Progress on Hydrogen Hubs

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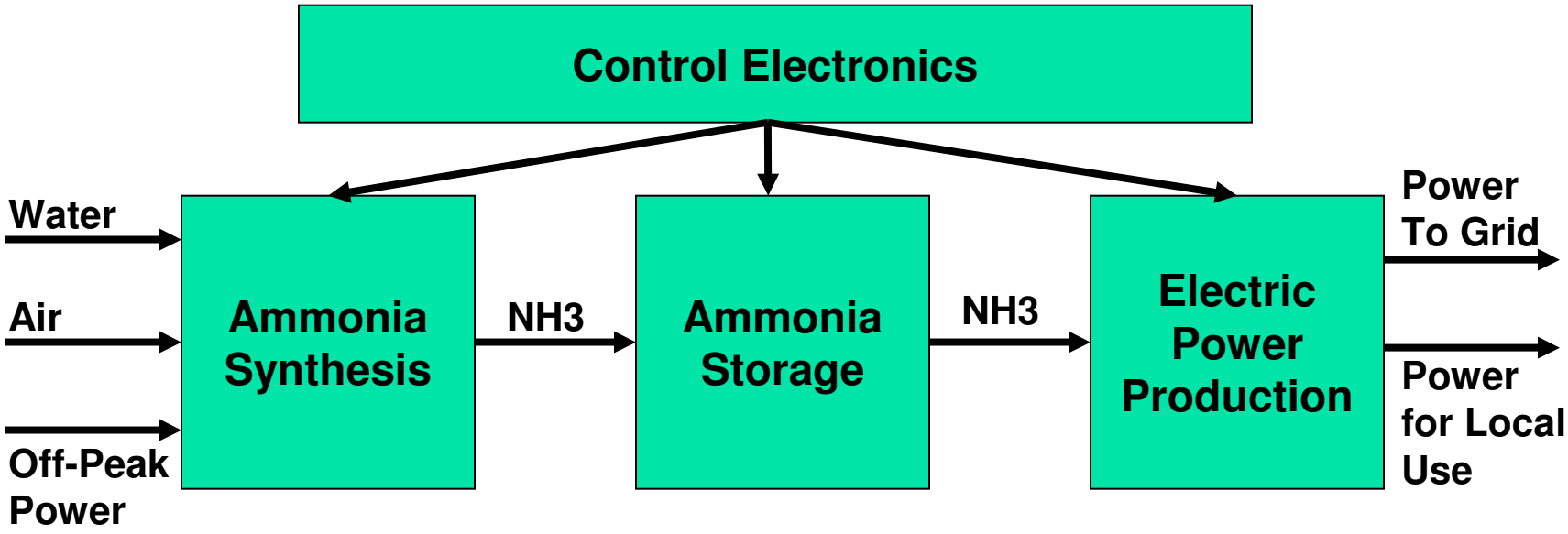
What is a Hydrogen Hub?

- Back-up or peak electricity generation using NH3 as fuel
- Synthesize and store green NH3 from cheap off-peak electricity (e.g. spring snow melt in northwest)
- ~10 MW output per Hub; duration (e.g. stored NH3) relatively short, 24 to 400 hours
- Converted diesel or gas generators; combustion turbines down the road
- Emission-free/zero carbon footprint generation
- Distributed or central NH3 production
- Fuel cost comparable or less than diesel

