Energy Alternatives for Sustainable Prosperity

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Canada

AECL Atomic Energy of Canada Limited

EACL Énergie atomique du Canada limitée

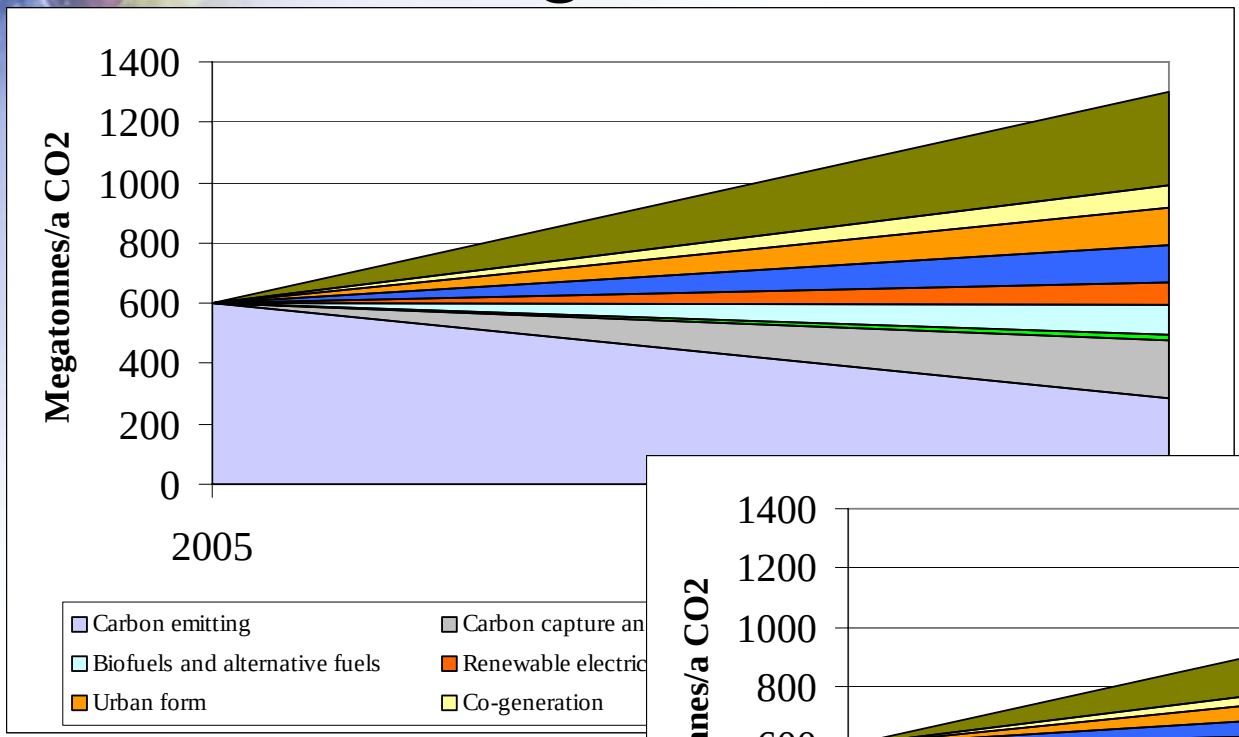
Focus of Presentation: Making Hydrogen Using Nuclear

- Reminder of why we need hydrogen (H_2) as a fuel
  - Water electrolysis is a low CO_2 emitter *if electricity comes from a suitable source*
- Look at costs of making H_2
  - By SMR, with a realistic natural gas price and CO_2 capture & storage
  - By continuous electrolysis
  - By intermittent electrolysis
  - Mixing in electricity from wind power
  - High-temperature thermochemical processes

