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Lignocellulosic Waste Supply Chain Network Design for Sustainable Aviation Fuels Production through Solar Pyrolysis

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ABSTRACT

This study optimizes the Sustainable Aviation Fuel Supply Chain Network (SAFSCN) in the Czech Republic, using wheat straw as feedstock. It integrates geospatial data, transportation logistics, and economic feasibility, applying mixed-integer linear programming (MILP) to optimize pyrolysis plant locations and minimize costs. Sensitivity analysis varied wheat production growth by ±0.1% and ±0.2%. Results confirm Sustainable Aviation Fuel (SAF) production is technically and economically viable, with costs projected to decline up to 30.64% and revenues rising 49.07% from 2030 to 2050 due to technological advancements, improved logistics, and economies of scale. The findings underscore the critical role of SAF in achieving EU aviation decarbonization targets and highlight the importance of efficient supply chain planning for scaling SAF production.

Keywords: Biomass, Biofuels, Sustainable Aviation Fuel, Supply Chain Network Model, Optimization

INTRODUCTION

The EUROCONTROL main report [4] outlines long-term forecasts for flights and CO_2 emissions across three scenarios—low, base, and high. In the base scenario, Europe's aviation sector is expected to grow significantly, with flights increasing by 44% from 2019 levels, reaching 16 million annually by 2050. This growth in flights will drive a corresponding rise in fossil fuel demand, resulting in millions of gigatons of CO_2 emissions from aviation. According to Wang et al., renewable aviation fuel holds the highest potential for reducing CO_2 emissions, while biomass is the only renewable energy source capable of capturing CO_2 emissions. This makes biomass-based fuel production a promising option for achieving a net-zero carbon balance through CO_2 fixation via photosynthesis [18]. Similarly, Martinez-Valencia emphasizes that the production of renewable fuels is critical for global efforts to reduce greenhouse gas emissions [11]. This aligns with the Eurocontrol report, which identifies scaling up the production, distribution, and use of Sustainable Aviation Fuels (SAFs) as a key strategy to help the aviation industry achieve net-zero CO_2 emissions by 2050. In the base scenario, SAFs are projected to contribute 41% of the necessary emission reductions. While there is no single solution, the long-term impact of SAF scaling is expected to be the largest, with operational improvements providing more immediate benefits, alongside contributions from governments and regulators [4]. To address the growing CO_2 emissions from aviation, the European Union introduced the ReFuelEU Aviation Regulation, which aims to reduce greenhouse gas emissions by promoting SAF usage. Starting in 2025, aviation fuel suppliers will be required to provide a minimum SAF blend of 2% at EU airports, with this percentage increasing over time. By 2030 and 2050, the required SAF blend is expected to reach 6% and 70%, respectively, with 35% of this coming from synthetic aviation fuels (e-fuels). This regulation is projected to cut CO_2 emissions by more than 60% by 2050 compared to 1990 levels, playing a crucial role in the EU's broader decarbonization efforts [7]. The Renewable Energy Directive II (RED II) provides a comprehensive framework for promoting renewable energy in the EU, with a focus on advanced biofuels (second-generation biofuels), which are derived from non-food feedstocks such as straw, nut shells, and husks. This distinction helps reduce competition with food crops and mitigates the risk of indirect land-use change [6]. Currently, Sapp's research on seven certified processes under ASTM D7566 allows up to 50% SAF blends with fossil jet fuel [15]. SAFs must ensure low lifecycle carbon emissions, renewability, and sustainability, avoiding competition with food production, ecosystem harm, and deforestation, while also being economically viable. Masum et al. highlight the importance of developing an efficient supply chain for large-scale SAF production and distribution. A comprehensive approach involves key elements like feedstock availability, optimization of production pathways by exploring technological options, assessing infrastructure and logistics for transporting feedstocks to pyrolysis plants and bio-oil to refineries, and ultimately utilizing Supply Chain Optimization Modeling. Mixed-integer linear programming (MILP) models can simulate and optimize the supply chain over time, aiding decisions on facility locations, transportation routes, and inventory management to minimize both costs and environmental impact [12].

