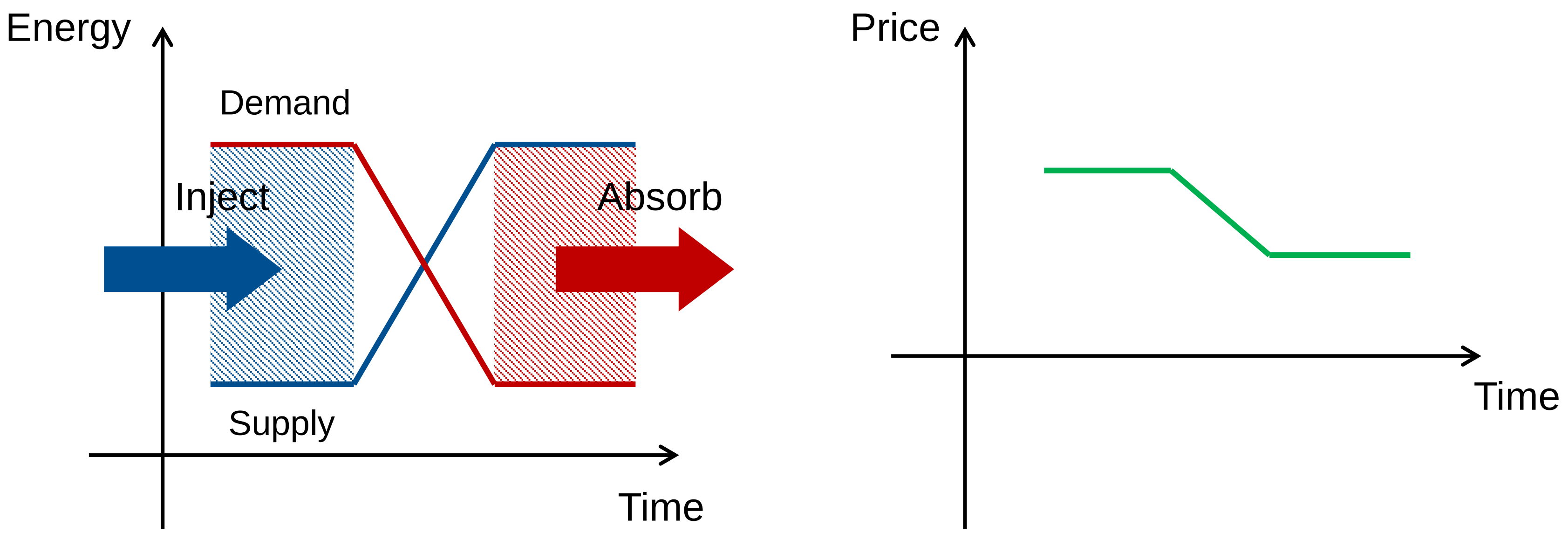
- For cost comparisons, need to consider:
  - HVDC has "unlimited" capacity
  - HVDC does not need to replenish energy → offer energy in both directions
  - Studies show that even with storage, network reinforcements are necessary → synergies can arise

