FINAL REPORT

Project 032 Worldwide Life Cycle Analysis (LCA) of Greenhouse Gas (GHG) Emissions from Petroleum Jet Fuel

Massachusetts Institute of Technology (MIT)

Project Lead Investigator

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- P.I.(s): Professor Steven Barrett,
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- Period of Performance: December 4, 2014 to September 30, 2016
- Task(s):
    1. Preliminary global baseline analysis for 2005 and 2020
    2. Analysis of changes to the baseline in 2050, and assessment of opportunities for reduction in lifecycle GHG emissions
    3. Analysis of world region baseline for recent past and 2020
    4. Final report and data handover

Project Funding Level

$150,000 FAA funding and $150,000 matching funds. Sources of match are approximately $39,000 from MIT, plus 3rd party in-kind contributions of $111,000 from Byogy Renewables, Inc.

Investigation Team

Principal Investigator: Prof. Steven Barrett
Co-Investigator: Dr. Robert Malina, Tasks 1-4
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Dr. Pooya Azadi, Postdoctoral Associate, Tasks 1, 3, 4
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Project Overview

The total greenhouse gas impact of petroleum-derived fuels includes both direct combustion emissions and the well-to-pump (WTP) emissions associated with extraction, transportation, and refining of crude oil and transportation of refined products. In this project, the WTP life cycle emissions of petroleum-derived jet fuel were quantified. The analysis addressed both temporal and spatial variation in WTP emissions of jet fuel.

Tasks

Task 1: Preliminary global baseline analysis for 2005 and 2020

1.1 Analysis of global portfolio for crude recovery emissions
1.2. Analysis of global transportation emissions developed
1.3 Analysis of global refinery emissions
1.4 Completion of white paper for use at ICAO steering group meeting

Task 2: Analysis of changes to the baseline in 2050, assessment of opportunities for reduction in lifecycle GHG emissions

2.1 Assessment of 2050 emissions baseline for jet fuel from petroleum
2.2 Quantification of opportunities for reduction in lifecycle GHG emissions by lifecycle stage

Task 3: Analysis of world region baseline for recent past and 2020

3.1. Analysis of crude mix profiles by world region
3.2 Analysis of transportation and refinery emission profiles by world region accounting for differences in straight-run and hydroprocessed processing
3.3 Analysis of lifecycle GHG emissions baseline for jet fuel from petroleum by world region
3.4 Refinement of preliminary global baseline using world-region results

Task 4: Final report and data handover

4.1 Completion of white paper on project available for sponsor review
4.2 Data preparation for handover to Argonne National Laboratory for use in GREET model

Objectives

The main objective of this project was to calculate GHG emissions estimates for petroleum jet fuels for the recent past and for future scenarios in the coming decades. Results were reported globally and broken out by world regions, and the impact of changes in future demand for certain petroleum products and of changes in crude properties were quantified. Opportunities for reductions in GHG emissions along the supply chain were estimated.

Research Approach

Background

To date, only a limited number of analyses of GHG emissions for jet fuel from petroleum sources exist, limited to the United States and generally relying on 2005 data (Skone and Gerdes 2009, Stratton et al. 2012). A recent update to the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) developed and maintained by Argonne National Laboratory includes more recent data on refining efficiency from a report by Elgowainy et al. (2014), but is still U.S.-specific, only. Furthermore, existing estimates of lifecycle emissions are limited temporally, with no known projections of short- or long-term future.

To the best of our knowledge, no baseline value for jet fuel from petroleum has been established in other world regions. In Europe, for example, baseline values are calculated for diesel fuels from petroleum, but not for jet fuel (JEC 2014). Moreover, there is no baseline value on a global scale that describes average lifecycle GHG intensity of using jet fuel from petroleum, either for fuel produced now or for scenarios of projected future petroleum-derived jet fuel use. Existing values for jet and diesel that are used in the US and the EU are summarized in Figure 1.

