Prefeasibility analysis of biomass gasification and electrolysis for hydrogen production

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Presentation outline

- Introduction
- Objective
- Methodology
- Results and Discussion
- Conclusions and Acknowledgments
- References

1. Introduction

World energy demand

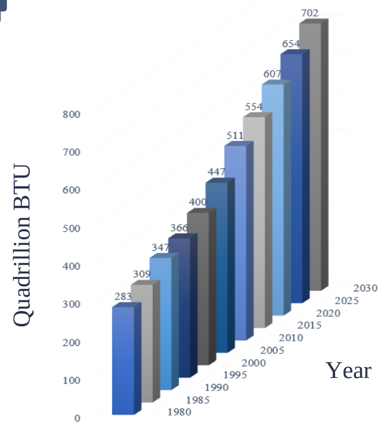


Fig1 World energy demand [1]

Fossil fuels dependence

Coal and crude oil are the most common raw materials for producing heat and electricity.

According to the World Coal Association, the available existences of coal are about 892 million tons. However, these reserves may be exhausted in **110 years** [2].

ENERGY TRANSITION
Renewable energies

Technological advances in the development of renewable energies have been possible thanks to several **studies and research** carried out at laboratory, pilot and industrial scale.

Hydrogen

High value-added chemical product

Energy carrier

Hydrogen

Annual production in 2021 was approximately 94 tons[3] and the consumption increases annually by 5%.

Petrochemical route
Steam reforming of methane

Thermochemical route
Gasification

Electrolytic route
Alkaline electrolysis

Biological route
Dark fermentation

Analysis of the technical, energetic, and economic pre-feasibility of new hydrogen production routes with lower environmental impacts than conventional routes.

[1] "Innovation Insights Brief - Global Energy Scenarios Comparison Review | World Energy Council.
[2] A. Brisse, J. Schefold, and M. Zahid, "High temperature water electrolysis in solid oxide cells," Int J Hydrogen Energy, vol. 33, no. 20, pp. 5375–5382, Oct. 2008, doi: 10.1016/J.IJHYDENE.2008.07.120

2. Problem statement and objective of the study

Fossil fuel dependence

- Energy crisis

Depletion of non-renewable resources [3]

- Environmental pollution

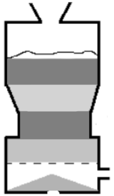
Increase in global temperature [4]

ENERGY TRANSITION
Renewable energies
Hydrogen

Production routes
Petrochemical processes: Conventional (High environmental impacts)
Thermochemical and electrolytic
Biological: Low yields

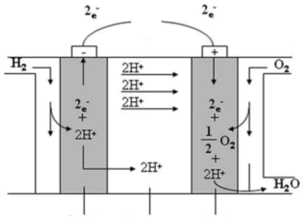
Experimental procedure

Gasification (GF)



Wood chips
GEK Gasifier 10 kW
Motor generator: Mecc Alte

Electrolysis (ET)



Water
NaOH 3%-5%.
Electrodes: metal oxides

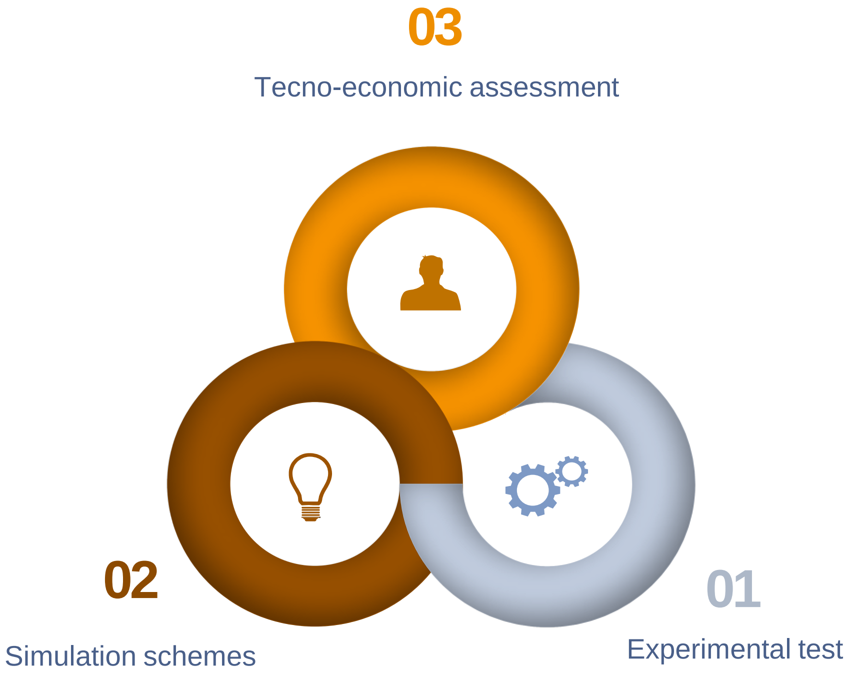
[3] M. Ni, D. Y. C. Leung, M. K. H. Leung, and K. Sumathy, "An overview of hydrogen production from biomass," Fuel Process. Technol., vol. 87, no. 5, pp. 461–472, 2006, doi: 10.1016/j.fuproc.2005.11.003.
[4] N. Sazali, "Emerging technologies by hydrogen: A review," Int. J. Hydrogen Energy, vol. 45, no. 38, pp. 18753–18771, 2020, doi: 10.1016/j.ijhydene.2020.05.021

