

CO-PRODUCTION OF HYDROGEN AND ELECTRICITY WITH CO₂ CAPTURE

Authors: **John Davison** **(IEA - Greenhouse Gas R&D Programme)**
 Rosa Maria Domenichini **(Foster Wheeler Italiana)**
 Silvio Arienti **(Foster Wheeler Italiana)**

Presented by **Rosa Maria Domenichini** **(Foster Wheeler Italiana)**

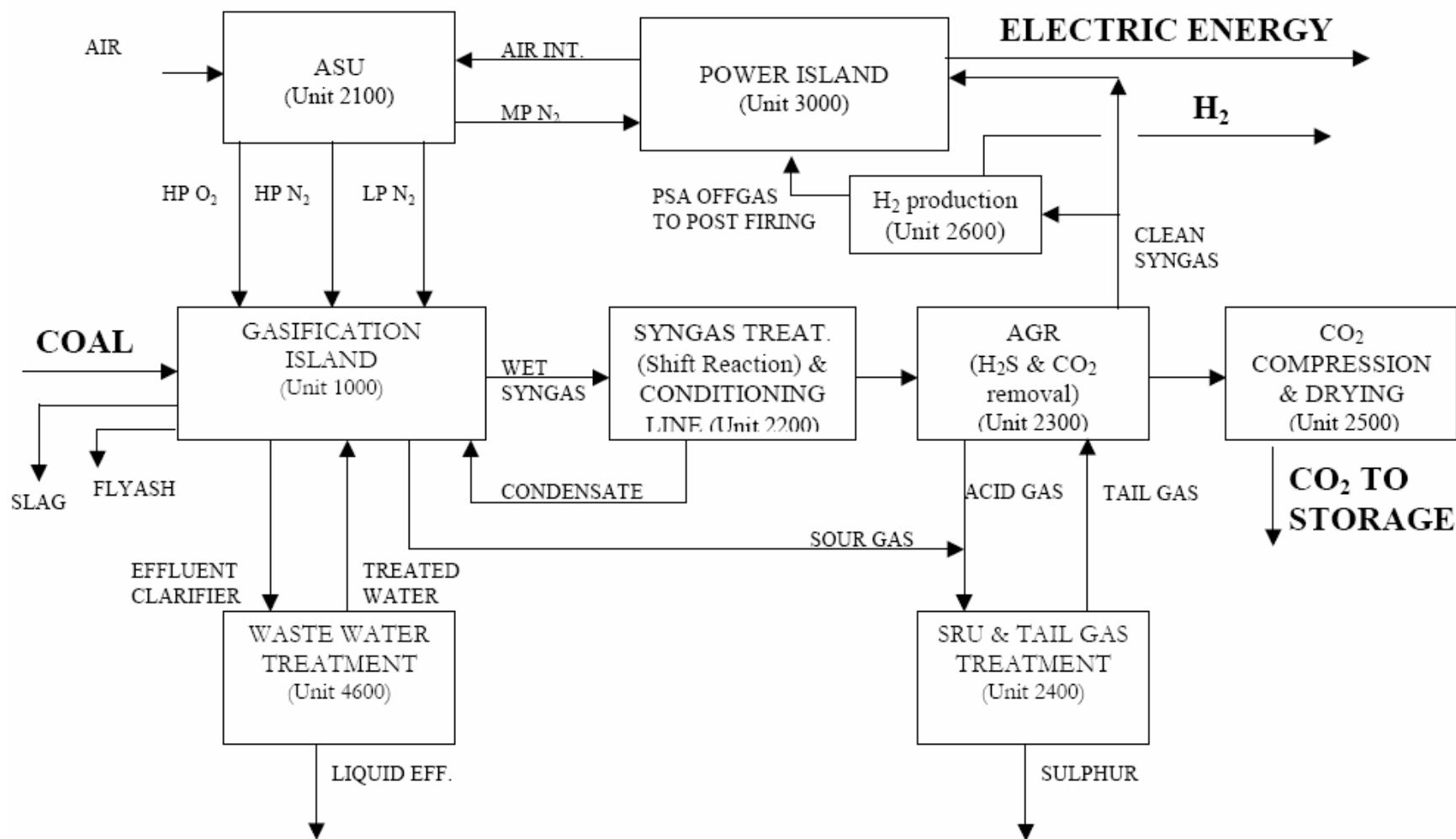
AGENDA

- Hydrogen based scenario
- Bases of Design
- Electric Energy and Hydrogen Consumption of the Netherlands and USA
- Technologies Comparison for Gasification and AGR
- Hydrogen Storage
- Review of Alternative Designs
- Co-production scenarios
- Conclusions

