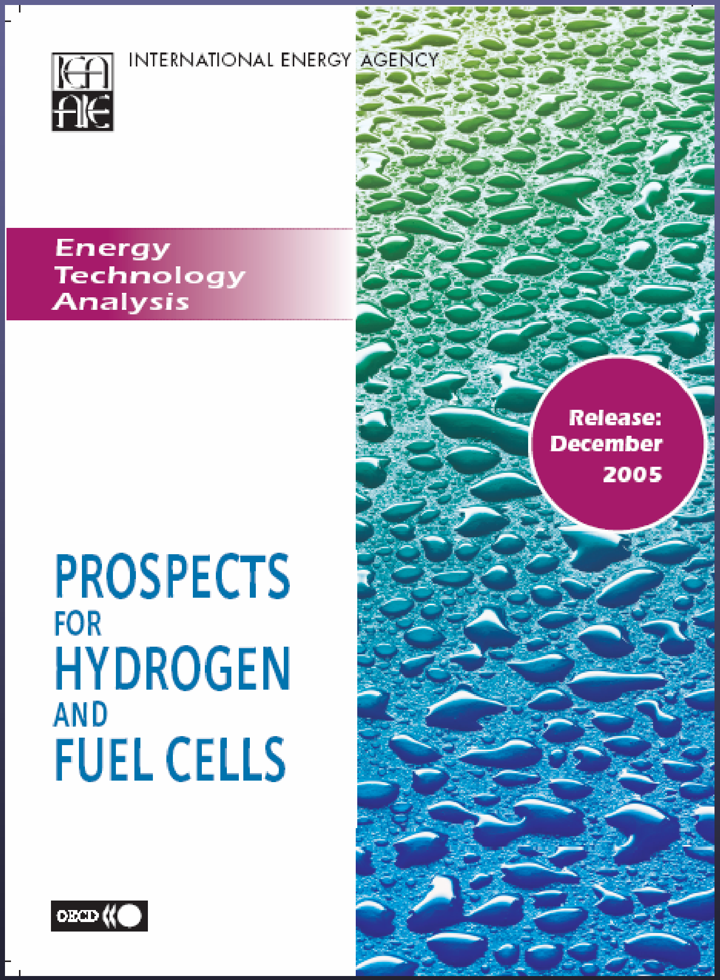
Prospects for Hydrogen and Fuel Cells



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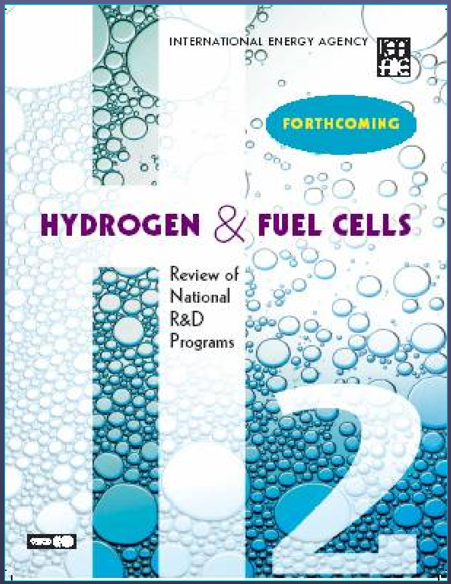
TRB, Washington DC
25 January 2006

RD&D Investment

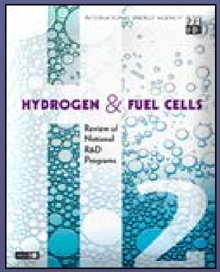
- Public Sector OECD countries: $ 1 bill. /a
  ~ 1/8 total energy R&D budget, 50% for FCs
- National programmes :
  - US ~ $ 1.7 bn, 5 anni
  - Japan ~ $ 300 mill./a
  - EC (EU) ~ € 200-300 mill./a in 6thFP,
  - plus … Can, D, F, I, K, DK, N, CH …



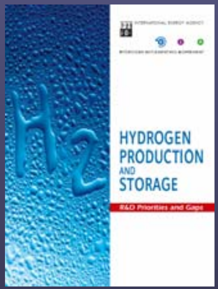
- Larger efforts in the private sector
- Demos: 70 FC buses, 200 vehicles, 60 fueling stations, some 60 MW stationary uses
- International co-operation: IEA, IPHE, EUTP

Context of the Study …

The IEA Hydrogen Co-ordination Group (HCG), established in April 2003 with four tasks:

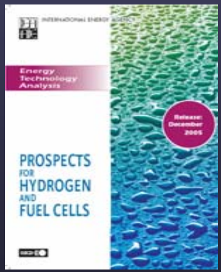


1 Review national R&D programmes in IEA countries
(Report by the Secretariat, published Dec. 2004)



2&3 Review IEA R&D activities and collaborations
(Paper by the Hydrogen IA, published Jan. 2006)

