Method	Critical Parameters / Parts Notice	Plant Size	Efficiency1	[$/kWhth]
Fossil				
Catalytic Steam Reforming of Natural Gas	Cheapest method, sensitive to feedstock prices	240 mio kg H2/a	78%	0.021 to 0.026
Hydrogen from Coal Gasification	High capital costs	240 mio kg H2/a	58% / 63%	0.053 to 0.065
Combined Coal Gasification with High Temperature Electrolysis		240 mio kg H2/a	57%	0.056
Syngas Production from Crude Oil, Followed by Water-gas Shift + CO2 Separation	Sensitive to capital costs	240 mio kg H2/a		0.033 to 0.047
Mixed				
Solar Reforming of Natural Gas	Syngas prod. cost: 0.0264 $/kWhth		Reformer: 85-90%	0.0264
Solar Thermal Decarbonisation of Natural Gas (Aerosol Flow Reactor)	60% of costs are heliostat field and reactor	1 mio kg H2/a		0.032 to 0.051
Renewable				
Solar High Temperature Thermal Dissociation of Steam	Very high temperatures critical for material and methods			
Electrolysis	Based on electricity at 0.049 $/kWhe	Several hundred MWe	65-75%	0.068 to 0.081
Trough System + Electrolysis	Electricity prices dominate costs	Several hundred MWe	Power: 20%	0.20
Power Tower System + Electrolysis	Electricity prices dominate costs	Several hundred MWe		0.16
Dish/Sterling System + Electrolysis	Electricity prices dominate costs	Several hundred MWe	Power: 20%	0.26
Solar Thermal Electricity + High Temperature Electrolysis	Electricity from Power Tower; sensitive to size, voltage and operating temperature of the HTE	200 MWth input	Electrolyzer: 80%	~0.13
Solar Photovoltaic Electricity + Electrolysis	Projection for 2010	5 mio kg H2/a		0.24 to 0.28
Solar Photoelectrochemical Production	High voltage; corrosiveness			
Solar Thermo Chemical Production				
- ZnO/Zn cycle	Very high temperatures critical for material; early stage of development	90 MWth input	29%	0.13 to 0.15
- Iron/calcium oxide/bromide cycle				
- Sodium iodide/ammonium iodide cycle (Hitachi)				
- Solar Thermal Co-production of Zinc and Syngas	Costs very sensitive to efficiency and heliostat area	50 MWth input		0.14
- Hydrogen and Sulfur from H2S (Quench)	Based on electricity at 0.05 $/kWhe	3-4 MWe input		0.041
Wind Electricity + Electrolysis	Sensitive to scale and average wind velocity; assuming electricity price of 0.06 $/kWhe	Several 10 kWe input	Power: 40 to 50%	0.135 to 0.17
Biomass Combustion + Electrolysis	Early stage of development			
Steam Gasification of Biomass		~350 mio kg H2/a	60% max.	0.047 to 0.08
Biomass Fermentation				
Hydroelectricity + Electrolysis				0.1

1: Overall thermal efficiency, if not otherwise indicated

Figure 22: Overview of the discussed hydrogen production methods

from: HYDROGEN PRODUCTION___An Overview of Hydrogen Production Methods and Costs Today

Term Paper WS01/02 Rolf Fahrni April, 2002
Institute for Energy Technologies Professeur für Erneuerbare Energieträger