HYDROGEN BASED SCENARIO

- Hydrogen presently used in refineries, ammonia plant and for chemicals production
- Future uses :
 - vehicles
 - power generation
 - distributed heat and energy to buildings
- Possible hydrogen sources:
 - fossil fuel (coal – cheapest way)
 - renewable
- Hydrogen and electric power coproduction plant based on IGCC with CO₂ capture expected to be the best solution

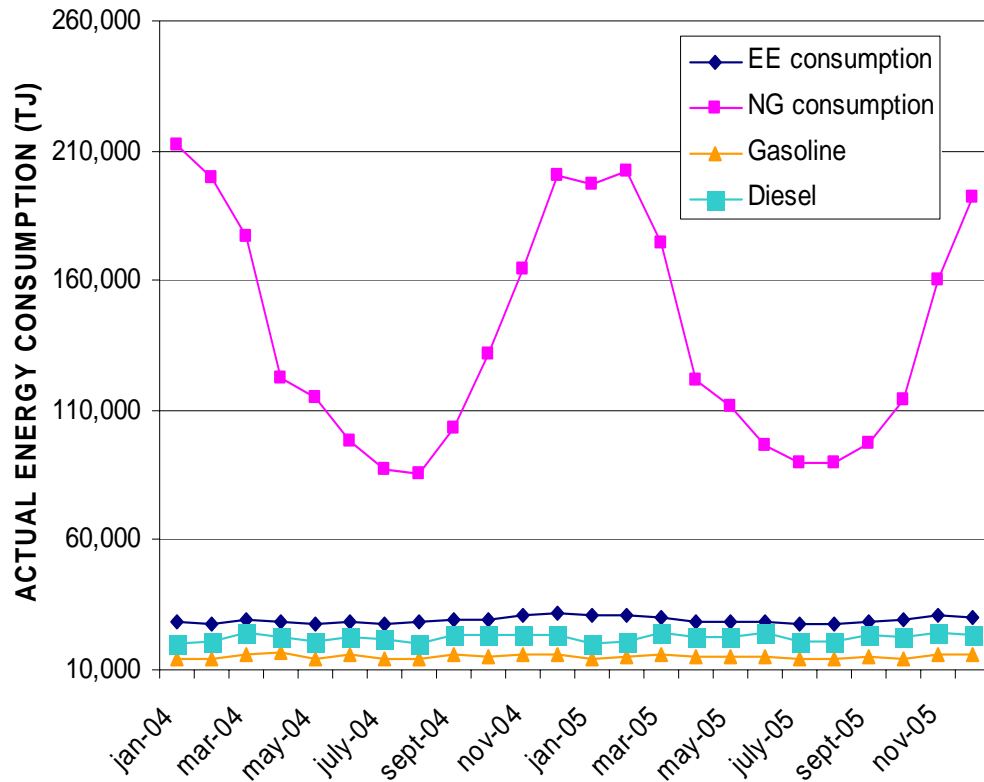
IGCC BLOCK FLOW DIAGRAM



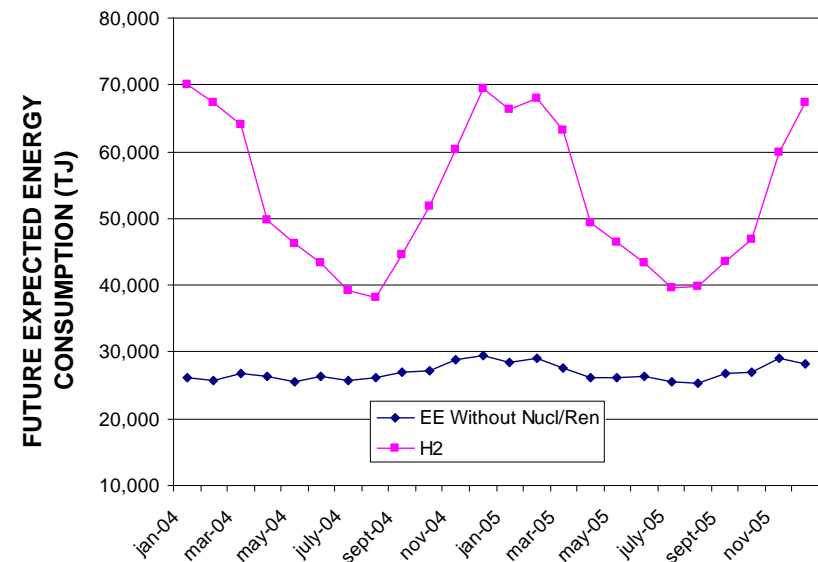
BASES OF DESIGN

- IGCC Nominal Capacity : 750 MWe
- Coal from eastern Australia : LHV= 25,870 kJ/kg
Sulphur content= 1.1% wt.
- Environmental Impact : very low NO_x, SO_x, particulate and CO emissions
85% CO₂ removed and sequestered
- By products : Sulphur (liquid or solid)
CO₂ (in case of EOR or ECBM)
- Main economic parameters : Discount rate 10%, plant life 25 years, coal price
1.5 \$/GJ