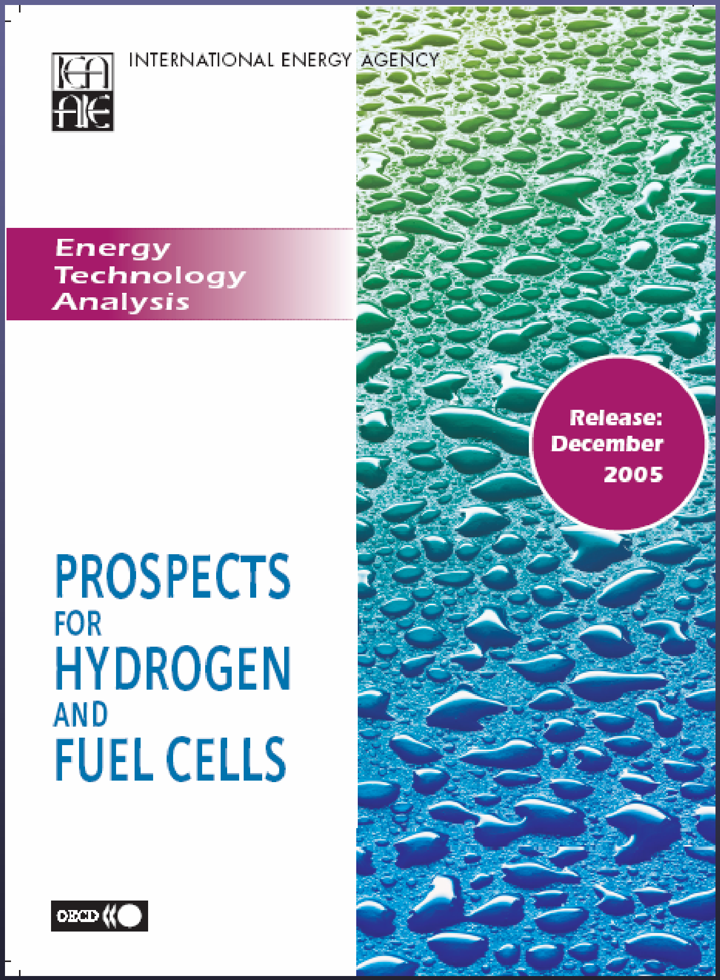
4 Analysis to Help Guide the IEA Work
"Prospects for Hydrogen and Fuel Cells"
(Report by the Secretariat, published Dec. 2005)



The Study …

- Analysis of H_2/FC potential using the IEA ETP model (scenarios to 2050)
- Work supported by many HCG countries
  Australia, Austria Canada, France, Germany, Japan, Italy, Netherlands, Spain, UK and US
- Experts' Workshop held on 28-29 June 2005 to discuss the first draft (input data & scenarios)
- Structure of the study:
  - Technology Assessment H2&FC
  - Scenario Analysis
  - Conclusions & Policy Insights

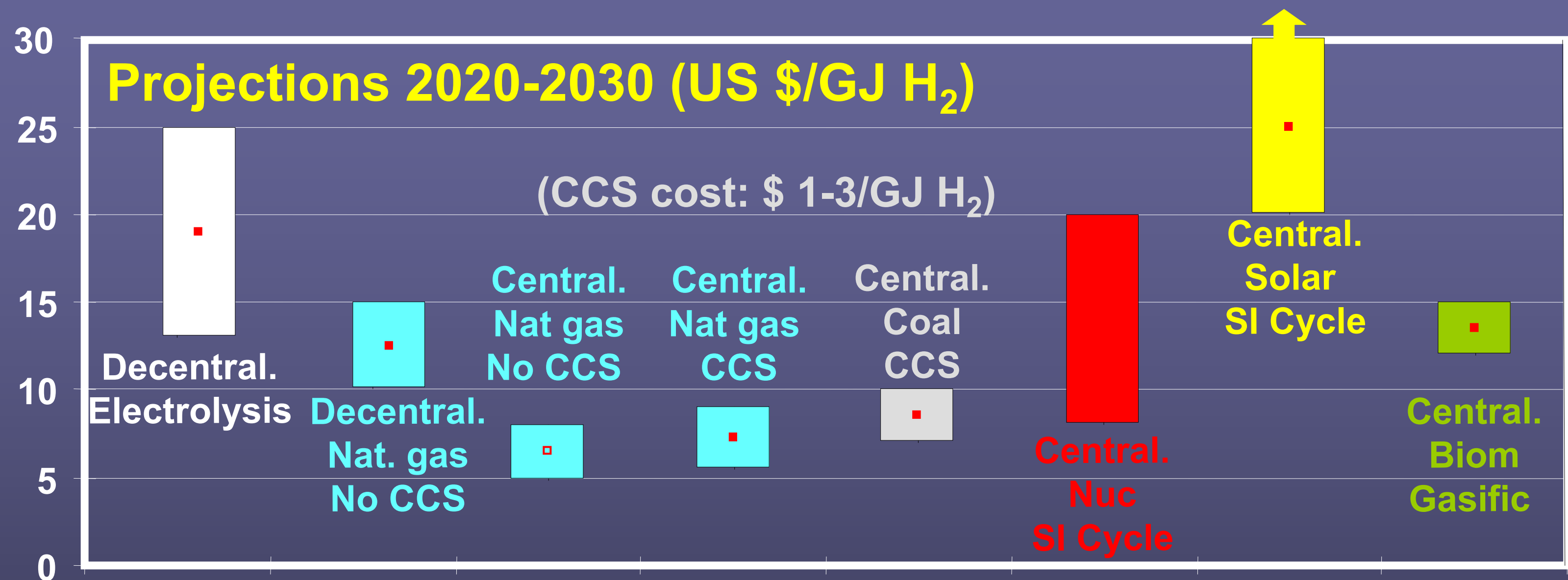
Technology Insights



H_2 Production Cost

- No surprises compared to NRC/H2A
- Current decentralized production > US$ 50/GJ H_2
- Various technologies promise H_2 at $ 10-15/GJ :
  - Natural gas reforming at below $ 15/GJ H_2 by 2030
  - Electrolysis at below $ 20/GJ H_2 by 2030
  - H_2 from coal gasification (IGCC) with CCS at below $ 10/GJ H_2
  - Sensitivity to natural gas and electricity prices
  - Long term, HT water splitting using nuclear heat at $ 10/GJ H_2
  - Long term, HT water splitting using solar heat at $ 20/GJ H_2
  - Higher costs for other advanced techs

H_2 Production Cost



- Decentralised gas reforming & electrolysis: < $15-20/GJ (*)
- Later, centralised H_2 from gas & coal with CCS < $10-12/GJ
- Higher cost, longer term for nuclear, biomass and solar H_2
- GJ-basis comparison is deceptive: FCV efficiency = 2.5xICE
- Fuel cost/km (ex tax) same as current ICE vehicles (*)

