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Life Cycle Assessment of Waste Oil-to-Jet Fuel Production via the HEFA Process with Integrated Co-generation

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Abstract

To reduce the reliance on external electricity and hydrogen in the hydroprocessing of waste oils for sustainable aviation fuel (SAF), this study adopts life cycle assessment (LCA) to compare the conventional HEFA process and the HEFA-PG process integrated with combined heat and power, and analyzes their environmental performance under power grid decarbonization and green hydrogen substitution scenarios. Taking 100 tonnes of bio-jet fuel as the functional unit, Aspen Plus simulation and the ReCiPe 2016 model are used to calculate environmental burdens. The results show that both bio-jet fuel pathways have far lower carbon footprints than fossil aviation kerosene. The HEFA-PG process delivers prominent emission reduction benefits through co-generated electricity, yet its carbon mitigation gains gradually decline with deep power grid decarbonization. Although wind-powered electrolytic hydrogen reduces carbon emissions, it leads to remarkably higher human toxicity potential (HTP), which mainly originates from the environmental loads of off-site sulfide tailings generated during wind power equipment manufacturing. Under current technical conditions, hydrogen produced via natural gas reforming presents superior comprehensive environmental performance. The toxicity drawbacks of electrolytic hydrogen can only be alleviated by cleaner production of wind power equipment or reasonable allocation of environmental burdens among co-products. Feedstock collection and transportation as well as hydrogen production are core environmental hotspots, and the HEFA-PG process is more applicable to low-carbon applications in the near and medium term of energy transition.

Keywords: Sustainable Aviation Fuel (SAF); HEFA process; Life Cycle Assessment (LCA); green electricity; green hydrogen.

1. Introduction

To quantitatively compare the environmental sustainability of two waste oil-to-SAF pathways, this study establishes life cycle inventory (LCI) datasets for the conventional HEFA and HEFA-PG routes integrated with combined heat and power, whose system boundaries are clearly defined based on Aspen Plus process simulation and standardized LCA methodologies. LCA outcomes of fossil aviation kerosene are introduced as a comparative benchmark to highlight the environmental merits and practical viability of the HEFA-PG design. Furthermore, the environmental performance of both pathways under diversified energy transition scenarios is analyzed against the backdrop of China's ongoing energy mix decarbonization.

2. LCA Modeling for Waste Oil-Derived SAF Production

2.1 System Boundaries and Core Assumptions for LCA

This study focuses on bio-jet fuel and adopts a cradle-to-grave system boundary, covering all major stages, including the collection and transportation of waste oils, the production of aviation fuel, and its distribution and end-use in aviation.

For the HEFA-PG system, the analysis also includes the environmental impacts of the combined heat and power unit. The electricity exported from this cogeneration system can offset grid electricity generated by conventional power plants, thereby providing a carbon credit through displacement.

