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The Oil-Climate Index: Assessing GHG Emission Impacts Across the Oil Value Chain

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A New Index to Manage Oil in a Warming World

Oil is one of the world's most durable global commodities. With few ready commercial substitutes, its extraordinary staying power is demonstrated by its enduring energy sector dominance, even as market prices fluctuate dramatically and geopolitical disruptions strike. In addition to ever present economic and security concerns, climate change is a third factor that must now be fully considered. This puts a premium on the ability to fully quantify greenhouse gas (GHG) emissions through the oil value chain to see how they vary in upstream production and crude transport, midstream refining, and downstream product transport and end use.

To address this knowledge gap, the Carnegie Endowment for International Peace, in collaboration with researchers at Stanford University and the University of Calgary, developed a *first-of-its-kind* Oil Climate Index (OCI).[1] This tool conducts a "crude-centric" lifecycle assessment of oil from the barrel forward through consumption of all its end products. The OCI demonstrates that total GHG emissions can vary significantly—by as much as nearly a factor of two from oil to oil, depending on the oil itself and operating conditions. And upstream and midstream emissions each range by a factor of 10 (Fig. 1).

In the first phase of the open-source OCI tool, sufficient data were collected for 30 global oils around the globe—approximately 5% of current global production. In OCI Phase 2 emissions for 75 global oils were analyzed, accounting for 25% of global production (Fig. 2).

OCI Input Data

The models that underpin the Oil-Climate Index (OCI) require consistent, comparable, and verifiable open-source data on crude oils and the processes employed in the value chain. These data include oil assays—analyses of predetermined data measuring a crude oil's chemical and physical characteristics—that are reported out in a specified format, upstream field-level operating specifications, midstream refining process input requirements, and downstream transport and end-use data (Fig. 3).

In creating the Oil-Climate Index, academic sources, technical documents, and industry reports, and oil companies were consulted to identify data. The oils modeled to date were prioritized based on their geographic, geologic, chemical, and physical diversity. But the final arbiter of the 75 global oils selected was data availability. Greater data transparency will make it possible to run additional global oils through the OCI in Phase 3.

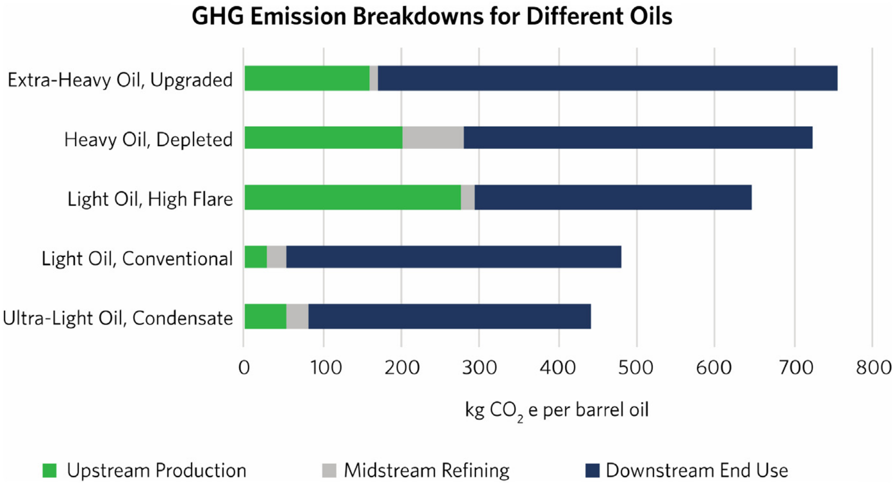

Fig. 1 GHG emissions per barrel for five sample oils. Source: Oil Climate Index, OCI.CarnegieEndowment.org, July 2016.

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[1] All results and input data associated with the OCI can be accessed at oci.carnegieendowment.org.

