HVDC Transmission: Part of the Energy Solution?

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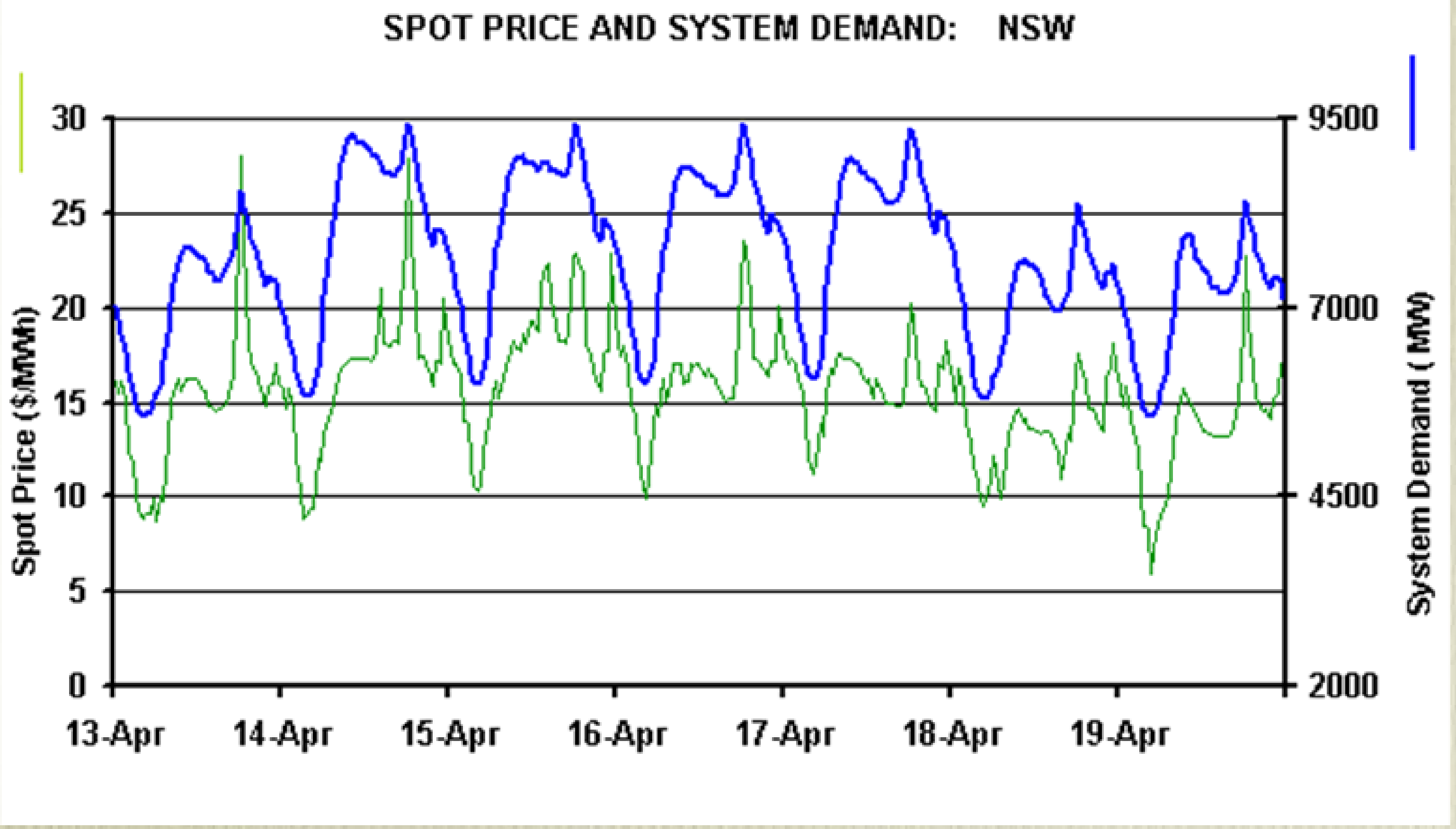
Why has HVDC taken off?

- HV is needed to transmit DC a long distance.
  - Semiconductor thyristors able to handle high currents (4,000 A) and block high voltages (up to 10 kV) were needed for the widespread adoption of HVDC.
  - Newer semiconductor VSC (voltage source converters), with transistors that can rapidly switch between two voltages, has allowed lower power DC.
  - VSC converter stations also are smaller and can be constructed as self-contained modules, reducing construction times and costs.

