Multi-Sourced Electricity for Electrolytic Hydrogen

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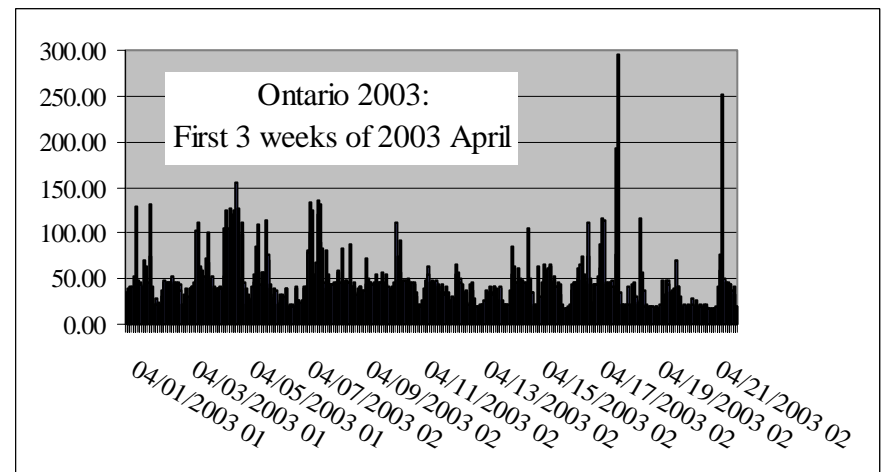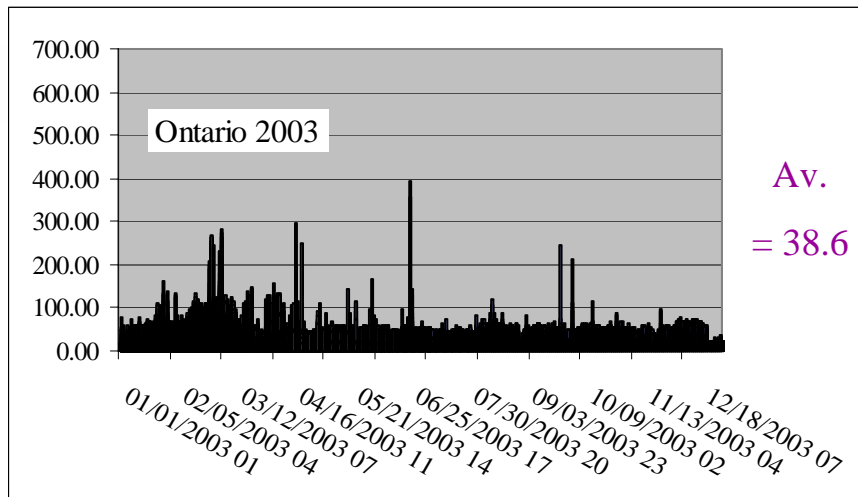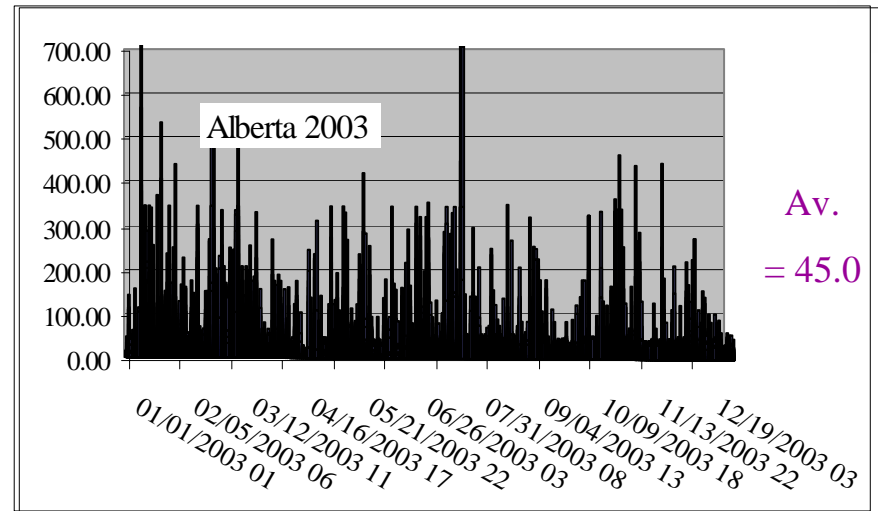EACL Énergie atomique du Canada limitée

Overview

- Economics of making H_2 from advanced nuclear by selling a mix of electricity and H_2

- Blending wind generation with nuclear
  - Accept extra current when available
  - Either to sell or convert to H_2
  - Avoids need for back-up generation
  - Simplified treatment with wind either on or off
  - For simplification, look at generation close to electricity source

- Encouraging results
  - Easily meets DOE's 2 $/gge target (2000 $/t H_2)

Non-Polluting Hydrogen for the Hydrogen Age

✓ Objective is non-polluting transport

   – Eliminate local pollution

   – Eliminate CO_2 emissions

✓ Source of H_2 production must be non-emitting

   – Nuclear and wind satisfy this requirement

✓ Electrolytic route is available and easy to deploy on all scales

   – Exploit fluctuation in electricity prices

  ✓ H_2 must be affordable

     • Using USDOE target (at production site) of 2 $/gge = 2000 $/t H_2

Fluctuating Electricity Buying Prices in Open Markets (US$/MW.h)