Hydrogen Hub Concept



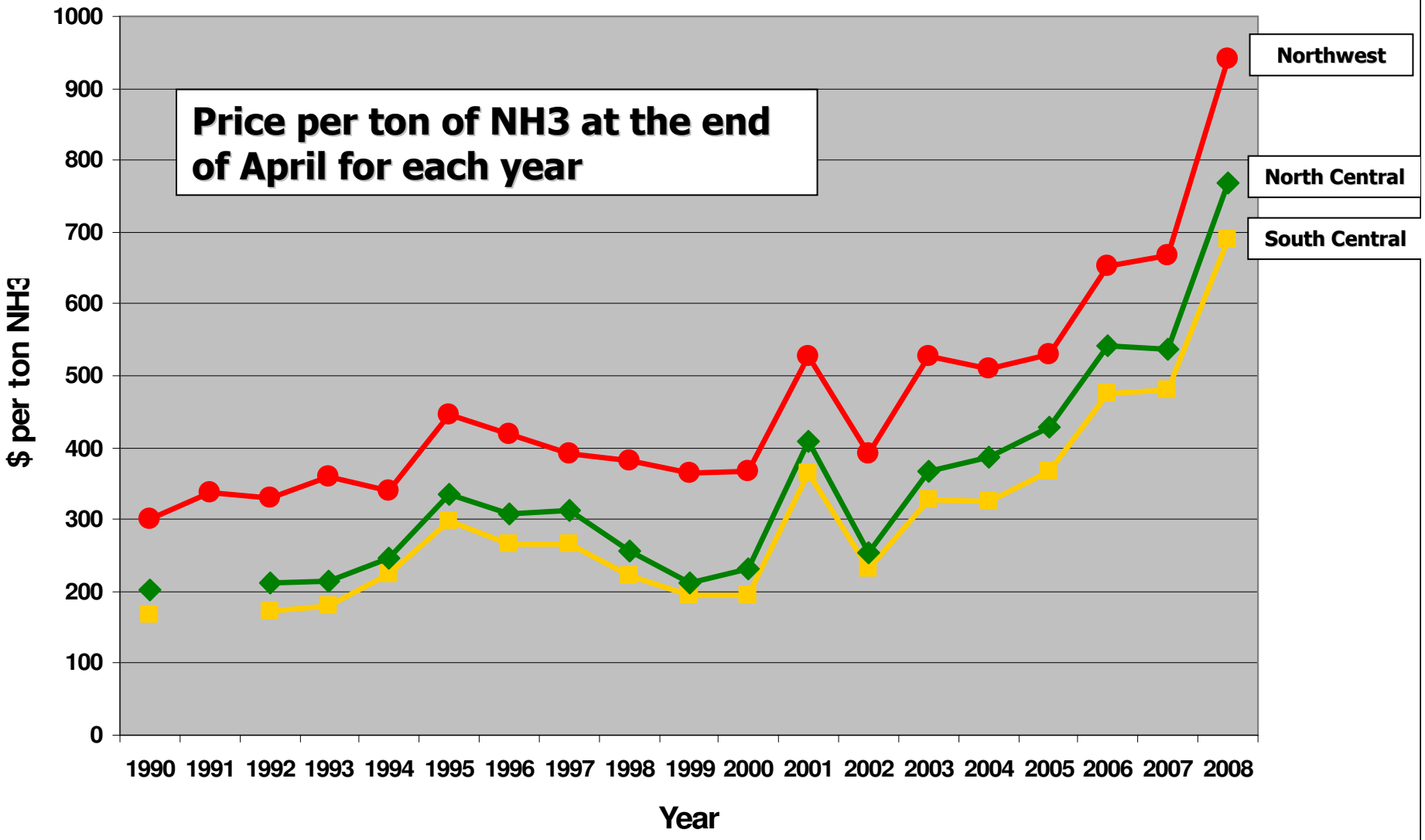
Benefits of H2Hubs

- Emission-free generation at center of load
- Avoids transmission infrastructure costs
- Domestic green NH3 synthesis -- energy independence
- Qualifies for renewable energy and carbon credits
- Can store cheaper spring Northwest energy
- Can back-up wind