Increased Benefits of Long-Distance Transmission

- Long distance transmission increases competition in new wholesale electricity markets.
- Long distance electricity trade, including across nations, allows arbitrage of price differences.
- Contractual provision of transmission services demands more stable networks.
- Bi-directional power transfers, often needed in new electricity markets, can be accommodated at lower cost using HVDC

Electricity Costs and Prices Fluctuate Substantially

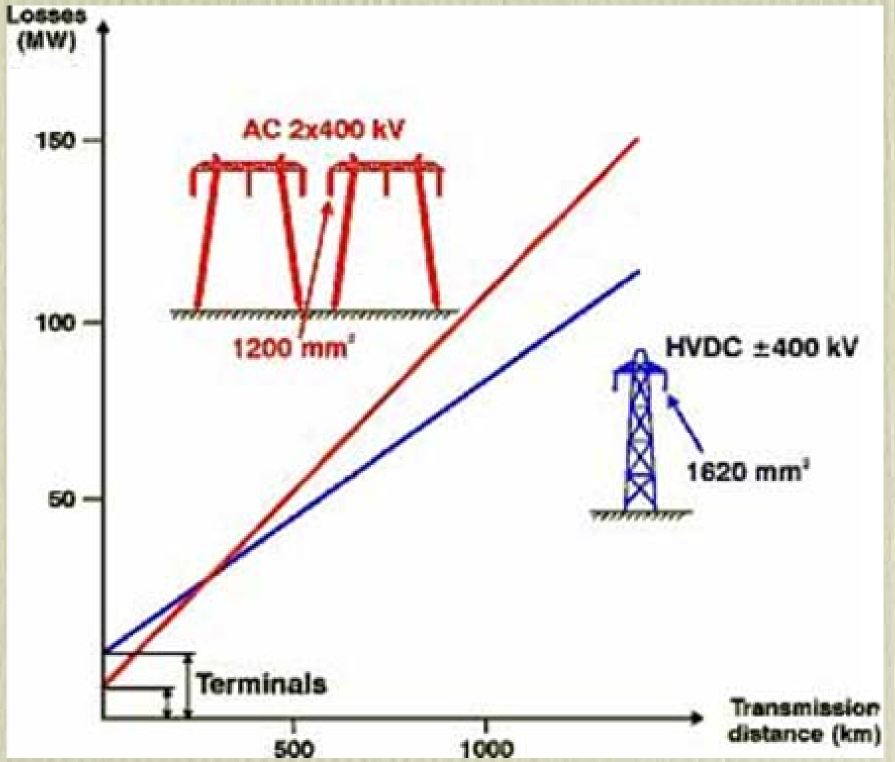


Source: NEMMCO Australia (2003)

