Asian Premium or North Atlantic Discount: Does Geographical Diversification in Oil Trade Always Impose Costs?

Nader Alkathiri, Yazeed Al-Rashed, Tilak K. Doshi and Frederic Murphy
Asian Premium or North Atlantic Discount?

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Key Points

Diversification of supply or demand is normally viewed as reducing risks but imposing costs. KAPSARC has developed a framework that suggests this is not always the case. Among our conclusions are:

- Large crude suppliers may increase their revenues by allocating volumes to more distant markets, if by doing so they capture locational rents from more proximate buyers.
- Based on the 2012 configuration of global oil markets, any significant coalition of Arabian Gulf exporters can exploit this opportunity.
- Large crude buyers may reduce their costs by purchasing volumes from more distant suppliers, counteracting the strategies of their nearest suppliers.
- No single buyer is currently large enough to position itself to benefit from supplier diversification.

Long-term future reconfigurations, such as North American volumes becoming available in the Pacific markets or a Russian supply pivot from Europe to North East Asia, might alter the ability of current Middle East exporters to increase revenues while achieving greater customer diversity.

Summary

It is popularly believed that importers of oil diversify their suppliers to achieve security of supply and that exporters diversify their customer base to achieve security of demand. However, this diversification comes at a cost, compared with buying from or selling to the most economically attractive counterparties—analogous to paying an insurance premium. In fact, our research suggests that this illustration may not properly describe the outcomes for large individual producers or consumers (or coalitions of these) and that diversification can also be a strategy for revenue maximization or cost minimization.

We have developed KAPSARC’s Global Oil Trade Model (GOTM), which is calibrated to the configuration of the global oil markets in 2012, to demonstrate our framework. Our model shows that, in 2012, the volumes of supply and demand and the trade flows constrain the valid candidates to combine diversification with economic gain. Only the trading pair of the Arabian Gulf exporters and North East Asian importers can benefit. This is the illustration that we develop in this paper. However, a future reconfiguration of crude flows—perhaps with growth in North American exports to the Pacific or a major pivot by Russia to sell material volumes to China and other North East Asian customers—could introduce new players. KAPSARC’s framework may prove valuable to understanding potential future dislocations in crude oil trade flows.

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One of the features of oil markets is that regional prices may not be aligned—the netback price (delivered price less transportation costs) of a Middle Eastern crude sold into Asia can be higher than the price of the same crude sold into Europe and North America. Some Asian governments view this as evidence of Middle Eastern sellers’ exercising market power, complain about an ‘Asian premium’ and have sought to develop countervailing strategies. Global oil markets include large exporters and importers and they balance multiple interests and concerns when they choose to whom they sell or from whom they buy.

When market conditions are right, a coalition such as OPEC can influence the supply/demand balance of crude and its price. Similarly, a large buyer or coalition of buyers can hold prices below competitive market levels. We examine whether a large producer and a large importer can increase revenues or lower expenditures by altering prices to secure desired market shares.
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The choice of labels, ‘Asian premium’ or ‘North Atlantic discount’, is implicitly a discussion of the drivers of the large players. For example:

- A producer can diversify its importers through allocations of volumes to specific regional customers to lower revenue risks. The reduction in the netback price of crude oil that the sellers must bear in doing so is viewed as an insurance premium aimed at achieving security of demand or securing geopolitical favor.

- Government-owned crude oil procurement companies in Asia can lower supplier risk by diversifying purchases and passing the costs of supply security onto their captive customers.

- A large exporter can segment customers by region, using resale restrictions that maximize revenues by capturing locational rents.

Missing from the Asian premium discussions is the possibility that a large importer can aim to lower its costs through its regional purchases. Consequently, we add a fourth driver:

- A large consuming country or coalition might agree long-term purchases from exporters that are not economically attractive on their own, in this way lessening its dependence on a large producer. The extra costs of these strategic purchases would be offset by the large producers no longer securing locational rents, thus reducing the importer’s aggregate purchase costs.

‘Either/Or’ versus ‘Both/And’

The framing of these four drivers implies a trade-off between risk and return. In this paper, we aim to challenge this assumption and demonstrate that producers can diversify customers and increase revenues and that importers can diversify suppliers and lower costs.

We developed KAPSARC’s GOTM to compare crude oil allocations that would have arisen in 2012 under conditions of ‘perfect competition’ with those in which exports are diverted to markets other than Asia in sufficient volumes to create locational rents for large Middle East exporters. These arise when the marginal barrels imported into Asia are sourced from more distant (and therefore logistically more expensive) West African sources. We also examine the consequences of strategic purchases by a large importer, or coalition of importers, which we locate in Asia. Strategic purchases—those made from suppliers who are not located closest to the buyer and therefore not lowest cost—are those that are made with the object of lowering average costs or providing diversification.

Running the model with a dominant large exporter and no strategic purchases by that large importer suggests that the large exporter can both increase the diversification of its customers and its revenues. That is, the dominant supplier does not have to make a trade-off between risk and return.

Turning to the question of strategic purchases, a large Asian importer would have to back out all Middle Eastern crudes by making strategic purchases from more expensive sources to have a lower-cost marginal supplier and a lower average price. Of course, based on the configuration of global oil markets in 2012, this was not feasible. A large Asian importer cannot reduce the average price below the marginal cost of buying from the Middle East. Pursuing strategic purchases at above market prices would likely reflect risk aversion, as this importer could not lower its average purchase price.

The situation is different when both the large exporter and importer engage in allocations and strategic purchases. A large Asian importer can adopt countervailing procurement strategies to reduce the location rents accruing to Middle East suppliers and so lower its total purchase costs. It both lowers its costs and increases the diversity of its suppliers. However, if there is no combination of
allocations and strategic purchases where neither player sees upside in changing its stance, the actions of both could lead to unstable markets, from a game theory perspective. Their risk aversion, and hence their willingness to pay perceived security premiums for regional diversification (of exports or imports), could stabilize markets, but at a cost—analogous to the balancing of risks and returns in financial investment portfolios.

The specific results presented in this paper are calibrated to 2012 conditions and depend on the sizes and locations of the producers and consumers and also on transportation costs. Significant later reconfiguration of markets might alter the results materially. The ability of large players to influence market outcomes can prove to be ephemeral.

Introduction

In a perfectly competitive oil market, not subject to concerns about security of supply or of demand, crude oil would flow from producers to importers in patterns that minimize the costs of transport and processing, related to the different qualities of crude oil. Refineries would optimize the product yields, given the costs of crudes delivered by competitive markets, and each producer would receive the same netback prices for its exports, regardless of the purchaser of them, and the netbacks would reflect the quality of the crude oil that a producer exports. The entire system would run in a way that minimizes costs where quality-adjusted netback prices are determined by transportation costs.

Of course, there are other factors that influence crude oil markets. Importers prefer to import from a diverse selection of suppliers and exporters prefer a diverse customer group, so as to mitigate macroeconomic, geopolitical and other risk factors. Crude trade flows and quality differentials change as new producing provinces rise and old ones decline.

In the short run, refineries use crudes that may not be ideal for their configuration, incurring added processing costs, because these crudes are more competitively priced. Eventually, the refineries adjust to the changing mix of crudes in the market to the extent that they can.