2. Problem statement and objective of the study

The objective of this work focuses on the energetic and techno-economic assessment of hydrogen production through gasification and electrolysis as transformation technologies.

The operating conditions and experimental results were used to evaluate the technologies at a high scale through **computational tools**, evaluating three scenarios:

(i) Gasification
(ii) Electrolysis
(iii) Hydrogen and electricity production by gasification and electrolysis in a biorefinery scheme.



[3] M. Ni, D. Y. C. Leung, M. K. H. Leung, and K. Sumathy, "An overview of hydrogen production from biomass," Fuel Process. Technol., vol. 87, no. 5, pp. 461–472, 2006, doi: 10.1016/j.fuproc.2005.11.003.
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3. Methodology

01 Experimental procedure

1. Biomass gasification: Hydrogen and electricity production
   - Residual biomass (*Pinus Patula*) characterization
   - Pilot scale gasification
2. Electrolysis

3.1. Experimental procedure

Gasification

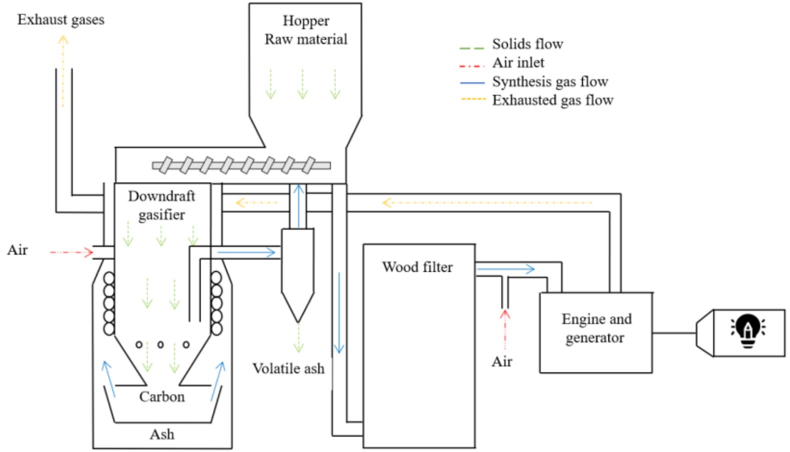


Fig2 Illustrative diagram of the gasification equipment used fro Pinus Patula. Downdraft gasifier

Raw material characterization

The wood chips (*Pinus patula*) were characterized by **proximate** and **elemental** analysis. Based on international standards, the proximate analysis involved quantifying **volatile matter, fixed carbon, ash content** and **low calorific value** (LHV)

Gasification

Blowtorch and gasoline were used to increase the temperatures up to **80°C,** then the gasifier was isolated.

Expected gasifier temperature about **750°C - 800°C**.
Total time of gasification experiment : **1 hour** (i.e., start-up, wood thermal decomposition, syngas production, and shut-down).

Finally, electricity was produced from an internal combustion engine (Mecc Alte) of **2-10 kW**.

3.1. Experimental procedure

Electrolysis

Electrolysis

The electrodes for hydrogen production were immersed in **400 mL** of electrolyte solutions of **1%** and **3% NaOH.**

The electrodes were made of metal oxides with a size of **70 mm.** Cathode: A graphite electrode with a size of **60 mm** was used.

Electric current and potential were measured using a Unit Ut39c+ digital multimeter (supplied by UNI-T), and the power supply was a **0-12V** and **5A** voltage source (supplied by RoMech).