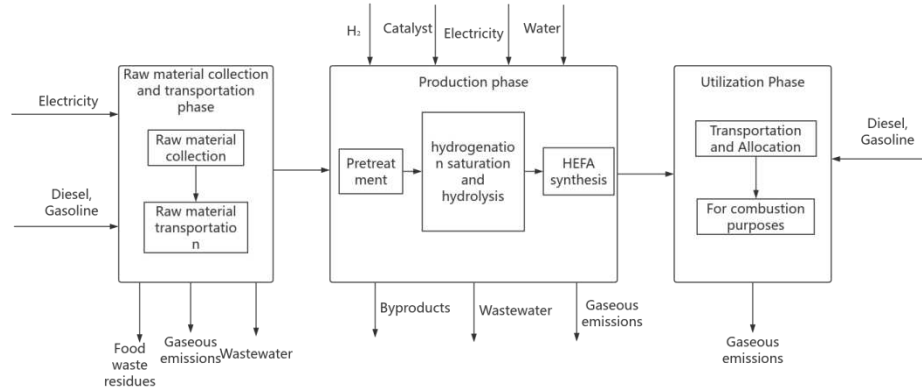


Figure 2-1 System boundary of LCA for HEFA process

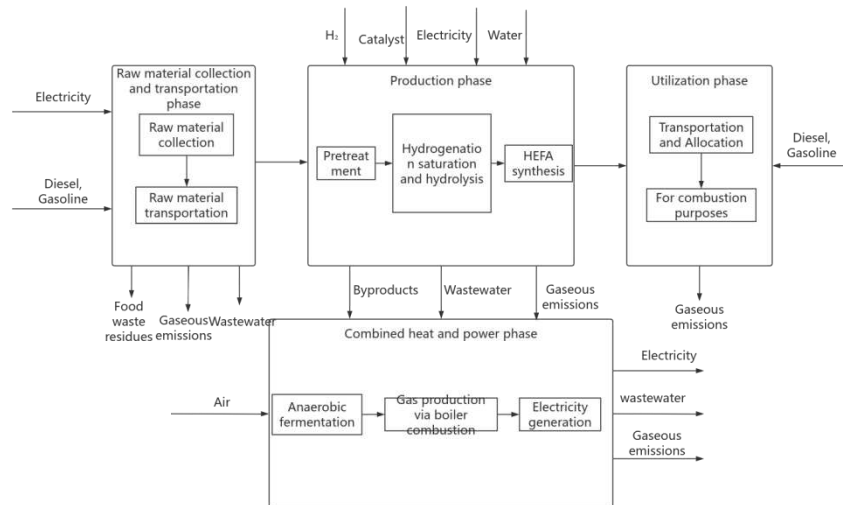


Figure 2-2 System boundary of LCA for HEFA-PG process

Figure 2-1 and Figure 2-2 illustrate the LCA system boundaries for the HEFA and HEFA-PG processes, respectively. In this study, waste cooking oil is used as the feedstock[1]. In the HEFA process, the collection and transportation stage primarily involves the gathering and logistics of waste cooking oil. The input inventory includes resource consumption such as electricity and water, as well as diesel fuel used by tanker trucks. The production stage includes pretreatment of waste oils, hydrogenation, and hydroprocessing steps. The input inventory encompasses key resources, including catalysts, hydrogen, and electricity. In the use stage, the input inventory mainly consists of diesel consumption by tank trucks during the distribution of bio-jet fuel. In addition to the

stages described above, the HEFA-PG pathway also includes a combined heat and power stage, whose primary input is air.

In addition, the core assumptions adopted for the LCA modeling are summarized as follows: (1) In LCA practice for petrochemical and biorefining systems, the design lifetime of production facilities and associated infrastructure is typically 20–30 years. Environmental emissions and material consumption from the construction phase are therefore allocated to the functional unit through depreciation over the plant's service life. The contribution of such capital investment to key impact indicators is generally below 2–3% [2]. Accordingly, emissions and energy use associated with system construction are excluded from the life cycle inventory in this study. (2) Carbon dioxide emissions from the combustion of bio-jet fuel are considered biogenic carbon and are therefore excluded from the LCA. (3) This study adopts the Beijing–Tianjin–Hebei region as the geographical system boundary for analyzing the production and use of bio-jet fuel.

2.2 Life Cycle Assessment Methodology

This study follows the ISO 14040 framework [3] and implements a four-stage LCA procedure: (1) The functional unit is defined as 100 tonnes of bio-jet fuel; (2) Development of a full life cycle inventory covering all material inputs and emission outputs; (3) The ReCiPe 2016 method [4] is adopted to conduct environmental impact assessment, covering six midpoint indicators: global warming potential (GWP), particulate matter formation potential (PMFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), human toxicity potential (HTP), and fossil fuel depletion potential (FFP)—as well as three endpoint indicators, namely resource availability (RA), ecosystem diversity (ED), and human health (HH); (4) Contribution analysis is conducted to identify key pollution hotspots within the system, and based on these results, targeted improvement recommendations were proposed.

2.3 Life Cycle Inventory Analysis

Based on the production characteristics of the HEFA and HEFA-PG processes, and following the allocation hierarchy principles defined in ISO LCA standards, an appropriate allocation method is selected for this study [5]. In the conventional HEFA process, by-products such as naphtha are entirely exported for external utilization and are therefore treated as outside the system boundary. Accordingly, a mass-based allocation method with strong stability and applicability is adopted to separate and allocate the environmental burdens associated with these co-products. In contrast, all by-products in the HEFA-PG process are internally utilized for combined heat and power generation, enabling a closed-loop energy use system with no external export of surplus co-products. Therefore, no mass allocation is required in this case [6]. In addition, electricity generated from co-production is accounted for using an avoided burden (substitution) approach. The displaced electricity is benchmarked against the average emission factor of the North China regional power grid, enabling the assessment results to more accurately reflect real-world production conditions.

(1) Collection and transportation of waste cooking oil stage

This study defines two transportation scenarios. For urban collection, waste cooking oil is collected directly from restaurants using collection trucks, with a designated collection radius of 40 km. For cross-city transportation within the Beijing–Tianjin–Hebei

region, feedstock transfer relies on the trunk logistics network, using tanker truck transportation with an average haul distance of 200 km [7]. Because the collected catering waste contains significant solid impurities and free water, it does not meet the feedstock requirements for bio-jet fuel production. Therefore, centrifugal separation technology is employed for feedstock pretreatment. The centrifuge was operated under industrial operating parameters: the installed power of the centrifuge is 90 kW, with a processing capacity of 60m³/h. The measured material balance indicates that 10 tonnes of catering waste produce 1 tonne of refined waste cooking oil after centrifugal pretreatment[8]. During the collection and transportation stage, water is also used for cleaning the collection and tanker vehicles. However, due to the relatively small quantity involved, its environmental impact is considered negligible and is therefore excluded from the analysis[9]. Based on process simulation data obtained from Aspen, this study adopts a mass-based yield of 59.2% derived from Aspen Plus modeling results. By integrating parameters such as transportation, pretreatment, and conversion efficiency, the energy consumption and environmental emissions of the pretreatment stage are calculated. The relevant data are summarized in Table 2-1.

Table 2-1 Inventory Analysis of the Waste Cooking Oil Collection and Transportation Stage

	Category	HEFA	HEFA-PG	Unit
Inputs:	Catering waste	1554.79	1691.68	t
	Tanker truck transportation	264314.30	287585.60	t×km
	Electricity	2332.19	2537.52	kWh
	Collection vehicles	9328.74	10150.08	t×km
Outputs:	Waste cooking oil	155.48	169.17	t
	Other catering waste	1399.31	1522.51	m ³

(2) Production stage

Material input and output data for the production stage are derived from Aspen Plus process simulations. The simulations indicate that, for the HEFA process, the mass ratio of bio-jet fuel to by-products is approximately 91.9:8.1, as detailed in Table 2-2.