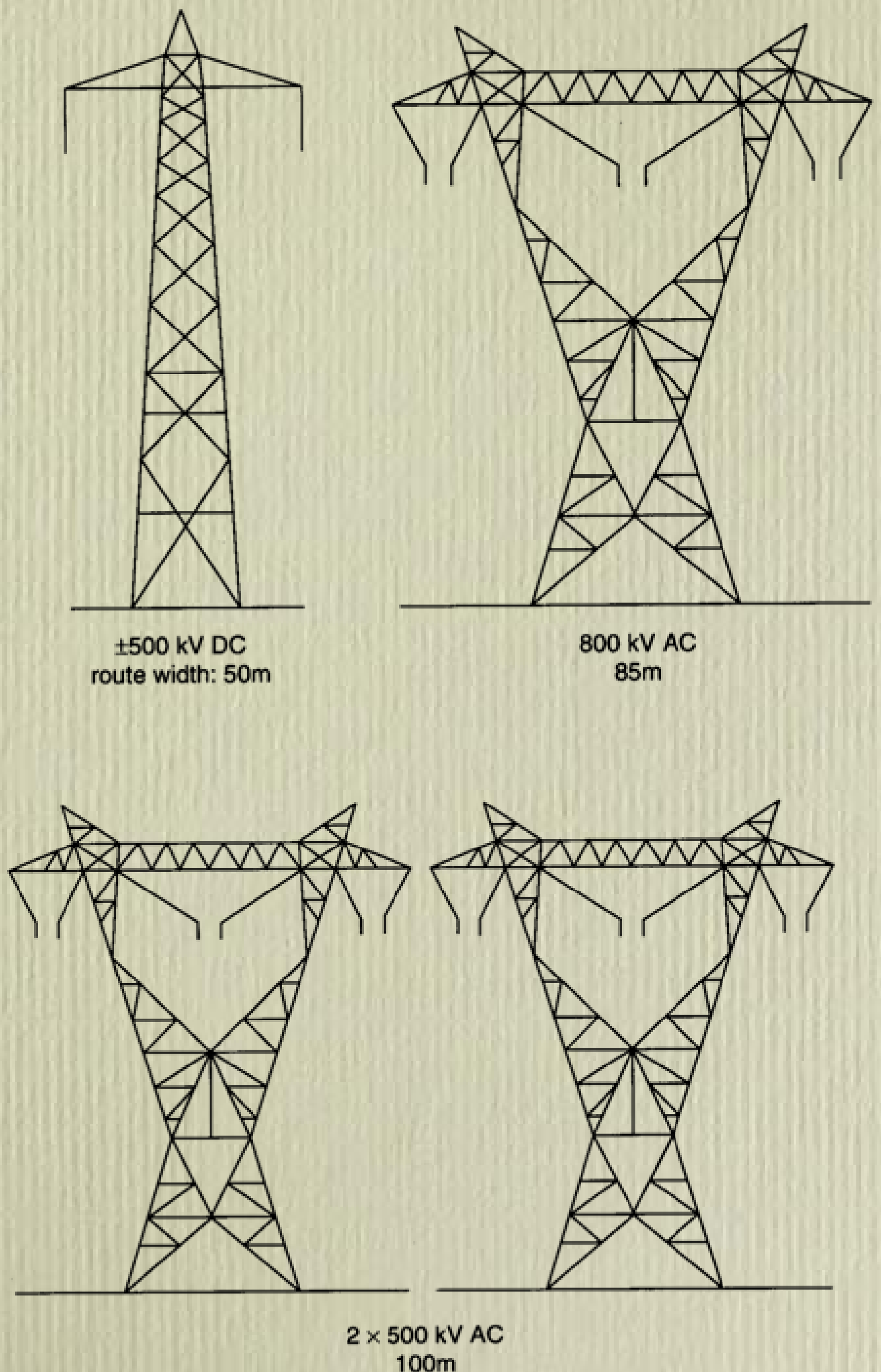
Relative Cost of AC versus DC

- For equivalent transmission capacity, a DC line has lower construction costs than an AC line:
  - A double HVAC three-phase circuit with 6 conductors is needed to get the reliability of a two-pole DC link.
  - DC requires less insulation ceteris paribus.
  - For the same conductor, DC losses are less, so other costs, and generally final losses too, can be reduced.
  - An optimized DC link has smaller towers than an optimized AC link of equal capacity.

Example Losses on Optimized Systems for 1200 MW



Source: ABB (2003)



Typical tower structures and rights-of-way for alternative transmission systems of 2,000 MW capacity.

Source: Arrillaga (1998)

AC versus DC (continued)

- Right-of-way for an AC Line designed to carry 2,000 MW is more than 70% wider than the right-of-way for a DC line of equivalent capacity.
  - This is particularly important where land is expensive or permitting is a problem.
- HVDC “light” is now also transmitted via underground cable – the recently commissioned Murray-Link in Australia is 200 MW over 177 km.
  - Can reduce land and environmental costs, but is more expensive per km than overhead line.

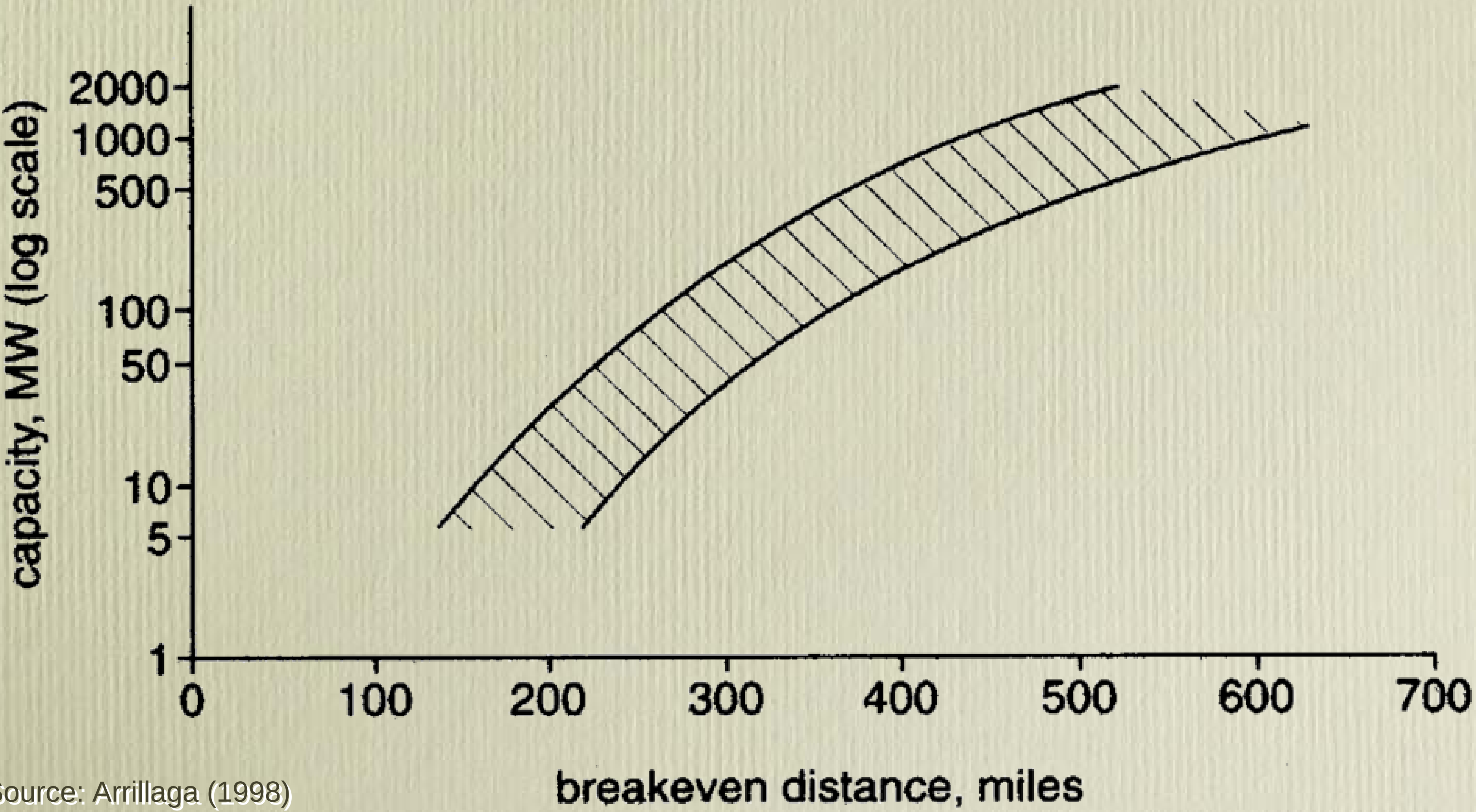
AC versus DC (continued)

- Above costs are on a per km basis. The remaining costs also differ:
  - The need to convert to and from AC implies the terminal stations for a DC line cost more.
  - There are extra losses in DC/AC conversion relative to AC voltage transformation.
  - Operation and maintenance costs are lower for an optimized HVDC than for an equal capacity optimized AC system.