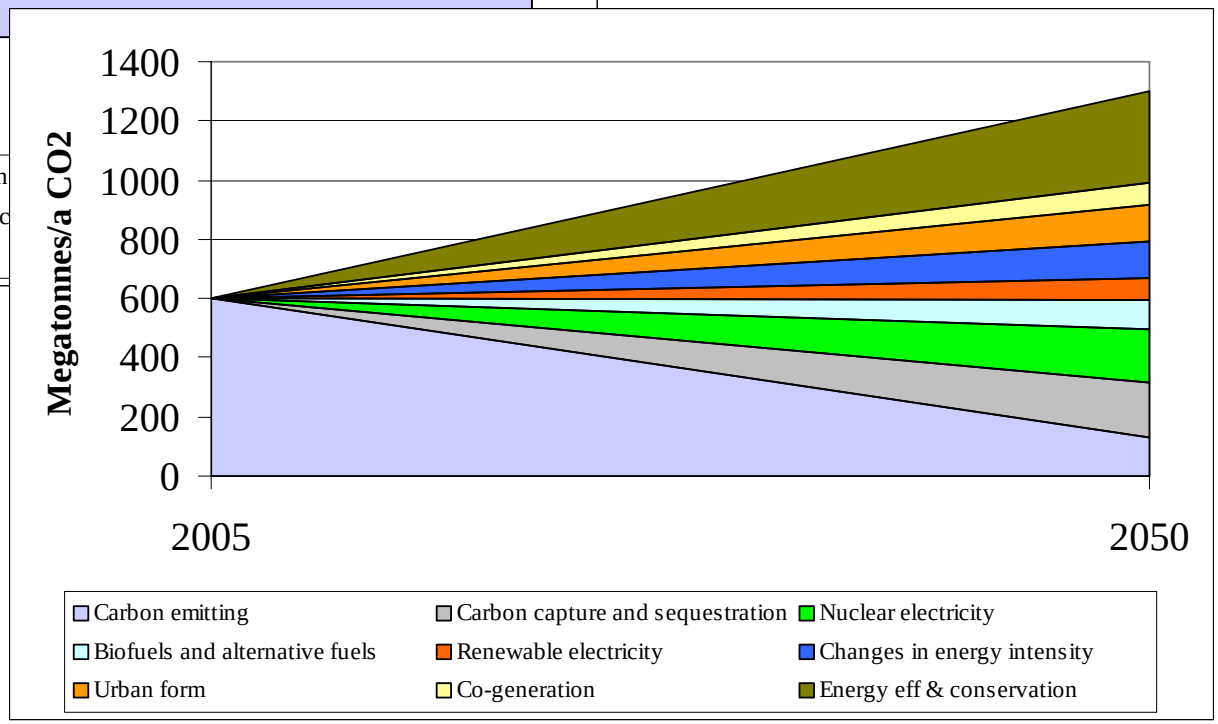
Overall Perspective

- The Earth is experiencing a surging epidemic of greenhouse gas emissions
  - CO_2:
    - 280 ppm (pre-industrial)
    - 315 ppm by 1958
    - 385 ppm now
    - Rise now exceeds 2 ppm/a
      - May be already in trouble
      - Need to stabilize
    - 450 ppm would be a good target
    - 550 ppm likely to cause huge disruptions
- Need to cut emissions to about 40% of 1990 levels

Placing Canada in Global Context



As in NRTEE:
⇐50% reduction



NRTEE + large nuclear deployment: 75% reduction ⇒

Canada's Energy Distribution

	(PJ)	(TW.h)	% Total
Residential/Agricultural	1677	466	21.9
Commercial/Government	1166	324	15.2
Industrial	2701	750	35.2
Transportation	2130	591	27.8
TOTAL	7674	2132	100.0
Of which electricity	1972	548	25.7
Of which carbon-based electricity	385	107	5.0

Transport? – Electricity and Hydrogen

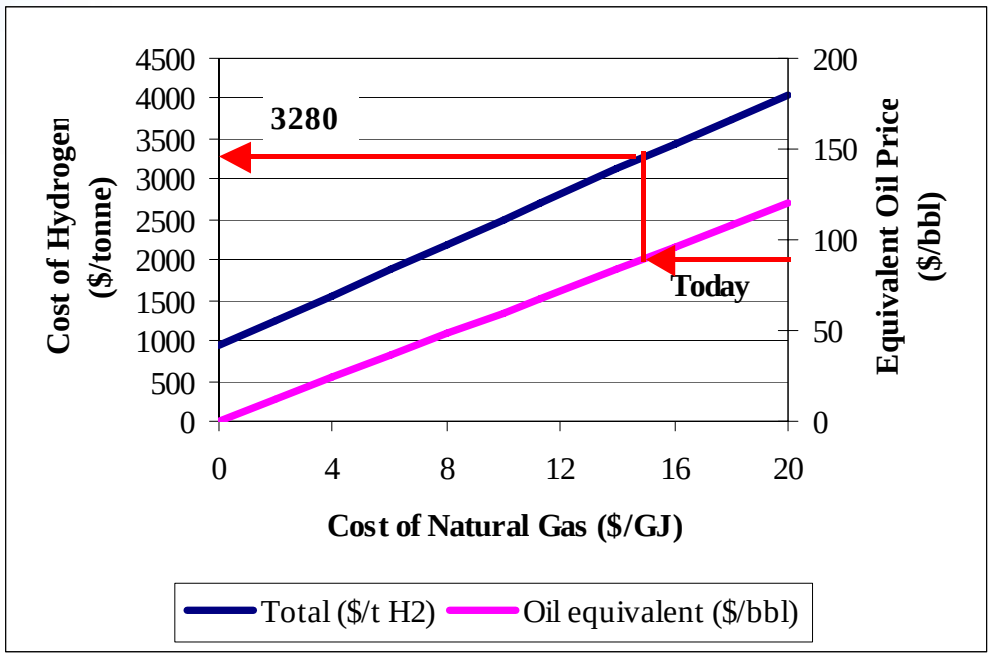
- Electricity and hydrogen both need a primary source
  - We must tackle transport (25+% of emissions): these are the choices
    - Biomass won't do the heavy lifting
  - Electricity & hydrogen both need a near-zero CO_2-emitting source
    - Electricity from a low-emitting source is very attractive
- Electricity or hydrogen? Flexibility would be useful
  - Deeply pluggable hybrids will likely take a good chunk of the light vehicle market
  - Heavier duties (trucks, ships, trains) will need hydrogen
    - For most Canadian routes, rail electrification is not cost-effective
    - Planes? Perhaps but later
      - Conservative industry with long lead times
      - Unresolved issue of adding more water vapour to the higher atmosphere