Reduce the volatility of the electricity prices



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

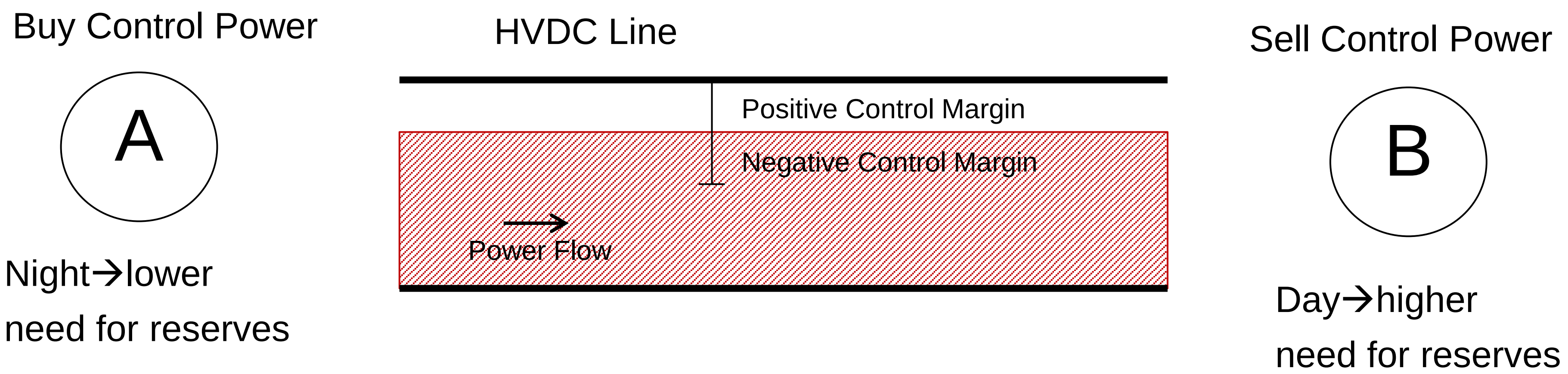
Reduce the volatility of the electricity prices



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

Minimize power reserves

- With increased RES integration, the amount of necessary power reserves will increase



- Global interconnections can offer such services, and thus:
- ***Defer the construction of new peaking power plants***
- Allow a more efficient use of the available capacity in the regional system

Enhance power systems security

- Additional line capacity relieves congestions
- Additional possible paths for power flows → a failure of a single element can be tolerated more easily
- HVDC lines can control the active and reactive power flow (especially the Voltage Source Converters technology)
- Offer reactive power and assist in voltage stability
- Inject/absorb active power and assist in transient stability

Additional Benefits

- Deliver the power directly to the load centers
- Increase the diversification of energy sources
  - Enhance security of supply
  - No strong dependence on a limited number of suppliers
- Countries with increasing energy demand and high carbon footprint can import green energy
- RES potential in countries with developing economies
  - Investments can stimulate economic activity
  - Assist in local development, e.g. desalination plants in regions with water shortage

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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

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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}

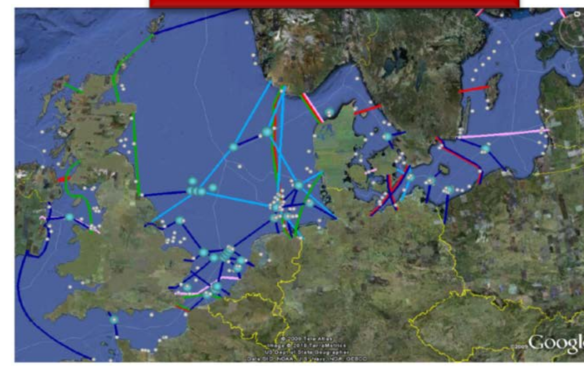
Europe:

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



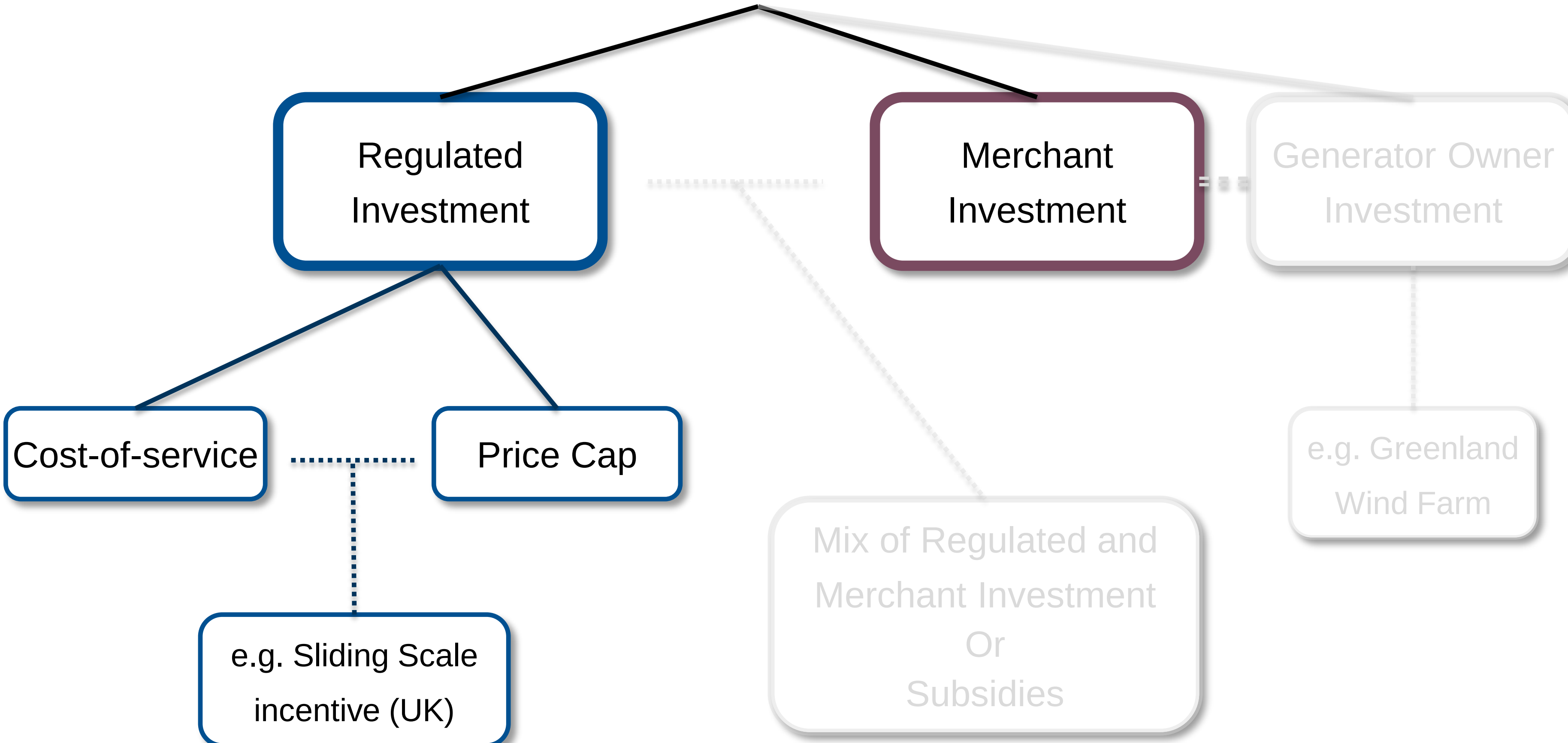
Offshore grid scenario 3: Wind-driven approach (blue = changes to base case, red = existing, pink = under construction, green = planned)

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

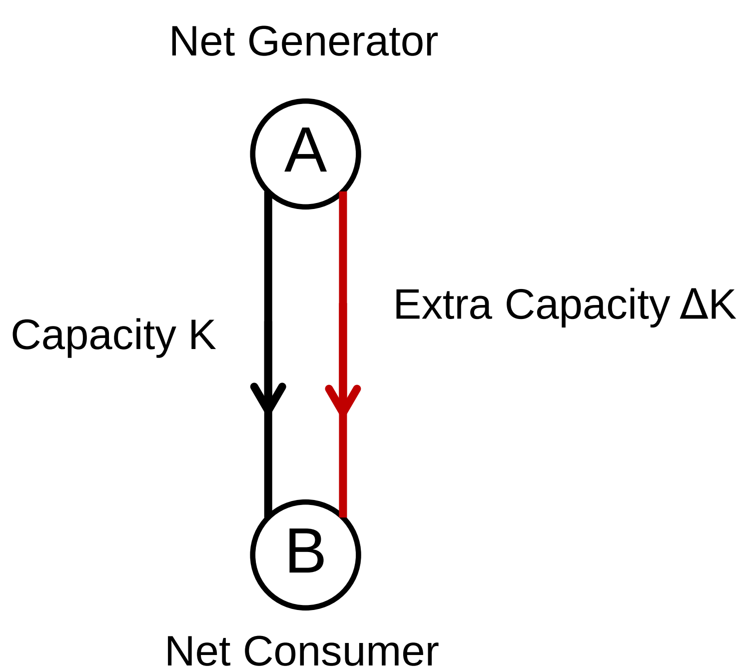
- Most common type of investment
- Until recently only TSOs and transmission owners
- EU, 2009: also third parties

