Life Cycle Assessment Based Environmental Impact of NARA Bio-jet Fuel

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The Life Cycle Assessment (LCA) method was used to estimate the overall environmental impact associated with producing bio-jet fuel from recovered residual woody biomass, as well as any net reduction in emissions to the atmosphere achieved by displacing fossil fuel-based bio-jet fuel. LCA is an internationally recognized methodology to assess the environmental impacts of a product or activity over its entire life cycle. A comprehensive LCA of forest residue based aviation fuel was performed using a 'cradle-to-grave' approach where 'cradle' is defined as forest residues collected into slash piles in the forest and 'grave' is defined as the combustion of the jet fuel during flight in an aircraft. Utilizing a 'Woods-to-Wake' (WoTW) LCA approach, which is comparable to a Well-to-Wake (WTW) LCA for petroleum based aviation fuel, the environmental implications of feedstock recovery, production, and utilization of residual woody biomass based bio-jet fuel were assessed. A comparative assessment of the LCAs for petroleum based jet fuel and bio-jet fuel from woody biomass was then conducted to assess the overall environmental impact of substituting bio-jet fuel for fossil-based jet fuel.

System boundary

Identifying a system boundary is key to understanding the overall scope of the assessment as is identifying the processes that are included as part of the entire life cycle system and the assumptions specific to the system being assessed. The product system is woody biomass based bio-jet fuel whose function is to fuel an aircraft during flight. The functional unit of the system is 1 GJ of energy produced by fuel combustion. The study is based on a production facility which is scaled to produce 112,980 tons of IPK (bio jet fuel) using 700,000 bone dry metric tons of screened woody biomass. The overall system boundary for developing the LCA of the bio-jet-fuel consists of the following components: (i) feedstock collection and delivery to the conversion facility, (ii) calculating the carbon credit for the avoided carbon emissions derived from not burning the slash pile in the forest, (iii) conversion of the biomass to isoparaffinic jet fuel, and (iv) combustion of the bio-jet fuel in the jet engine. These individual components of the LCA process are explained in the following sections. A mass allocation between logs and the residual woody biomass (tops and branches) is used to identify the upstream environmental burdens associated with the piled woody biomass at harvest landing. In addition, two non-energy wood based co-products, activated carbon and lignosulphonate, are also produced during the production process. Another mass allocation was performed to allocate the environmental burdens associated with the bio-jet fuel, and the two co-products produced during the manufacturing process. The additional activities undertaken for value addition of the co-products are outside the bio-jet fuel system boundary and therefor are not considered.

Feedstock

Woody slash piles (a.k.a. harvest residues) at forest landings are generated during harvest operations, with a significant portion of the residual biomass being scattered around the forest floor during the harvest and skidding operations. Based on empirical time-motion studies, it is estimated that approximately 65% of the residual biomass is accumulated into slash piles located at the primary forest landings (Perez-Garcia et al. 2012) while the remaining 35% remains scattered across the forest floor. After factoring in the loss of biomass during the in-woods collection and grinding processes, it is estimated that only 58.5% of the total harvest residuals generated during the timber harvest operation will be delivered to the pre-treatment facility for conversion into biofuel.

This study assumes that the collection of residual biomass from the harvest landings will be used as the feedstock for bio-conversion into bio jet fuel. The biorefinery conversion facility is estimated to consume 700,000 bone dry metric tons of screened woody biomass annually. Assuming a 9% reject rate, the total feedstock demand is estimated to be 770,000 bone dry metric tons of unscreened residual woody feedstock per year delivered to the gate of the screening facility. Geographic location, regional forest type and topographic characteristics can influence the environmental impacts associated with collecting and transporting woody residues from the forest landing to the biomass processing facility. This paper focuses on the production of woody biomass in the Western Washington region. A mass allocation approach is used to account for the upstream burdens associated with the feedstock (including the harvesting, forwarding and skidding operations).