Hydrogen from Nuclear

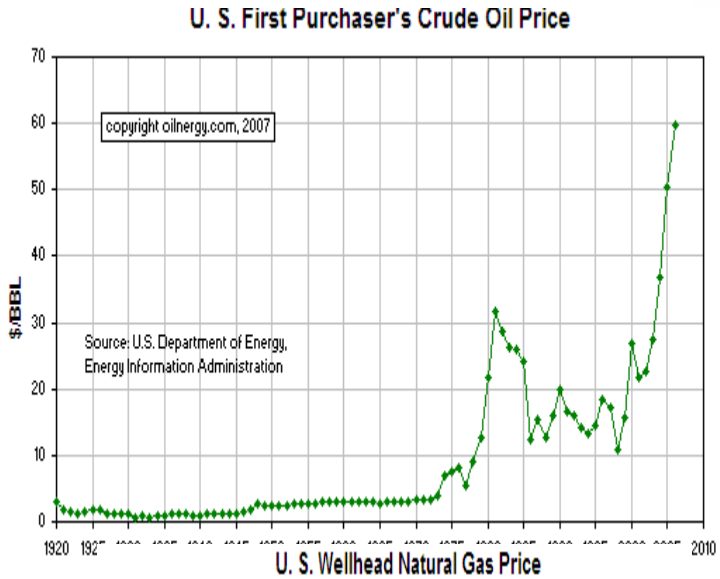
- Central Issues:
  - Is it price competitive?
    - ✓ Can use intermittent production at off-peak prices
    - ✓ Fits well with nuclear replacing coal since uninterrupted nuclear is best
  - Will the price be stable?
    - ✓ Yes
  - Is it environmentally friendly?
    - ✓ Near-zero CO_2
    - ✓ Waste amounts are very small
      - 100 g U from a CANDU = 1 tonne methane = 3 tonnes CO_2
      - 14 mL U_3O_8 = 1500 m^3 CO_2 at ambient pressure (eight orders of magnitude)
  - With intermittent production, can one achieve continuity of supply?
    - Either use H_2 storage in underground caverns
      - Unusual but ICI have done on Teesside for 30 years
    - Or embed in a larger H_2 system

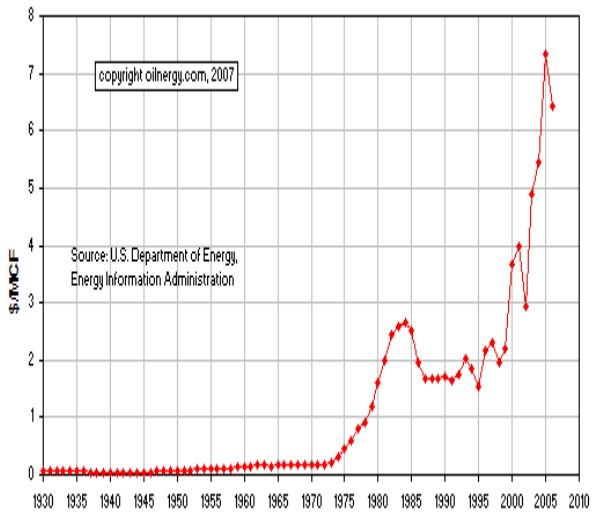
Cost of Hydrogen by Steam-Methane Reforming (SMR)

- Basis
  - 400 $/t for capital and operation
  - 70 $/t CO_2 for capture and sequestration (allowing for collateral CO_2 emissions)
  - 1 bbl oil = 6 GJ of natural gas



3280 $/tonne H_2





Cost of Continuous Electrolytic Hydrogen

- ~50 MW.h per tonne
- Cells cost 550 $/kW or ~ 365 $/t H_2

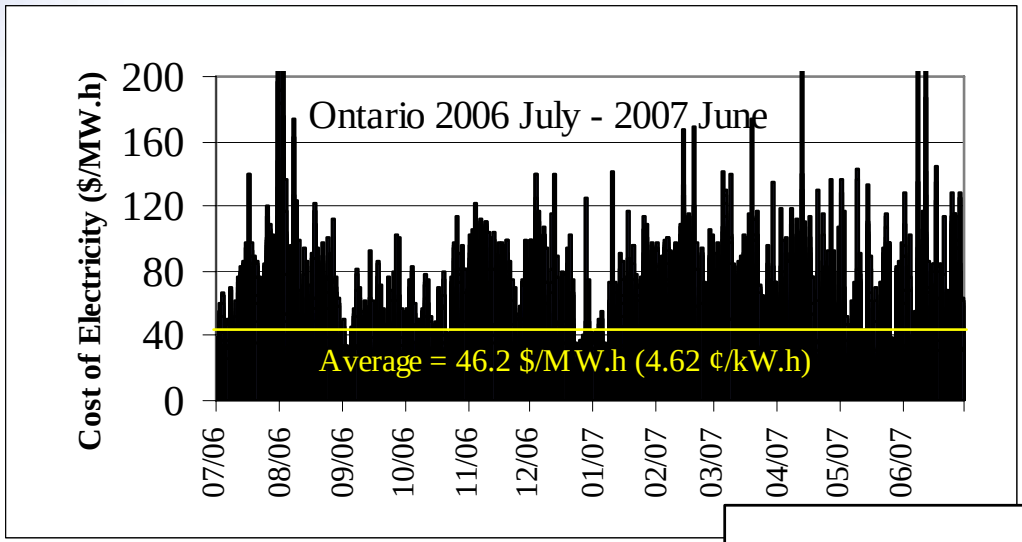
  (using 11.7%/a capital recovery – 10%/a over 20 years)
- Operation adds ~ 137 $/t H_2
- (Electricity costs 2310 $/t H_2

  (using average 2006/7 Ont. grid price)

