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Effect of Different Parameters and Variables on the Cost of Hydrogen Produced from Biomass Using Gasification Plants of Low to Medium Thermal Capacity

G. Braccio, D. Matera, M. Gamberale, V. Addabbo and V.K. Sharma

Abstract *- Economic analysis has been conducted to investigate the effect of different parameters and variables on the cost of hydrogen produced using low to medium capacity gasification plants. Three different plants of 1.3 MW (pilot-scale bubbling fluidised bed air gasification plant realised by ENEA) and its simulated scale-up of 10 MW and 20 MW, have been analysed. Results obtained from the comparison between use of traditional fossil fuels and hydrogen produced from biomass (in the transport sector), are presented. It has been observed that the values, no doubt, bit high compared to the energetic cost of conventional fossil fuels still appear to be interesting, especially in the free-tax situation.*

Keywords **- Biomass esource, Gasification, Hydrogen production, and Economic analysis**

1. INTRODUCTION

Considering limited availability of conventional fuels worldwide along with ever increasing energy demand, especially in the developing World, it is imperative to exploit new alternative sources to supplement or substitute the traditional ones. Due to its strategic role in the sustainable worldwide development, use of biomass for energy purposes has gained a considerable attention over the last couple of years. Considerable interest has been demonstrated for production of hydrogen using gasification plants of low to medium thermal capacity. It is therefore not surprising that the 'Italian White Paper for the Valorisation of Renewable Energy Sources' (1999) describes the aim to promote the use of biofuels for both heating purposes and public transportation.

Potential use of hydrogen as future energy source is associated with a critical aspect of its production using sustainable technologies and, in particular, the primary renewable energy resources. Amongst different technologies employed for the production of hydrogen using biomass [1-3], gasification certainly represents one of the most potential and interesting options both as a well-established technology and having a variety of applications [4]. Gasification plants of low-to-medium thermal capacity appear to be of considerable interest since they help to optimise transport infrastructure and distribution of hydrogen locally but eliminate large structural and distribution carriers, generally required in case of conventional energy, as well [5-7].

In the above context a feasibility study of the distributed system has been carried out considering the biomass gasification technologies with fluidized bed reactors. Three different plants of 1.3 MW (pilot-scale air gasification plant realised by ENEA) and its simulated scale up of 10 MW and 20 MWt have been analysed. It is to be noted that plants under investigation could produce up to 20, 152, 304 kg/h of hydrogen, respectively and are suitable for the realisation of stand-alone systems for the refuelling of vehicles. Process based on biomass gasification with oxygen and vapour has also been considered. The resulting producer gas with hydrogen content of 20-30% Vol $_{dry}$, was subjected to cleaning, enrichment and separation, as well.

Economic analysis has been conducted to investigate the effect of different parameters and variables on the cost of hydrogen produced. Cost estimation for the hydrogen produced under different solutions investigated demonstrates that it strongly depends upon the size and type of the plant used (with or without energy recovery).

Delivered cost of hydrogen from biomass has been estimated to be approx. 11 to 12 €/GJ. The value, no doubt, a bit high compared to the energetic cost of conventional fossil fuels still appears to be interesting, especially in the free-tax situation. Comparison between use of traditional fossil fuels and hydrogen produced from biomass in the transport sector has been made and results obtained will be discussed in the present communication.

2. BASIC PLANT FOR PROCESS SIMULATION

The basic plant used for process simulation is a bubbling fluidized bed gasification plant of thermal capacity 1.3 MWt, using air as the gasifying agent. The plant (photo 1) designed by ENEA Research Centre Trisaia, is tested experimentally.

The plant comprises of a bubbling fluidised bed reactor. The gasification plant utilises biomass residues in a low pressurised gasification process coupled with internal

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reciprocating combustion engine. The plant does not work in the cogeneration mode.

Principal technical characteristics of the plant are shown in table 1.