It is possible to compare the actual market flows of crude oil with those that would result from a theoretically competitive market that is constrained by the existing infrastructure. A calculation of the additional transportation and processing costs that are incurred from this ‘non-optimal’ allocation of crude oil might be considered an ‘insurance premium’—the cost that exporters and importers are prepared to pay in aggregate to achieve their diversification objectives.

However, viewing diversification only in terms of the costs it imposes is too simplistic. In this paper, we explore how a large crude oil exporter, or group of exporters, can increase revenues by varying regional allocations of a given volume of crude oil across the major consuming regions, Asia, Europe and North America. We then explore how large importers can respond to the producers’ allocations.

We developed KAPSARC’s GOTM to examine the trade-offs among: the origin and destination of the quantities of crude oil in question, the crude quality and the configurations of refineries at a regional level. We use API gravity as a proxy for crude quality because the API gravity index is a measure of density that broadly correlates with the proportions of light and middle distillates and residual fuel produced by a distillation refinery. We apply a simplified, but representative, data–rich characterization of refinery flexibility by using information on refinery flexibility and the API gravity of crude oil processed.
Our reference case is based on the actual patterns of crude oil supply and demand and refinery capabilities in 2012. It assumes that crude oil flows to locations in such a way that total costs (freight and costs of processing sub-–optimal grades of crude at a refinery) are minimized and that no exporter or importer overrides these market–based movements to satisfy its strategic objectives. We then develop a further representation of oil markets based on a large exporter, or coalition of exporters, allocating its supply regionally as the leader in a Stackelberg game, where all other producers and importers are price takers on the competitive fringe. We then examine the ability of a large importer to engage in strategic purchases rather than act as a price taker.

We call the large supplier, which can be a single country or a coalition of countries, BOX (Big Oil Exporter(s)). We locate BOX in the Arabian Gulf and give the exported oil the qualities representative of exports from the Middle East because we use 2012 data which shows the Middle East as the current dominant supplier. At the same time, we view our results as applicable to any large exporter or coalition of exporters that may emerge in the future. Given the shale oil revolution and the oil sands resources in Canada and Venezuela, the discussion here would apply equally to an Americas–centric dominant supplier if such a supplier were to become a large net exporter. Alternatively, a major Russian supply pivot to direct large volumes of crude oil to its Pacific coast terminal and thence to Asian markets would alter the locational rents available to Arabian Gulf exporters.

We assume that BOX can supply the market with varying volumes of crude, ranging from 1.5 million barrels per day (MMbbl/d) to 15 MMbbl/d and can choose to allocate its export volumes—subject to the maximum level of demand for imports—to any market. Although securing such market access would likely be through pricing competitively relative to other suppliers, the KAPSARC model focuses only on regional price differences and does not consider the absolute level of oil prices, as measured by some benchmark such as Brent. All other producers and all importers are assumed to form a competitive fringe that minimizes the costs of meeting the remaining demand in response to BOX’s strategic decisions. There are costs in allocating crude oil to markets that are more remote and/or more inflexible than the closest and most flexible buyers. However, these costs can possibly be offset by the locational rents BOX captures when importers are forced to spend more for crude oil from more distant markets than in a purely competitive market, increasing the relative price in that region.

Just as BOX can act strategically, large importers can make strategic purchases that lower the costs of buying from other exporters. We term such an importer BIM (Big Importer(s)). We locate BIM in North East Asia because that is currently the largest importing region and the most recent source for growth in imports, compared with the decline in North America and stagnation in Europe. As with BOX, this importer can be a country or a coalition of countries. If BOX did not exist, BIM would be a Stackelberg leader. With both BOX and BIM in the market we have two Nash players and a competitive fringe.

The analyses presented in this paper move beyond the previous understandings of regional pricing by showing how the motivations of large oil market players are more nuanced and complex than a simple profit maximization motive. Beginning in the 1980s and accelerating with the oil price collapse of 1986, the OPEC administered pricing system has been superseded by the use of formula prices linked to highly liquid crude oil benchmarks such as WTI, Brent and Oman/Dubai. Middle Eastern crude oil exporters have adopted a market-responsive approach using formula prices based on spot and forward oil markets, making regional oil markets increasingly globally integrated.
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There is a growing literature around the thesis that the world oil market is “one great pool”, propounded by Adelman in 1984, primarily focused on the interdependence of regional oil prices as a measure of market integration. Weiner (1991) provided one of the first empirical assessments of whether markets are globalized or regionally fragmented. His correlation and regression analyses found “a surprisingly high degree of regionalism” and speculated that the regionalization of prices “could be due to the ability of crude oil sellers to engage in price discrimination” (Weiner, p. 107). The evidence of the literature is mixed, however. For example, Sauer (1994) examined six key global price series for landed crude oil for the U.S., Japan, and Northern and Southern Europe and found that long run co-integration relationships are “relatively stable over the period examined” (July 1980–March 1987) and hence more supportive of Adelman’s original ‘pool’ thesis.

The academic literature on inter-regional crude oil price differentials outside these econometric assessments is relatively sparse. Nevertheless, there has been one commonly cited example of a regional crude oil price ‘gap’. In trade journals this has often been reported as the ‘Asian premium’ and there have been several publications on the subject by government-funded research institutions in Japan, South Korea and China. These have estimated the extent to which Asian countries pay higher prices relative to the regional European and North American markets for Middle East crude oil (Gong and Shan, 2003; Koyama, 2003; Lee, 2003).

Among the reasons identified in the literature for the existence of an Asian premium, three are usually noted:

- First, the idea that countries such as Saudi Arabia and other Gulf states such as Kuwait supply a relatively high level of oil exports to the U.S. and Europe to maintain market share for political objectives, such as the presumed benefits of military and political support in the conduct of international relations. This argument implies that the ‘Asian premium’ is effectively a ‘North Atlantic discount’. That is, the Middle East exporters view any financial losses from their allocations to these regions as an insurance premium for perceived political risk coverage.

- Second, it has also been argued that regulations in Asian energy markets could be one of the factors behind crude oil importers’ willingness to pay higher prices than their counterparts in Europe and the U.S. (Horsnell, 1997). If, for example, government-owned crude oil procurement companies value perceived ‘security of supply’ as a risk management tool, they may be willing to pay rates at the margin which exceed those that international oil companies are willing to pay in Europe and the U.S. The public choice literature on state-owned enterprises is voluminous, and there are compelling models of institutional behavior that reduce the incentives for cost minimization and the demand response to higher prices. Typically, national oil companies can be expected to pursue a number of activities not directly related to oil production, such as social welfare programs (Hartley and Medlock, 2008). Public choice models can also explain the common practice of regulating retail prices in the refined oil products sector, thus insulating importers from price signals that crude oil purchasers face in international markets. Regulating prices lowers the response to higher prices relative to unregulated markets in the EU and the U.S.

- Third, a reason often cited as the cause of the Asian premium runs contrary to the geo-political one cited above. It is that large crude oil exporters can increase revenues by regional price discrimination, segmenting markets among
end-users using resale restriction clauses in sales contracts (Soligo and Jaffe, 2000). In their illustrative monopolist price discrimination model, Soligo and Jaffe find that an optimal revenue maximizing solution for Saudi Arabia would be to charge Asian customers 3.8 percent to 28 percent more than European customers.