} ~ 2800 $/t H_2

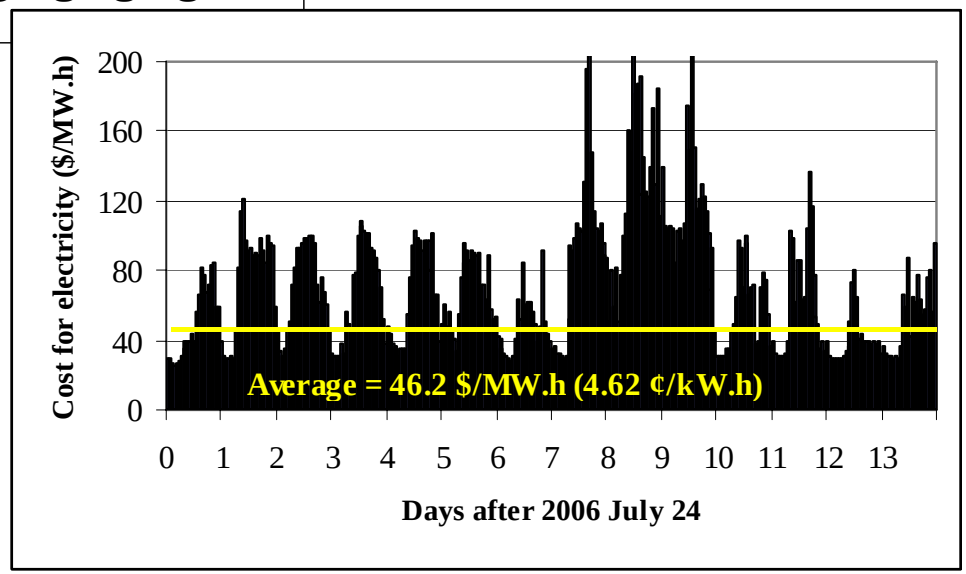
- <u>Value H_2 at 3280 $/t</u>
- Do-able but 2006/07 was an unusually a low-price period