Flow diagram for hydrogen production from biomass comprises of:

- Gasification section
- Gas- cleaning section
- Gas "shift" section
- Separation section
- Energy recovery section

2.1 Gasification Section

Gasifier is a bubbling fluidised bed reactor connected directly to a cycle and ash discharge (figure 1). Air is used for fluidisation and gasification. The gasifier comprises of both central (reactor) and a lateral body. Circulation of solid material is achieved by dividing the reactor into two different chambers (subject to different velocity of fluidisation) using an adjustable baffle. Solid particles (ash and char) from the gasifier are separated using a cyclone placed at the reactor exit. Air for gasification is fed through a distributor comprising a set of horizontal tubes. The internal equilibrium reactions have been simulated using a specific programme "ChemCad" [11].

The main characteristics of the gasifier (dimensional and fluid dynamics) are given in table 2.

The main characteristics of the process have been simulated based upon the experiences gained from the experiments conducted with gasification plants of 1.3 MWt [8] using air and vapour, along with the experimental and modelling data reported in the literature [9-10]. Process based on biomass gasification with oxygen and vapour that produces a gas with hydrogen content of 20-30% Vol_{dry}, has been considered in the present study. The gas produced is subjected to cleaning, enrichment and separation.

For greater simplicity, plant scheme with relative balance sheets has been conducted under stationary conditions. The process flow sheet is as shown in figure 2.

2.2 Filter Section

Filter section considered involves the use of a separator and filter with steel sleeve to eliminate the solid particulate comprising mainly of char, ash and bed material, at a temperature of about 250 to 300 °C.

2.3 Shift Section

Gas obtained from the gasification section contains a considerable amount of carbon monoxide. In order to increase the hydrogen production, a shift section comprising of two stages and at different temperature conditions, has been realised.

2.4 Enrichment Section

The hydrogen enrichment section consists of four stages: a cooling stage, a section for cleaning of syngas, a cooling compression stage and a stage for final separation. The cleaning stage comprises of absorption of composite acids (HCl and H_2S) and removal of tars. The separation stage to obtain hydrogen consists of an adsorption system [12] (PSA; Pressure Swing Adsorption) that operates at a pressure of about 15 to 20 bar. PSA has been assumed to function [13] at certain conditions that permit cleaning of nearly 99.9% of the gas with a recovery of nearly 80% pure hydrogen.

2.5 Section for Energy Recovery

Separation section based on the adsorption systems enables the recovery of nearly 80% of the hydrogen present in the inlet stream. The remaining 20% is found in the exhaust flow composed of different gases (CO_2, CH_4 and CO) having low calorific value (equivalent to 6000 kJ/Nm^3) supposed to be recovered in a micro/mini gas turbine.

Other plants are of similar technology but higher thermal capacity, namely 10 MWt and 20 MWt, respectively. The three plants considered in the present study could produce nearly 20, 152, 304 kg/h of hydrogen and are, thus, suitable for the realisation of stand-alone systems for the refuelling of vehicles. A typical refinery-scale steam methane reformer (SMR) producing 60 to 240 T/day could fuel a fleet of 225,000 to 900,000 hydrogen fuel cell-powered cars. A small-scale SMR or electrolyzer rated at 240 to 2400 kg/day could fuel a fleet of 900 to 9000 hydrogen fuel cell cars or 14 to 140 buses [6].

3. TECHNICAL RESULTS OBTAINED RELEVANT TO THE BASE PLANT

Feedstocks considered were almond shells, olive residue and wood chips. Results obtained from the statistical proximate and ultimate analyses, for the above-mentioned feedstock mix, are presented in table 3.

Results obtained from the analysis using specific programme "ChemCad" with respect to basic plant operating at feedstock flow rate of 330 kg/h and moisture content of 15%, are reported in table 4.

It is to be noted that while operating the system at higher flow rates of 2500 and 5000 kg/h, the hydrogen production will be increased in proportion to the flow rate, whereas the values for the various components reported in table 4, remains the same.