(*) Today: H_2 > $35-50/GJ; Oil ($40/bbl) $7/GJ; Gasoline ($2/g) $16/GJ

H_2 On-board Storage

Target: low-cost, compact storage of some 5 kg H_2 for 500 km FCV drive

- Current options do not meet requirements
- Gaseous storage at 350-700 bar and Liquid storage at -253°C are commercially available but costly options ($ 600-800/kg H_2; electricity for compression-liquefaction is 15-40 % of H_2 energy)
- Solid storage holds potential advantages, but still in R&D phase
- At present, gas storage at 700 bar is the ref. option, but it can hardly meet drive-range and cost targets for FCVs

On-board storage is an urgent issues!
It may impact the choice of H_2 infrastructure

Fuel Cell Stack Cost

- Analysis of H2/FC potential using the IEA ETP model (scenarios to 2050)
- Today's prototype/demo cost: ≥ $ 2000/kW (Nafion, Pt catalyst)
- Today's cost for mass production: $100-250/kW (?); efficiency 2-3 x ICE; durability 1/3-1/2 x ICE
- Less than $100/kW unlikely with current technologies
- Target cost : < $ 50/kW (ICEV cost) through technology learning, mass production, new materials (HT membranes)

Future PEM cost

	Cost (USD/m²)	Cost (USD/kW)	Share (%)
Membrane	50	17	16
Electrode	150	50	49
Bipolar plates	91	30	29
Platinum catalyst	8	3	3
Peripherals	4	1	1
Assembly		2	2
Total		103	100

FCV Drive Systems Cost

- PEM with double current density 50 USD/kW
- Electronics, gas treatment etc. (BOP) 15 USD/kW
- Electric engines 15 USD/kW
- H2 storage 15 USD/kW
- Total 100 USD/kW
- This is too expensive, further cost reductions are needed
- This will require additional R&D

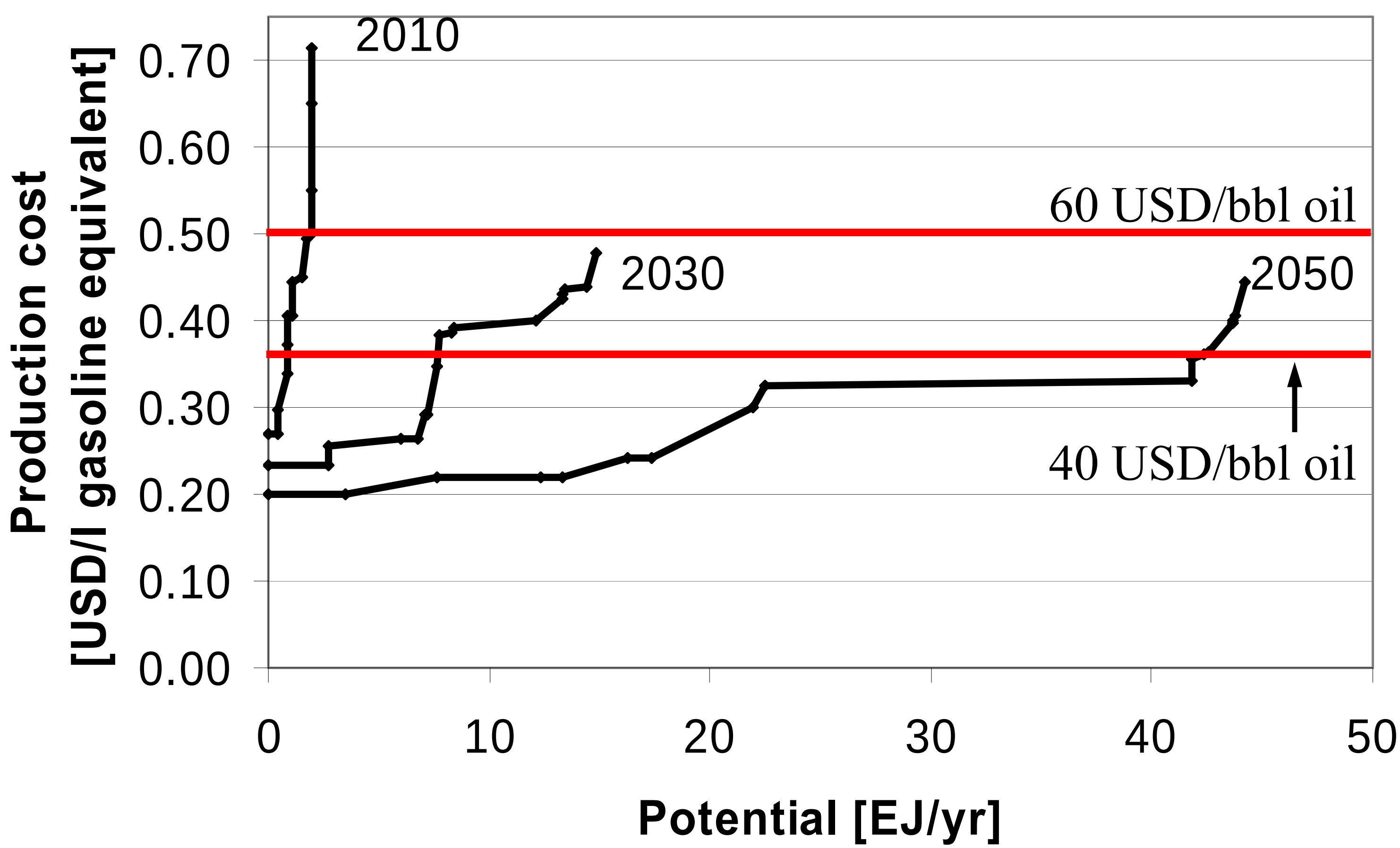
H_2 Transport & Distribution

- **Pipeline**, the only practical option ...
  Cost: 2x nat. gas; Pumping energy: 5x nat. gas
- **Adds \$ 1-2/GJ H_2** to the production cost ...
  new components needed for pipelines;
  Use of nat. gas pipeline questionable
- **Liquefaction: + \$ 7-10/GJ H_2**; ~ 30-40% H_2 energy
- **Refueling stations: + \$ 3-6/GJ H_2**
  (includes compression; no decentralised H_2)