Table 2-2 Life Cycle Inventory Analysis of the Production Stage

	Category	HEFA	HEFA-PG	Unit
Inputs:	Waste cooking oil	155.47	169.17	t
	hydrogen	4.44	4.83	t
	Catalyst	2.82	3.07	t
	Industrial water	6.45	7.02	t
	Electricity from the external grid	4579.3	4983	kWh
Outputs:	Bio-jet fuel	100	100	t

	Industrial wastewater	32.37	-	t
	Solid waste emissions	27.497	17.86	t

(3) Distribution and Use Stage

In constructing the aviation fuel distribution model, this study performed scenario fitting based on the actual infrastructure layout and market consumption structure of the Beijing–Tianjin–Hebei aviation cluster. Within the Beijing–Tianjin–Hebei region, the Beijing “dual-hub” airports (Beijing Capital International Airport and Beijing Daxing International Airport) account for more than 80% of the region’s total aviation kerosene consumption[10]. Given the extremely large fuel demand, it is difficult to meet supply solely through tanker truck transportation; therefore, the system relies heavily on pipeline transport. Accordingly, it is assumed that 80% of the total fuel output is transported via pipelines, based on the regional aviation fuel consumption structure. The remaining 20% of production capacity is allocated to meet demand from local airports in Tianjin and airports in Hebei Province, where distribution is primarily carried out via tanker trucks.

In terms of transport distance, based on the real-world “Tianjin–Beijing oil pipeline,” the straight-line distance from Tianjin’s aviation fuel refining and distribution hub to Beijing Capital International Airport or Beijing Daxing International Airport is approximately 120–140 km. Considering that underground pipeline routing must avoid sensitive areas, the actual installed pipeline length is typically 150–180 km. This study adopts a median value of 160 km as the representative pipeline haul distance[11]. For road transportation, the distance from the Tianjin Nangang/Lingang refinery to Tianjin Binhai International Airport is approximately 40–60 km, compared with 200–300 km for destinations in Hebei Province. Considering that tanker truck transportation is mainly concentrated in short-haul distribution around Tianjin and suburban Beijing transfer hubs, while long-distance deliveries to Hebei are relatively limited in frequency and volume, this study applies a volume-weighted average of short-distance (approximately 50 km) and limited medium-to-long-distance (approximately 250 km) transport. The resulting average road distribution radius is approximately 100 km[12]. The corresponding inventory data are summarized in Table 2-3.

Table 2-3 Life Cycle Inventory Analysis of the Distribution and Use Stage

	Category	HEFA	HEFA-PG	Unit
Inputs:	Pipeline transportation	12800	12800	t×km
	Tanker truck transportation	2000	2000	t×km
Outputs:	CO ₂	315	315	t
	NO _x	1.25	1.25	t
	H ₂ O	123	123	t
	SO ₂	0.05	0.05	t

3 LCA Results and Comparative Environmental Analysis

3.1 Stage-Wise Environmental Contribution of Two SAF Pathways

To comprehensively evaluate the potential environmental benefits of process improvements, this study conducted a multi-dimensional environmental impact contribution analysis of the conventional HEFA process and the improved HEFA-PG co-production process. Figures 3-1 and 3-2 respectively illustrate the distribution and contrast of environmental impact indicators over all life cycle stages of the two production pathways.

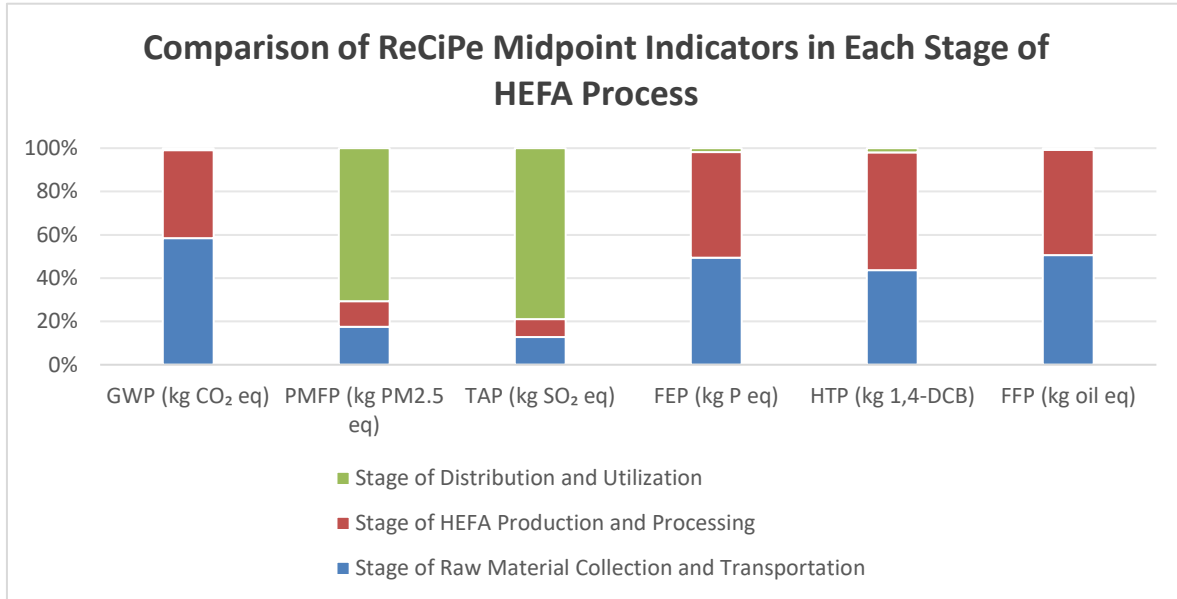


Figure 3-1 Comparison of ReCiPe midpoint indicators across different stages of the HEFA process