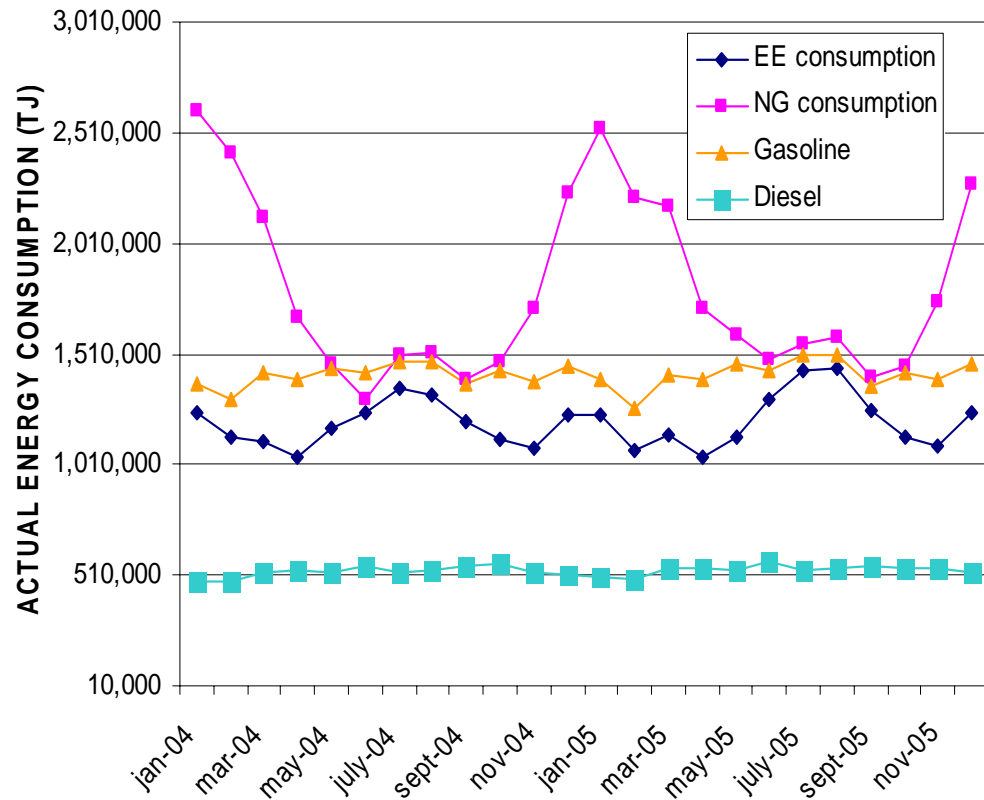
ELECTRIC ENERGY AND HYDROGEN CONSUMPTION IN THE NETHERLANDS YEAR 2004-2005



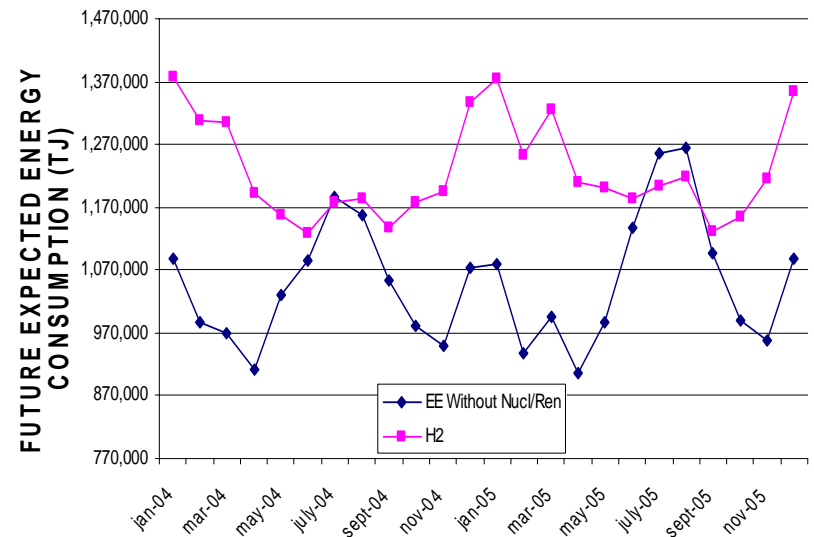
Nuclear and Renewable Energy % of Total Electric Power Production	7.1%
Power Generation and Industrial Natural Gas % of Total consumed Gas	58.0%
Natural Gas actualization factor	0.60
Gasoline actualization factor	1.00
Diesel actualization factor	1.00
Gasoline Motor Efficiency	25.0%
Diesel Motor Efficiency	40.0%
Fuel Cell Efficiency	70.0%



ELECTRIC ENERGY AND HYDROGEN CONSUMPTION IN THE USA YEAR 2004-2005



Nuclear and Renewable Energy % of Total Electric Power Production	12.7%
Power Generation and Industrial Natural Gas % of Total consumed Gas	61.0%
Natural Gas actualization factor	0.60
Gasoline actualization factor	1.00
Diesel actualization factor	1.00
Gasoline Motor Efficiency	25.0%
Diesel Motor Efficiency	40.0%
Fuel Cell Efficiency	70.0%



GASIFICATION TECHNOLOGIES COMPARISON

		Case 0A GEE Gasifier	Case 0B Shell Gasifier	Case 0C Siemens Gasifier
ACID GAS REMOVAL TECHNOLOGY		Selexol	Selexol	Selexol