H_2 is not the only option

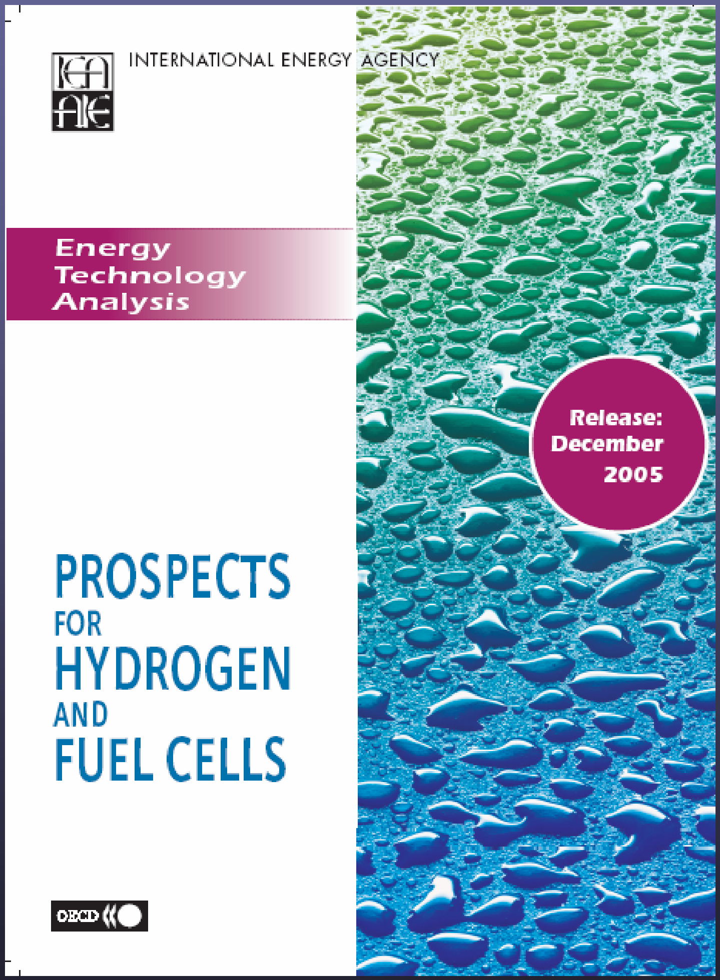
Supply Security benefits	Emissions increase	Low or no reduction	Emissions reduction
High	Heavy oil Oil sands Oil shale FT-coal DME/MeOH coal	Enhanced oil recovery Non-conventional oil + CCS FT-coal + CCS DME/MeOH coal + CCS	Energy efficiency (e.g. hybrids, FCVs) *FCV + H2 from coal, nuclear or renewables* Bioethanol FT-biomass CO_2- EOR
Low Or none	Refinery products from ME oil FT-natural gas CNG vehicles DME/MeOH natural gas	FT-natural gas + CCS DME/MeOH natural gas + CCS	Hydrogen from natural gas + CCS

Global Bioethanol Supply Curves



Prolongued high oil prices and new technology will result in lots of alternative fuels

Scenario Analysis



Analysis Structure

WEO Reference & Alternative SCENARIO (RS, AS)
Analysis of H/FC potentials w/o new energy policies

