Economic study of water steam production by biomass or domestic waste incineration
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Economic study of water steam production by biomass or domestic waste incineration

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Abstract

This work presents an economic and potential study of water steam production by incinerating biomass and domestic waste, for the purpose of producing hydrogen. Biomass presents non-negligible Heating Values (HV) for heat exchange in incineration units and emits green CO_2. Besides, domestic waste incineration reduces municipal waste discharges and contributes with high energy recovery. For both sources, water steam production would be coupled with High Temperature Electrolysis (HTE) process for hydrogen production. This economic study of steam generation is based on investment and operation costs of waste incineration units. For biomass incineration, the estimated steam production costs are between 1.9 and 4.0 c€/kg and for domestic waste incineration between 3 and 5.3 c€/kg. Considering the total conversion of steam into hydrogen, all water steam produced using both energy sources, could supply the needs of almost 72 millions hydrogen vehicles per year.

Keywords: Biomass, domestic waste, incineration, steam, hydrogen production.

Nomenclature

A_{biom}	Incinerated biomass, (kg/yr)
A_r	Annual refunding, (€/yr)
A_{waste}	Annual domestic waste resources, (kg/yr)
C_{inc}	Incineration cost, (€/ton)
C_n	Fuel mass flow in furnace, (tons/h)
C_{steam}	Steam production cost, (€/kW)
C_{var}	Variable costs, (€/ton)
H_{water}	Enthalpy, (kW/kg)
H_b	Moisture in fuel, (%)
HHV	High Heating Value, (kJ/kg) (kW/ton)
H_t	Hydrogen production, (kg/yr)
%H	Hydrogen content in fuel molecule, (%)
I_i	Investment, (millions of €)
LHV	Low Heating Value, (kJ/kg) (kW/ton)

$\dot{m}_i$	Mass flow, (kg/s)
M_i	Molecular weight, (kg/kmol)
N	Hydrogen conversion
X_v	Water vaporisation heat, (W/kg)

Greek symbols

η	Heat exchange efficiency, (%)

Subscripts

Biom	Biomass
fraction furn	Furnace contribution
furn	Furnace
H_2	Hydrogen
H_2O	Water
inc	Incineration
th	thermal
tot	Total
waste	Domestic waste
vap	Vapour

Introduction

Nowadays, energy recovery and reduction of greenhouse gas emissions are becoming a priority. The present study considers hydrogen production using water steam produced by biomass or domestic waste incineration. We focused on the available biomass and domestic waste in France, which are not currently valorised. This study presents an estimation of the incineration units' investment and operation cost, as well as a steam production cost and potentialities for both sources when dedicated to this process, even if other usages could be in competition with this hydrogen production proposal.

The evaluation of steam generation potentiality was considered under a hydrogen production context, looking for a steam source which would be coupled with the High Temperature Electrolysis (HTE) process. According to Harvego et al. [1], the HTE process seems to be a promising process for massive hydrogen production, compared with other production processes. Moreover, according to Shin et al. [2], Utgikar and Thiesen [3] and Sigurvinsson et al. [4], HTE presents higher energy efficiency, kinetic and thermodynamic advantages, than alkaline electrolysis which is operated at lower temperatures.

1. Biomass in France

We carried out an estimation of the availability of biomass in France by expounding its definition, which states that biomass is all degradable product issued by the agriculture, silviculture and their industries [5]. Nowadays, the 56% of the French land is dedicated to agriculture, 28% to woods and forests and the rest of land is either urbanized or unused (See figure 1).