Encyclopedia of Sustainable Technologies, First Edition, 2017, 407–415

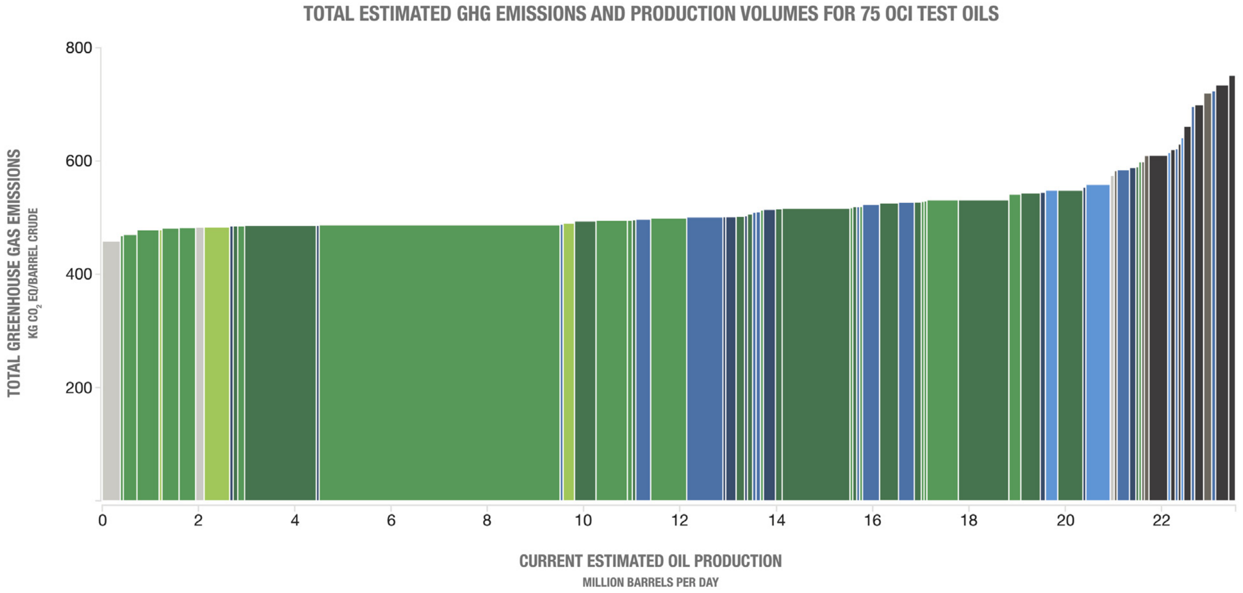

Fig. 2 Emissions supply curve for 75 global oils modeled using the OCI. Source: Oil Climate Index, OCI.CarnegieEndowment.org, August 2016; This high-resolution image was produced by Development Seed.

OPGEE Data

The Oil Production Greenhouse Gas Emissions Estimator (OPGEE) technically requires up to 60 data inputs, but the use of smart defaults allows the model to assign reasonable estimates based on just a few key characteristics, such as steam injection, steam-oil-ratio (SOR), API gravity, water–oil ratio, and flaring rate.[2] The upstream data inputs for OCI Phase 2 test oils, including references and sources, are noted in the OPGEE operating data workbook.[3]

PRELIM Data

The Petroleum Refinery Life-Cycle Inventory Model requires crude oil assays that use a specified number of temperature cuts. Assays provided in a different format (e.g., too few temperature cuts or different temperature bands) must be transformed—a process that can introduce errors into PRELIM. In the OCI web tool,[4] the assay sources for the 75 Phase 2 sample oils modeled are specified in "oil details." When there is no directly corresponding assay for an OPGEE oil field, a proxy assay is selected that closely fits the sample oil's characteristics. As actual assays are collected, proxy assays will be replaced in future phases of the OCI. The assay data used in OCI calculations are available in the PRELIM model workbook on the Assay Inventory worksheet.[5]

OPEM

The Oil Products Emissions Module data inputs require a detailed product slate (in barrels or kilograms of product per barrel of oil, which are reported out in PRELIM) to calculate both the GHG emissions associated with transporting petroleum products from the refinery outlet to the end-use destination and the GHG emissions associated with petroleum product combustion. Additional OPEM data needed include the distances petroleum products travel to market, the mode of transport and transport fuel used, and the vehicle fuel emission factors from the Argonne National Laboratory's GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model.[6] End-use emissions from the combustion of petroleum products are calculated using US Environmental Protection Agency (EPA) emission factors.[7]

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[2] Brandt, A. R., Sun, Y. and Vafi, K. (2015). "Uncertainty in regional-average petroleum GHG intensities: Countering information gaps with targeted data gathering," *Environmental Science & Technology*, 49(1), 679–86, http://dx.doi.org/10.1021/es505376t.