- In these models, however, implied revenue maximizing regional price ratios are highly sensitive to the parameter values chosen. For example, Parsons and Brown (2003) postulate a coalition of Arabian Gulf OPEC members with market shares of 30 percent and 80 percent in Europe and Asia respectively. They use similar values for the European and Asian price elasticities of demand for Gulf OPEC and non-Gulf OPEC crudes and similar price elasticities of supply. They find an imputed price ratio that yields an extreme 215 percent premium for Asian markets, very much higher than that calculated by Soligo and Jaffe for Saudi Arabia alone.

- The extreme sensitivity of the results to the parameters limits the value of the numerical results, while the qualitative conclusion on the effect of demand elasticities remains. In addition, since importers can switch suppliers, whatever the price increases seen in the standard, revenue-maximizing price-discrimination model, the upper limit on the quality-adjusted price differential cannot normally exceed tanker rates from the next best alternative source of supply to Asia.

The papers on the Asian premium draw from the classic literature on price discrimination and the results are driven by the different regional supply and demand elasticities. Our approach differs from this in that we broaden the question of the Asian premium to examine the motivations of the players. We explore the potential of large players to allocate export quantities between regions to exploit locational rents at the same time as achieving diversification of their customer base. We also consider the potential for Asian producers to lower their average costs through strategic purchases, even when faced with export allocations by Middle East producers.

Data Sources and Model Design

KAPSARC’s GOTM was developed to examine multiple aspects of oil markets, including the extent to which the behaviors of large players influence inter-regional price differentials. It provides a framework for exploring the relative abilities of large exporters and importers to influence inter-regional price differentials by regionally allocating their sales or purchases.

GOTM estimates relative crude oil price differentials by location and the direction and volume of crude oil trade flows, with exogenously fixed regional supply and demand volumes and transport costs. It is not a forecasting model but a platform for counterfactual analyses of strategic alternatives relating to specific configurations of global crude oil markets in terms of transport costs, crude oil quality and refinery complexity. In other words, it does not compute absolute prices of crude oil, nor does it forecast the quantities produced and consumed, permitting a computationally simpler representation of markets.

Data Sources

The analysis in this paper uses benchmark data from 2012, the most recent year for which we can construct a consistent data set appropriate for measuring regional supply and demand flows by type of crude oil quality, refinery complexity and transport costs. The data from 2012 is appropriate for our purposes, as we are analyzing patterns of regional price differentials and revenue or cost shifts related to the ability of large players to allocate their export or import patterns among regions, not forecasting the absolute size of the Asian or North Atlantic premia or discounts.
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Market Power: Potential for Long-term Changes

One of the consequences of using 2012 data is that we locate our example large producer in the Middle East. If we had been carrying out this analysis 75 years ago, we would have chosen North America as the location of the large producer/exporter. The future location of the Stakelberg leader could be very different. For example, if Venezuela, Mexico, and Canada expand exports and the U.S. continues to reduce imports, the big producer’s location would return to the Americas. Similarly, successful exploitation of tight oil by Russia and a pivot from Europe to send most of its exports to the Pacific coast to serve North East Asian markets might result in unpredictable reconfiguration of crude oil flows.

Our large importer is located in Asia because that region is the largest importer of oil. After tight oil peaks in the U.S., and if Canada and Mexico and other Latin-American countries do not increase production significantly, then North America would return to being a major importing region.

The data studied covers some 289 crude oil types by volume produced and API gravity. It includes the 774 oil refineries (including condensate splitters) in operation globally in 2012. For each refinery we have the volume of the crude runs, the weighted-average API gravity of its crude inputs and a technical complexity measure of the refinery’s processing configuration.

The production data for 2012 comes from the Energy Intelligence Group (EIG), including production volumes and assay data for major crudes traded globally, accounting for approximately 60 Mbbl/d (70 percent of global production), covering 190 distinct crude grades. The data includes production rates for small crude streams in major producing countries, but does not provide assays for those crudes. The BP Statistical Review records global crude oil production in 2012 of 86 Mbbl/d, leaving some 26 Mbbl/d that are not included in the EIG dataset. We add in the missing crude with an API gravity that sets the weighted average API gravity of overall supply as equal to the estimated weighted average API gravity of refinery feedstock in 2012.

On the demand side, we use the IHS EDIN Midstream Refinery database’s list of the 774 oil refineries, including condensate splitters, in operation in 2012. The data for each refinery includes the volume of crude runs, the weighted-average API of its crude inputs and a technical complexity measure of the refinery’s processing configuration.

At the current stage of GOTM’s development, we do not take sulfur content into account, despite the important role it plays in refinery process planning. Currently accessible data does not provide reliable estimates of sulfur content, but we plan in our future work to incorporate sulfur penalties. The specific gravity of crude oil is far more important than sulfur (and other typical impurities in crude oils) in determining the value of a crude. Hence we do not believe this simplification is critical to the overall assessment of global crude oil flows and relative prices.

Our measure of demand is taken from the crude oil and condensate inputs into refineries. Total crude demand for refineries listed in the IHS EDIN database for 2012 is roughly 89 MMbbl/d, 3 percent higher than the total crude oil supply noted earlier. To satisfy this demand and ensure the market clears in GOTM, supplies of all crudes are increased uniformly by 3 percent.

Any analysis of global oil markets must cope with data that reflects varying levels of aggregation, differing definitions of geographical regions and
other factors including accounting for non-refinery demand for crude oil such as direct use as fuel. Nonetheless, we believe the data is adequate for the purposes of GOTM’s focus on inter-regional flows and relative prices at an aggregate level.

**Model Overview**

We develop three representations of oil markets to understand the potential for a large producer, or coalition of producers, and/or a large importer, or coalition of importers, to exercise market power by strategically allocating exports to different importing regions:

- A competitive market, which minimizes global transport costs and the cost for refiners of deviating from the annual average crude slates that refineries were running in 2012, and in which no supplier strategically allocates its crude among demand regions. We estimate the distribution pattern and price differentials of a competitive global oil market determined solely by transport costs and the costs for refiners of diverging from the crude slates they were running in 2012—which are assumed to approximate the optima for their configurations at that time.

- A Stackelberg game, where BOX, the Stackelberg leader, strategically allocates exports to specific regions and where all other producers and all importers form a competitive fringe that takes relative prices as given.

- A Stackelberg-Nash game with a large producer, a large importer, and a competitive fringe. In a Nash game the large players interact under the Nash assumption of presuming the other large player does not react to the first large player’s actions. The Stackelberg aspect comes in because the smaller, fringe players adjust their actions based on the actions of the large players. In this game BIM and BOX make strategic purchases to maximize revenue and minimize cost respectively.

The engine of GOTM is a linear program that determines the least-cost flows of crude oil, including both transportation costs and the extra costs of operating refineries with average API gravities different than they had in 2012. The solution to a linear program without any strategic regional allocations simulates the competitive market solution. The competitive equilibrium provides the baseline for examining the extent to which producers can alter their revenues. With fixed strategic allocations by the large players, the linear program finds the equilibrium after the actions by the competitive fringe.

