**Economic Feasibility of Thermochemical Conversion for Woody Biomass-Derived Liquid Fuels in Spain**

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Abstract

The global shift to renewable biomass resources is crucial for sustainable industrial growth and reducing greenhouse gas emissions. Aligned with the European Green Deal and the Paris Agreement, Spain targets ambitious climate and renewable energy goals for 2030. This study focuses on thermochemical conversion processes, evaluating economic implications within the Spanish context. Using a network optimization framework, we assess technologies like biomass gasification, Fischer–Tropsch synthesis, and methanol-to-gasoline for converting woody biomass into profitable liquid fuels. Economic viability is apparent, with a minimum selling price of 1.506 $/kg for gasoline and 1.863 $/kg for ethanol, below current market rates. Gasoline and ethanol meet market demands, emphasizing their profitability. Further research is needed for cost-effective production of other liquid fuels.

**Keywords**: biomass gasification, economic feasibility, gasification pathways, renewable liquid fuels, linear optimization.

* 1. Introduction

Shifting society from petroleum to renewable biomass resources is crucial for a sustainable industrial society and energy independence, aligning with global agreements like the Paris Agreement and European Green Deal (Commission, 2019). Spain, within the framework of the European Green Deal, has set ambitious climate and energy targets for 2030, including a renewable energy target of at least 42% of the final gross energy consumption (Carpio Martínez, 2018). The Paris Agreement's goal to cut global GHG emissions by 50% by 2030 has spurred biomass adoption, with Spain's expanding forests providing abundant resources from olive trees, pine, vine residues, and Eucalyptus (*Ministry of Agriculture, Fishery, and Food*, 2019).

Biomass, a low-cost renewable source, plays a key role in a clean energy transition. Incorporating CO2 capture in biomass systems aims for negative CO2 emissions, projected to reach 5.5 billion metric tons by 2050 globally (DC, 2020). Biomass is poised to replace part of fossil fuel energy, producing liquid fuels, power, and heat. This study focuses on thermochemical conversion techniques to transform biomass into synthetic liquid fuels (SLFs), contributing to the evolution of a sustainable energy landscape. These SLFs, also known as second-generation fuels, currently face challenges in terms of profitability compared to fossil-based first-generation fuels. However, an integrated approach that combines the co-production of e-fuels with value-added products has the potential to lower production costs and increase the market competitiveness of fuel prices (Stichnothe et al., 2020). The production of SLFs in this study encompasses various thermochemical pathways, including diesel production from fast pyrolysis, aviation fuel production from Fischer-Tropsch (FT) synthesis, and gasoline production from methanol and dimethyl ether. Li et al. (2019) reported the minimum selling price of jet fuel produced from FT synthesis through biomass gasification, which was approximately 0.699 $/kg, approximately 22% higher than that of traditional fossil-based fuel (M. Li et al., 2019). Another study by Wang et al. (2022) compared the prices of jet fuel produced from FT synthesis and pyrolysis, reporting prices of 2.2 $/liter and 3.2 $/liter, respectively (Wang et al., 2022).

Fast pyrolysis is another viable thermochemical route that involves controlled thermal decomposition of biomass at moderate temperatures in the absence of oxygen, resulting in the production of pyrolysis oil and gas (Basu, 2018). Sorunmu et al. (2019) estimated a wide range of minimum selling prices for gasoline derived from pyrolysis, ranging from 2.5 to 4.5 $/gal (Sorunmu et al., 2020). Another study by Li et al. (2019) examined the relationship between greenhouse gas emissions and the minimum fuel selling price in a pyrolysis-bioenergy-biochar platform, revealing a range of minimum fuel selling prices from 2.2 to 3.5 $/gal (W. Li et al., 2019). This study employs a robust mixed-integer linear optimization framework developed in Python using the Pyomo library to assess the feasibility of renewable liquid fuel production in Spain through various thermochemical pathways. Notably, our work features a Python-based 2-D network optimization framework, considering factors like capital, operating costs, biomass availability, and specific fuel demand in the dynamic Spanish market. Additionally, our optimization model determines the Minimum Selling Price (MSP) of renewable liquid fuels, contributing to economic viability analysis.

