IGCC PLANTS TO MEET THE REFINERY NEEDS OF HYDROGEN AND ELECTRIC POWER

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Introduction: Conversion of Refinery bottom of the barrel

The Refinery Industry is confronted with a difficult challenge: crude oils are getting heavier and more contaminated while the demand and the quality of light products, i.e. transportation fuels, are increasing. These two facts are in conflict and force the industry to invest heavily to convert heavy products to light products and improve their quality, to satisfy the requirements of progressively severe environmental regulations.

Conversion technologies have been developed and improved over the years under the pressure of this challenge. However the zero residue production still remains an impossible target. Conversion, even in its most advanced and costly form, leaves the refiner with a residual bottom product reduced in volume but more contaminated with sulphur and metals, thus more difficult to dispose.

Integrated Gasification Combined Cycle (IGCC) is a promising answer to these refinery needs: it is a commercially proven technology available for the combined production of hydrogen, to satisfy its increasing demand, and electric power from fossil fuels, heavy residue oils as well as from coal and petcoke.
The IGCC (Integrated Gasification Combined Cycle) can be supplied with the most exhausted and unvalued refinery products, either liquid (asphalt) or solid (petcoke).
The alternative refinery schemes leading to the production of asphalt of petcoke are shown in the following drawings. In both schemes hydrogen is produced in the IGCC and used in the cracking units of the Refinery, where heavy hydrocarbons are transformed in valuable light products.

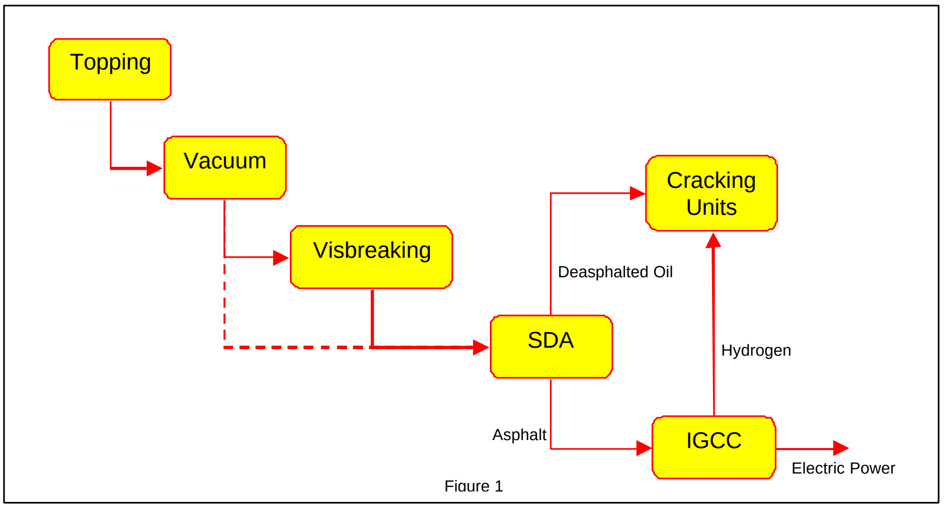


Figure 1

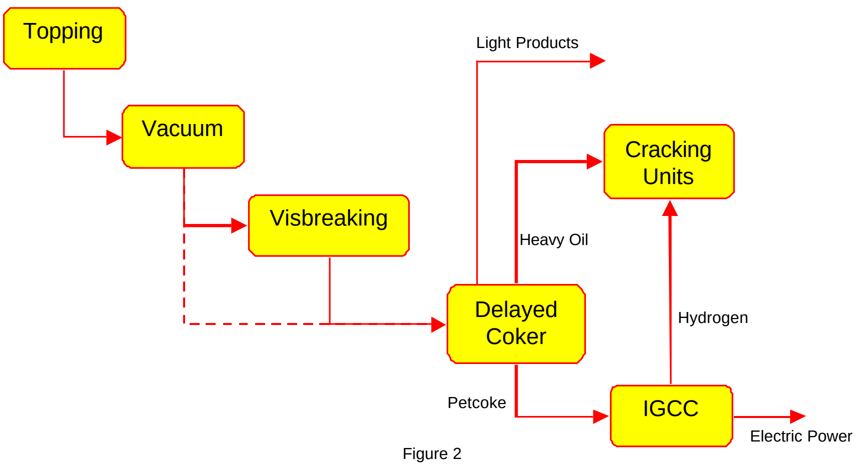


Figure 2

Scope of the study

This paper describes some IGCC plant alternatives, based on oxygen blown entrained bed gasification, sized to produce different amounts of hydrogen and electric energy. Overall performances and investment costs are evaluated and discussed through a sensitivity analysis on Cost of Electricity and Cost of Hydrogen. Loss of performances due to the CO_2 sequestration is also evaluated.