AC versus DC (continued)

- The cost advantage of HVDC increases with the length, but decreases with the capacity, of a link.
- For both AC and DC, design characteristics trade-off fixed and variable costs, but losses are lower on the optimized DC link.
- The time profile of use of the link affects the cost of losses, since the MC of electricity fluctuates.
- Interest rates also affect the trade-off between capital and operating costs.

Typical Break-Even Distances

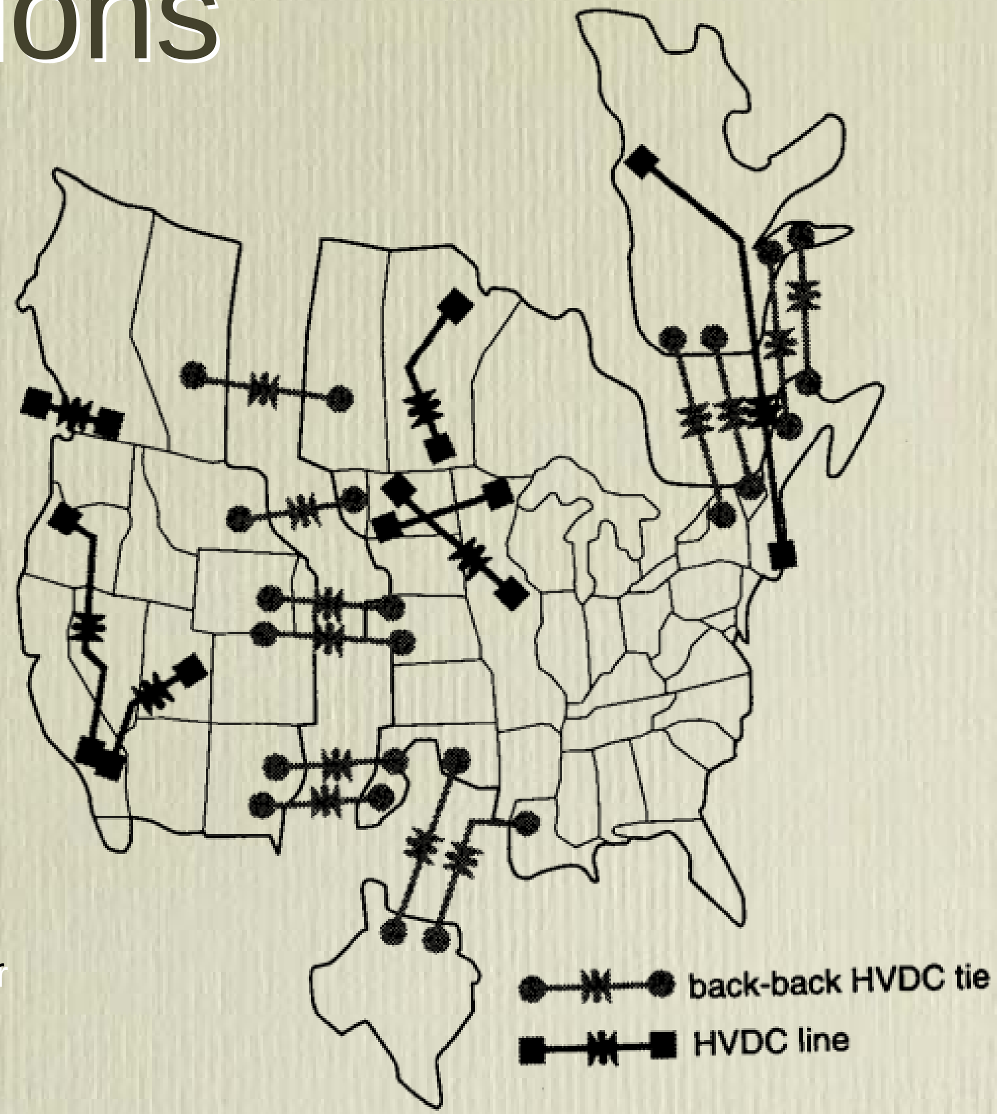


Source: Arrillaga (1998)

Special Applications of HVDC

- HVDC is particularly suited to undersea transmission, where the losses from AC are large.
  - First commercial HVDC link (Gotland 1 Sweden, in 1954) was an undersea one.
- Back-to-back converters are used to connect two AC systems with different frequencies – as in Japan – or two regions where AC is not synchronized – as in the US.