Competitors

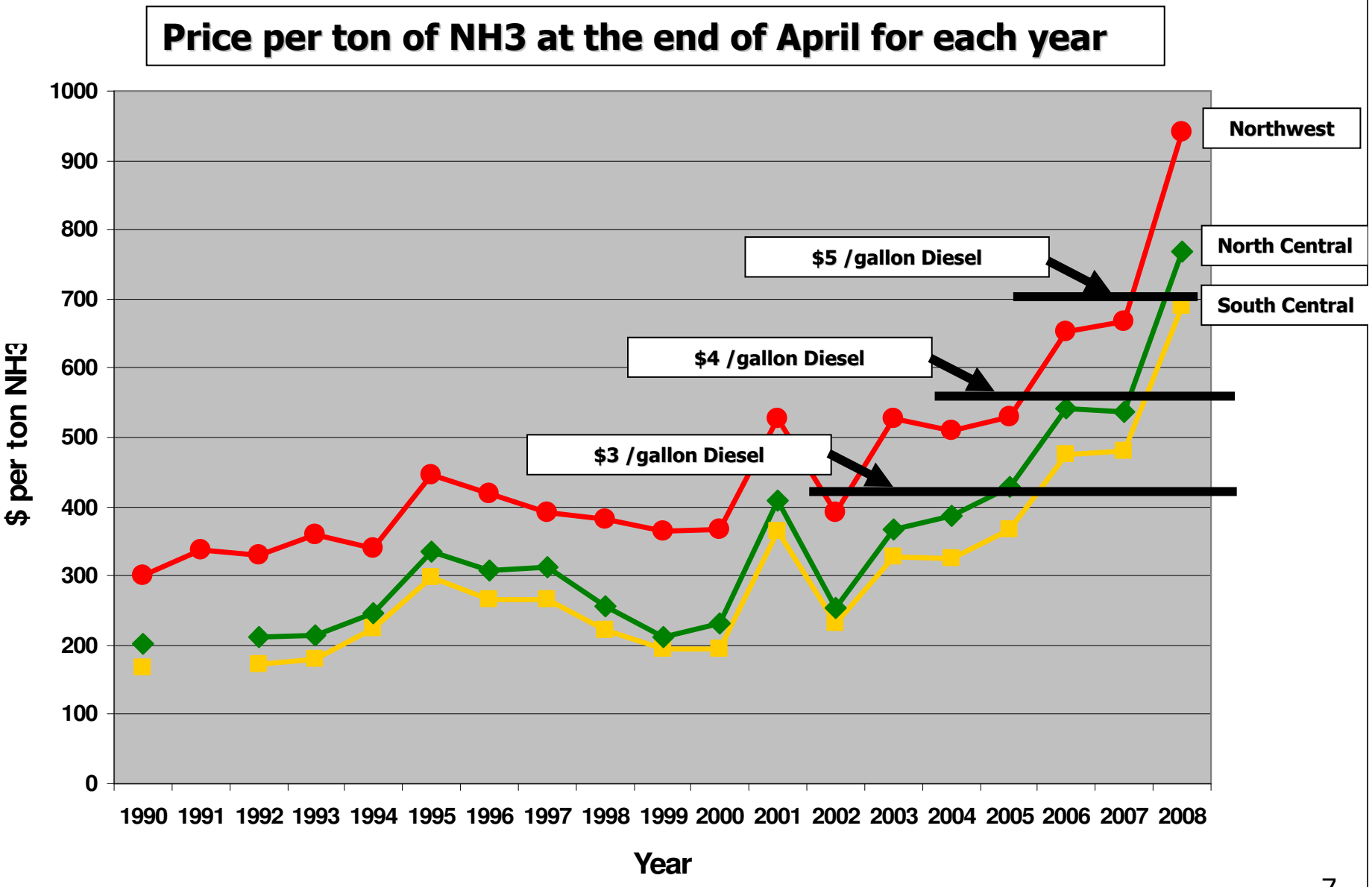
- Pumped hydro
- Compressed air
- Diesel generators
- Gas turbines peakers or wind back-up
- Additional baseload generation
  - Natural gas
  - Wind