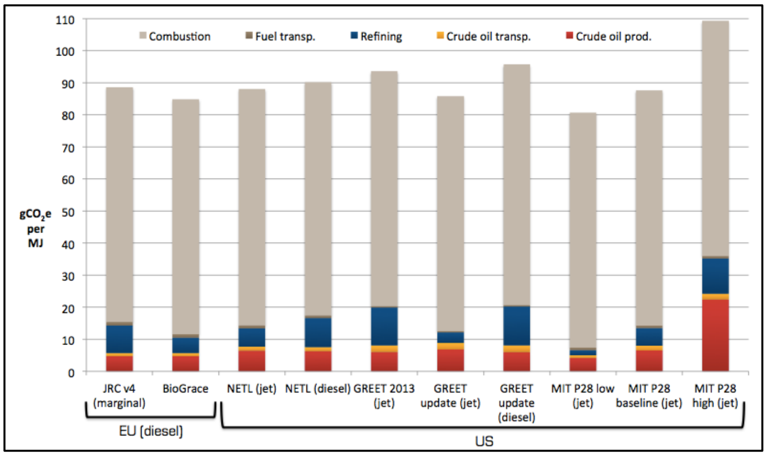

Figure 1: Lifecycle GHG emission values used as baselines in the EU and U.S. (Malina et al. 2014).

This is a particularly important research gap given the ongoing efforts under the Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO) to include alternative fuels into a global system of market-based measures, CORSIA (Carbon Offsetting and Reductions Scheme for International Aviation). Alternative fuels require the existence of a petroleum-centric benchmark for comparison, so that airlines can receive appropriate monetary credits for using these fuels. Moreover, a baseline is required for current work under the Alternative Fuels Task Force (AFTF) of ICAO CAEP to estimate the potential contribution of large-scale alternative jet fuel introduction to mitigating aviation's climate impact by the year 2050.

From a temporal perspective, the crude mix used in refineries changes over time, as do refining and recovery practices and product slates produced. These factors might impact associated lifecycle emissions for jet fuel from petroleum both globally and within specific world regions. For example, the average lifecycle GHG emissions attributable to jet fuel from petroleum in the U.S. are estimated at 85.8 g CO_2e per MJ of jet fuel via the 2015 update to GREET, whereas Skone and Gerdes (2009) reported 88.0 g CO_2e per MJ (Malina et al., 2014). Aside from crude quality and refinery changes, other technological or policy factors may change in the future as well, and need to be considered in future projections.

Methodology

Extraction

For both conventional and unconventional (e.g., oil sands, shale) petroleum-derived jet fuels, we investigated and quantified greenhouse gas emissions in all stages of the petroleum-derived jet fuel lifecycle (crude recovery, feedstock transportation, feedstock-to-fuel conversion, jet fuel transportation, and jet fuel combustion). For the recovery stage, we built upon existing analyses on emission profiles for different representative crude types and recovery practices such as the analyses by Rahman et al. (2014), Bouvart et al. (2013), Garg et al. (2013), Charpentier (2009) and Skone and Gerdes (2009). In the case of missing data for emissions associated with recovery of certain crude types, we approximated them with emissions from crude types with similar recovery practices. For analyses of future emissions, projections of changes in constituent emissions indices and production capacity have also been utilized (Jiang, 2011; Exxon 2015; IEA 2014; Brandt, 2011).

Data on crude mixes used in the different world regions has been obtained from existing analysis mentioned above and by data from the International Energy Agency (IEA, 2014 and 2015) and the Energy Information Administration (EIA, 2015). This data was necessary both for assigning recovery emissions to jet fuel produced in a particular word region, and for estimating refinery emissions. Future crude quality was assessed using global projections (OPEC, 2015 and EIA, 2015).

Refinery

Refinery GHG emissions were based on refinery usage statistics in world regions where this data wass available (i.e. U.S. and Europe), and estimated based on refinery configurations and capacities in other regions. Characteristics of the input crude slate, such as sulfur content and API gravity, have been used to determine process energy requirements and resulting emissions. We used available information to estimate the relative amounts of straight-run and hydroprocessed jet fuel that are produced by refineries worldwide. We used insights from process-level refinery linear programming (LP) models to estimate the emissions from both the production of straight-run and hydroprocessed jet fuels. As well as, these LP models were used to understand how changes in relative transportation fuel demand affects refinery energy usage and GHG production, and how those changes affect the GHG emissions attributed jet fuel.

For future scenarios where demand for jet fuel may exceed straight-run production capabilities, emissions were estimated for the upgrading processes needed to convert other fractions of the input crude to jet fuel. The ratio for demand amongst different crude products (e.g. jet fuel versus diesel) will also impact refinery operations. Future demand for petroleum fuels has been projected by other agencies, and was used in the 2050 analysis (WEC 2011 and 2013; IEA 2014; IEA 2015).

