Effect of Crude Oil Carbon Accounting Decisions on Meeting Global Climate Budgets

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Abstract

The Intergovernmental Panel on Climate Change quantified a cumulative remaining carbon budget beyond which there is a high likelihood global average temperatures will increase more than 2 °C above pre-industrial temperature. While there is global participation in mitigation efforts, there is little global collaboration to cooperatively mitigate emissions. Instead, countries have been acting as individual agents with independent emission reduction objectives. However, such asymmetric unilateral climate policies create the opportunity for carbon leakage resulting from the shift in embodied carbon emissions within trade networks. In this analysis, we use an optimization-based model of the global crude trade as a case study to demonstrate the importance of a cooperative, system-level approach to climate policy in order to most effectively, efficiently, and equitably achieve carbon mitigation objectives. To do this, we first characterize the cost and life cycle greenhouse gas emissions associated with the 2014 crude production and consumption system by aggregating multiple data sources and developing a balanced trade matrix. We then optimize this network to demonstrate the potential for carbon mitigation through more efficient use of crude resources. Finally, we implement a global carbon cap on total annual crude emissions. We find that such a cap would require crude consumption to drop from 4.2 gigatons (Gt) to 1.1 Gt. However, if each country had an individual carbon allocation in addition to the global cap consistent with the nationally determined contribution limits resulting from the 2015 United Nations Climate Change Conference, allowable consumption would further decrease to approximately 770 million metric tons. Additionally, the carbon accounting method used to assign responsibility for embodied carbon emissions associated with the traded crude further influences allowable production and consumption for each country. The simplified model presented here highlights how global cooperation and a system-level cooperative approach could guide climate policy efforts to be more cost-effective and equitable, while reducing the leakage potential resulting from shifting trade patterns of embodied carbon emissions. Additionally, it demonstrates how the spatial distribution of crude consumption and production patterns change under a global carbon cap given various carbon accounting strategies.
1. Introduction

Through international climate negotiations, such as at the Paris Climate Change Conference in 2015, policy-makers have agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above the preindustrial average global temperature (UNFCCC 2016). In order to curb the average global temperature rise, climate models have demonstrated a limit to the cumulative emissions that can be sustained by the climate system. This limit is called the global carbon budget. The Intergovernmental Panel on Climate Change (IPCC) reported that this budget is in the range of 870-1,240 Gt CO₂-eq between 2011 and 2050 in order to have a 56% chance of not exceeding this 2°C temperature increase (IPCC 2014).

Limiting emissions to within the global carbon budget would require substantial greenhouse gas (GHG) mitigation efforts. McGlade and Ekins (2015) used an integrated assessment model to explore the implications of this emissions limit for fossil fuel production (McGlade and Ekins 2015). In their scenario to keep average global surface temperature rise below 2°C for all years to 2200, they found 2050 GHG emissions must be constrained to 21 Gt CO₂-eq. This is compared to the 48 Gt CO₂-eq emitted in 2010, and a baseline 2050 projection of 71 Gt CO₂-eq given no emissions mitigation. This latter projection would result in almost a 5°C global average temperature rise (McGlade and Ekins 2015).

While there is general agreement on a cumulative emissions mitigation target, little policy consensus has been reached globally as to how to implement such GHG emissions reductions. Climate policy is a complex issue that involves multiple stakeholders, competing objectives, economic barriers, and issues of equity and responsibilities (IPCC 2015). As a result, the current approach has been to allow each country to determine its own contribution towards emissions reduction targets. The most recent United Nations Climate Change Conference, COP21, in Paris resulted in 188 committing to Nationally
Determined Contributions (NDCs). Each NDC was developed independently, without regard for the effect one country’s mitigation efforts would have on another country.

However, due to the expansiveness of the global commodity trade network, an individual country’s NDC has implications for the effectiveness of global mitigation efforts on the macro scale. An important consequence of international trade is that commodities produced in one country may be consumed in another country. This concept of emissions being released in one country to produce goods for the benefit of another country through international trade is referred to as embodied carbon (Kanemoto et al. 2016; Peters and Hertwich 2008). Studies have demonstrated that shifts in production and trade patterns can influence global carbon emissions (Strømman et al. 2009; Weber and Peters 2009).

Embodied carbon emissions present two key impediments in the implementation of NDCs. The first obstacle is that some countries’ NDCs are more constrictive than others. As a result, rather than the countries with binding NDCs reducing their consumption and therefore contributing to global emissions reductions, those countries may potentially instead shift the upstream production emissions (embodied emissions) to countries with non-binding NDCs. This shift in trade patterns resulting from asymmetric country specific emissions targets is referred to as carbon leakage (Bohringer et al. 2012; Condon and Ignaciuk 2013; Felder and Rutherford 1993; Strømman et al. 2009; Weber and Matthews 2007; Wyckoff and Roop 1994). Carbon leakage occurs when action taken by countries to reduce emissions is partially or wholly offset by increased emissions elsewhere in the world. Arroyo-Curras et al. (2015) assessed carbon leakage in the energy sector under various climate policies using an integrated assessment model. The results of the study indicate carbon leakage in the energy sector is likely in the short-term due to fragmented climate policies, but could be offset in the future if the initial unilateral climate actions ultimately lead to a cooperative, global idealized climate policy.

The second challenge arising from the trade of emissions embodied in the production of commodities is how to assign responsibility for the emissions. Because some countries are net carbon exporters while others are net carbon importers, each potential emissions
tracking mechanism affects countries differently. Tracking emissions relies on carbon accounting methods that traditionally tally only emissions sources within the country. This has expanded in recent years to consider emissions occurring along the supply chain (i.e., carbon footprint, or embodied carbon). Some commonly discussed carbon accounting frameworks include location-based, where countries are responsible for what is emitted within their borders, production-based, where the producer would be responsible for the full life cycle emissions of what they produce, and consumption-based, where countries are responsible for all life cycle emissions of what they consume (Steininger et al. 2015). While all methods are theoretically equivalent from a global perspective, they function differently in a fragmented climate policy regime (IPCC 2013).

For example, Jakob and Marschinski (2012) argue that the dynamics of fragmented policy regimes need to be better characterized in order to guide policies to effectively reduce global emissions (Jakob and Marschinski 2012). Gonzales-Eguino et al. (2016) define a fragmented climate regime as being characterized by different climate policies across regimes and sectors, that may lead to the relocation of production to regions with less stringent mitigation rules. Several recent studies have used integrated assessment models to demonstrate the potential for carbon leakage associated with such asymmetric climate policies (Arroyo-Currás et al. 2015; Luderer et al. 2015; Otto et al. 2015; Schaeffer et al. 2015).

Importantly, within a fragmented climate regime, the carbon accounting strategy has implications for carbon leakage given the same set of NDCs. For example, under a consumer-based method, the NDC of a net carbon exporter would largely be non-binding, and therefore provides opportunity for significant carbon leakage. Alternatively, under a producer-based method that same country’s NDC could limit domestic economic activity. Therefore, when evaluating the effectiveness of NDCs, it is important to do so within the context of a given carbon accounting mechanism.

This study contributes to the literature by developing a theoretical model to explore the impact of unilateral climate goals on mitigation efficiency based on a case study of the global crude trade. Using an optimization-based approach, we develop a framework that
characterizes the potential for NDCs to limit the effectiveness of climate mitigation efforts as compared to a cooperative international climate policy under a strict global carbon budget. Additionally, while under a global climate policy all carbon accounting methods should yield equivalent mitigation efficiencies (Steckel et al. 2010), the model explores how carbon accounting alternatives further interact with the fragmented climate policy-based NDCs to shift the geospatial dynamics of production and consumption.

The optimization model developed for this analysis demonstrates the influence of shifting trade patterns under different climate policies and carbon accounting strategies. While the model is simplified and theoretical, the results offer meaningful insights into potential emissions mitigation opportunities and demonstrate the importance of globally cooperative climate policies. The analysis extrapolates a simplified economy, focusing on the crude sector as a theoretical self-contained entity. Because crude is a widely traded commodity with a high degree of embodied emissions, the global crude trade is a valuable case study to demonstrate how climate policies and carbon accounting strategy interactions can incentivize or dis-incentivize cost effective carbon mitigation measures. Davis et al. (2011) found that 37% of global emissions are from fossil fuels traded internationally (Davis et al. 2011). Of the approximately 32.4 billion barrels (bbls) of oil produced each year (4.4 Gt), approximately 64% (21 billion bbls, or 2.8 Gt) is exported from one country to another (BP Statistical Review of World Energy 2015), primarily by vessel movements (17 billion bbls, or 2.4 Gt) (Reuters 2016).

2. Methods

Throughout this study, we analyze annual international crude trade under the modeling constraint of a market approaching a stable equilibrium at a point in the future. This theoretical construct enables us to explore the potential interactions between climate policies, emissions abatement potential, cost of crude as a primary energy source, and the global distribution of consumption under a range of restrictions. While computable general equilibrium (CGE) models characterize the progression of change over time as part of a feedback loop of price, supply, and demand, we use a single year time scale to
understand how the global system would behave at its optimal configuration (i.e., future equilibrium). The analysis begins by estimating the current, baseline crude trade network. This crude network is then optimized to demonstrate how shifting trade patterns impact cost and emissions. Finally, a carbon cap is imposed to compare the outcomes of a cooperative global climate policy versus a fragmented climate policy under three carbon accounting strategies (Figure 1). The production and consumption parameters for the baseline model are from 2014. The global crude trade model in our analysis consists of 62 countries, accounting for 4 Gt of crude (29.3 billion bbls), or approximately 95% of total 2014 production. As a proxy for both price and GHG emissions, we used API gravity, which is a measure of density and is often taken as an indicator of crude quality. All data used to develop the trade network were aggregated from 2014 data whenever possible. Exceptions to this are indicated throughout the methods section.

![Flow diagram outlining the progression of the methods described in the following sections](image)

**2.1 Reference Trade Network**

In order to quantify the potential for cost and emissions savings, we first characterized the existing trade network. The volume of crude traded from each country to each other country is known and is compiled in existing, proprietary datasets; however, these datasets are not publicly available and are expensive to obtain (IEA 2014). Some of these data are published in aggregate form. For example, the BP Statistical Review contains
trade data of totaled crude and petroleum products aggregated by region (BP Statistical Review of World Energy 2015), while other datasets such as the JODI-Oil Database publish total imports and exports by country but do not publish the volume of crude traded between specific country pairs (JODI-Oil World Database 2014). Other datasets have a high resolution of detail, but are only available for limited countries. For example, the EIA maintains a detailed database of crude imports to the United States by country (EIA 2015). A frequently used publicly available data source for international trade analysis is the United Nations database (UN Comtrade Database 2014). While comprehensive, these data are self-reported and therefore may be subject to reporting errors, missing data, or inconsistencies from year to year. As an example of a shortcoming of this dataset, the flows are not balanced, meaning total imports do not necessarily equal total exports; in 2014, petroleum imports totaled 14 billion bbls while exports totaled 12.6 billion bbls, a difference of ~10% (assuming a specific gravity of 0.88, or 140 kg per bbl of crude). A summary of the crude trade data sources used in this analysis is outlined in Table 1.