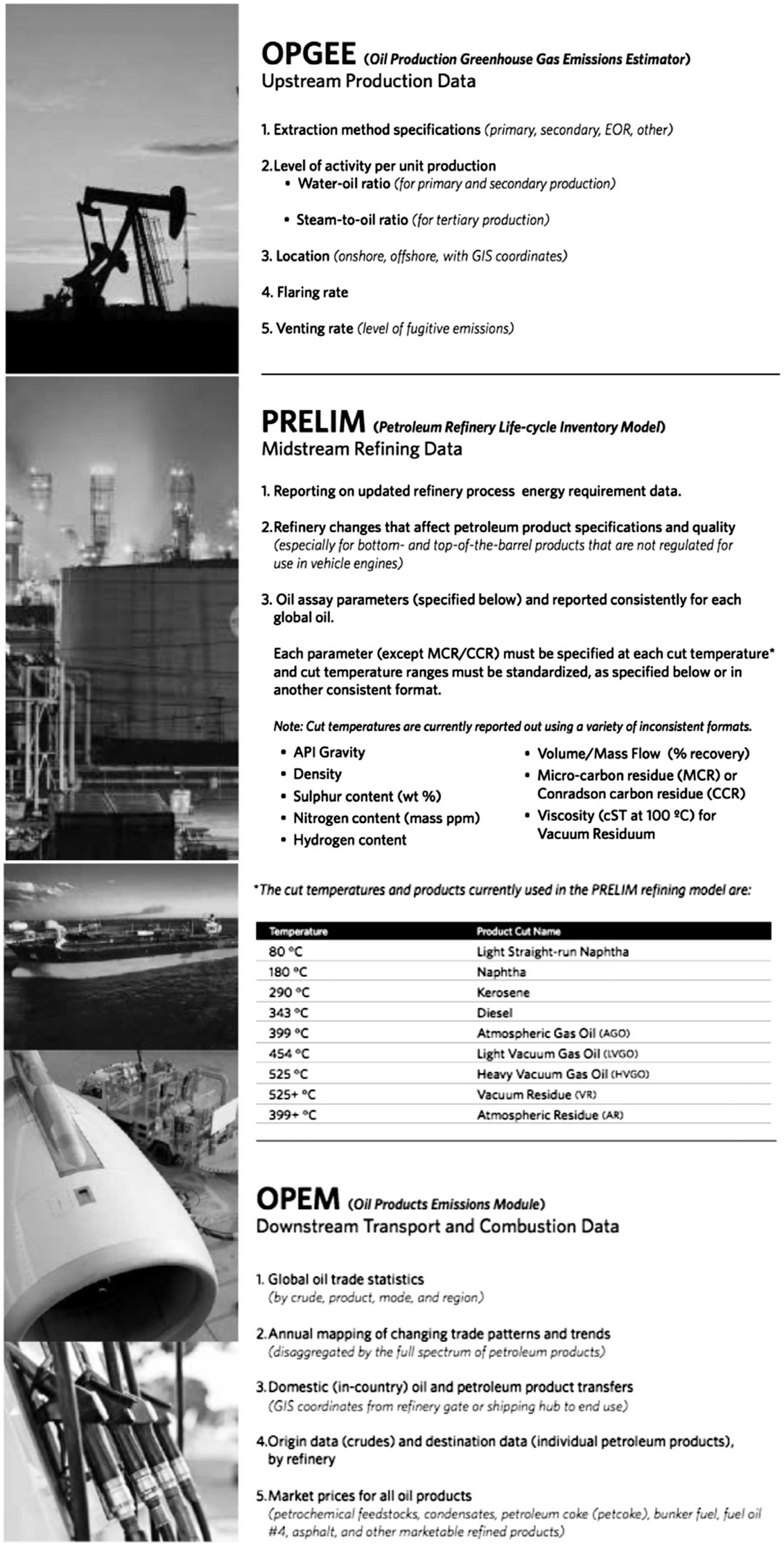
[3] See OCI web tool methodology for OPGEE and PRELIM operating data workbooks.

[4] The OCI web tool can be found at oci.carnegieendowment.org.

[5] Data discrepancies may arise when one set of model inputs does not accurately represent the practices in place at large oil fields with varying conditions at different wells. See the OCI.CarnegieEndowment.org. See "Special Cases" in the Methodology section for more information.

[6] For more information see: https://greet.es.anl.gov/.

[7] U.S, Environmental Protection Agency, "Emission Factors for GHG Emission Inventories," Updated Last Modified: 19 November 2015, https://www.epa.gov/sites/production/files/2015-11/documents/emission-factors_nov_2015.pdf.



OPGEE ***(Oil Production Greenhouse Gas Emissions Estimator)***
Upstream Production Data

1. **Extraction method specifications** *(primary, secondary, EOR, other)*
2. **Level of activity per unit production**
    - **Water-oil ratio** *(for primary and secondary production)*
    - **Steam-to-oil ratio** *(for tertiary production)*
3. **Location** *(onshore, offshore, with GIS coordinates)*
4. **Flaring rate**
5. **Venting rate** *(level of fugitive emissions)*

PRELIM ***(Petroleum Refinery Life-cycle Inventory Model)***
Midstream Refining Data

1. **Reporting on updated refinery process energy requirement data.**
2. **Refinery changes that affect petroleum product specifications and quality** *(especially for bottom- and top-of-the-barrel products that are not regulated for use in vehicle engines)*
3. **Oil assay parameters (specified below) and reported consistently for each global oil.**

Each parameter (except MCR/CCR) must be specified at each cut temperature* and cut temperature ranges must be standardized, as specified below or in another consistent format.

Note: Cut temperatures are currently reported out using a variety of inconsistent formats.

- API Gravity
- Density
- Sulphur content (wt %)
- Nitrogen content (mass ppm)
- Hydrogen content
- Volume/Mass Flow (% recovery)
- Micro-carbon residue (MCR) or Conradson carbon residue (CCR)
- Viscosity (cST at 100 ºC) for Vacuum Residuum

**The cut temperatures and products currently used in the PRELIM refining model are:*

Temperature	Product Cut Name
80 °C	Light Straight-run Naphtha
180 °C	Naphtha
290 °C	Kerosene
343 °C	Diesel
399 °C	Atmospheric Gas Oil (AGO)
454 °C	Light Vacuum Gas Oil (LVGO)
525 °C	Heavy Vacuum Gas Oil (HVGO)
525+ °C	Vacuum Residue (VR)
399+ °C	Atmospheric Residue (AR)

OPEM ***(Oil Products Emissions Module)***
Downstream Transport and Combustion Data

1. Global oil trade statistics *(by crude, product, mode, and region)*
2. Annual mapping of changing trade patterns and trends *(disaggregated by the full spectrum of petroleum products)*
3. Domestic (in-country) oil and petroleum product transfers *(GIS coordinates from refinery gate or shipping hub to end use)*
4. Origin data (crudes) and destination data (individual petroleum products), by refinery
5. Market prices for all oil products *(petrochemical feedstocks, condensates, petroleum coke (petcoke), bunker fuel, fuel oil #4, asphalt, and other marketable refined products)*

Fig. 3 Detailed OCI data requirements. Source: Carnegie Endowment for International Peace, "Open Source Oil-Climate Modeling," 2015.

