Hydrogen from Nuclear Energy:

A Canadian R&D perspective

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IPHE Steering Committee Meeting
Paris, France
26-28 January 2005

Canada

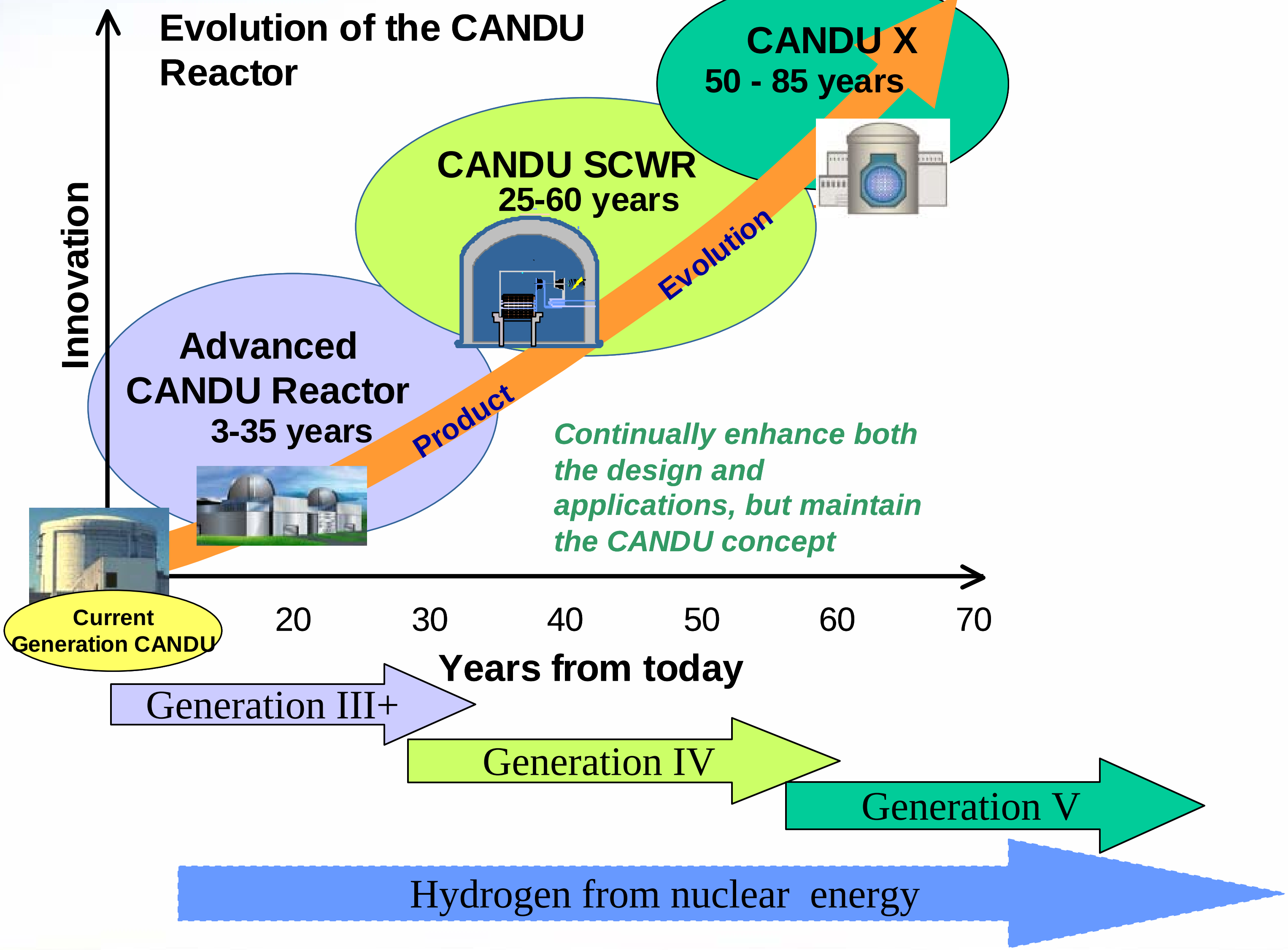
AECL
Atomic Energy of Canada Limited

EACL
Énergie atomique du Canada limitée

Comments on Nuclear Energy and Hydrogen

- Huge potential and benefit
- Issue is cost of manufacturing and infrastructure
- Distributed vs. centralized production and phased introduction
- Derive benefits and potential via UNIPCC scenarios and market data
- Not focussed on a single reactor type or technology path
- Focussed on logical nuclear reactor development pathways, economics, markets and technology options
- Proposed synergism potential of nuclear (base load) with renewables (intermittent) in competitive power markets
- Hydrogen penetration is timed in transition, and initially tuned to distributed electricity and transportation
- Large central industrial use potential (oil sands, refineries and chemical plants)
- Emphasize available applications technologies