Transportation

Feedstock and product transportation emissions for each world region were calculated by combining representative transportation distances with emission profiles of representative means of transportations accessible in the GREET and/or SimaPro tools.

Future and Opportunities

Projections for future emissions were created through a scenario-based analysis, similar to that used by the IPCC and others (IPCC, 2010). Scenarios were created in order to conceptualize different potential ways in which the future may unfold. To create these scenarios, first key drivers of emission within the petroleum lifecycle were identified. Once identified, future emissions regarding how these factors change by the year 2050 were collected. This literature data was then be used to create scenarios, such that each scenario was coherent and has consistent assumptions. These scenarios were then assessed using the LCA model so that the lifecycle emissions could be determined.

Opportunities for reducing lifecycle GHG emissions of jet fuel from petroleum were investigated and quantified through sensitivity analyses of different factors. These factors included those utilized in the 2050 scenario construction, as well as additional ones. For example, the emissions intensity of key inputs was varied, such as hydrogen production (ICAO, 2015; ANL, 2005), electricity generation (PSI, 2014; WEC, 2013), and transportation.

Milestones

Due Date	Milestone
May 1st, 2015	MS 1 (related to Task 1): Crude extraction emission's profiles compiled
August 1st, 2015	MS 2 (related to Task 1): Preliminary global baseline results available for FAA discussions
Mid October 2015	MS 3 (related to Task 1): Presentation of preliminary global baseline emissions at CRC Workshop
November 1st, 2015	MS 4 (related to Task 1): White paper available on preliminary global baseline for use at ICAO Steering group meeting
March 1st, 2016	MS 5 (related to Task 2): Preliminary results of GHG emissions baseline for 2050 available for discussion
May 1st, 2016	MS 6 (related to Task 3): World-region specific baseline results available for discussion
June 1st, 2016	MS 7 (related to Task 2): Opportunities for lifecycle GHG reductions for jet fuel from petroleum available for discussion
September 30th, 2016	MS 8 (related to Task 4): White paper on project available for FAA review

Major Accomplishments

The emissions associated with extraction of crude and global baseline results of jet fuel WTP emissions have been calculated (MS1 & MS2). The analysis is based on a country-specific life cycle model encompassing data on each lifecycle stage that allows for calculating world-region-specific and global WTP emissions for each fuel type. We have gathered the required raw data from over twenty international and national agencies, as well as private companies. In total, 72 sources of emission associated with crude production in 90 countries, refining in 687 refineries across 112 countries, and global crude and product movements have been quantified.

For the year 2005 (Figure 2), we estimate the global mean WTP emissions for an average unit of gasoline, diesel, jet fuel, and bunker fuel to be 21.5, 18.6, 14.6, and 12.7.0 gCO2-e/MJ, respectively. The differences in WTP emissions of these petroleum-based fuels are primarily attributed to the differences in the extent to which catalytic cracking, hydrocracking, and hydrotreating refinery units contribute to producing each fuel.

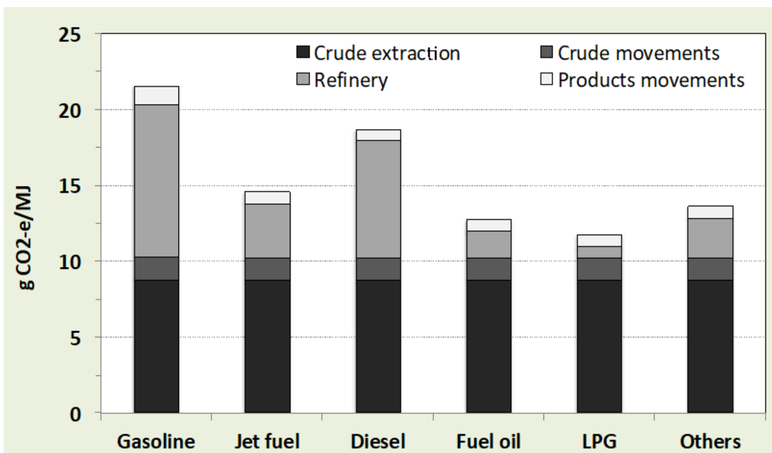

Figure 2: Global average Lifecycle GHG emission values of petroleum-derived fuels in 2005.