Our study presents a comprehensive approach to optimizing a Sustainable Aviation Fuel Supply Chain Network (SAFSCN), with a focus on the Czech Republic.

METHOD

This study outlines a SAF supply chain network, with the process divided into four stages. In Stage 1, geospatial data including wheat production and developed area data (2002-2023) from the Czech Statistical Office [1], administrative boundaries (Nomenclature of Territorial Units for Statistics - NUTS 3) provided by the EUROSTAT website [2], road distances between regions cities (point in the map) and refineries, Direct Normal Irradiance (DNI) data from SOLARGIS [17], and the locations and capacities of existing refineries are gathered. For this study, wheat straw is chosen as the feedstock for SAF production, aimed at replacing a portion of Jet A-1 fuel. In Stage 2, the methodology followed for the wheat straw estimation was first to calculate the dry matter production of wheat which is 90% [10]. Then, the yield (production/developed surface) was calculated for each year and the straw quantification estimation was calculated by using the residues-to-product ratio (RPR) empirical function by Scarlat et al., 2010 as reported by Karan & Hamelin [10, 16]. The RPR is as follows:

$$RPR = -0.3629*\ln(Y)+1.6057\ 0.28 \quad (1)$$

where Y is the Yield, and this function derived best-fit logarithmic function curves for RPR by plotting the values for RPR and crop yield based on data available in the literature. This approach determines the theoretical potential of straw production, by using the following formula as reported in the Karan and Hamelin study [10]:

$$\text{Straw Production} = RPR * \text{Yield} * \text{Surface area} \quad (2)$$

For estimating available straw production, it is important to take into account crucial parameters such as the removal rate of residues from the terrain and the amount that is used in competitive uses. Removal rates must be sustainable in order to protect soil quality, biodiversity, and erosion control, and in this study, the sustainable removal rate of wheat and rye residues is 40% [17], and the amount of straw needed for animal bedding is 16% of the collectable crop [14]. The formula that was followed to calculate the available potential straw production is as follows:

$$\text{Available residues} = \text{Theoretical potential (dry matter)} - \text{Removal rate \%} - \text{Competitive uses \%} \quad (3)$$

This approach is based on the approach mentioned by Elbersen et al. [3] and has been applied to the AdvanceFuel Horizon Project [8]. Using the historical data, forecasting of feedstock for the short-mid term (2030) and long term (2050) was performed by applying the 'Commission' method. In this method, the production area of wheat was forecasted based on the annual growth percentage of these crops given in Agricultural Outlook 2023-35 [2]. For the crop period 2013-2023, the annual growth percentage of soft wheat was 0.1% for the period of 2013-2023 and 2023-2035. This growth rate was applied to project wheat production areas for 2030 and 2050. Crop production was then estimated by multiplying the projected production areas by the average yield of these crops, which was derived from a historical dataset spanning 22 years. For this study, a sensitivity analysis was conducted by varying the annual growth rate (AGR) of wheat production within a range of ±0.1% and ±0.2% from the historical data. This approach accounts for potential fluctuations in productivity due to factors such as climate variability, thereby enhancing the robustness of the results.

In the present study, an initial quantitative assessment of SAF production was conducted based on the availability of feedstock, as outlined above. The calculations followed the material flow from dried feedstock to the final SAF product, utilizing a system coupling fast pyrolysis with solar energy, as proposed in the CIRCULAR FUELS project and presented in Figure 1 [9].

The SAF demand was forecasted for 2030 and 2050, considering the required minimum SAF blending

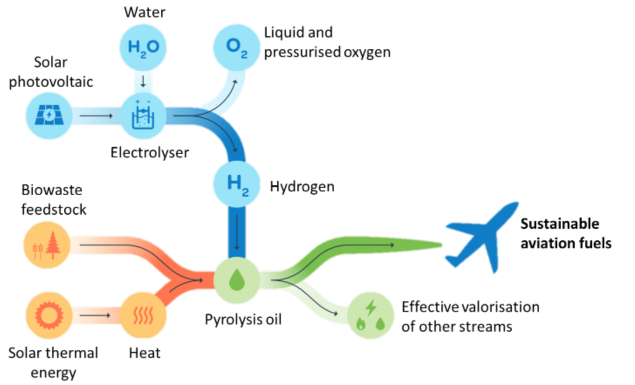

Figure 1. The Circular Fuels project process shows the conversion of renewable feedstock to sustainable aviation fuel (CIRCULAR FUELS).