N. American Transmission Regions



Source: Arrillaga (1998)

Four major independent asynchronous networks, tied together only by DC interconnections:

1. *Eastern Interconnected Network* – all regions east of the Rockies except ERCOT and Quebec portion of the NPCC reliability council.
2. *Quebec* – part of the NPCC reliability council.
3. *Texas* – the ERCOT reliability council.
4. *Western Interconnected Network* – the WSCC reliability

Special Applications (continued)

- HVDC links can stabilize AC system frequencies and voltages, and help with unplanned outages.
  - A DC link is asynchronous, and the conversion stations include frequency control functions.
  - Changing DC power flow rapidly and independently of AC flows can help control reactive power.
  - HVDC links designed to carry a maximum load cannot be overloaded by outage of parallel AC lines.

Some Early HVDC Projects

- Most early HVDC links were submarine cables where the cost advantage of DC is greatest.
- Others involved hydroelectric resources, since there is no practical alternative to long distance high voltage transmission of hydroelectric energy.
- Pacific DC tie installed in 1970 parallel to 2 AC circuits – system stabilization was a major issue.
- Square Butte link in N. Dakota (750 km, 500 MW, 250 kV) displaced transporting coal, with system stabilization a major ancillary benefit.

Selected Recent Projects

- Itaipu, Brazil: 6,300 MW at ±600 kV DC.
  - Two bipolar DC lines bring power generated at 50 Hz in the 12,600 MW Itaipu hydroelectric plant to the 60Hz network in São Paulo.
- Leyte-Luzon, Philippines: 350 kV monopolar, 440MW, 430 km overhead, 21 km submarine.
  - Takes geothermal energy from Leyte to Luzon
  - Assists with stabilizing the AC network.

Selected Projects (continued)

- Rihand-Delhi, India: 1,500 MW at ±500 kV
  - Existing 400 kV AC lines parallel the link.
  - Takes power 814 km from a 3,000 MW coal-based thermal power station to Delhi.
  - HVDC halved the right-of-way needs, lowered transmission losses and increased the stability and controllability of the system.

Selected Projects (continued)

- Proposed Neptune Project: 1,000 km 1,200 MW submarine cable from Nova Scotia to Boston, New York city and NJ.
  - Take natural gas energy to NY with less visual impact, while avoiding a NIMBY problem in NY and allowing old oil-fired plant in NY to be retired.
  - Help improve network stability and reliability.
  - The southern end has a summer peak demand, the northern end a winter one, so a bi-directional link allows savings from electricity trade.

HVDC versus Gas Pipeline

- Variable costs of an overhead HVDC link are less than the variable costs of pipeline gas.
  - For 1,000–5,000 MW over 5,000 km pipeline gas is about 1.2–1.9 times more expensive (Arrillaga, 1998).
- Relative costs depend on the cost of land, and the price of gas among other factors.
- LNG also competes with HVDC for exploiting some gas reserves.