4 ECONOMIC ANALYSIS WITH DIFFERENT DESIGN SOLUTIONS

The economic investigation has been conducted by analysing various cost terms associated with configurations of the plant studied and hence enables the estimation of the cost of hydrogen produced. Plants of three different sizes have been considered.

i) Plant with thermal power of nearly 1.3 MWt, using a biomass flow rate of nearly 330 kg/h.
ii) Simulated plant similar to (i) above, but with thermal power of 10 MWt and biomass feed rate of nearly 2500 kg/h.

iii) Simulated plant similar to (i) above, but with thermal power of 20 MWt and biomass feed rate of nearly 5000 kg/h.

The economic analysis was done in a classical mode considering cost of investment, operating and maintenance costs, depreciation and financing charges.

4.1 Cost of Investment (CI)

Cost of investment is sum of both direct and indirect costs. These are broken down as follows:

4.1.1 Costs of direct investment (CID)

Direct cost comprises of all costs relevant to construction of the plant (cost of the land, preparation of land, different components of the plants for its construction, electro-mechanical work etc.). The costs have been evaluated considering the data available in literature and based upon the values provided for various components by the manufacturers. These are broadly divided into two groups, namely plant components and civil works. Plant components include system for the receipt and storage of biomass, system to feed gasifier, system for the distribution of auxiliary fuels, gasification section, filtering section, thermal recovery section, metallic structure and accessories, treatment of feed water, supply and assembling of electrical instruments, mechanical assembling and piping, separation section, O2 feeding section. On the other hand civil works comprise of building of control room and offices, floors for the machine and cemented network, preparation of area, roads and platforms, wall enclosure, sewage of water, fire-fighting network, etc.

4.2.2 Cost of indirect investment

Indirect costs include expenses for the plant designing (engineering aspects), testing, etc. The cost of engineering and supervision is taken as 10 to 20% of the total cost of direct investment.

General costs constitute 5 to 20% of the total cost of direct investment.

4.2 Total Installation Cost

Total of cost investment (CI) is equivalent to 135-123% of CID. The above-mentioned costs have been stimulated by the summation of cost of investment for gasification section, shift section, separation section, oxygen production section, energy recovery section, etc.

Cost of direct investment as a function of plant's potential variation, can be obtained using an exponential relationship based on the existing cost data. If C_1 is the cost of equipment or a part of plant of output M_1, then the cost of a similar device, of output M_2, can be calculated using the relationship [14-17]:

$$C_2 = C_1 \cdot \left(\frac{M_2}{M_1} \right)^S$$

where the value of the exponential factor S depends on the type of equipment or plant. The correlation of exponential cost has been developed for specific parts and/or sections of plant. In many cases the cost has to be correlated in terms of parameters related to the plant output.

4.2.1 Direct cost for gasification plant

Cost of gasification plant on pilot scale, including section for heat recovery and cleaning, has been calculated based on the analysis of the cost of pilot plant 1.3 MWt. The cost calculation relevant to the plant on large-scale has been done using values obtained from the exploitation of the pilot plant as well as literature data [17, 18].

4.2.2 Direct cost for shift section

Prices used have been taken from the data available in literature [15, 19] providing a relationship between the plant cost and actual molar flow rate of $CO+H_2$.

4.2.3 Direct costs for PSA separation section

Costs for the separation section have been taken from the data available in literature [15, 19], that provide a relationship between cost of the plant and actual molar flow rate of gas, in addition to data provided by companies that supply separation systems.

4.2.4 Compression section

Cost for the compression section appears to be nearly 70.900 k€ per kW_e, multistage cooling compressor β=15-18.

4.2.5 Direct costs for the section producing oxygen

Costs for the separation section have been taken from the data available in literature [15] that report a relationship between plant cost and actual daily O_2 production. The data has been compared with data provided by market analysis of a small O_2 generating set based on PSA system [20].

4.2.6 Direct cost for energy recovery section

Costs for the energy recovery section have been taken from the data provided by market analysis of a micro and mini generating set based on micro/mini turbine system [20]. All investment costs of a plant, in general, are summarised in table 5. It is, however, to be noted that the direct cost depends upon the type of the plant under investigation. The same is evident from the insignificant difference between the cost of hydrogen produced, irrespective of the fact whether the oxygen is produced onsite or elsewhere.