targets of 6% by 2030 and 35% (with 70% of SAF, including at least 35% synthetic aviation fuels or e-fuels) by 2050, as outlined in Annex IX of the ReFuelEU Aviation regulation [7]. The Jet A-1 supply projections for 2030 and 2050 are based on EUROCONTROL's main report, using the base case scenario, which predicts a 14% increase in flight activity over 2019 levels by 2030 and a 44% increase by 2050 [4]. The analysis then assessed whether the SAF quantities required to meet the ReFuelEU regulation targets for 2030 and 2050 would be sufficient to satisfy demand. In Stage 3, potential sites for the pyrolysis plant are identified by calculating a trade-off score that balances feedstock capacity and DNI. First, the transportation cost of feedstock is calculated and normalized for different regions, taking into account straw availability and a distance constraint of up to 150 km. Then, a combined score function is applied to compute a trade-off score, incorporating the two normalized factors: transportation cost and DNI. This function helps assess how transportation costs and solar energy potential contribute to the overall system performance, allowing for a balanced decision. The weights used for this evaluation were 0.7 for transportation cost and 0.3 for DNI. The function operates by multiplying the normalized transportation and DNI scores by their respective weights, and then summing them to obtain the final trade-off score. This score, which ranges from 0 to 1 (assuming normalized scores between 0 and 1), provides an integrated metric where 0 represents the least favorable scenario (either high transportation costs or low solar potential) and 1 indicates the optimal combination (low transportation costs and high solar potential).
The combined score is calculated as:

$$\text{Combined score} = (\text{weight transport} \times \text{transportation normalized}) + (\text{weight DNI} \times \text{DNI normalized}) \quad (4)$$

For the final selection of plant sites, a two-thirds capacity constraint was implemented to ensure that each selected plant receives a minimum amount of straw to maintain operational efficiency. By enforcing this threshold, the algorithm avoids underutilized plants and prioritizes locations with sufficient biomass supply.