Advanced development vision



Nuclear + Hydrogen R&D Areas

- Key Driver: use of nuclear energy for hydrogen-enhanced energy economy, with low GHG emissions
- Collaborative Areas for R&D
  - Complementary production options under Generation IV
    - *Higher temperature direct methods – VHTR*
    - *Lower temperature options – SCWR*
    - *Electro-steam reforming, plasmolysis, low-cost conventional electrolysis ....*
  - Utilization options *– Fuel cells, hydrogen safety program*
  - Timescales compatibility *– Potential N + H_2 indirect (c 2010+) and direct (c2030) production consistent with renewables introduction (2005+), carbon market shifts (2010+) and hydrogen in transportation (2010-2020+ ?)*
  - Nuclear + Hydrogen impacts *– assessment and modeling for substitution of nuclear energy through conversion to H_2, and enabling economic hydrogen production*

Setting the Scope and the Scale

Potential Impacts of a More Diverse Generation Mix

Examine vigorous displacement of carbon-emitting energy, especially coal for power and oil for autos

- Displace 80% of coal-fired electricity (between 2010 and 2030)
- Convert 80% of transportation to hydrogen (from non-C sources) between 2020 and 2040
- In line with 60% carbon reduction target for stabilization
- The replacement energy sources must only be near-zero carbon emitters
  - Nuclear
  - Wind, solar, hydraulic, etc.
  - Carbon-based with sequestration

Example using IPCC B2:

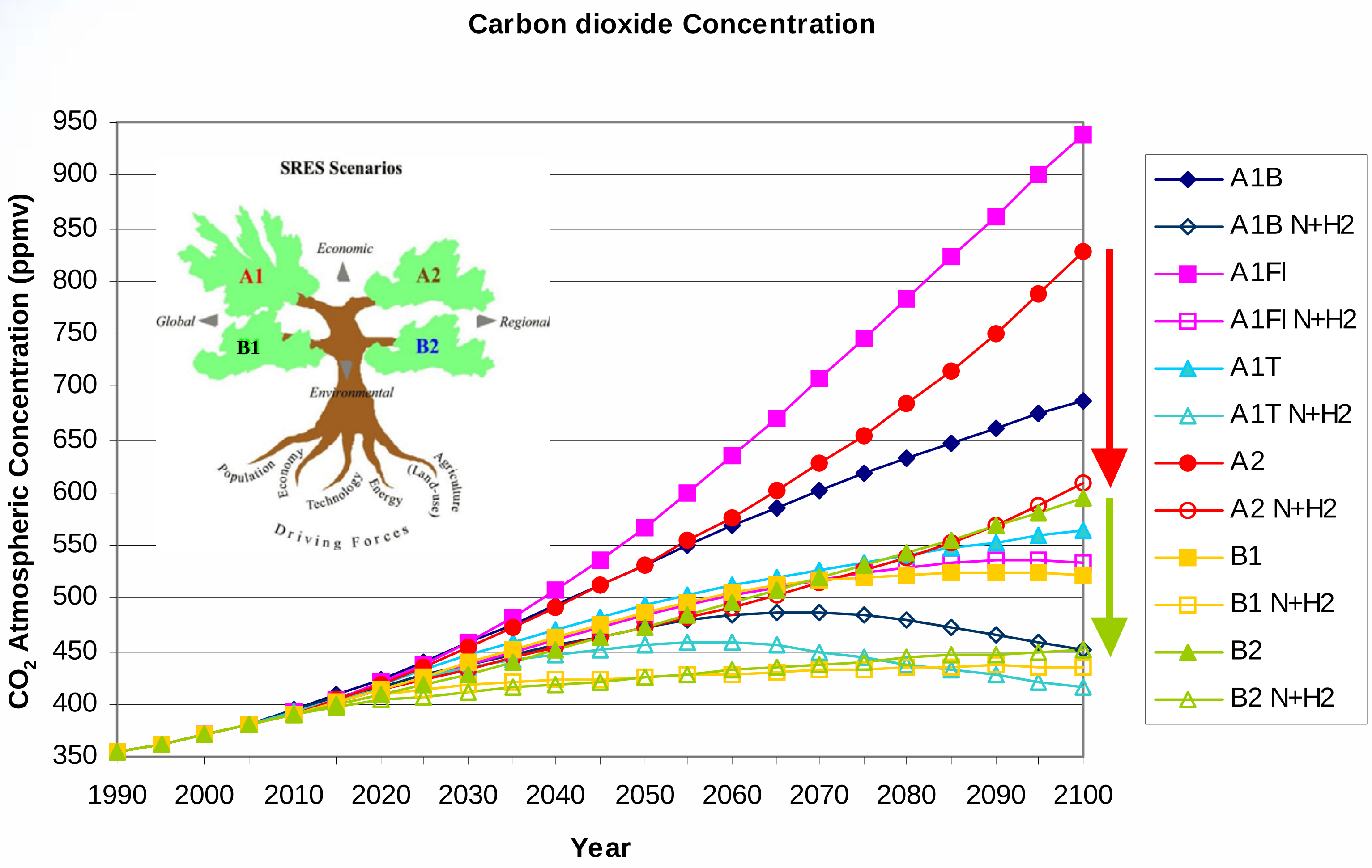
Extent of Potential Nuclear Substitution is Large