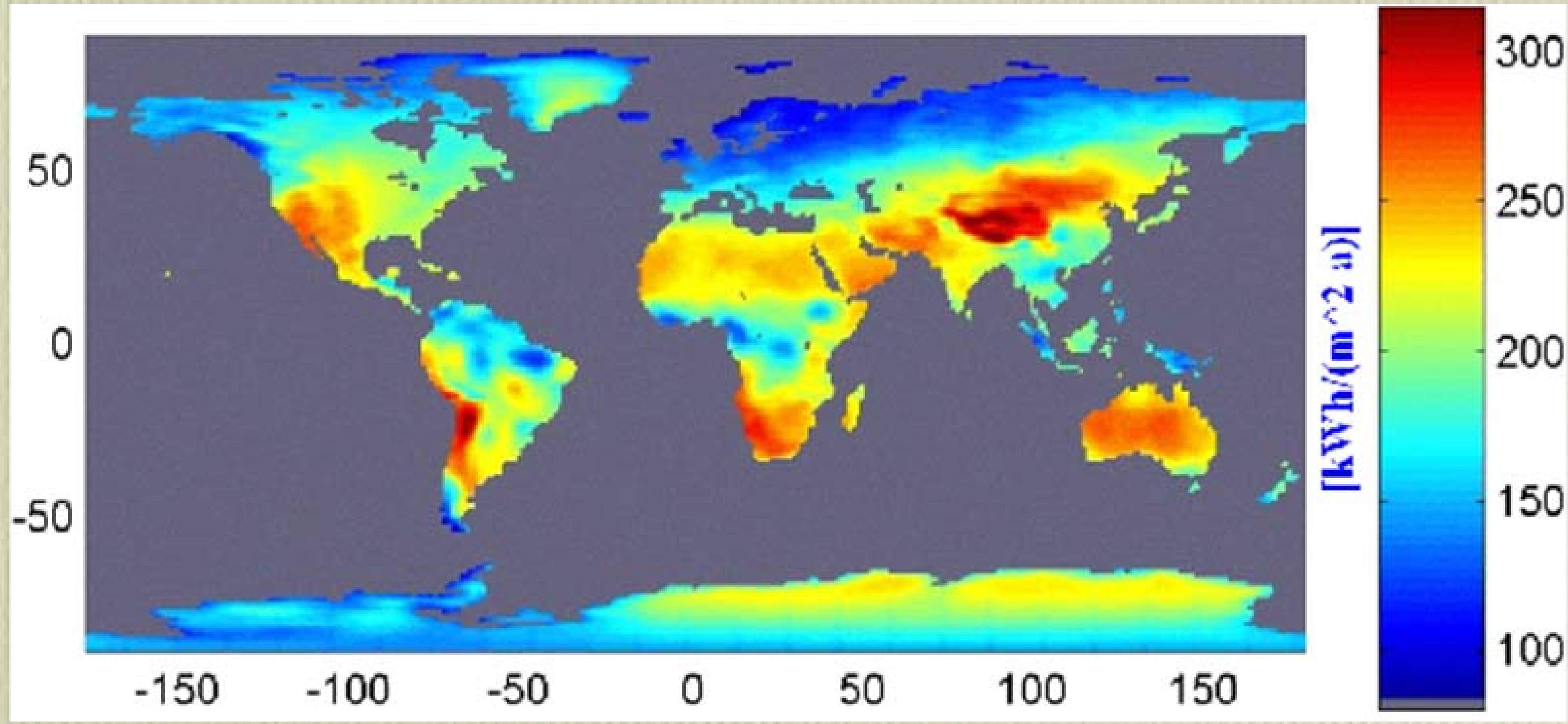
Renewable Energy & HVDC

- HVDC seems particularly suited to many renewable energy sources:
  - Sources of supply (hydro, geothermal, wind, tidal) are often distant from demand centers.
  - Wind turbines operating at variable speed generate power at different frequencies, requiring conversions to and from DC.
  - Large hydro projects, for example, also often supply multiple transmission systems.

HVDC & Solar Power

- HVDC would appear to be particularly relevant for developing *large scale* solar electrical power.
- Major sources are low latitude, and high altitude deserts, and these tend to be remote from major demand centers.
- Photovoltaic cells also produce electricity as DC, eliminating the need to convert at source.

Average Potential Electricity From Photovoltaics (1983-92)