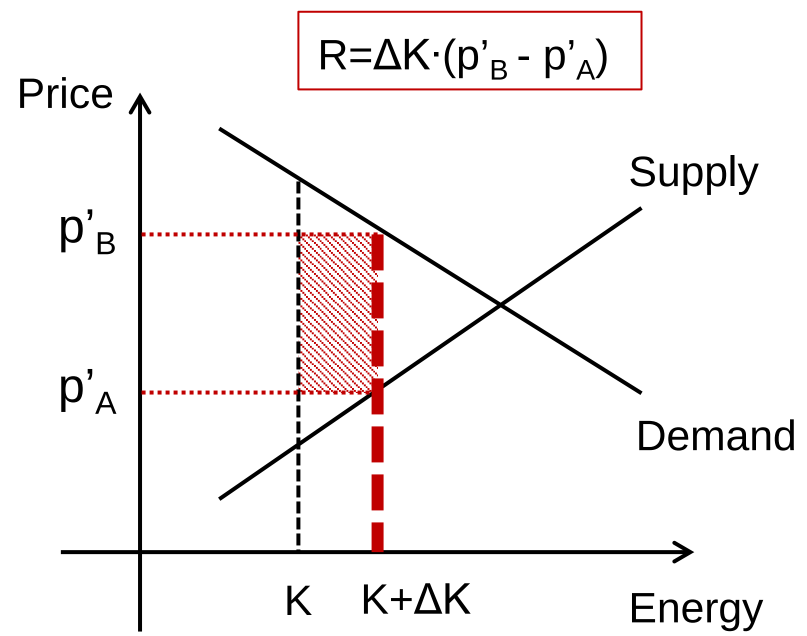
- Subject to a cost-benefit analysis
- Supervised from the regulator (or ISO)