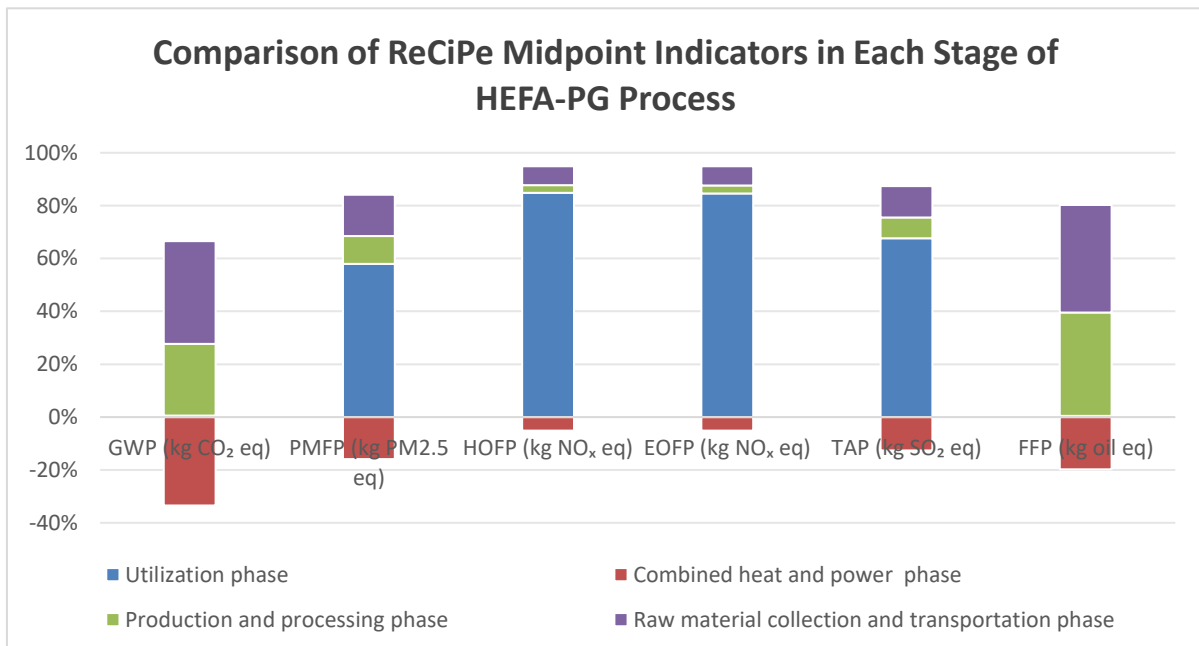


Figure 3-2 Comparison of ReCiPe midpoint indicators across different stages of the HEFA-PG process

For the environmental impacts of the HEFA process, GWP, FEP, and FFP are primarily dominated by the feedstock collection and transportation stage, with each contributing more than 50%. In contrast, due to the inevitable formation of nitrogen oxides and fine particulate matter during high-temperature aviation fuel combustion, this stage contributes approximately 70% of PMFP and 80% of TAP. In comparison, the HEFA-PG process achieves stable green electricity output, thereby generating a significant negative-emission effect during the combined heat and power stage. Comparative results show that the system's net GWP footprint is reduced from the baseline 100% to approximately 66%. Meanwhile, for FEP, HTP, and FFP, the combined heat and power stage provides an offset effect of about 35% for each indicator.

3.2 Benchmark Comparison with Conventional Fossil Aviation Kerosene

To provide an intuitive comparison of the environmental impacts of the HEFA and HEFA-PG processes, fossil-based aviation kerosene is introduced as a reference baseline. Using the ReCiPe 2016 method, a comparative assessment is conducted from both midpoint and endpoint perspectives[13]. The fossil-based aviation kerosene scenario includes crude oil extraction, atmospheric and vacuum distillation, hydrocracking, and product distribution and use. The inventory data are obtained from the Ecoinvent database within the SimaPro software[14]. All three pathways were evaluated with 100 tonnes of aviation fuel as the functional unit for environmental impact comparison.

3.2.1 Life Cycle Inventory of Conventional Aviation Fuel Production and Bio-jet Fuel Distribution

The life cycle boundary of fossil-based aviation kerosene includes four stages: crude oil extraction, overseas transportation, refinery processing, and finished fuel distribution and use. Among these, the crude oil transportation stage is a major contributor to the overall life cycle environmental impacts[15]. This study defines transportation parameters based on China's crude oil import structure, approximately 90% of which is transported via long-distance maritime tankers, primarily sourced from the Middle East, Africa, the Americas, and Russia, with a weighted average shipping distance of about 13,500 km. The remaining 10% is imported via pipelines, represented by major routes such as the China–Russia, China–Myanmar, and China–Kazakhstan pipelines, with a weighted average transport distance of about 1,800 km. For the finished fuel distribution stage, this study refers to the actual transportation pattern from major domestic refineries to primary airports, assuming that pipeline transportation accounts for 50% with an average distance of 100 km, while railway transportation accounts for the remaining 50% with an average distance of 1,100 km[16]. These parameters are used as input data for the life cycle inventory of fossil-based aviation kerosene, enabling comparative assessment with the HEFA and HEFA-PG processes.