This work is the prosecution of the study presented by FWI at the Palermo H2: www@sicily Conference (Palermo, Italy, October 16-19, 2005): "*Combined production of hydrogen and electric power from heavy residues: the IGCC answer to the refinery needs*".
While that study was based on asphalt as feed of the IGCC, this study takes into account both asphalt and petcoke and compares the IGCC based on the different feeds.

IGCC in the industry

Gasification is the conversion of either a solid (coal, coke, biomass, solid waste) or a liquid fuel (oil, tar, pitch) into a gas, often identified as syngas, in which the major components are hydrogen (H_2) and carbon monoxide (CO).

In the last decades of the past century, gasification was mainly used in the petrochemical industry for the manufacture of chemical products.
Today gasification is also integrated with power production, acting as a bridge between coal, petcoke or heavy fuel oils and the gas turbines. Gasification of such fuels generates a fuel gas that, after cleaning, can be used in a gas turbine combined cycle power plant. The resulting process configuration (Integrated Gasification Combined Cycle – IGCC) is the only power technology that, even burning coal or high sulphur residues, can approach the environmental performance of natural gas fired systems.

In fact the syngas, before firing in the gas turbine, can be cleaned to reduce to very low levels contaminants such as sulphur compounds and particulates. Furthermore, the syngas can be mixed with nitrogen and/or saturated with water to reduce similarly the nitrogen compounds originated in the combustion.

In addition, IGCC represents the most promising technology for the CO_2 capture, based on the only utilization of the state-of-art technologies.

In summary, the design of the IGCC plant can be adjusted to meet separately or together several needs of the current market:

- Environmental: emissions well below the current limits without penalizing plant efficiency and investment cost. The IGCC configuration can easily accommodate a CO_2 capture section.
- Production capacity: flexible design to meet different requests of hydrogen or electric energy.
- Productions costs: competitive Cost of Electricity (C.O.E.) and Cost of Hydrogen (C.O.H.) for selling in the market.

Bases of design for the study

This paper describes six alternative IGCC plant configurations for the combined production of hydrogen and power, starting from an asphalt produced in a refinery Solvent Deasphalting Unit, plus three cases from petcoke produced in a refinery Delayed Coker.

For the six cases on asphalt, the IGCC is designed considering different power generation plants to produce alternatively 150,000, 100,000 or 50,000 Nm^3/h (99.8 % purity) of hydrogen at 30 barg, and approx 350 MWe of electric power. Both the alternatives with and without capture of the produced CO_2 are considered.
For the three cases on petcoke different power generation plants are considered to produce alternatively 150,000, 100,000 or 50,000 Nm^3/h (99.8% purity) of hydrogen at 30 barg and approx 350 MWe of electric power.
Plants are designed to process, in an environmentally acceptable manner, asphalt, which is produced by a deasphalting unit fed with Visbroken Vacuum Residue (LHV equal to 38,124 kJ/kg and 7.58 % wt sulphur content), or petcoke (LHV equal to 33,867 kJ/kg and 6.73% wt sulphur content)

The site conditions assumed for the IGCC plant are a green field on a seacoast with an average air temperature of 9°C and an average sea water temperature of 12°C. Table 1 summarizes the nine cases that have been evaluated.

Table 1 – Description of the process alternatives.

CASE	Feed Type	CO_2 capture	Hydrogen production, Nm^3/h
A.1	Asphalt	No	150,000
A.2	Asphalt	Yes (1)	150,000
B.1	Asphalt	No	100,000
B.2	Asphalt	Yes (1)	100,000
C.1	Asphalt	No	50,000
C.2	Asphalt	Yes (1)	50,000
D.1	Petcoke	No	150,000
E.1	Petcoke	No	100,000
F.1	Petcoke	No	50,000

Note (1): 85% of asphalt carbon content.