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

Merchant Investment

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



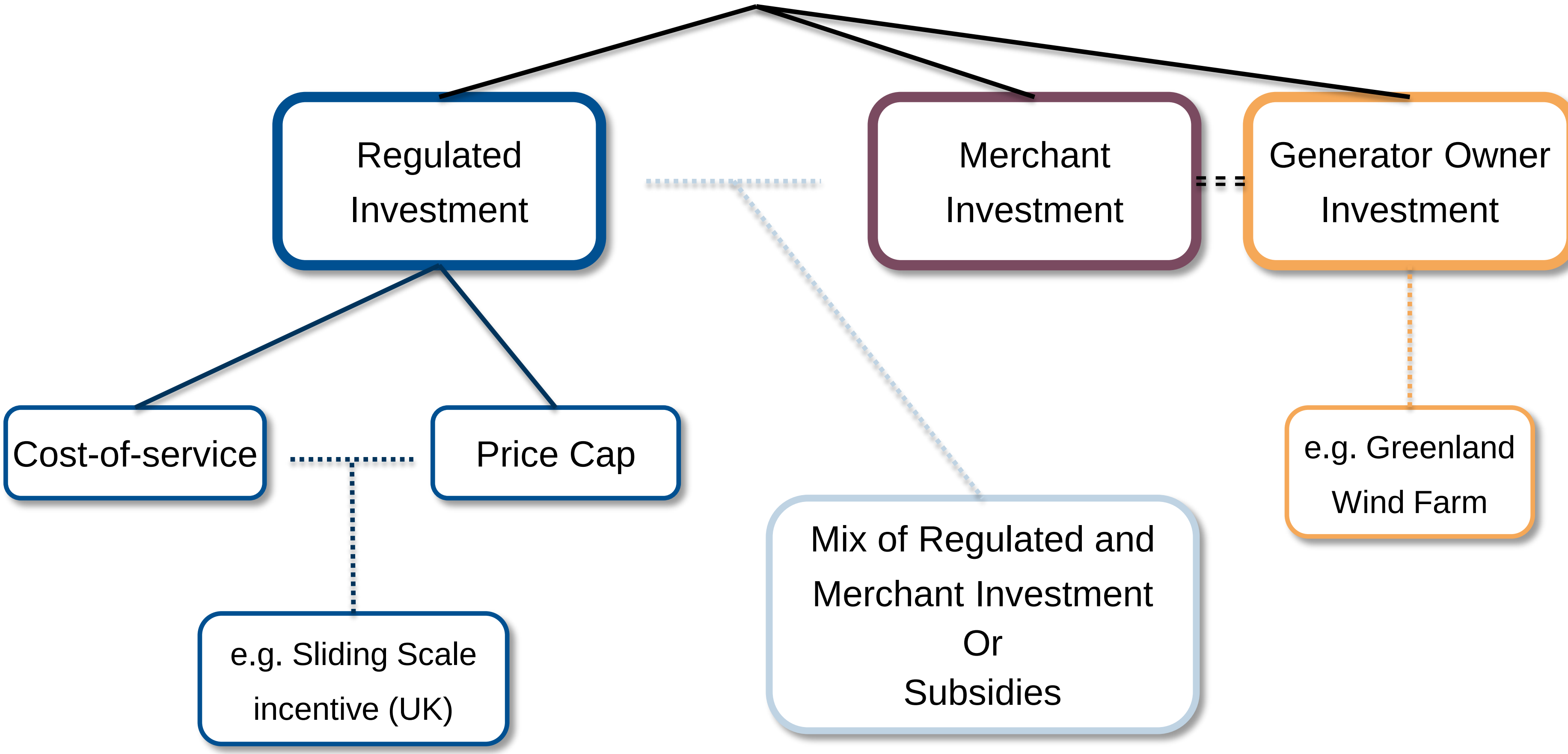


Regulated vs. Merchant Investment

- 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

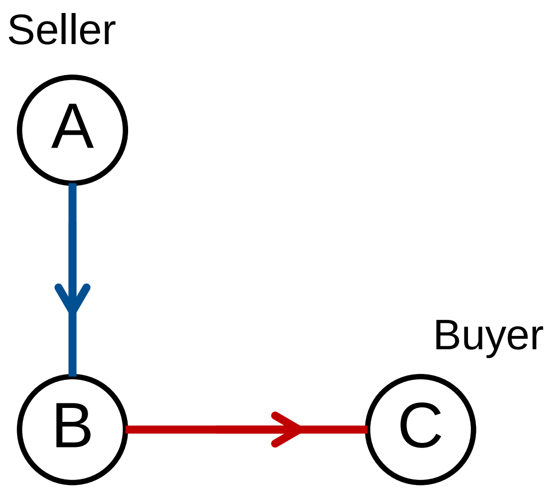
Regulation

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

- Europe, 2011, ACER: Agency for the Cooperation of Energy Regulators

Capacity Allocation

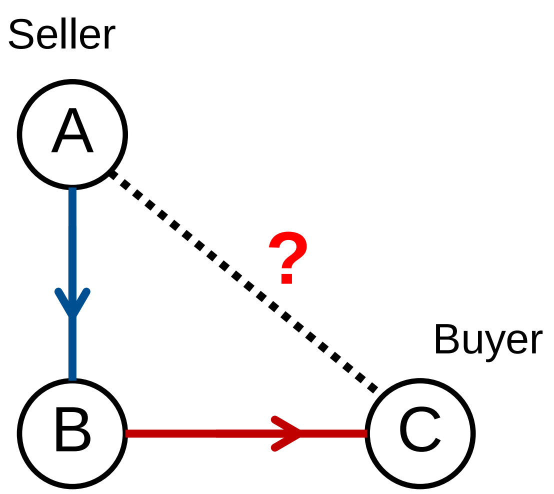
- Explicit Auction



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

Capacity Allocation

- Explicit Auction