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

	Estimated Costs			Method
[$/kWhth]		[$/GJth]		
	CONVERSION FACTOR=		277,777778	
low	high	low	high	
				Fossil
0,021	0,026	5,83	7,22	Catalytic Steam Reforming of Natural Gas
0,053	0,065	14,72	18,06	Hydrogen from Coal Gasification
0,056		15,56		Combined Coal Gasification with High Temperature Electrolysis
0,033	0,047	9,17	13,06	Syngas Production from Crude Oil, Followed by Water-gas Shift + CO2 Separation
				Mixed
0,0264		7,33		Solar Reforming of Natural Gas
0,032	0,051	8,89	14,17	Solar Thermal Decarbonisation of Natural Gas (Aerosol Flow Reactor)
				Renewable
				Solar High Temperature Thermal Dissociation of Steam
0,068	0,081	18,89	22,50	Electrolysis
0,2		55,56		Trough System + Electrolysis
0,16		44,44		Power Tower System + Electrolysis
0,26		72,22		Dish/Sterling System + Electrolysis
0,13		36,11		Solar Thermal Electricity + High Temperature Electrolysis
0,24	0,28	66,67	77,78	Solar Photovoltaic Electricity + Electrolysis
				Solar Photoelectrochemical Production
				Solar Thermo Chemical Production
0,13	0,15	36,11	41,67	- ZnO/Zn cycle
				- Iron/calcium oxide/bromide cycle
				- Sodium iodide/ammonium iodide cycle (Hitachi)
0,14		38,89		- Solar Thermal Co-production of Zinc and Syngas
0,041		11,39		- Hydrogen and Sulfur from H2S (Quench)
0,135	0,17	37,50	47,22	Wind Electricity + Electrolysis
				Biomass Combustion + Electrolysis
0,047	0,08	13,06	22,22	Steam Gasification of Biomass
				Biomass Fermentation
0,1		27,78		Hydroelectricity + Electrolysis

from: HYDROGEN PRODUCTION___An Overview of Hydrogen Production Methods and Costs Today

Term Paper WS01/02 Rolf Fahrni April, 2002

Institute for Energy Technologies Professeur für Erneuerbare Energieträger

prepared by C.Royère, IMP/CNRS, Dec 2002

Les coûts de production de H2: tableau 6

Table 2. Estimated current future nuclear electricity and hydrogen production costs

	Units	Grid electricity industrial rate	New nuclear capacity	Current electrolysis	Advanced reactor design	Advanced electrolysis
Interest rate	Per cent/year		12	12	12	12
Project lifetime	Years		20	20	20	20
Load factor	Hours/year		7 500	7 900	7 900	8 300
Capital costs	$/kWe		2 450	600	1 120	400
Capital charges	mills/kWh		44.05	10.19	21.02	6.43
O&M costs	mills/kWh		10.33	7.61	1.15	3.60
Fuel costs	mills/kWh		7.39	110.46	3.64	38.72
Total electricity costs	*mills/kWh*	*50*	*61.77* (6)		*25.81*	
Hydrogen production costs	*$/GJ*	*25-30*		*30.7*		*13.5*
	$/bbl	*140-171*		*175*		*77*

[6] Based on a 12% discount rate and 20-year project life. Nuclear generating costs drop to 40 mills/kWh and 54 mills/kWh if 5 and 10% discount rates and a 30-year project life are assumed.