The gasification is based on oxygen-blown entrained bed gasification, operating at a pressure at least suitable to feed the gas turbine (42 barg). For each alternative the IGCC plant design capacity is fixed to fulfil both the required production of hydrogen and the appetite of one gas turbine General Electric Frame 9FA. This gas turbine is representative of the current state-of-the-art of large commercial gas turbines suitable for syngas operation.

The IGCC Complex main products are hydrogen and electric energy; by-products are: sulphur (liquid or solid), solid by-products (metal cake) and carbon dioxide (alternatives recovering CO_2).

The overall gaseous emissions from the IGCC Complex, referred to dry flue gas with 15% volume O_2, shall not exceed the following limits:

- ♦ NOx (as NO_2): $\leq$ 50 mg/Nm^3

- ♦ SOx (as SO_2): ≤ 10 mg/Nm^3
- ♦ CO: ≤ 30 mg/Nm^3
- ♦ Particulate: ≤ 10 mg/Nm^3

These limits are lower than those defined by the applicable European Directive and are set in order to reduce the emissions without penalizing the plant efficiency and investment cost.

Description of the IGCC complex

The IGCC Plant is a multi unit complex (process and utility units), which is called to operate simultaneously in an integrated way. Its design can be easily optimised to meet the desired hydrogen and electric power production.

The following description makes reference to Figure 1, showing the IGCC block flow diagram and the main process streams. The main process blocks of the complex are:

- Feedstock storage and preparation;
- Air separation (cryogenic technology);
- Gasification, including black water/grey water treatment;
- Syngas treatment and conditioning, including acid gas removal (AGR);
- Hydrogen production.
- Combined cycle power generation.

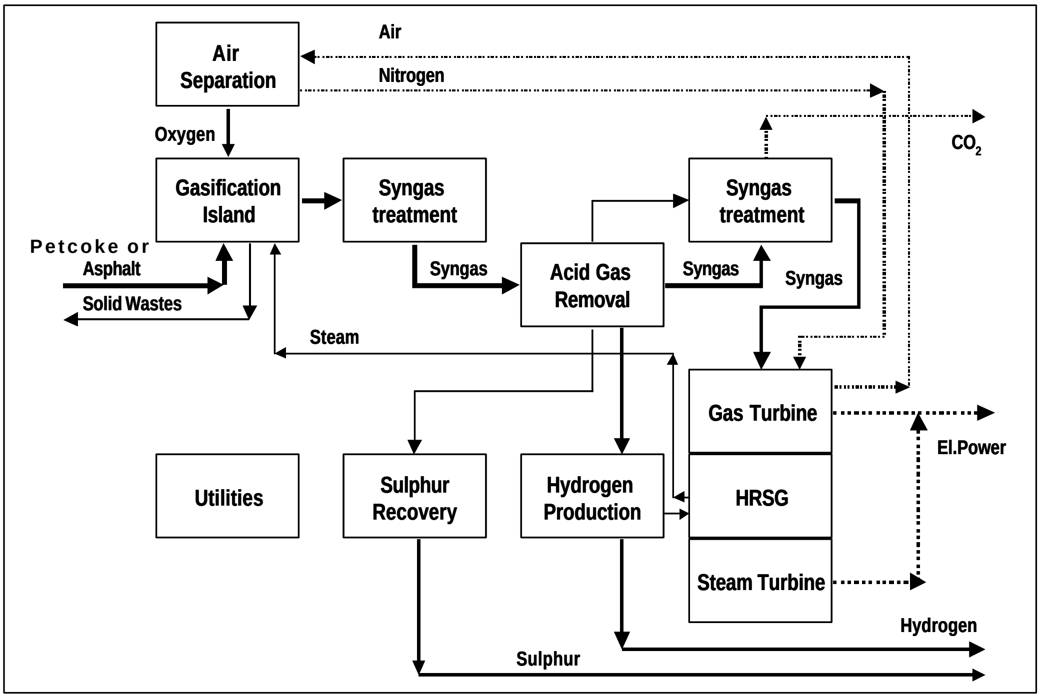


Fig. 3 – IGCC Block flow diagram.