CO₂ Capture Efficiency	%	84.8	85.1	84.7
CO₂ Capture Flowrate	t/h	623	548	631
Coal Flow Rate A.R.	t/h	323.1	273.1	316.6
Thermal Energy of Feedstock	MWth	2321.8	1962.5	2275.1
Gross Equivalent Electric Power Output	MWe	960	853.5	871.3
H₂ produced	MWth	598	599	593.4
H₂ produced	Nm ³ /h	200,510	200,858	199,022
H₂ equivalent electric power	MWe	334.9	335.4	332.3
Auxiliary Consumption	MWe	234.3	201	216.1
Net Equivalent Electric Power Output	MWe	725.7	652.5	655.2
Gross Equivalent Electrical Efficiency	%	41.3	43.5	38.3
Net Equivalent Electrical Efficiency	%	31.3	33.3	28.8
(H₂/effective EE) ratio	MWt/MWe	1.5	1.9	1.8
Total Investment	10 ⁶ €	1476.8	1336.9	1317.5
O&M Costs	MM€	136.2	116.5	129.4
C.O.E (DCF=10%)	€/kWh	0.071	0.071	0.073

GASIFICATION TECHNOLOGIES SELECTION

- The three alternatives show a similar cost of electricity (COE)
- Shell has been selected due to the following reasons:
 - syngas composition more suitable for the H₂/EE of The Netherlands
 - better efficiency, consequent lower production of CO₂ and lower cost for transport and storage