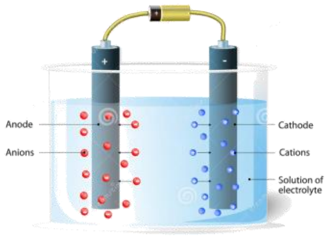


Fig3 Illustrative diagram of the electrolysis equipment used.

Gas composition

The hydrogen (**H_2**), carbon monoxide (**CO**), carbon dioxide (**CO_2**), and methane (**CH_4**) volumetric compositions in gasification and electrolysis process were registered by using a portable gas analyzer (**GASBOARD 3100p**, Wuhan, China).

Fig4 Portable infrared Gas Analyzer Gasboard-3100P

3. Methodology

02 Biorefineries (Simulation procedure) → Scenarios description → Mass and energy indicators Economic assessment

3.2. Biorefineries based on the gasification and electrolysis process

Scenarios

01 Wood chips gasification

01 Water electrolysis

01 The hydrogen was produced by **gasification** and the **exhausted gas** (witch CH_4 and other combustion gases) allowed the production of **electricity** that can supply an **electrolysis stack**.

Gasification

01 *Feedstock conditioning*:

Particle size: 2cm-3cm
Moisture content to 13% by weight

02 *Biomass gasification*:
Pyrolysis process
Combustion chamber: Produced CO_2, CO, H_2O, and heat (ER3)
Cyclone separated the ash and coal from syngas in the reduction stage

03 *Hydrogen separation and purification*:

Use of hollow fiber membranes was proposed
Electricity: Brayton cycle by Lan, et al. [6]

[5] M. Sánchez, E. Amores, D. Abad, L. Rodríguez, and C. Clemente-Jul, "Aspen Plus model of an alkaline electrolysis system for hydrogen production," *Int J Hydrogen Energy*, vol. 45, no. 7, pp. 3916–3929, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.027
[6] W. Lan, G. Chen, X. Zhu, X. Wang, C. Liu, and B. Xu, "Biomass gasification-gas turbine combustion for power generation system model based on ASPEN PLUS.," *Sci Total Environ*, vol. 628–629, pp. 1278–1286, Feb. 2018, doi: 10.1016/J.SCITOTENV.2018.02.159

3. Methodology

02 Biorefineries (Simulation procedure) → Scenarios description → Mass and energy indicators / Economic assessment

3.2. Biorefineries based on the gasification and electrolysis process

Electrolysis

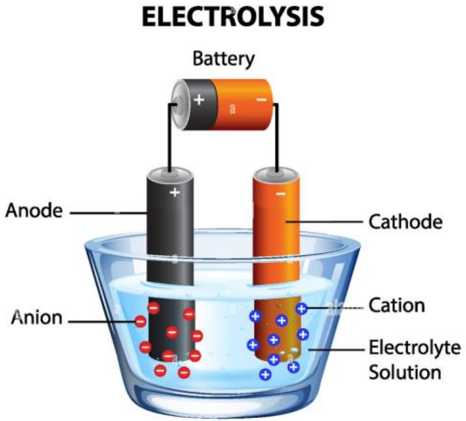
Electrochemical model previously reported by Sánchez et al. [5] and considers the input: electrical power, the number of cells, the temperature and pressure of the stack, the active area of the electrode, and the operating time

The polarization curve

$$V_{Cell} = V_{Rev} + [(r_1 + d_1) + r_2 T + d_2 P]i + sLog\left[\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right) i + 1\right]$$

The gas volume can be related according to Faraday's Law.

$$n_{H_2} = n_F\left(\frac{1}{iNA}\right) \qquad n_{O_2} = \frac{1}{2} n_{H_2}$$



[5] M. Sánchez, E. Amores, D. Abad, L. Rodríguez, and C. Clemente-Jul, "Aspen Plus model of an alkaline electrolysis system for hydrogen production," *Int J Hydrogen Energy*, vol. 45, no. 7, pp. 3916–3929, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.027
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3.2. Biorefineries based on the gasification and electrolysis process

Energy assessment

The energy balance was determined based on the net energy balance (E_n), involving the energy content of the system products (**hydrogen** and **electricity**), and the energy requirements of the process.

$$E_n = \sum E_{outputs} - \sum E_{Inputs}$$

$$E_n = E_{H_2} + E_w - E_{Heating} - E_{Power}$$

E_{H_2}, E_w, $E_{Heating}$, and E_{Power} the energies associated with hydrogen production, electricity, heating requirements, and energy consumed in the process, respectively