Alberta 2002 — Av. = 29.3

Alberta 2003 — Av. = 45.0

Ontario 2003 — Av. = 38.6

Ontario 2003: First 3 weeks of 2003 April
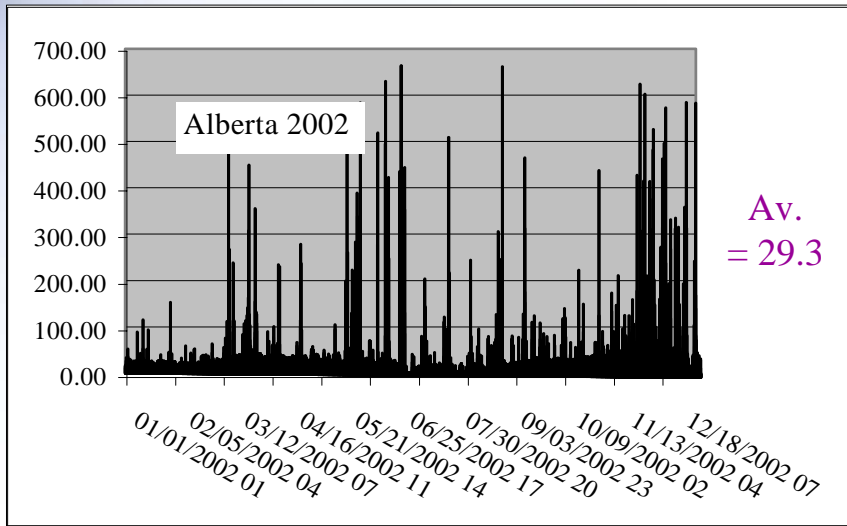
Exploit the Variation to Sell H_2 and e^-

- **Electricity production costs must be low**
  - 3 US¢/kW.h
  - Expected to be available from either wind or advanced nuclear
- **Sell as electricity when grid price is high**
- **Make H_2 when the grid price is low**
  - Needs enlarged electrolysis capacity to catch up
  - Needs H_2 storage
- **Electricity used for electrolysis could sometimes be sold for more but:**
  - More stable revenue stream with H_2 and e^- co-products
  - New off-peak capacity does not undermine the market price
  - Gives desired return on investment

Is AECL's ACR Electricity Cost Target Realistic?

– The target for AECL's ACR™ is ~ 3 US¢/kW.h at generation

- Based on Qinshan experience
- Gain 5% on conversion efficiency (higher pressure/temperature)
- Saving 7.5% on less D_2O;
- 6% with smaller core size;
- 11.5% on simplification, elimination, better materials;
- 5% on BOP optimization; and
- 10% with modularization, construction advances, engineering tools

Turning e⁻ into H_2

- Prices in open electricity markets are very variable
  - Not just by the hour and the day but from year to year
- With 3 US¢/kW.h electricity, could a reactor owner smooth the market by selling a blend of electricity (at times of peak demand and price) and hydrogen at other times and make a good profit?
- Set a H_2 production rate (as a proportion of all-H_2 production)
  - Apply to actual hourly electricity price data and minimize cost of H_2 production while maintaining constant H_2 supply by optimizing:
    - The size of the electrolysis installation
    - The size of storage
   - Rules on when to switch on electrolysis