Sce :Rogner, IAEA, NEA-OCDE, 2000

C.Royère

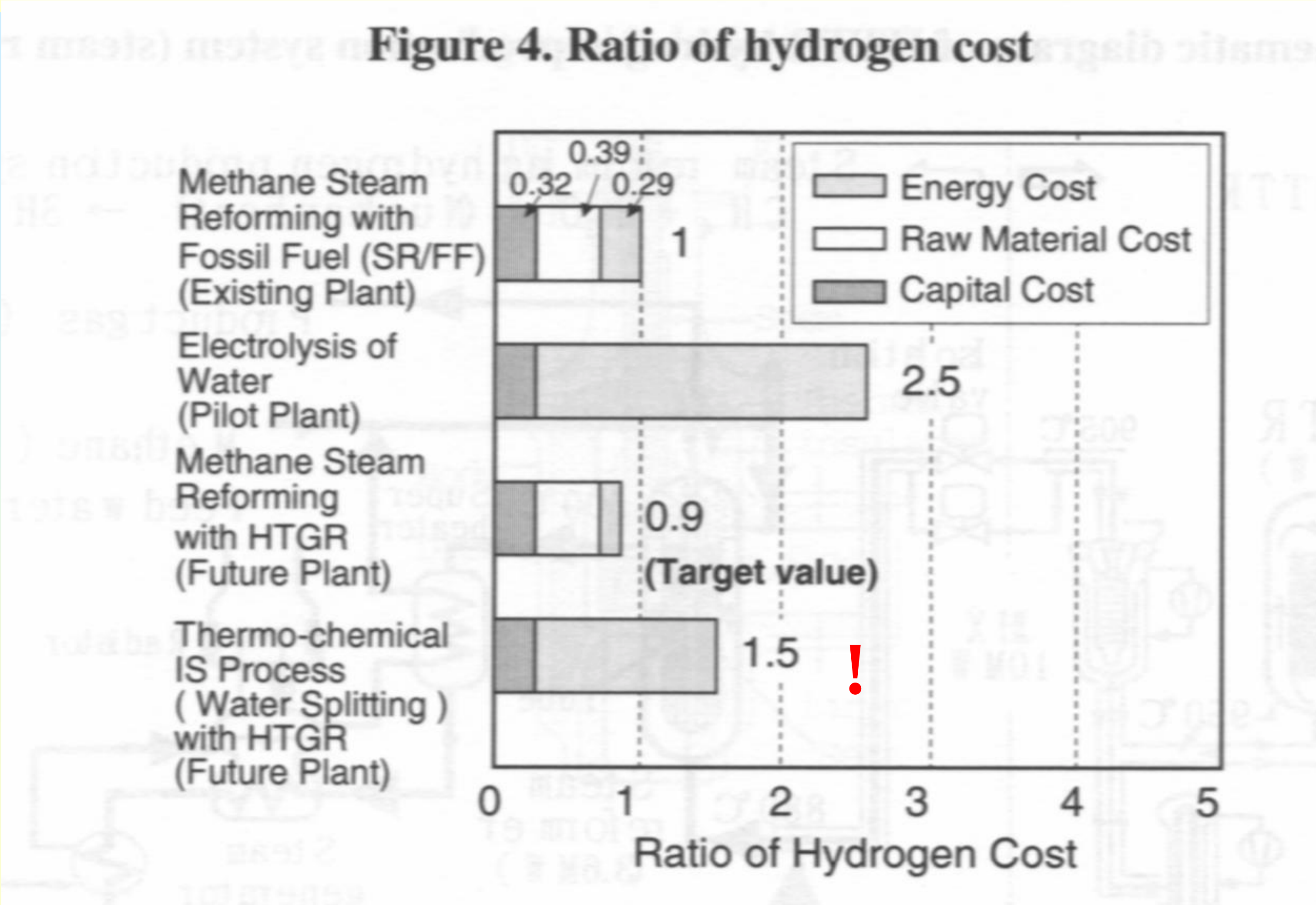
Les coûts de production : tableau 7

Hydrogen from renewable	0,75-10 DM/m^3	0,38-5,11 €/m^3 35-473 €/GJ **(€/m^3X92,7=€/GJ)**
Hydrogen from hydrocarbons or coal	0,1-0,12 DM/m^3 (synthèse de l'ammoniaque) raffineries et cokeries : 0,03-0,05 DM/m^3 SR gaz naturel : 0,03-0,06 DM/m^3	0,05-0,06 €/m^3 4,6-5,6 €/GJ 0,015-0,026 €/m^3 1,39-2,4 €/GJ 0,015-0,03 €/m^3 1,39-2,8 €/GJ
Hydrogen from nuclear electricity via electrolysis (baseload)	0,13-0,22 DM/m^3 0,09-0,11 DM/m^3* 0,05**	0,067-0,113 €/m^3 6,2-10,5 €/GJ 0,046-0,056 €/m^3 4,3-5,2 €/GJ 0,0256 €/m^3 2,4 €/GJ
Hydrogen from thermal processes (nuclear primary energy from HTR)	< 0,12 DM/m^3 (SR gaz naturel)	0,061 €/m^3 5,65 €/GJ
Données **Stoll, 2001** : (Stoll 2001) Electrolyse : 4,5 kWh/m^3 H_2 (futur* : 3 à 3,5 kWh/m^3) ; électricité nucléaire : 0,03-0,05 DM/kWh , rendement 30% (futur** :45%) ; électricité solaire (évaluation « optimiste ») : 0,5-2 DM/m^3 ; électricité éolienne (non subventionnée) : 0,25-0,3 DM/m^3 ; 1,95583 DM/€ ; LHV(H_2) : 10,786 MJ/m^3 STP		
Préparé par C.Royère, Septembre 2002		