3.2.2 Comparative Analysis of Sustainable Bio-jet Fuel and Conventional Aviation Fuel Production Processes

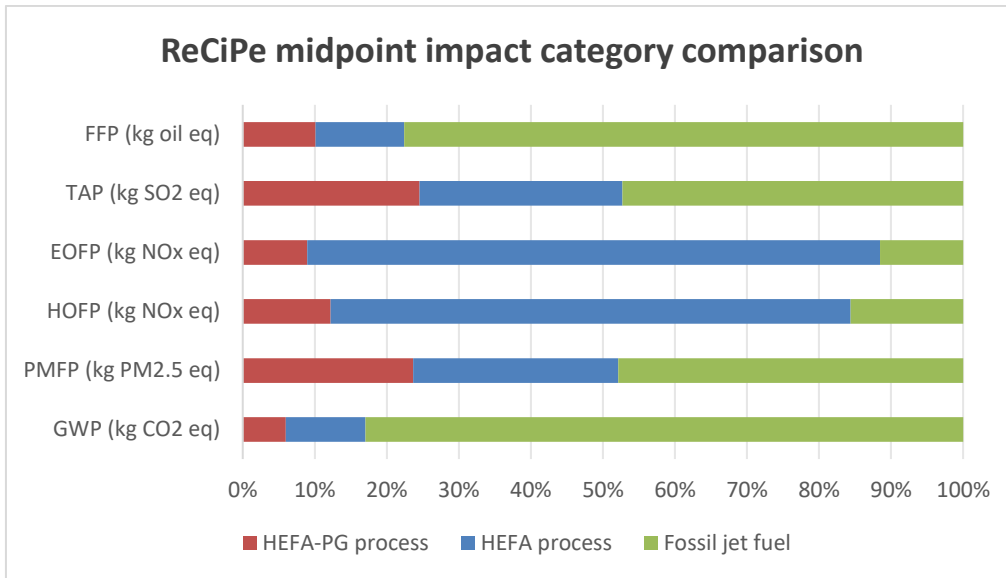


Figure 3-3 Comparison of ReCiPe midpoint environmental impact indicators for different aviation fuel production pathways

Based on Figure 3-3, both HEFA and HEFA-PG bio-based aviation fuel pathways show significant advantages over fossil-based aviation kerosene in terms of GWP and FFP, with GWP values reduced to 13.3% and 7.2%, respectively, and a consistent reduction trend observed for FFP. For ozone formation-related indicators, HEFA-PG demonstrates the most notable improvement: in the conventional HEFA process, reliance on externally purchased electricity leads to EOFP and HOFP contributions as high as 80%. With the introduction of combined heat and power, self-supplied green electricity is achieved, reducing the overall contribution to approximately 10% and significantly mitigating ground-level ozone formation. TAP and PMFP follow a descending order of fossil fuel > HEFA > HEFA-PG, indicating progressively lower environmental burdens across the three pathways.

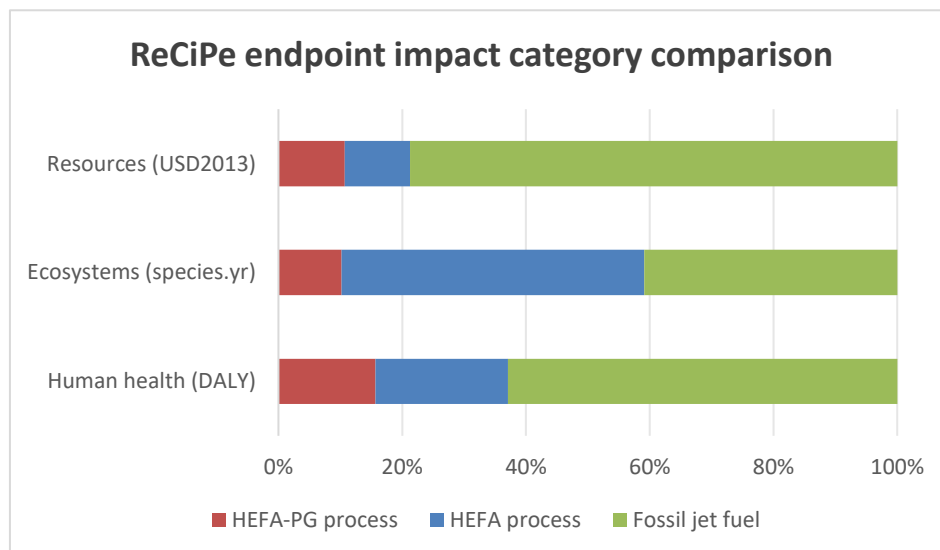


Figure 3-4 Comparison of ReCiPe endpoint environmental impact indicators for different aviation fuel production pathways

Based on Figure 3-4, the depletion of non-renewable resources accounts for 13.4% and 13.6% for the HEFA and HEFA-PG processes, respectively. HEFA-PG demonstrates a clear advantage in Ecosystem Quality, with its contribution reduced to 10%, primarily due to green electricity self-sufficiency and credits from coal power substitution. Human health impacts follow the order of fossil-based aviation kerosene > HEFA > HEFA-PG, indicating progressively lower health burdens. The HEFA-PG pathway further reduces population health risks through process integration and heat utilization optimization.