Table 1: Summary of relevant crude trade data used in this analysis

| Data Source                          | Advantages                               | Disadvantages                                    |
|--------------------------------------|------------------------------------------|--------------------------------------------------|
| BP Statistical Review (BP Statistical Review of World Energy 2015) | Thorough, compiled from multiple sources, balanced | Aggregated by regions, combines crude and products in trade matrix, does not include trade within regions |
| UN Comtrade (UN Comtrade Database 2014) | Reported by specific trade partner pairs | Self-reported data, reporters are inconsistent across years, imports do not match exports |
| JODI database (JODI-Oil World Database 2014) | Country level detail | Imports and Exports are aggregated by country, volumes traded between individual countries are not available |
| IEA OECD matrix (Energy Balances of Crude only; country specific trade partners | Does not include non-OECD imports |
OECD Countries

2015

| Reuters vessel data (Reuters 2016) | Comprehensive, port to port data | Does not include crude traded by pipeline |

The first objective of this study was to aggregate these various data sources in order to characterize the global crude system, including production, imports, exports, and domestic consumption. By taking advantage of the positive attributes of each dataset, we were able to realistically represent global trade. The 62 countries included were chosen based on the availability and consistency of data for these countries across all datasets, and together represent 95% of total crude production. While there is no clear method for validating this matrix without access to proprietary data, we ensured the system balanced and that the trade ratios (i.e., net importers and net exporters) were accurate through an iterative smoothing process implemented using linear optimization.

To develop this global crude matrix, we first aggregated the UN Comtrade data with two other obtained data sources. From the Comtrade data, we included exports from 2014 reported under the Harmonized Commodity Description and coding system (HS) commodity code 2709 (petroleum oils, oils from bituminous minerals, crude). The second dataset is the IEA’s trade balance of OECD countries. This includes import/export data from 2014 for 34 OECD countries, importing from 61 countries and exporting to 30 countries. The third dataset is of port-to-port oil tanker movements in 2015 obtained from Reuters (Reuters 2016). This dataset includes approximately 25,000 vessel movements, with vessel capacities ranging from 56 thousand bbls to 2 million bbls. In aggregating these datasets, we found some trade partners were reported only in one of the datasets, while others were reported in multiple datasets. Where a trade partner pair was reported in one dataset only, we used the reported quantity as the trade value. Where a trade partner pair was reported in two or three of the datasets, we used the maximum of the reported values. This was to account for the fact that some of the data were self-reported and therefore might be biased towards underreporting trade values.
In addition to international trade, we added domestic consumption of a country’s own production to the trade matrix. To do this, we obtained 2014 production and consumption data by country from the BP Statistical Review of World Energy (BP Statistical Review of World Energy 2015), and filled in missing country production and consumption data from the JODI-Oil database (JODI-Oil World Database 2014). We assumed a country’s production minus its exports represented the domestic consumption of domestically produced oil. Therefore, the complete mass balance for any given country must be that annual production plus annual imports minus annual exports is equal to total consumption (refinery inputs). Because the compiled trade partner pair data described above did not balance with the production and consumption data, we followed an iterative process to “smooth” the trade data, thereby producing a self-consistent production, trade, and consumption matrix. This smoothing was done using a linear optimization (Eq. 1). The decision variables were the trade values between partner pair countries. The optimization was constrained such that the ratio of trade among partners should be maintained as closely as possible to the trade ratios from the original compiled trade matrix. The objective of the model was therefore to minimize the sum of the absolute value of the differences between the optimized trade ratios and the original trade ratios. Rather than minimize the differences evenly across the system, however, the differences were weighted by the country’s contribution to supply and consumption such that larger consumers and producers were given higher importance in achieving correct trade ratios.

\[
\text{minimize } \sum_{e=1}^{C} \left( \sum_{i=1}^{C} \left( \text{abs} \left( \frac{x_{e|i}^{\text{TR}} - \sum_{i=1}^{C} x_{e|i}^{\text{TR} \cdot \text{exp}}}{\text{Difference in trade ratio across each country's export trade partners}} \right) + \text{abs} \left( \frac{x_{e|i}^{\text{TR}} - \sum_{i=1}^{C} x_{e|i}^{\text{TR} \cdot \text{imp}}}{\text{Difference in trade ratio across each country's import trade partners}} \right) \right) \cdot w_e \right) (1)
\]

with respect to

\[x_{e|i}^{\text{TR}} \in \mathbb{R} \]

\[\forall i \in \{1, \ldots, C\}, e \in \{1, \ldots, C\}, c \in \{1, \ldots, C\}\]
subject to

\[ p_c + \sum_{e=1}^{C} x_{eC}^{TR} - \sum_{i=1}^{C} x_{ci}^{TR} = u_c \ \forall c \ \text{(2)} \]
\[ p_c - \sum_{i=1}^{C} x_{ci}^{TR} \geq 0 \ \forall c \ \text{(3)} \]

where \( x_{ei}^{TR} \) is the volume of crude traded from exporter \( e \) to importer \( i \); \( r_{ei}^{\text{EXP}} \) is the designated proportion of exporter \( e \)'s product that can be traded with partner country \( i \); \( r_{el}^{\text{IMP}} \) is the designated proportion of importer \( i \)'s total imports that can be imported from partner country \( e \); \( p_c \) is the designated production volume of a given country; \( u_c \) is the designated consumption volume of a given country; \( w_e \) is the weight of the exporting country’s accuracy importance; \( C \) is the total number of countries in the trade network.

Equation (2) ensures each country’s trade pattern balances such that its production plus its imports minus its exports is equal to its total consumption. Equation (3) ensures no country exports more crude than it produces, i.e., that no re-exports of imported product are allowed in the system (re-exports were < 0.06% of total exports in 2014 according to the UN Comtrade Database).

### 2.2 Cost and GHG Emissions Associated with Trade

#### 2.2.1 API estimates

In this analysis, both cost and emissions are based on the API of crude as an indicator for crude quality. The API gravity is a measure of a crude’s density relative to water, and can vary from <27° (heavy crude) to >50° (very light crude). Even within a given oil field, crude API can vary as a function of location and/or age of field production. Different crude qualities can be blended together to create a blended API. Refineries are able to accept a narrow range of blended crude APIs. Based on historical time series data showing input blended APIs averaged by PADD region for the United States between 1985 through 2015, the average API blended in a given region tends to vary by \(-3-7°\) each year (Figure S2).
To address the importance of crude quality on price and emissions, we compiled a comprehensive database of crude APIs produced within each country. These data were aggregated from the Knovel Crude Oil Assay Database (Speight 2015), a crude oil life cycle assessment conducted by the California Air Resources Board (CARB) which analyzed all crudes imported to California (LCFS Crude Oil Lifecycle Assessment), a report by the International Council on Clean Transportation which compiled data on all crudes combusted within the European Union (ICCT 2014), and estimates from the International Energy Agency (IEA) (IEA 2016). Each of these studies reported several API gravities of crudes from different countries. To determine the average API gravity of crude produced by each country as input to our analysis, we took the average of all crudes within a country in the aggregated dataset. While a production weighted average or maintaining a range of crudes for each producer would have been preferred over using the average value, specific production volume by crude type was not available for all countries. Where a country was not represented within either of these three datasets, we used the average regional API estimated by the IEA (IEA 2016).

2.2.2 Cost Estimates
Several crude pricing models have explored relationships between crude quality parameters, socio-political issues, and crude pricing differentials (Kaufmann 2016; Kaufmann and Banerjee 2014; Reboredo 2011). These studies suggest that given the cooperative equilibrium nature of our theoretical optimization model, where price differential effects due to country risk, supply shocks, etc. are irrelevant, it is reasonable to assume the crude market is unified. Therefore, we assume the price relationship between benchmark crudes will remain consistent, and that crude API serves as a proxy for crude quality (see SI section S.4). To estimate the baseline 2014 total crude network cost, we compiled cost data from fourteen benchmark crudes, ranging in API from 13 to 38 from Deloitte’s 2015 Oil and Gas Price Forecast report (Deloitte 2015). We use a line of best fit to represent the relationship between API and price. The line is fit as a differential between a crude’s API/price and that of Brent crude (API 38) such that any price can be inputted for Brent to determine crude price as a function of API for the other
crudes. Since this study is based on 2014 data, the 2014 average price for Brent crude oil was used as the baseline.

In this model, shipping costs are estimated based on shipping distance and a oil tanker freight rate of $.004/tonne-mile. This estimate is based on the Worldscale shipping rate (WS), which is widely used as the basis for shipping price negotiations between a ship owner and a charterer. In this study shipping distances were modeled using the great circle distance based on a geographically representative subset of port locations from the World Port Index (World Port Index 2016) (Figure S4). A circuity factor of 1.3 was applied to account for variations from the great circle path (TRB 1997). Because shipping costs and emissions were found to be marginal relative to total life cycle emissions, the results of this study are not sensitive to this simplifying assumption. Additional information regarding shipping cost and port-to-port distances is available in SI Section S.3.

2.2.3 Crude Life Cycle Emissions

Crude emissions can be quantified according to life cycle stages. In this model, we include upstream (extraction), shipping, midstream (refining), and downstream (combustion) emissions. The relationship between crude and the emissions from these life cycle stages is complex and driven by several different factors such as extraction technique, vent-to-flare ratio, fugitive emissions, refinery configuration, and finished product mix.

We used API as an indicator for crude-specific emissions from each life cycle stage, based on a linear fit of the results in the Oil-Climate Index report (Gordon et al. 2015), which uses the Oil Production Greenhouse gas Emissions Estimator (OPGEE) (OPGEE 2016) model to estimate oil field specific extraction emissions and the Petroleum Refinery Life Cycle Inventory Model (PRELIM) (PRELIM 2016) to estimate midstream emissions. While API alone does not determine life cycle emissions of a given crude, as demonstrated by the Oil-Climate Index report (Gordon et al. 2015), it is highly correlated with life cycle emissions. The exception to this is for upstream emissions, where the
linear interpolation for points above the API range used to generate the line would result in negative emissions for very light crudes. To adjust for this, we assumed any crude with API over 45 would have the same upstream emissions factor (i.e., the marginal upstream emissions reduction plateaus for very light crudes), and revised the best-fit line accordingly. While the report is specific to US default refinery configurations, product mix, and transportation end use, we take these emissions to be generally representative of global midstream and downstream emissions in the absence of country-specific additional data.

Several studies quantify emissions from the shipping sector (Corbett and Winebrake 2008; Psaraftis and Kontovas 2009; Third IMO Greenhouse Gas Study 2014) (Endresen et al. 2003). According to a report by the International Maritime Organization (IMO), international shipping resulted in over 800 million tonnes CO₂-eq in 2012. Oil tankers had the third largest fuel consumption (almost 40 million tonnes fuel), surpassed only by container ships and bulk carriers. The oil tanker fleet is comprised of more than 7,000 vessels ranging in size from a few thousand dead weight tons (dwt) to more than 200,000 dwt. Emissions from oil tankers alone were responsible for more than 120 million tonnes of CO₂ emissions in 2012 (Third IMO Greenhouse Gas Study 2014). The IMO study was a bottom up assessment, in which vessels were categorized by fuel type, shipping category, and dwt to develop an emissions estimate.

Shipping emissions in this study are quantified based on the port-to-port distances described above and a tanker’s CO₂ emission factor of 0.005 kg/tonnes-km (Third IMO Greenhouse Gas Study 2014 2014). This emissions factor was a bottom up estimate based on crude vessel sizes and the portion of time spent idling at port or otherwise operating in inefficient modes (see SI section S.3).