* 1. Methodology

Our study employs an optimization framework to guide researchers in optimal processing paths, considering sustainability, resource availability, and economics. Technologies vary in advantages, limitations, and feedstock compatibility, with superstructure optimization serving as a key decision-making tool, addressing conversion efficiency, environmental impact, and cost-effectiveness. Drawing upon network optimization models proposed by Kim et al. (2013) our analysis focuses on the Spanish market prices for feedstock and products, as depicted in Figure 1 (Kim et al., 2013). Utilizing Python's Pyomo library, our superstructure involves woody biomass with 47 technologies, 37 intermediates, feedstock, products, and co-products. The optimization framework defines feedstock availability (*βi*, kg/year) and costs (*PCi*, $/kg), which incorporates harvesting, and average 100km distance travelled. The final product demand (*Di*, kg/year), and corresponding prices (*PC*i, $/kg) Table 1. Within the superstructure, each technology is characterized by the unit technology cost (*TCj*, $/kg), unit energy requirement (*TEj*, kWh/kg), energy cost (*ECj*, $/kWh), and mass ratio parameter (*mbi*, the product-to-input ratio).

A set of compounds $i\in I$ : feedstocks $\left(I^{F}\right)$, intermediates $\left(I^{I}\right)$, and final products $\left(I^{P}\right)$.

|  |  |
| --- | --- |
| $PCi \ne 0 $ $∀i I^{F},I^{P}$ | (1) |
| $$PC\_{i}=0 ∀i I^{I}$$ | (2) |
| $$D\_{i}=0∀i\in I^{F},I^{I}$$ | (3) |
|  |  |

Unit technology cost $\left(TC\_{j},\$/kg\right.)$ has been disintegrated into three costs, unit product capital cost (*UPCC*), unit product raw material cost (*UPRMC*), and unit product operating cost (*UPOC*). The variables in the set *Pi,* and *Si* are the feedstock purchased and amount of product sold, respectively.



Figure 1: Superstructure depicting feedstock (black node), different processes, and products (grey nodes are main products and white nodes represent by-products).

Table 1: Feedstock availability and product demand with their associated prices\*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ID | Name | Availability*βi*(Mt/y) | Demand*Di*(kt/y) | Market price*PCi*($/kg) |
| i1 | Biomass | 57.565 |  | 0.065 |
| i13 | DME |  | 4.1 | 0.600 |
| i11 | Methanol |  | 932.4 | 0.488 |
| i14, i18, i28, i34 | Gasoline |  | 5759.0 | 1.620 |
| i17 | LPG |  | 2000.0 | 1.062 |
| i20 | Ethanol |  | 283.0 | 2.447 |
| i23 | Diesel |  | 31144.0 | 1.899 |
| i31 | Jet fuel |  | 3280.0 | 0.817 |

\*The values have been retrieved from literature sources not shown due to paper length limitations.

The constraint of mass balance defines the equation as the amount of feedstock purchased and the product produced must be equal to the amount of any product consumed and sold.

|  |  |
| --- | --- |
| $$P\_{i}+\sum\_{j\in JOUT}^{}  mb\_{ij}X\_{j}=S\_{i}+\sum\_{j\in J^{IN}}^{}  mb\_{ij}X\_{j}∀$$ | (4) |

However, the products sold must fulfil the market demand, and feedstock is constrained by its availability. In addition, the selling price of all intermediates and feedstock and the purchase price of any product are set to zero.

|  |  |
| --- | --- |
| $$S\_{i}\geq D\_{i} ∀\_{i}\in I^{P}$$ | (5) |
| $$P\_{i}\leq β\_{i }∀i\in I^{F}$$ | (6) |
| $$S\_{i}=0 ∀i\in I^{F},I^{I}$$ | (7) |
| $$P\_{i}=0 ∀i\in I^{I}$$ | (8) |

The following objective function is enforced to find the optimal processing network for minimum selling price utilizing the raw material cost, capital cost, operating, operating, and energy cost.

|  |  |
| --- | --- |
| $$MSP=∑\_{i\in I^{F}} PC\_{i}P\_{i}+∑\_{j} X\_{j}\left(UPCC\_{j}+UPRMC\_{j}+UPOC\_{j}+TE\_{j}EC\_{j}\right)$$ |  (9) |
|  |  |