  - Value H_2 at 2000 US$/tonne (the DOE's centralized plant

Electrolytic Hydrogen

- Focus on low-cost electrolysis
  - 300 US$/kW
  - Accept some premium on electricity use (total equivalent to 2 volts or 53.6 kW.h/kg H_2)
- Storage
  - Use 400 000 US$/tonne H_2 for tube-trailers
  - Store at least 12-hours of average demand
- Optimize
  - Cheaper power
    - $=$ Less time on-line
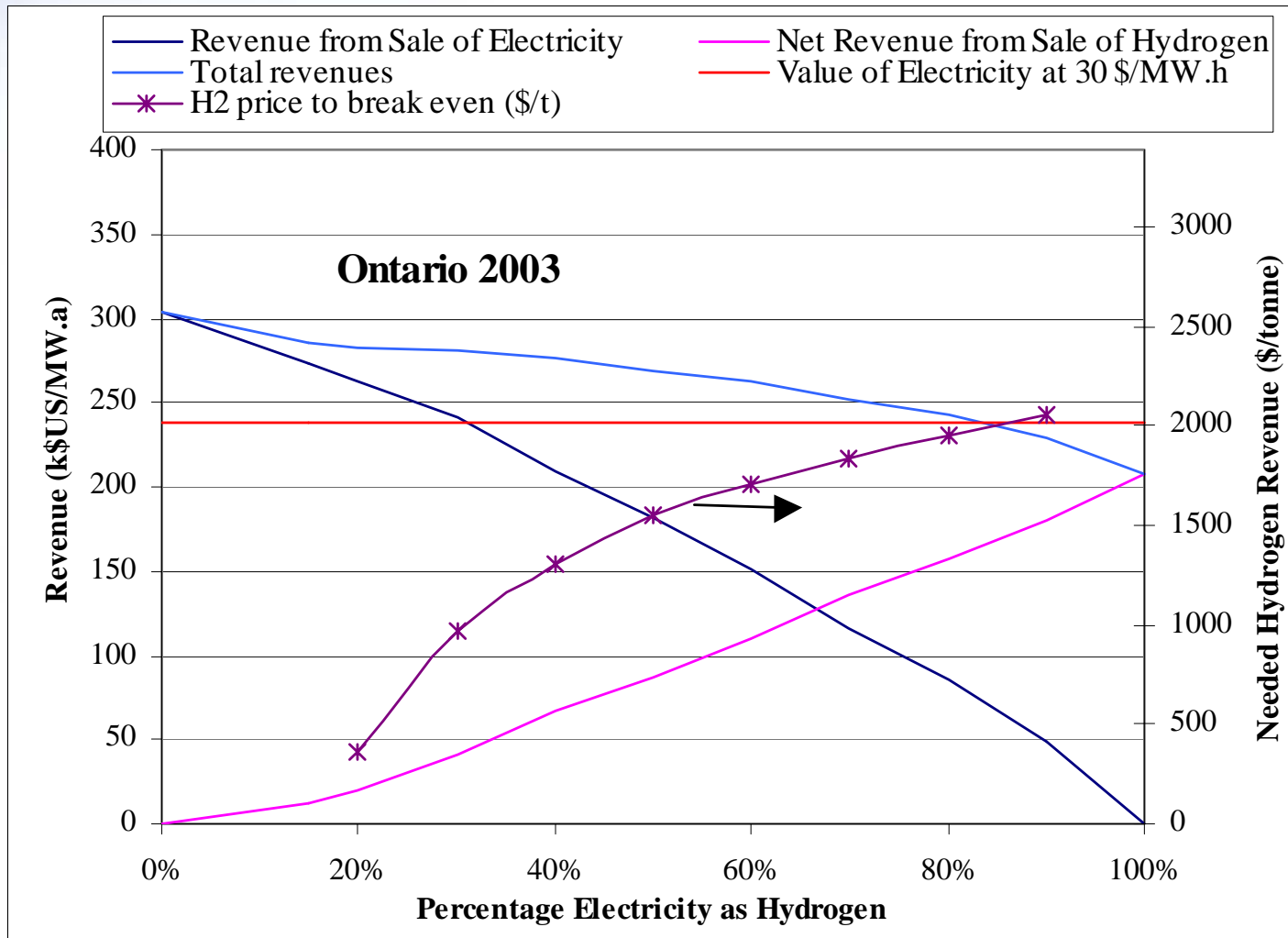   - $=$ More electrolysis cells
    - $=$ More storage

Making H₂ Electrolytically in Ontario
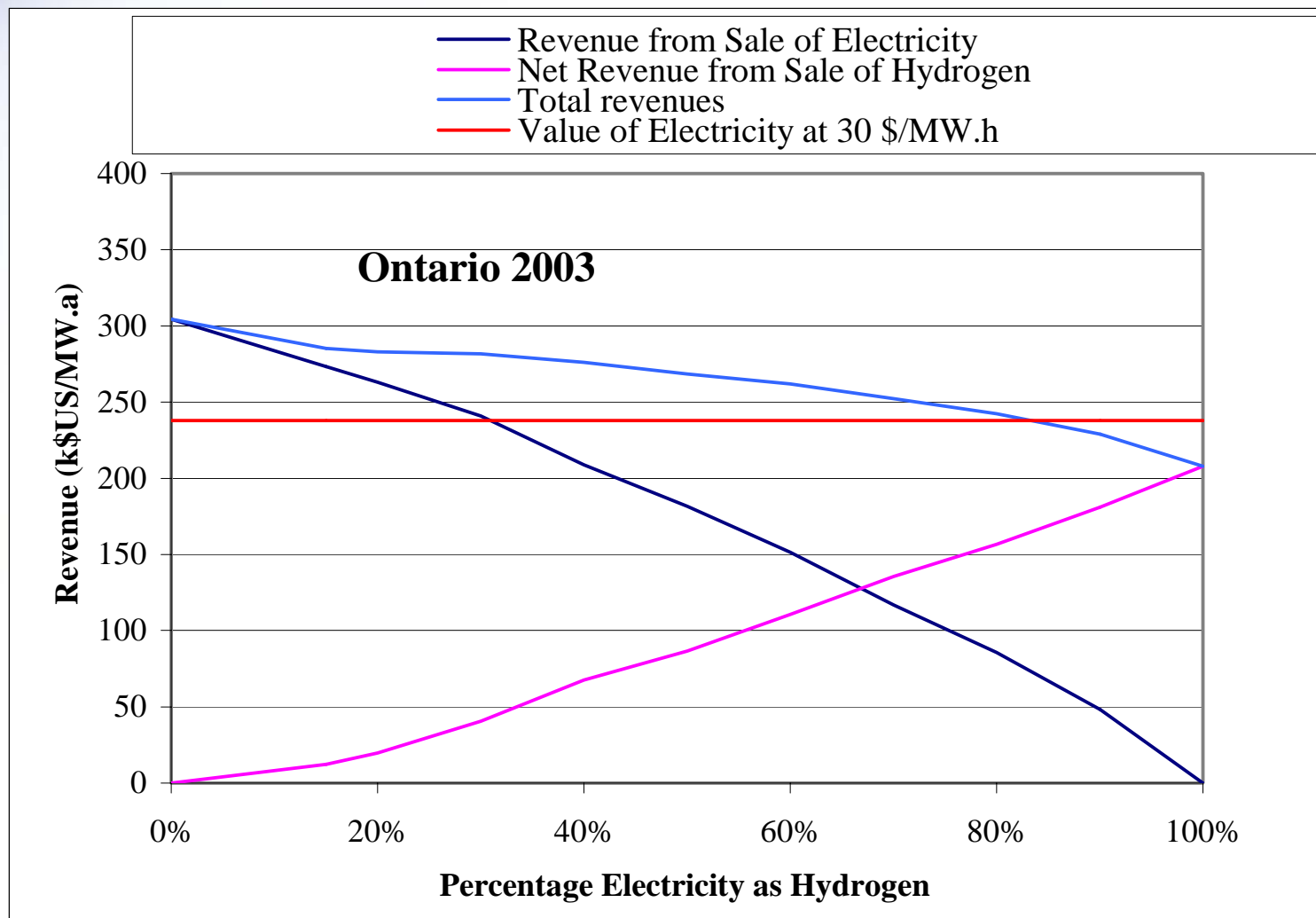
Making H$_2$ Electrolytically in Ontario