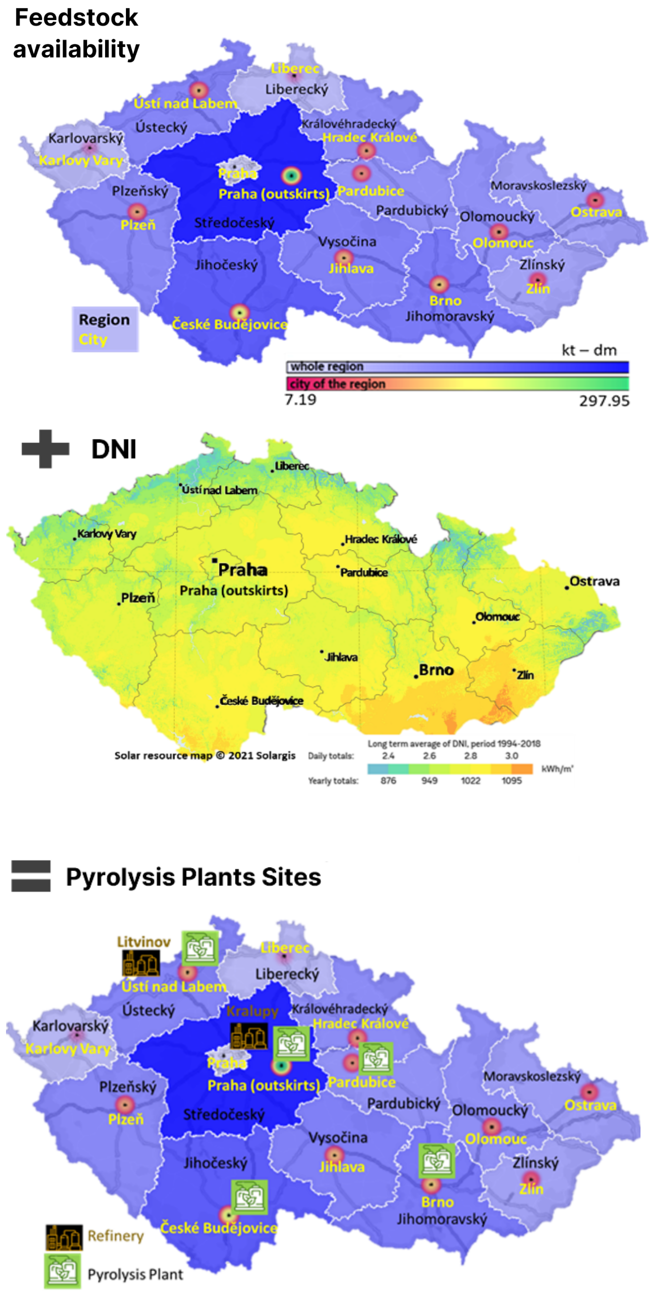

Figure 2. Selected pyrolysis plant sites, by using a trade-off score between feedstock capacity and DNI for 2030.

Mennicken et al. reported that when calculating transportation costs in Europe using straight-line distances, it is recommended to apply a correction factor (detour index) ranging from 1.1 to 1.3. In this study, a correction factor of 1.1 was applied [13]. In Stage 4, the supply chain network model was run to provide the optimal allocation of feedstock to the potential pyrolysis plant sites and bio-oil to the nearest refinery. Finally, the OPEX, CAPEX breakdown, Revenues per site, and SAF replacement satisfaction in 2030 and 2050 were calculated.

Supply Chain Network Model

The model in this study represents a three-stage supply chain for converting feedstock into SAF. It begins with straw collection from the regions, then transported to a storage facility where it is stored until needed for processing, which is located in the plant site area. The available straw of each region is transported to one plant site only. At the plant site, the feedstock undergoes initial treatment processes to prepare it for pyrolysis. Solar energy is utilized to support sustainable operations at the plant. In the pyrolysis plant, a wastewater treatment plant is located for treating the aqueous phase, where the purified water is used in the electrolysis. The pyrolysis plant includes two upgrading steps to begin refining the pyrolysis oil. Following the upgrading process, the resulting bio-oil is transported to the nearest refinery, where it undergoes further processing in a distillation column to produce biofuels, including SAF, biodiesel, and biogasoline. Each stage of the supply chain is interconnected through truck transportation, with transportation costs calculated in both directions. A 30% discount is applied to return trips. For this study, a plant capacity of 300 kt was assumed. It is assumed that the available straw in each region is concentrated at the regional city center to facilitate the calculation of distances. The plant sites are established in regions with the highest combined scores and are designated according to the names of these regions.

The objective function seeks to minimize the total costs, which include feedstock, transportation, storage, operational, and capital expenditure costs associated with pyrolysis plants, while accounting for the revenue generated from biochar and SAF.

Index Sets:

R = {r|region in the country}

RF = {rf| refinery in the county}

Decision Variables:

X_r = 1 if r has a plant, otherwise 0

$Y_{r,r'}$ = 1 if the straw is transported from region r' to plant in region r, otherwise 0.

$Z_{r,rf}$ = 1 if HDO from r is transported to rf; otherwise, 0.

Parameters:

DNI_r = Direct Normal Irradiance at a region

S_r = biomass availability in a region

S_p = available straw in a plant

$TC_{r,r'}$ = Full-truck transport cost per km with TC capacity

TC = Truck capacity (tn)

$CT_{r,r'}$ = Transportation cost per km per tn ($TC_{r,r'}$ / TC)

$D_{2,r,r'}$ = Two directions distance between r and r' ϵ R

BD = Bulk density of biomass (kg/m³)

SC = Storage and loading cost per m³

CAP = Maximum straw processing plant capacity (kt)

CAP_{rf} = Maximum refinery capacity (bbl)