US Ammonia Prices



Source – W-Y Huang, USDA, 2008

Ammonia Can Be Cheaper Than Diesel

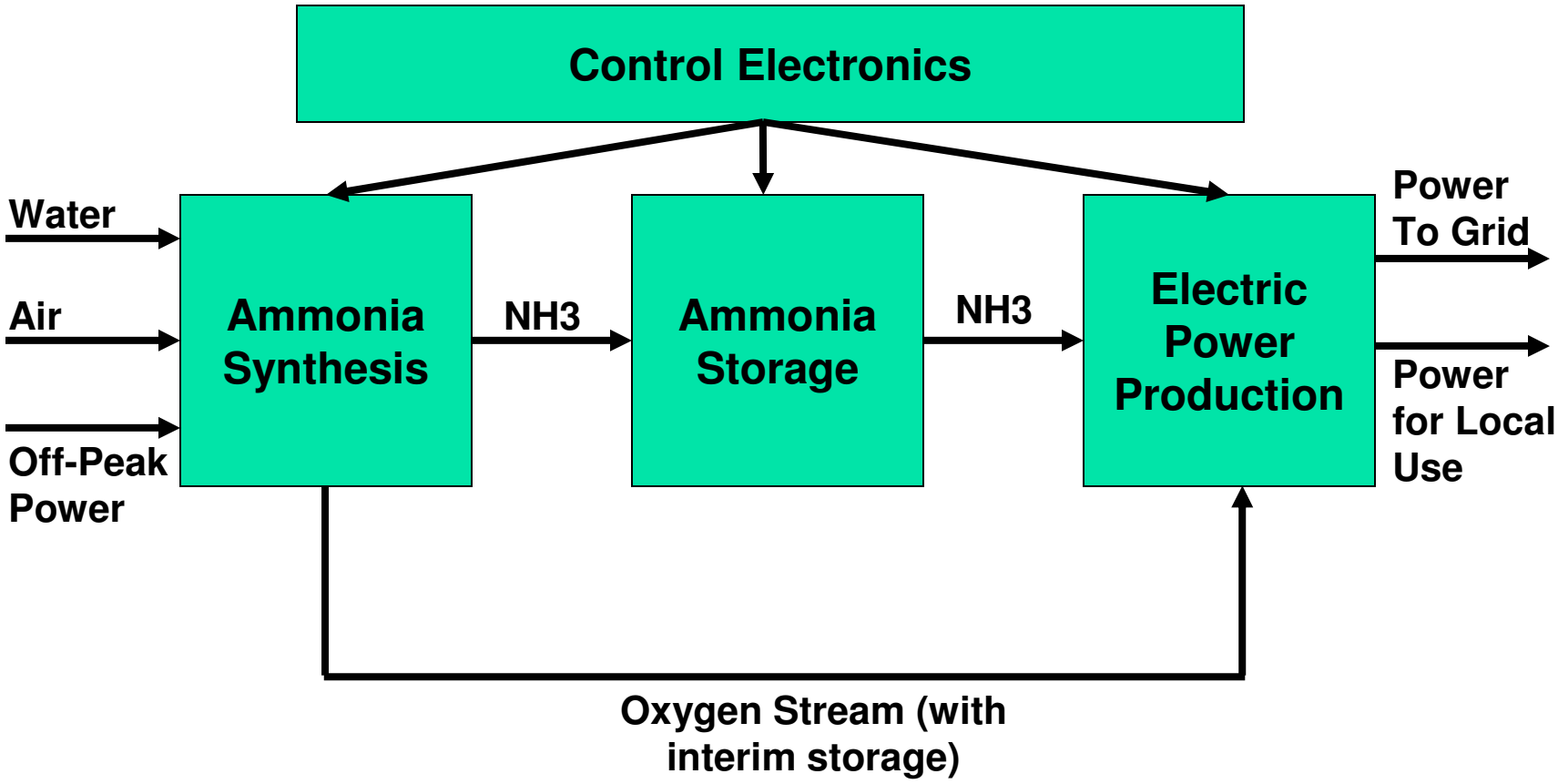


Types of H2Hubs

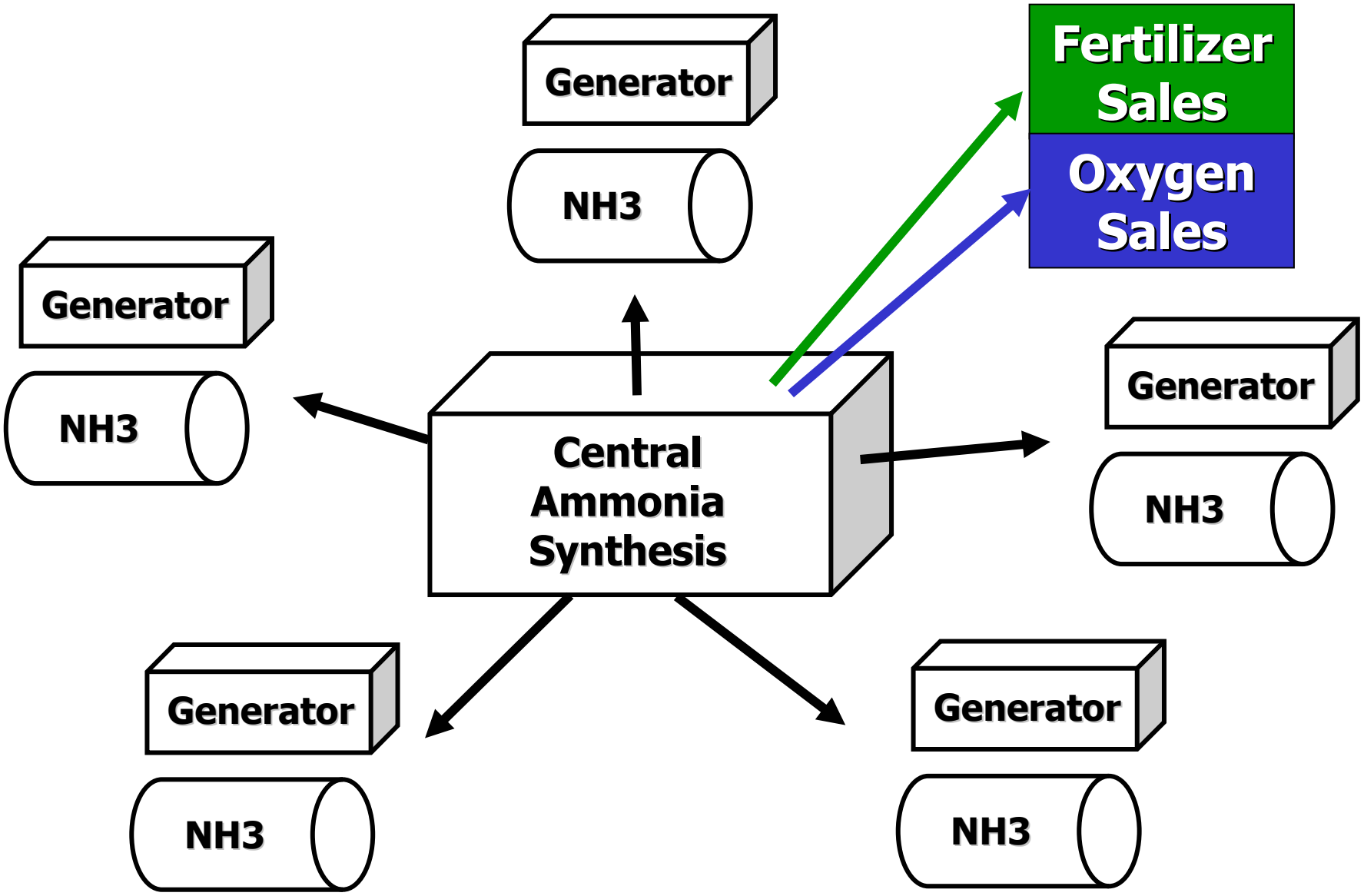
- **Distributed (On-site) NH3 synthesis**
  - NH3 synthesis/storage only part of year when electric power cheap
  - Resulting low capacity factor for synthesis equipment
  - By-product O2 stream available to increase generator efficiency
- **Central NH3 synthesis**
  - Year-round NH3 production
  - Feeds multiple generator hubs
  - Surplus NH3 sold as fertilizer
  - By-product O2 stream can be sold