Sce :Stoll, 2001

C.Royère

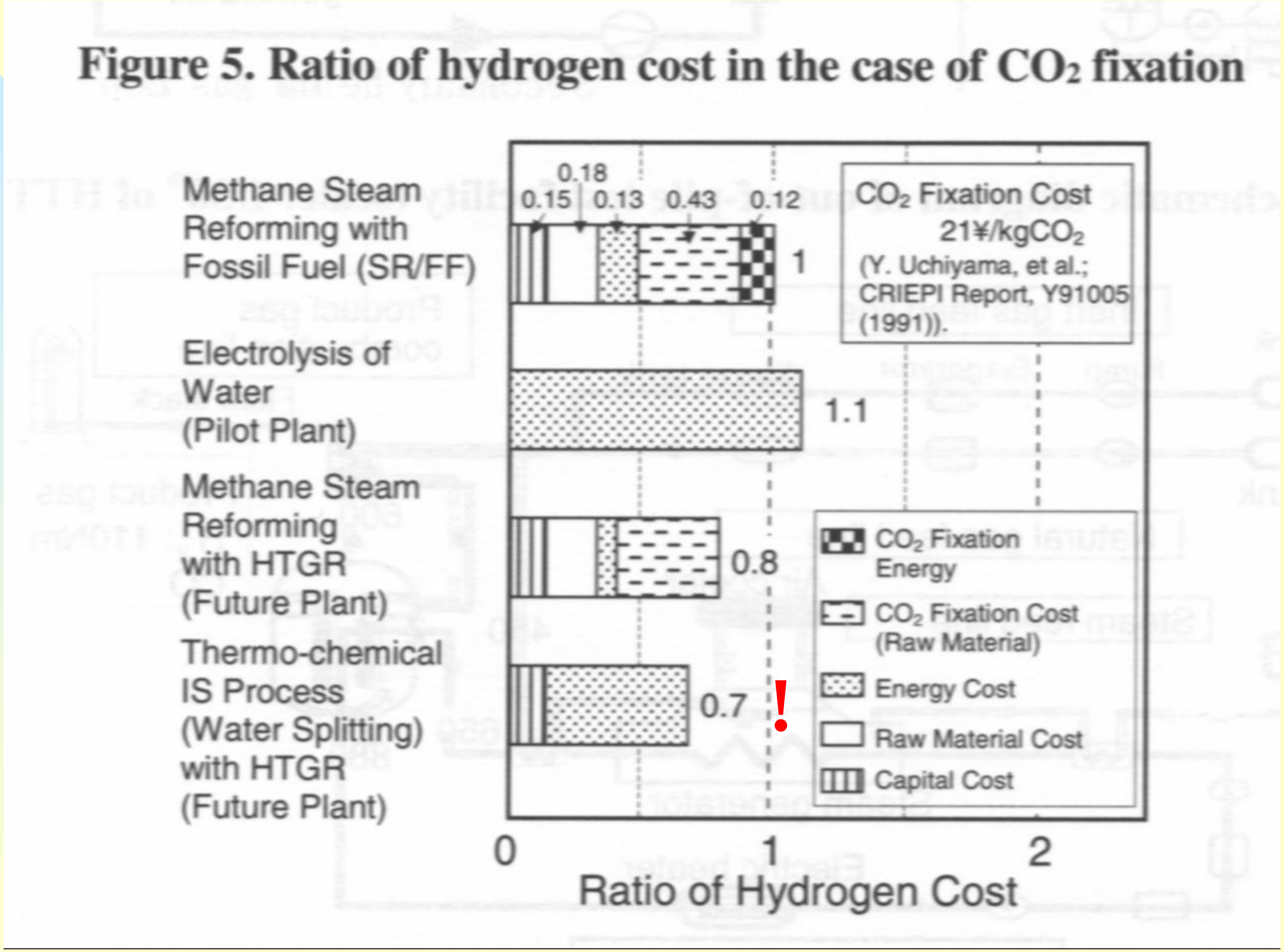
Les coûts de production: figure 38



Sce :Shiozawa et al. JAERI, HTGR-HTTR project, NEA-OCDE, 2000

C.Royère

Les coûts de production: figure 39



Sce :Shiozawa et al. JAERI, HTGR-HTTR project, NEA-OCDE, 2000

C.Royère

Les coûts de production: données figure 40

Economic assumptions span a wide range

Description	GT-MHR	MHR alone	SI-H_2 Cycle	H_2-MHR
Total Overnight Cost, $M	1,290	968	504 - 1,008	1,472 - 1,976
	($1120/kWe)		($210-420/kWt)	
Operating Cost, $M/year	127	95.3	33.6 - 67.2	128.9 - 162.5
Efficiency — production	48%			40 - 60%
— electrolysis	65 - 95%			
Electrolysis Unit Cost	$288M–1.2B			
	($250-1000/kWe)			
Electricity Distribution Cost Multiplier	1.0 - 3.0			
Capital Recovery Rate	5 - 20%	5 - 20%	5 - 20%	5 - 20%
Transmission distance	0-1000 mi			0-1000 mi