MAP SCENARIO
Analysis of H/FC potentials with new energy policies

↓

SENSITIVITY ANALYSIS
30 model runs

↓

SCENARIO ANALYSIS

SCENARIO A ESTEC - - ++ -	SCENARIO B ESTEC 0+++ -
SCENARIO C ESTEC 0+ - - -	SCENARIO D ESTEC +++++

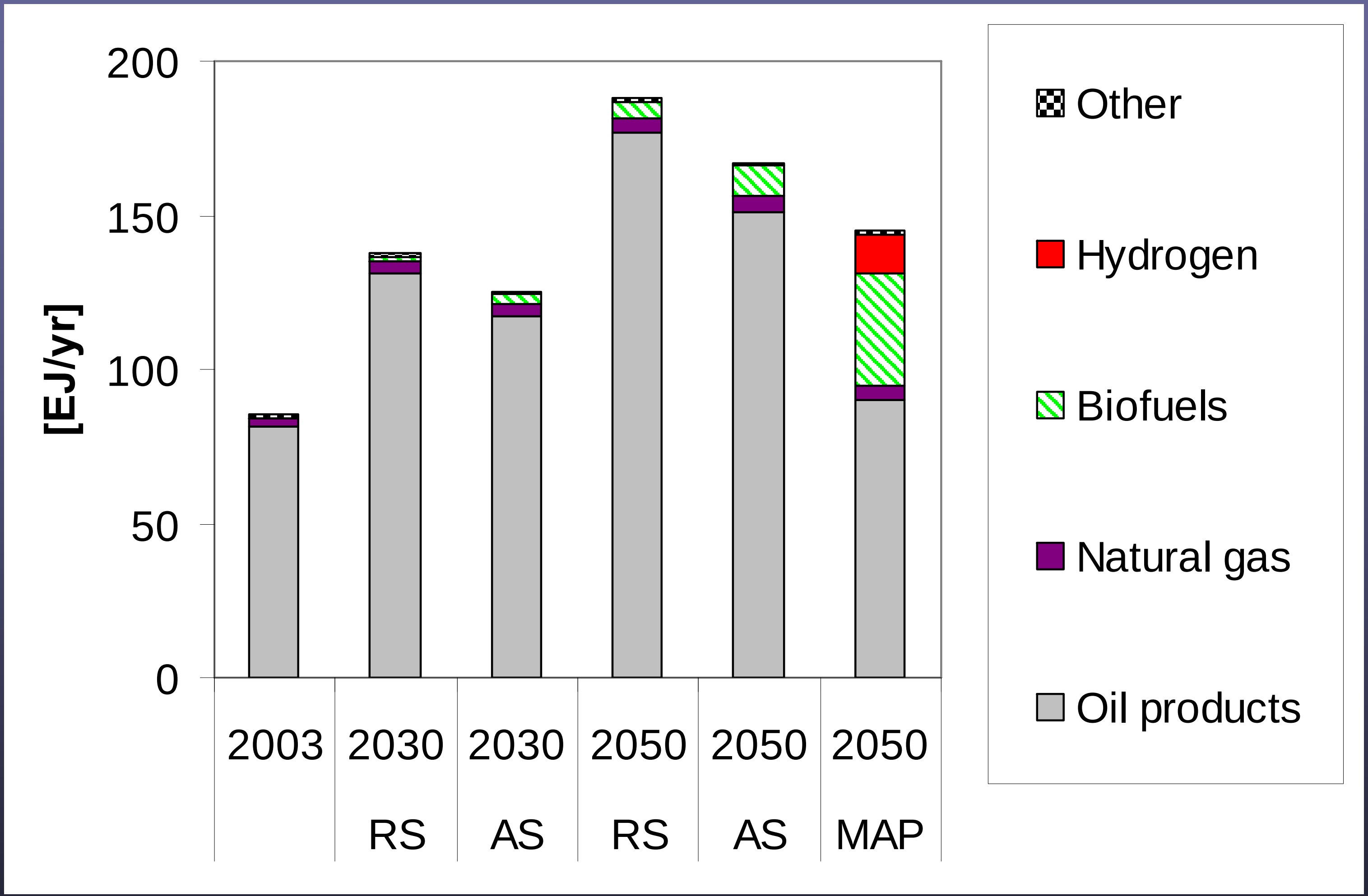
ESTEC Scenarios

- E Environment
- S Supply Security
- T Technology Prospects (H2/BC)
- E Economic Conditions
- C Competing Options

- + Favourable assumption for H2/FC
- 0 Neutral
- - Unfavourable assumption for H2/FC

- Scenario D: ESTEC +++++ most favourable for H2/FC

Fuels for Transport



Hydrogen is favored by CO_2 policies (MAP scenario) (\$ 50/t CO_2 abatement incentive)

Sensitivity Analysis I

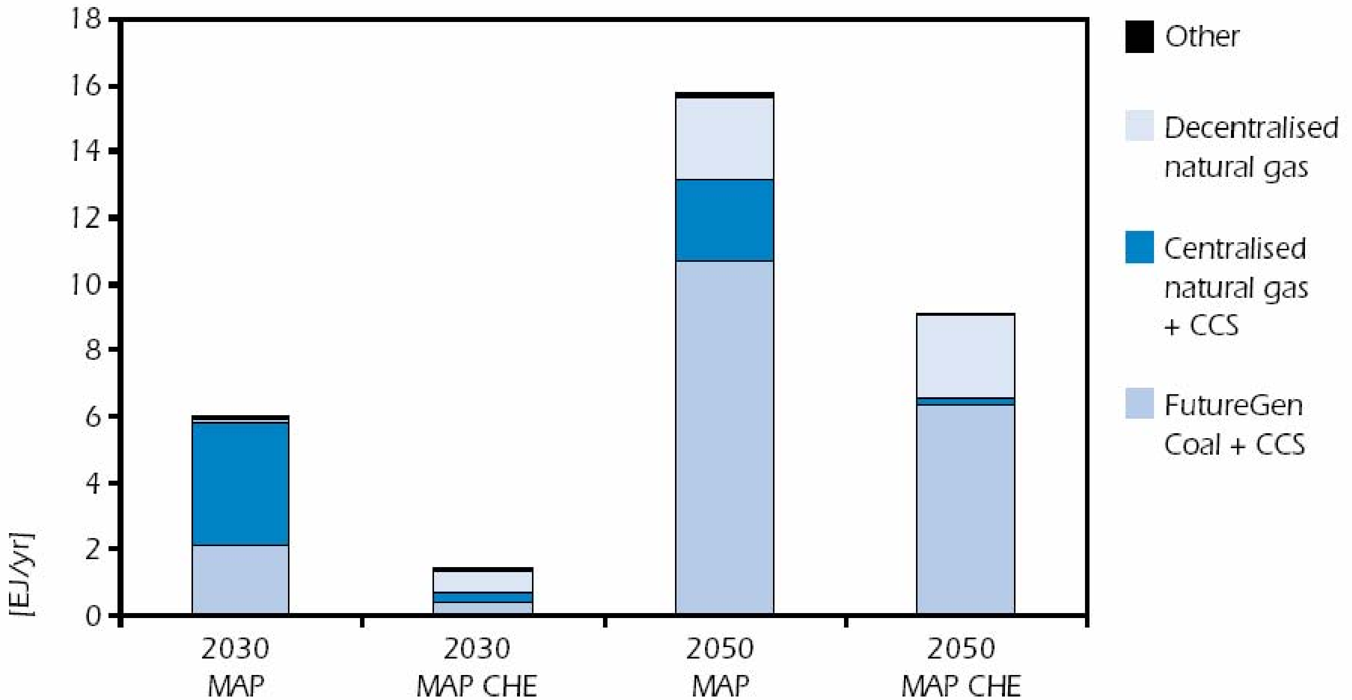
	Sensitivity parameter	Assumption	H_2 use 2050 (EJ)	Change (%)
	MAP scenario		15.7	-
Policies and socio-economic parameters	CO_2 incentives	BASE	3.6	-77
		USD 25/t of CO_2	13.4	-15
		USD 100/t of CO_2	28.3	+80
	CO_2 policy scope	USD 50/t, Kyoto countries only	9.1	-42
		USD 25/t, Kyoto countries only	3.7	-76
	CO_2 policy timing	CO2 policy delayed 15 years	16.1	+3
	Supply security	Max. 33% transportation fuels from imported conventional oil	16.1	+3
	Market structure	MAP, but high "hurdle-rate" for transport sector	10.9	-31
	Market structure	MAP, but low "hurdle-rate" for residential/commercial sector	14.6	-7
	Fuel tax regime	Converging taxes for all transportation fuels	16.7	+6
		No fuel tax on hydrogen	21.7	+38
	Fuel prices	A high oil price of USD 40/bbl	20.5	+30
	Planning time horizon	2070	8.9	-43