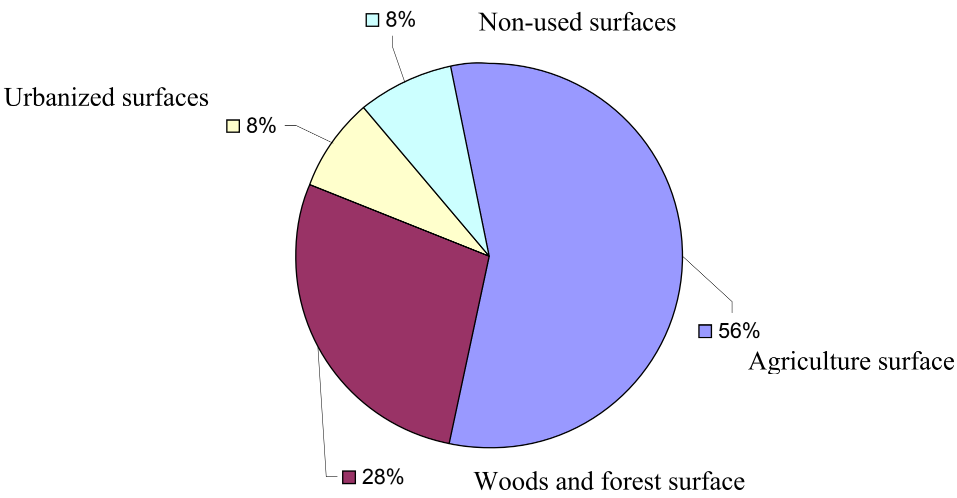

Fig 1. Surface usage distribution in France [3]

The biomass as wood, wheat straw, chips and other biomass kinds, which is available all over this country, basically from the agriculture lands and woods, is increasingly used as an energy source and further the French Ministry of Agriculture [6] has implemented a program for wood-energy consumption (biomass) in order to encourage the usage of this green energy source. The current annual consumption of wood, for incineration, reaches 40 million m^3 (almost 7.8 Mtep) [7] which represent 69% from total wood production, so almost 3.5 Mtep are still available. Moreover, the available wheat straw reaches 5 million tons i.e. almost 1.5 Mtep per year [6]. In 2003, the energy recovery from these non-fossil sources were 95% valorised as thermal energy and 5% for electricity generation [5]. So, the incineration of non valorised biomass could still be envisaged as a thermal energy source for steam production without environmental damages.

2. Domestic waste availability in France

Instead of sending domestic waste to waste disposals, which currently occupy large land surfaces, domestic waste incineration could be seen as an energy recovery process. The ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) [8] measured the increase of waste produced per French inhabitant for the last 45 years and, at the present time, it seems to stabilize at around 350 kg. In 2002, the total quantity of domestic waste available for incineration reached 26 million tons, and only 48% was converted into electric or thermal energy. As for biomass, most of the domestic waste energy is recovered as thermal energy, but most of waste incineration units are suited to work in electricity and heat cogeneration [8].

Several studies were carried out in France [9] in order to estimate the domestic waste generation to come and its properties for the next years until 2020. Most of them envisage an important increase in waste disposal, but, the current stabilisation which was mentioned before approaches to scenario 1 of the study [9]. For all scenarios presented in figure 2, the recycling and gas emission policies will change the properties of domestic waste for incineration [9]. For example, according to [9], if a rigorous recycling policy was enforced, the recycling of the concerned materials in domestic waste could reach 20%, and at the same time, it would lead to a 17% increase of the HV.

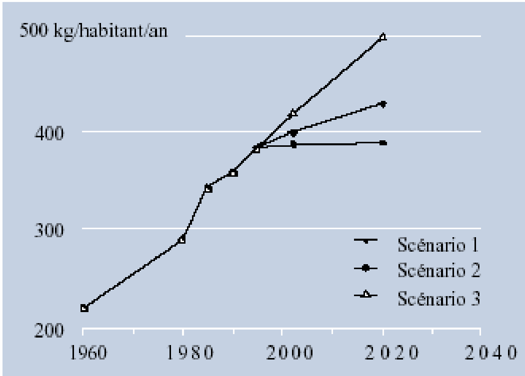

Fig 2. Scenarios for domestic waste production per inhabitant in France [9]

Considering the quantity of domestic waste as a constant value and the annual quantity of domestic waste that could be incinerated for the next 13 years, we could evaluate non-valorised waste up to 11 million tons per year.

3. Incineration and unit investment

For both non-fossil fuels studied in this work, the estimation of the incineration unit investment has been carried out considering the steam nominal production and the fuel properties, Heating Values (HV) and moisture. As mentioned, the target is to use the water steam produced in the units for hydrogen production, so the steam nominal mass flow was estimated as a function of hydrogen demands. A maximum hydrogen production of 1 kg/s was considered in order to estimate the water steam needs and incineration costs for each unit. Additionally, a sensibility study of water steam cost was carried out for steam flows needed to produce less than 1 kg/s of hydrogen.