These basic blocks are supported by other ancillary units, such as sulphur recovery, tail gas treatment, and a number of utility and offsite units, such as cooling water, flare, plant/instrument air, machinery cooling water, demineralized water, auxiliary fuels, etc.

Each process unit of the complex may be a single train for the total capacity or split in two or more parallel trains, depending on the maximum capacity of the equipment involved or on the necessity to assure, through the use of multiple parallel trains, a superior degree of reliability.

The key and first process step is the entrained flow gasification, which is suitable both for solid and liquid feed. In this type of gasifier the feed, atomized oil or petcoke slurry flows co-currently with the gasification agents (O_2 and steam). Residence time is very short, between 0.5 and 5 seconds; the temperature inside the gasifier is uniform and very high, from 1,300° to over 1,500°C, well above the ash fusion temperature.

Recovery of gasifier sensible heat is made through a water quench inside the gasifier and subsequent recovery of the degraded heat in external waste heat boilers, producing medium and low-pressure steam. The quench system permits to remove efficiently solids from the raw gas, before entering the downstream facilities. In addition, water quench is attractive for the downstream CO shift reaction, which increases the H_2/CO ratio. In fact CO shift requires large amounts of water in the gas, which can be conveniently added in the quench.

Syngas main components are H_2, CO, CO_2, H_2O and, additionally, H_2S and COS that need to be removed, and inerts. Downstream gasification, the shift reaction occurs on a catalyst suitable to process H_2S containing syngas (sour shift) to convert CO and water to H_2 and CO_2. The shift catalyst promotes also the COS hydrolysis with its conversion to H_2S and CO_2. Raw syngas is then treated in the syngas treatment and conditioning unit to remove all the contaminants and prepare the syngas to produce both hydrogen and electric energy.

A physical solvent washing makes the removal of acid gases (H_2S and CO_2). For alternatives without the CO_2 capture, in the acid gas removal (AGR) two clean syngas streams are produced: the first one taken from the H_2S absorber outlet is ready to be fed to the power island. The second one is further washed to remove CO_2 and then sent to a pressure swing adsorption unit for hydrogen purification. The hydrogen produced with a purity of 99.8% is sent to the plant battery limits at 30 barg, to be delivered to users by means of a dedicated pipeline. The CO_2 rich stream is compressed and mixed to the clean syngas upstream of the gas turbine.

For alternatives with the CO_2 capture, CO_2 is removed by the entire syngas stream entering AGR, and than dried/compressed to 110 bar in order to be delivered to geological storage reservoirs. The cost of CO_2 storage depends on local factors, such us transport distance, pipeline diameter and type of reservoir. At some locations CO_2 could have a positive value for enhanced oil recovery but at other locations transport and storage results in additional substantial costs.

In the sulfur recovery unit, the H_2S rich stream coming from the AGR regenerator is burned in the presence of oxygen in a muffle furnace, followed by two reactors in series where the Claus reaction takes place to produce liquid sulfur.

The oxygen required both for the gasification reaction and the Claus reaction is produced in the air separation unit (ASU), where air is fractionated by cryogenic distillation. The ASU is partially integrated with the power island as a portion of the compressed air required by the oxygen plant is delivered from the gas turbine compressor. For alternatives with the CO_2 capture, the absence of CO_2 as medium for NOx control and power augmentation is compensated with compressed nitrogen from the ASU, added to the syngas before feeding the gas turbine.

Performance data

The performance data of the nine alternatives are summarised in Table 2.

Both electrical and thermal efficiency of the plant are referred to the feedstock Low Heating Value. The IGCC thermal efficiency is related to the hydrogen production.
The total efficiency is the sum of thermal and net electrical efficiency.
The feedstock flow rate shown in Table 2 is different for each alternative whose target is to produce sufficient syngas to fulfil both the required hydrogen production and the appetite of one GE 9FA gas turbine.

Table 2 – Performance data.

