



OPTIMIZING E-SAF PRODUCTION FROM RENEWABLE METHANOL IN BRAZIL: A MIXED INTEGER LINEAR PROGRAMMING APPROACH

Autores: Jorge Eduardo Infante Cuan¹, Víctor Fernández García¹, Guilherme Oliveira², Reynaldo Palacios¹, Adriano Viana Ensinas²,

¹ Center of Engineering, Modeling and Social Science Applied, Federal University of ABC, Santo André 09210-580, Brazil

² Department of Engineering, Federal University of Lavras, Lavras 37000-200, Brazil

ABSTRACT

The urgent need to decarbonize the aviation sector has prompted research into sustainable aviation fuels (SAFs) produced from renewable resources. This study analyzes the production of e-SAFs from sugarcane in Brazil, integrating methanol obtained from both bagasse and CO₂. A mixed-integer linear programming (MILP) model was developed to optimize the supply chain, simultaneously considering technological, economic, and logistical factors. The results show that the system is capable of fully meeting the projected SAF demand for 2037, with approximately 67% of the methanol produced from bagasse and the remaining 33% through CO₂ conversion with green hydrogen. The co-generated production of ethanol, renewable diesel, renewable gasoline, and biomethane contributes to the overall system efficiency, achieving an energy efficiency of 57%. The investment analysis shows that methanol production from bagasse and hydrogen generation through PEM electrolysis are the most capital-intensive processes. From a financial perspective, the project has a net present value (NPV) of 53,156.35 MUSD, an internal rate of return (IRR) of 10%, and a discounted payback period of 14.07 years, indicating the economic viability of the initiative. A minimum sales price of 5.05 USD/L was also calculated to ensure the project's profitability under current market conditions.

Keywords: E-fuel, Methanol-to-Jet, hydrogen, renewable energy, techno-economic analysis.

1 INTRODUCTION

The climate crisis and the urgent need to limit the global average temperature increase to below 1.5°C by midcentury have made the energy sector central to mitigation strategies (Guilloteau et al., 2025; IEA, 2023). The aviation industry is responsible for approximately 2-3% of global CO₂ emissions (Ali et al., 2025), and their relative share is projected to increase if decisive measures are not implemented. In this scenario, sustainable aviation fuels (SAFs) are one of the most promising solutions because they reduce emissions without requiring alterations to airport infrastructure or existing aircraft. (Khalifa et al., 2025; Ten Cate et al., 2025).

In recent years, e-fuels have emerged as a central component of SAF production routes due to their integration of renewable electricity, green hydrogen, and carbon dioxide (Dahiru et al., 2025; Dybiński et al., 2025). In this category, e-SAF produced using the methanol-to-jet (MTJ) route is an attractive technological alternative because it combines the flexibility of various raw materials with well-researched catalytic processes (Elwalily et al., 2025). Methanol has established itself as a versatile energy carrier that can be obtained from fossil resources, biomass, or a combination of green hydrogen with biogenic or atmospheric CO₂ (Abdulghaffari; Kazemeini, 2024).

Brazil's sugar-energy industry is one of the most developed in the world, offering unique conditions for producing advanced biofuels. In addition to its role in producing first-generation ethanol, sugarcane generates large volumes of bagasse, a



lignocellulosic residue traditionally used in electric cogeneration that has high potential for thermochemical processes such as gasification (Deuber et al., 2023). Through gasification, bagasse is converted into synthesis gas ($\text{CO} + \text{H}_2$), which can then be transformed into methanol and, finally, into e-SAF. This approach diversifies the use of sugarcane biomass beyond electricity and bioethanol production by integrating the concept of a biorefinery.

In addition to bagasse, the production of ethanol generates two significant streams of biogenic CO_2 that can be used in the synthesis of methanol. The first stream is the CO_2 released during alcoholic fermentation. The second stream corresponds to the CO_2 separated during the purification of biogas generated from the anaerobic digestion of vinasse. Vinasse is a liquid waste that poses a significant environmental challenge for distilleries (Fuess; Zaiat, 2018). To improve the use of biogas as biomethane, the CO_2 must be separated, providing an additional flow that can be used in e-methanol production. The combined use of bagasse, fermentation CO_2 , and biogas CO_2 creates a circular economy, where waste from one process becomes an input for another. This contributes to reducing net emissions (Abdulghaffari; Kazemeini, 2024; Eyberg et al., 2024).