The Stackelberg version of GOTM in formal terms is a mathematical program subject to equilibrium constraints (MPEC) in which a large producer maximizes its revenues subject to the linear program. The equilibrium is found following the actions of the large producer. Like most MPECs, this one is non convex, which means standard optimization methods cannot be used. We use search methods to find the optimal actions for the large players. To find the equilibrium in the Stackelberg game, we calculate the impact of different levels of exports to the U.S. and Europe and find the allocation that maximizes revenues for BOX at different levels of allocations to the North American market, given two different allocations to Europe.

The Stackelberg-Nash game is formally known as an equilibrium problem, subject to equilibrium constraints. Here each large player solves the MPEC with the other large player’s allocations fixed and the competitive fringe responding to the allocations of both players. If there is a point where neither player can do better by changing its actions, and the competitive fringe is at its equilibrium, then we have an equilibrium solution subject to equilibrium constraints. This equilibrium may or may not exist, unlike the Stackelberg equilibrium, which always exists.
Price Elasticities of Crude Oil Demand

Our focus is on the comparative static revenue and cost effects of regional allocation policies of sales and purchases by exporters and importers and we ignore the effect of price elasticities on demand. This is reasonable, based on the econometric estimate of elasticities in 23 major consuming countries that found short-term price elasticities of crude oil demand for the period 1979 – 2000 ranging from -0.02 to -0.1. China exhibited an even lower elasticity of -0.01 (Cooper, 2003). Further support for our simplification is provided by Dahl (1993) and Gately, Dermot and Huntington (2002).

These elasticities cannot be applied to the prices calculated in GOTM, which are relative prices, reflecting transport costs and quality deviation penalties. The absolute prices of delivered oil are large relative to these logistical costs. For example, using an absolute price of $60 per barrel, a doubling of the relative price might represent only a 3 percent increase in the absolute price. The reduction in demand implied by even the highest observed elasticities would be less than 0.3 percent in this case and less if the oil price were higher than $60/bbl.

We believe that the GOTM results yield reasonable approximations for relative price shifts and the associated cost and revenue shifts that occur due to varying inter-regional distribution of crude oil sales and purchases.

As previously stated, the model estimates relative price shifts and incremental revenues due to varying regional allocations of crude oil sales rather than absolute market prices and total revenues. Global crude oil supply is set at a slightly larger volume than demand in the model, and so unused supply at the margin has a shadow price of zero. All other prices are differentials from this value; that is, all prices are relative prices.

The model is driven by the three basic attributes of the global crude oil trade:

- **Freight costs** between supply and demand nodes. These are determined by the distances, and hence voyage durations, that tankers must travel and the charter day rates for tankers of the size that typically ply that route.
- **Quality** of each grade of crude oil supply as determined by its API gravity.
- **Processing configuration** of refineries in the demand nodes. More complex refineries can alter the chemistry of the crude oil stream to convert heavier molecules into lighter molecules such as gasoline and diesel, which typically command higher values than heavier products.

The key variables in the configuration of GOTM used in this paper are the regional movements of given volumes of crude oil exports by selected producers among key importer markets. The model does not allow for an imported crude to be re-exported even if this were economically viable, representing the destination restrictions that prohibit importers from reselling what is shipped. Importing regions, except North America, can export indigenous crude. The North American export restriction implements the legal restriction in the U.S. on crude oil exports.

**The Structure of the GOTM Linear Program**

The objective function of the linear program minimizes the sum of global freight costs and the costs to refiners of deviating from the weighted average API gravity of their input slates as reported for 2012, subject to the supply and demand constraints of each region. Appendix A contains a mathematical statement of the model. Appendix B
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provides a more detailed explanation of how the model derives relative prices.

The outputs of the linear program are the minimum total costs in the objective function, consisting of global transportation and API gravity deviation costs, the flows of crude oil, relative supply prices and relative delivered prices. The solution can be interpreted as competitive market equilibrium subject to the actions of the large player(s), BOX and/or BIM.

To understand its structure, the GOTM can be viewed as a transportation model combined with penalties for refiners for deviating from the ‘ideal’ weighted-average API gravity of their crude input slates, which is taken to be that reported for each refinery in 2012. Each crude oil stream is identified with a source and has its own transportation activities to the possible destinations, allowing the linear program to calculate the average delivered API gravity.

The Transportation Component

Incorporating 289 crude streams and 774 refineries into GOTM would result in over 220,000 equations. We simplify the model by aggregating the supply and demand sources and destinations into 18 regions, which captures the global crude oil flows without losing significant granularity in inter-regional freight cost differentials. Figure 1 shows the sources and destinations in the model. They include:

- four in the Americas;
- four in Europe;
- two in Africa;
- two in the Middle East (BOX and the remainder of the Middle East);
- two in the FSU;
- four in Asia.

![Figure 1 – Geographic Location of Import and Export Nodes in the Model](image-url)
They are chosen based on the volumes supplied and delivered, and they cover the vast majority of observed flows in 2012.

Each crude oil is assigned to a single supply node. Similarly, refineries are serviced by an assigned import node. Within the region served by a particular transport node, transport costs to and from the wellheads upstream and refineries downstream are ignored. Figure 2 shows a portion of the network of the transportation model, the crudes that feed into the supply nodes and the refineries associated with demand nodes. Since local crudes can be exported, one location can be both a supply and demand node. The model does not include any representation of shipping crude through a third country, as if destination restrictions applied to all sales. For crudes that are not regionally allocated, importing and re-exporting a particular crude oil stream is never economic and does not have to be represented in the linear program, since shipping the crude directly to its final destination always has the same or lower costs.

Freight costs for 2012 are yearly averages assembled from a global data base of freight rates provided by Platts®, a major price-reporting agency. Platts, a division of McGraw Hill, provides freight assessments for most of the major oil transport routes. For frequently used routes with widely reported rates, we use the rates for the largest vessels traveling a route, as they have the lowest transport cost. For less frequently traveled routes with no transport costs available in the database, we estimate the costs using a simple OLS linear regression with transport cost as the dependent variable and nautical shipping distance as the sole regressor.
Four major global pipeline routes are specified in our model: the ESPO pipeline connecting the East Siberian oil fields to China and the Russian Pacific port of Kozmino, Canada-U.S. (simplified to one pipeline), the Druzhba pipeline connecting Russia to Northern Europe, and the Kazakhstan-China pipeline. As pipeline volumes are typically governed by long-term contracts, piped crude flows are exogenously fixed in the model.

Refinery Flexibility

In order to handle the different APIs and the varying processing configurations of refineries, we model the trade-off between crude quality and refinery flexibility by introducing a ‘deviation penalty’ term that approximates each refinery’s cost in changing the weighted-average API of its crude input from its ‘ideal level’. We measure a refinery’s complexity using an index termed the technical complexity factor. This is an index developed by IHS and is a function of the cost of the process units in each refinery.

Each refinery’s ‘ideal’ crude slate is presumed to be its actual weighted average API over all crude runs as reported in the benchmark year 2012, given the refinery’s processing capabilities and the prevailing demand conditions for refined products. The deviation penalty in the model is a step function that allows costless substitution within small API ranges, but increases the cost as the magnitude of the deviation increases beyond tier defined threshold values.

The width of the steps is a function of the refinery’s reported complexity factor. We use an approximate logarithmic relationship between the complexity factor and step width to reflect decreasing marginal increase in flexibility, with the maximum width of a tier being 10 percent of total crude throughput. This is shown in Figure 3.