2.3 Theoretical Optimized Trade Network

The linear models representing the relationship between crude API and cost/emissions can be used both to characterize the existing global system, as well as to assess the changes in cost/emissions resulting from variations in the global crude system. Because
cost and emissions are presented as a function of API and distance, using this method, any different pattern of trade can be analyzed as long as the average API blend being produced by each country is known.

After developing the reference global crude system, we then explored how the network would shift as a result of minimizing cost or GHG emissions. To establish this theoretical optimal trade system, we developed a second linear optimization model that considers the potential for redistribution of traded oil while meeting the same global crude consumption as established by the reference network based on cost or GHG emissions:

\[
\text{Minimize } \sum_{i=1}^{C} \left( \sum_{e=1}^{C} c_e^{CR} x_{ei}^{TR} + \sum_{e=1}^{C} c^{SH} d_{ei} x_{ei}^{TR} \right) \\
\text{with respect to} \\
x_{ei}^{TR} \in \mathbb{R} \\
\forall i \in \{1, ..., C\}, e \in \{1, ..., C\}
\]

subject to

\[
\sum_{e=1}^{C} x_{ei}^{TR} = u_i \ \forall i
\]

(5)

where:

\[c_e^{CR} = (API_e \times 0.87 + 66) \times 0.0000073 \text{ ($/million tonnes)}\]
\[c^{SH} = 1.8 \text{ ($B/(million tonnes – million km))}\]

\[API_e\] is the average API produced in a given country

\[API_i\] is the target weighted average API consumed by a given country

\[d_{ei}\] is the distance between exporter \(e\) and importer \(i\)

The optimization defined above assumes any country can supply any volume of its assigned (averaged) API crude and each country can refine any API blend. This is the
most flexible alternative and results in the upper bound cost and GHG mitigation potential. Constraints can then be added to limit the supply to that of the 2014 reference network:

Supply constraint:
\[ \sum_{i=1}^{C} x_{ei}^{TR} = p_e \forall e \]  \hspace{1cm} (6)

Additionally, a second constraint can be added to limit countries to consuming crude with a blended API consistent with their refinery fleet, as determined by the 2014 reference crude network. This is representative of refinery infrastructure limitations; if a country’s crude API blend changes beyond what can currently be processed by that country’s refinery portfolio that country would potentially need to invest in refinery updates to reconfigure the refinery to accept the new crude blend:

API blend constraint:
\[ \sum_{i=1}^{C} API_e x_{ei}^{TR} = \left( \sum_{e=1}^{C} x_{ei}^{TR} \right) API_l \forall i \]  \hspace{1cm} (7)

2.4 Theoretical Trade Network Under Climate Policies

By adding additional constraints on the total crude emissions and/or on country-specific crude emissions to the optimization, we can observe how the trade network shifts under either a global or fragmented climate policy with a carbon limit.

2.4.1 Global Climate Policy

To model a global climate policy scenario in which the international community cooperates to mitigate cumulative emissions to avoid the 2°C average global temperature increase, we set a global annual carbon cap across the system (refer to SI section S.2). To extrapolate a crude-specific, annual carbon cap from the global carbon budget, we considered the current portion of crude emissions; in 2014, the transportation sector contributed approximately 14% of global emissions (EPA 2016). Assuming this portion
of total emissions approximately represents crude’s contribution to global emissions, we attribute 14% of any global carbon budget as the carbon budget specific to the crude trade. For example, given a global annual carbon cap of 21 Gt CO$_2$-eq, the associated global crude annual carbon cap would be 3 Gt CO$_2$-eq. The constraint that limits total emissions to the global cap is as follows:

**Carbon budget constraints:**

\[ \sum_i^C \sum_c^C x^{TR}_{ic} \cdot (GHG^{UP}_e + GHG^{SH} d_{ie} + GHG^{MID}_e + GHG^{DWN}_e) = GHG^{TB} \]

(8)

where:

- \( GHG^{UP}_e \) = \((-3.0 \cdot \text{API}_e + 180) \times (0.0073) \) (tonne CO$_2$/tonne crude)
- \( GHG^{MID}_e \) = \((-1.4 \cdot \text{API}_e + 81) \times (0.0073) \) (tonne CO$_2$/tonne crude)
- \( GHG^{DWN}_e \) = \((-3.3 \cdot \text{API}_e + 544) \times (0.0073) \) (tonne CO$_2$/tonne crude)
- \( GHG^{TB} \) is the total global carbon budget
- \( GHG^B_c \) is the fraction of total GHG emissions allocated to country \( c \)
- \( GHG^{SH} = 16 \) (tonnes CO$_2$/tonne-km)

### 2.4.2 Fragmented Climate Policy

To do this, we first determined each country’s allocated portion of total emissions based on the estimated 2020 GHG targets as determined by each country’s nationally determined contribution (NDC) resulting from the Conference of the Parties (COP) 21 in Paris in 2015 (Fenhann 2016). If no 2020 or 2025 estimate was present in the data for a given country, we instead used a 2012 emissions value reported by the World Resources Institute (WRI 2016). These allocations indicate that if a carbon budget exists restricting emissions, each country in turn would have to restrict emissions based on its proportional 2020 emissions targets. For example, if a country’s NDC target results in it emitting 10% of 2020 emissions, it would be allocated 10% of any future global carbon budget.
2.4.3 Carbon Accounting Strategies
For both the global and fragmented climate policy optimization scenarios, we can implement different carbon accounting strategies in order to explore the underlying dynamics of carbon leakage and embodied carbon. In the location-based carbon accounting strategy, the upstream producing country was held accountable for upstream emissions, while the consuming country was held responsible for the shipping, midstream, and downstream emissions (Eq. 9). For simplicity, this assumes all refined products are used in that country, rather than being exported elsewhere. While in this study shipping emissions are attributed to the upstream producing country, in reality currently the responsibility for GHG emissions associated with shipping does not fall within the jurisdiction of any individual country (ICTSD 2010). In a producer based accounting framework, upstream producing countries are held responsible for all embodied emissions throughout the crude life cycle (Eq. 10). Finally, in a consumption-based accounting framework, the consuming country is held responsible for all embodied emissions, including upstream extraction emissions (Eq. 11). The following constraints can be used to specify a carbon accounting strategy:

Location-based:
\[
\sum_c GHG_{cUP} x_{ic}^{TR} + \sum_c x_{ce}^{TR} * (GHG_{cSH} d_{ce} + GHG_{cMID} + GHG_{cDWN}) = GHG_{cB} G * GHG_{TB} \forall c \tag{9}
\]

Producer-based:
\[
\sum_c x_{ic}^{TR} * (GHG_{cUP} + GHG_{cSH} d_{ic} + GHG_{cMID} + GHG_{cDWN}) = GHG_{cB} G * GHG_{TB} \forall c \tag{10}
\]

Consumer-based:
\[
\sum_e x_{ce}^{TR} * (GHG_{eUP} + GHG_{eSH} d_{ce} + GHG_{eMID} + GHG_{eDWN}) = GHG_{cB} G * GHG_{TB} \forall c \tag{11}
\]
If the carbon constraints bound the problem such that meeting demand $x_t^{CS}$ is infeasible, instead of minimizing total cost, we minimize the difference between the calculated consumption and the target consumption $x_t^{CS}$ to maintain consistency between the theoretical optimized consumption patterns and the 2014 reference network (Eq. 12).

\[
\text{Minimize } \sum_{t=1}^{C} \left( \text{abs} \left( \frac{\sum_{e=1}^{c} x_{el}^{TR}}{\text{calculated consumption}} - \frac{x_t^{CS}}{\text{target consumption}} \right) \right)
\]  

(12)

3. Results and Discussion

In this section, we first show the reference trade network resulting from the iterative smoothing process and explore the implications of carbon accounting strategies on country-level emissions inventories. We then demonstrate the cost and emissions reduction potential achievable through shifting trade patterns and show how these patterns are influenced by global and fragmented climate policies.

3.1 Baseline Balanced 2014 Trade Matrix

The baseline 2014 global crude system developed in this analysis includes 62 countries representing 95% of total crude production. The emissions associated with these current trade flows were calculated according to the three different carbon accounting strategies and can be seen in (Figure 2), based on the estimated crude life cycle emissions (see SI section S.4). Figure 2A shows the emissions by country given producing countries are responsible for extraction emissions and consuming countries are responsible for all other life cycle emissions. In contrast, Figure 2B shows embodied life cycle carbon emissions being attributed to the upstream producer, while Figure 2C shows embodied life cycle emissions being attributed to the downstream consumer. For a more detailed look at the impact of carbon accounting method on individual country’s emissions profile, see Figure S7. Due to the asymmetric impact of carbon accounting methods on different countries, any global carbon accounting policy should carefully consider equity issues such as economic impact to developing countries. In general, many African countries would be
responsible for a significant portion of emissions under a producer based accounting strategy, while many European and Asian countries would be responsible for more emissions under a consumer- or location-based accounting strategy. Consumer- and location-based strategies yield similar emissions trends because crude life cycle emissions are dominated by downstream combustion (i.e. consumption).

More specifically, countries that export crude and consume very little crude, such as Algeria, a producer-based approach would result in high crude carbon emissions (Figure 2B), while location-based (Figure 2A) or consumer-based (Figure 2C) approach would result in low crude carbon emissions. Similarly, for countries who are crude importers and produce very little crude such as Ireland and Israel, a location-based and consumer based approach would yield similar carbon accounting results, while a producer based approach would result in them being responsible for few crude carbon emissions. This reveals the influence that carbon accounting has on emissions profiles and demonstrates the challenge to adopting a globally agreed upon method for tracking emissions. If countries are not consistent in how they record their emissions, it could be possible for each country to meet mitigation targets under different accounting schemes, without significant change in overall global emissions.

3.2 Reference Crude Trade Network
Using this established reference network as input, combined with the life cycle GHG emissions estimates (see SI section S.4), the developed crude cost model (SI section S.4), the shipping cost as a function of distance and quantity shipped (SI section S.3), we compute an optimized trade network under a variety of constraints (Table 2).

![Figure 2: Greenhouse gas emissions from crude trade by country in 2014 assuming A) location-based, B) producer-based, and C) consumer-based carbon accounting strategy](image-url)
When minimizing by cost, the least cost scenario for any producer country is to reduce exports and use its own crude oil first before importing crude. This allows the total global cost to drop from $3 trillion to $2.4 trillion ($590/t of oil consumed) as a result of reduced transportation, but results in a GHG emissions increase of approximately 4 Gt CO$_2$-eq. Allowing supply to vary freely but constraining the weighted average consumed API gravity by country to remain the same as in the baseline 2014 network also decreases costs by ~$230B across the system to $690/t crude consumed but does not account for technical or resource constraints limiting crude extraction in each country.