Details of an Example

✓ e.g. In Ontario in 2003 with 50% sales as electricity; 50% H_2

- 126 (storage) + 670 (electrolysis) + 720 (electricity) = 1516 $/t H_2

- Achieves 3 US¢/kW.h but apparently forgoes 920 $/t H_2 on electricity value

- Converting electricity below 3.68 US¢/kW.h

- If storage more than half-empty, converting electricity up to 14.9US¢/kW.h

- Storage of 12.5 h of average production

- Electrolysis installation is 85.6% of 100% dedicated size

✓ Does meet the 2000 $/t H_2 target

Now Add Wind

- Assumptions:
  - Advanced nuclear with 90% capacity factor, 3 US¢/kW.h
    - Actuals:
      US average for 2002 = 91%, 2003 = 89%, 2003 CANDU-6s = 88%
  - Wind with 35% average capacity factor, 3 US¢/kW.h
  - Electrolysis installation including energy for gas compression
  - Basic 55.3 kW.h/kg H_2
  - Electricity use varies as (41.66 + 7.955 A) + (4.545/A) + 1.11 kW.h/kg H_2
    - Where A is current relative to reference mA/cm^2

Allow wind to be added to extent preferred by the optimizer

- Results are per MW of nuclear augmented by whatever the optimizer likes for additional capacity in the form of 35%-available wind, distributed in a pseudo-random way as 12-hour blocks

- Wind and nuclear production costs for e$^-$ are assumed equal at 3 US¢/kW.h

- Power from both sources is dispatched to the grid whenever the price is high (according to the optimized thresholds)

- Wind takes advantage of the excess capacity needed in any case to rebuild inventory after production interruptions

- Wind also feeds up to 36% extra current to the cell (which has been designed to accept this, though at 10% greater capital cost than normal)

Typical Result

✓ Pure nuclear case in Ontario in 2003 with 50% sales as electricity, 50% H_2

  - 90% capacity factor

– 126 (storage) + 670 (electrolysis) + 720 (electricity) = 1516 $/t

✗ Pure wind, same scenario

  - 35% capacity factor

– 324 (storage) + 1723 (electrolysis) + 720 (electricity) = 2767 $/t

  - Too expensive, though calculation neglects small benefit of lower average current density

✓ Blend nuclear and wind

  - Take advantage of spare cell capacity (accommodating intermittency)
  - Design electrolysis to allow wind to drive up current density by as