- Two Stages:
  - Reserve Capacity A→B *and* B→C
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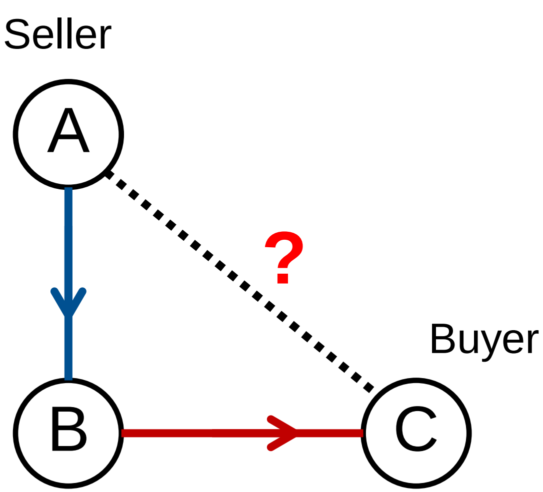
- Flow-Based Allocation (Implicit Auction)

Capacity Allocation

- Explicit Auction



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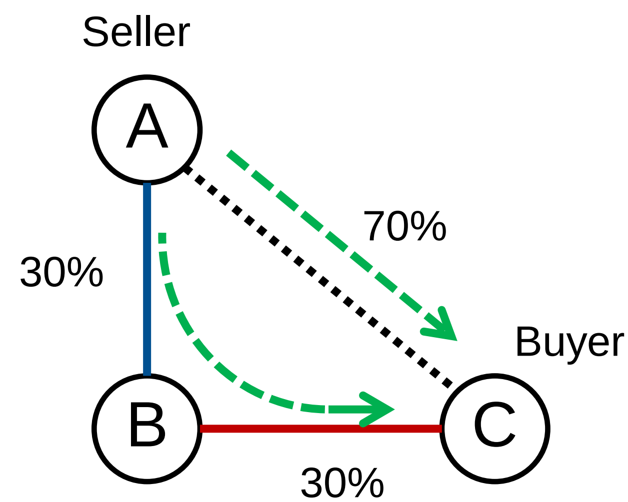
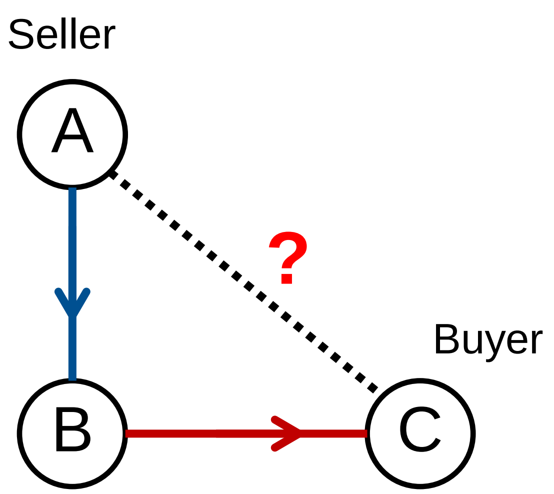


- Trade electricity A→C
  - Internal network model
  - Calculate flows
  - Allocate capacity implicitly

Capacity Allocation

- Explicit Auction



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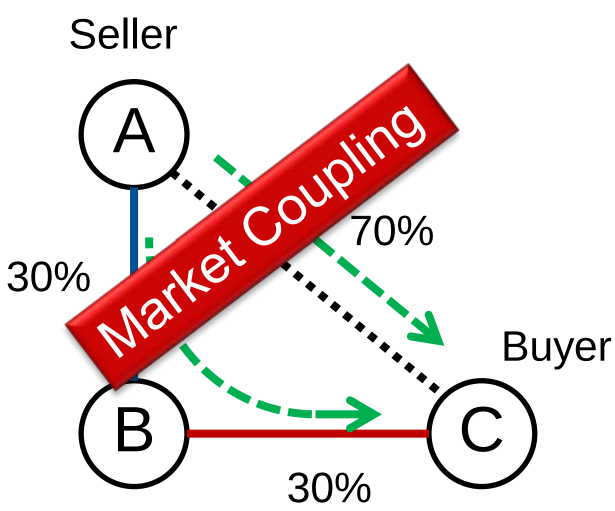