Table 2: Summary of scenario results. Cost = cost minimized, demand constraints only; Cost_SL = cost minimized, supply and demand constrained; Cost_API = cost minimized, demand and API constrained; GHG = GHG minimized; GHG_SL = GHG minimized, supply and demand constrained; GHG_API = GHG minimized, demand and API constrained

|                | Baseline Scenario | Minimize Cost Scenarios | Minimize Emissions Scenarios |
|----------------|-------------------|-------------------------|------------------------------|
|                | Cost ($) trillion | Cost | Cost_SL | Cost_API | GHG | GHG_SL | GHG_API |
| Cost (Shipping) | 0.14              | 0.07 | 0.02   | 0.00     | 0.09| 0.02   | 0.01    |
| Crude          | 2.8               | 2.3  | 2.7    | 2.8      | 3.35| 2.7    | 2.9     |
| Total          | 3.0               | 2.4  | 2.75   | 2.8      | 3.5 | 2.75   | 2.9     |
| GHG (Shipping) | 0.3               | 0.15 | 0.04   | 0.01     | .19 | 0.04   | 0.01    |
| Crude          | 16.1              | 20.3 | 16.4   | 16.1     | 10.9| 16.4   | 15.3    |
| Total          | 16.5              | 20.5 | 16.4   | 16.1     | 11.1| 16.4   | 15.3    |
| Consumption (billion tonnes) | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| $/tonne oil consumed | 750 | 590 | 688 | 693 | 865 | 688 | 715 |
| GHG/tonne oil consumed | 4.0 | 5.1 | 4.1 | 4.0 | 2.8 | 4.1 | 3.8 |

When minimizing total GHG emissions within the system, there are again distinct differences in cost and emissions savings across the three scenarios. When each country is allowed to supply any volume of crude to contribute to satisfying global demand rather than constraining countries to their 2014 production limits, global GHG savings of about 5.5 Gt CO$_2$-eq are realized for an additional cost of about $500 billion. This translates to a relatively low cost of abatement of $90/t CO$_2$-eq. When supply is constrained to 2014...
production volumes or weighted average API is constrained to 2014 API consumption, there are smaller emissions savings (100 million tonnes of oil and 1.2 Gt CO₂-(eq, respectively) while reducing total costs over the baseline ($25 billion and $15 billion, respectively). The tradeoffs in cost savings and emissions reductions are further explored in the supplementary material (see SI sections S.6-S.7). Because the largest emission reductions in this emissions-based optimization are achieved in the scenarios without production or API refining limitations, a key result is that the more flexible we can make the crude system, the more opportunity there would be for efficient consumption (low CO₂-eq /t oil consumed). This is important because the more efficient consumption can be, the less total crude consumption would need to be reduced in order to achieve the same climate outcome, as long as minimizing emissions is the priority over minimizing cost.

3.3 Climate Policy Scenarios
The optimized trade network under an extrapolated crude oil global carbon limit is designed so that each country is allocated a portion of the global budget. The country-specific apportionment is done to approximate the impact of fragmented climate policies as compared to the benefits of global cooperation. This allocation is characterized by the NDCs resulting from COP21, suggesting that the ratio of emissions contributions will remain consistent with the ratio of committed 2020 COP21 targets in the future. While in reality the NDCs do not specify how they will be achieved (i.e., how the oil industry would be affected by each country’s mitigation efforts), here we highlight the implications each sector would be reduced by the committed percentage. The percentage of total carbon emissions allocated to each region is shown in Table S1. These limits can either be set as absolute limits, or the model can be run such that a country pays a penalty (i.e., carbon tax) for any emissions above its allocated budget. The latter formulation, with a global carbon budget and payments made to exceed individual country allocations, could be designed to mimic a global cap and trade policy.
In addition to designating emissions allocations by country, the climate policy version of the model must also specify a carbon accounting strategy. As previously discussed, the three main accounting strategies are 1) location-based, in which the upstream emissions are allocated to the producer and all other life cycle emissions are allocated to the consumer, 2) producer-based, in which all embodied life cycle emissions are allocated to the producer, and 3) consumer-based, in which all allocated life cycle emissions are allocated to the consumer. In this model, each country tries to stay as close to its demand as possible while remaining within its carbon budget. The results of the optimization are summarized in Table 3, and detailed results can be found in Table S2 through Table S4.

Table 3: Summary of optimization results under a 3 Gt global carbon budget with NDC constraints compared to a 3 Gt global carbon budget under global cooperation (no country specific NDC restrictions), and to the baseline trade network for reference. 3GT_L = location based carbon accounting strategy; 3GT_P = production based carbon accounting strategy; 3GT_C = consumption based carbon accounting strategy.

|                | Baseline Scenario | 3 Gt Global Carbon Budget | 3 Gt Global Carbon Budget, with NDC Constraints |
|----------------|-------------------|---------------------------|-----------------------------------------------|
|                |                   |                           | 3GT_L | 3GT_P | 3GT_C |
| Total Cost ($ trillion) | 3.0               | 0.93                      | 0.55  | 0.55  | 0.52  |
| Total GHG (Gt CO_2-eq)  | 16.5              | 3                         | 3     | 3     | 3     |
| Consumption (billion tonnes of oil) | 4                 | 1.1                       | 0.77  | 0.77  | 0.73  |
| $/t oil consumed     | 750               | 850                       | 714   | 714   | 712   |

Figure 3: Crude producing countries by percentage of total production under various accounting strategies with a three Gigatonne global crude carbon cap: A) location-based, B) producer-based, and C) consumer-based accounting strategy.
The results in Figure 5 demonstrate that the trade matrix shifts dynamically depending on which accounting strategy is chosen. For example, using a location- or producer-based carbon accounting, the supply is geographically dispersed and supplying countries are constrained by their NDC. In contrast, under a consumer-based accounting strategy, only Canada and the Philippines (the countries with the heaviest and lightest crudes, respectively) produce crude. These results arise as consuming countries attempt to balance high emissions and low costs from heavy crude with the lower emissions and high costs of light crude; because the exporting countries are not responsible for extraction emissions, the heaviest and the lightest API countries are the sole exporters. For reference, Figure S7 shows the average API produced by each country used as input to the optimization.

Regardless of the specific carbon accounting scenario, a strict 3 Gt annual carbon cap for oil would constrain demand to at most 770 million tonnes per year (an 80% decrease over the 2014 baseline consumption) (Table 3). Under such a restrictive global carbon budget, the carbon accounting strategy used to track emissions becomes influential in determining the structure of the trade network. In the case of crude trade, where emissions decrease as a function of API and price increases as a function of API, countries face tradeoffs in reducing their cost and reducing their emissions. However, in reality, as demand for higher API (lower emitting) crudes increases under a carbon constrained policy environment, the price differential between heavy and light crudes would widen with the high API crudes commanding a premium. Because this is not an economic model, these demand affects are not considered in this analysis, but would likely lead to additional complexities in determining leakage under a fragmented climate policy scenario.
When considering specific accounting strategies, the different methods for carbon emissions attribution influences the total demand that can be satisfied while maintaining a global carbon budget of 3 Gt. For example, models using the location and production-based accounting strategies enable 770 million tonnes of oil demand to be met, while the consumer-based accounting model only allows for 730 million tonnes. Therefore, the ratio of total emissions to total consumed is 4.1 tonne CO$_2$-eq/tonne of oil consumed, which is higher than the 4.0 tonne CO$_2$-eq/tonne of oil consumed ratio found for the baseline and 3.9 tonne CO$_2$-eq/tonne of oil consumed for other two carbon accounting strategies. In other words, consumption based accounting does not allow the global system to satisfy as much demand as a production based accounting method would. This strategy also results in a 10% higher carbon intensity.

The carbon accounting strategies discussed in the previous paragraph assume each country is allocated a specific fraction of the global carbon cap based on the ratio of COP21 NDC emissions targets for 2020. However, if this allocation constraint is relaxed such that there is a global carbon cap but no country-specific carbon limits, the total demand satisfied increases to 1.1 billion tonnes for a cost of $930 billion ($850/tonne oil consumed). Therefore, without unilateral carbon limits, the volume of demand satisfied increases by over 40%, for a lower cost per unit consumed than under the consumption based carbon accounting method with country specific carbon targets. This demonstrates there may be competing influences among the interactions between NDCs and carbon accounting strategies in the long run that could inhibit the cost effectiveness of climate change mitigation efforts. For example, under a producer-based accounting strategy, a developing country with a less constrained NDC could export a significant amount of embodied carbon to countries with more constrained NDCs, resulting in less mitigation than would have occurred under a consumer-based strategy. However, the results of the scenario without NDC-based country-specific carbon budgets show the available crude is consumed by a limited number of countries; only ten countries receive crude, compared to 56 consuming product in the consumption based model. Therefore, while unilateral policies may be less efficient, they may be used as a mechanism to help ensure equitable distribution of consumption. For example, under consumption-based accounting with
NDCs, all countries receive a portion of demand. In contrast, with no NDCs, the optimal solution based on minimizing GHG emissions is for 10 countries to receive a portion of demand. Unilateral policies could also incentivize supply security. Under the production-based accounting strategy with NDCs, all countries contribute to supply, but with no NDCs, the optimal solution is for a single supplier with the highest API. These results demonstrate the importance of considering interactions between national and global policy objectives in achieving effective and equitable carbon mitigation.

The optimization model developed for this analysis extrapolates a simplified economy, focusing on the crude sector as a theoretical self-contained entity. Like many theoretical examples in the literature, it does not take into consideration the competition with other economic activities for factors of production nor does it consider substitution of crude for other products. However, substitution effects from direct crude consumption are likely minimal compared to substitution effects of coal versus natural gas for example. In reality, there are other industries that would be affected by these substitutions such as the petro-chemical sector, which can substitute petroleum-based inputs for natural gas based inputs. While not predictive in nature, the results of the model suggest there are important underlying dynamics of fragmented climate policy goals that may impede overall global advances toward carbon abatement. Due to the nature of this optimization model, it represents the extremes of abatement efficiencies gained through global cooperation. This simplified model reveals tradeoffs in GHG reductions and cost savings, as experienced by countries with differing constraints, varied resources, and disparate incentives. In remaining simplified, this analysis is able to isolate the existence of problematic outcomes associated with a fragmented climate policy without relying on highly uncertain, estimated country specific social-behavioral parameters such as price elasticities and substitution effects. In doing so, this analysis is a demonstration tool; it is not intended to replicate historical trade patterns nor predict future trade patterns or quantify carbon leakage.
4. Conclusion

This analysis uses the global crude trade as a case study to explore the way in which unilateral, fragmented climate policies may unintentionally inhibit the effectiveness of carbon mitigation efforts. While these model results are simplified and theoretical, they offer meaningful insights into potential emissions mitigation possible within the crude trade without affecting consumption. These potential emissions savings primarily evolve by shifting crude production to fields with lighter crudes; emissions reductions from shifting tanker routes are negligible. As a result, current global crude consumption can be achieved more efficiently (a lower carbon footprint) by investing in refinery upgrades to increase flexibility for refining heavier crudes and by incentivizing the purchase of the more expensive lighter crudes through carbon taxes or other market mechanisms (see SI section S.7).

The insights from this study highlight the need for policy makers to understand the implications of the scale of climate policy and the accounting framework on mitigation potential in order to effectively reduce global carbon emissions. While the consumption-based accounting strategy is the most widely discussed in climate negotiations, and all accounting methods should yield the same outcomes under a unified, global climate policy, the IPCC has recognized there are important underlying dynamics that occur under a fragmented climate regime. The results of this study confirm this premise; different countries benefit under different accounting schemes, and the global emissions abatement cost is affected accordingly.