Nuclear and Wind Combination
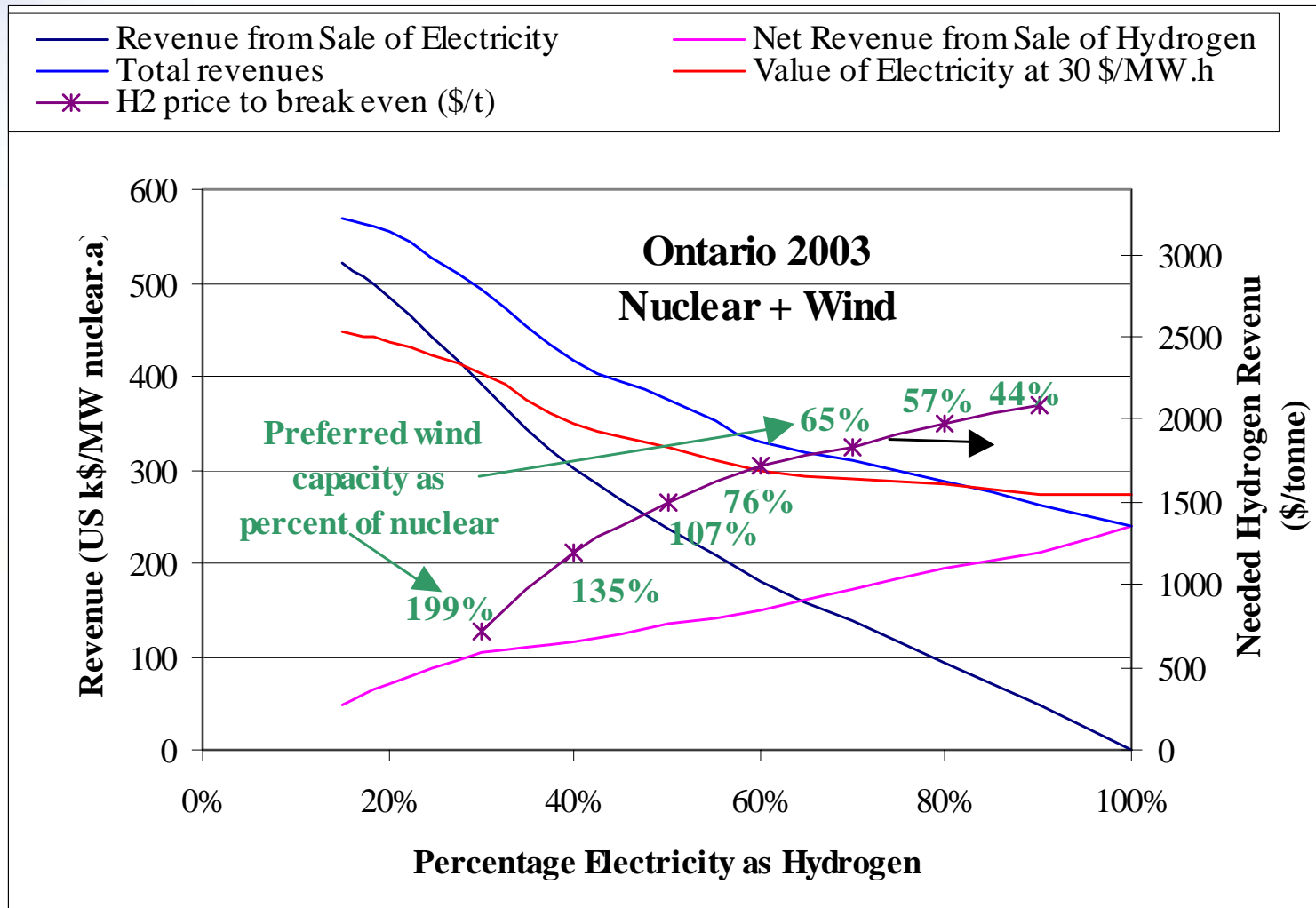
Nuclear + Wind Blend

- Economics are comparable to nuclear alone
  - 131 (storage) + 481 (electrolysis) + 891 (electricity) = 1502 $/t
  - Compared to pure nuclear's:
  - 126 (storage) + 670 (electrolysis) + 720 (electricity) = 1516 $/t

- There is no external cost associated with back-up for the wind generation

- Substantial contribution from wind
  - Production of H_2 is 32% higher

- Cost is comparable to a large SMR with 5 $/GJ natural gas
  - About 1500 $/tonne H_2 on this scale, including estimated cost for CO_2 separation and sequestration, where sequestration is practicable

Conclusions

- Slightly more revenue would usually accrue to 100% sale of electricity (Alberta in 2002 would have been an exception)
  - But this assumes that extra supply at times of lower demand does not glut the market and depress prices
  - Hence H_2 is a very attractive co-product for a blend of nuclear and wind electricity generation
    - Both technologies where operating costs are very low and base-loading highly desirable
- Electricity can be profitably produced at 3 US¢/kW.h for mixed sales of electricity and H_2 sales at prices matching the SMR cost

What next?

- More sophisticated optimization of variable current cells
- To realize the full advantage of electrolytic H_2, need to utilize its capacity for distributed, modularized production
- Mark-up for electricity distribution is crucial
  - Requires an unconventional attitude to charges for distribution
  - Practically, making H_2 when electricity demand is off-peak should not require grid expansion
  - In line with Ontario's drive toward time-of-day pricing to have time-of-day distribution costs
 - Apply data more representative of real wind generation

Detail of Spreadsheet Calculation

Date (HE)	Price ($)	System Demand (MW)	Storage (h)	On-Off Flag	Value of electricity used	Sold to Grid	Value elect. sold	No H2	Fill for electrol.	Current for electrol.	Wind avail. ?	<--- Chosen RAND()
01/10/2003 03	18.8	6685	8.24	0	13.33	0.29	5.5	0	0.714	0.708	0	0.223
01/10/2003 04	18.9	6683	8.26	0	13.38	0.29	5.5	0	0.714	0.708	0	0.223
01/10/2003 05	18.7	6758	8.29	0	13.22	0.29	5.5	0	0.714	0.708	0	0.223
01/10/2003 06	19.2	6828	8.32	0	13.61	0.29	5.6	0	0.714	0.708	0	0.223
01/10/2003 07	49.0	7192	7.63	1	0.00	1.00	49.0	0	0.000	0.000	0	0.223
01/10/2003 08	62.6	7706	6.94	1	0.00	1.00	62.6	0	0.000	0.000	0	0.223
01/10/2003 09	56.7	7965	6.97	0	40.14	0.29	16.6	0	0.714	0.708	0	0.223
01/10/2003 10	57.7	7912	7.00	0	40.84	0.29	16.8	0	0.714	0.708	0	0.223
01/10/2003 11	58.0	7944	7.02	0	41.09	0.29	16.9	0	0.714	0.708	0	0.223
01/10/2003 12	57.4	7883	7.05	0	40.64	0.29	16.8	0	0.714	0.708	0	0.223
01/10/2003 13	55.4	7862	7.73	0	77.84	0.67	36.9	0	1.363	1.404	1	0.676
01/10/2003 14	40.1	7855	7.04	1	0.00	2.07	82.9	0	0.000	0.000	1	0.676
01/10/2003 15	56.2	7825	7.71	0	78.88	0.67	37.4	0	1.363	1.404	1	0.676
01/10/2003 16	55.9	7695	7.03	1	0.00	2.07	115.6	0	0.000	0.000	1	0.676
01/10/2003 17	34.3	7746	7.70	0	48.19	0.67	22.8	0	1.363	1.404	1	0.676
01/10/2003 18	57.1	8019	7.02	1	0.00	2.07	118.1	0	0.000	0.000	1	0.676
	37.5		**12.9**									