Case	Fuel	Gross Power Output	Hydrogen production		Aux. Cons.	Net Power Output	Thermal Efficiency	Net Electrical Efficiency	Total Efficiency
	t/h	MWe	Nm^3/h	MWth	MWe	MWe	%	%	%
A.1	165.9	466.0	150,000	449.1	124.9	341.1	25.6	19.4	45.0
A.2	168.0	461.2	150,000	449.1	188.1	273.1	25.2	15.3	40.5
B.1	142.4	451.0	100,000	300.1	104.4	346.6	19.9	23.0	42.9
B.2	144.2	446.1	100,000	300.1	159.3	286.8	19.6	18.7	38.3
C.1	118.7	436.0	50,000	150.0	84.7	351.3	11.9	28.0	39.9
C.2	120.1	430.9	50,000	150.0	131.2	299.7	11.8	23.5	35.3
D.1	219.0	429.6	150,000	449.1	77.2	352.4	21.8	17.1	38.9
E.1	187.9	418.0	100,000	300.1	64.0	354.0	16.9	20.0	36.9
F.1	156.8	407.0	50,000	150.0	51.9	355.1	10.2	24.1	34.3

Investment cost data

The investment cost data of the nine IGCC plants are reported in Table 3, showing the total investment cost split into the main sections of the IGCC Complex. Figures represent the total investment cost including the EPC and the Owner's cost.

Table 3 – Total Investment cost data.

CASE	MAIN IGCC SECTIONS INVESTMENT					Total Investment 10^6 Euro
	Air Separation	Process Units	CO_2 Compression	Power Island	Utilities & Offsites	
	10^6 €	10^6 €	10^6 €	10^6 €	10^6 €	
A.1	95	269	0	167	112	643
A.2	99	274	22	166	112	673
B.1	86	245	0	164	105	600
B.2	93	250	20	163	105	631
C.1	69	207	0	162	98	536
C.2	78	211	18	161	98	566
D.1	129	353	0	162	135	779
E.1	117	318	0	159	125	719
F.1	104	282	0	157	114	657

Production costs

The following Table 4 provides the cost of electricity (C.O.E.) of the nine alternatives.

The cost of electricity has been evaluated on the basis of the following assumptions:

- Cost of Asphalt: 20 Euro/t (Asphalt value could be below 0)
- Cost of petcoke: 15.6 Euro/t
- Price of hydrogen: 0.095 Euro/Nm^3
- No selling price is attributed to the sequestered CO_2.
- 7,884 equivalent syngas operating hours of the 100% capacity for the Asphalt cases.
- 7,621 equivalent syngas operating hours of the 100% capacity for the Petcoke cases.
- Total investment cost as given in Table 3.
- 10% discount rate on the investment cost over 25 operating years.
- Maintenance cost equivalent to approx 3.5% of the total capital costs.

Table 4 – Cost of electric power production.

CASE	**Hydrogen prod.**, Nm^3/h	**Cost of H_2** cent/Nm^3	**C.O.E.** cent/kWh
A.1	150,000	9.5	1.50
A.2	150,000	9.5	2.15
B.1	100,000	9.5	2.43
B.2	100,000	9.5	3.20
C.1	50,000	9.5	3.19
C.2	50,000	9.5	3.97
D.1	150,000	9.5	2.35
E.1	100,000	9.5	3.18
F.1	50,000	9.5	3.96

Sensitivity Analysis

To complete the evaluation, six diagrams are attached to the end of the paper:

- Fig. 4 - Cost of Electricity (C.O.E.) versus hydrogen production, asphalt and petcoke, no CO_2 capture;
- Fig. 5 - Cost of Electricity versus Cost of Hydrogen (C.O.H.), asphalt and petcoke no CO_2 capture;
- Fig. 6 - Cost of Electricity versus hydrogen production, asphalt, with and without CO_2 capture.
- Fig. 7 - Cost of Electricity versus Cost of Hydrogen (C.O.H.), asphalt, with and without CO_2 Capture.
- Fig. 8 - Cost of Electricity versus Carbon tax, expressed in €/t of CO_2 emitted, a cost of H_2 equal to 9.5 c€/Nm^3, asphalt with and without CO_2 capture.