In addition to fragmented climate policies having implications for carbon accounting methods, a fragmented climate policy in which countries independently plan the degree of their own abatement efforts creates unique dynamics that may increase global cost of carbon mitigation. While the NDCs represent the negotiation concept of “common but differentiated responsibilities,” a principle that recognizes historical differences in the contributions of countries to environmental problems and differences in their respective economic and technical capacity to tackle the problems (UNFCCC 1992), climate negotiators should consider more nuanced meanings of the tenet and other means of
transferring resources and differentiating responsibilities under a unified, global climate policy (Brunnee and Streck 2013; Frumhoff et al. 2015).

Without a globally consistent abatement strategy, it is possible that individual NDCs could be seemingly achieved with minimal real impact on global greenhouse gas mitigation efforts. Furthermore, through this study we find the NDCs and carbon accounting schemes incentivize different patterns of trade. This indicates that although COP21 NDCs might be short-term agreements (to 2025), they influence investments made in infrastructure that could potentially hinder longer-term mitigation efforts. While in the short-term NDCs may protect developing countries by shifting the mitigation responsibility to developed nations, our results show that under a strict global carbon budget, the total cost and consumption outcomes for each country are non-intuitive. Furthermore, these are highly sensitive to the carbon accounting strategy implemented.

Therefore, while the NDCs from COP21 were an important step in committing the global community to address climate change, mitigation efforts could be more efficient and cost-effective given a system-level approach rooted in more cooperative and interactive target setting. While this analysis is primarily theoretical, it provides key insights into the dynamics of climate policy at the unilateral and globally cooperative scales. The most important sensitivities that affect these results are the crude reserves and operational supply limitations for each country, the relationship between cost and crude type, and the price elasticity of demand. These parameters could be investigated thoroughly at a technical level in the future. However, for the purposes of this scoping exercise to demonstrate the importance of a systems level approach to climate policy, the simplifying assumptions made in the analysis are appropriate and relevant. Greenhouse gas mitigation to the level at which we would remain within the globally accepted cumulative carbon budget would require extensive social, behavioral, political, and economic shifts. Global cooperation and a system-level policy approach could guide such efforts to be cost-effective and equitable.

In addition to further exploring the economic interaction between crude supply and demand by incorporating price elasticities, future work could expand on this model by
including additional petroleum-related sectors such as the chemical and plastics industries and consider potential substitution effects of petroleum-based inputs for natural gas derived feedstocks. Alternatively, this analysis framework could be applied to assess emissions mitigation potential from other globally traded commodities with high degrees of embodied carbon such as food and other agricultural products. Future work could also assess the dynamics of a partially collaborative climate policy in which a subset of countries participates in cooperative mitigation target setting. Finally, this model could be used to explore how country-specific adjustments to the COP 21 NDCs could improve the mitigation potential of a fragmented climate policy.

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**Supporting Information Available**
The supplementary text includes supplementary results and references.
5. References

Arroyo-Currás, Tabaré, Nico Bauer, Elmar Kriegler, Valeria Jana Schwanitz, Gunnar Luderer, Tino Aboumahboub, Anastasis Giannousakis, and Jérôme Hilaire. "Carbon leakage in a fragmented climate regime: the dynamic response of global energy markets." Technological Forecasting and Social Change 90 (2015): 192-203.

Bohringer C, Balistereri EJ, Rutherford TF (2012) The Role of Border Carbon Adjustment in Unilateral Climate Policy: Insights from a Model Comparison Study. Harvard Kennedy School, http://belfercenter.ksg.harvard.edu/publication/22361/role_of_border_carbon_adjustment_in_unilateral_climate_policy.html. Accessed 12/2016

BP Statistical Review of World Energy (2015). British Petroleum Co., http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html. Accessed 12/2016

Brunée, J, Streck C (2013) The UNFCCC as a negotiation forum: towards common but more differentiated responsibilities Climate Policy 13:589-602

Clark SS, Seager TP, Selinger E (2015) A development-based approach to global climate policy Environment Systems and Decisions 35:1-10

Condon M, Ignaciuk A (2013) Border Carbon Adjustments and International Trade, 2013. OECD Trade and Environment Working Papers, 2013/06, OECD Publishing, Paris

Corbett J, Winebrake J (2008) Emissions Tradeoffs among Alternative Marine Fuels: Total Fuel Cycle Analysis of Residual Oil, Marine Gas Oil, and Marine Diesel Oil Journal of the Air & Waste Management Association 58:538-542

Corbett JJ, Winebrake JJ, Green EH, Kasibhatla P, Eyring V, Lauer A (2007) Mortality from Ship Emissions: A Global Assessment Environmental science & technology 41:8512-8518

Davis SJ, Peters GP, Caldeira K (2011) The supply chain of CO2 emissions PNAS 108:18554-18559

Deloitte (2015) Oil and Gas Price Forecast. http://www2.deloitte.com/ca/en/pages/resource-evaluation-and-advisory/articles/deloitte-canadian-price-forecast.html. Accessed 12/2016.

EIA (2016) Company Level Imports. http://www.eia.gov/petroleum/imports/companylevel/. Accessed 12/2016

Endresen O, Sorgard E, Sundet JK, Dalsoren SB, Isaksen ISA, Berglen TF, Gravir G (2003) Emissions from international sea transportation and environmental impact Journal of Geophysical Research 108:4560

Energy Balances of OECD Countries (2015). International Energy Agency (IEA), https://www.iea.org/statistics/relateddatabases/energybalancesofoecdcountries/ Accessed 12/2016

EPA (2016) Global Greenhouse Gas Emissions Data. https://www3.epa.gov/climatechange/ghgemissions/global.html. Accessed 12/2016

Felder S, Rutherford TF (1993) Unilateral policies and impact on international trade Journal of Environmental Economics and Management:162-176
Fenhann J (2016) Pledge Pipeline. United Nations Environment Programme (UNEP) Denmark Technical University (DTU) Partnership, http://www.unep.org/climatechange/pledgepipeline/ 12/2016

Frumhoff PC, Heede R, Oreskes N (2015) The climate responsibilities of industrial carbon producers Climatic Change 132:157-171

Gonzalez-Eguino M, Capelian-Perez I, Ansuategi A, Markandya A (2016) Industrial and terrestrial carbon leakage under climate policy fragmentation. Basque Centre for Climate Change (BC3),

Gordon, Deborah, Adam Brandt, Joule Bergerson, and Jonathan Koomey. "Know Your Oil: Creating a global oil-climate index." Carnegie Endowment for International Peace 29 (2015).

ICCT (2014). Upstream Emissions of Fossil Fuel Feedstocks for Transport Fuels Consumed in the European Union. Authors: Chris Malins, Sebastian Galarza, Anil Baral, Adam Brandt, Hassan El-Houjeiri, Gary Howorth, Tim Grabiel, Drew Kodjak. Washington D.C.: The International Council on Clean Transportation (ICCT) https://circabc.europa.eu/sd/a/0ee6ba6-280f-4bcd-a804-3a6bd7794d78/ICCT_Upstream-emissions-of-EU-crude_Feb2014.pdf. Accessed 12/2016.

ICTSD (2010) International Transport, Climate Change and Trade: What are the Options for Regulating Emissions from Aviation and Shipping and what will be their Impact on Trade? http://www.ictsd.org/downloads/2011/12/international-transport-climate-change-and-trade.pdf. Accessed 12/2016

IEA (2014) World Energy Statistics and Balances online data service

IEA (2016) Crude Oil Import Cost Questionnaire. International Energy Agency. https://http://www.iea.org/statistics/topics/pricesandtaxes/. Accessed 6/2016

IPCC (2013) Climate Change 2013 the physical science basis. Intergovernmental Panel on Climate Change (IPCC), http://www.ipcc.ch/report/ar5/wg1/. Accessed 12/2016

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/syr/. Accessed 12/2016

Jakob M, Marschinski R (2012) Interpreting trade-related CO2 emission transfers Nature Climate Change 3:19-23

JODI-Oil World Database. (2014) Joint Organisations Data Initiative (JODI). https://http://www.joidata.org/oil/support/user-guide/data-available-in-the-jodi-oil-world-database.aspx. Accessed 12/2016

Kanemoto K, Moran D, Hertwich EG (2016) Mapping the Carbon Footprint of Nations Environmental science & technology 50:10512-10517

Kaufmann RK (2016) Price differences among crude oils: The private costs of supply disruptions Energy Economics 56:1-8

Kaufmann RK, Banerjee S (2014) A unified world oil market: Regions in physical, economic, geographic, and political space Energy Policy 74:235-242

LCFS Crude Oil Lifecycle Assessment (2015). MCON Inputs Spreadsheet for Crude Lookup Table. California Environmental Protection Agency; Air Resources Board, https://www.arb.ca.gov/fuels/lcfs/crude-oil/crude-oil.htm. Accessed 12/2016
Luderer G, Bertram C, Calvin K, De Cian E, Kriegler E (2015) Implications of weak near term climate policies on long term mitigation pathways. Climatic Change 138:127-140

McGlade C, Ekins P (2015) The geographical distribution of fossil fuels unused when limiting global warming to 2 degrees C Nature 517:187-190

Reuters (2016) Oil Flows Data, Obtained from Reuters via personal communication

OPGEE: the Oil Production Greenhouse gas Emissions Estimator (2016) Stanford School of Earth, Energy & Environmental Sciences.
https://pangea.stanford.edu/researchgroups/eao/research/opgee-oil-production-greenhouse-gas-emissions-estimator. Accessed 12/2016

Otto, Sander AC, David EHJ Gernaat, Morna Isaac, Paul L. Lucas, Mariësse AE van Sluisveld, Maarten van den Berg, Jasper van Vliet, and Detlef P. van Vuuren. "Impact of fragmented emission reduction regimes on the energy market and on CO2 emissions related to land use: a case study with China and the European Union as first movers." Technological Forecasting and Social Change 90 (2015): 220-229.

Peters GP, Hertwich EG (2008) CO2 Embodied in International Trade with Implications for Global Climate Policy Environmental science & technology 42:1401-1407

PRELIM: the Petroleum Refinery Life Cycle Inventory Model (2016)
http://www.ucalgary.ca/lcaost/prelim. Accessed 12/2016

Psaraftis HN, Kontovas CA (2009) CO2 Emission Statistics for the World Commercial Fleet WMU Journal of Maritime Affairs 8:1-25.