The overall process efficiency was defined as the ratio between the overall energy balance and the energy available in the **feedstock**. RW: Raw materials, $\dot{F}_{RM}$ is the raw material flow rate (kg/h), and LHV_{RM} is the low heating value of the raw material (MJ/kg).

$$\eta = \frac{E_n}{\dot{F}_{RM}\ LHV_{RM}}$$

Economic assessment

Table 1. Raw materials, utilities, and parameter economics

Component	Value	Units	Economic parameters		
Pinus patula	0.127	USD/kg	Operating time	8000	Hours/year
Water	0.326	USD/m³	Shifts	3	Shifts/day
Electricity	0.055	USD/kWh	Working time	8	Hours/day
High P. Steam (105 bar)	8.15	USD/ton	Project lifetime	20	Years
Middle P. Steam (30 bar)	8.07	USD/ton	Depreciation method	Linear	
Low P. Steam (3 bar)	7.89	USD/ton	Salvage value	15	%

Aspen Process Economic Analyzer v9.0
Flow rate 50 tons/day

Calculated : Operating expenditure (OpEx)
Capital expenditure (CapEx)
Net present value (NPV)

aspentech

4. Results

4.1. Experimental results

Gasification

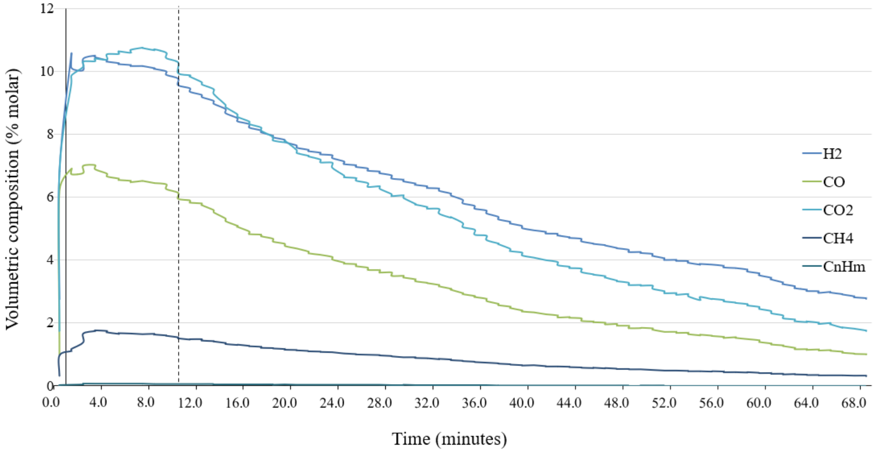


Fig5 Syngas composition of wood chips gasification.

The average concentration of the components was

CO 6.31% H_2 9.68%
CO_2 9.84% O_2 3.23%
CH_4 1.49%

Raw material characterization

Table 2. Proximate and elemental analysis of the raw material

Proximate analysis (%wt. dry)	
Volatile matter (VM)	82.13
Fixed Carbon (FC)	17.63
Ash (AS)	0.22
VM/FC	4.66
Ultimate analysis (%wt. dry)	
Carbon	49.77
Hydrogen	6.02
Oxygen	44.18
Higher Heating Value (HHV-MJ/kg)	18.48

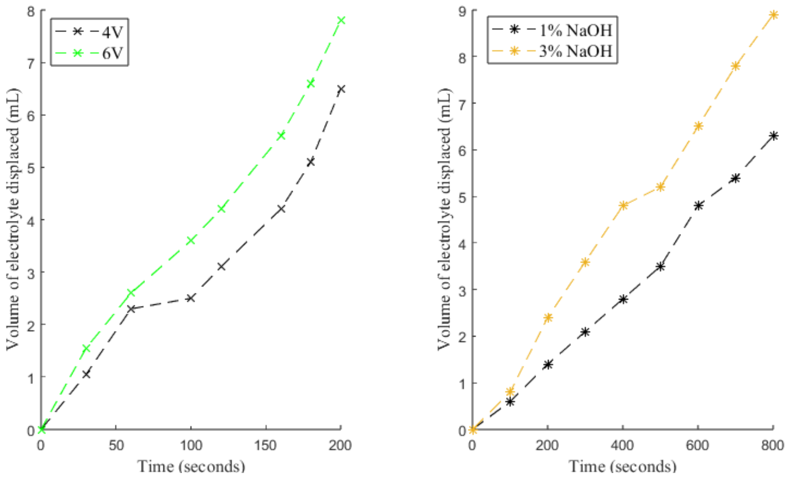
Wood chips presented a similar VM to other reports for rice husk and presented lower amounts of ash than other woods [7]

According to the All-Power Labs industry, the recommended VM/FC ratio for thermochemical processes should be established between 3-4 [8].