Sensitivity Analysis II

	Sensitivity parameter	Assumption	H_2 use 2050 (EJ)	Change (%)
	MAP scenario		15.7	-
Competing options	High nuclear electricity	No constraints on nuclear	12.6	-19
	Low H_2 production cost from nuclear S-I	No constraints on nuclear	21.4	+36
	Cheap renewables for renewables	More technology learning	14.9	-5
	Less biomass	100 EJ primary biomass potential	17.2	+9
Hydrogen technologies	IGCC cogeneration	No FutureGen type plant with CCS	10.6	-33
	CCS	No CCS	7.5	-52
	Technology learning	High FCV system cost of USD 105/kW	6.3	-80
	FC life span	One fuel cell replacement during vehicle life	13.1	-17
	Engine power	60 kW instead of 80 kW	16.7	+6
	Future FCV efficiency compared to advanced ICE	Factor 2.95 instead of 1.82	16.6	+7
	Technology development path	FCV cost reduction delayed by 15 years	11.6	-26
		FCV cost reduction 10 years earlier	16.5	+3
	Transition issues	Including transition issues	9.1	-42
	Hydrogen production scale	Only decentralised	7.2	-54
	Low hydrogen distribution cost	In the residential sector	17	+8

Figure 6.9

Hydrogen production mix (MAP and MAP CHE scenarios)

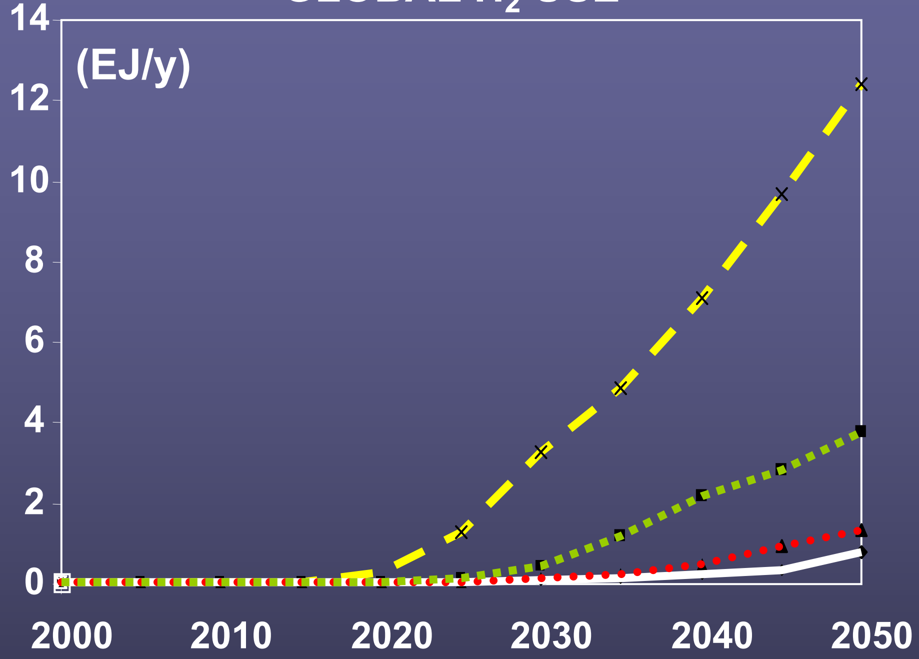


Note: The MAP CHE scenario delays the use of centralised production until after significant demand emerges, allowing for the chicken-or-egg hydrogen transition issues.

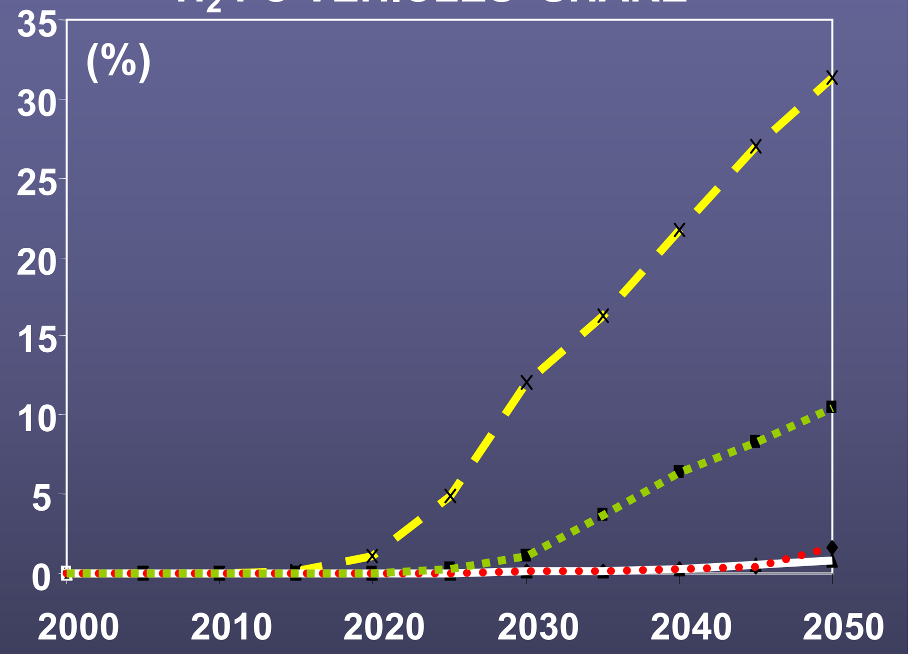
Key point: Transition issues reduce hydrogen demand and affect the production mix