4.3 Operational and Maintenance Costs

Operational and maintenance costs have been defined as the costs necessary for the functioning of the plant. The items considered include: fuels, electric energy, chemicals, different materials consumed, personnel involved, etc.

4.3.1 Fuel cost

The quantity of biomass needed annually to run the plants at their normal load of 330 kg/h, 2500 Kg/h and 5000 kg/h is approx. 2500, 19500 and 39000 T/year, respectively. The biomass is furnished using: husk (nearly 20%), almond-shell (nearly 15%), waste from the sawmill (nearly 65%). The total cost comprises of the material cost (approx. 20 Euro/t) and the transport cost, which depends upon the distance, type of material and the conveyance used. Considering average distance of approx. 50 km, the overall cost of biomass inclusive of supply and transport is approx. 26 Euro/t.

4.3.2 Cost of man-power involved

Cost of labour involved depends on so many factors such as size of the plant, automatic dependency, different existing norms relevant to the use of different machines, possibilities of realising plants in the already existing industrial areas, etc. It is hypothesized that the plants are autonomous i.e. do not belong to other industrial plants with number of persons engaged for the plant (i) equal to 9 while for the plants (ii) and (iii), are 11 and 15 respectively. The average specific cost for the specialised technical staff is of the order of 30 k€.

4.3.3 Electric energy

Electric energy (cost approx. 10 c€/kWh) consumed by the plant is considered jointly for the three sections with major electric power engaged:

- gasification section around 40 kWh/t biomass
- oxygen section is nearly 0.3 kWh/kg oxygen
- compression section for PSA at 15 to 18 bar.

4.3.4 Oxygen cost

Cost of oxygen for industrial purposes supplied by the manufacturing companies depends on various factors, in particular, annual consumption, and the distance from the main producing centre. On the whole, it varies between 4 to 9 c€/kg. In the present analysis oxygen cost of 6 c€/kg is applied.

4.3.5 Other relevant costs

Other relevant costs include the cost of chemicals, additives and consumables, mechanical and maintenance operations, etc. On the whole, such cost has a fixed value equivalent to nearly 4% of the cost of investment for the realisation of the plant.

4.4 Fiscal and Financial Rate

The main fiscal and financial rates adopted in the present study are the inflation rate 2%, discount rate 5% and taxation level 35%.

4.4.1 Depreciation

Depreciation of the plant under investigation is regulated for its fiscal effects under the existing norms of law. The percentage values considered appears to be constant over a period of 10 years.

4.4.2 Benefit derived

The benefits obtained are associated to the sale of electric energy produced and the Green Certificates. The gain derived from the sale of electric energy produced has been assumed to be 0.05 €/kWh, whereas the gain relevant to the Green Certificates has been assumed to be nearly 0.08 €/kWh.

5. RESULTS

The cost of hydrogen referred to its low calorific value has been obtained by determining [21] the "Levelised Cost of Energy", LC or the effective cost of energy produced as given by:

$$LC = \frac{(I + L_e + M - R)}{E \cdot \sum_{t=1}^{n} \frac{1}{(k_n + 1)^t}}$$

where

I	=	effective cost of investment
L_e	=	effective sum of energy costs
R	=	effective sum obtained from the sale of electric energy
M	=	effective sum of operation and maintenance costs
E	=	annual energy production

Estimation of the hydrogen production cost with prominent, determined or assumed economic data, for the solutions investigated, varies between 30.26 to 36.12 €/GJ, 12.32 to 18.11 €/GJ and 10.59 to 16.28 €/GJ, as shown in table 6. Cost reduction is sensible in plants with energy recovery where there is, not only a cancellation of the electric energy cost, but the plant produces the electric energy, as well while the LC difference from oxygen onsite/outside production is reduced as reported in table 7.

