Appendix: Research Methods

This Appendix describes in greater detail the scenarios presented in the report. To illustrate the greenhouse gas emissions consequences of policies to phase out crude oil production, we consider three scenarios:

- **Business as Usual Scenario** uses oil supply information from the EIA's Annual Energy Outlook 2019 (AEO19) Reference Case for Liquid Fuels.
- **Domestic Demand Only Scenario** maintains the domestic oil production levels from AEO19, but pairs that with a rapid decline in domestic demand for crude oil. This scenario illustrates the impacts of successful demand-side policies to reduce U.S. oil consumption, but not corresponding policies to limit production.
- **Aligned Policies Scenario** matches the steep decline in domestic demand with a similar decline in domestic production, illustrating the impacts of aligning demand- and supply-side policies in a comprehensive approach.

This report presents preliminary results from a simplified model and we hope to extend and refine these results in future research. Key assumptions in constructing these scenarios include:

- We only consider greenhouse gas emissions from crude oil, and not other liquids such as NGLs or biofuels. As such we calculate emissions for each scenario in terms of lifecycle emissions from a barrel of crude, rather than an accounting of refined petroleum products.
- We consider two markets for crude oil -- the U.S. and the rest of the world (ROW) -- and we assume that ROW crude consumption reacts to changes in ROW crude supply consistent with published market elasticities. As discussed below, uncertainty in this ROW market response is likely the largest uncertainty in the final results.
- We also assume that trends in U.S. crude consumption can be independent of trends in domestic production, in certain scenarios.

Business as Usual Scenario: AEO19 Reference Case

As our baseline we adopt EIA's Annual Energy Outlook 2019 (AEO19) Reference Case for Liquid Fuels.[1] In comparison to the previous iteration AEO18,[2] EIA now projects a much larger increase in domestic oil production (up from ~12 MMb/d to >14 MMb/d at its peak), which is offset by a decrease in net imports that leaves total crude supply roughly the same between the two scenarios. For historical domestic oil production we also use EIA data for production[3] and crude oil disposition.[4] We refer to this as the Business as Usual Scenario, which provides our baseline for carbon emissions from crude oil consumption from 2017 to 2050.

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[1] U.S. EIA. 2019f. Annual Energy Outlook 2019. Table: Petroleum and Other Liquids Supply and Disposition. [link]; The Reference Case is the EIA's estimate for the energy market response to their central assumptions for future economic growth, future oil prices, the size of domestic energy resources, and technological change in the context of current law and regulations. For more information see U.S. EIA. Annual Energy Outlook 2019 Case Descriptions. [link]

[2] U.S. EIA. 2018. Annual Energy Outlook 2018. Table: Petroleum and Other Liquids Supply and Disposition. [link]

[3] U.S. EIA. Petroleum & Other Liquids: Crude Oil Production. [link]

[4] U.S. EIA. Petroleum & Other Liquids: Supply and Disposition. [link]

A barrel of crude oil in the AEO can be produced in the U.S. (some of which are then directly exported as crude) or imported. Crude which is not exported is then refined into petroleum products, which are either exported or consumed domestically. The goal of our analysis is to follow barrels of crude through the system and account for the lifecycle greenhouse gas emissions from those barrels. This differs from a full emissions analysis of all liquid fuels, which will be a subject of future research.

EIA defines Total Crude Supply (TCS) as (domestic crude production) + (net crude imports) + (other crude supply):

$$TCS = C_{prod} + (C_{imp} - C_{exp}) + C_{other}$$

Other Crude Supply refers to stock additions and withdrawals, which are small compared to the other terms, and which the AEO sets to zero in later years. Crude exports are not included in TCS, by definition. All quantities are time series running from 2017 to 2050.

For this analysis, we wish to distinguish between crude that is consumed in the U.S. and crude that is exported and consumed abroad. To do this we estimate the fraction of TCS that is consumed domestically by looking at AEO19 information on petroleum products.