$TC_{r,rf}$ = Transportation cost per km of a full tanker truck with TTC capacity

TTC = Tanker truck capacity (gallons)

$CT_{r,rf}$ = Transportation cost per km per bbl ($TC_{r,rf}$ / TTC*α)

$D_{2,r,rf}$ = Two directions distance between regions r and rf ϵ R

HDO = bio-oil (bbl)

α = Convector factor from gallons to barrels

γ = Conversion factor for SAF

δ = Conversion factor for HDO

Biochar and SAF selling price (€)

Objective function:

$$min[\sum_{\substack{r,r' \in R \\ r\neq r'}} \mathrm{r, r' \, Yr, r'} * S_r * D_{2r,r'} * CT_{r,r'} + \sum_r BD * S_p * SC + \sum_{r,rf} Z_{r,rf} * HDO_r * D_{2,r,rf} * CT_{r,rf} + \sum_r (OPEX + CAPEX)] - \sum_r (Biochar\ revenues + SAF\ reveneues)] \quad (5)$$

Constraints:

Feedstock Supply: $S_{min} * Y_r \leq \sum_r X_r * S_r \leq S_{max} * Y_r, \forall r$ (6)

Region Supply: $\sum_r X_r \leq 1, \forall r$ (7)

Ensures that each region supplies biomass to only one plant.

Straw Utilization: $\sum_r S_p \leq \sum_r S_r$ (8)

Ensures the straw used in all plants does not exceed the total straw supply.

Straw Allocation: $\sum_r Y_{r,r'} * S_r \leq CAP, \forall r$ (9)

Ensures that the allocation of straw from each region to a plant does not exceed the plant's capacity.

Trade-off Score: X_r * Combined score ≥ Tmin (10)

Two-Thirds Plant Capacity: $S_r \geq 2/3 * Smax, \forall r$ (11)

Transportation Distance: $D_{r,r'} \leq 150, \forall Y_{r,r'}=1$ (12)

Ensures transportation distances do not exceed 150 km for regions where biomass is transported.

SAF Production: $\sum_r \gamma * S_p \geq$ SAF DEMAND (13)

Ensures that the total SAF production meets the demand.

HDO Refinery Capacity: $\sum_r \delta * S_p \leq \sum_{rf} CAP_{rf}$ (14)

Ensures that the HDO produced at all plants does not exceed the total refinery capacity.

Refinery Transportation: $\sum_{rf} Z_{r,rf} = 1, \forall p$ (15)

Ensures that each region where a plant is located sends its produced HDO to exactly one refinery.

Solar Collector Energy Production: energy produced by solar collectors must meet or exceed the daily thermal energy requirement for the pyrolysis process.

num collectors needed * energy per collector per day kWh ≥ total thermal energy kWh per day (16)

The installed electrolyzer and PV systems must be sufficient to meet the hydrogen production demand.

electrolyzer capacity kW ≥ (H_2 needed per year / operating hours per year) (17)

pv capacity kW ≥ [(H_2 needed per year * production efficiency)/operating hours per year] (18)

RESULTS

By executing the Supply Chain Network Model code in Python, the optimal locations for the pyrolysis plant in 2030 and 2050 for all the cases (AGR ±0.1% and ±0.2% from the historical data) and bio-oil transportation to the nearest refinery are presented in Figure 3.

In the short to mid-term (2030), the model does not exhibit sensitivity, as it selects the same plant sites. However, in the long term (2050), the model demonstrates sensitivity by selecting different plant sites. In all scenarios, the plant sites in Praha (outskirts) and České Budějovice are consistently chosen. Additionally, the results indicate a well-optimized and scalable pyrolysis-based SAF production system with high straw utilization (94–100%) across all cases, as presented in Table 1.

Refinery capacities remain sufficient to handle bio-oil production, supporting seamless integration into existing fuel infrastructure.

Despite fluctuations in biomass availability, SAF production consistently meets 6% and 35% of Jet A-1 fuel demand for 2030 and 2050 respectively, highlighting supply chain resilience.