Reboredo JC (2011) How do crude oil prices co-move? A copula approach Energy Economics 33:948-955

Schaeffer M, Gohar L, Kriegler E, Lowe J, Riahi K, van Vuuren D (2015) Mid- and long-term climate projections for fragmented and delayed-action scenarios Technological Forecasting and Social Change 90:257-268

Speight, James G. Crude Oil Assay Database (2015) vol 2016. Knovel.
https://app.knovel.com/web/toc.v/cid:kpCOAD0005/. Accessed 12/2016

Steckel JC, Kalkuhl M, Marschinski R (2010) Should carbon-exporting countries strive for consumption-based accounting in a global cap-and-trade regime? Climatic Change 100:779-786

Steininger KW, Lininger C, Meyer LH, Muñoz P, Schinko T (2015) Multiple carbon accounting to support just and effective climate policies Nature Climate Change

Strømman AH, Hertwich EG, Duchin F (2009) Shifting Trade Patterns as a Means of Reducing Global Carbon Dioxide Emissions Journal of Industrial Ecology 13:38-57

Third IMO Greenhouse Gas Study 2014 (2014). International Maritime Organization, TRB (1997) A Guidebook for Forecasting Freight Transportation Demand. Transportation Research Board; National Cooperative Highway Research Program, http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_388.pdf

UN Comtrade Database (2014). https://comtrade.un.org/. Accessed 12/2016

UNFCCC (1992) United Nations Framework Convention on Climate Change. United Nations, https://unfccc.int/resource/docs/convkp/conveng.pdf. Accessed 12/2016

UNFCCC (2016) Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 11 December 2015 Framework Convention on
Climate Change, [http://unfccc.int/resource/docs/2015/cop21/eng/10.pdf](http://unfccc.int/resource/docs/2015/cop21/eng/10.pdf). Accessed 12/2016

Weber CL, Matthews HS (2007) Embodied Environmental Emissions in U.S. International Trade, 1997-2004 Environmental science & technology 41:4875-4881

Weber CL, Peters GP (2009) Climate change policy and international trade: Policy considerations in the US Energy Policy 37:432-440

World Port Index. (2016) [http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015](http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015). Accessed 12/2016

WRI (2016) CAIT Climate Data Explorer. World Resources Institute. [http://cait.wri.org/](http://cait.wri.org/). Accessed 12/2016

Wyckoff AW, Roop JM (1994) The embodiment of carbon in imports of manufactured products: Implications for international agreements on greenhouse gas emissions Energy Policy
Effect of Crude Oil Carbon Accounting Decisions on Meeting Global Climate Budgets

Supplemental Information

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S.1 Historical Crude Trends
United States oil production had been steadily declining from 1985 until about 2009 when production rapidly began to increase (Figure S1A in the Supplemental Information). Between 2010 and 2014, US production increased by 14%, and the United States currently accounts for approximately 13% of the world’s crude supply, making it the largest global producer of oil (Figure S1B) (BP Statistical Review of World Energy 2015). This estimate includes conventional crude oil, tight oil, oil sands, and natural gas liquids. While historically oil production has been from conventional sources, it is projected that the percentage of crude supply from unconventional sources may increase substantially in the future depending on resource constraints, fuel prices, elasticity of demand, and potential climate policies (Brandt et al. 2010)

Figure S1: Crude production A) since 1985 by the 2014 top six producers in thousand barrels per day (kbpd), and B) by top 15 producers, accounting for 80% of total oil supply (2014) (BP Statistical Review of World Energy)
S.2 Projected Crude Oil Consumption

While a carbon budget generally refers to cumulative emissions over an extended period, in this study we extrapolate the carbon budget to an annual carbon cap for a single sector. For the petroleum sector, this is a meaningful as simulations conducted for the IPCC 5th Assessment Report across three climate models suggest the portion of crude oil serving as primary energy source remains relatively consistent through 2100 despite changes in nuclear, renewable, and natural gas contributions as primary energy sources (IPCC 2014) (see SI section S.3). The IPCC used three climate models to project primary energy sources to 2100 (Figure S3). The model results demonstrate consistency in the proportional contribution of crude as a primary energy source. Given global climate targets and carbon budgets, each sector would have to reduce by 50-80%. If one sector, such as transportation, falls short of these goals, the other sectors must overcompensate in order to achieve global carbon targets.

The climate models used in the IPCC report incorporate assumed marginal abatement cost curves (MACCs), which orders abatement activity by increasing cost across all sectors. Additionally, these climate models include assumptions about changes in technology, price, and availability of renewable technologies. Therefore, while we do not explicitly consider MACCs and advances in renewable energy in this study, they are implicitly accounted for in our assumption that crude consumption remains stable based
on these model projections to 2100. Global climate targets are not limited to a single sector. However, if one sector, such as transportation, falls short of cumulative emissions targets, the other sectors would have to overcompensate in order to achieve global carbon targets. Because this work is not meant to be predictive, but rather a tool to demonstrate the importance of global coordination in emissions abatement planning, isolating the crude sector in this way serves as a case study. In particular, the international interconnectedness of the trade, varying crude qualities, geospacially ranging consumption patterns, substitutability of crude types, and the predicted consistency of crude consumption over time makes the crude sector a dynamic one to isolate for illustrative purposes. In addition, assessing the theoretical limits of application of a carbon budget to crude highlights the some of the challenges and opportunities of reducing GHGs from the petroleum production and use.
Figure S3: Projected primary energy source contributions by fuel type through 2100 according to three climate models (IPCC 2014)
S.3 Shipping Cost and Emissions Estimates

The estimated shipping emissions factor (0.005 kg CO$_2$/t-km) was validated by estimating a shipping emissions factor; assuming residual fuel oil is used with an energy intensity of 14 kJ/t-km (Wang 2009) and emissions factor of 77.4 t CO$_2$/TJ consistent with the assumption used by the IPCC (2014), the calculated shipping emissions factor is 0.00108 kg CO$_2$-e/t-km. This is reasonable because it is on the same order of magnitude, and slightly lower as expected due to operational factors and vessel capacity not being taken into account.

The worldscale rate is an annual reference rate based on the weighted average shipping distances, average bunker fuel price, port prices, etc. for a standard vessel including four days of port time (New Worldwide Tanker Nominal Freight Scale). For example, in January-May of 2013, the WS varied between 36-43 $/ton for the route between West Africa and China (Review of Maritime Transport 2013). Assuming an average WS of 40, and a distance of 10,600 miles (Port Distance Calculator), this equates to $0.0037/ton-mile. The order of magnitude of this estimate is validated by several other sources (Devanney 2009; Environmentally Conscious Transportation 2008). In reality, these costs would vary by ship size, fuel price, vessel demand, and load/discharge port.

International shipping can be monitored in a variety of ways. One widely used method is through the Automatic Identification System (AIS), which is a system through which vessels report their location in regular intervals throughout their voyages. Historically, only shore-based AIS receivers were available with a limited range of 50 miles. This low coverage led to extensive uncertainty about the shipping sector. However, since 2009, satellites have been used to collect AIS data, thereby greatly improving the quality of fleet operational data available (Third IMO Greenhouse Gas Study 2014 2014). As a simplification, in this study shipping distances were modeled using the great circle distance based on a geographically representative subset of port locations from the World Port Index (WPI) (World Port Index) (Figure S4). A circuity factor of 1.3 was applied to
account for variations from the great circle path (A Guidebook for Forecasting Freight Transportation Demand 1997). Because shipping costs and emissions were found to be marginal relative to total life cycle emissions, the results of this study are not sensitive to this simplifying assumption.

Figure S4: Selected ports from the World Port Index

S.4 Crude Cost and Emissions Estimates

The linear cost model representing crude cost as a function of crude API was developed from thirteen benchmark crudes (Figure S5). It is expressed as a differential from Brent (API of 38). In this analysis, because 2014 is the baseline year, we use the 2014 average price of Brent ($99/bbl) (Deloitte 2015).
The upstream, midstream, and downstream emissions for a given crude is estimated based on the Oil-Climate Index (OCI) report (Gordon et al. 2015). While API alone does not determine life cycle emissions of a given crude, it is generally correlated with life cycle emissions. Therefore, in this study we use API as a proxy for crude-specific emissions from each life cycle stage, based on a linear fit of the results in the report. The upstream, midstream, and downstream emissions were estimated by linear fits to the results of the Oil-Climate Index report as shown in equations (S1)-(S3) (Gordon et al. 2015) (Figure S6).
For reference, the average API crude produced by each country used in this analysis is shown in Figure S7.

Figure S6: Line of best fit representing the relationship between crude API and emissions for the upstream, midstream, and downstream life cycle stages

\[
\begin{align*}
GHG^{UP} &= -3.9 \times API + 186 \quad \text{(S1)} \\
GHG^{MID} &= -1.4 \times API + 81 \quad \text{(S2)} \\
GHG^{DWN} &= -4.4 \times API + 600 \quad \text{(S3)}
\end{align*}
\]

Figure S7: Produced crude average API gravity for each country
S.5 Estimated Trade Matrix Results

In the 2014 baseline balanced trade matrix, the sum of each country’s production and imports equals its exports plus consumption (Figure S8). From these balances, it is clear which countries are net importers, net exporters, or largely domestic consumers of their own crude production. These values were derived from the iterative smoothing process, used to compile the various data sources such that each country’s combined production plus import volume equals its consumption plus export volume.
Supplemental Information. Please cite the final version of this paper: Abrahams, L. S., Samaras, C., Griffin, W. M., & Matthews, H. S. (2017). Effect of crude oil carbon accounting decisions on meeting global climate budgets. *Environment Systems and Decisions*, 1-15. [https://doi.org/10.1007/s10669-017-9638-5](https://doi.org/10.1007/s10669-017-9638-5)

Figure S8: Production, consumption, and trade mass balance by country. Net importers are indicated with an asterix.
Based on the reference trade network, Figure S9 shows the relative impact of each of these carbon accounting methods for each country. Each bar represents the ratio of producer-, location-, and consumer-based emissions inventory for a given country. In this figure, if the three accounting measures each have a third of the total (see Argentina for example), then that country’s emissions are not sensitive to the accounting strategy used. If instead, however, one color dominates the bar, that country is highly sensitive to the carbon accounting method. For example, using a production-based carbon accounting strategy would greatly affect Yemen’s emissions profile.
Figure S9: Relative impact of location, production, and consumption based carbon accounting methods on country emissions
S.6 Country-Specific Costs and Savings

As seen in Figure S10 some countries realized cost savings as a result of the optimization, while some countries experienced losses (see Table S2-S4 for additional detailed cost results). This is primarily a result of shifting crude consumption rather than shipping savings; shipping savings costs are nominal relative to crude savings for a given country. As an example of a country with a high potential for reducing cost, the United States has the potential to save on the order of a hundred billion dollars per year. These savings arise from consuming domestically produced crude only in the optimized model, rather than importing crude.

![Figure S10: Cost savings from the optimized network over the 2014 network, where demand was constrained to 2014 levels, but supply by country and consumed blended API were allowed to vary freely.](image)

S.7 Multi-Objective Optimization

In addition to estimating the potential for cost and greenhouse gas savings within the 2014 crude system assumptions, we can use this optimization model to characterize the dynamics within the system resulting from various climate policies. For example, we can implement a carbon tax across the system and set the objective to minimize total cost, consisting of crude cost, shipping cost, and GHG emissions times the carbon tax. This multi-objective optimization allows for the development of a Pareto frontier describing
the tradeoffs in cost and emissions. As a starting point, we set the carbon tax at $13/tonne CO$_2$-eq, which is consistent with the 2015 social cost of carbon ($2015, 5\%$ discount rate) as estimated by the Interagency Working Group on the Social Cost of Carbon (Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis 2014) and vary it parametrically up to $300/tonne$ CO$_2$-eq.