Given current limitations posed by the reporting of global petroleum product transport data, in Phase 2, the OCI assumes that all petroleum products follow the same route. Petroleum products are transported via pipeline from Houston to New York (2414 kilometers or 1500 miles) and then by heavy-duty tanker truck to either the Washington, DC, or Boston metropolitan areas (380 kilometers, about 236 miles). Scenario runs indicate that product transport is not a significant GHG emission driver, except under extreme cases. Future iterations of OPEM will allow for user-defined inputs as well as for more complex parameter settings.

Global Warming Potentials

OCI GHG emission estimates consider several GHGs, including carbon dioxide, methane, and nitrous oxide. These emissions are combined into a single result using global warming potentials (GWPs) that reference all climate forcing gases to carbon dioxide. The OCI uses data reported by the United Nations Intergovernmental Panel on Climate Change (IPCC) in their 2013 assessment report (AR5), 100-year GWP with climate-carbon feedbacks. As such, the GWP for carbon dioxide (CO_2) is 1, and methane (CH_4) is 34 times greater than CO_2, while nitrous oxide (N_2O) is 298 times greater.[8]

Data Quality and Transparency

The degree of uncertainty in the GHG emission estimates modeled through the OCI depends on the quality of the input data. Two parameters—crude assay and field-characterization methods on the one hand, and characterization of real-world operations on the other—affect data quality. Natural and technical variability, especially as these relate to changing operations over time, affect the quality of the OCI data. In order to characterize the quality of data along these parameters, the OCI developed a new protocol to assign each oil a data score, depending on reliability and reproducibility, consistency and completeness, and accuracy (Table 1). The data quality analysis is expected to be updated in OCI Phase 3.

Three data quality levels are established to assess the data used in OCI Phase 2. These include:

- Does not meet minimum requirements: Data provide enough information to use standardized methods of analysis to make a basic representation of a crude's performance. Because not all data requirements are met, the impact of the data on results for crude differentiation is low.
- Meets minimum requirements: Data are relevant for the purposes of the analysis and comply with most modeling needs. Some standardized methods are applied. The data can be considered to have a medium impact on crude differentiation.
- Exceeds minimum requirements: Data provide additional information for modeling that improve reliability and/or allow for further evaluation of a crude. The data can provide enough information to have a high impact on crude differentiation.

OCI Modeling Methods

The OCI integrates three bottom-up engineering models. OPGEE and PRELIM are distinct models that are run separately. The product volumes reported in PRELIM are used as inputs to OPEM. The outputs of the three models are then summed to calculate total GHG emissions. All outputs are converted into the same functional units before they are summed, and the default is GHG emissions per barrel of input crude. The OCI models are under continued development. The versions used in OCI Phase 2 are presented briefly below.

OPGEE Version 1.1 Draft E

OPGEE was developed by Adam Brandt and his colleagues at Stanford University.[9] The California Air Resources Board has supported its development and used the model in GHG emission rulemaking. Under California regulations, OPGEE reports GHG emission outputs in units of grams of CO_2 equivalent per megajoule of petroleum products generated. [10] These outputs are converted into emissions per barrel by multiplying them by the lower heating value of each oil (in megajoules per barrel), determined by correlations between the crude's API gravity and its energy density.

The oil field and oil data specified are used to generate OPGEE's bulk assessment tool for each oil. The bulk assessment tool is then used to calculate base-run GHG emission outputs for each oil. OPGEE also considers the transport of oil to the refinery inlet. In Phase 2, the OCI continues to assume that all oil is transported from its country of origin to Houston via the mode that is nearest to the oil field.

The petcoke produced upstream during oil-sand and extra-heavy-oil upgrading, requires an offline calculation to estimate the net petcoke produced. This considers the OPGEE-derived portion of petcoke used as an upstream energy source and subtracts that from

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[8] See IPCC AR5 global warming potentials on page 714, Table 8.7.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura T., and Zhang, H. (2013). Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley P.M. (eds.). *Climate change 2013: The PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY, USA: Cambridge University Press, Cambridge.

[9] Stanford School of Earth, Energy, and Environmental Sciences, "OPGEE: the Oil Production Greenhouse gas Emissions Estimator," accessed June 28, 2016, pangea.stanford.edu/researchgroups/eao/research/opgee-oil-production-greenhouse-gas-emissions-estimator.

[10] See California Air Resources Board, *Low Carbon Fuel Standard*, http://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf.