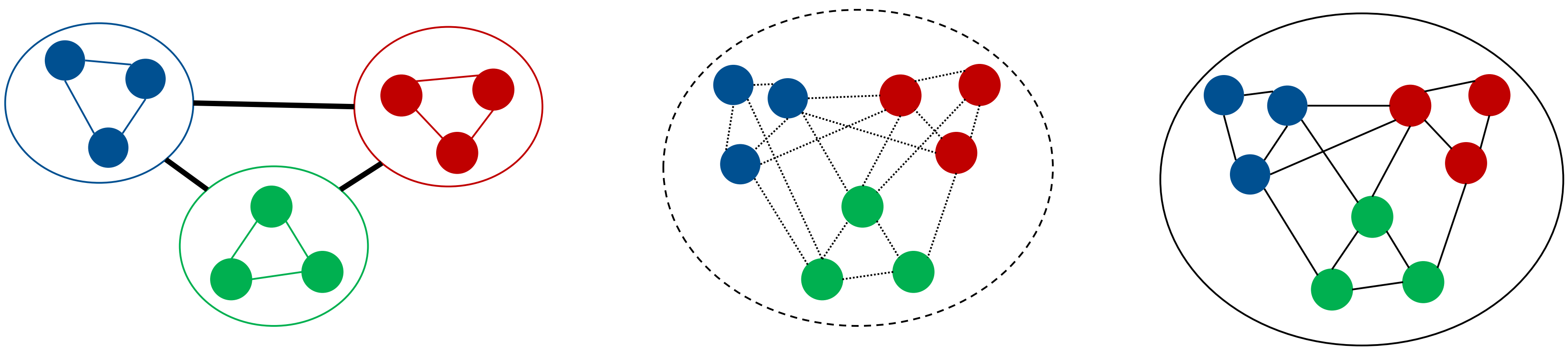
- Trade electricity A→C
  - Internal network model
  - Calculate flows
  - Allocate capacity implicitly

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

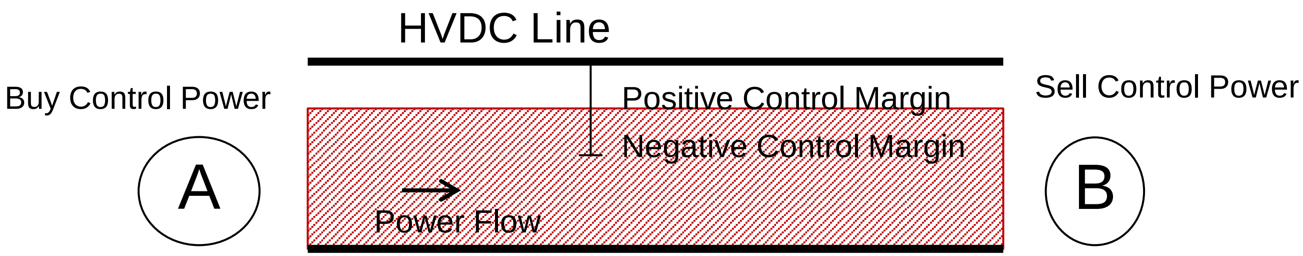
Possible Operational Schemes of the Global Grid
(2nd stage)

- Hierarchical
  - Flow-Based Allocation (Two-Layer)
- Horizontal
  - Global Power Exchange
  - Flow-Based Allocation (Single-Layer)



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
- Political unrest in regions with significant RES potential
  - But, electricity cannot be stored in bulk quantities

  → less room for conflict is expected in comparison with fossil fuels
- Power Systems Security → Global Blackouts?

Alternatives to the Global Grid

- Business as Usual: Electricity from 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
  - Possibility of a Global Gas Network could be investigated
  - 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
- Detailed feasibility studies
- Open questions that need to be addressed from the research community

Thank you!

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