Hydrogen Use

GLOBAL H_2 USE



H_2 FC VEHICLES SHARE



Scenario A - Weak new CO_2 Policy with Tech. Development and Market

Scenario B - Strong new CO_2 Policy in Kyoto countries with Tech. Development

Scenario C - Strong new CO_2 Policy in Kyoto countries with Tech. Lag

Scenario D - Strong new CO_2 Policy world wide, with Tech. Development

- Up to 12.5 EJ H_2 by 2050, almost all in transport
- Up to 30% vehicles fuelled by H_2 fuel cells

Potential Market Share

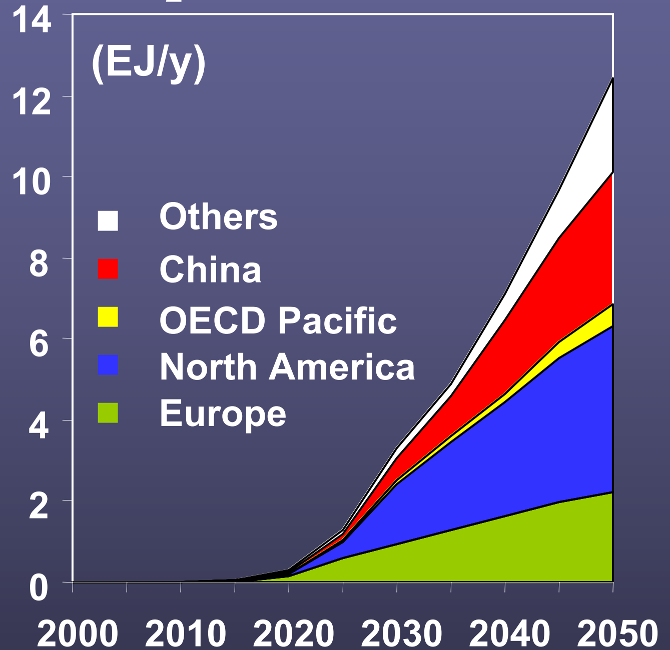
- **Max potential under most favorable conditions:** ~ 30 % FC vehicles by 2050 (penetration since 2025)
- **High efficiency:** 12.5 EJ H_2 (less than 3% TPES) to fuel 30% global fleet (some 700 million fuel cell cars)
- **Total H_2 use by 2050 (energy use + other uses):** more than 22 EJ H_2 (more than four-fold current production)
- **With less optimistic assumptions**, H_2/FC are unlikely to reach the critical mass for market uptake. Other options (biofuels, FT synfuels) play a major role.
- **Stationary uses:** in all scenarios, 200-300 GW FC by 2050 (5% electrical capacity); most natural-gas SOFC e MCFC for CHP in residential-industrial sector; robust technology option, not sensitive to assumptions

Regional Prospects

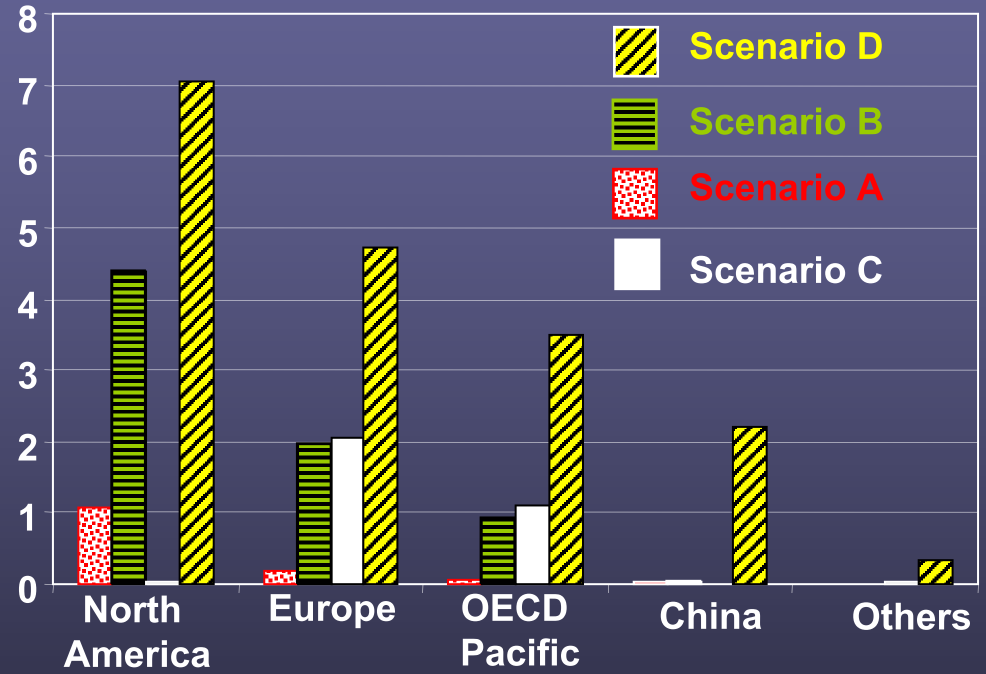
- Potential for transport use in OECD regions and China
- Under most favorable assumptions 60% FCVs in China by 2050, 42% India and US, 36-48% Europe, 35% Canada, 22% Japan, 10% Australia
- Penetration from 2020 in EU & NA, 2025 elsewhere
- Differences across regions due to economic conditions, discount rate, infrastructure, consumers' attitude for capital-intensive investment, fuel taxes, mobility needs, car-mileage.