Although some refineries have complexity factors exceeding 60, the most complex processing units mainly lead to refinery complexity factors ranging between 6 and 10. Hence, at a complexity factor beyond 10, the slope of the logarithmic curve is quite shallow. This reflects the lower marginal contribution of complexity to the ability of the refinery to expand its capability to process a crude mix very different from its ideal slate.

![Figure 3](image-url)
The height of the steps represents the cost of deviation. Increasing the penalty (the height of the steps) is equivalent to decreasing refinery flexibility. Similarly, the flatter the penalty function, the more flexible the refineries are in the system. Figure 4 shows the different step functions used in the linear program.

We introduce the deviation penalty term in the objective function of the linear program instead of incorporating unit capacities, intermediate product streams, and blending constraints as in a standard refinery model. This provides the model with the ability to represent the flexibility of refineries in accepting crude oil grades that are either ‘too light’ or ‘too heavy’ relative to the technical configuration of the refinery.

Making refineries ‘fully flexible’, that is, indifferent to the specific gravity of the processed crude oil (measured in the weighted average API), has the same consequences as assuming crude oil is homogeneous. As flexibility is decreased, the heterogeneity of crude oils leads to different crude oil flows and relative prices, and subsequently different consequences from varying crude oil allocations by region.

Results and Discussion

We begin with the competitive case and compare it to actual crude flows. Since some countries are currently pursuing geographical allocation strategies, we impose those strategies, based on historical flows, to see how well the model replicates what is happening in the market. We then examine the outcome of the Stackelberg game with BOX as the leader. To cover all possibilities, we assess whether BIM can be a Stackelberg leader. Then we look at what happens when both BOX and BIM function as large players.

The Competitive Case

We first present the results for the competitive equilibrium. This case allows us to estimate the flows that would occur with completely competitive markets and provides a baseline for estimating the gains or losses to supplier revenues from regional allocations of crude oil and the increases or decreases in importer costs from strategic purchases.

Figure 5 shows import shares of crude oil for North America, Europe and Asia by regional sources of supply (North America, Latin America, Europe, Former Soviet Union, Africa, Asia and the Middle East). It compares the competitive market scenario, with no allocations, to the estimated inter-regional crude oil flows in 2012, as reported by BP. There is a broad level of congruence between the GOTM model results in the competitive scenario and the reported inter-regional crude oil flows in 2012.

There are some key differences, however. In terms of North American crude oil imports, this region imported significantly less crude oil from Latin America than predicted by the model results. These lower imports from the neighboring crude oil suppliers, such as Venezuela and Colombia, are matched by higher import shares (relative to model results) of crude oil imports from the Middle East and West Africa. If we look at crude oil import shares for Asia, the model results in the competitive case show almost all crude being supplied by the Middle East except for a small share provided by the former Soviet Union, which results from the export of East Siberian crudes into China by pipeline, and into Northeast Asia and other markets from the Pacific port of Kozmino, as well as exports delivered by pipeline from Kazakhstan to China. However, actual data for 2012 show a significant diversity of crude oil imports into Asia, including imports from Africa and Latin America.
Figure 4 – The Step Function Representation of Refinery Flexibility
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One of the major reasons for the difference in the model’s competitive scenario results and the data reported by BP is the significant market share of Middle-East crude oil in the U.S. and European markets due to the allocation policies of large Middle East exporters. The export of Latin American crude into Asia, largely based on Venezuela’s government-to-government term contracts with India and China, constitute another key deviation of real world inter-regional crude oil flows from the GOTM competitive scenario results. Stackelberg games, where BOX allocates significant volumes of crude oil exports to the U.S. and Europe, yield inter-regional crude flows that better match the reported flows.

In the GOTM competitive markets case, as previously noted, most African crude oil moves into Europe and the U.S., since most of the Asian market is supplied by the Middle East. However, once actual Middle-East crude oil export allocations to Europe and the U.S. are imposed on the competitive model, the model results come closer to representing the actual pattern of inter-regional crude oil flows.

### The Stackelberg Game: A Large Player Leads

In this Stackelberg game, we examine the range of strategic allocations that BOX can make to Europe and North America, with the remainder distributed to customers by the linear program. We also examine the ability of BIM to make strategic purchases as the Stackelberg player.
Exporter as the Stackelberg Leader

BOX’s incremental revenues are the sum of regional price differentials above the baseline price at the BOX export hub (set as zero in the model), minus transportation costs, times the volume shipped. Another way to describe the revenue formula is that the revenues are the incremental netback prices times the volume shipped. Note that when the allocations by BOX are low, the competitive solution can result in more crude than the allocation being delivered to a region. Say, for example, BOX shifts a volume of crude from Asia to North America, to just above the point where the allocations are binding. Since North America has a lower netback price than Asia, and the regional prices do not change, then BOX’s revenues decrease. By shifting more crude to North America, to the point where Asian importers have to buy crude from more distant sources and Middle East crudes are no longer the marginal crudes, the relative price increases in Asia and BOX can increase its net revenues. This can be illustrated as follows:

- When BOX supplies enough crude oil to Asia, that region does not have to purchase oil from Latin America or West Africa, the next lowest cost suppliers to Asia on the logistics and processing cost curve. Figure 6 shows Asian demand clearing, based on Middle East volumes and delivered prices.

- If BOX cuts back shipments to Asia because of increased shipments to Europe and/or North America, West Africa becomes the marginal supplier, as shown in Figure 7. Because of the higher transportation costs, the price increases in Asia and all suppliers from FSU and the Middle East increase revenues by the rent shown.

None of the standard optimization algorithms can guarantee a solution with the maximum revenues because the optimization of the Stackelberg Leader is non-convex. Thus we enumerate a range of solutions and pick the one that maximizes revenue.

We examine two different allocation cases. In the first we start with a lower limit of zero volume in North America and increase this by 0.05 MMbbl/d until we reach a maximum of 5 MMbbl/d. Because we observe the model diverting BOX oil from Europe to North America, rather than reducing shipments to Asia, we include a case where we impose a lower limit on shipments from BOX to Europe at the 2012 level and repeat the increments on the floor to North America.

The linear program finds the competitive equilibrium given the aggregate crude oil allocated to the U.S. and we treat BOX’s remaining unallocated oil as a source of competitive supply. Using the prices and quantities from each equilibrium, we calculate the incremental revenues accruing to BOX and identify the allocation that maximizes the incremental revenues.

The change in prices explains the peak in revenue when BOX diverts enough crude oil away from Asia to bring West Africa into the Asian supply mix.

Figure 8 has the following features:

1. In the early iterations, the volume strategically allocated to North America is below the competitive equilibrium flow allocation, so the allocation does not alter the equilibrium and there are no revenue gains or losses.

2. As BOX diverts more barrels into North America, the marginal barrels displaced come from successively West Africa, the North Sea, and Latin America. As these sources of supply successively drop out, North American prices fall. The market clearing price leads to a steeper discount each time one of these producers is driven out of the North American market. This discount corresponds to the step changes in the North American revenue curve. As the minimum strategic allocations to North America increase, these losses deepen until
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Figure 6 — Illustrative Supply and Demand Curves Showing Consequences of Asia’s Importing the Marginal Barrel from Middle East

Figure 7 — Illustrative Supply and Demand Curves Showing Consequences of Asia’s Importing the Marginal Barrel from West Africa
the allocations reach 2.65 MMbbl/d. At that point, the revenue gains from Asia spike, driven by the Asian price increases resulting from the emergence of West Africa as the marginal supplier for Asia.