Between 2005 and 2012, changes in regional supply and demand for the different fuel products and increasing exploitation of unconventional petroleum resources increased WTP emissions while reductions in flaring and fugitive emissions reduced WTP emissions. The global mean WTP emissions for an average unit of gasoline, diesel, jet fuel, and bunker fuel to be 22.5, 18.7, 14.8, and 13.0 gCO2-e/MJ, respectively (Figure 3). The differences in WTP emissions of these petroleum-based fuels are primarily attributed to the differences in the extent to which catalytic cracking, hydrocracking, and hydrotreating refinery units contribute to producing each fuel. Overall, per-unit WTP emissions increased by 4% between 2005 and 2012.

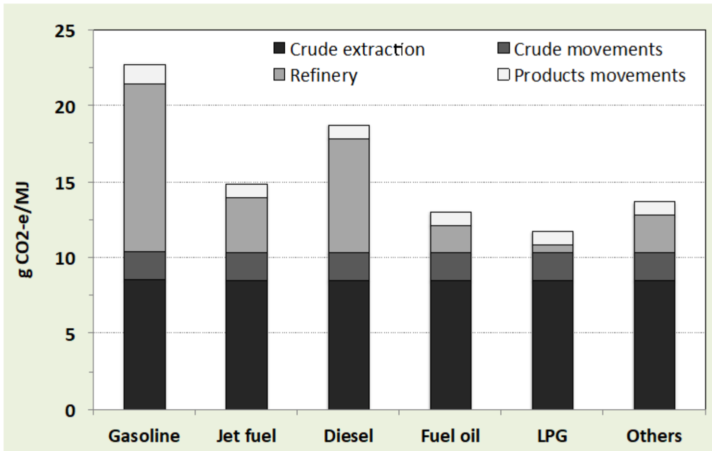

Figure 3: Global average Lifecycle GHG emission values of petroleum-derived fuels in 2012.

Furthermore, we estimate that by 2020, global mean emissions will be 4% higher than in 2012 baseline (Figure 4) mostly due to higher shares of unconventional crudes and hydroprocessed refined products.

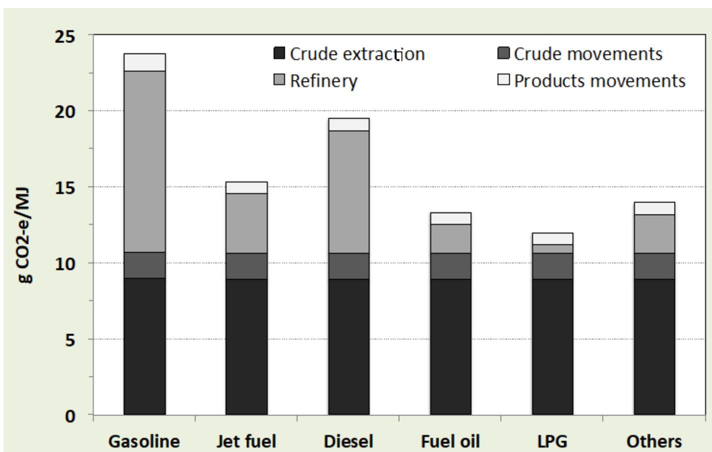

Figure 4: Estimated global average Lifecycle GHG emission values of petroleum-derived fuels in 2020.

Figure 5 demonstrates the refinery emissions associated with production of jet fuel from major production pathways. Depending on the processes involved, the jet fuel refinery emission can vary from 0.9 to 16.9 g CO_2-e/MJ with the global average of 4.2 g CO_2-e/MJ. After accounting for the share of emissions from refinery flaring and credits from refinery co-generation, the global average refinery emission attributable to jet fuel is estimated at 3.7 g CO_2-e/MJ.