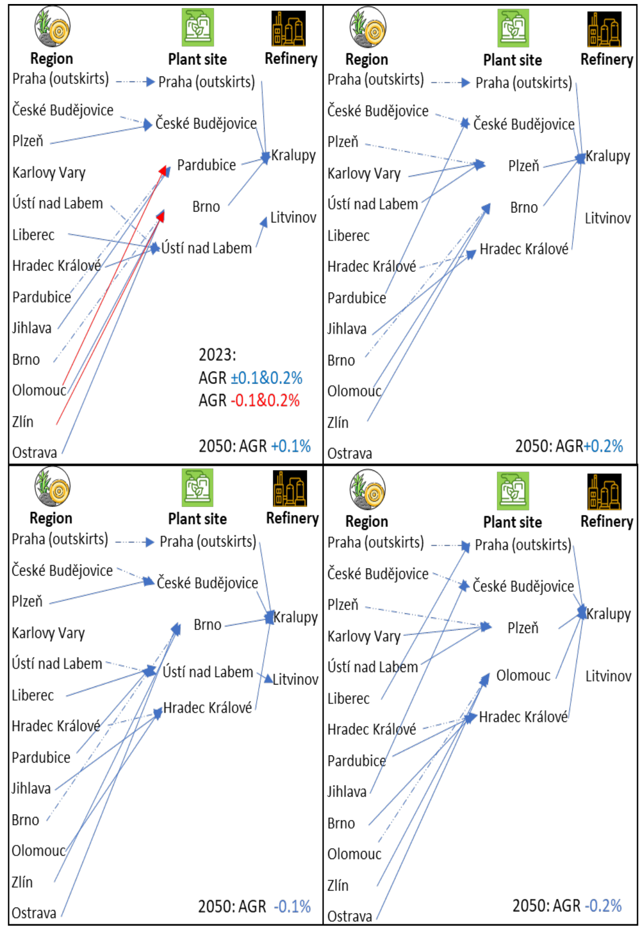

Figure 3. The three-supply chain network for 2030 and 2050. The dashed lines do not represent straw transportation but rather indicate that the straw from a region is utilized at the plant site located within the same region.

Table 1: Estimated wheat straw utilization and SAF production plant in 2030 and 2050 for all the cases.

	Straw Utilized %		SAF produced (kt)	
	2030	2050	2030	2050
AGR+0.1%	94.4%	94.4%	199.05	202.1
AGR -0.1%	98.6%	98.5%	204.3	200.1
AGR+0.2%	94.4%	93.7%	200.1	205.2
AGR -0.2%	98.5%	100%	202.5	197.4

Total cost shows a downward trend over time, suggesting improved cost efficiency due to technological advancements. Specifically, in 2030 cases the economic feasibility is maintained, with total costs ranging from €755M to €884M, while biochar and SAF revenues contribute up to €214M, while in 2050 cases the total costs vary between €542M and €613M, while biochar and SAF revenues contribute up to €319M, ensuring economic feasibility. Praha (outskirts) consistently emerges as the most economically viable plant site location for all the cases. Solar collectors play a crucial role in meeting heat demand, reducing external energy dependence, and ensuring sustainability.

Overall, the analysis confirms that the current strategy is robust, adaptable, and viable for long-term SAF production, while also highlighting a cost-effective approach with strong long-term profitability and energy security.

CONCLUSION

This study confirms that SAF production in the Czech Republic is both technically and economically viable. The total costs are projected to decline by up to 30.64% from 2030 to 2050, while revenues are estimated to increase by approximately 49.07% over the same period. Strategic site selection based on feedstock availability, transportation costs, and solar energy potential enhances efficiency, with Praha outskirts emerging as a key production hub. CAPEX and OPEX (total cost) estimates show declining costs over time, especially with advancements in solar collectors and energy efficiency improvements.

The results align with EU decarbonization goals, demonstrating that SAF, supported by optimized supply chain networks, can play a pivotal role in reducing aviation emissions. Continued investment in SAF infrastructure, technological advancements, and regulatory support will be essential to ensuring a sustainable and cost-effective transition to greener aviation fuels.

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