3.1 Biomass

The unit investment basically depends on the envisaged hydrogen production. Once the hydrogen production is fixed, the unit investment was estimated as a function of the furnace investment, which depends itself on the Low Heating Value (LHV) of the biomass. In order to estimate the fuel flow in the furnace, we selected the High Heating Values (HHV) for two biomass sources (pine tree and wheat straw) from Cordero et al. [11]. Then, the LHV was estimated from HHV from each biomass by using equation (1). LHV for pine tree wood and wheat straw at different moisture percents are presented in Table 1.

$$LHV_i = HHV_i \left[\frac{(100 - H_b)}{100}\right] - X_v \left[\frac{\left(\left(\frac{M_{H_2O}}{M_{H_2}}\right)\%H + H_{\mathbf{b}}\right)}{100}\right] \qquad (1)$$

The fuel flow in furnace, in this case biomass depends on the envisaged hydrogen production, so we fixed it at 0.05, 0.1, 0.5 and 1 kg/s. Then using equation (2) we carried out the fuel mass flow estimation, considering total conversion from water steam into hydrogen, a furnace efficiency of 80% and enthalpies of steam temperatures from 350°C to 550°C at 4.0 MPa. The results from equation (1) and (2) were used in equation (3) in order to estimate the furnace investment, as in [10], by considering the nominal fuel flow C_n.

Table 1. LHV estimations for pine tree and wheat straw biomass as a function of moisture content.

	LHV - W/kg	
	Pine tree	Wheat straw
Hydrogen content - %	6.0	5.6
HHV – W/kg	5615	5042
Moisture		
10%	4676	4177
20%	4056	3641
30%	3436	3051
40%	2815	2488

$$\dot{m}_{Biom} = \frac{\dot{m}_{H_2} \times H_{water}}{LHV_{Biom} \times \eta \times \mathrm{N}} \times \left(\frac{M_{H_2O}}{M_{H_2}}\right) \qquad (2)$$

$$I_{furn} = 0.1218 \times [-0.98 \times \log C_n + 2.88] \times C_n \times \left(\frac{LHV}{2100}\right)^{0.7} \qquad (3)$$

The incineration unit cost was based on the economic hypotheses retained from the ADEME study [10]:

- the incineration unit investment is not subsidized
- taxes are not included in investment estimation
- the incineration cost involves the feasibility and engineering study cost, the refunding of unit investment, the unit operation cost and the unit management cost.

Taking into account these hypotheses, we modelled the furnace investment contribution in the total unit investment from the ADEME work [10], using a quasi-Newton method, in a valid fuel (biomass) mass flow range up to 9.16 kg/s (33 tons/h). This furnace investment contribution was estimated using equation (4), which is function of the fuel flow. Then the total investment was estimated with equation (5).

$$\%_{fraction\ furn} = -0.0001\,C_n^{\ 2} + 0.0072\,C_n + 0.0923 \qquad (4)$$

$$I_{tot} = \frac{I_{furn}}{\%_{fraction\ furn}} \qquad (5)$$

The annual refunding of the biomass incineration unit investment was based on the following data [6]:

- a 20 years refunding period
- discount rate of 6%
- unit availability: 85% of the year
- heat exchange efficiency: 80%

Once the investment refunding of the incineration unit was estimated, the global incineration cost per biomass ton was estimated with the additional operation costs as follows: 0.00533 € per kilogram of fuel for the incineration unit's electricity needs, 0.0036 € per kilogram of fuel for services, 0.00182 € per kilogram of fuel for gas removal [10] and a fuel cost of 8.3 € per MWh_{LHV} [7]. These incineration costs, represented in equation (6), were used to estimate the steam production cost by using equation (7).

$$C_{inc} = \frac{A_r}{A_{biom}} + \sum C_{var} \qquad (6)$$

$$C_{steam} = \frac{C_{inc} H_{vap}}{LHV_{Biom} \times \eta} \qquad (7)$$

3.2 Domestic waste

As for biomass, the waste incineration unit investment depends on the LHV, so HHV and LHV for waste were considered as a function of waste composition. For each location, waste presents different compositions. In a French context, the ADEME [12] evaluated a general composition of waste and the LHV for each waste component, as shown in Table 2. In the future, an increase of polymer content in waste is expected which would lead to a LHV of 3100 W/kg in 2020 [9].