Analysis and conclusions

The analysis performed in this study lead to the following conclusions:

- Hydrogen and electric power are produced with an acceptable efficiency both for asphalt and petcoke feedstocks, taking into account the feedstock quality and the environmental performances, which are far superior to that of any other power producing technology known today, based on solid or liquid fossil fuels.
- The IGCC plant configuration and size can be easily adjusted to fulfil different requirements of electric power and hydrogen production. The CO_2 capture can also be made by using state-of-art technologies.
- The cost of electricity, obtained assuming a hydrogen price of 9.5 cents/Nm^3, is attractive for all alternatives, including cases with the CO_2 capture, demonstrating the advantage of their combined production. This demonstrates that, in a competitive electric power market, the IGCC will always be able to dispatch power still maintaining hydrogen cost compatible with the market value.
- The convenience is demonstrated through a wide range of both the hydrogen production flow rate and the cost of hydrogen, values as can be deducted from the sensitivity analysis diagrams reported; it should be considered that asphalt has been priced as a valuable feedstock, while it is recognized that it is really a burden.
- The Cost of Electricity strongly depends on the feedstocks cost. Conservative commercial costs have been considered in this study. Significantly lower C.O.E. could be obtained if specific conditions of the refinery allow lower feedstock costs.
- With reference to Figures 4 and 5, independently from the Hydrogen production, the Cost of Electricity in Petcoke IGCC is higher than in Asphalt IGCC by approx 0.75÷0.85 cents/kWh. This is due both to the higher Capex and to the lower efficiencies of the Petcoke IGCC.
- In Asphalt cases, the penalties on the C.O.E., due to the CO_2 capture, depends both on the cost of hydrogen and the hydrogen production, increasing the cost as a maximum by 90% (case with maximum Hydrogen production and high Cost of Hydrogen) with respect to the alternative without the CO_2 sequestration. (Fig. 7)
- With reference to Figures 5 and 7, for alternatives without the CO_2 capture, hydrogen and electric energy are equally produced, independently from the hydrogen flow rate, for a C.O.E. and a C.O.H.

respectively equal to 4.0 cents/kWh and 4.0 cents/Nm^3 in case of Asphalt and 4.7 cents/kWh and 4.0 cents/Nm^3 in case of Petcoke. In Asphalt cases, for alternatives with the CO_2 sequestration, the same considerations are made for a C.O.E. and a C.O.H. respectively of 4.8 cents/kWh and 4.8 cents/Nm^3.

- For Asphalt cases, the capture of the CO_2 leads to a higher investment cost and to a loss of efficiency with respect to the alternatives without the CO_2 capture (Fig 6 and 7). However, with reference to figure 8, the plant with CO_2 capture is economically convenient even at low level of carbon tax (less than 8 €/t for case with 100,000 Nm^3/h of Hydrogen and 9.5 cent/Nm^3), depending on the hydrogen production and hydrogen cost.
- Improvements in the main areas like the gas turbines, gasifiers and Air Separation Unit are expected in the next years, thus making the IGCC alternative more and more attractive.