In this optimization, the objective function is the sum of monetized GHG emissions (weighted by the given social cost of carbon) and the total system cost (from crude purchases and shipping). Figure S11A shows a Pareto frontier of tradeoffs between total cost and GHG emissions. The extreme end points represent the cost minimized system (SCC = $0/tonne$) and the GHG minimized system, respectively. The points between these extremes illustrate the influence of parametrically varied SCC between $13/tonne$ (2015 SCC, 5\% discount rate) to $300/tonne$. This figure shows that there is a threshold between $110$ and $120/tonne$ where there is a significant emissions reduction and cost increase. Figure S12B shows the change in cost over the savings in GHG emissions. For lower SCCs that incentivize an emissions reduction, the GHG savings are expensive. For example, at a SCC of $66/tonne$, every Gt of CO$_2$ avoided costs $22$ trillion. However, as the SCC increases, the cost of avoided emissions decreases until it reaches the limit of the GHG minimized scenario ($8.7$ trillion/Gt).
Supplemental Information. Please cite the final version of this paper: Abrahams, L. S., Samaras, C., Griffin, W. M., & Matthews, H. S. (2017). Effect of crude oil carbon accounting decisions on meeting global climate budgets. Environment Systems and Decisions, 1-15. https://doi.org/10.1007/s10669-017-9638-5

Figure S11: A) Pareto frontier between total cost and total GHG emissions, and B) dollars spent per metric tonne CO₂ avoided, as a function of social cost of carbon

S.8 Nationally Determined Contribution Limits

Table S1: Percentage of total carbon budget allocated by country/region based on the NDCs

| Country or Region          | Percentage of Total Carbon Budget Allocated |
|----------------------------|--------------------------------------------|
| Canada                     | 2%                                         |
| Africa                     | 5%                                         |
| Middle East                | 5%                                         |
| Former Soviet Union        | 6%                                         |
| India                      | 7%                                         |
| OECD Pacific Countries     | 7%                                         |
| Other Asia Pacific         | 9%                                         |
| Central and South America  | 9%                                         |
| Europe                     | 11%                                        |
| US                         | 14%                                        |
| China                      | 25%                                        |
S.9 Detailed Results

The following tables present detailed model results across all scenarios. The baseline is the 2014 trade network.

Baseline = 2014 balanced network
Cost = cost minimized, demand constraints only
Cost_supply = cost minimized, supply and demand constrained
Cost_API = cost minimized, demand and API constrained
GHG = GHG minimized
GHG_supply = GHG minimized, supply and demand constrained
GHG_API = GHG minimized, demand and API constrained
3GT = 3 Gt carbon cap, no NDC constraints
3GT_Location = location based carbon accounting, 3 GT carbon cap
3GTProducer= production based carbon accounting, 3 GT carbon cap
3GT_Consumer = consumption based carbon accounting, 3 GT carbon cap

Table S2: Detailed cost results by country for each scenario ($B)

| Country          | Baseline | Cost | Cost supply | Cost API | GHG | GHG supply | GHG API | 3GT | 3GT location | 3GT producer | 3GT consumer |
|------------------|----------|------|-------------|---------|-----|------------|---------|-----|--------------|--------------|--------------|
| Algeria          | 0        | 12   | 16          | 16      | 18  | 16         | 17      | 0   | 3            | 0            | 4            |
| Angola           | 1        | 1    | 1           | 1       | 2   | 1          | 1       | 0   | 1            | 0            | 2            |
| Argentina        | 19       | 17   | 19          | 18      | 25  | 19         | 19      | 0   | 5            | 5            | 6            |
| Australia        | 28       | 25   | 28          | 27      | 35  | 28         | 27      | 0   | 11           | 0            | 7            |
| Bangladesh       | 0        | 0    | 0           | 0       | 0   | 0          | 0       | 0   | 0            | 0            | 0            |
| Belgium          | 26       | 19   | 23          | 23      | 29  | 24         | 24      | 0   | 2            | 14           | 2            |
| Brazil           | 86       | 81   | 87          | 85      | 122 | 87         | 87      | 0   | 9            | 29           | 25           |
| Brunei           | 0.2      | 0.1  | 0.2         | 0.2     | 0.2 | 0.2        | 0.2     | 0.2 | 0.2          | 0            | 0.1          |
| Bulgaria         | 0        | 0    | 0           | 0       | 0   | 0          | 0       | 0   | 0            | 0            | 0            |
| Canada           | 67       | 65   | 65          | 65      | 99  | 65         | 66      | 0   | 0            | 0            | 10           |
| Chile            | 10       | 9    | 10          | 10      | 13  | 10         | 10      | 0   | 1            | 0            | 1            |
| China            | 369      | 316  | 366         | 342     | 446 | 366        | 350     | 446 | 156          | 114          | 104          |
| Colombia         | 10       | 9    | 10          | 10      | 14  | 10         | 10      | 0   | 0            | 0            | 3            |
| Congo            | 0        | 0    | 0           | 0       | 0   | 0          | 0       | 0   | 0            | 0            | 0            |
| Denmark          | 7        | 5    | 6           | 6       | 8   | 6          | 6       | 0   | 1            | 6            | 1            |
| Ecuador          | 8        | 8    | 8           | 8       | 12  | 8          | 8       | 0   | 0            | 0            | 2            |
| Egypt            | 34       | 26   | 30          | 29      | 37  | 30         | 30      | 0   | 4            | 0            | 4            |
| Equatorial_Guinea| 0        | 0    | 0           | 0       | 0   | 0          | 0       | 0   | 0            | 0            | 0            |
| Finland          | 8        | 6    | 7           | 7       | 8   | 7          | 7       | 0   | 1            | 7            | 1            |
| France           | 65       | 50   | 64          | 60      | 74  | 64         | 62      | 0   | 7            | 0            | 7            |
| Gabon            | 0        | 0    | 0           | 0       | 0   | 0          | 0       | 0   | 0            | 0            | 0            |
| Germany          | 99       | 72   | 82          | 86      | 107 | 82         | 89      | 0   | 12           | 13           | 14           |
| Country      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Greece       | 13  | 9   | 11  | 11  | 14  | 11  | 11  | 0   | 1   | 11  | 2   |     |
| India        | 168 | 121 | 143 | 160 | 171 | 143 | 170 | 0   | 60  | 59  | 44  |     |
| Indonesia    | 49  | 40  | 52  | 47  | 56  | 52  | 48  | 56  | 28  | 37  | 22  |     |
| Iran         | 69  | 62  | 69  | 68  | 89  | 69  | 71  | 0   | 10  | 14  | 7   |     |
| Iraq         | 19  | 16  | 19  | 18  | 23  | 19  | 19  | 0   | 3   | 0   | 3   |     |
| Ireland      | 6   | 4   | 5   | 6   | 5   | 5   | 5   | 0   | 1   | 1   |     |     |
| Israel       | 10  | 7   | 8   | 8   | 10  | 8   | 9   | 0   | 1   | 0   | 2   |     |
| Italy        | 45  | 37  | 43  | 38  | 55  | 43  | 38  | 0   | 0   | 0   | 6   |     |
| Japan        | 190 | 129 | 155 | 174 | 184 | 155 | 184 | 150 | 24  | 13  | 19  |     |
| Korea        | 103 | 68  | 81  | 96  | 100 | 81  | 100 | 100 | 11  | 82  | 9   |     |
| Kuwait       | 16  | 15  | 16  | 16  | 21  | 16  | 16  | 0   | 2   | 0   | 2   |     |
| Lithuania    | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |
| Malaysia     | 30  | 24  | 29  | 29  | 33  | 29  | 30  | 33  | 8   | 0   | 5   |     |
| Mexico       | 63  | 55  | 63  | 62  | 83  | 63  | 63  | 0   | 9   | 0   | 11  |     |
| Netherlands  | 35  | 26  | 31  | 31  | 38  | 31  | 32  | 0   | 3   | 32  | 3   |     |
| New Zealand  | 6   | 5   | 5   | 5   | 5   | 7   | 5   | 5   | 0   | 1   | 0   | 1   |
| Nigeria      | 2   | 2   | 2   | 2   | 3   | 2   | 2   | 0   | 2   | 2   | 3   |     |
| Norway       | 9   | 7   | 8   | 8   | 10  | 8   | 8   | 0   | 1   | 4   | 1   |     |
| Oman         | 7   | 6   | 8   | 7   | 9   | 7   | 7   | 0   | 2   | 3   | 1   |     |
| Pakistan     | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |
| Peru         | 6   | 6   | 6   | 6   | 8   | 6   | 6   | 0   | 0   | 3   | 2   |     |
| Philippines  | 14  | 10  | 11  | 13  | 13  | 11  | 13  | 13  | 3   | 0   | 2   |     |
| Poland       | 25  | 15  | 18  | 20  | 23  | 18  | 21  | 0   | 7   | 0   | 7   |     |
| Portugal     | 9   | 7   | 10  | 8   | 11  | 10  | 9   | 0   | 1   | 0   | 1   |     |
| Qatar        | 8   | 7   | 8   | 8   | 10  | 8   | 8   | 0   | 1   | 8   | 1   |     |
| Romania      | 9   | 6   | 7   | 8   | 9   | 7   | 8   | 0   | 2   | 0   | 2   |     |
| Russia       | 117 | 95  | 114 | 115 | 139 | 114 | 118 | 0   | 33  | 0   | 36  |     |
| Saudi Arabia | 109 | 94  | 109 | 108 | 136 | 109 | 111 | 0   | 7   | 28  | 6   |     |
| Singapore    | 65  | 45  | 53  | 59  | 62  | 54  | 62  | 62  | 1   | 8   | 1   |     |
| South Africa | 19  | 16  | 18  | 18  | 23  | 18  | 18  | 0   | 6   | 0   | 5   |     |
| Spain        | 50  | 38  | 47  | 46  | 58  | 47  | 48  | 0   | 5   | 0   | 5   |     |
| Sudan        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |
| Sweden       | 13  | 9   | 11  | 11  | 14  | 11  | 12  | 0   | 1   | 0   | 1   |     |
| Syria        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |
| Thailand     | 44  | 35  | 42  | 41  | 49  | 42  | 42  | 49  | 6   | 0   | 4   |     |
| Trinidad_Tobago | 1  | 1   | 1   | 1   | 2   | 1   | 1   | 0   | 1   | 1   | 1   |     |
| Tunisia      | 2   | 1   | 2   | 2   | 2   | 2   | 2   | 0   | 0   | 0   | 1   |     |
| Turkey       | 23  | 18  | 21  | 21  | 26  | 21  | 22  | 0   | 6   | 23  | 7   |     |
| Ukraine      | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |     |
| UAE          | 31  | 26  | 31  | 30  | 37  | 31  | 31  | 0   | 3   | 0   | 2   |     |
| UK           | 59  | 45  | 55  | 54  | 67  | 55  | 56  | 0   | 7   | 29  | 9   |     |
| US           | 616 | 498 | 576 | 587 | 754 | 577 | 605 | 0   | 74  | 0   | 92  |     |
Table S3: Production by country for each modeled scenario (million metric tons)