ACID GAS REMOVAL SOLVENT COMPARISON

- Two solvents evaluated for AGR : Selexol lower investment cost
Rectisol lower operating cost
- Pay back for Rectisol : 6 years with GEE gasification
>20 years with Shell gasification
- Solvent chosen for the study : Selexol (with Shell gasification)

HYDROGEN STORAGE

- Considered to match periodical demand variations
- Several options evaluated:
 - Metal Hydride: very costly, suitable for small quantity only
 - Above ground compressed gas: costly, adequate as storage for short periods
 - Underground compressed gas: adequate for long periods and large quantities, low cost
 - Liquid hydrogen: specific applications related to high degree of safety and low storage density, requires expensive cryogenic facilities

UNDERGROUND HYDROGEN STORAGE

Underground compressed gas storage:

- convenient for large quantities of gas, long-term storages
- chosen for this study
- wide range of capital cost (geological configuration dependent): 1 - 40 €/Kg of stored gas
- storage cost considered for the study, based on present experience: 1.5 €/Kg

Underground storage main references:

- **Wade A. Amos, "Cost of storing and transporting hydrogen"; National Renewable Energy Laboratories, November 1998**
- **George D. Parker, "Hydrogen Cavern operation", Presentation at IPCE 2006, ConocoPhillips, Bartlesville, OK, USA**

FIVE PLANT ALTERNATIVES

- Case 1 : production of electric energy (EE), without CO₂ capture (case taken as reference)
- Case 2 : production of EE only; with CO₂ capture
- Case 3 : co-production of maximum H₂ quantity; production of EE for internal consumption only; with CO₂ capture
- Case 4 : co-production of H₂ and EE at fixed ratio (future ratio evaluated for The Netherlands); with CO₂ capture
- Case 5 : co-production of H₂ and EE at flexible ratio with CO₂ capture

REVIEW OF ALTERNATIVE DESIGNS

Case #1 plant	Case #2 plant	Case #3 plant	Case #4 plant
w/o CO ₂ capture, w/o H ₂ production	CO ₂ capture; w/o H ₂ production	CO ₂ capture; maximum H ₂ production	CO ₂ capture; H ₂ production; optimum fixed H ₂ /EE ratio;

Gasification	Coal consumption	t/h	250.6	273.1	273.1	273.1
	PSA	Hydrogen production (99.5% purity)	Nm ³ /h	n/a	n/a	372,400.0
Power Island	Gas turbines total power output	MWe	553.6	572	87.6	286
	Steam turbine power output	MWe	338.3	303	121	232.1
	Net electric power output (B)	MWe	762.3	654.7	0.10	317.1
CO ₂ capture	CO ₂ to Storage	kmol/h	n/a	12458	12458	12458
	CO ₂ Emissions	kmol/h	n/a	2183	2183	2183
Cost	Capital cost	EUR	1,041,278,700	1,560,120,000	1,196,050,000	1,336,860,000
	O&M fixed cost	EUR/y	39,560,000	54,930,000	40,670,000	46,290,000
	O&M variable cost	EUR/y	62,455,000	70,270,000	70,250,000	70,260,000

REVIEW OF ALTERNATIVE DESIGNS (cont.'d)

Case #4 plant	Case #5 plant-R low	Case #5 plant-R high
CO2 capture; H2 production; optimum fixed H2/EE ratio;	CO2 capture; H2 production; flexible H2/EE ratio; R low	CO2 capture; H2 production; flexible H2/EE ratio; R high

Gasification	Coal consumption	t/h	273.1	273.1	273.1
PSA	Hydrogen production (99.5% purity)	Nm ³ /h	200,858.0	162,240.0	246,160.0
Power Island	Gas turbines total power output	MWe	286	286	286
	Steam turbine power output	MWe	232.1	279	157.4
	Net electric power output (B)	MWe	317.1	363.1	236.6
CO2 capture	CO2 to Storage	kmol/h	12458	12458	12458
	CO2 Emissions	kmol/h	2183	2183	2183
Cost	Capital cost	EUR	1,336,860,000	1,350,140,000	1,350,140,000
	O&M fixed cost	EUR/y	46,290,000	46,780,000	46,780,000
	O&M variable cost	EUR/y	70,260,000	70,270,000	70,270,000