Table 1 Criteria for OCI data quality

OPGEE	
Reliability and reproducibility	● Representativeness: from how many samples are field data selected?
	● Vintage: how recent are field data?
	● Transparency: from what sources do field data come?
Consistency and completeness	● OPGEE primary parameters (steam-to-oil ratio, API gravity, water-to-oil ratio): how many primary parameters are included in inputs?
	● OPGEE secondary parameters (field depth, productivity index, number of wells, production rate): how many secondary parameters are included in inputs?
	● Availability of flaring data: are data available from satellite imagery and reporting?
PRELIM	
Reliability and reproducibility	● Representativeness: from how many samples is the assay selected?
	● Vintage: how recent is the assay?
	● Transparency: from what sources does the assay come?
Consistency and completeness	● PRELIM alignment: how do crude properties align with OPGEE inputs?
	● PRELIM minimum assay data transformations: how complete are the assay data as required by PRELIM?
Accuracy	● Certainty in applicable refinery configuration: how accurately can PRELIM model the default refinery configuration?
	● PRELIM hydrogen modeling approach impact: how does the way in which PRELIM models hydrogen production affect GHG emission estimates?
OPEM	
Reliability and reproducibility	● Representativeness: are emission factors for each product representative of the range of real-world product emission factors?
	● Transparency: are oil and product volumes, modes of transport, fuels utilized in transport, commodity routing, and market prices available from reliable sources?
Consistency and completeness	● Alignment with PRELIM and OPGEE: are products and emission factors consistent with the outputs of PRELIM and the crudes described in OPGEE?
Accuracy	● Product transport modeling approach: how accurately does OPEM model transport of products?

the total petcoke production reported by the Alberta Energy Regulator.[11] Lacking detailed reporting in Venezuela, OPGEE uses the average relative amounts of petcoke production reported for Canadian oil sands for Venezuelan extra-heavy-oil upgrading.

The OCI web tool has several upstream oil field operating parameters that users can modify allowing users to make different operating assumptions and see how these affect GHG emissions.

Flaring emissions are estimated in OPGEE by aligning satellite measurements of flares with outlines of the oil fields. The flares and volumes were identified with data from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, which, when combined with the Nightfire Algorithm, can detect and provide estimates to quantify flare location and volume.[12] The Nightfire Algorithm, developed by the National Oceanic and Atmospheric Administration (NOAA), develops annual estimates for flaring volumes and aggregates the data into a spatial database that designates the type of flare as production, refining, or processing. The flaring rates are computed as the average of 2010–14 flaring volumes located in the fields within this analysis. A rare exception is made when government-reported flaring data or gas-to-oil ratios are lower than VIIRS-assessed flaring data; in this case, OCI Phase 2 uses the lower government data rather than VIIRS.

PRELIM Version 1.1

PRELIM was developed by Joule Bergerson and her colleagues at the University of Calgary.[13] PRELIM version 1.1 contains 103 oil assays in its inventory. These assays are run through the "Results All Assays" macro three times, each run corresponding to a different refinery configuration—hydroskimming, medium conversion, and deep conversion (the last two with fluid catalytic cracking and gas-oil hydrocracking units).

The default refinery is chosen by PRELIM using an API gravity and sulfur-content categorization scheme, as summarized below. Users can run oils through different refinery configurations in the OCI web tool to estimate how GHG emissions change.[14]

- Deep conversion refinery—heavy crude with any sulfur level
- Medium conversion refinery—medium sweet crude (22—32 API, with less than 0.5% sulfur content by weight); medium sour crude (22—32 API, with more than 0.5% sulfur content by weight); and light sour crude (over 32 API, with more than 0.5% sulfur content by weight)
- Hydroskimming refinery—light sweet crude (over 32 API, with less than 0.5% sulfur content by weight)

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[11] See Alberta Energy Regulator, "ST39," accessed June 28, 2016, https://www.aer.ca/data-and-publications/statistical-reports/st39.

[12] Elvidge, C., Zhizhin, M., Hsu, F.-C. and Baugh, K. (2013). "VIIRS Nightfire: Satellite Pyrometry at Night," *Remote Sensing*, **5**, 4423–4449.

[13] The OCI has used a version of PRELIM that, at the time of writing, has not yet been publicly released, but which will be available at the following webpage: University of Calgary, "LCAOST, Life Cycle Assessment of Oil Sands Technologies: PRELIM: the Petroleum Refinery Life Cycle Inventory Model," accessed June 28, 2016, http://www.ucalgary.ca/lcaost/PRELIM.

[14] For exceptions to the refinery rule in OCI Phase 2 see: OCI.CarnegieEndowment.org "Special Cases" in the Methodology section below.

PRELIM version 1.1 refines crude oils using optimal use of processing units (float case). Coproducts, including petrochemical feedstock, asphalt, and petcoke, can be turned on and off. A crude blending tool was added for OCI Phase 2 and may be expanded in Phase 3. Additionally, a hydrogen surplus that results from lighter oils is noted but not credited for these oils or debited to heavier oils in PRELIM version 1.1; this will be considered in OCI Phase 3 as it is of consequence for GHG emissions from the lightest condensates to the heaviest oil sands. PRELIM version 1.1 also allows users to specify output ratios (fixed case) for products like gas, diesel, among others.