	World Totals (EJ/a)											
	IPCC				IPCC + N				IPCC + N + H2			
Year	C	N	R	T	C	N	R	T	C	N	R	T
1990	289	24	24	337	289	24	24	337	289	24	24	337
2000	336	26	30	392	336	26	30	392	336	26	30	392
2010	429	35	39	503	399	47	39	485	399	47	39	485
2020	569	51	50	670	473	90	50	612	438	103	50	592
2030	732	79	70	881	493	175	70	737	383	219	70	672
2040	928	108	100	1136	614	234	100	947	391	323	100	814
2050	1156	137	138	1431	776	289	138	1203	499	400	138	1037
2060	1295	155	201	1651	937	298	201	1436	626	423	201	1249
2070	1421	177	254	1852	1075	315	254	1645	734	452	254	1440
2080	1534	201	297	2032	1191	338	297	1826	823	486	297	1605
2090	1483	217	352	2052	1069	383	352	1803	713	525	352	1590
2100	1433	233	407	2073	947	427	407	1782	603	565	407	1575

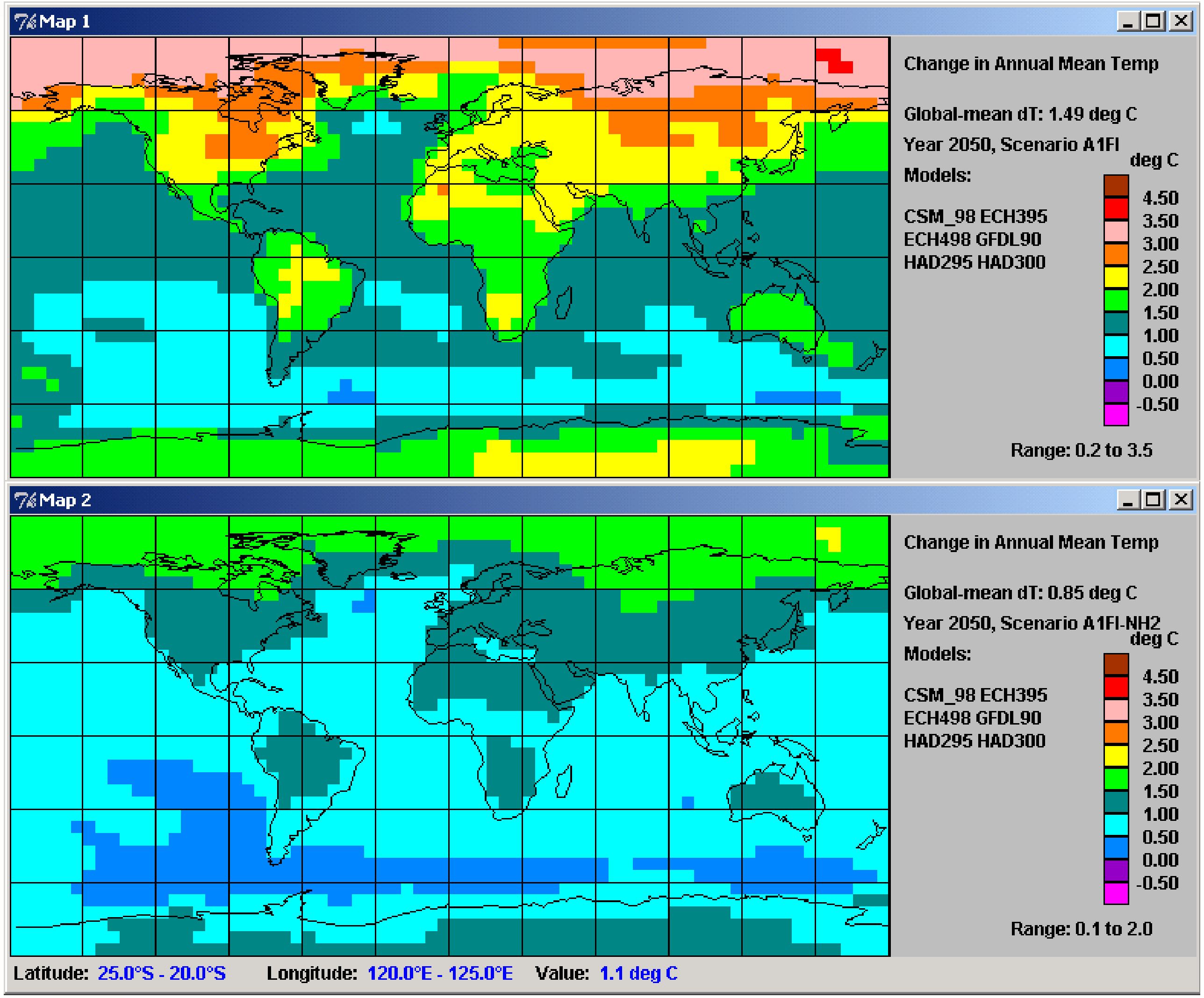
N = Nuclear; C = Carbon; R = Renewables; T = Total