Obviously, additional significant cost reduction could be obtained with the increase of plant size. In conclusion, although the cost of production of hydrogen from biomass gasification is still high (nearly 11 to 12 €/GJ) compared to actual technologies for its production from fossils, the same appears to be the most competitive renewable energy source with additional possibilities to lower the cost through optimisation of both plant size and process.

5.1 Sensitivity Analysis of Hydrogen Cost

Sensitivity analysis has been conducted to investigate the cost of LC with a variation of different input parameters of the project. In particular, attention has been focused on four main design inputs: residual cost, cost of oxygen, cost of investment, labour and maintenance cost. The variation assumed has been considered for all the sizes within ± 20%. Plant with energy recovery and on-site oxygen production appears to be the best. The results obtained from the analysis are shown in figure 3.

Design appears to be sensitive to the variation in prices, particularly, cost of work, maintenance and investment that become relevant for a plant of small size. Comparison with the cost of hydrogen at the industrial level shows a significant difference. It is however advisable to follow the investigation that promises further reduction in the cost with the establishment of large number of plants.

6. COMPARISON WITH TRADITIONAL FOSSIL FUELS

In the text to follow, a comparison between use of traditional fossil fuels and hydrogen produced form biomass, especially when used in the transport sector, has been made. It is necessary to note that in addition to the delivered cost of hydrogen (approx. 11 €/GJ), some additional cost relevant to its compression, and refuelling station, amounting to nearly 5 €/GJ [5] needs to be added.

Therefore, the cost of hydrogen produced using biomass and ready to be fuelled in the vehicle has been estimated to be 16 to 17 €/GJ. So far use of traditional fuels in transport is concerned, the same is subject to series of fiscal taxes such as sale tax of 20% and excise tax, which varies widely depending on fuel type.

From the analysis, it appears that the cost of hydrogen from biomass of nearly 16 to 17 €/GJ, though higher than the pre-tax selling price of fossils is lower than the actual selling price of the fossil fuels.

So, considering a possible hypothesis of excise tax reduction relevant to production of hydrogen (an option already practised for other renewable fuels such as bio-diesel and bio-ethanol), it would be possible to achieve cost of hydrogen in the range that could be quite competitive relative to the cost of fossil fuels.

Fixing maximum energetic value equal to that of petrol, without VAT, i.e. 26€/GJ, it could be seen that in case of hydrogen produced from biomass without any taxes, there is possibility of an additional range of approximately 0 to 10 €/GJ with respect to the cost as mentioned above (i.e. 16 € /GJ). Probability, however, varies in accordance with the excise duty applied in the range 0 to 10 € /GJ.

Principal taxes in terms of energy content for the main fossil fuels are presented in table 8. Evolution of net cash flow as a function of the above-mentioned variations has been shown in figure 4 along with net cash flow for a conventional electricity generating plant using biomass as feed raw material.

7. FIGURES AND TABLES

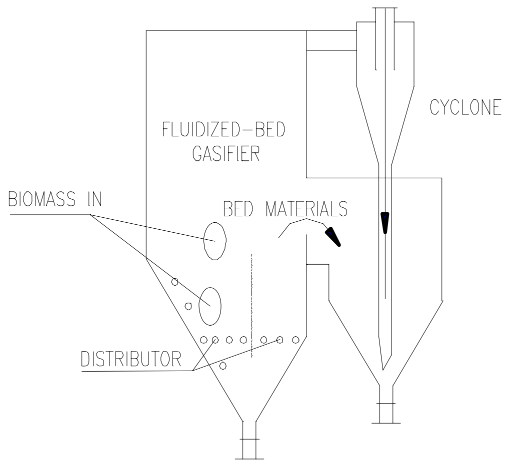

Fig. 1. BFB: Gasification section.

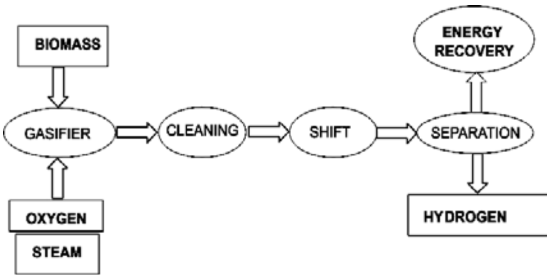

Fig. 2. Process flow sheet.