Avoided Slash Pile Burn Credit Framework

The feedstock used for producing bio-jet fuel is residual harvest slash left over from commercial timber harvest operations. Recovering harvest residues to produce bio-jet fuel results in avoided emissions attributed to the reduced amount of slash pile burning that occurs in the forest. Existing slash treatment options include burning of the slash pile or collecting, chipping and selling it as hog-fuel or pulpwood. Based on the WA biomass calculator ("Washington State Biomass Calculator. Available at: Http://wabiomass.cfr.washington.edu," n.d.), given the existing demand for residual biomass, a conservative estimate of the amount of biomass consumed in non-burn alternatives (excluding the biomass scattered on the forest floor) ranges from between 20 - 40%, depending on the location of the slash piles. Given the low demand for hog-fuel and pulpwood in the region, this would suggest that between 60 and 80% of the biomass in the slash pile is disposed of by pile burning. Based on ISO 14044 guidelines (ISO 2006b), the avoided environmental impacts of slash pile burning attributed to collecting the biomass for bio-jet fuel production can be incorporated in the LCA as a credit. In this paper we considered a 50% and a 100% slash pile burn scenario for the avoided emission credit, to evaluate the beneficial environmental impacts of not burning the slash piles in the forest.

Biomass Conversion and Biofuel Refinery

The scenario considered in this analysis assumes an integrated biomass conversion facility, where the biomass storage, extraction of sugar from the woody biomass and the conversion of the sugar into bio-jet-fuel, are all undertaken at the same location. The conversion process uses a mild bisulfite pre-treatment of the biomass feedstock to liberate the C6 sugars and break down the lignocellulosic material. This slurry is then mixed with a cellulase enzyme and hydrolyzed to produce a fully saccharified sugar stream. The fermentable sugars are then converted to isobutanol (iBuOH) using a proprietary bio-catalytic fermentation and oligomerization process to produce bio-jet fuel (iso-paraffinic kerosene, IPK). Therefore, in this study the overall process for converting residual woody biomass to aviation biofuel is separated into four different sub-processes; (i) pre-treatment of the residual woody biomass, (ii) enzymatic hydrolysis, (iii) fermentation

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and oligomerization of the hydrolysate to produce iso-paraffinic kerosene (IPK), and (iv) boiler, wastewater treatment and other utilities.

IPK combustion

The model assumes that 6.818 kg of bone dry clean woody biomass produces 1kg of IPK. In the analysis we assumed a calorific value of 43.1 MJ kg-1 for the petroleum based jet fuel and 43.2 MJ kg-1 for the bio-jet fuel (Johnston 2013). Combustion emissions were estimated using the Ecoinvent database for intercontinental air freight since primary data for IPK combustion are not available (Ecoinvent 2013).

Location of the bio-refinery

The location of the bio-refinery plays a significant role in the overall LCA analysis. There were a number of factors used in the analysis that are location specific, while others are specific to the region. The annual feedstock demand for the facility is scaled at 700,000 bone dry metric tons of screened woody biomass to produce 112,980 tons of IPK per year. The overall impact of the feedstock collection, in-woods processing and transportation to the bio-refinery is heavily dependent on the location of the facility (e.g., road transportation distance from forest landing to bioprocessing facility). The LCI data associated with the local electricity grid, the cost of diesel fuel, baseline jet fuel prices, etc., are region specific (e.g., for electricity we used the 'Electricity, at eGrid, NWPP', which is recommended for the PNW). For the analysis presented in this paper, we used a hypothetical location in Grays Harbor county in Western Washington. This site was selected based on its proximity to a reliable and sustainable supply of feedstock to supply the bioconversion facility, the availability of the necessary support infrastructure and a site suitable for building a bioconversion facility of the proposed scale.

Evaluation methods and model assumptions

This study followed the ISO 14040 and 14044 standard (ISO 2006a; ISO 2006b) for the overall LCA framework. The environmental impacts were assessed using TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare 2011). The following impact categories were included in the LCA analysis: global warming, smog, acidification, eutrophication, carcinogenics, non carcinogenics, respiratory effects and ecotoxicity. The life cycle inventory analysis and impact assessments were conducted using SimaPro 8. As per the IPCC Fifth Assessment Report, this paper reports the 100 year impact for the global warming potential for both the bio-based jet fuel and the fossil-based jet fuel (IPCC 2013).