Alberta in 2002
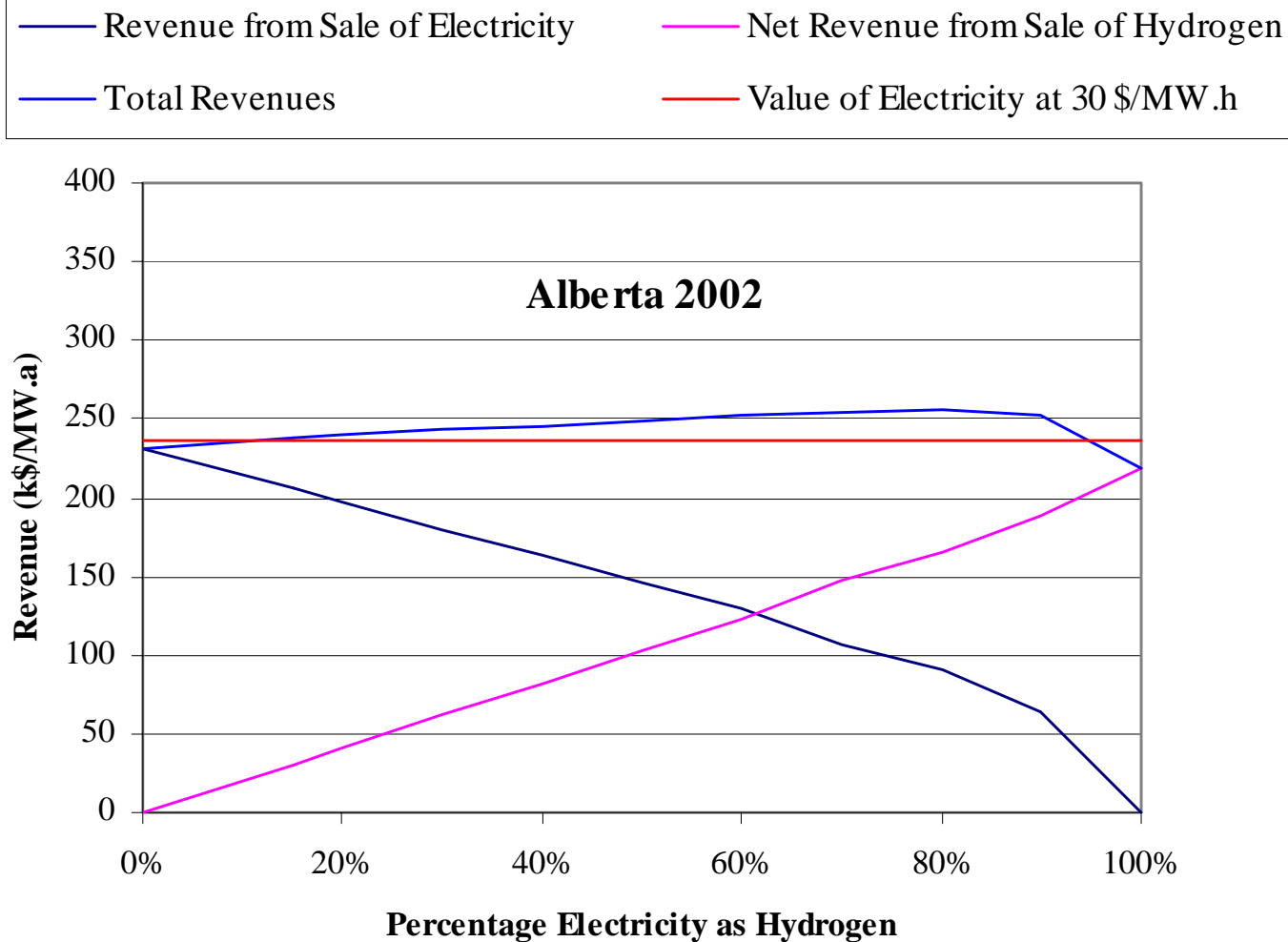
Alberta in 2002