3.3 Sensitivity Analysis of Power Grid Decarbonization Scenarios

Against the backdrop of carbon neutrality, the Chinese government is actively promoting the development of green electricity[17][18]. Electricity is a key sensitive parameter in the life cycle of bio-jet fuel production. To further advance sustainable development and achieve carbon neutrality targets[19], this study constructs a time-series framework based on projected changes in China's power generation mix for 2030, 2040, 2050, and 2060. Three electricity scenarios—thermal power, wind power, and solar power—are considered[20]. This framework aims to investigate how the transition of the national energy structure at the macro level influences the overall environmental performance of the two production pathways. Since this study focuses on the structural evolution among three electricity generation types—thermal power, wind power, and solar power—other sources such as hydropower, nuclear power, and biomass are excluded from the analysis. Therefore, the original data are normalized accordingly, and the results are presented in Table 3-1.

Table 3-1 Normalized Shares of Different Power Generation Types from 2030 to 2060

Year	Thermal Power	Wind Power	Solar Power
2030	46.8%	23.3%	29.9%
2040	27.4%	29.8%	42.9%
2050	11.1%	34.6%	54.3%
2060	4.8%	37.8%	57.4%

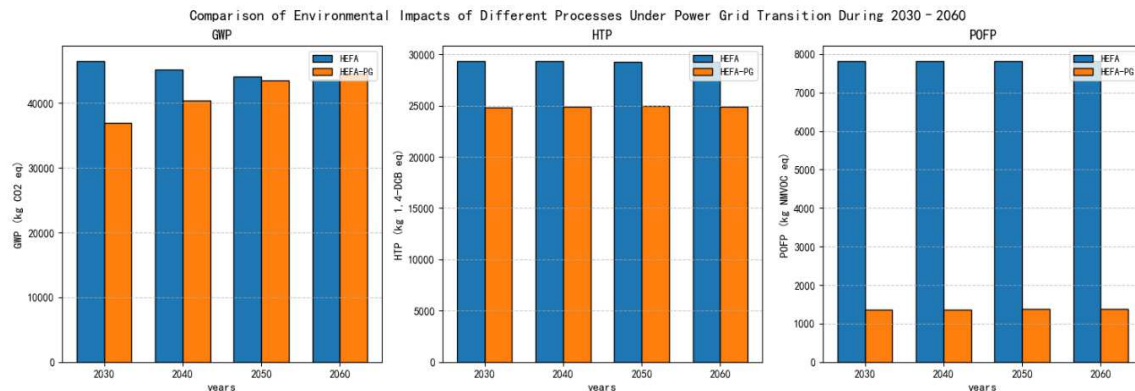


Figure 3-5 illustrates the evolution trends and divergence characteristics of HEFA and HEFA-PG processes in terms of GWP, HTP, and POFP in the context of power grid decarbonization from 2030 to 2060.

For GWP, as the electricity mix becomes progressively cleaner, the HEFA process shows a gradual decline due to the reduced carbon intensity of purchased electricity. In contrast, the GWP of the HEFA-PG co-production pathway increases year by year, driven

by the diminishing carbon credit benefit from co-generated electricity, and eventually surpasses that of HEFA around 2060.

In comparison, HTP is relatively insensitive to electricity decarbonization, as its environmental burden is mainly concentrated in waste oil collection and pretreatment, as well as hydrogen production. Through process integration and substitution of fossil-based electricity with internally generated power, HEFA-PG significantly reduces upstream toxic emissions and associated health impacts from the power supply chain, thereby achieving a marked reduction in HTP.

Regarding POFP, its key precursors are primarily derived from external fuel combustion for energy supply. HEFA-PG substantially reduces the consumption of external high-emission fuels through internal energy cascading, achieving a reduction of over 80% in POFP. This advantage is particularly pronounced and remains robust regardless of the decarbonization of the power grid.

3.4 Sensitivity Analysis of Green Hydrogen Substitution Scenarios

Currently, hydrogen production via natural gas reforming and coal gasification significantly increases the overall life cycle environmental impacts of aviation kerosene production. To further explore the deep decarbonization potential of the system, the introduction of renewable green hydrogen has become an important direction for process optimization. This study defines a “green hydrogen scenario” based on water electrolysis hydrogen production, replacing the baseline natural gas reforming hydrogen pathway, in order to conduct comparative environmental benefit assessment and sensitivity analysis [21]. The system boundaries for both hydrogen production pathways remain consistent, encompassing both infrastructure construction and the operational production stage. It is assumed that the produced hydrogen is directly fed into the bio-jet fuel production process within the plant, and subsequent steps such as hydrogen compression, storage, and long-distance transportation are excluded from the system boundary [22]. In terms of life cycle modeling, the hydrogen production module is uniformly constructed in the SimaPro software. Upstream background inventory data regarding energy and raw material consumption are retrieved from the Ecoinvent database, where the RoW dataset is selected as the baseline background system. Based on the previous analysis of macro-level power system transitions, this scenario assumes that all electricity used for water electrolysis is supplied exclusively by wind power.