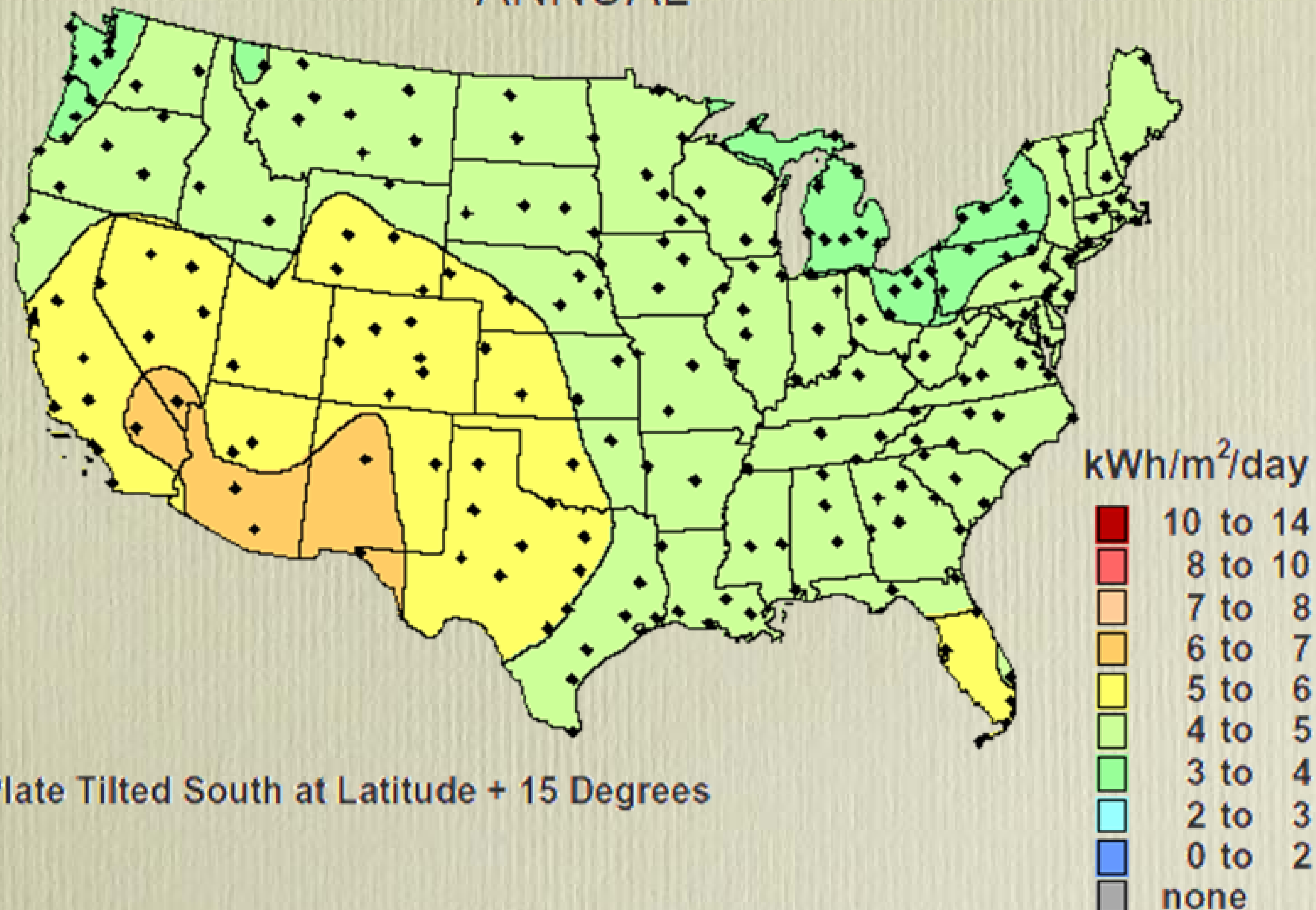


Source: Institut für Solare Energieversorgungstechnik

Panels are assumed to have an efficiency of 14% at peak radiation and standard temperature reduced to approximately 13% efficiency due to system losses.

Average Daily Solar Radiation Per Month

ANNUAL



Flat Plate Tilted South at Latitude + 15 Degrees

Source: National Renewable Energy Laboratory

Potential power from SW of USA, Northern Mexico

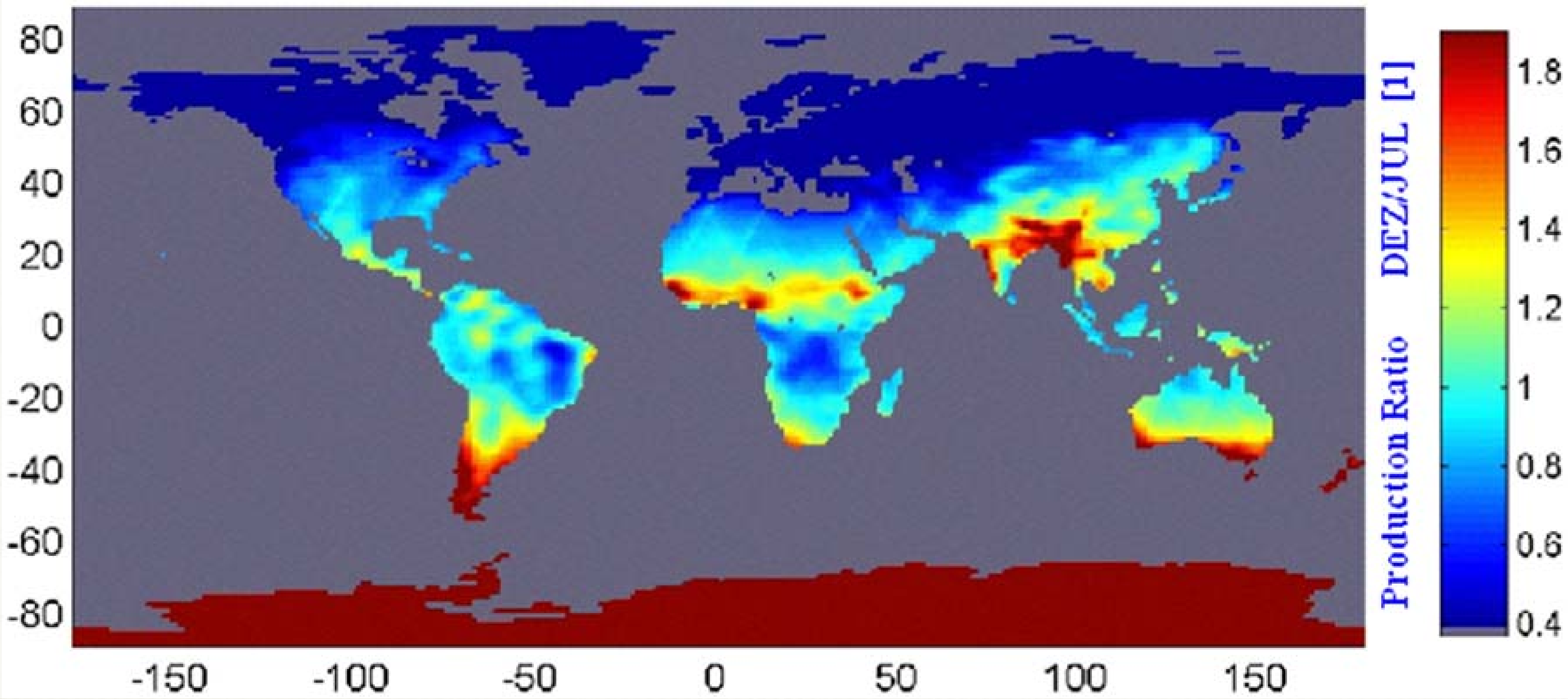
- 6 kWh/m^2 light a day yields about 280 kWh/m^2 of electricity a year for panels at 13% efficiency.
- For average distances of 5,000 km, HVDC transmission losses would be about 25%.
- About 20 panels each 30km×30km ($18{,}000km^2$) would be needed to replace the 3,800 billion kWh of electricity produced in US in 2000.

Grid-Connected PV Plants

- First installed in Japan (Saijo) and USA (Hesperia) in the early 1980s.
- Now more than 25 plants world-wide with peak power output from 300 kW to more than 3 MW
- Most of the plants have fixed, tilted structures, without tracking.
- These plants have proved easy to monitor and control and have achieved a 25% annual capacity factor even with modest downtime.