However, implementing these value chains presents significant technological, economic, and logistical challenges. Due to this complexity, mathematical optimization models, particularly those based on mixed-integer linear programming (MILP), have become essential for planning advanced biofuel supply chains (Rahemi et al., 2020; Ravi et al., 2023). These models allow for the simultaneous representation of strategic (e.g., plant investments and location), tactical (e.g., production scale and transport routes), and operational (e.g., mass and energy balances and costs) decisions, integrating the technological and economic dimensions into a single framework (Garcia; Palacios; Ensinas, 2024; Infante Cuan et al., 2025).

This study analyzes the production of e-SAF from renewable methanol synthesized using sugarcane bagasse and CO_2 released during alcoholic fermentation and separated during vinasse biogas purification. Using a MILP model, the study integrates technological, economic, and logistical processes into an optimization framework to identify supply chain configurations. The results help evaluate the viability of this approach for decarbonizing air transport and consolidating Brazil as a leader in the bioeconomy and sustainable fuel production.

2 CASE STUDY AND METHODOLOGY

In this case study, conducted in Brazil and conditioned by the regional availability of sugarcane (Table 1), an integrated model was used. Sugarcane, concentrated mainly in the states of São Paulo, Goiás, Minas Gerais, Mato Grosso do Sul, Paraná, and Mato Grosso, constitutes the strategic input that supports the system. Its abundance and transportation logistics allow for the evaluation of the viability of a decentralized and integrated biorefinery model, in which milling and fermentation byproducts play a fundamental role in generating added value.

The system begins at the first-generation distillery, which converts sugarcane into ethanol and generates strategic byproducts such as bagasse, vinasse, and carbon dioxide. The bagasse is valorized to obtain renewable methanol, while the vinasse is sent to biodigesters, producing biomethane and additional CO_2 . These streams become key elements for integration with e-fuel synthesis routes. In parallel, the carbon dioxide released during fermentation and biodigestion is not considered waste, but an essential resource. This captured CO_2 is combined with green hydrogen—produced through proton exchange membrane (PEM) electrolysis using renewable electricity—for the additional synthesis of methanol. Thus, the model contemplates two complementary methanol production routes: one based on the utilization of bagasse and the other on the reaction of CO_2 with



INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

hydrogen. Both methanol streams converge in the system and constitute the central raw material for producing e-SAF. Additionally, the system produces co-products such as green electricity, gasoline, and diesel, which strengthen the economic balance of the model and diversify the energy supply.

Table 1 - Raw material availability by location (IBGE, 2025).

Local	Sugarcane (t/year)
Goiás	81,599,588
Mato Grosso	19,060,217
Mato Grosso do Sul	51,789,876
Minas Gerais	82,544,375
Paraná	38,586,024
São Paulo	439,098,082

To estimate future demand for SAF, the year 2037 was established as the target date. Based on 2024 data (ANP, 2025), an annual growth rate of 3.5% was applied, projecting the expected increase in aviation fuel consumption and the need for progressive substitution of fossil fuels. It is important to note that this demand was calculated based on the main fuel distribution centers in Brazil, which allows the required volumes to be associated with the existing logistics infrastructure and the consumption hubs concentrated at the most important airports. This methodology ensures a better match between the potential supply of biomass in sugarcane-producing states and the actual demand of the aeronautical sector, strengthening the feasibility analysis of the e-SAF supply chain.

This study presents a mixed integer linear programming (MILP) model that optimizes the production of sustainable aviation fuels (SAFs) from renewable resources while considering technological, economic, and logistical factors. The implemented model was based on studies of (Garcia; Palacios; Ensinas, 2024; Infante Cuan et al., 2025; Khalid et al., 2025). The mathematical formulation was implemented in LINGO v.20 software (LINGO, 2022). It is structured into three interrelated submodels: (I) A physical model; (II) An economic model and (III) A regional logistics model. The physical model ensures that the annual production of each resource aligns with the input, output, and consumption balances for each unit and location. The economic model calculates cash flows, operating costs, raw material costs, and transportation costs, as well as revenues from the sale of sustainable aviation fuel (SAF) and other by-products. The objective function maximizes the net present value (NPV) (Equation 1) of the system over a 20-year planning horizon by discounting future cash flows at an 8% minimum rate of return. The logistics model evaluates different supply chain configurations and determines the optimal locations for conversion units and operating levels that minimize costs. This ensures the efficiency of sustainable aviation fuel (SAF) supply in Brazil.

$$NPV = -\text{Investment} + \sum_t \frac{\text{Cash flow}}{(1+\text{MARR})^t} \quad (1)$$

The developed MILP model is structured around sets, parameters, variables, and constraints. This structure allows for a comprehensive representation of the system's physical, economic, and logistical aspects.