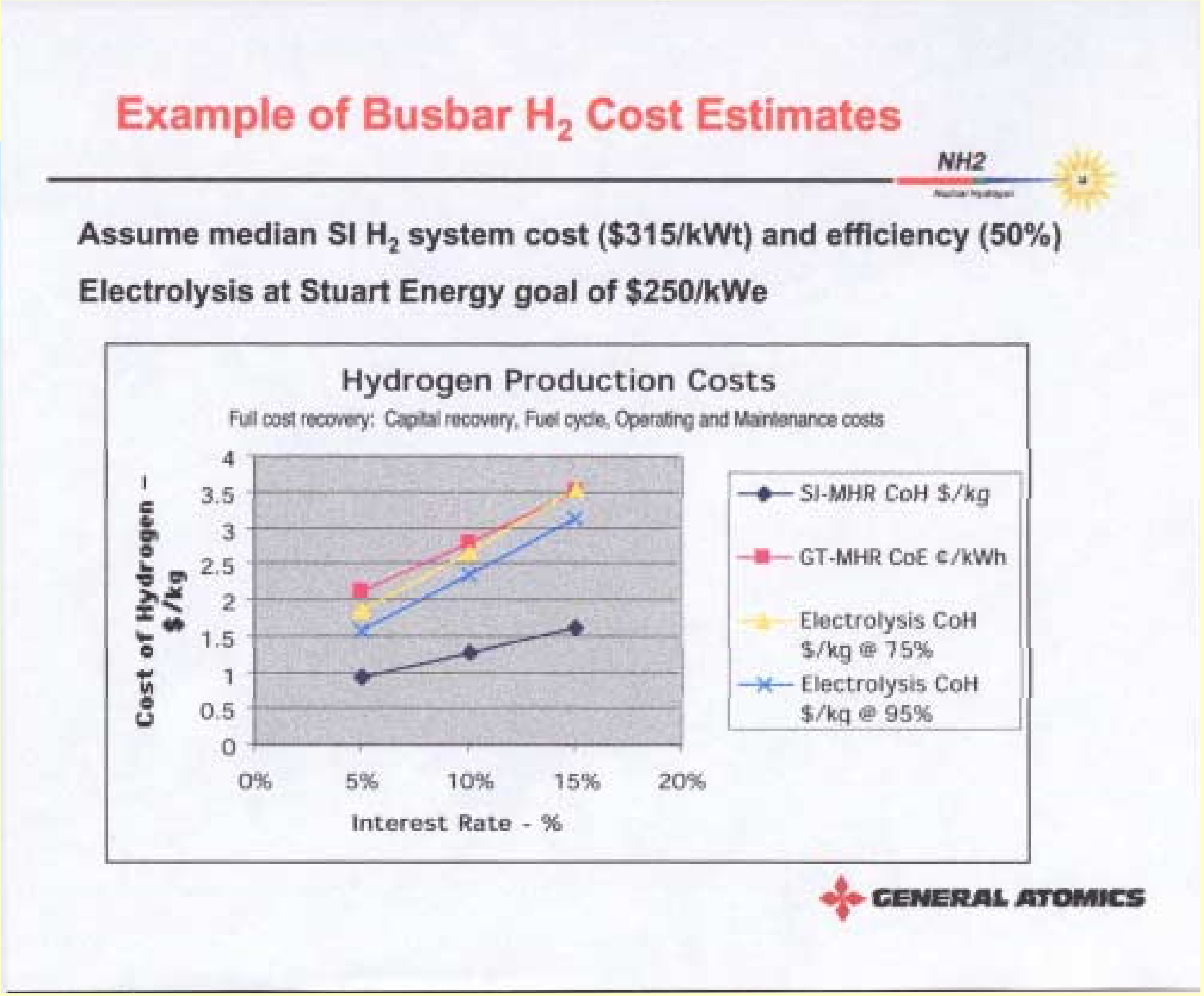
Intent: Use model parametrically

GENERAL ATOMICS

cf fig. suiv. ; sce : GA Golden 2002)

C.Royère

Les coûts de production: figure 41



(cf sup. ; sce : GA Golden 2002)

Les coûts de production : tableau 8-a

Kaarstad (1997) (Kaarstad and Audus 1997)	
Nat Gas	3 $/GJ
Coal	2 $/GJ
Electricity from Hydro	10 $/GJ (3,6 US$c/kWh)
Petroleum	35 $/bl (6,10 US$/GJ 7,32 US$c/kWh – 0,3 eff)
<u>Hydrogen production costs</u>	
H2 from Nat. Gas	5,6 US$/GJ
H2 from Nat. Gas + CO_2 sequ	6,9 US$/GJ
H2 from coal + CO_2 sequ	13,2 US$/GJ
H2 from electrolysis (electricity from hydro)	20 US$/GJ
<u>Electricity production costs</u>	
Electricity from Hydro	10 US$/GJ (3,6 US$c/kWh)
Electricity from new coal plant	12,5 US$/GJ (4,5 US$c/kWh)
Electricity from Nat Gas (3 US$/GJ) + CO_2 removed and stored	18,8 US$/GJ (6,8 US$c/kWh)
Electricity from Coal + CO_2 removed and stored	21,9 US$/GJ (7,9 US$c/kwh)

Sce : Kaarstad (1997)

Les coûts de production : tableau 8-b

Gaudernack, 1998 (Gaudernack and Lynum 1998)	
Hydrogen production costs	
H_2 from Electrolysis (Electricity 4,5 US$c/kWh)	24 US$/GJ
CB&H	6,5 US$/GJ
SMR + CO_2 sequest.	7 US$/GJ