EIA defines Total Primary Supply (TPS) to be the total amount of liquid fuel refined products supplied to domestic sources. The AEO also breaks down TPS by sector and product. TPS is defined as: (total crude supply) + (natural gas plant liquids)[5] + (other liquids, including a small quantity of biofuels)[6] + (gross product imports) + (refinery processing gain) - (product exports):

$$TPS = (TCS + NGL + L_{other} + P_{imp}) + R_{gain} - P_{exp} .$$

The total volume of refined products (which we refer to here as refinery outputs, or RO) is then the sum of TPS (which is domestic only) and product exports (P_{exp}). From this we define the fraction of refined products that are consumed domestically (D):

$$D = TPS/(TPS + P_{exp})$$

[5] U.S. EIA. 2012. What are natural gas liquids and how are they used? Today In Energy, April 20. [link]
[6] AEO19, footnotes 6 and 7.

Figure A1 shows the flow of oil through the system for the AEO19 reference case in the year 2030.

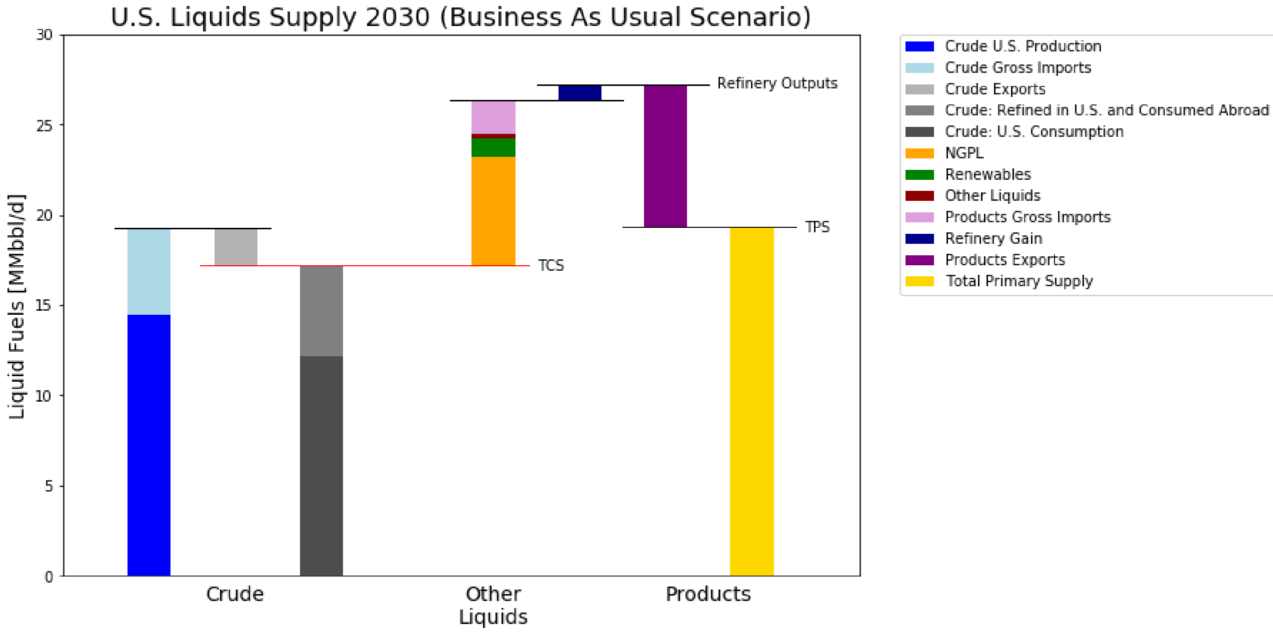

Figure A1: Waterfall diagram for crude oil in the Business As Usual Scenario.

Since we are basing our carbon calculations on estimates of lifecycle emissions of a barrel of crude, rather than a more complex accounting of various refined products, we report all production in terms of crude, rather than products. We use the ratio D to estimate the fraction of TCS that is consumed domestically (denoted C_{dom}) and the fraction (1-D) that is refined in the U.S. but exported and consumed abroad (denoted C_{row}).

The left hand side of Figure A1 illustrates how domestic crude production (dark blue) and gross product imports (light blue) are partitioned into these three categories: C_{dom} (dark gray), C_{row} (medium gray), and direct crude exports C_{exp} (light gray).

Crude oil that is not consumed domestically is then exported, either directly as crude or as refined products. The *net* of these two forms of exports

$$(C_{exp} - C_{imp}) + ((1 - D) * TCS - P_{imp})$$

we take to be the net contribution to the rest-of-world (ROW) oil supply, which we discuss below.[7] Figure A2 shows the time series of five crude oil quantities 2017 to 2050 in the Business as Usual Scenario: C_{prod} (blue), TCS (red), C_{dom} (dark gray), C_{row} (medium gray) and C_{exp} (light gray).