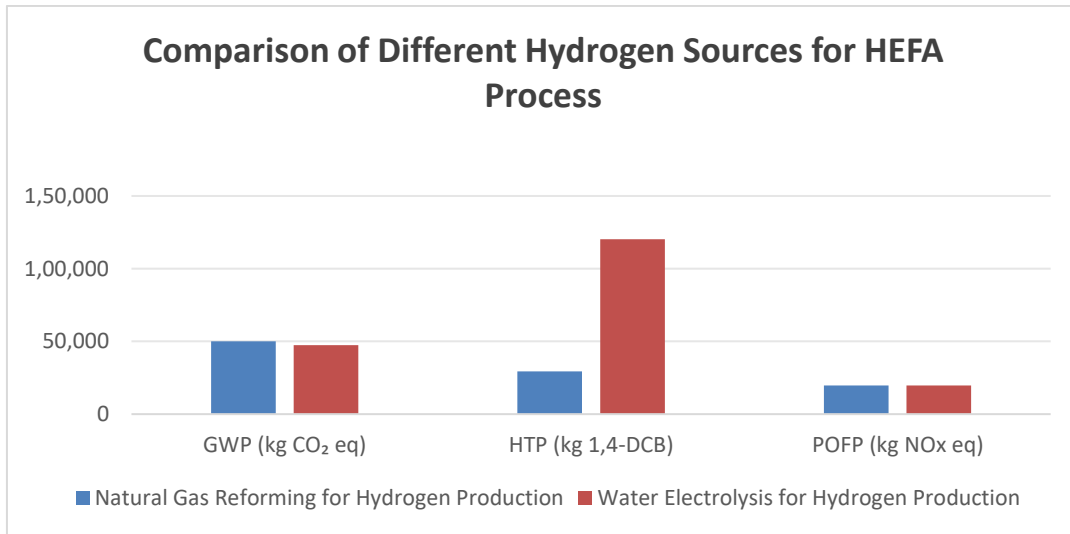


Figure 3-6 Environmental impacts of different hydrogen inputs in the HEFA process

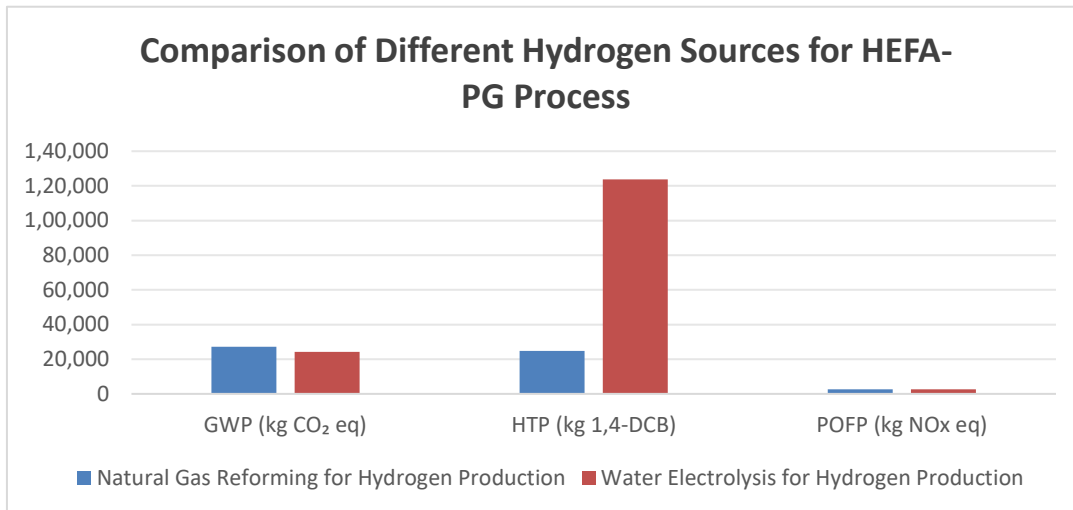


Figure 3-7 Environmental impacts of different hydrogen inputs in the HEFA-PG process

From the LCA results shown in Figure 3-6 and Figure 3-7, it is evident that the HEFA-PG co-production system demonstrates substantial environmental advantages in both climate mitigation and air quality improvement dimensions. Regardless of the hydrogen production pathway adopted, HEFA-PG reduces the life cycle GWP by nearly 50% compared to the baseline HEFA process. Meanwhile, the POFP is significantly reduced by approximately 86%.

These results indicate that the HEFA-PG process not only effectively replaces externally purchased high-carbon grid electricity, thereby substantially reducing indirect carbon emissions, but also avoids ozone-related emissions associated with by-product disposal, achieving dual benefits in carbon reduction and pollutant mitigation.

On this basis, the introduction of water electrolysis hydrogen further enhances the system's low-carbon potential, leading to additional optimization of the GWP indicator for both pathways. However, despite its advantages in carbon reduction and ozone control, electrolysis-based hydrogen production exhibits a notable limitation in terms of HTP.

Under both process configurations, HTP increases to more than four times that of the natural gas reforming hydrogen scenario.

Although wind power is used to drive electrolysis, the upstream manufacturing of large-scale wind turbines involves energy-intensive metal extraction and smelting processes, which are associated with significant toxic emissions such as heavy metal wastewater and mining tailings. This burden is further amplified in the HEFA-PG system due to the absence of co-product allocation that could otherwise offset environmental impacts[23].