The Price of Electricity Varies



Typical detail →

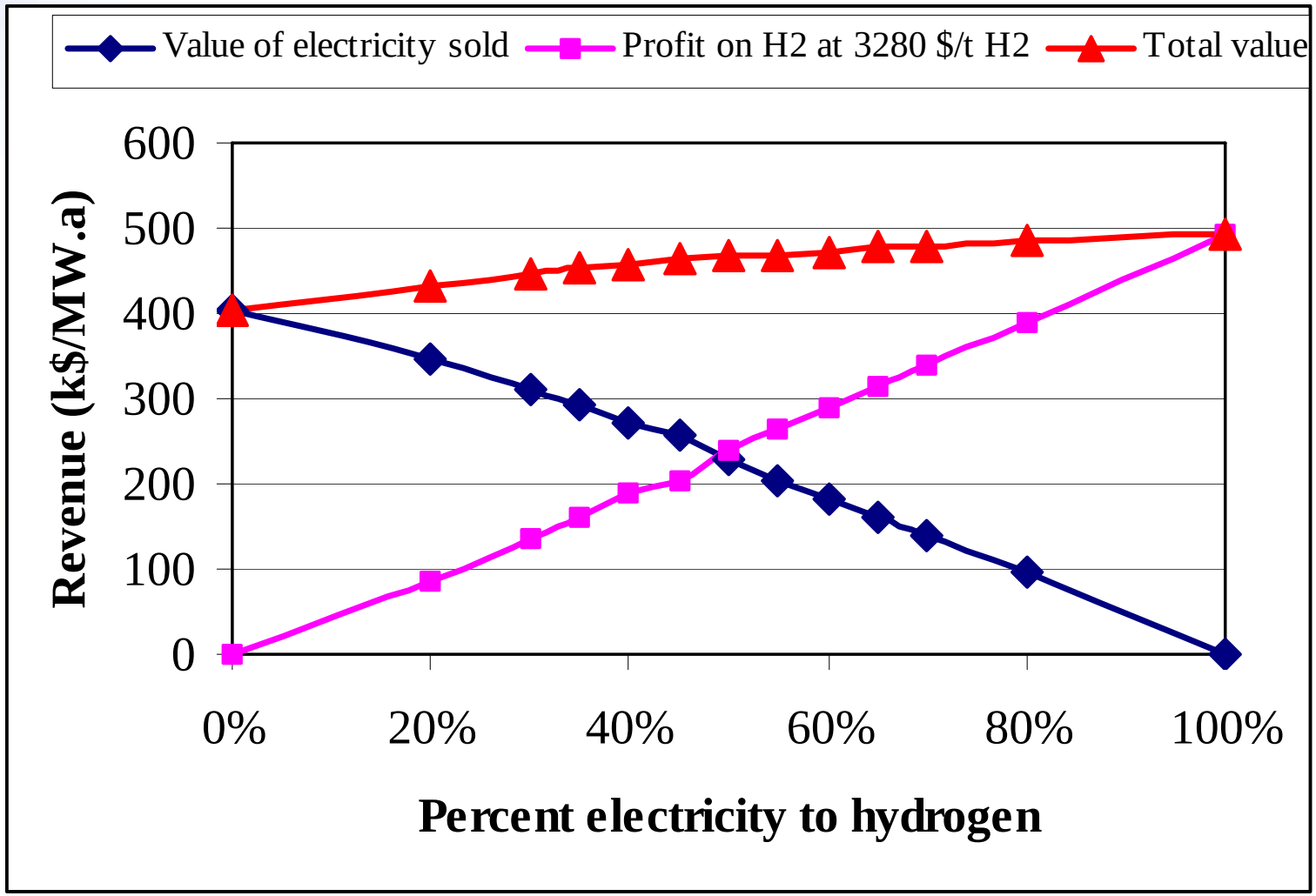
Late July/
Early August



Making hydrogen intermittently

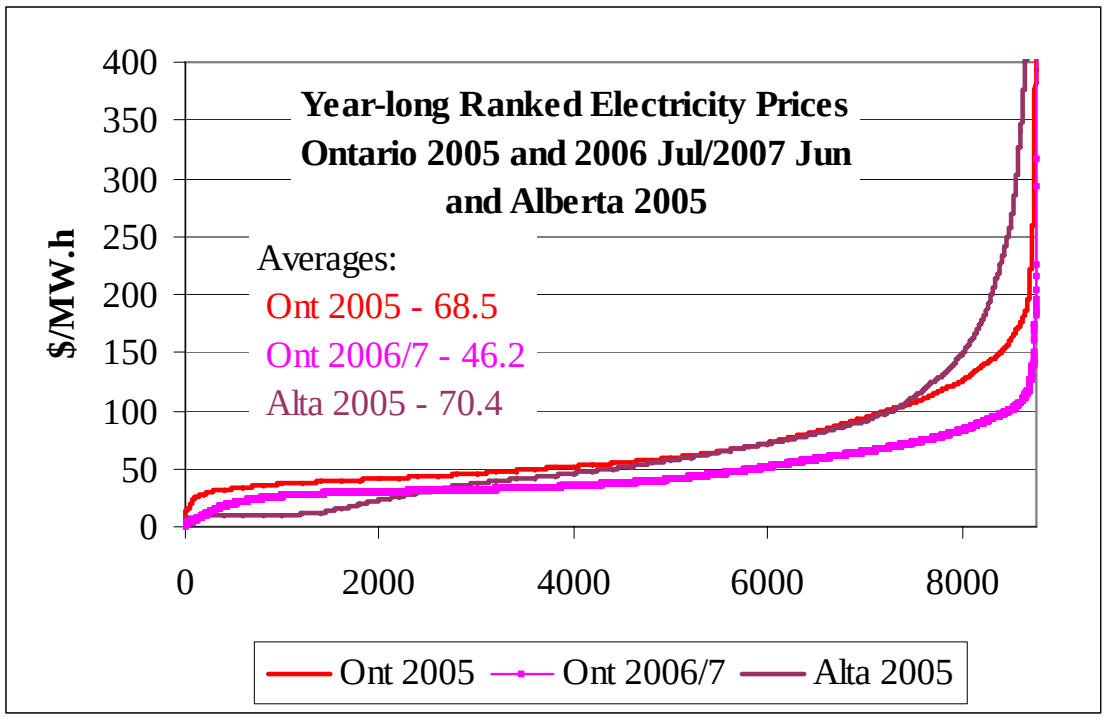
- Take real price data from Ontario (IESO)
- Set a conversion level for whole year
- Provide salt cavern storage (assumed 5000 $/t)
- Use cells with some flexibility to vary current density
  - range of +/- 17%
    - which mildly influences cell voltage
- Feed data to a large EXCEL spreadsheet and optimize cost
  - Vary grid cost above which electricity will be sold
  - Vary cell capacity
  - Vary storage capacity
  - Never empty storage

Revenue from Electricity and H_2



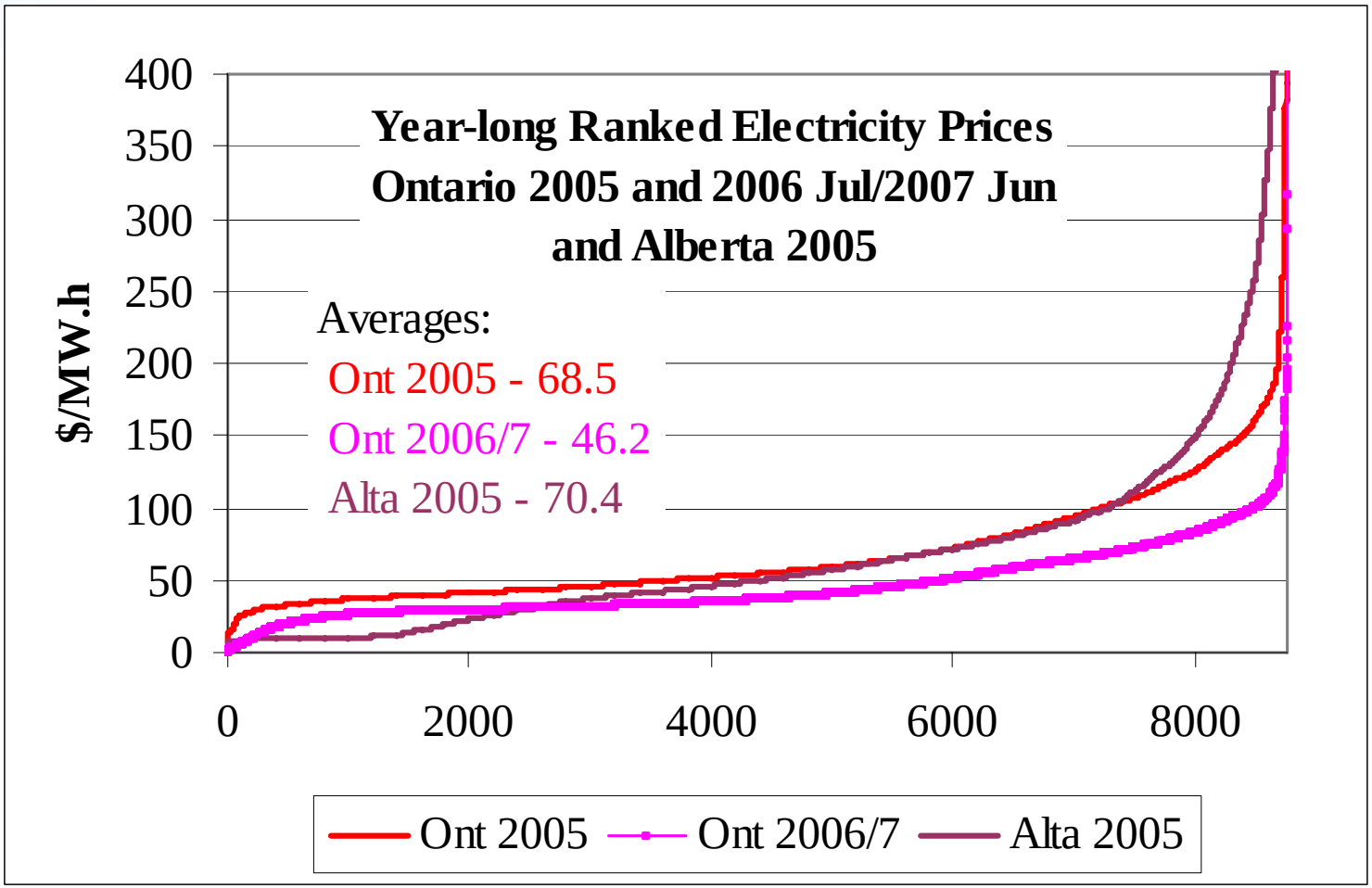
Will it pay?