|              | Baseline | Cost | Cost supply | Cost API | GHG | GHG supply | GHG API | 3GT | 3GT location | 3GT producer | 3GT consumer |
|--------------|----------|------|-------------|----------|-----|------------|---------|-----|---------------|--------------|--------------|
| Algeria      | 46       | 0    | 66          | 0        | 66  | 0          | 0       | 0   | 4             | 0            | 0            |
| Angola       | 83       | 0    | 83          | 0        | 83  | 0          | 0       | 10  | 3             | 0            | 0            |
| Argentina    | 29       | 0    | 29          | 0        | 29  | 0          | 0       | 7   | 0             | 0            | 0            |
| Australia    | 19       | 0    | 19          | 36       | 19  | 38         | 0       | 11  | 0             | 0            | 0            |
| Bangladesh   | 0        | 0    | 0           | 168      | 0   | 312        | 0       | 91  | 5             | 0            | 0            |
| Belgium      | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 0   | 2             | 0            | 0            |
| Brazil       | 122      | 0    | 122         | 111      | 0   | 122        | 130     | 89  | 27            | 0            | 0            |
| Brunei       | 6        | 0    | 6           | 0        | 6   | 0          | 1       | 0   | 0             | 0            | 0            |
| Bulgaria     | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 19  | 1             | 0            | 0            |
| Canada       | 411      | 211  | 224         | 206      | 113 | 0          | 59      | 12  | 411           |              |              |
| Chile        | 0        | 0    | 13          | 0        | 0   | 14         | 0       | 0   | 2             | 0            | 0            |
| China        | 211      | 0    | 471         | 0        | 211 | 499       | 0       | 47  | 174           | 0            | 0            |
| Colombia     | 52       | 0    | 14          | 0        | 53  | 15         | 0       | 18  | 3             | 0            | 0            |
| Congo        | 15       | 0    | 198         | 15       | 15  | 160       | 0       | 40  | 6             | 0            | 0            |
| Denmark      | 8        | 0    | 8           | 0        | 8   | 0          | 0       | 1   | 0             | 0            | 0            |
| Ecuador      | 29       | 0    | 9           | 0        | 30  | 13         | 0       | 11  | 2             | 0            | 0            |
| Egypt        | 35       | 0    | 35          | 0        | 35  | 0          | 0       | 5   | 0             | 0            | 0            |
| Equatorial Guinea | 13    | 0    | 13          | 0        | 13  | 0          | 0       | 3   | 0             | 0            | 0            |
| Finland      | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 1   | 0             | 0            | 0            |
| France       | 1        | 0    | 1           | 0        | 1   | 0          | 0       | 8   | 0             | 0            | 0            |
| Gabon        | 12       | 0    | 12          | 0        | 12  | 0          | 0       | 1   | 0             | 0            | 0            |
| Germany      | 2        | 0    | 2           | 0        | 2   | 0          | 0       | 16  | 0             | 0            | 0            |
| Greece       | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 2   | 0             | 0            | 0            |
| India        | 42       | 0    | 42          | 0        | 42  | 0          | 0       | 72  | 0             | 0            | 0            |
| Indonesia    | 41       | 0    | 41          | 0        | 41  | 0          | 0       | 36  | 0             | 0            | 0            |
| Iran         | 169      | 0    | 169         | 0        | 169 | 0          | 0       | 12  | 0             | 0            | 0            |
| Iraq         | 169      | 0    | 169         | 0        | 169 | 0          | 0       | 12  | 0             | 0            | 0            |
| Ireland      | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 1   | 0             | 0            | 0            |
| Israel       | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 2   | 0             | 0            | 0            |
| Italy        | 6        | 0    | 6           | 57       | 0   | 60         | 0       | 37  | 7             | 0            | 0            |
| Japan        | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 32  | 0             | 0            | 0            |
| Korea        | 0        | 0    | 63          | 0        | 89  | 0          | 0       | 17  | 0             | 0            | 0            |
| Kuwait       | 151      | 0    | 151         | 0        | 151 | 0          | 4       | 3   | 0             | 0            | 0            |
| Lithuania    | 0        | 0    | 0           | 0        | 0   | 0          | 0       | 8   | 1             | 0            | 0            |
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Table S4: Detailed consumption results by country across all modeled scenarios (million mt)

| Country       | Baseline | Cost supply | Cost API | GHG supply | GHG API | 3GT production | 3GT location | 3GT consumer |
|---------------|----------|-------------|----------|------------|---------|----------------|--------------|--------------|
| Argentina     | 0        | 20          | 20       | 20         | 20      | 20             | 0            | 5            | 0            | 4            |
| Angola        | 2        | 2           | 2        | 2          | 2       | 2              | 2            | 2            | 0            | 2            |
| Argentina     | 27       | 27          | 27       | 27         | 27      | 27             | 0            | 8            | 7            | 7            |
**Supplemental Information.** Please cite the final version of this paper: Abrahams, L. S., Samaras, C., Griffin, W. M., & Matthews, H. S. (2017). Effect of crude oil carbon accounting decisions on meeting global climate budgets. *Environment Systems and Decisions*, 1-15. [https://doi.org/10.1007/s10669-017-9638-5](https://doi.org/10.1007/s10669-017-9638-5)

| Country      | 41 | 41 | 41 | 41 | 41 | 41 | 0  | 13 | 0  | 11 |
|--------------|----|----|----|----|----|----|----|----|----|----|
| Australia    | 41 | 41 | 41 | 41 | 41 | 41 | 0  | 13 | 0  | 11 |
| Bangladesh   | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Belgium      | 33 | 33 | 33 | 33 | 33 | 33 | 0  | 3  | 17 | 2  |
| Brazil       | 136| 136| 136| 136| 136| 136| 15 | 45 | 27 |    |
| Brunei       | 0.2| 0.2| 0.2| 0.2| 0.2| 0.2| 0.2| 0.2| 0.2| 0.2 |
| Bulgaria     | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Canada       | 114| 114| 114| 114| 114| 114| 0  | 0  | 0  | 12 |
| Chile        | 15 | 15 | 15 | 15 | 15 | 15 | 0  | 2  | 0  | 2  |
| China        | 527| 527| 527| 527| 527| 527| 527| 199| 174| 174|
| Colombia     | 16 | 16 | 16 | 16 | 16 | 16 | 0  | 0  | 0  | 3  |
| Congo        | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Denmark      | 9  | 9  | 9  | 9  | 9  | 9  | 0  | 1  | 9  | 1  |
| Ecuador      | 13 | 13 | 13 | 13 | 13 | 13 | 0  | 0  | 0  | 2  |
| Egypt        | 43 | 43 | 43 | 43 | 43 | 43 | 0  | 6  | 0  | 5  |
| Equatorial_Guinea | 0 | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Finland      | 9  | 9  | 9  | 9  | 9  | 9  | 0  | 1  | 9  | 1  |
| France       | 85 | 85 | 85 | 85 | 85 | 85 | 0  | 9  | 0  | 8  |
| Gabon        | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Germany      | 122| 122| 122| 122| 122| 122| 0  | 18 | 19 | 16 |
| Greece       | 16 | 16 | 16 | 16 | 16 | 16 | 0  | 2  | 16 | 2  |
| India        | 199| 199| 199| 199| 199| 199| 0  | 75 | 72 | 72 |
| Indonesia    | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 41 | 52 |
| Iran         | 102| 102| 102| 102| 102| 102| 0  | 14 | 20 | 12 |
| Iraq         | 27 | 27 | 27 | 27 | 27 | 27 | 0  | 5  | 0  | 4  |
| Ireland      | 7  | 7  | 7  | 7  | 7  | 7  | 0  | 1  | 0  | 1  |
| Israel       | 11 | 11 | 11 | 11 | 11 | 11 | 0  | 2  | 0  | 2  |
| Italy        | 62 | 62 | 62 | 62 | 62 | 62 | 0  | 0  | 0  | 7  |
| Japan        | 217| 217| 217| 217| 217| 217| 217| 176| 34 | 16 |
| Korea        | 119| 119| 119| 119| 119| 119| 119| 119| 17 | 119|
| Kuwait       | 24 | 24 | 24 | 24 | 24 | 24 | 0  | 3  | 0  | 3  |
| Lithuania    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Malaysia     | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 10 | 8  |
| Mexico       | 94 | 94 | 94 | 94 | 94 | 94 | 0  | 14 | 0  | 12 |
| Netherlands  | 44 | 44 | 44 | 44 | 44 | 44 | 0  | 4  | 44 | 4  |
| New_Zealand  | 8  | 8  | 8  | 8  | 8  | 8  | 0  | 1  | 0  | 1  |
| Nigeria      | 3  | 3  | 3  | 3  | 3  | 3  | 0  | 3  | 3  | 3  |
| Norway       | 11 | 11 | 11 | 11 | 11 | 11 | 0  | 1  | 6  | 1  |
| Oman         | 10 | 10 | 10 | 10 | 10 | 10 | 0  | 2  | 5  | 2  |
| Pakistan     | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Peru         | 9  | 9  | 9  | 9  | 9  | 9  | 0  | 4  | 2  |    |
| Philippines  | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 4  | 0  | 4  |
| Poland       | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 0  | 9  | 0  |
| Portugal     | 12 | 12 | 12 | 12 | 12 | 12 | 0  | 1  | 0  | 1  |
| Qatar        | 11 | 11 | 11 | 11 | 11 | 11 | 0  | 2  | 11 | 2  |
| Romania      | 10 | 10 | 10 | 10 | 10 | 10 | 0  | 3  | 0  | 3  |
| Country       | Allocation values |
|---------------|-------------------|
| Russia        | 163               |
| Saudi Arabia  | 157               |
| Singapore     | 73                |
| South Africa  | 26                |
| Spain         | 65                |
| Sudan         | 0                 |
| Sweden        | 16                |
| Syria         | 0                 |
| Thailand      | 58                |
| Trinidad_Tobago | 2          |
| Tunisia       | 2                 |
| Turkey        | 30                |
| Ukraine       | 0                 |
| UAE           | 43                |
| UK            | 76                |
| US            | 867               |
| Venezuela     | 42                |
| Vietnam       | 21                |
| Yemen         | 0                 |
S.10 References

BP Statistical Review of World Energy (2015). British Petroleum Co.,
http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html. Accessed 12/2016

Brandt AR, Plevin RJ, Farrell AE (2010) Dynamics of the oil transition: Modeling capacity, depletion, and emissions Energy 35:2852-2860

Devanney J (2009) The Impact of Bunker Price on VLCC Spot Rates. Martingale Inc, USA

Deloitte (2015) Oil and Gas Price Forecast.
http://www2.deloitte.com/ca/en/pages/resource-evaluation-and-advisory/articles/deloitte-canadian-price-forecast.html. Accessed 12/2016.

Elgowainy A, Han J, Cai H, Wang M, Forman GS, DiVita VB (2014) Energy efficiency and greenhouse gas emission intensity of petroleum products at U.S. refineries Environmental science & technology 48:7612-7624

Environmentally Conscious Transportation (2008). John Wiley & Sons, Inc., Gordon, Deborah, Adam Brandt, Joule Bergerson, and Jonathan Koomey. "Know Your Oil: Creating a global oil-climate index." Carnegie Endowment for International Peace 29 (2015).

A Guidebook for Forecasting Freight Transportation Demand (1997). Transportation Research Board; National Cooperative Highway Research Program

IPCC (2013) Climate Change 2013 the physical science basis. Intergovernmental Panel on Climate Change (IPCC), http://www.ipcc.ch/report/ar5/wg1/. Accessed 12/2016

Johnston, Daniel and Johnston, David (2006) Introduction to Oil Company Financial Analysis. PennWell Books,

Nelson WL (1976) Nelson complexity index Oil and Gas Journal:20-27

New Worldwide Tanker Nominal Freight Scale. (2016) Worldscale Association https://www.worldscale.co.uk. Accessed 12/2016

Port Distance Calculator. (2016) Sea-distances.org. http://www.sea-distances.org/. Accessed 12/2016

Review of Maritime Transport (2013). United Nations Conference on Trade and Development, New York and Geneva

Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis (2014). Interagency Working Group on Social Cost of Carbon,

Third IMO Greenhouse Gas Study 2014 (2014). International Maritime Organization

Wang M (2009) The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model; . Argonne National Laboratory,

World Port Index. (2016) National Geospatial Intelligence Agency.
http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015. Accessed 12/2016
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