* 1. Results and Discussion

The study revealed a methanol production cost of 0.725 $/kg, which stands in contrast to the market price of 0.488 $/kg, as shown in Table 2. To contextualize Poluzzi et al., (2022) conducted a comprehensive investigation into various gasification techniques and proposed that indirect gasification could yield methanol at a competitive cost of 0.64 $/kg (Poluzzi et al., 2022). Similarly, Sun et al., (2021) explored methanol production from biomass, conducting a thorough assessment of its thermodynamic and economic performance, with a notably low production cost of 0.479 $/kg (Sun & Aziz, 2021). The MSP of jet fuel, as shown in Table 2, stands at 1.120 $/kg, while the market selling price is notably lower at 0.817 $/kg. Kreutz et al. (2020) and Guimarães et al. (2022) respectively explored the economic viability of 100% biomass-based Fischer-Tropsch jet fuel with a cost of 1.08$/L due to negative greenhouse gas intensity and the comparative advantages of an integrated gasification and Fischer-Tropsch synthesis process, revealing a lower production cost of 0.52 $/L with reduced capital expenditure (Guimarães et al., 2022; Kreutz et al., 2020).

The MSP for diesel, produced through fast pyrolysis of biomass, amounted to 2.865 $/kg. This cost significantly exceeds the market rate, which stands at 1.899 $/kg, as shown in Table 2. On the contrary Hu et al., (2023) explored the production of renewable diesel using fast pyrolysis, employing a combination of algal and straw biomass as feedstock. Their research demonstrated the potential to achieve a highly competitive production cost of only 1.08 $/kg (Hu et al., 2023). In a similar pursuit, Patel et al., (2019) explored fast pyrolysis of Canadian biomass feedstocks, including wheat straw, maize stover, and spruce, finding the potential to produce diesel at a more affordable cost of 1.25 $/kg (Patel et al., 2019).

Figure 2 illustrates the optimized pathway for gasoline production through the methanol-to-gasoline (MtG) process via gasification. According to Table 2, the Minimum Selling Price (MSP) for gasoline is 1.506 $/kg, while the market price is slightly higher at 1.62 $/kg. These numbers reveal a competitive pricing structure for gasoline production in our study. The break-even price of ethanol, as determined by the optimization solver in our study, is 1.863 $/kg. It is worth noting that alternative studies, such as Melin et al. (2022), exploring biomass gasification for ethanol production with syngas purification through a membrane, have reported substantially lower MSP, achieving a levelized cost of 0.88 $/kg (Melin et al., 2022). Similarly, Rigs et al. (2023) proposed that co-utilization of green hydrogen and fermented syngas could achieve an MSP of 0.97 $/kg for ethanol (Regis et al., 2023).

* 1. Conclusions

The study supplies a thorough exploration of various thermochemical pathways for renewable liquid fuel production in Spain. Using a network optimization framework, technologies like biomass gasification, Fischer–Tropsch synthesis, and methanol-to-gasoline are assessed for converting woody biomass into economically feasible liquid fuels. The economic feasibility of the proposed liquid fuel production pathways is underscored by a compelling MSP of 1.506 $/kg for gasoline and 1.863 $/kg for ethanol, both below current market rates. This underscores their potential to not only meet market demands but also contribute significantly to the renewable energy landscape in Spain. Moreover, a comprehensive evaluation, including detailed supply chain and life cycle analyses, is imperative to assess the environmental impact of any future thermochemical facility within the Spanish territory.



Figure 2: Optimized superstructure

*Table 2: Minimum Selling Price (MSP) of each product with feedstock and the associated energy consumed.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Product | Price ($/kg) | MSP ($/kg) | BiomassConsumed | Co-Product | Co-reactant | (kWh/kg) |
| MeOH | 0.488 | 0.725 | 2.327 | - |  | 1.064 |
| DME | 0.600 | 0.989 | 2.952 | - |  | 1.447 |
| Gasoline | 1.620 | 1.506 | 8.679 | LPG |  | 2.423 |
| Diesel | 1.899 | 2.865 | 7.739 | - | 0.2054\* | 3.542 |
| Jet fuel | 0.817 | 1.120 | 2.931 | Gasoline |  | 1.019 |
| Ethanol | 2.447 | 1.863 | 4.828 | Propanol |  | 6.034 |

\*Hydrogen is consumed as co-reactant in this case.

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