[7] We note that using P_{imp} in this formula is an approximation of the net change to ROW crude oil supply, since product imports include NGLs, biofuels and other liquids.

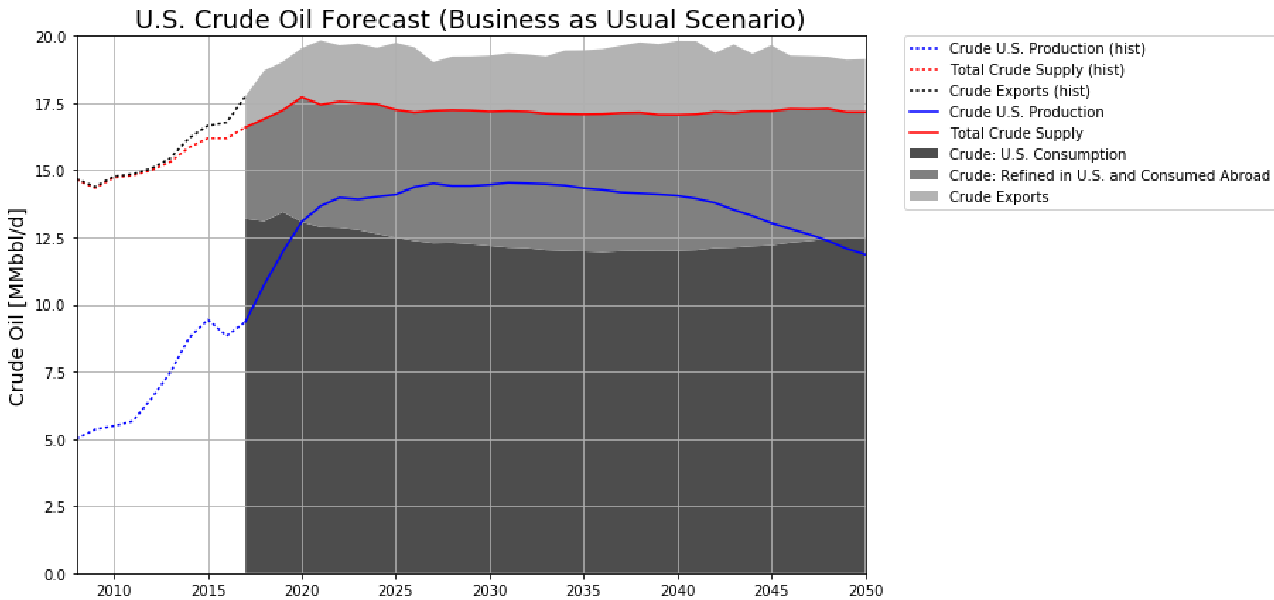

Figure A2: Time series of crude oil quantities in the Business As Usual Scenario.

Domestic Demand Only Scenario: Declining domestic demand leads to increased exports

In the Domestic Demand Only Scenario we consider a world where domestic oil production remains at the level found by AEO19, but U.S. domestic demand for petroleum products declines steeply from 2020 to 2050. In general, we find that a decrease in domestic demand coupled with high levels of production leads to greater exports, and a corresponding increase in ROW carbon emissions that partially undermine domestic emissions reductions.

Successful policies to reduce domestic demand for refined petroleum products would lead to a decline in TPS (varying by sector and product, which we don't consider here). The industry can respond to a decline in TPS either by increasing product exports, reducing overall refinery outputs, or some mixture of the two. Assuming (for this Scenario) that domestic crude oil production remains unchanged, a decrease in refinery output implies a decrease in net crude imports. We can parametrize this choice by specifying that a fraction (r) of the decline in TPS will go to decreased refinery outputs and (1-r) will go to increased product exports.

Note that the value of r does not matter for our carbon accounting, since both crude and product exports increase the ROW oil supply and we are considering lifecycle emissions from a barrel of crude. The value of r, and hence the ratio of crude to product exports, would determine the level of refinery capacity in the U.S.