CO-PRODUCTION SCENARIOS

- Scenario 1 : EE only and H₂ only production plants, without H₂ storage
- Scenario 2 : non-flexible co-production plants without H₂ storage
- Scenario 3 : non-flexible co-production plants with H₂ storage
- Scenario 4 : flexible co-production plants without H₂ storage
- Scenario 5 : flexible co-production plants with H₂ storage

**Scenarios compared on electricity production cost
at fixed H₂ price 9.5 €cent/Nm³ (8.8 €/GJ)**

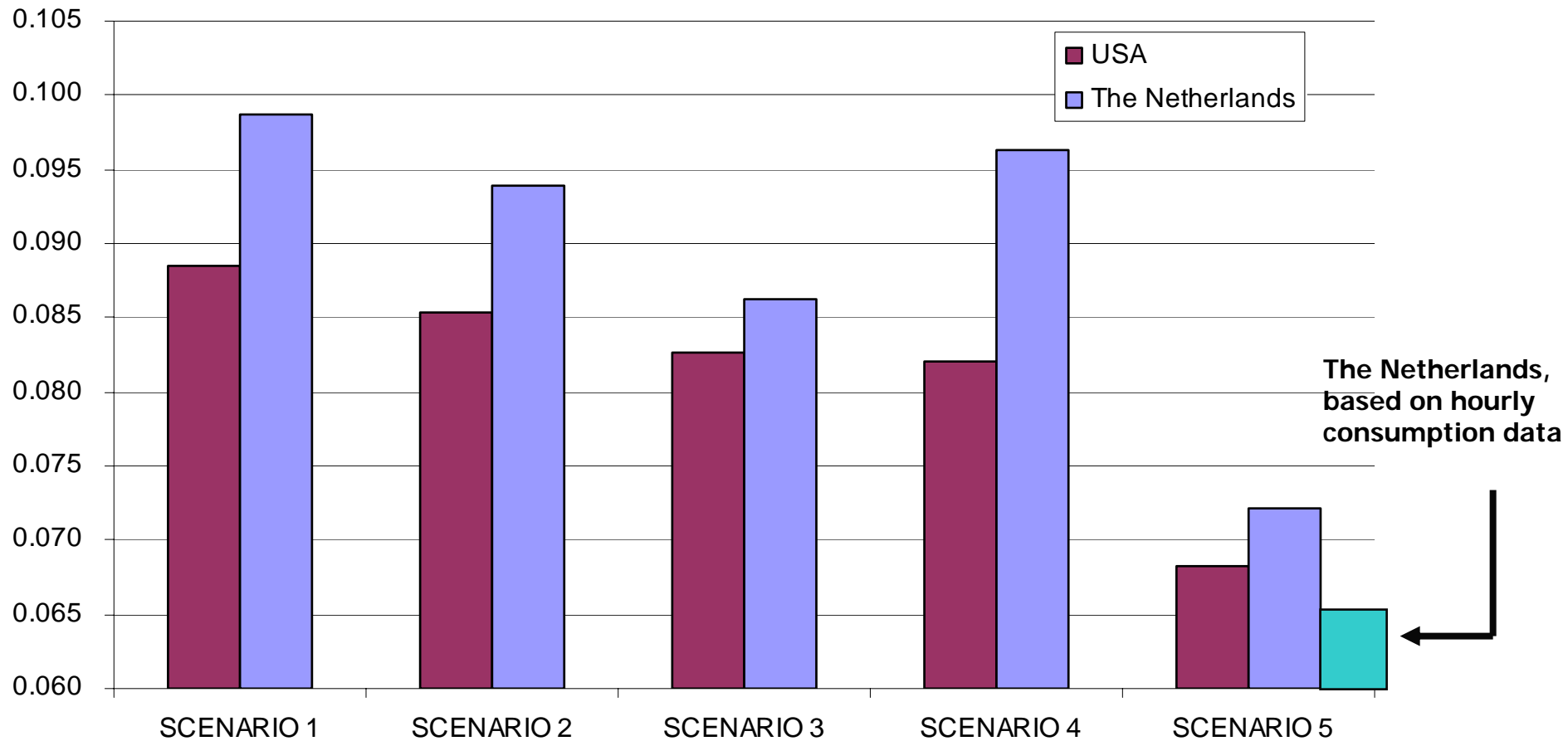
THE NETHERLANDS CO-PRODUCTION SCENARIOS COMPARISON