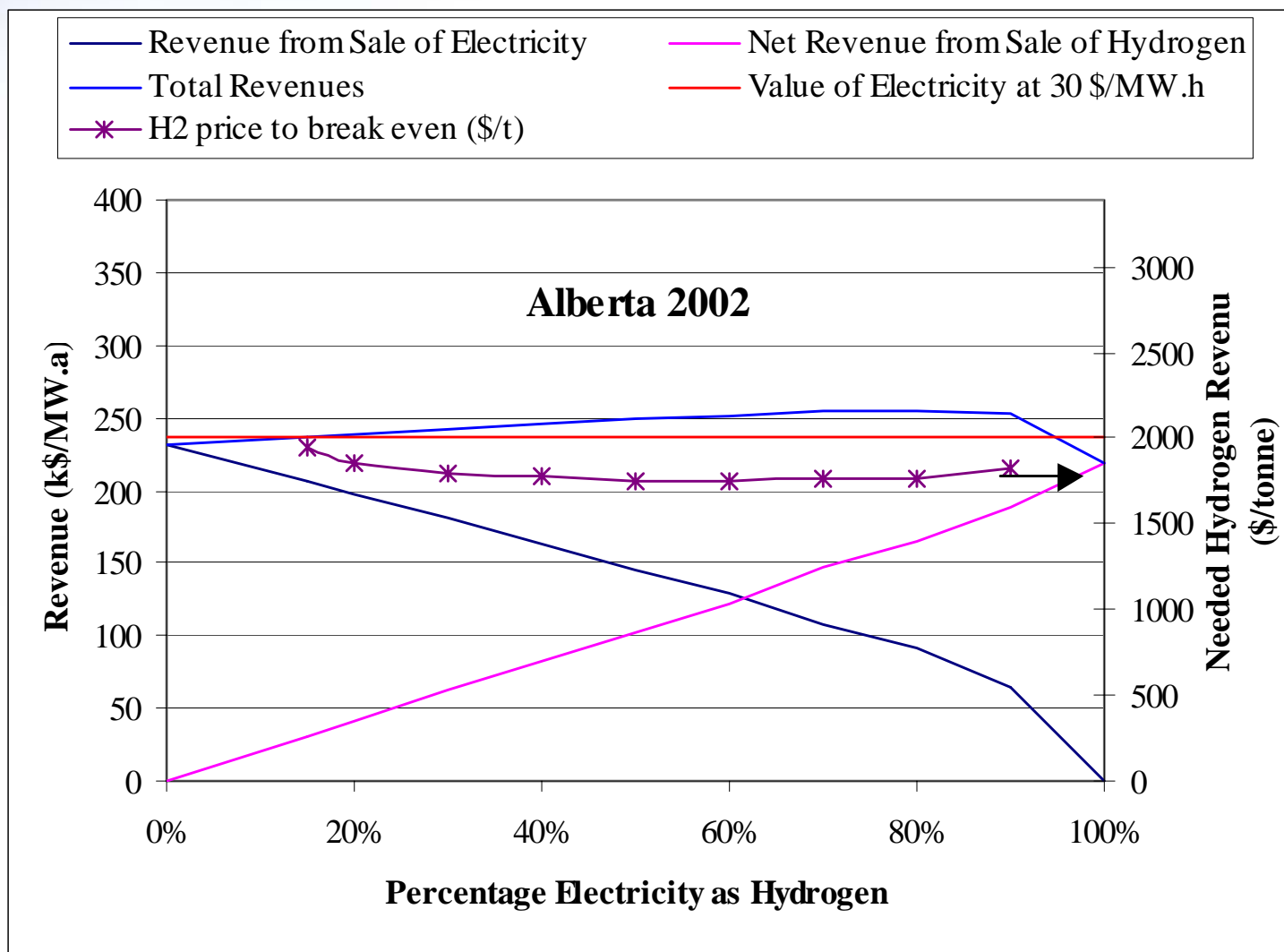
Alberta in 2003
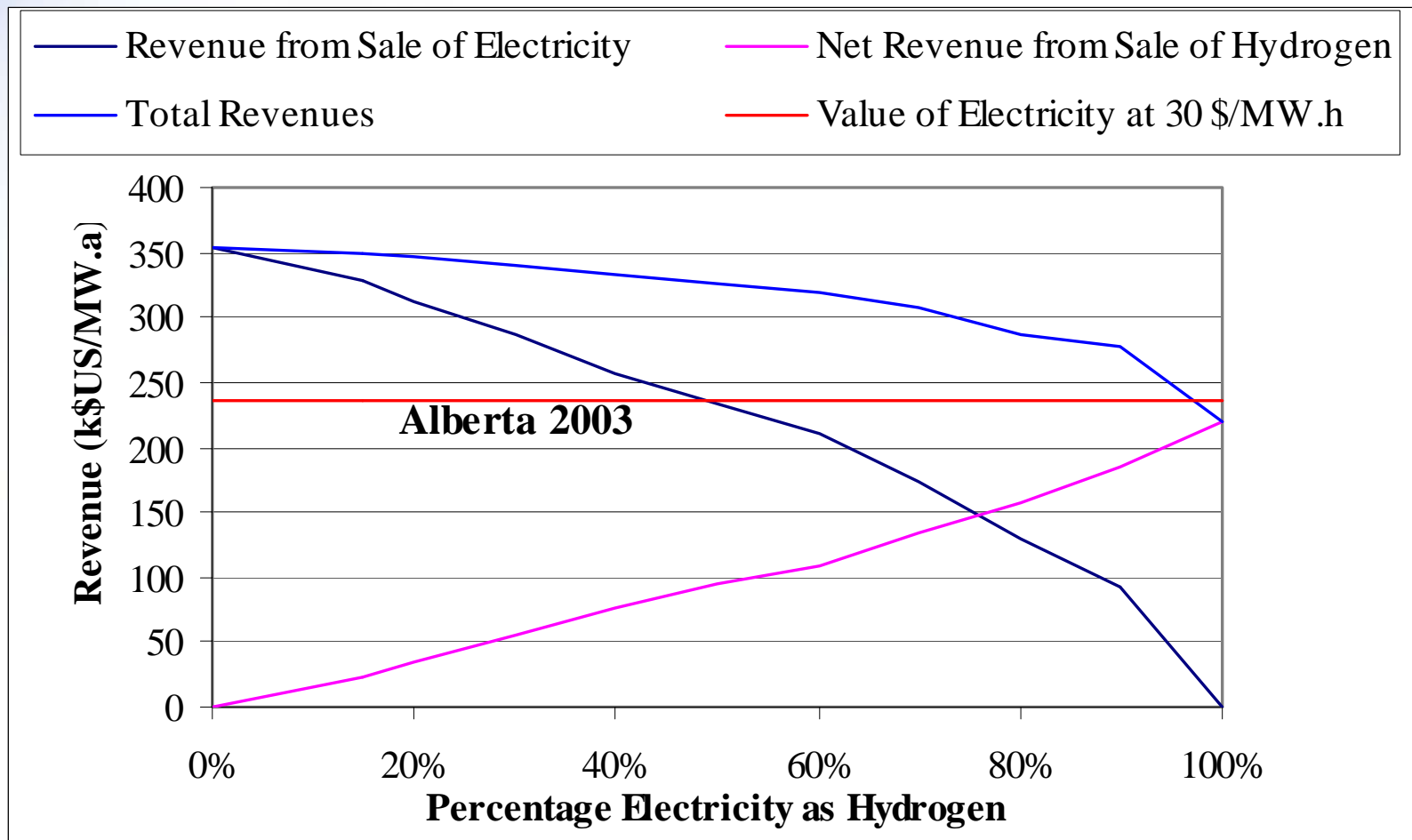