OPEM Version 1.1

OPEM was developed by Deborah Gordon and Jonathan Koomey and their colleagues at the Carnegie Endowment for International Peace and Stanford University.[15] An overriding goal of OPEM is to include in the default GHG emission calculation—and thereby avoid carbon leakage from—all petroleum products and co-products. Historically, petroleum end use has centered on transport fuels, including gasoline and diesel, and has ignored or incompletely and inconsistently accounted for GHGs from petroleum co-products like petcoke, fuel oil, residual fuels, asphalt, and petrochemical feedstocks. OPEM version 1.1 includes these co-products; those that are not yet displayed in the OCI Phase 2 web tool will be added to a revised OPEM version 2.0 in Phase 3.

The default product slate output from PRELIM can be found in the worksheet "PRELIM Product Slates" in the OPEM workbook. Alternative product slates can be generated by running PRELIM. OPEM defaults to 100% complete combustion of all petroleum products refined from a barrel of oil. In the current OCI default, petrochemical feedstock is used for refinery fuel gas. If instead, petrochemicals are produced and not combusted in their end use, their potential GHG emissions savings are offset by the natural gas used to fuel the refinery. Potential GHG emission savings from producing petrochemicals from ultra-light oils, such as condensates, merit further investigation in Phase 3 as their refinery fuel gas requirements may result in surplus end product of petrochemical feedstock. In terms of product end use, depending on the quality of the engine in which a fuel is burned, EPA emission factors may result in a best-case (lowest emission) estimate. This will be investigated in Phase 3.

Converting Emission Outputs to Other Metrics

The default functional unit or metric in the OCI is GHG emissions per barrel of oil input. The OCI web tool also converts emissions to other metrics, including emissions per megajoule (MJ) of petroleum products and emissions per US dollar of petroleum products or barrel of crude oil (where available for priced and tracked global oils). These conversions are calculated by multiplying default results by reported lower heating values (in megajoule per barrel) and product or oil prices (in dollars per barrel, excluding all taxes), respectively.

Prices default to March 2016 data, and historic February 2015 prices are also presented for comparisons. The OCI web tool permits users to adjust petroleum product prices for both updating and forecasting purposes. These results will show when the user selects GHG emission results based on the metric of emissions per dollar of petroleum products or barrel of crude oil.

OCI Phase 2 Findings

The OCI results for 75 oils, representing about 25% of global oil production, reveal that production and refining greenhouse gas (GHG) equivalent emissions per barrel each vary by about a factor of 10 from lowest to highest.[16] There is a 60% difference in total GHG emissions between the lowest and highest emitting oil, and this emissions difference increases to nearly 75% when assuming that associated gas is utilized instead of wasted.

The OCI identifies certain oils that are more challenging to manage in terms of their climate impacts. These include depleted, gassy and flared, and extra-heavy oils. And given available data, tomorrow's prospective unconventional oils can be modeled using the OCI to identify opportunities to successfully manage their GHG emissions.

Managing Depleted Oils

Oil extraction processes require force in order to lift oil out from reservoirs underground. At first, enough of a pressure differential exists between the reservoir and the well that oil will flow up, with some assistance from pumps that further reduce pressure at the surface; this technique, known as primary recovery, can be used to extract around 10% of the oil in the reservoir. Secondary recovery methods supplement the natural pressure by flooding the reservoir with water or other solvents or gases to displace the oil; this can recover up to 40% of the oil in the reservoir.[17]

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[15] A complete list of the researchers involved can be found in the About section of the OCI web tool. A link to the OPEM workbook can be found at: http://oci.carnegieendowment.org/assets/OPEM1.0.xlsx.

[16] OCI.CarnegieEndowment.org.

[17] U.S. Department of Energy, "Enhanced Oil Recovery," accessed 23 February 2016, http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery.

For the oil that remains, tertiary recovery, also known as enhanced oil recovery (EOR), is required for extraction. Tertiary recovery is different from primary and secondary in that it aims to change a chemical property of the oil—generally, lowering its viscosity—either by heating the oil with steam, or by injecting the reservoir with gas or with some other kind of solvent. When producers transition from primary to secondary to tertiary recovery, the common-sense economic logic of resource extraction is at work: the lowest cost, most easily accessible resources are extracted first. The particular EOR method used will depend on the geological characteristics of the reservoirs from which the oil is extracted, as well as on the cost of EOR technologies. OCI estimates suggest that some EOR methods, particularly steam flooding, can have an outsized impact on the GHG emissions of depleted oils.