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
	EE PLANT AND H2 PLANT ONLY	NON FLEX COPROD PLANT W/O H2 STORAGE	NON FLEX COPROD PLANT WITH H2 STORAGE	FLEXIBLE COPROD PLANT W/O STORAGE	FLEXIBLE COPROD PLANT WITH STORAGE -
Quantity Plants #2	21	7	4	7	0
Quantity Plants #3	29	13	5	9	0
Quantity Plants #4	0	29	36	0	0
Quantity Plants #5	0	0	0	33	40
Total quantity of plant	50	49	45	49	40
Monthly average installed plants #2 load factor	89.1%	66.5%	35.1%	45.9%	
Monthly average installed plants #3 load factor	75.0%	47.1%	32.5%	45.6%	
Monthly average installed plants #4 load factor		100.0%	100.0%		
Monthly average installed plants #5 load factor				100.0%	98.4%
Max quantity hydrogen in storage (million Nm3)	n/a	n/a	2,389	n/a	4,564
Overall coal consumption (t/h)	9392	9234	9060	9358	9135
Plants Capital Cost (excluding storage) (milions EUR)	67,448	65,238	60,348	66,240	54,006
Underground Storage Capital Cost (including extra PSA unit) (milions EUR)	n/a	n/a	390	n/a	670
Total Capital Cost (including underground)(milions EUR)	67,448	65,238	60,738	66,240	54,675
Total O&M Cost million EUR/y (underground) (base on monthly average)	4,749	4,631	4,432	4,702	4,212
Electricity Prod Cost [Euro/kWh]	0.099	0.094	0.086	0.096	0.072