Alberta in 2003
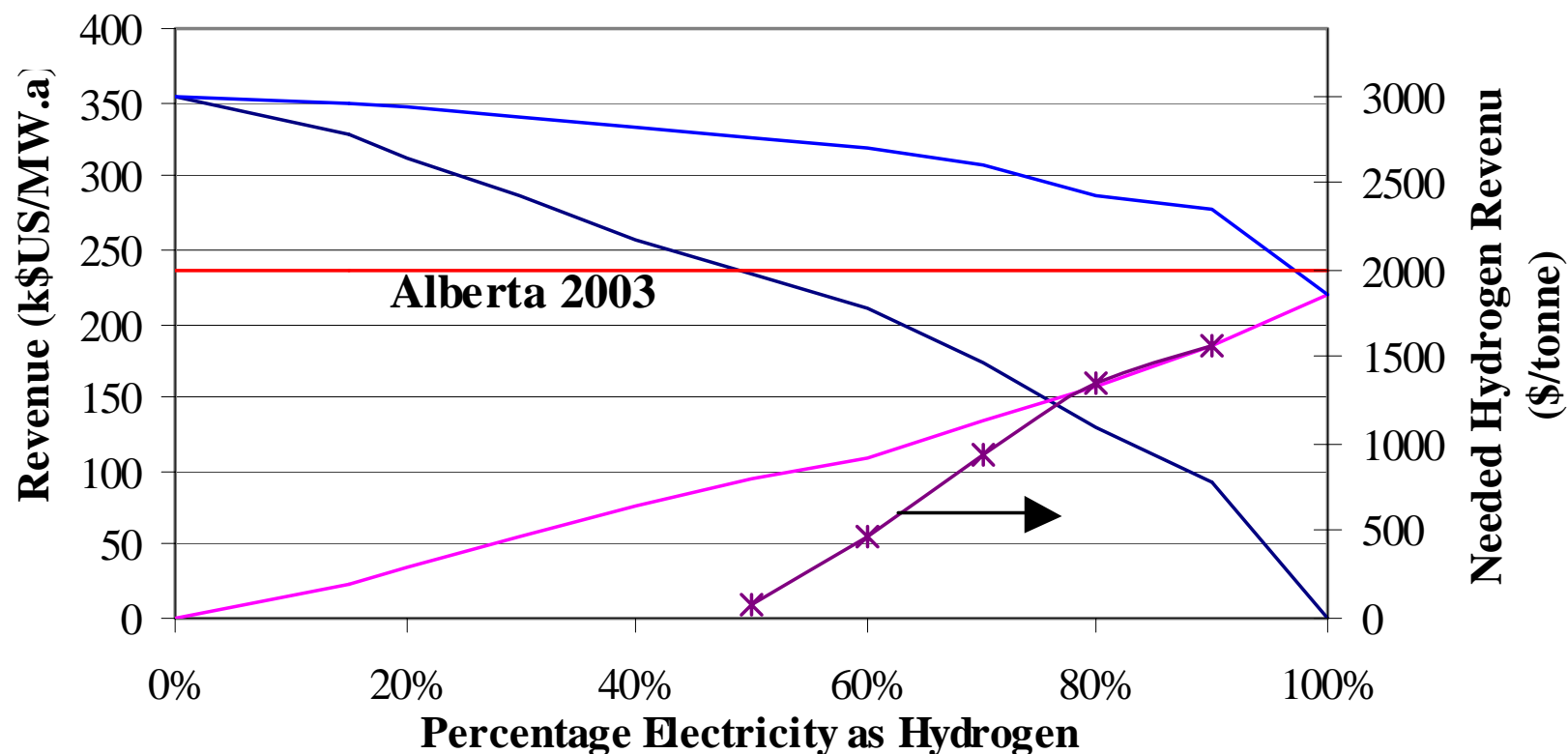
Revenue from Centrally Produced H$_2$