Fig. 4 - C.O.E. vs H_2 production

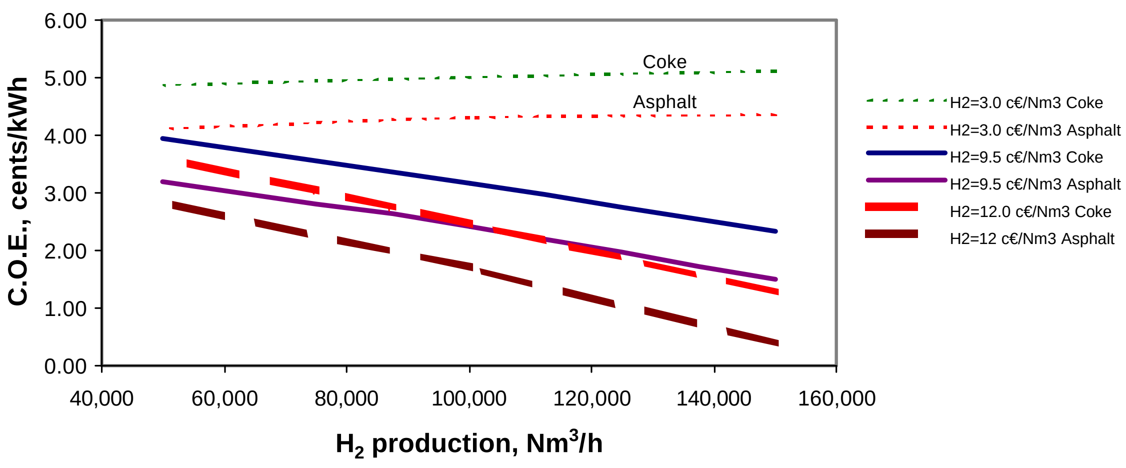


Fig. 5 - C.O.E. vs Cost of H_2

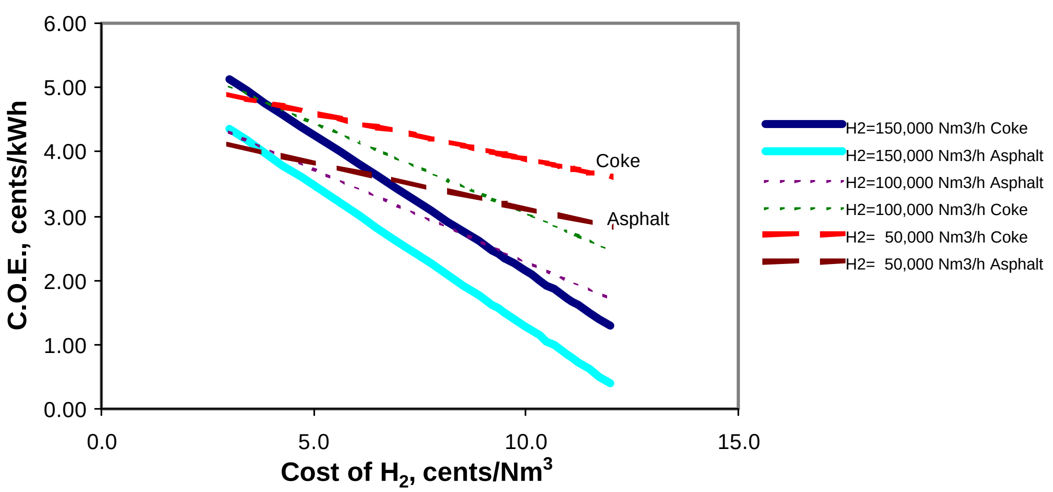


Fig. 6 - C.O.E. vs H_2 production

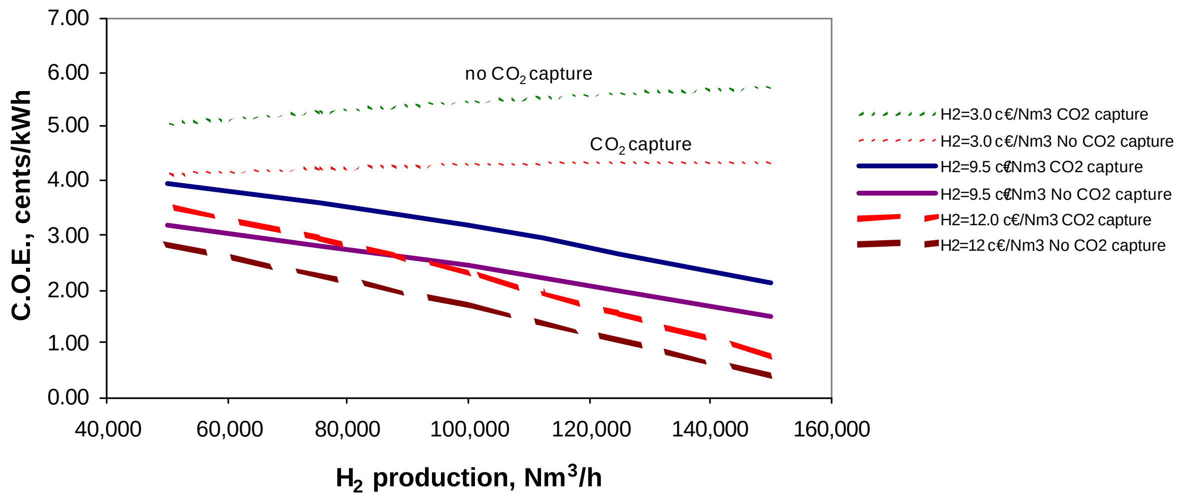