We start by defining a decline profile, L, for the years considered in these scenarios to describe the decline in domestic consumption. Applying this profile to the Business as Usual TPS defines TPS for the Domestic Demand Only Scenario:

$$TPS_{DDO} = TPS_{BAU} \cdot L$$

We then use the parameter, r, to apportion the difference between TPS in the two scenarios, and use this to define P_{exp} and refinery outputs (RO) for the Domestic Demand Only Scenario.

$$P_{exp,DDO} = P_{exp,BAU} + (1-r) \cdot (TPS_{BAU} - TPS_{DDO}) = P_{exp,BAU} + (1-r) \cdot (1-L) \cdot TPS_{BAU}$$
$$RO_{DDO} = RO_{BAU} - r \cdot (TPS_{BAU} - TPS_{DDO}) = RO_{BAU} - r \cdot (1-L) \cdot TPS_{BAU}$$

Note that subtracting these expressions reduces to TPS_{DDO} as it should, and both parameters are then defined solely in terms of quantities from the Business As Usual scenario, the decline profile L, and the parameter r.

Most of the other quantities in the scenario (TCS, NGL, L_{other}, P_{imp}, R_{gain}, and C_{imp}) are simply scaled by the ratio of refinery outputs between the two scenarios. For example, TCS is scaled thusly:

$$TCS_{DDO} = TCS_{BAU} \cdot (RO_{DDO}/RO_{BAU}) = TCS_{BAU} \cdot (1 - rD \cdot (1-L))$$

which is simplified using the definition for the domestic fraction D above. Since C_{prod} is held constant between the two scenarios, this formula also defines C_{exp} for the Domestic Demand Only Scenario. Figure A3 shows the flow of oil through the Domestic Demand Only Scenario for the year 2030 for r=0.5.

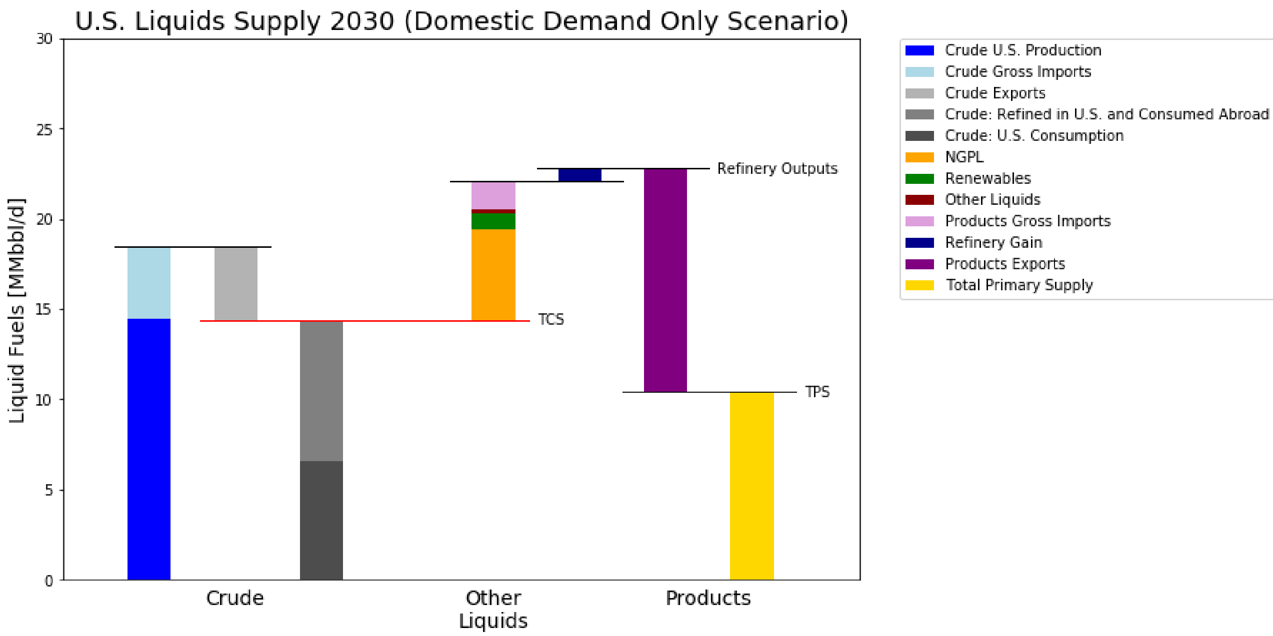

Figure A3: Waterfall diagram for crude oil in the Domestic Demand Only Scenario.