[7] A. Demirba, "Calculation of higher heating values of biomass fuels," Fuel, vol. 76, Issue 5, pp. 431-434, 1997, doi.org/10.1016/S0016-2361(97)85520-2
[8] All Power Labs (2015) Biomass feedstock requirements. In: Power pallet technicians manual. pp 1–20

4.1. Experimental results

Electrolysis



a) b)

Fig6 Volume of gas produced (hydrogen) as a function of (a) different voltages and (b) different electrolyte concentration

The highest rate was **4.6** mL/min using a 3% NaOH solution.

The production rate improves as

The **electrolyte concentration** increases

The **voltage** (potential difference) increases, causing a migration of ions from the dissociation of NaOH in water, which triggers an increased production of gases at the electrodes.

4. Results

4.2. Simulations results

Tecno-economic assessment

		Yield	Production cost	Energy efficiency
Scenario 1 GF	Hydrogen	3.50 MJ/kg RM	**820.2** USD/ton	18.33%
Scenario 2 ET	Hydrogen Oxygen	0.15 MJ/kg H_2O	4690.7 USD/ton 130.1 USD/ton	1.69%
Scenario 3 GF-ET	Hydrogen Electricity	**3.78** MJ/kg RM	915.5 USD/ton 2.24 kWh/ton	**19.87%**

Senario 1 and 3

Higher yields and lower hydrogen production costs

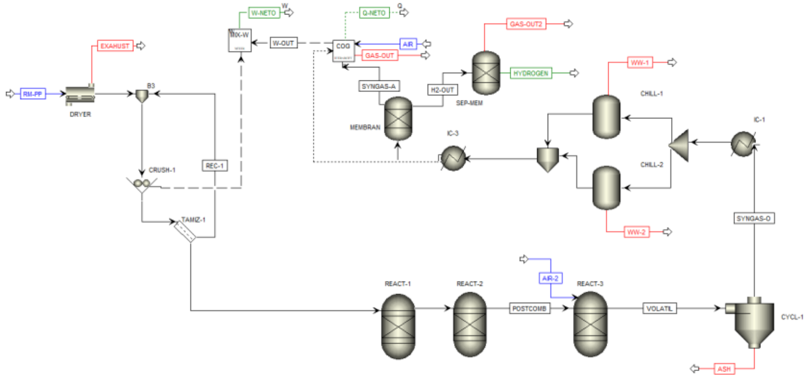


Fig7 Flow diagram of hydrogen production by gasification processes

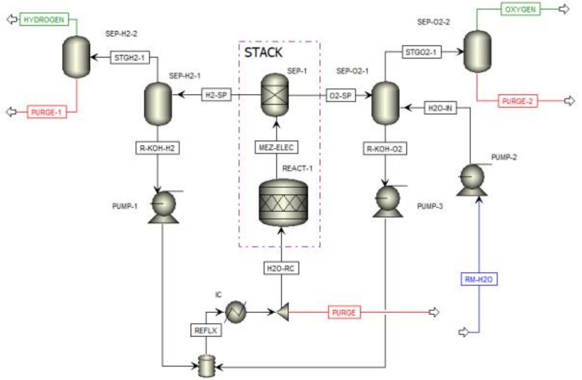


Fig8 Flow diagram of hydrogen production by electrolysis processes

4. Results

4.2. Simulations results

Tecno-economic assessment

Table 3. Operating and investment costs of the evaluated schemes

Item	Scenario 1	Scenario 2	Scenario 3
		Cost (USD/year)	
OpEx			
Raw materials cost	2.31	0.44	2.31
Utilities cost	1.08	0.12	1.12
Maintenance cost	0.19	0.14	0.30
Labor cost	0.08	0.08	0.08
Fixed & General Costs	0.13	0.10	0.20
Plant Overhead	0.14	0.11	0.20
Capital Depreciation	0.34	0.25	0.54
Other operating costs	0.10	0.08	0.15
CapEx (M-USD)	1.85	1.71	3.20
MPSEF* (ton/day)	2.38	50.21	2.42
NPV (M-USD)**	968.8	43.1	965.8

*Minimum processing scale for economic feasibility ** Net present value

Gross revenues (M-USD/year)

Sc1. **115.37**
Sc2. 5.01
Sc3. 114.94

Profit (%)