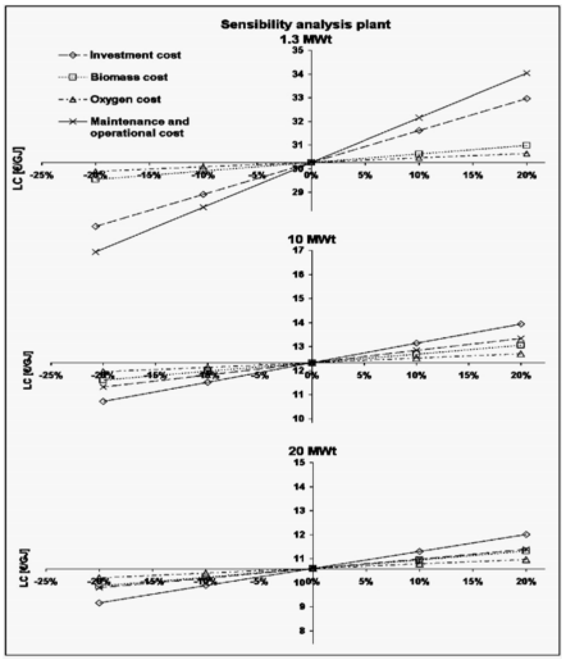

Fig. 3. Sensitivity analysis of hydrogen cost.

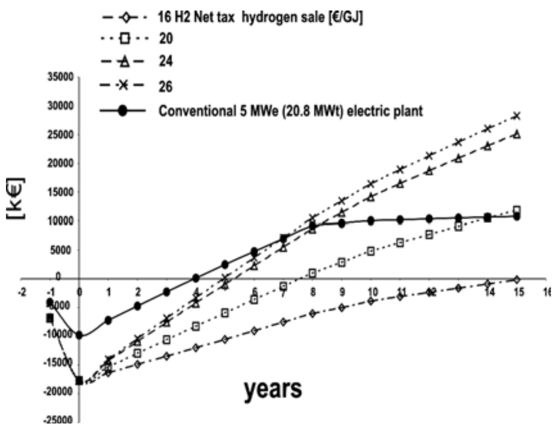

Fig. 4. Net cash flow of a 20 MWt hydrogen plant.

Table 1. Principal Technical Characteristics of the Plant at ENEA CR Trisaia

Gasifier type	BFB
Power	0.9 – 1 MW
Fuel input	280 kg/h
Electric efficiency	16 – 20%
Gasification pressure	0.2 barg
Gasification temperature	800 °C
LHV gas	6000 MJ/Nm3

Table 2. Main Characteristics of Gasifier

Minimum fluidisation velocity	0.133 m/s
Bed height	1200 mm
Expanded bed height	1500 mm
Height of gasifier	4200 mm
Minimum length	800 mm
Maximum length	2000
Breadth	500 mm
TDH	2.2 m
Distributor	Set of horizontal tubes of diameter 2 mm

Table 3. Biomass Analyses

C [%$_{daf}$]	**50**
H [%$_{daf}$]	**06**
O [%$_{daf}$]	**42**
N [%$_{daf}$]	**0.3**
Ash [%$_{dry}$]	**1.4**
Humidity [%]	**15**
LHV [kJ/kg]	**15000**

Table 4. Main Process Flows

	Gasifier	**Shift**	**PSA Product**	**PSA Offgas**
T [°C]	830	250	95	95
P [barg]	0.1	0.1	18	0.1
F[kmole/h]	24.67	27.85	10.07	17.78
H_2	34.8	45.2	99.99	14.2
CO	20.0	3.4	0	5.3
CO_2	23.4	24.1	0	53.4
H_2O	8.8	10.0	0	15.7
CH_4	8.2	7.2	0	11.5