Sets: Several sets were defined to structure the model. The RESOURCE set includes all the resources involved (everything that enters or leaves a unit). The UNIT set corresponds to the process units, and the LEVEL set defines the capacity levels of each unit. The LOCAL set represents the locations considered for raw material availability and demand, and the MODAL set represents the available modes of transport.



INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

Parameters: The main parameters used are IAR and OAR (consumption and production coefficients per unit), CapMax and CapMin (maximum and minimum capacities), investment costs (capCostA and capCostB), operating and transportation costs, resource availability (avail), regional demand (demand), and distance between locations (dist). We considered an annual operating factor of 5,040 hours (fop) and a discount rate of 8% (MARR).

Variables: The model includes binary variables for unit and level selection (y, yLevel), continuous variables for production and consumption (prod, cons), as well as economic variables.

Constraints: The following constraints were incorporated: maximum and minimum capacity, selection of operating levels, annual balances of inflows and outflows for each resource, local mass balance per resource, and availability and demand. These constraints ensure that the production, transportation, and consumption of resources comply with the system's physical, economic, and logistical limits, allowing for an optimal solution that maximizes the project's Net Present Value.

4 RESULTS AND DISCUSSION

The implemented MILP model allowed for a comprehensive evaluation of sustainable aviation fuel (SAF) production from sugarcane, considering co-generated products such as ethanol, renewable diesel, renewable gasoline, and biomethane. Optimization results showed that the projected e-SAF demand of 8,197,732 tons can be fully met with a total production of 6.91×10^7 tons of methanol. Of this total, approximately 67% is generated from sugarcane bagasse, and the remaining 33% is generated from CO₂ captured during the production process. This demonstrates the integration of complementary production routes and the use of by-products to optimize the system's overall efficiency. In terms of resources, the model showed significant consumption of sugarcane (580,436,200 tons), water (703,850,200 tons), and electricity (283,784,800 MW). With an average yield of 77.749 tons/hectare, approximately 7,466,000 hectares of cane would be required to supply the system. This represents approximately 74% of the 10,065,599 hectares cultivated in Brazil in 2023 (IBGE, 2025). Thus, large-scale implementation of e-SAF could compete directly with ethanol and sugar production for the food market. This would generate potential land use conflicts and pressure on existing agricultural systems. This finding underscores the importance of evaluating strategies for sustainable expansion or crop diversification to minimize socio-environmental impacts. The optimization of the model generated the following main products: ethanol (37,612,260 tons), SAF (8,197,732 tons), renewable diesel (13,609,160 tons), renewable gasoline (5,158,124 tons), and biomethane (1,555,577 tons). The overall efficiency of the process was 57%, considering the ratio between the energy contained in the final products and the energy contained in the processed sugarcane and the electricity consumed. In energy terms, ethanol accounted for 46% of the energy produced, SAF 15%, diesel 26%, gasoline 10%, and biomethane only 3%. This indicates that, although SAF represents a smaller percentage in absolute volume compared to ethanol, its energy and strategic contribution as a sustainable fuel is significant (Figure 1).

The economic evaluation of the advanced fuel production system shows that the total investment required for the plants amounts to 283,109.402 MUSD, with a raw material cost of 35,967,755 MUSD/year, and transportation costs of 609,629 MUSD/year. Annual revenues from the sale of products was estimated at 99,137,734 MUSD/year, generating an average cash flow of 34,249.41MUSD/year. Analysis of the relative contribution of each product to profits shows that SAF accounts for 58% of total revenues, followed by ethanol with 27%, renewable diesel with 10%, renewable gasoline with 4%, and biomethane with 1% (Figure 2). This distribution highlights the centrality of SAF as the economic driver of the system, despite representing only