Steinfeld, 2002 (Steinfeld 2002a)	
H_2 from Zn/ZnO TC	41,7 US$/GJ
H_2 from SMR (Nat Gas 2,8-3,3 US$/GJ)	8,3-11,1 US$/GJ
H2 from electrolysis (electricity from Solar troughs at 33,3 US$/GJ)	55,6 US$/GJ
H2 from electrolysis (electricity from Wind at 16,7 US$/GJ)	47,2 dec to 27,8 US$/GJ
Electricity from solar H_2 and FC	91,7 US$/GJ (0,33 US$/kWh)

Sce : Gaudernack, 1998; Steinfeld, 2002

Les coûts de production : tableau 8-c

Rogner, 2001 (Rogner and Scott 2001)	US$/GJ electricity	US$/GJ H_2 from electrolysis
Grid electricity 50 mills/kWh	13,9	25-30
New nuclear plants electricity 62 mills/kWh	17,2	31
Current average nuclear electricity 20 mills/kWh	5,6	13
Advanced reactor designs electricity 20 mills/kWh	7,2	13,5

IS GA thermochemical cycle (55,5 % eff, **Bilgen et al., 1995**) (Ozturk et al. 1995) HTGR primary heat (1,7-6,9 US$/GJ)	3-12,4 US$/GJ (H2 production energy cost)

UT-3 thermochemical cycle 45% eff with membrane gas separator, cogeneration (nuclear HTGR heat : 6 US$/GJ) (**Tadokoro, 1997**) (Tadokoro et al. 1997)	27,5 US$/GJ ($H_2$ production cost)
Préparé par C.Royère, Septembre 2002	

Sce : Rogner, 2000; Bilgen et al., 1995;Tadokoro, 1997