Comparative Assessment Framework

The overall environmental impact associated with the production of bio-jet fuel was then compared against the emissions associated with the production of petroleum-based jet fuel. For the comparative analysis, it is critical to use comparable system boundaries for both of the jet fuel production processes under consideration. A simplified diagram of the system boundaries associated with the production and utilization of woody biomass based bio-jet fuel (Panel A) and petroleum based jet fuel (Panel B) is shown in Figure 1. For this analysis, the LCA emissions associated with 1 GJ of energy produced using bio-jet fuel (iso-paraffinic kerosene, IPK) were compared with those emitted using fossil-based jet fuel (kerosene). The results for the global warming potential were also compared against the baseline for the life cycle GHG emissions from fossil-based jet fuel sold or distributed in the United States, as specified by the

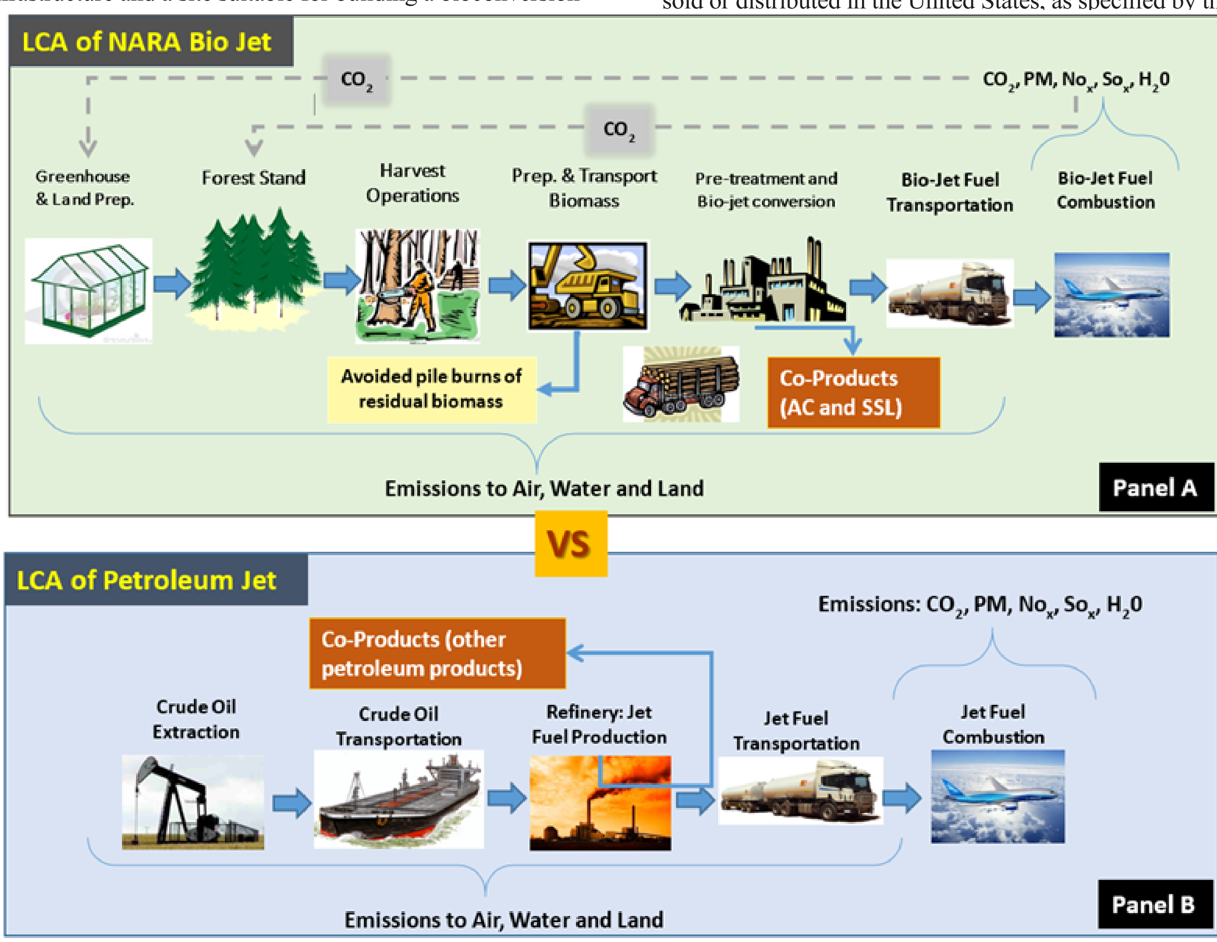

Figure 1: Comparable system boundaries for the production of bio-jet fuel and fossil-based jet fuel

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Energy Independence and Security Act of 2007 (EPA 2007).