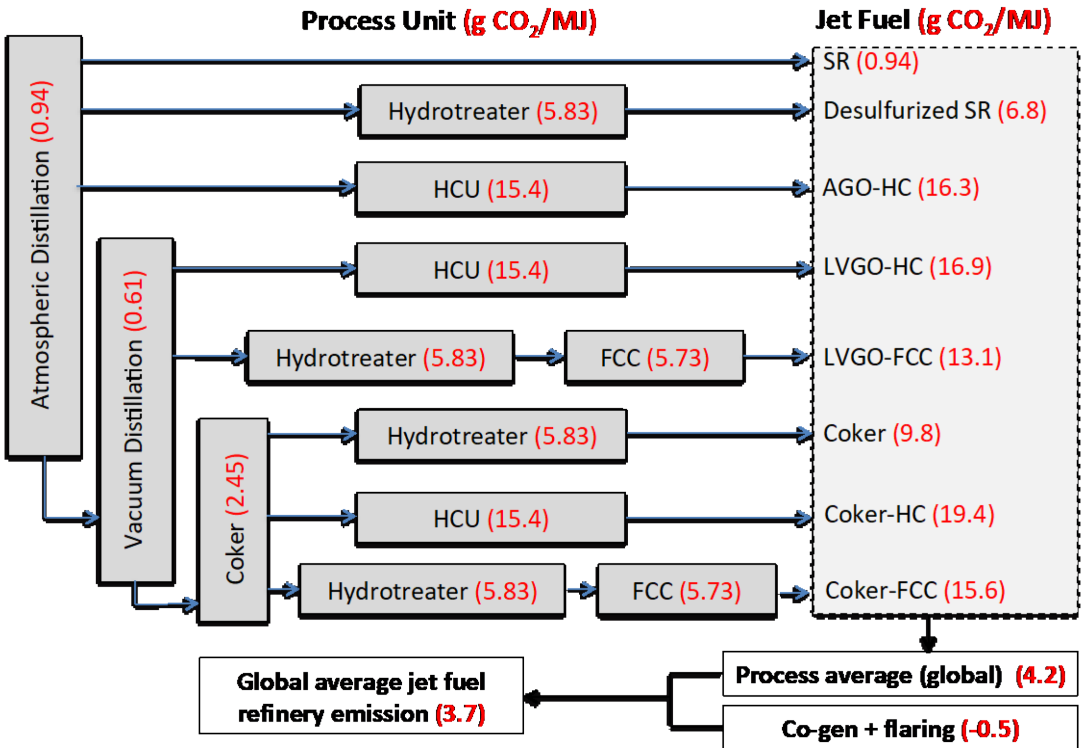

Figure 5: Jet fuel refinery GHG emissions under different production pathways.

For the 2050 analysis, scenarios have been constructed through the methodology discussed above (Research Approach – Methodology – Future and Opportunities). The key factors identified included: production capacity and emissions indices of conventional and unconventional extraction methods, crude quality (API and sulfur content), hydrogen production, electricity generation, and refinery impacts of varied demand for petroleum products. Relevant literature on these factors was surveyed, so that projections of their values in 2050 could be assessed. This data is summarized below in Table 1.

Table 1: Life cycle inventory data for 2020 and 2050 analysis

Category	Factor	Reference Case: 2020 Analysis	2050 Case: Current Policies	2050 Case: Moderate New Policies	2050 Case: Strong New Policies
Extraction	Tight Oil Emissions Index [g CO_2 / MJ]	MIT 2020 (6.3)	Medium (6.3)	Medium (6.3)	Low (1.8) Jiang et al, 2011
	Tight Oil Production [kbbl / d]	MIT 2020 5.2 (5.2%)	High 12.2 (9.9%) Exxon, 2015	Medium 5.7 (5.5 %) IEA, 2015	Low 3.5 (5.5%) IEA, 2014
	Heavy Oil Emission Index (1) [g CO_2 / MJ]	MIT 2020	MIT 2020	MIT 2020	Low Brandt, 2011
	Heavy Oil Production [kbbl / d]	MIT 2020 6.0 (6.0 %)	High 9.6 (7.8%) Exxon, 2015	Medium 8.0 (7.7%) IEA, 2015	Low 4.9 (4.9%) IEA, 2014
	Crude Oil API (2)	MIT 2020	Uniform – projected decrease: 0.4 to 1.9 OPEC, 2014 and EIA, 2015		
Utilities	Electricity Generation Emission Index (2) [g CO_2 / MJ]	MIT 2020 PSI, 2014	MIT 2020 PSI, 2014	Medium ("jazz" case) WEC, 2013	Low ("symphony" case) WEC, 2013
	Hydrogen Production Emission Index [g CO_2 / MJ]	MIT 2020 (0.099)	High (0.099) ICAO, 2015	Medium (0.068) ANL, 2005	Low (0.028) ICAO, 2015
Refinery	Global Middle Distillate Demand [mmbbl / d]	MIT 2020 (35)	High (66.3) ("freeway" case) WEC, 2011	Medium (44.5) ("jazz" case) WEC, 2013	Low (33.1) ("symphony" case) WEC, 2013
	Global Jet Fuel Demand [mmbbl / d]	MIT 2020 (5.4)	High (19.5) ("freeway" case) WEC, 2011	Medium (17.0) ("jazz" case) WEC, 2013	Low (10.3) ("symphony" case) WEC, 2013
	Ratio of Jet Fuel to Middle Distillate	0.15	0.29	0.38	0.31
	Crude Sulfur Content (2)	MIT 2020	Uniform – projected increase: 0.1 to 1.4 OPEC, 2014 and EIA, 2015		