3. Revenues fall with increases in the minimum level of exports to North America beyond the 2.65 MMbbl/d level because the prices set in Asia by West-African and Latin-American imports stabilize, while BOX crude has to be increasingly discounted to expand its market share in North America. In addition, the added shipments to North America lead to a lower volume shipped to Asia, where the price is higher than in North America.

BOX’s export revenue gain peaks at $18 million per day, or $6.6 billion per year, when the volumes diverted to North America reach 2.65 MMbbl/d.

Thus, allocating export volumes strategically to markets that do not offer the highest price may increase overall revenues for a major producer or coalition of producers.

So far, BOX’s allocations have been based on an assumption of moderate refinery flexibility. The degree of refinery flexibility included in the GOTM influences the results. In Figure 9 we can see the impact of representing refinery flexibility, simulated in our model by decreasing or increasing the step height of the API penalty function. If the penalties for divergence (measured in $/bbl) become high, then ensuring the average API gravities of crudes match the optimum configuration of the refinery becomes increasingly important to a refiner’s ability to convert crude oil into a given set of refined products. Less flexible refineries in nearby locations add to the costs of accessing more distant markets.

Figure 8 — BOX’s Revenue Gain from Asia vs. Revenue Loss to North America
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with the buyers that are willing to pay more for the most suitable grades result of crude oil.

As shown in Figure 9, reducing refinery flexibility (i.e. as the deviation penalty P faced by refiners increases from $0/bbl to $10/bbl) accentuates BOX’s revenue gains. In other words, in a heterogeneous crude oil market with quality differentials, crude oil is less of a commodity and there is a greater cost to a refinery in deviating from the average API of its crude slate. This increases the locational rents achieved by the Stackelberg leader.

Importer as the Stackelberg Leader

By contrast, when we examine whether BIM can use strategic purchases to be a Stackelberg leader while BOX and all other players form the competitive fringe, we find that all BIM’s actions as Stackelberg leader result in negative returns. This is because, given the 2012 global market configuration, BOX remains the marginal supplier to Asia, keeping the relative price in Asia the same, and BIM’s strategic purchases are bought at a higher cost relative to the perfect competition scenario, leading to a higher average price.

The Stackelberg-Nash Game: The Large Importer Acts Strategically

In the Stackelberg game, BOX not only diversifies its customers but also increases its revenue. Now we consider the possibility of BIM’s making strategic purchases to lower its costs to counter BOX. As the context for the Stackelberg-Nash game, BOX had a total crude oil supply of 29 MMbbl/d and BIM had a demand of 27 MMbbl/d in 2012.

In a two-player Nash game each player optimizes its position related to the actions of the other player and at equilibrium neither player can improve its outcome relative to the other player’s position. In our Stackelberg-Nash game, at an equilibrium, if it
exists, neither large player can improve its outcome compared with the other large player’s position and the response of the competitive fringe.

The revenues and the costs can go up and down in unpredictable steps as the allocations increase and as the level of strategic purchases increase. Consequently, we construct a grid of allocations of sales and purchases by BOX and BIM, respectively, and for each grid point we find the market equilibrium that results from the actions of the competitive fringe, considering the players’ actions at that grid point. For the set of market equilibria we construct two tables that consist of the pay-offs for BOX and BIM. If we can find a grid point where BOX maximizes its revenue following BIM’s action and BIM minimizes its purchase costs as a result of BOX’s actions, then we have an equilibrium.

Absence of a Nash Equilibrium

In the pay-off tables no such point exists. What we observe is that BIM’s best response to any BOX allocation level is to always make a strategic purchase from further afield, such as Latin America, which eliminates the need to buy crude from West Africa and nullifies BOX’s revenue increase from Asia. In addition, if BOX makes no strategic allocation, then, as in the game with BIM as the Stackelberg leader, BIM can only raise its cost by making strategic purchases. That is to say, BIM’s best response to no strategic allocation by BOX is to make no strategic purchases.

So we have a situation where BOX’s best response when BIM does not make a strategic purchase is the Stackelberg allocation described above, where BIM’s best response to BOX’s strategic allocation is making strategic purchases that take the profit away. Moreover, there is no pair of decisions in the tables where the pay-offs of both players satisfy the Nash condition. That means there is no equilibrium to the game.

Not having an equilibrium can have three possible meanings:

1. The market is unstable and the players are constantly shifting their positions. This has been observed in Edgeworth cycles (Edgeworth, 1925) in a different context.

2. The objective functions of the players may be incomplete in the model. We have not included any value for diversification of allocations and strategic purchases. GOTM focuses on direct revenues and costs. If there were some utility function that assigned value to diversification and that value were high enough, an equilibrium would exist despite the implementation of both strategic allocations and purchases.

We have not tried to estimate the diversification value. However, it is worth noting that, if adding diversification value leads to an equilibrium, then the players are effectively trading off higher revenues or lower costs for diversification. They cannot achieve both the increased revenues or lower costs and diversification seen in the Stackelberg game.

3. The players can redefine the game as a cooperative game and look for potential joint gains by enlarging the value of their relationships beyond crude oil transactions.
Conclusions

We originally posed the questions of whether regional price differences represent a premium or a discount and what this says about what drives the large players. It is widely believed that there is a trade-off between diversification and economic optimization.

KAPSARC’s framework suggests this is not always the case because:

- Large sellers may increase their revenues by allocating volumes to more distant markets, if by doing so they capture locational rents from more proximate buyers.
- Large buyers can theoretically reduce their costs by purchasing volumes from more distant suppliers, counteracting the strategies of their nearest suppliers.

Based on the 2012 configuration of global oil markets, any significant coalition of Arabian Gulf exporters can exploit this opportunity, provided that a large Asian buyer or coalition of buyers does not deploy a countervailing strategy. In addition, no single buyer or coalition of buyers is currently large enough to position itself to reduce its supply costs through supplier diversification. In other words, any countervailing strategy makes both the exporters and the importers worse off.

Potential longer-term market reconfigurations, such as North American volumes becoming available in the Pacific markets or a Russian supply pivot from Europe to North East Asia, might alter the ability of current Middle East exporters to increase revenues while achieving greater customer diversity.

When both large players seek to make strategic regional allocations of their sales and purchases, there is no combination of decisions where they both come out ahead financially. For an equilibrium to exist in this situation, they would need to place a value on diversification.