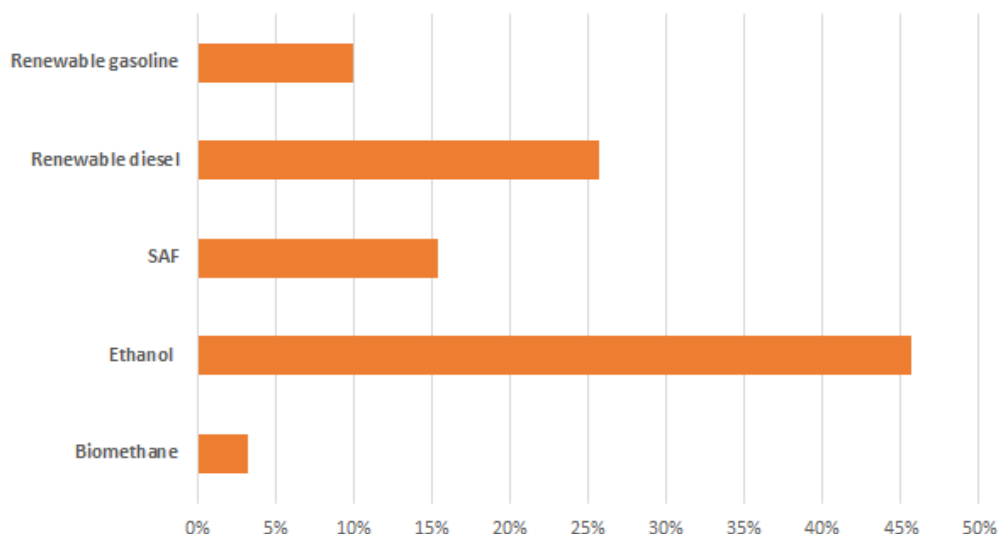


INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

a fraction of total fuel production. For this scenario, the sale value of SAF was assumed to be USD 10,500/ton, as a theoretical reference for evaluating the economic viability of the project. However, this value is well above current market prices, so the results reflect an idealized scenario that allows for comparison of the relative contribution of products under favorable conditions.

Figure 1 – Energy distribution of products and by-products



To make the analysis more realistic, the minimum sale price (MSP) of sustainable aviation fuel (SAF) was calculated. The MSP is defined as the price that ensures the net present value (NPV) of the project is zero. In this case, the MSP was 5.05 USD/L. This provides a tangible economic indicator with which to assess the project's viability under current market conditions, where high theoretical prices are not sustainable. The project's financial indicators show an NPV of 53,156.35 MUSD, a discounted payback period of 14.07 years, and an IRR of 10%. These results reflect the system's ability to generate positive returns on the initial investment. In terms of raw material cost, sugarcane accounts for 43%, electricity accounts for 55%, and water accounts for only 2%. This reflects the process's high energy intensity and the importance of optimizing electricity and biomass consumption to improve profitability (Figure 3).

Figure 2 – Distribution of revenues

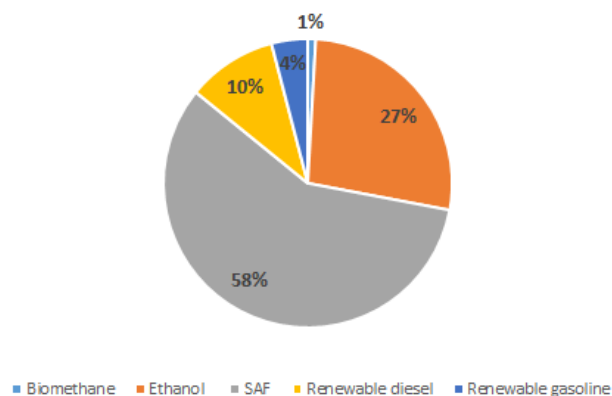
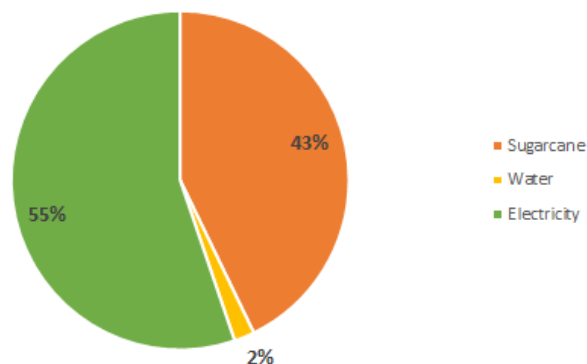