(1) Values vary with extraction method (e.g. bitumen vs. SCO, in-situ vs. surface)
(2) Values vary by world region or country

This was then used to create three future scenarios. These scenarios focus on actions and policies regarding environmental issues, and how the stringency of these approaches may vary. The lowest level of stringency scenario is Current Policies, for which no new environmental actions are taken in addition to current policies. Moderate New Policies and Strong New Policies build on Current Policies through the addition of more stringent actions or policies. These three scenarios vary on three main axes: the extent to which unconventional resources are restricted (with respect to capacity and emissions), the extent to which hydrogen and electricity utilities are decarbonized, and the extent to which demand for different petroleum products is abated.

Together, the data for each of these scenarios was utilized in the LCA model. These results, as well as those for the Opportunities for Emissions Reductions are shown below in Figure 6.

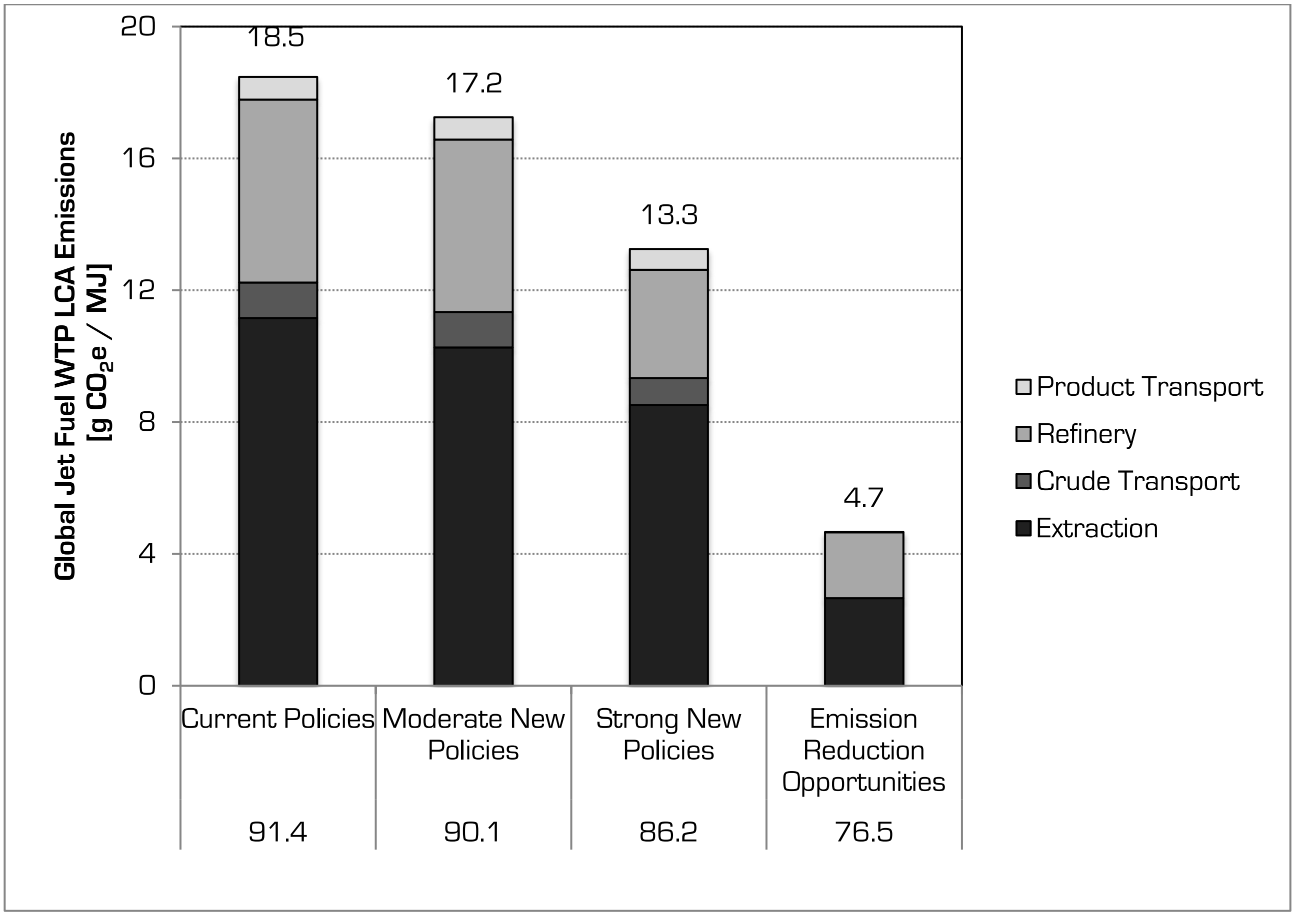

Figure 6: Global lifecycle GHG emission for jet fuel in the year 2050 for three scenarios

The well-to-pump emissions are shown on the y-axis and above the bars in the figure, and the well-to-wake emissions are shown below the x-axis. Compared to the WTP emissions for 2020 of 16 g CO_2e/MJ, the emissions in 2050 may increase by 2.5 g CO_2e/MJ or decrease by 2.7 g CO_2e/MJ. Which scenario path is taken is largely dependent on choices regarding human action and government policy.

Opportunities for emissions reduction were also identified. Additional factors to those considered in the 2050 analysis were examined. These included: venting, flaring, and fugitive gases; emissions intensity of transportation; electrically powered extraction processes; jet fuel composition in relation to combustion emissions. By reducing the aromatic content of jet fuel within the specification range, the combustion CO_2 emissions can be decreased by 1.8 g CO_2e/MJ. Taken together, these various opportunities resulted in WTP lifecycle emissions of 4.7 g CO_2e/MJ, as shown in Figure 6 above. These opportunities can be examined individually, as shown below in Figure 7.

Opportunities such as extraction processes being powered through fossil free methods, or hydrogen being produced with zero emissions, yield the biggest opportunities for reduction, at about 3 g CO_2e/MJ each. Opportunities such as electricity generation with zero emissions, or carbon neutral transportation, yield the smallest opportunities for reduction, at about 1.0 g CO_2e/MJ. This indicates that some opportunities are able to reduce emissions more than others.