- Depends on the hydrogen value, of course
  - At \$3280/t H_2, any amount of hydrogen is more profitable than selling electricity
  - True for up to ~40% conversion down to about \$2500/t H_2
- Ontario electricity costs were unsustainably low in 2005/6
  - Averaging 46.2 \$/MW.h
  - Averaged 68.5 \$/MW.h in 2005
- Price spreads as it average rises
- Replace coal with nuclear and price spread will rise more

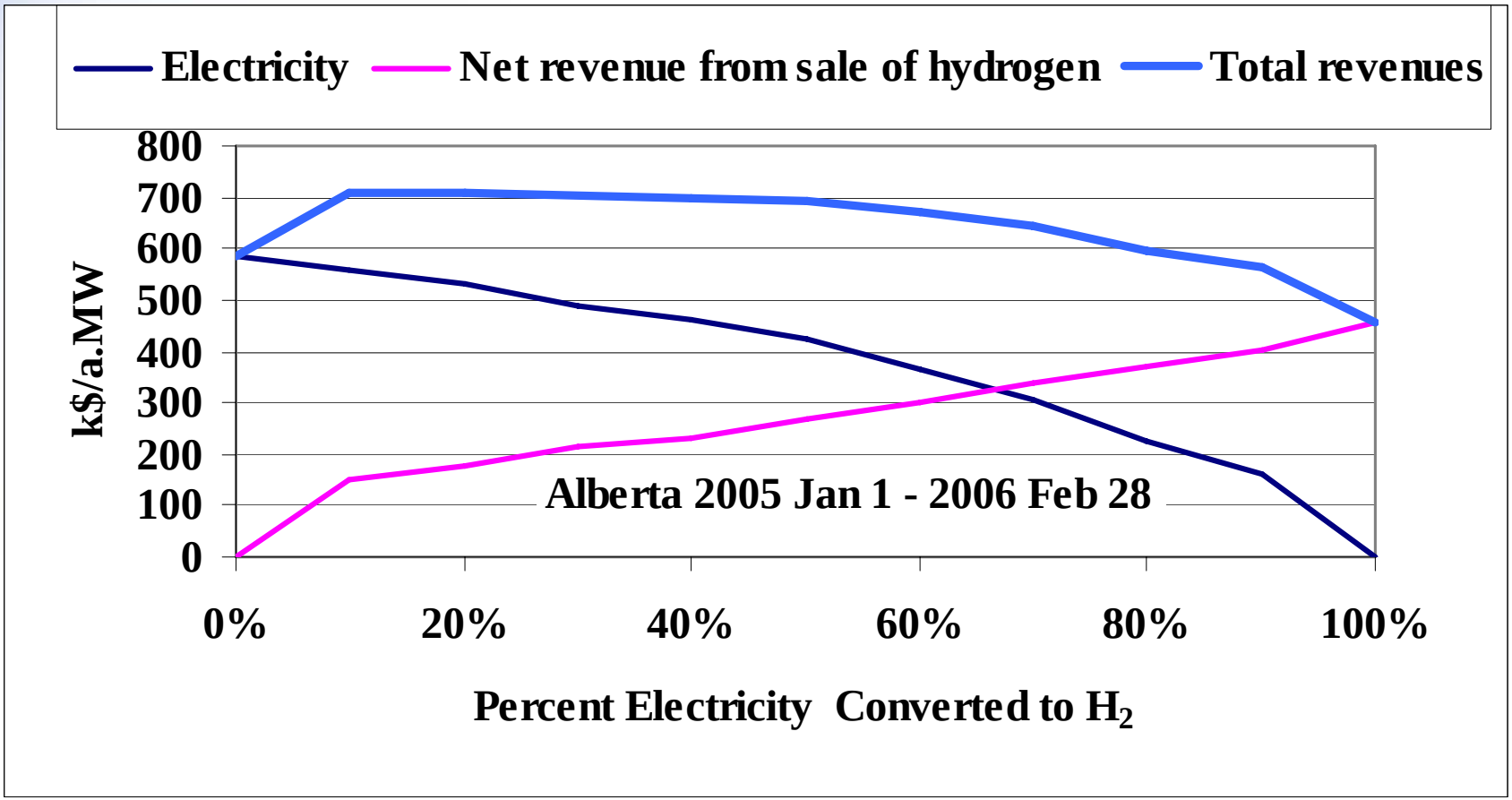


Electricity prices vary …

… but systems under strain can show bigger range



Alberta in 2005



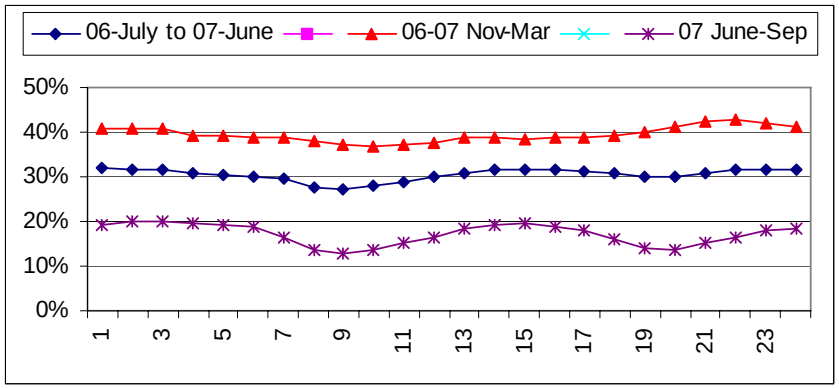
What of the future?