IPCC energy use definitions imply 2.5C units displaced = 1 N unit

Reduced Projections of CO_2 Concentrations due to Nuclear + H_2



The impact of $N+H_2$ is globally significant…even for aggressive future energy use



Delay carries a heavy penalty

Global ΔT for switch from B2 to B2+N+H_2

Year of	Start 2010	Start 2020	Start 2030	Start 2040
2030	0.67	0.67	0.67	0.67
2040	0.81	0.86	0.86	0.86
2050	0.89	1.00	1.05	1.05
2060	0.95	1.09	1.20	1.25
2070	1.07	1.16	1.29	1.39
2080	1.07	1.22	1.36	1.48
2090	1.13	1.28	1.41	1.55
2100	1.18	1.34	1.48	1.61

Global ΔT for switch from A1FI to B2+N+H_2

Year of	Start 2010	Start 2020	Start 2030	Start 2040
2030	0.67	0.67	0.67	0.67
2040	0.81	0.97	0.97	0.97
2050	0.89	1.17	1.31	1.31
2060	0.95	1.33	1.58	1.71
2070	1.01	1.48	1.81	2.03
2080	1.07	1.60	2.01	2.30
2090	1.13	1.68	2.13	2.49
2100	1.18	1.77	2.24	2.63

Best estimates of where we are going (changes from 1990)

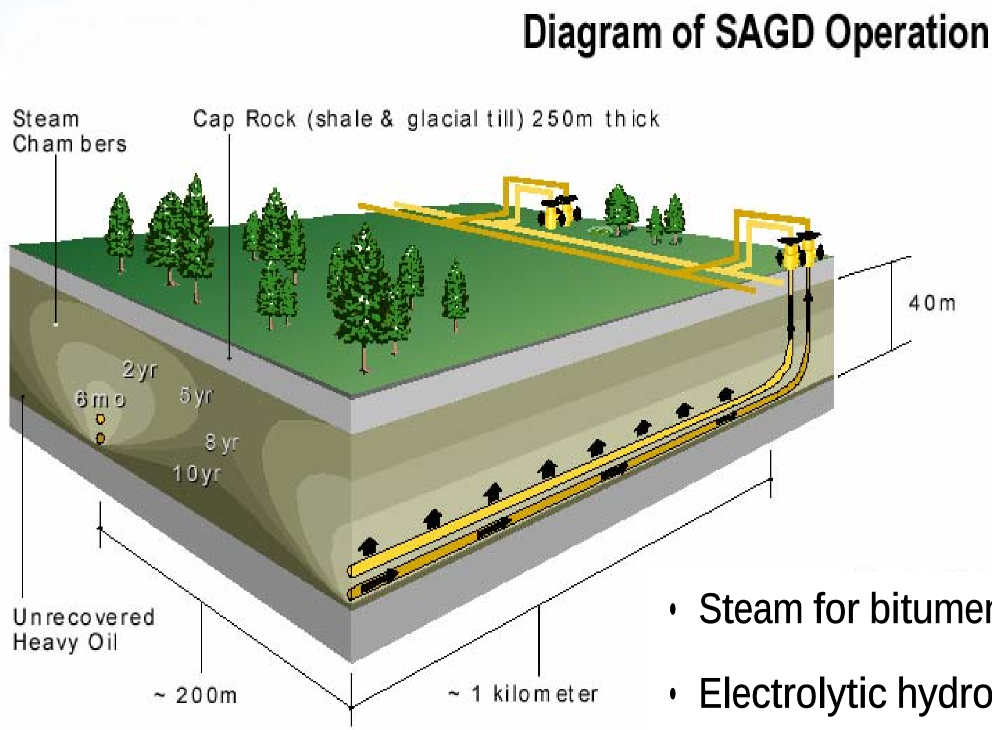
The Appearance of N+H_2

N = nuclear

H_2 = hydrogen for transport

The Distributed Future: Stuart Energy Vision
(source: SES 2003)

Centralized N+H_2 Vision: Nuclear Steam and Hydrogen for Upgrading Bitumen/Heavy Oil plus Electric Power for Plant Operations



- Reduce carbon intensity
- Avoid ~12 Mt CO_2 per year
- Free up the gas and oil reserves.