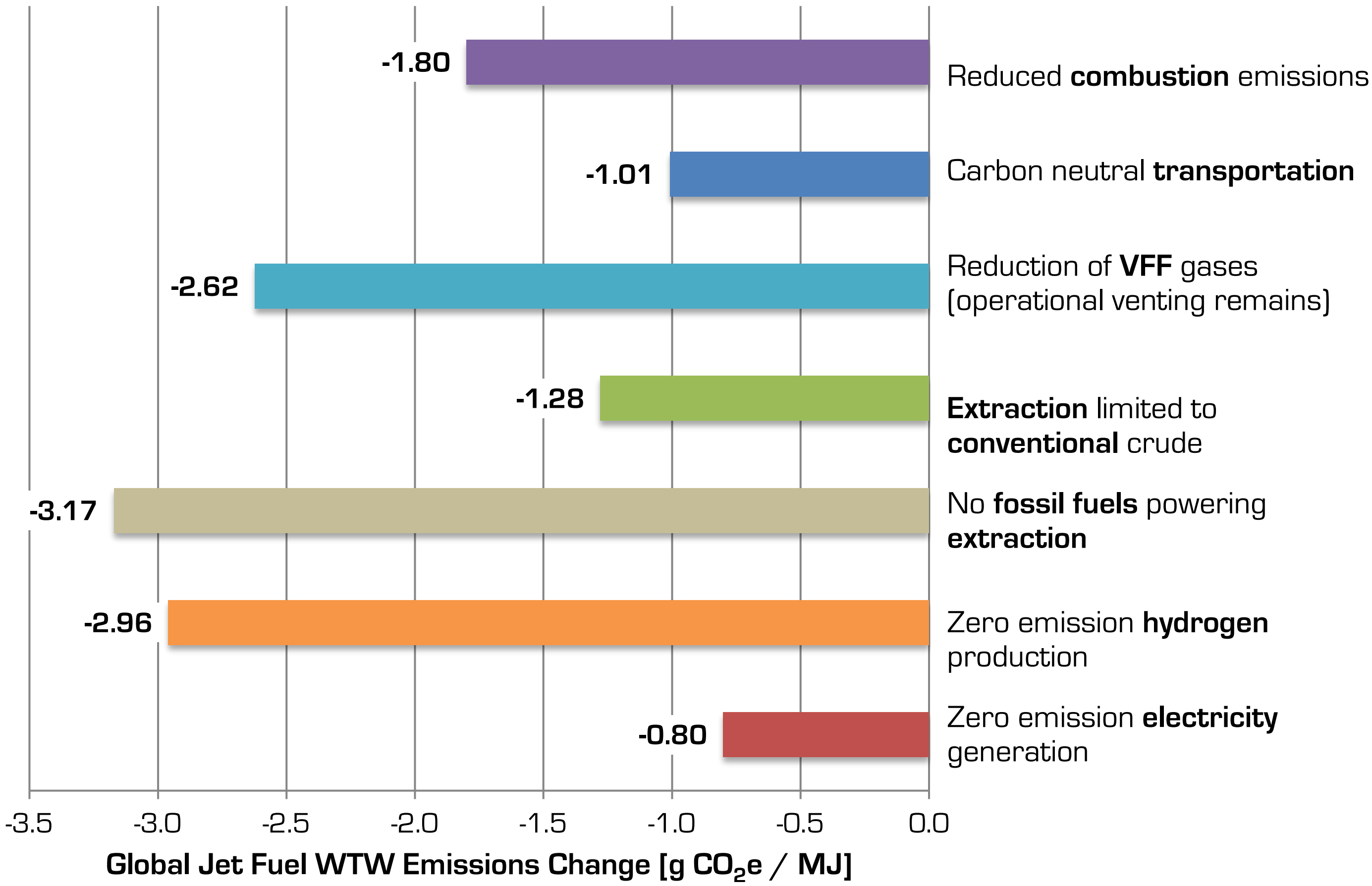

Figure 7: Opportunities for emissions reductions by action type

The remaining 4.7 g CO_2e/MJ emissions in the Opportunities for Emissions Reductions scenario come from extraction and refinery emissions. The 2.7 g CO_2e/MJ from the extraction stage are mainly from non-operational unavoidable venting, as well as land use change and fugitive gases. The 2.0 g CO_2e/MJ from the refinery stage are due to process units powered by refinery fuel gas and catalyst coke.

Overall, the results from 2005 through to 2050 show that lifecycle emissions for petroleum jet fuel tend to increase with time, unless action is taken to reduce them in the future. Depending on the policies implemented within the petroleum industry and beyond, long-term emissions may increase or decrease by about 2.5 g CO_2e/MJ from 2020 levels. If significant reductions are desired, opportunities for emissions reduction have been identified, which can result in a decrease of emissions by 11.3 g CO_2e/MJ from 2020 levels, a 71% reduction.

This work has established a baseline of petroleum jet fuel emissions for various geographical regions in the past, near-term, and long-term future. These values can be used when developing relevant policies. For example, the 2020 global result informed ICAO CAEP in its adoption of the reference values for international jet fuel. In addition, the 2050 global values were used in ICAO CAEP/10 Fuel Production assessment for quantification of GHG emission's benefit of long-term alternative jet fuel market penetration.