Results

The results presented here correspond to two of the most environmentally conservative and realistic scenarios developed by the NARA researchers. The 'cradle to grave' comparative analysis of fossil-based jet fuel and bio-jet fuel reveals that a more than 70% reduction in the global warming potential, as a result of the reduction in greenhouse gases (GHGs) into the atmosphere, can be achieved by substituting petroleum-based jet fuel by 100% residual woody biomass-based jet fuel, for both of the scenarios, Figure 2. The key environmental benefits associated with residual biomass based bio-jet fuel are the avoided emissions attributed to not burning the residual slash piles (which is indicated by the net negative 'respiratory effects' LCA impact category). The residual woody biomass based bio-jet fuel also showed a substantial reduction in the 'carcinogenics' (110% to 96%), 'non carcinogenics' (37%), 'smog' (5% to 27%) and 'ecotoxicity' (81%) LCA impact categories. Generally, eutrophication is one of the most important areas of concern for biofuels due to the high use of chemicals and enzymes during the conversion process, fertilizers during feedstock production, and waste water management and disposal within the bioconversion facility. In this respect, it is also worth noting the eutrophication impact of the bio-jet fuel is comparable (in the 50% avoided burn case), if not better (in the 100% avoided burn case) relative to fossil-based jet fuel.

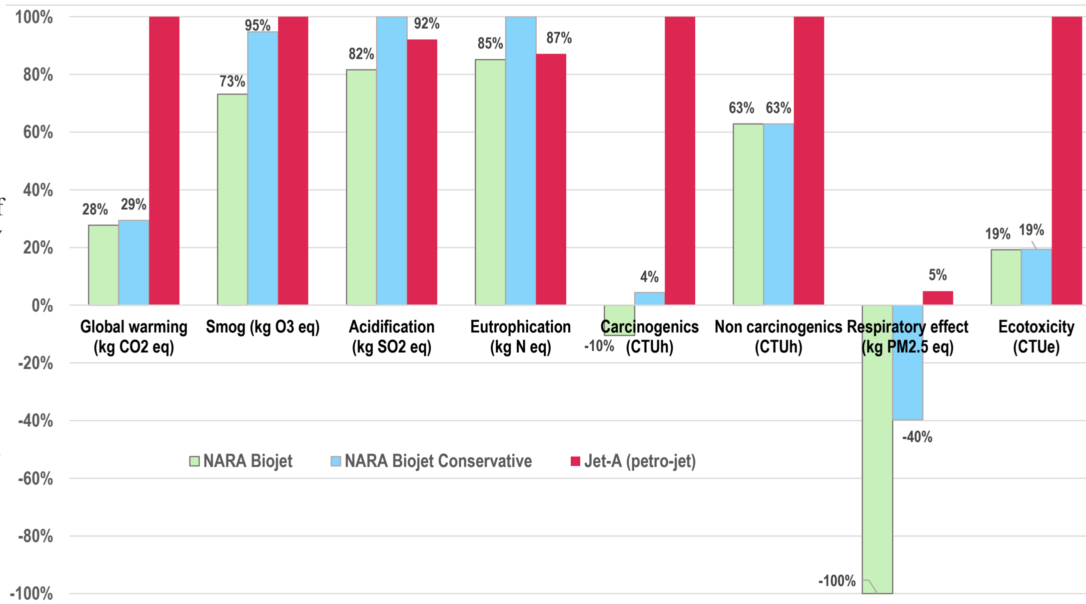

Figure 2. Comparative environmental assessment of fossil-based Jet-A vs NARA bio-jet IPK.

<u>Highlights</u>

- The WoTW/WTW comparative analysis of residual biomass-based and fossil-based jet fuel reveals that a more than 70% reduction in global warming potential (GWP) can be achieved by substituting 100% petroleum-based jet fuel with 100% residual woody biomass-based bio-jet fuel. This result is significantly better than the US Environmental Protection Agency mandated 60% GWP reduction that is required in order for bio-jet fuel to qualify as a bio-preferred fuel for public procurement programs.
- Another important environmental benefit associated with producing residual biomass-based bio-jet fuel is the avoided slash pile burns which improves local air quality and reduces the local health impacts caused by the harmful pollutants generated from burning slash piles in the forest.
- Using residual woody biomass based bio-jet fuel also contributed to a substantial reduction in the 'carcinogenics', 'non carcinogenics', 'smog' and ecotoxicity LCA impact categories. These positive local environmental benefits make residual woody biomass a much more environmentally appealing feedstock for energy production than fossil fuel-based alternatives.

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