As Figure A3 shows, the reduction in TPS is accommodated both by an increase in product exports (dark purple) and by an overall reduction in refinery output leading to an increase in crude exports, in comparison to the Business as Usual Scenario.

Figure A4 shows the time series of five crude oil quantities 2017 to 2050 in the Domestic Demand Only Scenario: C_{prod} (blue), TCS (red), C_{dom} (dark gray), C_{row} (medium gray) and C_{exp} (light gray).

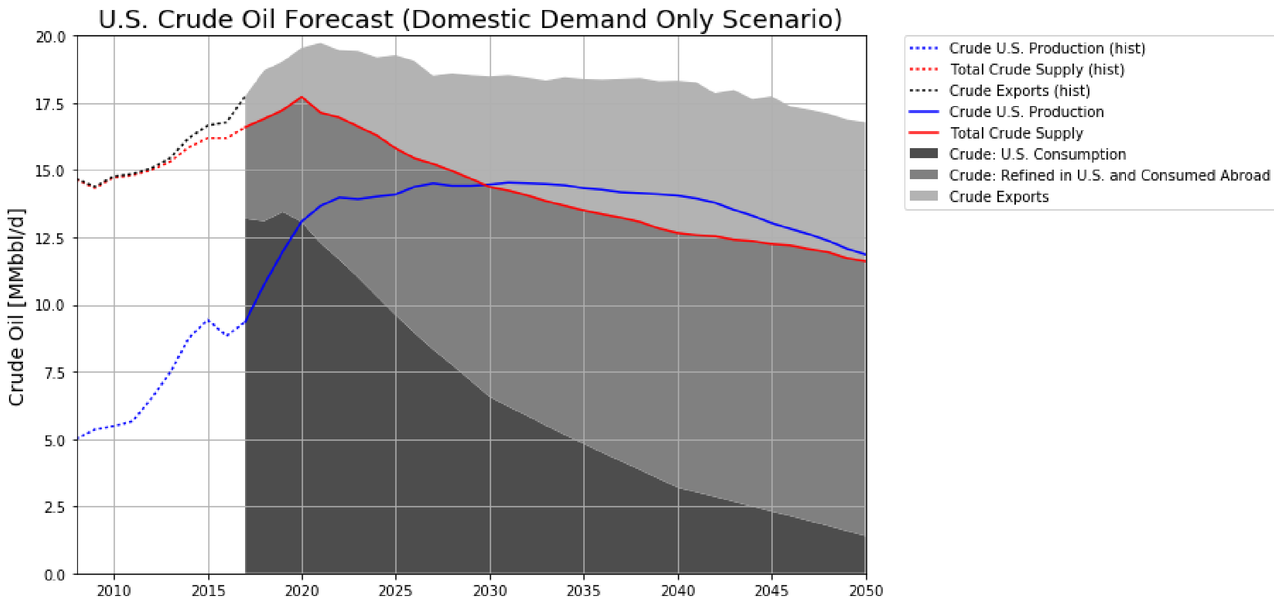

Figure A4: Time series of crude oil quantities in the Domestic Demand Only Scenario.

Aligned Policies Scenario: Declining Demand and Supply

In the Aligned Policies Scenario, we use the same scenario for reduced domestic demand (TPS) but match it with a similarly declining scenario for domestic oil production. Unlike in the Domestic Demand Only Scenario, with declining domestic demand and declining production, the industry would no longer have a choice to increase either crude or product exports (i.e. there is no r parameter). In this case, all inputs (TCS, NGL, product imports, renewable, and other liquids) are scaled down using the same decline profile, L. Figure A5 below shows the flow of oil through the Aligned Policies Scenario for the year 2030.