- Steam for bitumen extraction
- Electrolytic hydrogen for upgrading

Additional Issues for Thermochemical H_2

- Intrinsically centralized
  - So will have distribution costs
- Cannot switch to selling electricity instead of H_2
- For large-scale industrial use, will need a secure supply through a back-up source
  - One approach – applicable to any reactor-based H_2 supply – is to have a hybrid supply where one usually depends for 50% of the H_2 on an SMR
  - By oversizing the SMR's base capacity by a factor of 2, it can then double its output very rapidly

The Introduction of the N+H_2 Solution

N = nuclear
H_2 = hydrogen for transport

Short Term:
Making Hydrogen by Electrolysis

- Always important to keep the capital cost of the electrolysis low
  - Particularly true if not run continuously
- Essential that the input electricity be low-cost and clean
  - Significant cost reduction off peak
  - Peak-average difference is likely to grow if carbon replaced by nuclear
- Electrolysis is flexible and avoids need to build distribution networks before the demand is extensive (i.e. > 5 to 10 percent)
- Allows conversion to begin in the relatively near future (c 2005 -2010+)
  - Electricity at 30 US$/kW.h from reactors will be available
  - Grid is already available as is cell technology
- Need off-peak electrolysis to compete on cost
- Higher temperature electrolysis (SOFC) offers even higher efficiency
- Opportunity to switch hydrogen production of H_2 and Electricity synergistically between nuclear and renewable generation modes

Electricity cost target is realistic

The target Gen III + cost is ~ 30 US$/MW.h at generation site

- Based on proven build experience
- Innovations in design lower the capital cost
- Confirmed as competitive with coal and gas by studies in many countries
- Advanced GenIV plants should be even cheaper

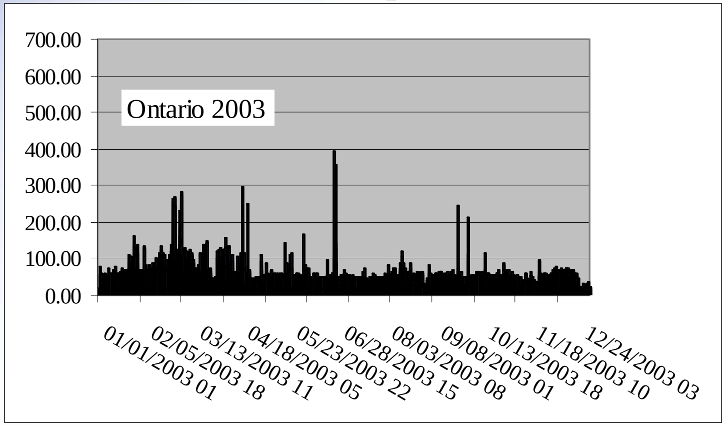
Turning electricity into H_2

- Prices in open electricity markets are highly variable
  - Not just by the hour and the day but from year to year
- With 30 US$/MW.h electricity, a reactor operator can smooth the market by selling a blend of electricity (at times of peak demand and price) and hydrogen at other times and make a good profit
- Set a H_2 production rate (as a proportion of all-H_2 production)
  - Apply to actual hourly electricity price data and minimize cost of H_2 production while maintaining constant H_2 supply by optimizing:
    - The size of the electrolysis installation
    - The size of storage
    - The Rules on when to switch on electrolysis
  - Value H_2 at 2000 US$/tonne (the DOE's centralized plant target)

N + R + H_2: wind added to extent preferred by optimization

- Results are per MW of nuclear augmented by whatever the optimizer likes for additional capacity of ~ 33 or 42%-available wind, distributed according to historical capacity data
- Wind and nuclear production costs for electricity are assumed exactly equal at 30 $US/MW.h (GenIII+ and wind costs)
- Power from both sources dispatched to the grid whenever the price is high (according to optimized thresholds)
- Wind takes advantage of the excess capacity needed in any case to rebuild H_2 inventory after production interruptions
- Wind also feeds extra current to the H_2 cell (which has been designed to accept this via ~10% greater capital cost than normal and a voltage penalty)
- The results show:
  - High proportion of wind capacity supported by nuclear
  - Affordable cost of producing H_2 using hybrid power
  - Electricity price and hydrogen price are coupled

N+R+H_2: Real time market pricing and hydrogen cost optimization is a complex interplay