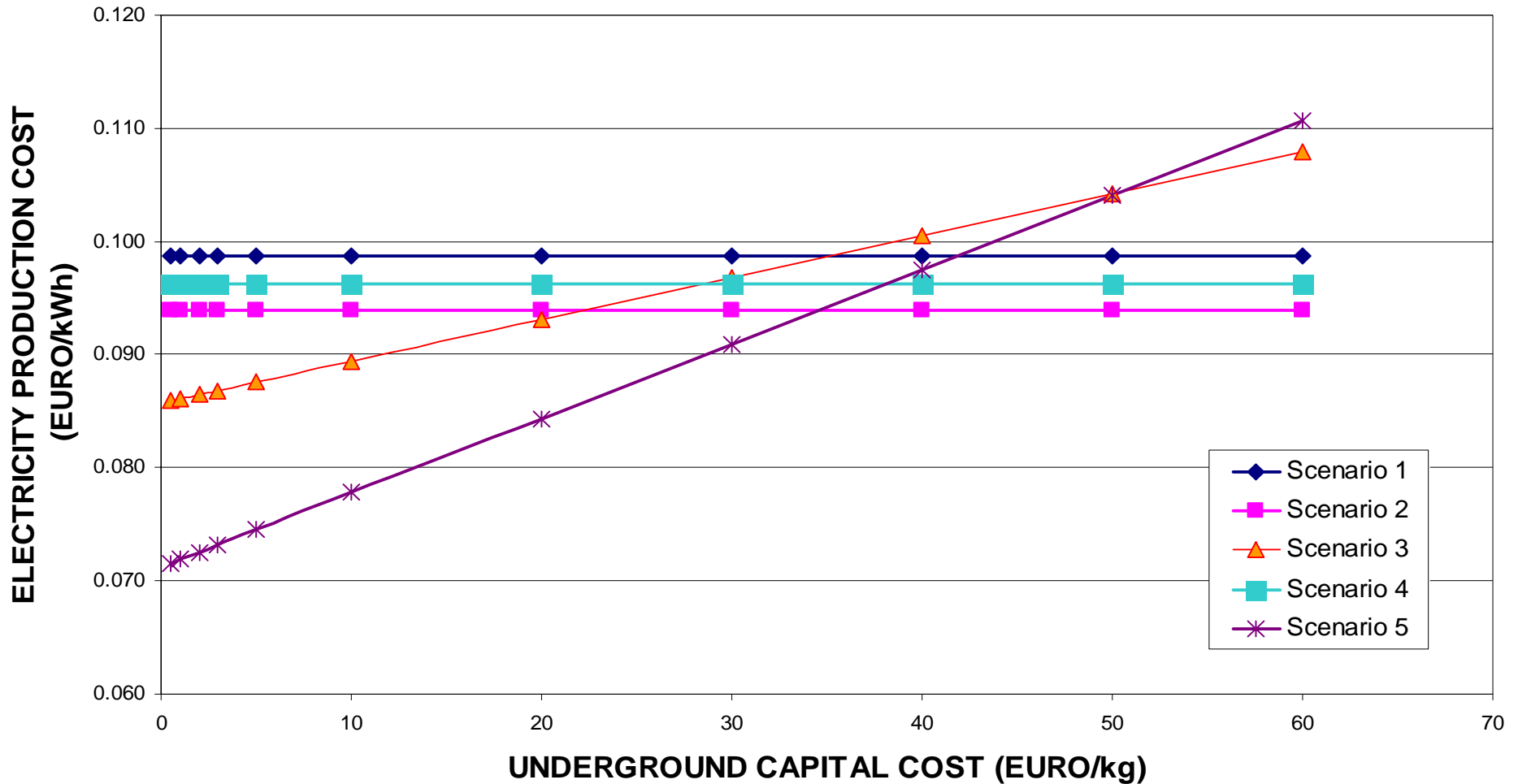
USA CO-PRODUCTION SCENARIOS COMPARISON

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
	EE PLANT AND H2 PLANT ONLY	NON FLEX COPROD PLANT W/O H2 STORAGE	NON FLEX COPROD PLANT WITH H2 STORAGE	FLEXIBLE COPROD PLANT W/O STORAGE	FLEXIBLE COPROD PLANT WITH STORAGE -
Quantity Plants #2	876	462	426	170	0
Quantity Plants #3	563	101	0	97	0
Quantity Plants #4	0	856	932	0	0
Quantity Plants #5	0	0	0	1132	1216
Total quantity of plant	1439	1419	1358	1399	1216
Monthly average installed plants #2 load factor	83.0%	67.6%	65.2%	40.1%	
Monthly average installed plants #3 load factor	89.2%	40.3%	0.0%	46.7%	
Monthly average installed plants #4 load factor		100.0%	100.0%		
Monthly average installed plants #5 load factor				100.0%	100.0%
Max quantity hydrogen in storage (million Nm ³)	n/a	n/a	37,830	n/a	41,968
Overall coal consumption (t/h)	285375	280681	280838	289100	282218
Plants Capital Cost (excluding storage) (milions EUR)	2,040,041	1,985,929	1,910,565	1,909,596	1,641,770
Underground Storage Capital Cost (including extra PSA unit) (milions EUR)	n/a	n/a	5,717	n/a	7,779
Total Capital Cost (including underground)(milions EUR)	2,040,041	1,985,929	1,916,281	1,909,596	1,649,549
Total O&M Cost million EUR/y (underground) (base on monthly average)	144,436	141,322	138,978	140,624	129,737
Electricity Prod Cost [Euro/kWh]	0.089	0.085	0.083	0.082	0.068

ELECTRICITY PRODUCTION COST (COE) (EURO/kWh)



UNDERGROUND STORAGE COST SENSITIVITY



CONCLUSIONS

1. Flexible co-production plants with H₂ underground storage is the best configuration:
 - electricity production cost for The Netherlands:
0.072 €/kWh (based on average monthly consumption)
0.065 €/kWh (more detailed analysis based on hourly consumption)
 - electricity production cost for USA:
0.068 €/kWh (based on average monthly consumption)
 - basis:
hydrogen price = 9.5 €cent/Nm³
hydrogen storage cost = 1.5 €/kg

CONCLUSIONS (cont.'d)

2. Configurations with storage appear more convenient for storage cost < 35 €/kg
3. Underground compressed H₂ storage is largely the most attractive for large quantities and long period storages
4. Use of underground storage requires H₂ compression and purification facilities: limited investment cost
5. Few underground stores are presently in operation: technology to be further developed

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Nicoletta_Falzone@fwceu.com