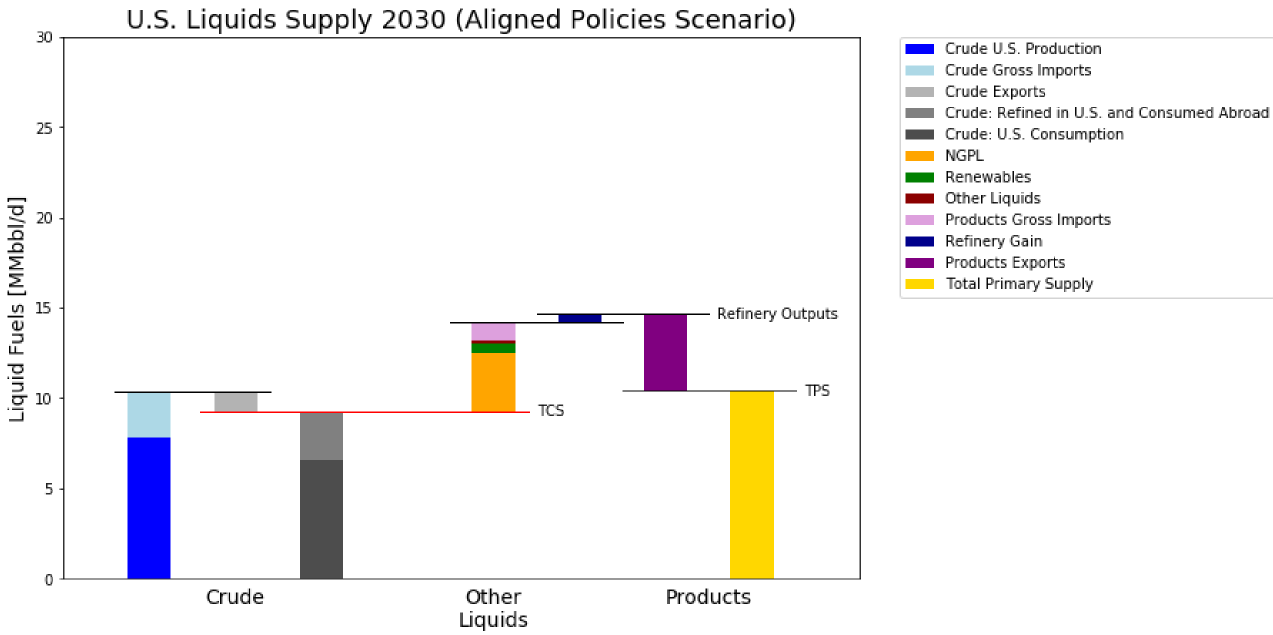

Figure A5: Waterfall diagram for crude oil in the Aligned Policies Scenario.

Figure A6 below shows the time series of five crude oil quantities 2017 to 2050 in the Aligned Policies Scenario: C_{prod} (blue), TCS (red), C_{dom} (dark gray), C_{row} (medium gray) and C_{exp} (light gray).

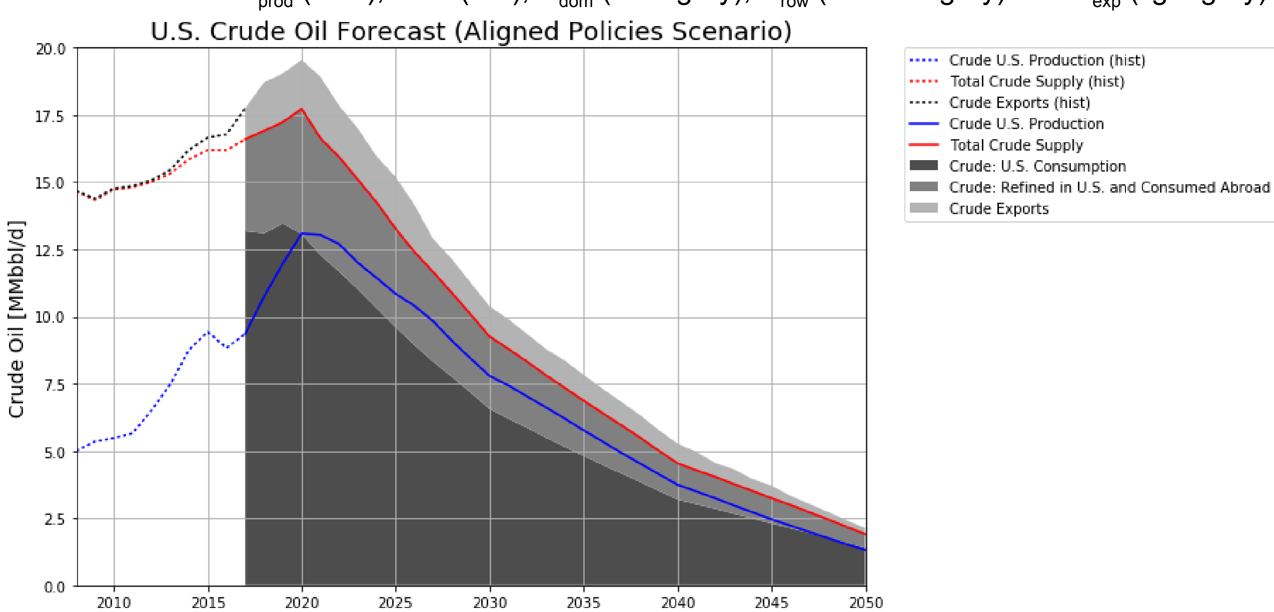

Figure A6: Time series of crude oil quantities in the Aligned Policies Scenario.