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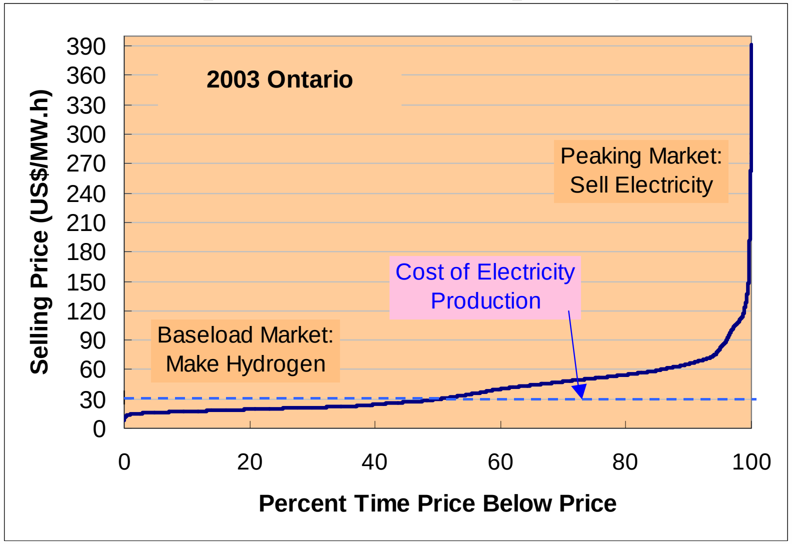

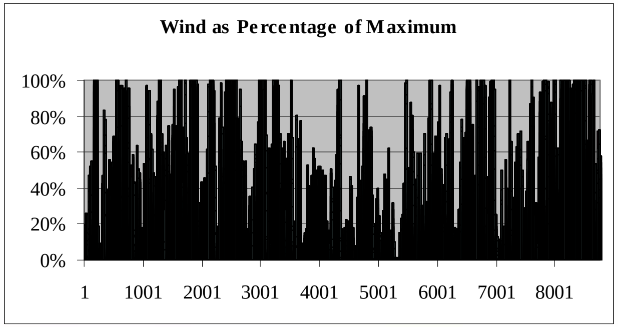

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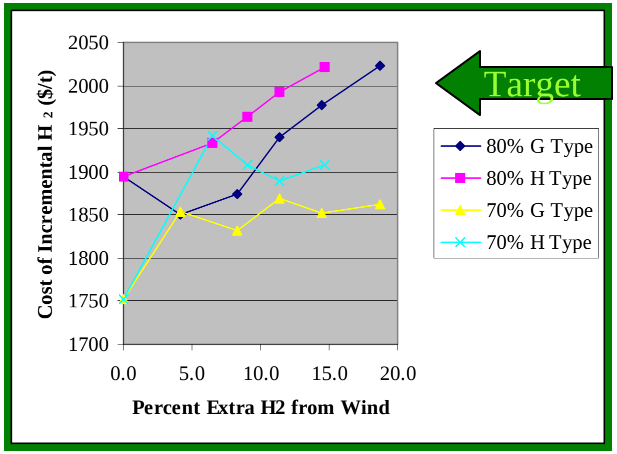


Distributed Hydrogen Production Perspective

- Studied in earlier analyses using grid to transmit
  - Small scale (1 tonne/d H_2)
  - Contains more uncertainty
    - Especially over cost of distributing electricity
- Distributed electrolytic production of H_2 should be more competitive with SMR at small scales
  - Avoids considerable cost of H_2 distribution
  - Attractive for early low-demand stages of H_2 market
  - Small local SMRs are possible, though more expensive per unit of output, but would not likely be able to sequester CO_2

Estimated Costs of Hydrogen Manufacture (Typical relative values)

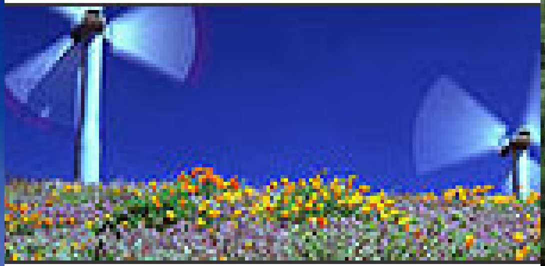
	Costs per Tonne of Hydrogen				
Large SMR (250 tonne/d; 5 $/GJ nat. gas)	Methane 744	Capital 200	CO_2 Sequestration 275	Distribution >2000	Total >3200
Small SMR (0.3 tonne/d; 5 $/GJ nat. gas)	Methane 744	Capital 2000	CO_2 Sequestration 275		Total 3019
Service Station Electrolytic H_2 (0.3 tonne/d)	Electricity 1231	Production Equipment 556	Storage 39		Total 1826
Home Electrolytic H_2 (0.4 kg/d)	Electricity 2093	Production Equipment 1689	Storage 0		Total 3962

Technical and Research implications

- Approach presented is a demonstration that N+H_2 makes sense: electrolytic H_2 can meet the US DOE's target for production cost
- To realize the full advantage of H_2, need to utilize its capacity for distributed, modularized production, and R&D on alternate options is desirable
- Nuclear (CANDU Gen III+) track record offers attractive route to clean H_2
- Future GenIV and GenV nuclear concepts are actively being researched
- Mark-up for electricity distribution is crucial
  - Making H_2 when electricity demand is off-peak should not require grid expansion
  - In line with drive toward time-of-day pricing to have time-of-day distribution costs
- Potential to integrate and optimize nuclear and wind generation
  - Cells can be operated at higher current and voltage
  - Hydrogen becomes a true currency, made and stored when cheap to make