- Analyses for both Ontario and Alberta give positive results for intermittent electrolytic hydrogen despite substantial variations in average prices of electricity
- Replacing load-following coal-fired stations with nuclear plants running continuously will tend toward increasing the range of peak – off-peak prices
- Can this scheme be extended to include wind-generated electricity?
  - Replace 20% of the electricity from nuclear with electricity from typical Ontario wind

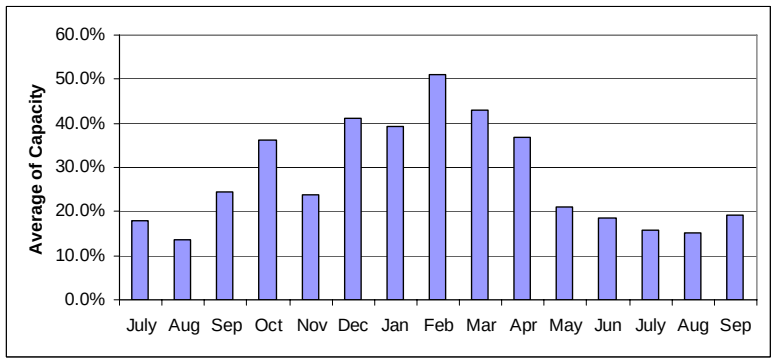
Converting wind-derived electricity to H_2

- The three longest-established Ontario wind farms achieved 30.4% of nameplate capacity in 2006 July – 2007 June; a good performance