Our results illustrate that trying to identify a single driver of the actions of large players is an oversimplification. A combination of factors may apply and the question really is the degree to which each influences outcomes.
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Appendix A: Mathematical Statement of the Model

The objective function and constraints are as follows:

**Objective function** - minimize the sum of total freight costs and refinery API gravity deviation penalties globally:

\[
\min \left( \sum_{i,j} C_{ij} x_{ij} + \sum_{k,j} P_k (Q^+_{k,j} + Q^-_{k,j}) \right)
\]  \hspace{1cm} (1)

Subject to the following constraints (dual variables in brackets):

The sum of the volumes of crude oil shipped to refineries \( j \) must not exceed its supply capacity:

\[
\sum_i x_{ij} \leq S_i, \quad (\mu_i)
\]  \hspace{1cm} (2)

The sum of crude oil volumes \( i \) shipped to refinery \( j \) must meet refinery demand:

\[
\sum_i x_{ij} \geq D_j, \quad (v_j)
\]  \hspace{1cm} (3)

API balance equation:

\[
\sum_i \left( \frac{API_{S_i}}{API_{D_j}} - 1 \right) x_{ij} + \sum_k Q^+_{k,j} - \sum_k Q^-_{k,j} = 0, \quad (\lambda_j)
\]  \hspace{1cm} (4)

Non-negativity conditions:

\[
x_{ij} \geq 0, \quad Q^+_{k,j} \geq 0, \quad Q^-_{k,j} \geq 0
\]  \hspace{1cm} (5)

Where:

\( C_{ij} \): Freight costs from supply node for crude \( i \) to refinery \( j \)

\( x_{ij} \): Crude oil flow from supply node for crude \( i \) to refinery \( j \)

\( P_k \): Penalty cost per deviation barrel

\( Q^+_{k,j} \): Heavier normalized ‘deviation’ barrels feedstock to refinery \( j \) for tier \( k \)

\( Q^-_{k,j} \): Lighter normalized ‘deviation’ barrels feedstock to refinery \( j \) for tier \( k \)

\( Q_{k,j} = Q^+_{k,j} + Q^-_{k,j} \): Total normalized ‘deviation’ barrels feedstock to refinery \( j \) for tier \( k \)

\( Q_j = \sum_k (Q^+_{k,j} + Q^-_{k,j}) \): Total normalized ‘deviation’ barrels feedstock to refinery \( j \) in all tiers

\( S_i \): Total supply of crude \( i \)

\( D_j \): Total demand of refinery \( j \)

\( API_{S_i} \): API gravity of crude \( i \)

\( API_{D_j} \): Ideal API gravity of feedstock to refinery \( j \)
\( \mu_i \): Supply price of crude \( i \) (dual variable of the supply constraint)

\( v_j \): Marginal value to refinery \( j \) (dual variable of the demand constraint)

\( \lambda_j \): Cost of deviating by one incremental ‘normalized’ barrel unit \( Q_j \) for refinery \( j \) (dual variable of the \( API \) balance equation)

The dual variables of the supply constraints (\( \mu_i \geq 0 \)) can be interpreted as the location and quality rents accruing to crude \( i \). A high value of \( \mu_i \) suggests the geographic and/or quality advantage crude \( i \) has relative to the marginal barrel of the system. This dual is also the difference relative to the baseline world price for oil due to its location and quality.

The dual variable of the demand constraints (\( v_j \geq 0 \)) can be interpreted as the cost of supplying this location plus the deviation cost from the ideal slate in what is supplied to refinery \( j \). This dual also represents the increase in the marginal value from the baseline world price due to the costs of transportation and crude quality.

The spatial price equilibrium conditions derived from the Karush-Kuhn-Tucker (KKT) optimality conditions are as follows:

\[
0 \leq x_{ij} \perp C_{ij} + \mu_i + \left(1 - \frac{API_{ji}}{API_{Dj}}\right) \lambda_j - v_j \geq 0
\]

(6)

The marginal cost of deviation \( \lambda_j \) represents the marginal cost of importing one additional unit of the ‘normalized’ barrel \( Q_j \). When \( \lambda_j \leq 0 \), refinery \( j \) deviates from its ideal crude slate to one with an average API gravity that is lighter \( (Q_j^+ > 0) \) and when \( \lambda_j > 0 \), it deviates to one with an average API that is heavier \( (Q_j^- > 0) \).

We define a new variable \( DC_{ij} \) to measure the marginal cost of deviation incurred by refinery \( j \) from deviating by one additional unit of crude \( i \):

\[
DC_{ij} = \left(1 - \frac{API_{ji}}{API_{Dj}}\right) \lambda_j
\]

(7)

If \( DC_{ij} > 0 \), an additional barrel of \( x_{ij} \) increases the deviation quantity \( Q_j \) at refinery \( j \) and incurs a deviation cost of \( DC_{ij} \). If \( DC_{ij} < 0 \), an additional barrel of \( x_{ij} \) decreases \( Q_j \) and results in a cost reduction of \( DC_{ij} \). Rewriting the spatial price equilibrium conditions in terms of \( DC_{ij} \) instead of \( \lambda_j \):

\[
0 \leq x_{ij} \perp C_{ij} + \mu_i + DC_{ij} - v_j \geq 0
\]

(8)

The spatial price equilibrium conditions can now be restated: for every existing crude oil flow \( x_{ij} > 0 \), the marginal value at the refinery \( j \) must equal the supply price \( \mu_i \) plus the transportation cost \( C_{ij} \), plus the marginal deviation cost (or cost reduction) from running crude \( i \) at the refinery \( j \).

The above spatial price equilibrium conditions hold only in the competitive market scenario where crude oil flows are determined by minimizing the global transport and deviation costs, without any strategic actions by the
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However, when producers or importers are allowed to take actions by setting a lower limit in any of the flows $x_{ij}$, the spatial equilibrium condition for the affected flow becomes:

$$b \leq x_{ij} \perp C_{ij} + \mu_i - \phi_{ij} + DC_{ij} - v_j \geq 0,$$

(9)

where $b \geq 0$ is the lower limit and $\phi_{ij}$ is the dual variable of the floor constraint of $x_{ij}$ which can be interpreted as either a discount from supplier $i$ to importer $j$ or a premium that importer $j$ must pay to import from supplier $i$.

The revenue gains or losses from allocating oil exports across different regions for BOX are calculated using the following formula:

$$\text{BOX Revenues} = \sum_{i=\text{BOX}} \sum_{j=\text{US}} \mu_i x_{ij} + \sum_{i=\text{BOX}} \sum_{j=\text{US}} (\mu_i - \phi_{ij}) x_{ij}$$

(10)

BIM measures its cost, including the cost of putting a lower limit on purchases of crude oil from specific supply regions, West Africa (WAF) and Latin America (LAM) as follows:

$$\text{BIM Costs} = \sum_{j=\text{BIM}} \sum_{i=\text{LAM, WAF}} v_j x_{ij} + \sum_{j=\text{BIM}} \sum_{i=\text{LAM, WAF}} (v_j + \phi_{ij}) x_{ij}$$

(11)

‘Costs’ here do not refer to absolute costs of crude oil, but the extra expense BIM incurs due to the strategic geographic sourcing of imports.
Appendix B: Price Discovery Mechanism in GOTM

1. Homogeneous Crude Oil

Using a simple example to demonstrate how the dual variables (prices) are determined, we assume two supply nodes and two demand nodes with a homogeneous crude stream to be traded (Figure A1).