H_2/FC Regional Prospects

Geographical distribution of H_2 use - Scenario D



H_2 use per capita in 2050 - (GJ H_2/capita)



Under favorable assumptions 60% FCVs in China by 2050, 42% India and US, 36-48% Europe, 35% Canada, 22% Japan, 10% Australia

Impact on CO_2 & Security

Living in the most favorable scenario w/o H_2/FC …

+ 5% total CO_2 emissions by 2050 (1.4 Gt)
+ 2% total oil use (conventional + unconv.)

- 30% FCV are replaced by ethanol vehicles (10%), natural gas, FT synfuels, adv. ICEV, hybrids (20%)
- Need for a rapid expansion of other oil substitutes

A limited impact but …

in an optimal, diversified system, the impact of a single technology is limited. No technology is crucial

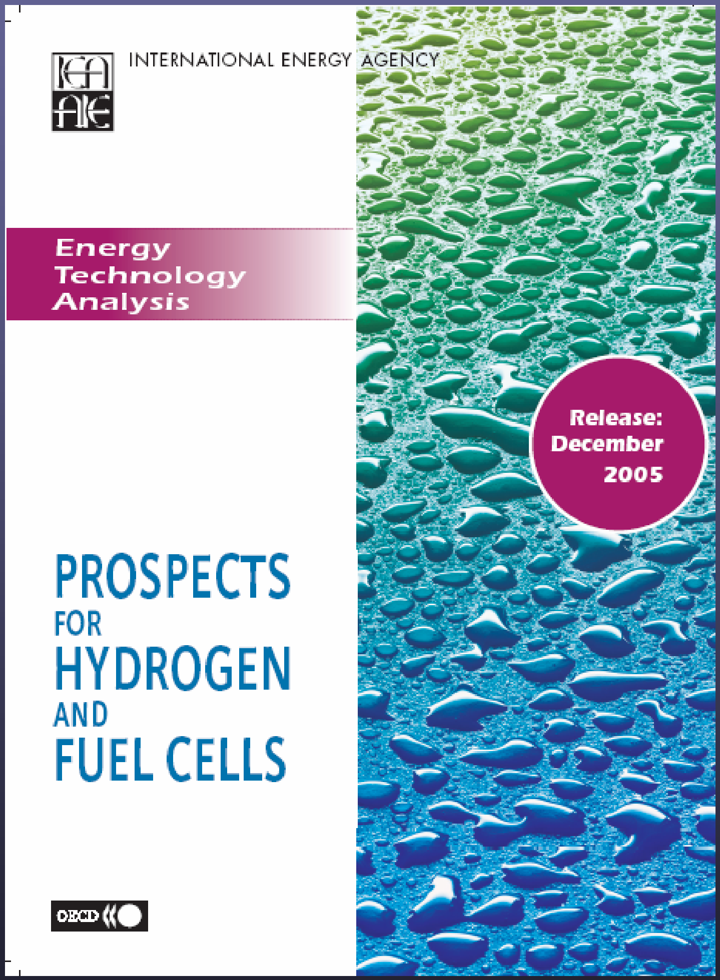
Infrastructure Investment

Global *Incremental (*)* investment in infrastructure and vehicles in the period 2000-2050 (tentative estimate)

- **Pipelines for transport sector: $ 0.1 – 1.0 trill.**
- **Refueling Stations: $ 0.2 - 0.7 trill.**
- **Fuel cells Vehicles: $ 1.0 - 2.3 trill.**

(*) Additional investment needs vs conventional, existing technologies

Policy Insights



Policy Insights 1

- H_2/FC is a costly option: the expected cost decline is unlikely to result in economic advantage vs. other techs
- H_2 may have a role if new, concerted CO_2 and energy security policies are in place. Security policies alone will not result in a transition to H_2 … Other options exist (coal) in a CO_2-unconstrained world
- Under favorable assumptions on future technology advances and energy policies .... Worldwide 30% H_2 FCVs by 2050, as a part of a broader technology portfolio

Policy Insights 2

- Deploying H_2 infrastructure is premature ... advances in FCs and H_2 storage may have an impact on infrastructure (e.g., operating pressure)
- R&D effort should focus on production of CO_2-free H_2, solid storage, FC costs & durability, but also on … H_2 transportation & distribution (possible bottleneck)
- Solid-state physics & material science might drive unexpected breakthroughs: photo-electrolysis, biological production, water splitting by nuclear/solar heat, solid H_2 storage, materials and FC concepts ... These technologies might have a major impact on future energy systems

Thanks

H_2 On-board Storage

Targets: volume, weight, T&P, load time & energy, and cost
(5 kgH_2 per 500km FCV; 5-6 wt% H_2; Tr. 80-150 C; $150/kg)

Ref. Option	Gaseous C-fiber vessels	Liquid Cryo-tanks	Solid Metal Hydrides
wt% H_2	4-6	4-5 (20)	8 ??
Volume, lt.	160	120-130	60-70 ??
P,T	700 bar	1 bar, -253 C	10-60 bar ??
Cost, $/kg	600-800	700-800	??
Status	Commercial	Commercial	Developmental R&D
Pro	temperature, time	volume, press., time	vol., press. energy, purity
Contra	Lifetime, vol., safety energy 15%, cost	lifetime, boiloff, safety energy 30-40%, cost	lifetime, weight, time, reversibility, cost ?
Other Options	Glass microspheres	$NaBH_4$, C_7H_{14}, C_7H_8	Nano-C, MOF, HAS, alanates borohydrides, th. hydrides

More R&D needed to meet requirements !