Conclusions: a sustainable future

- A switch to mostly nuclear energy for electricity and to hydrogen for transportation will indeed stabilize emissions, and broaden the sustainable energy base
- The extent of market penetration depends on meeting the cost targets for new nuclear plants and hydrogen-powered autos
- Electricity from nuclear can be profitably produced at 30 US$/MW.h giving mixed sales of electricity and H_2 sales at prices matching the H_2 target ($2000/t) cost
- Dedicated production of Hydrogen for 100% of the time using electrolytic systems is *uneconomic in all case studies of real market data*
- Producing a mix of Hydrogen and electricity is consistently economic with 50% ± 20% of the electricity used to produce H_2
- Hydrogen is a very attractive co-product for a nuclear plant, where operating costs are very low and base-loading highly desirable
- Nuclear and wind synergism is a key result, and is possible today with time of day pricing



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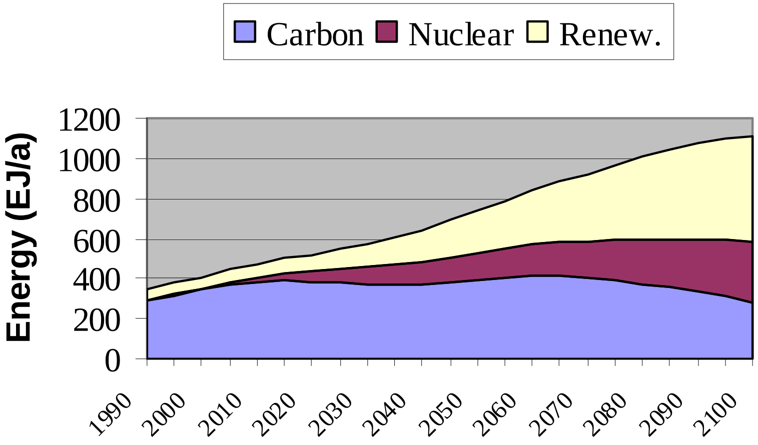


Carbon
Nuclear
Renew.
Energy (EJ/a)
1200
1000
800
600
400
200
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100

Appendix: Extra Technical Slides

Affordable – Cost Competitive H_2

Option	1	2	3	4	5
Concept Configuration	Remote SMR with pipeline	Remote SMR with trucks	Local SMRs	Local electrol. with off-peak electricity	Local electrol. operating continuously
Unit production size (Mg/d)	10	10	1	1	1
SMR or electrolysis capital cost (M$)	One at 9	One at 9	Ten at 2	Ten at 0.844	Ten at 0.703
Storage Configuration and Capital (M$)	Ten at 0.2	Ten at 0.4	Ten at 0.2	Ten at 0.28	Ten at 0.2
Production and storage capital (M$)	11	13	22	11.2	9.0
Capital charge for production + storage (M$/a)	2.2	2.6	4.4	2.2	1.8
Capital charge ($/GJ)	4.2	5.0	8.5	4.2	3.5
Energy cost ($/GJ)	7.3	7.3	7.3	12.8	15.6
Distribution cost ($/GJ)	13.3	5.9	0	0	0
Carbon charge ($/GJ)	1.6	1.6	>>1.6	0	0

Affordable – Adding up to

Costs are for systems supplying 10 tonnes H_2/day

Option	1	2	3	4	5
Concept	Remote SMR + Pipeline	Remote SMR + Trucks	10 Local SMRs	10 Local Electrolysis with off-peak power	10 Local Electrolysis running full-time
Total ($/GJ)	26.4	19.8	>>17.4	17.0	19.1
Total ($/tonne H_2)	3750*	2810*	>>2470	2410	2710
Total ($/tonne H_2)	With 600 $/kW cells			2870	3010
Total ($/tonne H_2)	If electricity is +1 $/MW.h				2765

- CO_2 sequestration cost is 37 $/t CO_2
  A change of 10 $/t CO_2 = 61 $/t H_2

What would “Off-Carbon” look like?

- For B2, in Canada:
  - ➢ Replace 80% of coal-fired electricity with nuclear by 2030
  - ➢ Between 2020 and 2040, replace 80% of road-transport with nuclear-produced H_2
  - = 32 new reactors of 1000 MW by 2030 (one every 7.5 months over 20 years starting in 2010)
  - + 12 more new reactors of 1000 MW by 2040
  - ➢ Compare 1971-1993 when 22 reactors entered service in Canada
- For B2, worldwide
  - ➢ 430 existing reactors would grow to ~4700
  - ➢ Uranium supply should suffice with existing reactor types, but can
    - ✓ Recycle fuel and use thorium: can last for 100s of years
    - ✓ Using only 1-2% of the resource; breeder reactors will last for millennia