Figure 3 – Distribution of raw material cost



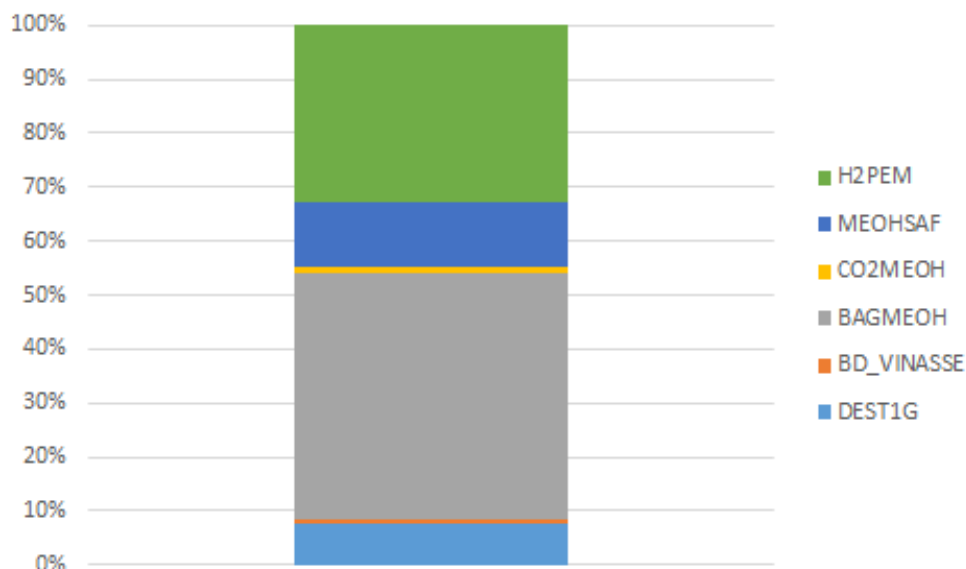


INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

In terms of investment per unit, the most expensive processes are methanol production from bagasse (46%) and hydrogen by PEM (33%), followed by methanol conversion to SAF (12%) (Figure 4).

Figure 4 – Distribution of investment costs by units



BAGMEOH: Methanol production from bagasse; BAGMEOH: Methanol production from carbon dioxide; H2PEM: Hydrogen production by electrolysis; MEOHSAF: Production of PBS from methanol; DEST1G: Sugarcane distillery; BD_VINASSE: Production of biomethane from vinasse.

5 CONCLUSIONS

This study, based on a mixed-integer linear programming (MILP) model developed for Brazil, allowed the optimization of the production of sustainable aviation fuels (e-SAF) from sugarcane, integrating both methanol obtained from bagasse and CO₂ streams generated during alcoholic fermentation and vinasse biogas purification. The use of MILP facilitated the simultaneous evaluation of technological, economic, and logistical factors, considering regional sugarcane availability, process efficiency, and byproduct integration, allowing the design of supply chain configurations capable of fully meeting the projected SAF demand by 2037. The results show that the system can produce e-SAF on a large scale with an overall energy efficiency of 57%. The investment is mainly focused on methanol production from bagasse and hydrogen generation through PEM electrolysis. Financial indicators confirm the project's viability under current market conditions, with a net present value (NPV) of 53,156.35 MUSD, an internal rate of return (IRR) of 10%, and a discounted payback period of 14.07 years, along with an estimated minimum SAF selling price of 5.05 USD/L. Finally, the results highlight that e-SAF production in Brazil not only contributes to the decarbonization of air transport but also promotes the circular economy by valorizing waste and CO₂ streams. However, large-scale implementation requires considering pressures on land use and the need for sustainable expansion strategies, agricultural diversification, and logistics optimization to minimize socio-environmental impacts.



INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

REFERENCES

- ABDULGHAFFARI, Amir Salar; KAZEMEINI, Mohammad. A framework for modeling of catalyst deactivation and coking free of main-reaction kinetics in methanol to gasoline process. **Fuel**, v. 358, p. 130333, fev. 2024.
- ALI, Syed Awais *et al.* Review on the Role of Electrofuels in Decarbonizing Hard-to-Abate Transportation Sectors: Advances, Challenges, and Future Directions. **Energy & Fuels**, v. 39, n. 11, p. 5051–5098, 20 mar. 2025.
- ANP. **Painel Dinâmico do Mercado Brasileiro de Combustíveis de Aviação**. Disponível em: <<https://app.powerbi.com/view?r=eyJrIjoiMjQ3ZWRhNTMtMDY2Yy00OThiLTg1OWUtYmFiZGZlNzE5ZDU5IiwidCI6IjQ0OTlmNGZmLTl0YTltNGI0Mi1iN2VmLTEyNGFmY2FkYzkyMyJ9>>. Acesso em: 5 jul. 2025.
- DAHIRU, Ahmed Rufai *et al.* Exploring circularity in sorption-enhanced methanol synthesis: a comparative life cycle assessment. **Sustainable Energy & Fuels**, v. 9, n. 17, p. 4681–4693, 2025.
- DEUBER, Raquel De Souza *et al.* Production of Sustainable Aviation Fuels from Lignocellulosic Residues in Brazil through Hydrothermal Liquefaction: Techno-Economic and Environmental Assessments. **Energies**, v. 16, n. 6, p. 2723, 15 mar. 2023.
- DYBIŃSKI, Olaf *et al.* Overview of the e-Fuels Market, Projects, and the State of the Art of Production Facilities. **Energies**, v. 18, n. 3, p. 552, 24 jan. 2025.
- ELWALILY, Ali *et al.* Sustainable aviation fuel production via the methanol pathway: a technical review. **Sustainable Energy & Fuels**, p. 10.1039.D5SE00231A, 2025.
- EYBERG, Vincent *et al.* Techno-economic assessment and comparison of Fischer–Tropsch and Methanol-to-Jet processes to produce sustainable aviation fuel via Power-to-Liquid. **Energy Conversion and Management**, v. 315, p. 118728, set. 2024.
- FUESS, Lucas Tadeu; ZAIAT, Marcelo. Economics of anaerobic digestion for processing sugarcane vinasse: Applying sensitivity analysis to increase process profitability in diversified biogas applications. **Process Safety and Environmental Protection**, v. 115, p. 27–37, abr. 2018.
- GARCIA, Victor Fernandes; PALACIOS, Reynaldo; ENSINAS, Adriano. Optimisation of Ammonia Production and Supply Chain from Sugarcane Ethanol and Biomethane: A Robust Mixed-Integer Linear Programming Approach. **Processes**, v. 12, n. 10, p. 2204, 10 out. 2024.
- GUILLOTEAU, Pierre *et al.* Production of sustainable aviation fuel: Influence of feedstock and plant capacity on fuel price. **International Journal of Hydrogen Energy**, v. 157, p. 150494, ago. 2025.
- IBGE. **Produção de Cana-de-açúcar no Brasil**. Disponível em: <<https://www.ibge.gov.br/explica/producao-agropecuaria/cana-de-acucar/br>>. Acesso em: 1 ago. 2025.
- IEA. **Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach – Analysis**. Disponível em: <<https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>>. Acesso em: 30 ago. 2025.
- INFANTE CUAN, Jorge Eduardo *et al.* Optimisation for Sustainable Supply Chain of Aviation Fuel, Green Diesel, and Gasoline from Microalgae Cultivated in Sugarcane Vinasse. **Processes**, v. 13, n. 5, p. 1326, maio 2025.
- KHALID, Halima *et al.* Technical, Economic, and Environmental Optimization of the Renewable Hydrogen Production Chain for Use in Ammonia Production: A Case Study. **Processes**, v. 13, n. 7, p. 2211, jul. 2025.



Fortaleza, Ceará
Centro de Eventos do Ceará

INTERNATIONAL SYMPOSIUM ON ENERGY

Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

KHALIFA, Ridab *et al.* A lifecycle assessment of waste-based sustainable aviation fuels blends for advancing the circular aviation economy. **Energy Conversion and Management: X**, v. 27, p. 101141, jul. 2025.

LINGO. **Lingo Systems Inc.** Portland, OR, USA, 2022. Disponível em:
<<https://lindo.com/index.php/products/lingo-and-optimization-modeling>>

RAHEMI, Hasti *et al.* Bioethanol supply chain network design considering land characteristics. **Renewable and Sustainable Energy Reviews**, v. 119, p. 109517, mar. 2020.

RAVI, Arvind *et al.* Supply Chain Optimization for Mainstreaming SAF in the Indian Aviation Sector. *In*:
PRADEEP PRATAPA, P. *et al.* (orgs.). Singapore: Springer Nature, 2023.

TEN CATE, Mats *et al.* From CO2 emissions to jet fuel: Analysis of potential sustainable aviation fuel supply chains in Europe. **Applied Energy**, v. 396, p. 126131, out. 2025.