The two suppliers have capacities of 700 and 301 barrels per day (bbl/d) respectively, and the two demand nodes require 500 bbl/d each. The objective function is to minimize total transport costs given supply and demand constraints:

$$\min \ x_{11} + 2x_{12} + 4x_{21} + 3x_{22}$$  \hspace{1cm} (B1)

Subject to:

$$x_{11} + x_{12} \leq 700$$  \hspace{1cm} (B2)

$$x_{21} + x_{22} \leq 301$$  \hspace{1cm} (B3)

$$x_{11} + x_{21} \geq 500$$  \hspace{1cm} (B4)

$$x_{12} + x_{22} \geq 500$$  \hspace{1cm} (B5)

$$x_{11}, x_{12}, x_{21}, x_{22} \geq 0$$  \hspace{1cm} (B6)

Solving the primal problem above, $x_{11} = 500$, $x_{12} = 200$, $x_{21} = 0$, $x_{22} = 300$. From the Karush–Kuhn–Tucker (KKT) optimality conditions we can derive the following spatial price equilibrium conditions:

$$0 \leq x_{ij} \perp C_{ij} + \mu_i - v_j \geq 0$$  \hspace{1cm} (B7)
The above complementarity conditions can be restated as:

For every existing flow between two nodes, the delivered price has to be equal to transport cost plus the supply price at node $i$.

We can then derive the following complementarity conditions between the supply constraints and their dual variables.

\[ 0 \leq \sum x_{ij} - S_i \perp \mu_i \geq 0 \]  \hspace{1cm} (B8)

Restating the above complementarity relationships as:

For every supply node $i$ with excess capacity, the associated dual variable (supply price) is equal to zero.

Using the above two complementarity conditions, we can now demonstrate how the dual variables are determined. Because total supply exceeds total demand $\sum S_i > \sum D_i$, one of the supply nodes will have excess supply, in this case $S_2$. Hence, its associated dual variable (supply price) is equal to zero.

Starting from this node, we can compute all the dual variables (prices) of the problem. For every demand node importing from $S_2$, its delivered price has to be equal to the supply price of $S_2$ plus the transportation cost between them. So the price of $D_2$ can be determined, as shown in Figure A2.

\[ x_{21} = 0 \Rightarrow \mu_2 + 4 \leq \nu_1 \]
\[ x_{22} > 0 \Rightarrow \mu_2 + 3 = \nu_2 \]
\[ \Rightarrow \nu_2 = 3 \]

Figure A2 – Dual Variable Calculation Sequence–First Step
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Figure A3 shows how the supply price of $S_1$ is computed from the delivered price of $D_2$

Now that the price of $S_1$ has been determined, we can compute the delivered price of $D_2$, shown in Figure A4

Note that every supply and demand node in the example is connected by a path of flows. When there is no link with positive flow connecting two or more subsets, the above calculations apply to each subset separately.

2. Heterogeneous Crude Oil

The previous example shows how we can compute the prices when crude oil is assumed to be homogenous. Once we differentiate crudes by API gravity, the spatial price equilibrium conditions change. In Figure A5, we have two types of crudes for each supply node and two refineries with distinct optimal mixes in each demand node. The crudes are differentiated by their gravity to represent their quality, and each refinery has an ideal feedstock gravity to represent the preferred crude type for a particular refinery configuration.
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The linear program for this example will be similar to GOTM, and is as follow:

\[
\min \sum_{i} \sum_{j} c_{ij} x_{ij} + \sum_{j} \left( \sum_{k} p_{k} (q_{k}^{+} + q_{k}^{-}) \right)
\]

Subject to:

\[
\sum_{i} x_{ij} \leq S_i \quad (\mu_i)
\]

\[
\sum_{j} x_{ij} \geq D_j \quad (v_i)
\]

\[
\sum_{i} \left( \frac{API_{S_i}}{API_{D_j}} - 1 \right) x_{ij} + \sum_{k} Q_{k}^{+} - \sum_{k} Q_{k}^{-} = 0. \quad (\lambda_j)
\]

\[
x_{ij} \geq 0, \quad Q_{k}^{+} \geq 0, \quad Q_{k}^{-} \geq 0
\]

Where \( x_{ij} \) is defined as the volume shipped of crude \( i \) to refinery \( j \), the spatial equilibrium conditions will be:

\[
0 \leq x_{ij} \perp c_{ij} + \mu_i + DC_{ij} - v_i \geq 0
\]

Where \( DC_{ij} = \left( 1 - \frac{API_{S_i}}{API_{D_j}} \right) \lambda_j \) is defined as the marginal cost of deviation incurred by refinery \( j \) from one additional unit of crude \( i \). The delivered price in this situation accounts for the value of crude \( i \) to refinery \( j \). If \( DC_{ij} > 0 \), the additional barrel of crude \( i \) increases the deviation quantity for refinery \( j \) and incurs a deviation cost of \( DC_{ij} \). When, \( DC_{ij} < 0 \), the additional barrel of crude \( i \) decreases the deviation quantity for refinery \( j \) and reduces the deviation cost by \( DC_{ij} \). Therefore, the difference between the spatial price equilibrium conditions in Appendix B1 and B2 is the term \( DC_{ij} \). The actual marginal value of crude \( i \) in refinery \( j \) is \( v_j - DC_{ij} \), which we treat as the delivered price. In the competitive market we have \( v_j - DC_{ij} = c_{ij} + \mu_i \). If we subtract the transportation cost from the delivered price we will have the netback price of the crude sold to refinery \( j \).
About the team

Shahad AlArenan is a Research Analyst focusing on oil markets. She holds a BSc in Electrical and Computer Engineering from Effat University.

Tilak K. Doshi is a Senior Research Fellow and Program Director for Markets and Industry at KAPSARC, specializing in oil and gas markets. He holds a PhD in Economics.

Ziyad AlFawzan is a Research Analyst focusing on oil markets. He holds a BSc in Industrial Engineering from King Saud University.

Nader AlKathiri is a Research Associate at KAPSARC specializing in modeling energy markets. He holds a MS degree from KAUST.

Frederic Murphy is a Senior Visiting Fellow and Professor Emeritus, Temple University. He has a PhD in operations research and a BA in mathematics from Yale University.

Yazeed Al-Rashed is a Senior Research Analyst at KAPSARC. He holds an SB in Chemical Engineering from MIT, and an MS in Energy Systems from Columbia University.

About the Project

Since the oil price shocks of the 1970s, the security of oil supply has been the main concern in academic and policy circles. The goal of this research project is to study the other side of the coin—the security of oil demand from the net-exporters perspective. How do large oil exporters trade off risk and rewards in ensuring security of demand?

In the first phase of this research project, the project develops a comparative static model of global oil trade to empirically measure the impacts of alternative crude oil market shares across segmented markets; to assess the strategic choice NOCs have in valuing alternative sales market portfolios in the context of the trade-off along the risk-reward frontier; and to compare IOC behavior as a benchmark for NOCs.

More specifically, this project will attempt to specify a parsimonious model of regionally segmented global oil trade calibrated to 2012 benchmark data which would allow comparative static exercises to simulate equilibrium impacts of alternative placement of term-contracted crude oil, including impacts on total revenues for crude oil producers. The model focuses on three fundamental variables that determine relative crude oil prices: transport costs, crude oil quality, and refinery flexibility.

In line with KAPSARC’s overall objectives, the intent is to produce policy-relevant insights that help actors in the oil industry understand the consequences of decisions taken by large exporters.

The workshop series fits into the overall project by providing a continuing dialogue that raises key issues, provides feedback on current work, and sets future directions. The workshops are an open collaborative forum that enables the discussion of particular themes that feed into identified research questions.