Recent developments in solar thermal EOR offer the hope of lowering GHG emissions. Rather than burn fossil fuels to generate steam, solar thermal EOR projects heat water by concentrating solar energy with arrays of mirrors; the steam generated is then pumped into the reservoir.[18] The two solar EOR designs currently in commercial use are the tower and enclosed trough systems.[19] Other novel approaches to EOR are under development that have yet to be modeled using the OCI, such as using carbon dioxide for the dual purpose of EOR and to permanently store CO_2 underground as another method of carbon capture and sequestration (CCS).[20]

Managing Gassy Oils

In many reservoirs, in Norway, Nigeria, North Dakota, and elsewhere, natural gas sits on top of or is dissolved into the gassy oils. This associated gas must be extracted and separated from the oil in order to refine the crude. Producers can handle this gas either by carefully containing and making efficient use of it or by wasting and burning or releasing this gas. The best way to manage associated gas is to capture it for operational or commercial use: producers can reinject the captured gas back into the reservoir to improve oil recovery; use it for fuel or for power generation onsite, or process the gas and sell it on the market. Moreover, producers can routinely monitor fugitive emissions so that associated gas does not unintentionally leak through fittings, tanks, valves, well casings, and other processing units.

Utilizing associated gas requires the development of gas collection, processing, and pipeline infrastructure that is ancillary to the oil supply chain. Without this infrastructure, however, managing gas associated with oil is often challenging. It can be combusted in a process called “flaring” or released into the atmosphere through “venting.” Though some small, random flaring episodes are necessary to avoid emergency pressure build-ups, when large volumes of gas must be quickly disposed of, flaring or venting gas can create environmental, safety, and health hazards. If flaring and venting become routine practices—and some countries regulate these operations better than others—they contribute greatly to oil’s upstream GHG emissions.

Methane, one of the principal components of associated gas, has a 100-year global warming potential with climate-carbon feedbacks that are 34 times that of carbon dioxide,[21] As such, the release of methane can be particularly damaging to the climate. Eradicating venting and flaring, and controlling fugitive emissions presents an opportunity to tackle some of the most important drivers of climate change.

Managing Extra-Heavy Oils

Extra-heavy oils have the potential to emit far more GHG emissions than conventional crudes because their carbon-to-hydrogen (C/H) ratios are naturally very high. The pathways employed to transform the heaviest oils from Canada, Venezuela, California, and elsewhere into petroleum products merit greater R&D to mitigate climate impacts. Currently, extra-heavy oils employ energy-intensive techniques either to produce synthetic crudes or to dilute them with gas liquids and condensates so that they can flow and be refined into petroleum products. Either way, their excess carbon must either be removed or significant hydrogen must be added to refine extra-heavy oils into high-value petroleum products.

In addition to the high GHGs emitted in their production and refining, however, extra-heavy oils that are either upgraded or run through deep-conversion coking refineries produce a low-value byproduct—petroleum coke (or petcoke). Employing petcoke in noncombustible uses, such as reclaiming oil sands mines in Alberta, can reduce extra-heavy oil emissions by over 20%. The higher the extra-heavy oil’s content, the lower quality the petcoke, the cheaper its price compared to coal, natural gas, and renewables. This resulting price differential can affect substitution of cleaner fuels used in power generation. Moreover, high sulfur petcoke (with as much as 9% sulfur) cannot be burned alone and is typically blended with lower-sulfur coal, which creates economic incentives and extends the life of coal-fired power plants. Lastly, there may be additional GHG emissions associated with petcoke that is currently unaccounted for when coke builds up on catalysts in fluid catalytic cracking (FCC) refineries. Recently, the US Energy Information Administration identified possible GHG undercounting of coke burned off the catalyst and used for FCC process energy. Since cat-coke cannot be collected and sold, it must be burned onsite, and is a significant source of GHG emissions.

Every link in the extra-heavy oil supply chain may connect to a lower emission future: mobile mining operations to diminish the need for trucks in surface mining, partial upgrading to reduce the need for diluent in transporting bitumen, solvents to reduce

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[18] Unlike photovoltaic systems, which utilize familiar solar panels to generate electricity from solar energy, concentrating solar power (CSP) utilizes sunlight to generate thermal energy. It is more efficient to use CSP rather than use PV to generate electricity from sunlight and transform the electricity into thermal energy.

[19] BrightSource Energy’s tower design employed at Chevron’s Coalinga field involves focusing an array of mirrors at a single tower in which water is heated and then injected into the reservoir. Enclosed troughs designed by GlassPoint Solar are glasshouse-encased parabolic mirrors that focus sunlight onto a tube of water to heat it as the water travels through apparatus. See: *Solar enhanced oil recovery: An in-country value assessment for Oman* (Ernst and Young, January 2014): 19–22.

[20] See for example, International Energy Agency (IEA), https://www.iea.org/topics/ccs/subtopics/storagethroughco2-eor/.

[21] The OCI uses a GWP for methane of 34 that includes climate feedbacks. See: U.S. Environmental Protection Agency, “Understanding Global Warming Potentials,” accessed on 13 March 2016, http://www.epa.gov/climatechange/ghgemissions/gwps.html.

the power consumption for steam-based situ operations, renewable steam generation, noncombustible uses for petcoke, renewable hydrogen to reduce petcoke production altogether while significantly reducing the overall emissions intensity of the total product slate, and using microbes to enhance oil recovery and sequester carbon. Each of these new pathways need to be assessed using the OCI in order to estimate their relative lifecycle GHG impacts from the development of extra-heavy oils.