Publications

Rosen, C.V. (2017) Scenario-Based Lifecycle Analysis of Greenhouse Gas Emissions from Petroleum-Derived Transportation Fuels in 2050. Master's Thesis. Massachusetts Institute of Technology. *https://doi.org/1721.1/111224*

Rosen, C.V.; Azadi, P.; Speth, R.L.; Malina, R.; Barrett, S.R.H. Scenario-Based Lifecycle Greenhouse Gas Emissions of Petroleum-Derived Transportation Fuels in 2050. In preparation.

Outreach Efforts

- Presentation at AFTF LCA Task group working meeting on fossil fuel baseline
- Presentation at CRC Workshop on Life Cycle Analysis of Transportation Fuels (October, 2015)
- Presentation at DOE BETO Alternative Aviation Fuel workshop (September, 2016)
- ASCENT Poster (April, 2016) and Presentation (September, 2016)
- FAA "External Tools Call" (December, 2016)

Awards

Professor Steven Barrett – newly Tenured Associate Professor, Department of Aeronautics and Astronautics, School of Engineering, MIT

Student Involvement

A Masters' Student, Cassandra Rosen, has been involved in this work from September 2015 – September 2016. She has worked on Task 2 and 4. She graduated from MIT in June 2017 with a Master's of Science in Technology and Policy.

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