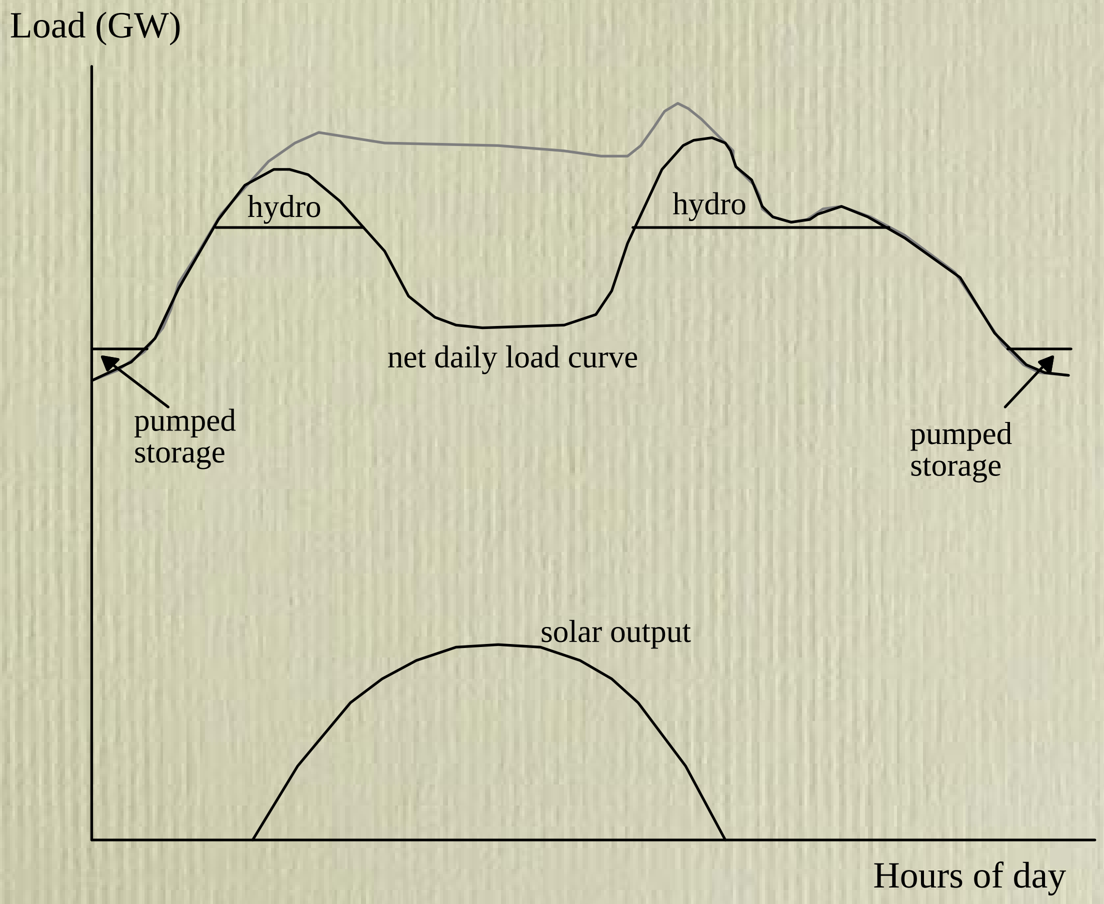
Seasonal Fluctuations

- Available sunlight does not vary greatly by season in the SW, while demand also peaks in summer.
- Following map is Dec/July means over 10 years.



Source: Institut für Solare Energieversorgungstechnik

Daily Fluctuations



- Capacity is needed to meet unexpected falls in output or demand surges.
- Balance of system capital costs depend on peak load net of solar output.
- Solar output is less peaked when panels track the sun, but this raises costs.
- For SW of US, power could be sent west in morning hours, east in the afternoons.

Spatial and Temporal Arbitrage

- High capacity HVDC (bi-directional) links between time zones, or different climates, can flatten peaks in solar output and in demand.
  - Only excess demands are traded as geographical differences in prices are eliminated through arbitrage.
- Hydroelectric capacity and pumped storage allow electricity prices to be arbitraged over time.
  - Hydrogen produced through electrolysis might be another cost-effective way to store electricity.

Transcontinental Energy Bridges

- Siberia has large coal and gas reserves and could produce 450-600 billion kWh of hydroelectricity annually, 45% of Japanese output in 1995.
  - A 1,800 km 11,000MW HVDC link would enable electricity to be exported from Siberia to Japan.
  - Siberia could also be linked to Alaska via HVDC.
- Zaire could produce 250–500 billion kWh of hydroelectricity annually to send to Europe (5-6,000 km) on a 30-60,000 MW link.
- Hydroelectric projects on a similar scale have been proposed for Canada, China and Brazil.

New Technologies Needed?

- For transfers of 5,000 MW over 4,000 km, the optimum voltage rises to 1,000–1,100 kV.
  - Technological developments in converter stations would be required to handle these voltages.
  - Lower line losses would reduce the optimum voltage.
- However, environmentalist opposition and unstable international relations may be the biggest obstacle to such grandiose schemes.