Table 2. Composition of waste and LHV for waste components [12]

Component	Mass fraction % (wet)	Moisture in fuel (%)	Average LHV W/kg (wet)
Organic waste	28.6	16.0	1 179
Paper	16.1	21.0	2 775
Carton	9.3	12.0	2 643
Complexes	1.4	3.0	4 202
Textil	2.6	5.0	3 976
Textil II	3.1	3.0	1 717
Plastic	11.1	33.0	6 356
Other fuels	3.3	6.0	3 828
Glass	13.1	<1.0	
Metals	4.1	<1.0	
Other non-fuels	6.8	<1.0	143
Special waste	0.5	<1.0	

In order to estimate the incineration cost of waste, three ADEME studies were considered [10, 13 and 14]. The first study [10] groups the incineration units by capacity and presents their incineration cost, as shown in Table 3. The second study [13] estimates an average investment from 42 incineration units at around 3 million euros per tonne of waste per hour and a unit exploitation cost of 0.032 € per kilogram of waste. This leads to an incineration cost of 0.078 € per kilogram of waste. The third study [14] presents a unit operation cost of 0.045 € per kilogram of waste and a total incineration cost between 0.084 and 0.107 € per kilogram of waste. Classify

Table 3. Incineration cost as a function of unit incineration capacity [10]

Unit capacity kg/year	Incineration cost €/kg waste
<20 000 000	0.114 – 0.137
[20 000 000, 100 000 000]	0.076 – 0.107
>100 000 000	0.076

We retained the costs proposed by ADEME [10] and using equation (9) with the average waste incineration costs, an average waste LHV of 2600 W/kg and the furnace heat exchange efficiency of 80%, the steam production cost was estimated.

$$C_{steam} = \frac{C_{inc} H_{vap}}{LHV_{Waste} \times \eta} \qquad (8)$$

4 Water steam production cost and potentialities.

4.1 Biomass

We carried out the estimation of the steam production cost by using equations (1) to (7) and the unit refunding. Results validated the size effect of the biomass incineration unit, as presented in figure 3. Besides, assuming a biomass cost of 8.3 € per MWh_{LHV} [7], as a biomass basic cost that will be discussed later, the steam production cost was estimated between 0.019 and 0.040 c€/kg. Table 4 summarizes all estimated values for steam production. A sensibility study that has been carried out for the biomass cost would be discussed later.

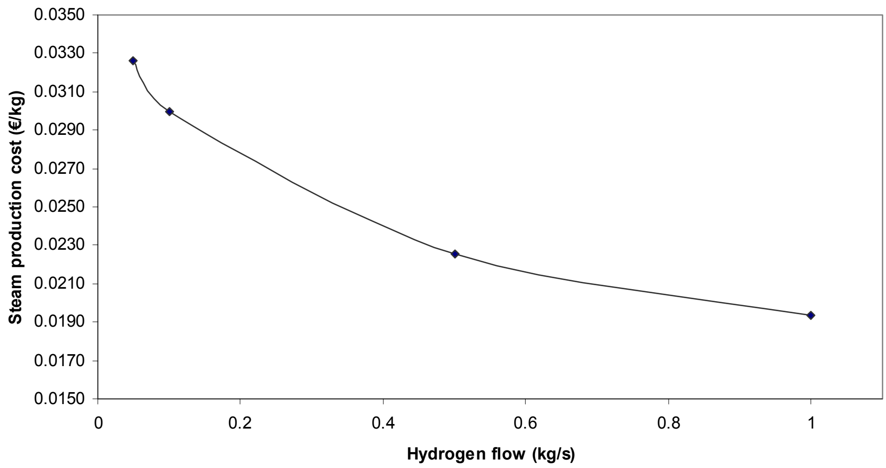

Fig 3 Sizing effect as hydrogen flow influence on steam production cost.

Table 4. Steam production costs for different fuel moisture and hydrogen production.

Biomass moisture	Hydrogen flow kg/s	Incineration cost €/ton	Steam production cost €/kg				
			Steam temperature (°C)				
			350	400	450	500	550
10.0%	1.00	77.56	0.019	0.020	0.021	0.021	0.022
	0.50	90.45	0.023	0.023	0.024	0.025	0.026
	0.10	120.10	0.030	0.031	0.032	0.033	0.034
	0.05	130.80	0.033	0.034	0.035	0.036	0.037
20.0%	1.00	67.62	0.019	0.020	0.021	0.022	0.022
	0.50	78.92	0.023	0.024	0.024	0.025	0.026
	0.10	106.11	0.031	0.032	0.033	0.034	0.035
	0.05	116.01	0.033	0.035	0.036	0.037	0.038
30.0%	1.00	57.84	0.020	0.020	0.021	0.022	0.023
	0.50	68.87	0.023	0.024	0.025	0.026	0.027
	0.10	94.70	0.032	0.033	0.035	0.036	0.037
	0.05	104.29	0.036	0.037	0.038	0.039	0.041
40.0%	1.00	48.31	0.020	0.021	0.022	0.022	0.023
	0.50	56.01	0.023	0.024	0.025	0.026	0.027
	0.10	77.37	0.032	0.033	0.035	0.036	0.037
	0.05	85.52	0.036	0.037	0.038	0.040	0.041

For 2020, an increase of heat exchange efficiency could reach 90% and then a decrease of biomass incineration cost could be expected. Nevertheless, for the mentioned year, a rigorous estimation of steam production cost would be intimately bonded to the future gas emission policies and control techniques.