Hydrogen Hub Concept

On-Site NH3 Synthesis Case



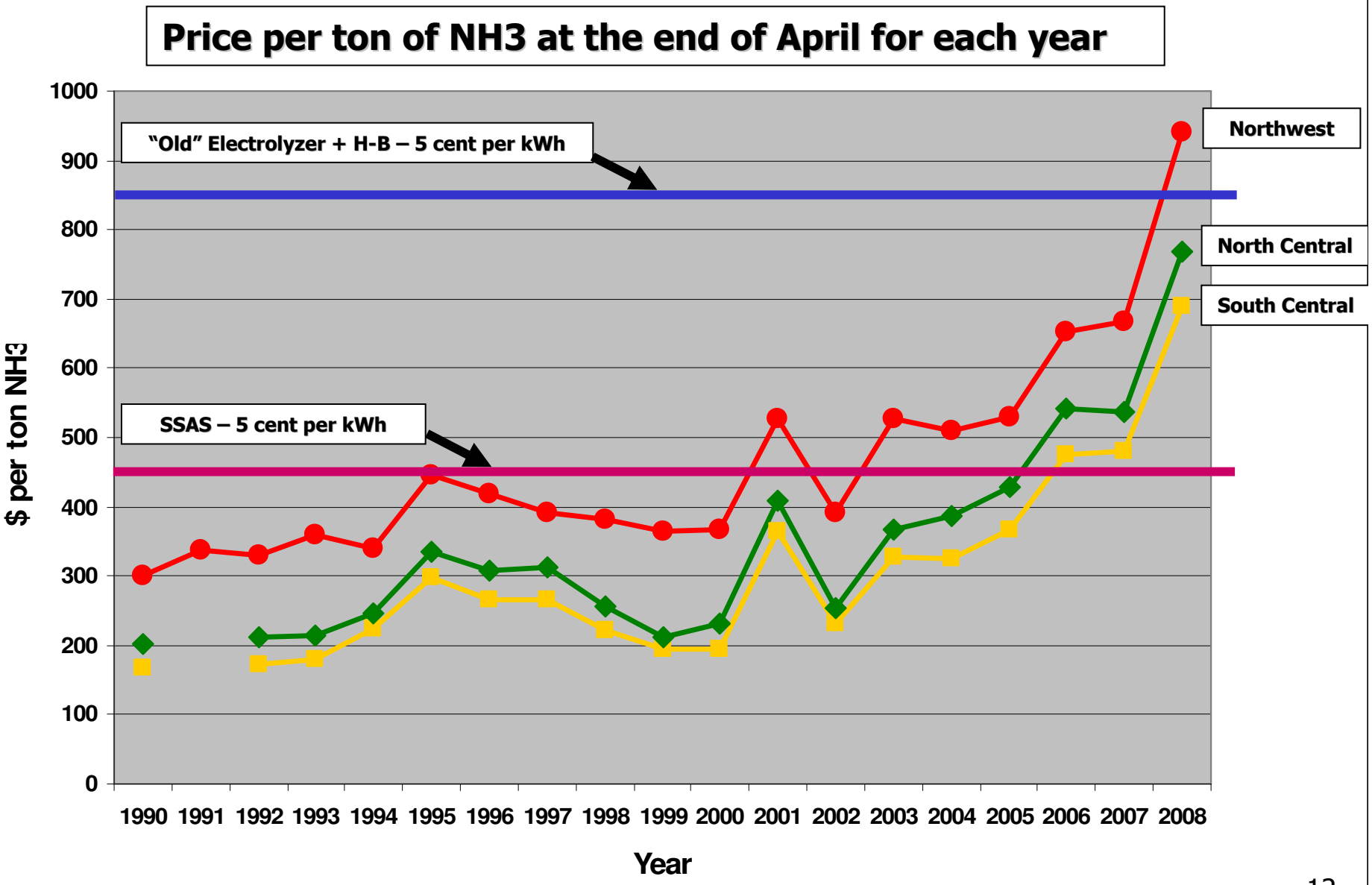
Central Synthesis/Satellite Hubs



Price of Green Ammonia will depend on Technology

- "Old" Electrolyzer + Haber-Bosch
  - ~$1.5 M per MWe capital costs
  - ~50% overall synthesis efficiency
- "Improved" Electrolyzer + Haber-Bosch
  - ~$850 K per MWe capital costs
  - ~50% overall synthesis efficiency
  - Limited availability at large scale
- Solid State Ammonia Synthesis
  - ~$650 K per MWe capital costs
  - Estimated 75% overall synthesis efficiency
  - Currently under development

US Ammonia Prices



Progress/Status

- Have met with several major northwest utilities and BPA
- Favorable reaction, and interest, particularly in green aspect of generation near population centers
- H2Hub approach "pencils out" cost-wise with other back-up and peaking solutions
- Generally more interest in centralized H2Hub architecture for better capacity factor, better use of capital