Fig. 7 - C.O.E. vs Cost of H_2

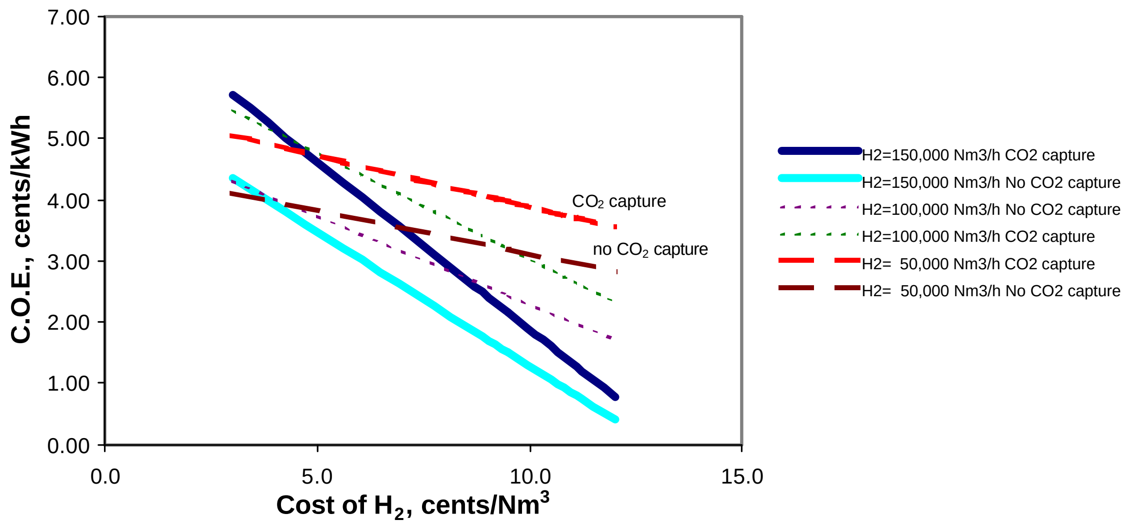
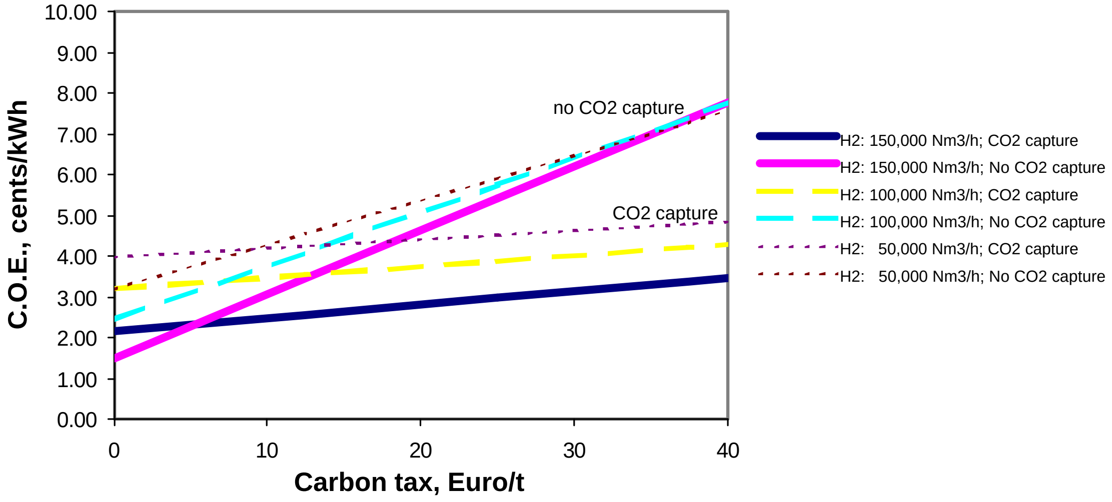


Fig. 8 - C.O.E. vs Carbon tax (Cost of H_2: 9.5 c€/Nm^3)



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