Sc1. **96.34%**
Sc2. 79.11%
Sc3. 95.92%

Scenario 1
Moderate CapEx and OpEx
Higher technical and energy yields

4. Results

4.2. Simulations results

Sensibility analysis

Electrolysis

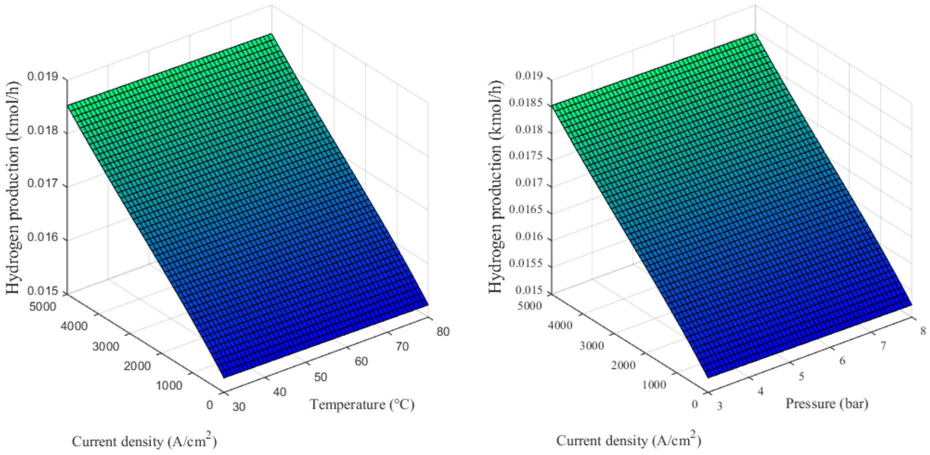


Fig9 Effect of temperature, pressure, and current density on hydrogen production

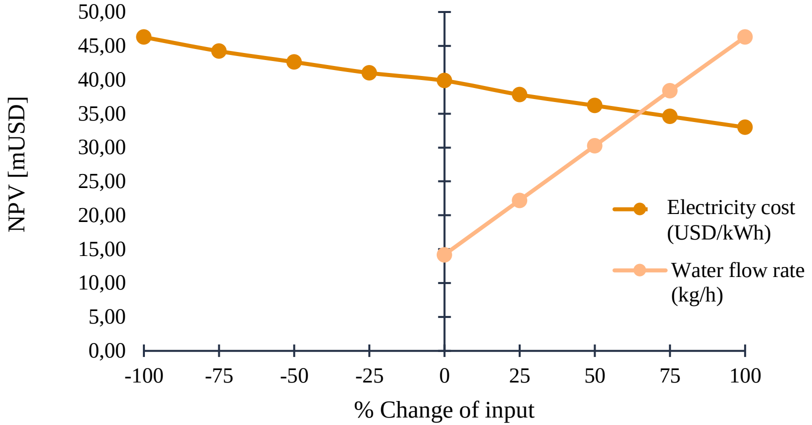


Fig10 Influence of electricity cost variation and recirculated water flow on the economic viability of electrolytic processes.

The cost of hydrogen production with the electrolysis process is directly proportional to the **current density** applied to the stack, which influences the operating costs (cost of **electricity**).

Production rate	
0.018 kmol/h	This work
0.019 kmol/h	Zeng et al. 2010 [9]
0.011 – 0.022 kmol/h	Ursúa et al., 2012 [10]

[9] K. Zeng and D. Zhang, "Recent progress in alkaline water electrolysis for hydrogen production and applications," *Progress in Energy and Combustion Science*, vol. 36, no. 3. pp. 307–326, Jun. 2010. doi: 10.1016/j.pecs.2009.11.002.
[10] A. Ursúa, L. M. Gandía, and P. Sanchis, "Hydrogen production from water electrolysis: Current status and future trends," in *Proceedings of the IEEE*, Institute of Electrical and Electronics Engineers Inc., 2012, pp. 410–426. doi: 10.1109/JPROC.2011.2156750.

5. Conclusions

1. Gasification: **Higher CapEx** and **OpEx** but **higher technical and energy yields**

   Economic pre-feasibility of gasification is strongly influenced by raw material and utilities costs.

2. Electrolysis: **Lower CapEx** and **OpEx** but yields >0.20 MJ/kg RM, which **increases production costs** by more than 4 times compared to gasification.

   The economic viability of electrolytic processes depends strongly on the level of **water recirculated** to the process and the **price of electricity** (current density in the stack).

Acknowledgments

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