Carrying out the estimation of steam production by biomass incineration, modifying equation (2), we found that recovering the 3.5 Mtep of woods and the energy from the 5 million tons of wheat straw, a hydrogen annual production up to 5.2 x 10^9 kg could be reached. It means that, considering the annual vehicle energy estimation in Werkoff et al. work [15], almost 46 million of vehicles could be fuelled with hydrogen in France.

4.2 Domestic waste

Considering the incineration cost values presented in Table 3, which are classed by waste incineration unit size, the incineration unit efficiency at 80%, steam outlet temperature at 450°C and a waste LHV of 2600 W/kg, we carried out the estimation of the steam production cost and the amount of hydrogen that could be produced by each kind of incineration unit. Results are presented in Table 5. The steam temperature corresponds to an average temperature of the waste incineration units.

Table 5. Steam production cost for domestic waste incineration units.

Unit capacity kg/year	Steam cost €/kg	Hydrogen kg/s
<20 000 000	0.057	< 0.15
[20 000 000, 100 000 000]	0.041	0.15 – 0.77
>100 000 000	0.033	> 0.077

Considering that, in France, 52% of waste was not valorised in 2002 and that this percentage remains constant, the amount of hydrogen that can be produced by recovering the energy from this waste can be evaluated: almost 2.8 x10^9 kg. This means that up to 26 million of vehicles could be fuelled with hydrogen in France using the non-valorised domestic waste.

Furthermore; the increase in French population is expected to be 4.5 millions in 2020 [16] and this would lead to an increase of one million tons of domestic waste per year. Besides, according to [9] this waste would have higher LHV up to 3100 W/kg due to an increase in the waste polymer content. This increase and an incineration efficiency of 90% could lead to a very large hydrogen production, by steam electrolysis, almost enough to feed 37 million vehicles per year. Nevertheless, the steam production cost would depend closely on the future technical improvements and the gas emissions regulations.

5. Discussion

This study presents the potential of the full usage of non valorised biomass and domestic waste in hydrogen production even if other uses of these energy sources are envisaged in other fields. The best choice between the different uses is beyond the scope of this paper.

Concerning the steam cost, if we compare the steam production cost from both energy sources, we observe that the steam produced by biomass incineration at 8.3 € per MWh_{LHV} could be lower than the waste incineration one. Both energy sources could be envisaged for steam production since there is not necessarily competition between them. Nevertheless, this difference on production cost is strongly linked to biomass cost, which also depends on biomass kind. In this paper we considered an industrial biomass cost of 8.3 €/MWh_{LHV} [7] but the biomass cost as fuel could be found up to 40€/MWh_{LHV} [17]. This difference between biomass costs would lead to increase the water steam production cost up to 0.06 to 0.08 €/kg. As a matter of fact, the initial contribution of biomass cost is between 9% and 12% of the total incineration cost, its contribution to the unit investment being between 59% and 79%. The five times increase on biomass cost would have an important impact on thermal energy cost, but not to the same extent, because of its initial small contribution to the total incineration cost.

At present, the energy recovery by the incineration of domestic waste already shows a high potential. The increase on the polymer content increases the waste HHV, increasing the energy to be recovered, which results in a steam production cost decrease. Nevertheless, the future regulations about the gas emissions could lead to more sophisticated gas processes and then, to higher steam production costs.

Conclusion

In a French context, biomass and waste incineration displays a high potential for water steam production. The cost estimation of steam production shows that steam produced by biomass incineration could be lower than the steam cost by waste incineration if biomass is purchased at a low cost. Considering both non-fossil fuels, a steam production cost between 0.02 and 0.08 €/kWh was estimated. This steam would be electrolysed by the HTE process to produce hydrogen. The estimated steam produced by biomass and waste incineration, considering a total conversion from water to hydrogen, shows that almost 46 millions of vehicles could be fed with hydrogen, produced by biomass incineration and 26 millions by domestic waste incineration, which corresponds to twice the French vehicle fleet.

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