- Varies extensively:
  mild daily
  biases



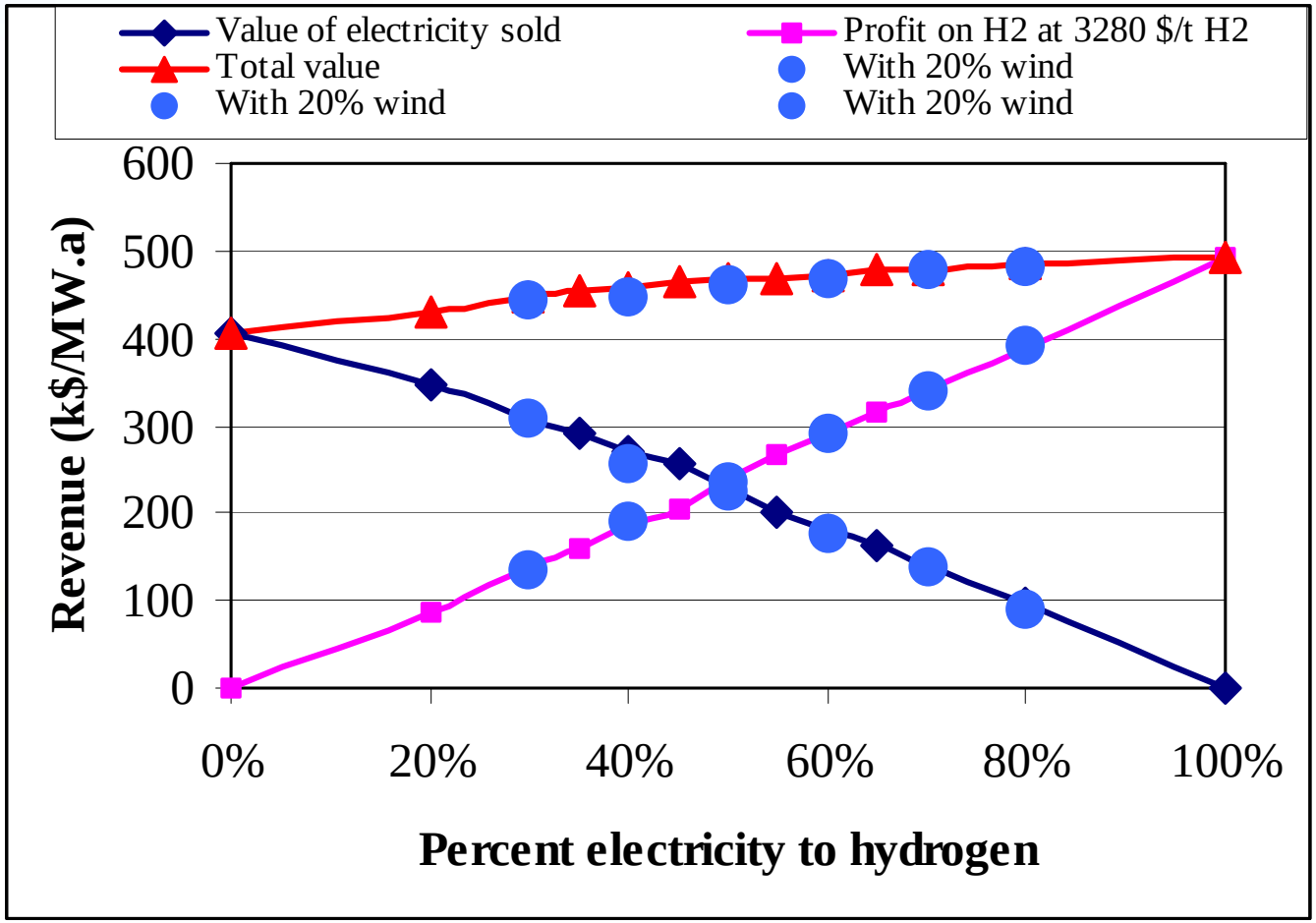
- and severe seasonal
  ones



Hydrogen from wind-produced electricity alone is very expensive

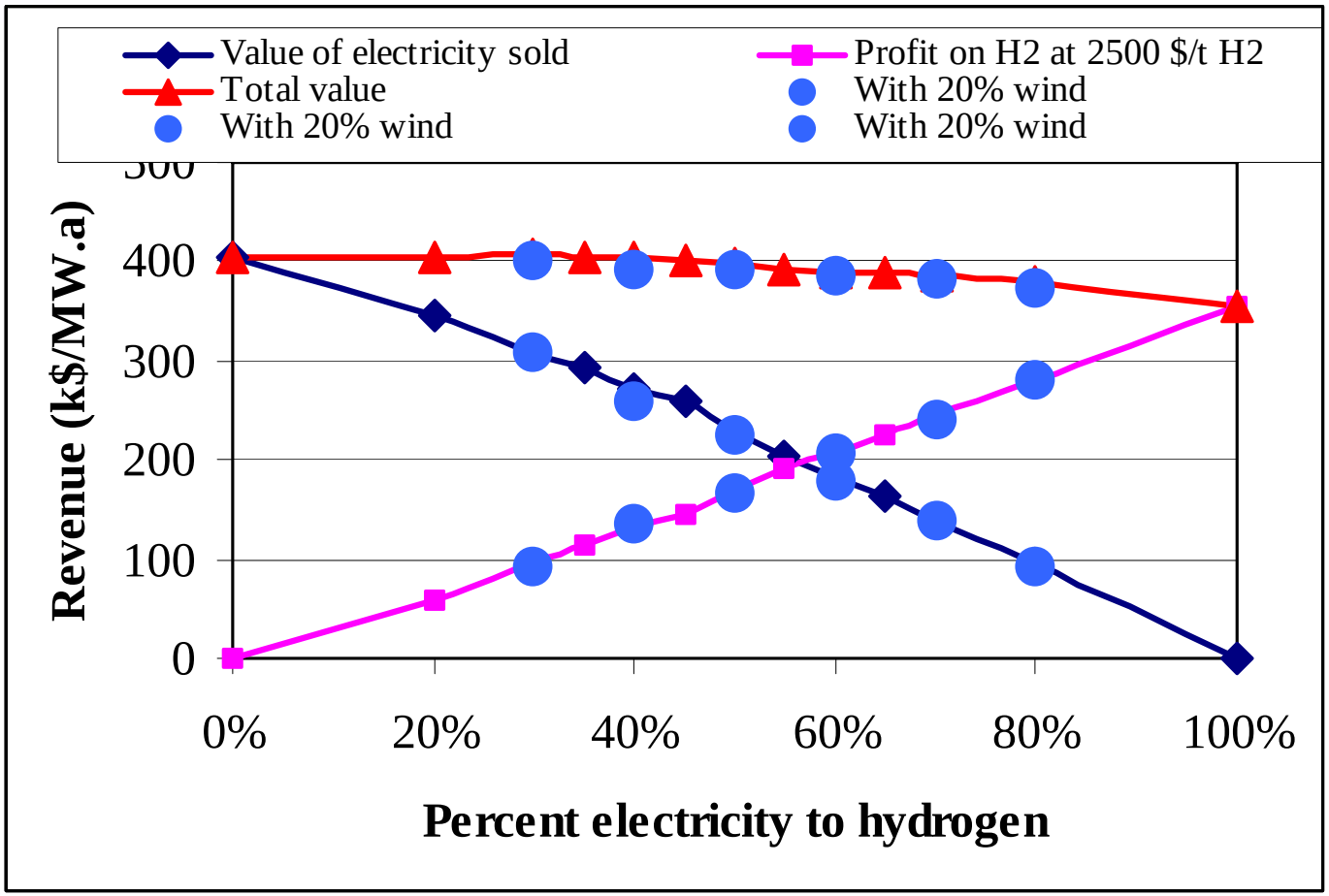
• Needs 234 days storage to maintain supplies from April to December (compared to ~2 days for an unvarying power source)	318 $/t
• Needs cell capacity 3.3 times more cell capacity	1197 $/t
• 3.3 times higher operating cost	450 $/t
• No benefit from power interruptibility	2282 $/t
• TOTAL	4247 $/t

But 20% wind and 80% nuclear blend easily with intermittent conversion



Only very slightly higher cost than nuclear alone

Even at $2500/t H_2



Revenues in k$/MW.a

Converted to H2	Value of electricity sold	Profit on H2 at 3280 $/t H2	Total value	With 20% wind	With 20% wind	With 20% wind
100%	0	493	493			
80%	97	390	486	91	392	483
70%	139	341	480	140	339	479
65%	162	315	477			
60%	181	291	472	178	290	469
55%	202	266	468			
50%	228	239	467	224	237	461
45%	258	205	463			
40%	271	188	458	258	191	449
35%	292	161	453			
30%	310	137	447	308	135	443
20%	346	85	432			
0%	405	0	405			

Thermochemical Hydrogen

- High-temperature water splitting
  - Numerous possibilities with temperatures between 500 and 850°C
  - Early stages of development
  - May never be economic
- A future possibility but they won't be deployable until late 2020s
- Helium-cooled Very High Temperature Reactors (VHTRs) do not have containment

Intermittent electrolysis including wind looks promisingly competitive for near future

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