The technical and social possibilities for reducing the climate and broader environmental impacts of oil-sands production continue to proliferate, with a variety of short-, medium-, and long-term opportunities, particularly in the Canadian context.[22] With forward-thinking policies, well-designed incentive structures, and climate-oriented institutional development, breakthroughs could extend far beyond Canada to other extra-heavy oil regions in Venezuela, Utah, and beyond.

Managing Other Unconventional Oils

New unconventional hydrocarbons could provide future sources of petroleum products. From new tight oil techniques to retorting kerogen to converting gas and coal to liquids, there are seemingly unlimited resources from which to make the liquid fuels the market highly values. Each of these resources could have different trade-offs in their GHG emissions and this offers new challenges and opportunities for lower-carbon management.

Moreover, as the kinds of hydrocarbon resources that can be utilized in oil production have expanded, so too have the kinds of ecosystems in which these resources are found. From boreal forests to rainforests to Arctic permafrost, the effects of land use on oils' upstream GHG emissions are understudied, and more information is needed to understand the climate impacts of hydrocarbon extraction from sensitive ecosystems—particularly the Arctic permafrost and in rain forests.

New feedstocks, updated production and refining processes, and different operating environments should be assessed using the OCI to estimate GHGs from tomorrow's oils.

The Road Ahead

Future phases of the OCI will continue to probe sustainability via innovation (Table 2). The OCI can provide new fundamental knowledge for those who are interested and engaged in supporting global climate goals. This approach also plays a critical role in comparing oils and defining a workable framework for evaluating various sustainable technologies.

Table 2 Potential future OCI research directions

OPGEE
- Reconfigure model for GHG estimates with co-generation
- Calculate GHG emission impacts of CO_2 injection and storage as an enhanced recovery alternative
- Collect and report GHG emissions embodied in oil reservoirs using oil reserve data, as available

PRELIM
- Create universal collection protocol for standardized, open-source assays (especially for unconventional oils, including condensates and extra-heavy oils)
- Reconfigure model to balance hydrogen running individual crudes to assign credits and debits for oils that produce and use hydrogen and, if possible, include renewable hydrogen calculations in the OCI
- Build model's fixed case capacity to maximize production of gasoline and diesel fuel into the OCI web tool
- Incorporate petrochemical feedstock and asphalt production in refinery fixed cases

OPEM
- Update user inputs for transportation end products
- Revise to reflect user-based options for crude and product transport and product combustion. Test scenarios to determine GHG emission sensitivities in downstream end use
- Update user inputs for transportation end products

OCI OVERALL
- Investigate new oil sands and extra-heavy oil pathways, including numerous novel options under consideration
- Increase the number of oils modeled in the OCI, including a wide range of types and geographies
- Update oil data reporting
- Expand OCI data quality and uncertainty analysis
- Add air quality modeling estimates to the OCI to evaluate oils on two dimensions—climate change and air pollution
- Include short-lived climate forcers to the OCI, including black carbon and tropospheric ozone
- Update land-use inputs in OPGEE model to reflect up-to-date knowledge, especially for oils in climate-sensitive ecosystems such as the Arctic and forests
- Include macroeconomic modeling, including petroleum coke and coal, gas, and renewables substitution effects and comparing the marginal cost of unconventional oil techniques to average oil costs
- Incorporate user suggestions to improve the OCI

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[22] See, e.g., Council of Canadian Academies, *Council of Canadian Academies, and Expert Panel on the Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development, Technological Prospects for Reducing the Environmental Footprint of Canadian Oil Sands*, 2015, http://www.deslibris.ca/ID/247029.

Technological breakthroughs in extracting and refining a diverse array of heavier, lighter, tighter, deeper, and depleted oils have made a resource once deemed scarce more abundant. As the global oil portfolio rapidly expands with the transformation throughout the value chain, we should pay attention not only to the climate impacts of increased oil consumption downstream but also to the impacts of these upstream and midstream techniques. While the cumulative consumption of 1.3 trillion barrels of oil to date has contributed mightily to global warming,[23] tomorrow's burning questions revolve around how to manage the trillions of barrels of oil that remain and whose use will accelerate our climate crisis.[24]

The variations in GHG emissions between oils are large enough to matter, and should prompt innovations in data, analysis, risk assessment, and policy design. The "crude-centric" approach can help producers, refiners, oil traders, policymakers, investors, academics, NGOs, and the public focus attention on new innovations, reducing climate risks, smarter policies, and successfully mitigating total GHG emissions from the oils sector. Accomplishing these goals will require widespread adoption of this new way of thinking, which must be underpinned by new data collection and analysis.

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[23] Miller, R. G. and Sorrell, S. R. (2014). "The Future of Oil Supply," *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, **372**(2006), http://dx.doi.org/10.1098/rsta.2013.0179.

[24] Jude Clemente, "How Much Oil Does the World Have Left?," *Forbes*, June 25, 2015, http://www.forbes.com/sites/judeclemente/2015/06/25/how-much-oil-does-the-world-have-left/.