Table 5. Investment Cost

Investment cost [k□]	**1.3 MWt**	**10 MWt**	**20 MWt**
Direct cost			
Gasification section	921.0	4483.0	7765.8
Shift section	105.0	395.0	630.0
Separation section	500.0	1195.0	1620.0
Compression section	57.0	433.0	866.0
Oxygen section	196.0	1329.0	2300.0
Energy recovery section	150.0	900.0	1750.0
Total direct cost	1929.0	8735.0	14931.8
Indirect cost	289.4	1310.3	2239.8
Start cost	96.5	436.8	746.6
Total investment cost	**2314.9**	**10482.1**	**17918.2**

Table 6. Estimated Cost of Hydrogen Produced

Size	**Biomass Consumed**	**Hydrogen Produced**	**Plant without Energy Recovery**	**Plant with Energy Recovery**
MWt	**kg/h**	**kg/h**	LC [□/GJ]	**LC [□/GJ]**
1.3	330	20	36.12	30.26
10	2500	152	18.11	12.32
20	5000	304	16.28	10.59

Table 7. Option Plants Hydrogen Cost

	LC [□/GJ]			
Size [MWt]	**Plant without energy recovery**		**Plant with energy recovery**	
	O_2 Onsite	**O_2 Outside**	**O_2 Onsite**	**O_2 Outside**
1.3	36.12	35.81	30.63	30.26
10	18.11	17.8	12.69	12.33
20	16.28	16.13	10.78	10.59

Table 8. Fossil fuel Taxation

	Diesel	Petrol	Methane
Value Added Tax	**20%**	**20%**	**20%**
Excise tax	0.40 €/l	0.56 €/l	0.01 €/m3
LHV	42705 kJ/kg	43543 kJ/kg	46892 kJ/kg
	35588 kJ/l	35169 kJ/l	34750 kJ/m3
Sale price	0.85 €/l	1.10 €/l	0.63 €/kg
	23.88 €/GJ	31.28 €/GJ	13.48 €/GJ
Value Added Tax (VAT)	0.14 €/l	0.18 €/l	0.11 €/m3
	3.98 €/GJ	5.21 €/GJ	3.03 €/GJ
Sale price without VAT	0.71 €/l	0.92 €/l	0.53 €/m3
	19.90 €/GJ	26.06 €/GJ	11.23 €/GJ
Excise tax	0.40 €/l	0.56 €/l	0.011 €/m3
	11.32 €/GJ	15.88 €/GJ	0.312 €/GJ
Sale price without tax	0.30 €/l	0.36 €/l	0.52 €/m3
	8.58 €/GJ	10.18 €/GJ	11.00 €/GJ

Photo 1. Bubbling fluidised bed gasification plant (Italy).

8. COMPARISON WITH USE OF BIOMASS FOR ELECTRICITY PRODUCTION

Generating electricity from biomass (in Italy) is supported financially in terms of Green Certificates with present value of nearly 8c€/kWhe. Considering the fact mentioned above, it could be observed that a plant of 10 MWt with net electric efficiency and overall availability of nearly 22% and 80%, respectively and with annual electricity production of approx. 1930 MWe, would attract an annual subsidy of nearly 1230 k€. If the same amount is used to provide financial support for hydrogen from biomass, it will be possible to achieve a subsidy of approx. 7.8 €/GJ. This implies that for the cost of hydrogen to be competitive, it is necessary to provide similar financial incentives as applied in case of electric energy (Green Certificates).

9. CONCLUSION

The cost estimation for hydrogen produced under different solutions investigated demonstrate that it strongly depends upon the size and type of the plant (with or without energy recovery) but appears to be less sensitive to the supply of oxygen on site or its production on-site. From the investigations undertaken it has been demonstrated that cost of hydrogen produced from biomass is approximately 11 to 12 €/GJ. This value though a bit higher than the energetic cost of conventional liquid fuel appears to be interesting, especially, in a free-tax situation. Under such circumstances, it is possible to consider a reference value equal to 60 to 70% of that applied for petrol. At the end it can be noted that such values are compatible with the one applied for other types of subsidies such as the Green Certificates.

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