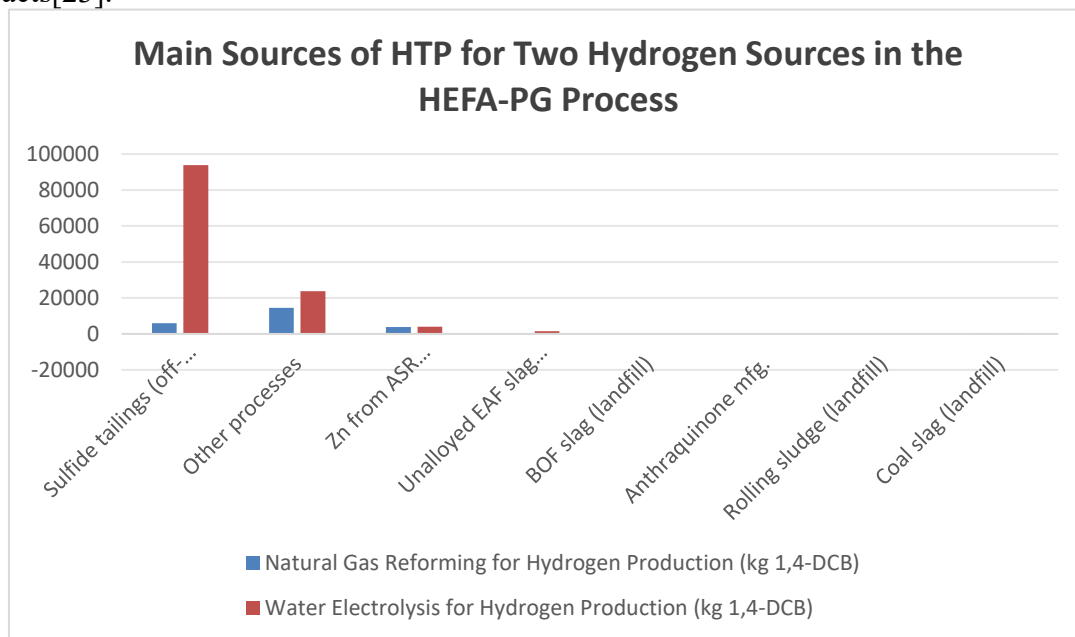


Figure 3-8 Environmental impacts of different hydrogen inputs in the HEFA-PG process

From the LCA results presented in Figure 3-8, it can be concluded that the human toxicity potential (HTP) of hydrogen produced via water electrolysis is considerably higher than that of hydrogen derived from natural gas reforming. This performance gap primarily originates from the environmental contributions associated with the off-site sulfide tailings disposal stage. Therefore, under current technical conditions, hydrogen from natural gas reforming delivers superior overall environmental performance within the HEFA-PG system. The toxicity disadvantage of electrolytic hydrogen can only be mitigated in two scenarios: first, the achievement of cleaner manufacturing for wind power facilities (e.g., low-carbon metallurgy and toxic emissions control), and second, the adjustment of production frameworks to enable the allocation of environmental burdens among multiple co-products.

3 Conclusions

This study employed an LCA approach to systematically compare the environmental impacts of the HEFA process, the HEFA-PG co-production process, and conventional fossil-based aviation kerosene. The analysis focused on the distribution of pollutants, emission sources, and upstream–downstream burden characteristics across the industrial chain. In addition, the study projected the evolution of environmental performance for the

HEFA and HEFA-PG pathways under future electricity grid transition scenarios. The main conclusions are as follows:

(1) For the conventional HEFA process, the feedstock collection and transportation stage dominate the overall GWP, FEP and FFP environmental burdens, whereas PMFP and TAP impacts mainly stemmed from fuel combustion at the end-use stage. While PMFP and TAP are dominated by combustion emissions during the fuel use phase. In contrast, the HEFA-PG process generates a significant avoided-emission effect through combined heat and power. The net GWP is reduced to 66% of the HEFA baseline. Meanwhile, FEP, HTP, and FFP achieve approximately 35% offset through electricity substitution effects, demonstrating substantially improved overall environmental performance compared with the conventional HEFA process.

(2) Compared with fossil-based aviation kerosene, the GWP of HEFA and HEFA-PG accounts for 13.3% and 7.2%, respectively, while FFP shows a consistent reduction trend. HEFA-PG achieves a reduction of approximately 70% in EOFP and HOFPP compared with HEFA. Both TAP and PMFP follow a decreasing order of fossil aviation kerosene > HEFA > HEFA-PG. The ReCiPe endpoint assessment further confirms that HEFA-PG achieves overall improvements across all three protection areas, including resource depletion, ecosystem damage, and human health impacts.

(3) Under the electricity grid decarbonization trajectory from 2030 to 2060, the carbon credit benefits of GWP in the HEFA-PG process gradually decline over time. In contrast, HTP remains largely insensitive to changes in the power mix and shows relatively stable variations. POFP is significantly reduced due to the avoidance of external fuel combustion enabled by the co-production configuration, demonstrating strong synergy in emission reductions.

(4) The introduction of electrolysis-based hydrogen can further reduce GWP; however, HTP values rose to over four times those observed under the natural gas reforming hydrogen production baseline scenario. Overall, the comparative assessment indicates that under current technological conditions, natural gas reforming hydrogen exhibits a more favorable overall environmental performance within the HEFA-PG system. Future improvements in the environmental performance of electrolysis hydrogen may be achieved if cleaner manufacturing of wind power equipment is realized or if co-product allocation mechanisms are introduced to distribute environmental burdens more effectively.

Statements & Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analysed during this study are included in this published article. The detailed inventory data of life cycle assessment and simulation results by Aspen Plus are available from the corresponding author on reasonable request.

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