Greenhouse Gas Emissions

U.S. domestic emissions from crude oil consumption are calculated by:

$$E_{dom} = D * TCS * F_{LC}$$

where F_{LC} is the lifecycle emissions of a barrel of crude, equal to 0.510 metric tonnes CO_2-eq per bbl. This value is the median U.S. oil grade (U.S. East Texas Field) analyzed by the Oil Climate Index.[8] A more complex carbon accounting could take into account down-, mid-, and upstream emissions for each category, but for this report we simply assign full lifecycle emissions to crude that is consumed in the U.S.

We then follow the methodology used and documented by the Stockholm Environment Institute (SEI) in calculating the increase in ROW oil supply, consumption and emissions due to these increased (crude and product) exports.[9,10] For each barrel of increased crude oil and refined product exports in the Domestic Demand Only and Aligned Policies Scenarios, we estimate an increase of 0.44 barrels of ROW crude oil consumption (in comparison to the Business As Usual baseline), and a corresponding increase in ROW greenhouse gas emissions.

We note that the primary results presented in this report are highly sensitive to this replacement fraction relating oil supply to consumption. Based on a review published elasticities, SEI presents a range of 0.2 to 0.6 for this replacement fraction for *global* oil consumption,[11] and for this report we adopt a factor of 0.44 for ROW oil consumption as an illustration of the effect. A full sensitivity analysis will be a topic for future research.

Domestic Emissions Are Identical

The Domestic Demand Only and Aligned Policies Scenarios are constructed so that domestic crude oil consumption (and hence domestic emissions from crude oil) are the same in each. This is a nice feature of the scenarios because it limits the differences between the Domestic Demand Only and Aligned Policies Scenarios to exports and global market effects. Crude oil consumed in the U.S. is then given by the product of TCS and D. We can then show that this product is equal for the Domestic Demand Only and Aligned Policies Scenarios:

$$D_{DDO} * TCS_{DDO} = D_{APS} * TCS_{APS}$$

To show this, we first note that the domestic ratio (D) is identical for the Business as Usual Scenario and the Aligned Policies Scenario:

$$TPS_{BAU}/RO_{BAU} = TPS_{APS}/RO_{APS}$$

This is because under the Aligned Policies Scenario, the decline profile, L, is applied equally to every term making up both TPS and RO, and so it can be factored out of the ratio.

For the Domestic Demand Only Scenario, each of the terms of TCS is proportional to the ratio of refinery outputs between the Business as Usual Scenario and the Domestic Demand Only Scenario. The initial equation we wish to prove becomes:

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[8] Carnegie Endowment for International Peace. Oil Climate Index: North America Region. [link]

[9] Erickson, P. & M. Lazarus. 2016. *How would phasing out U.S. federal leases for fossil fuel extraction affect CO2 emissions and 2°C goals?* Stockholm Environment Institute. [link]

[10] Erickson, P. 2016. U.S. again overlooks top CO2 impact of expanding oil supply, but that might change. Stockholm Environment Institute, April 30. [link]

[11] Erickson, P. & M. Lazarus. 2018. *How limiting oil production could help California meet its climate goals*. Stockholm Environment Institute. [link]; see discussion in Box 1, p. 3-4.

$$(TPS_{DDO}/RO_{DDO}) * TCS_{BAU} * (RO_{DDO}/RO_{BAU}) = (TPS_{APS}/RO_{APS}) * TCS_{BAU} * L$$

Canceling factors and substituting D_{BAU} for D_{APS}, we can write:

$$(TPS_{DDO}/RO_{BAU}) = (TPS_{APS}/RO_{APS}) * L = TPS_{BAU}/RO_{BAU} * L$$

which then simplifies to,

$$TPS_{DDO} = TPS_{BAU} * L$$

which was the original definition of the Domestic Demand Only Scenario.