Home-Produced Hydrogen

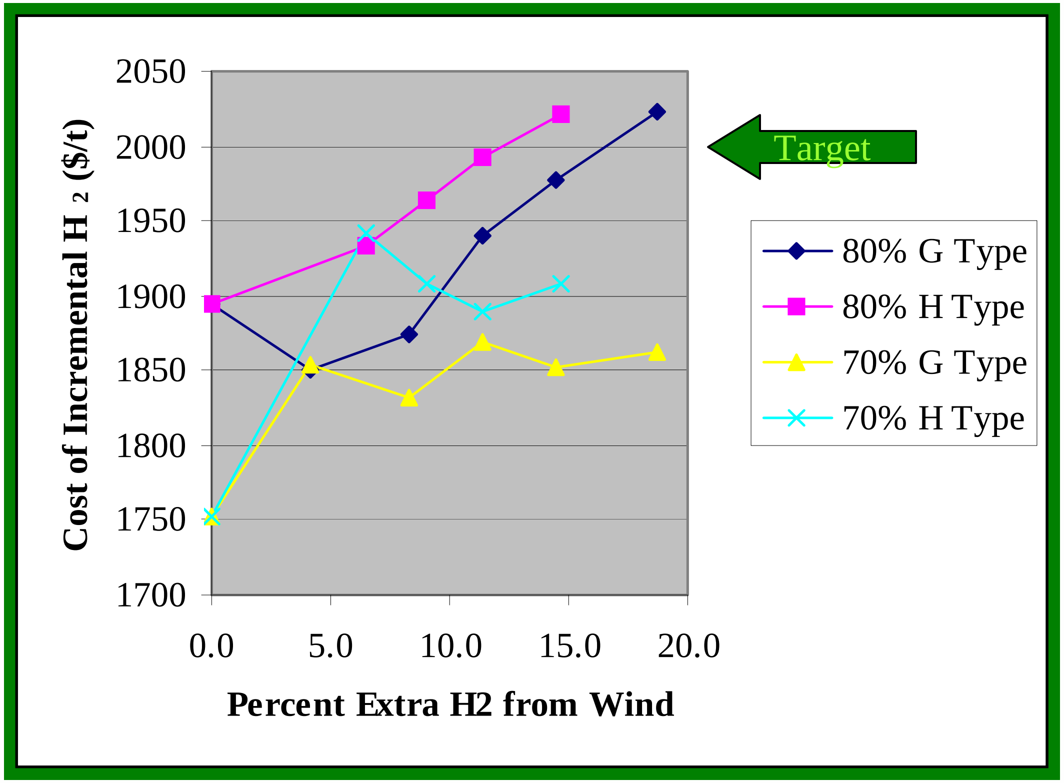
- Average Canadian car covers 21 000 km/a
- With a fuel cell, would need about 160 kg of H_2
  - Based on 2.1 volts = 9.1 MW.h/a
  - Assume retail off-peak power at 37 $/MW.h (including 20 $/MW.h of distribution costs) – available 75% of time in Alberta in 2002
  - Electricity cost is 337 US$/a (and needs 14.2 h/d for average demand)
  - Home-refueller electrolysis unit at 2000 US$ (for 1.7 kW unit), 6% financing over 10 years = 272 US$/a
  - Total of 610 US$/a
- Gasoline at 45 ¢/L *(which includes taxes)*
  - Annual 836 US$/a for a typical 11.3 L/100 km car (20.8 mpg)

And if one reversed the power flow?

- The figures are very approximate but:
  - In terms of fuel costs, H_2 is competitive
  - Interesting possibility of reversing the current
    - Not efficient (0.7 x 0.5) but pays if selling price for electricity is x3 of the buying price.
    - In Alberta in 2002, paid an average of 240 US$/MW.h for top 2.5% of time
      - Fuel cell can deliver 15.4 MW.h/a
      - Even 1% of time at that price, could earn 37 US$/a
      - Collectively, an interesting no-cost generating reserve for the grid

Adding Wind to Nuclear: $N+H_2+R$

- Percent is electricity proportion making H_2
- G and H Types are mean wind strength
- Electricity 30 $US/MW.h
- H_2 from 330 US$/kW cells (variable current)
- Off-peak H_2 generation
- Basis: 2003 Ontario data
- Result: $N+H_2+R$ makes renewables able to contribute to hydrogen



Context of Canadian Transport

- By 2030, transport use expected to have risen by 30%
  - If using fuel cells, will need just under 1 EJ/a
  - Suppose 50% conversion by then of all transport to run on hydrogen
    - = 24 nuclear reactors of 1000 MW(e) each
    - + 10 more reactors to displace all existing carbon-based electricity
- Current Canadian context
  - 20 reactors operating or being returned to service
- Less whatever can be provided by other sustainable energy sources
  - At competitive prices
- Extend the conversion to hydrogen to 80% before 2050