A Risk-Hedging View to Refinery Capacity Investment in OPEC Countries

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Abstract

Should oil-rich members of OPEC invest in the oil refinery industry? This is a crucial energy policy question for such economies. We offer theoretical models for a vertical integration strategy within an oil-producing economy, based on a risk-hedging view. The first model highlights the trade-off between return and risk-reduction features of upstream/downstream sectors. The dynamic model demonstrates the volatility of total budgetary revenue of each sector. Our theory-guided empirical analysis shows that though the average markup in the refining sector is significantly smaller than the profits in the upstream, downstream investment can provide some hedging value. In particular, the more stable and mean-reverting refining margins provide a partial revenue cushion when crude oil prices are low. We discuss the risk-hedging feature of the refinery industry when the crude oil market faces supply versus demand shocks.

Keywords: Refinery Industry, Hedging, Vertical Integration, Downstream Investment, Export Diversification

1. Introduction

Investing in the downstream sector to export refined products, as opposed to the export of crude oil, is an appealing and popular policy slogan in many oil-producing countries,

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including OPEC members. In 2010, OPEC's secretary general predicted that "over the next decade, members were expected to invest around $40 billion in refining capacity expansion."[3] The ambitious idea to invest in downstream is, however, not new. An Iranian government stamp published in 1973 promotes a national dream for a full-vertical integration in the country's oil industry from *well to the wheel* . Also, a recent Bloomberg news item discusses UAE's ambitious plans to heavily invest in the downstream [4].

The incentive for downstream investment is strong because it is indeed tempting to export final products instead of the raw material. The value-added in the downstream sector (i.e. processed primary commodities) is deemed to be larger than the upstream[5]. The idea that a possible negative correlation between upstream and downstream profits can motivate vertical integration in the oil industry is first introduced by McLean and Haigh (1954). Opponents of the vertical integration policy believe that the value-added in the oil refinery sector is limited and not much can be gained after exposing the country to substantial capital investment commitments, taking financial risks of the downstream business, and in some cases hiring expensive foreign labor.

To shed some light on the policy debate, we offer a analysis of the optimal downstream investing from a risk-hedging prospective. We build a static (single-period) model and a dynamic, forward-looking one. The first model highlights the trade-off between return and risk-reduction features of upstream/downstream sectors. The dynamic model characterizes the volatility of total budgetary revenue of each sector. We take both models to the data to provide some quantitative insights in the case of crude oil refinery investment decision. Our

[3] `http://www.downstreamtoday.com/news/article.aspx?a_id=23807&AspxAutoDetectCookieSupport=1`

[4] `https://www.bloomberg.com/news/articles/2018-05-10/as-saudis-pursue-aramco-ipo-abu-dhabi-hedges-to-stay-relevant`

[5] The perception of a large untapped value in the oil refinery sector is likely to be induced by observations from other commodity markets such as rare earth materials or coffee beans, in which the market value of final goods (e.g., solar panels or instant coffee) is much larger than raw primary commodity.

analysis is *normative* in natures; thus, we are not aiming at providing an *explanation*for the observe refinery capacities OPEC countries. Instead, our goal is to provide a framework to critically analysis such decisions.

Our theoretical models provide comparative statistics for the relative value of investment in the upstream and downstream sector. volatile crude oil prices expose oil exporting countries to major foreign exchange and government revenue risks, resulting in macroeconomic instabilities (especially in the presence of rigid exchange rate regimes) and causing the so-called resource curse effect (Van der Ploeg and Poelhekke (2009)). Commodity stabilization funds (Arrau and Claessens (1992)) and/or hedging through financial instruments (e.g. futures and options) are two commonly proposed methods to manage volatile oil prices (Devlin and Titman (2004)). Vertical integration along the supply chain is the third strategy, which we will discuss in more details. The low correlation of refinery markups and crude oil prices, as well as their different time-series dynamics, can potentially provide some degree of hedging to the current account of the oil-exporting country.

The optimal degree of vertical integration is a key input for the high-level energy and development discourse of oil-producing economies. Despite the obvious policy relevance and the potentially large resource commitment to invest in such industries, there is very little academic research on this highly relevant topic (especially in recent years). To the best of our knowledge, our paper is one of the very few academic papers in the past two decades specifically focusing on formal models and empirical results to analyze downstream investment in oil-rich countries. There are older papers (e.g. Al-Monsef (1998), Al-Obaidan and Scully (1993)) which consider the problem of vertical integration for national oil companies. Also, Mabro (2006) provides a non-technical overview of the issue in a chapter. Finally, a small body of literature focuses on energy policy choices of individual countries. For example, Krane (2015) discusses the incentives of Saudi Arabia for investing in downstream industries. We further develop the traditional analysis by offering a continuous-time revenue valuation model coupled with several empirical measures. Moreover, given the changes in the level of crude oil prices and refining margins, our paper offers an up-to-date analysis of the problem.

In short, our contribution has two major dimensions. First, we offer theoretical models to formally characterize hedging incentives for a downstream investment. Second, we show that the time-series dynamics of profits in the upstream and downstream sectors have different properties. In particular, due to the mean-reverting nature of cash-flows in the refinery, sector, the present value of the downstream revenues is significantly less volatile than the upstream.

2. Literature Review

Our work is built on insights from research in the natural resource and energy economics as well as the industrial organization (IO) literature. In a broad sense, our work is related to the large and mature literature on resource curse (Frankel (2010)) and the political economy of oil-producing countries (Beland and Tiagi (2009), Ross (1999)). The resource curve literature not only highlights the role of institutions (e.g., Cabrales and Hauk (2011)) but also emphasizes that the way natural resource revenues are spent plays a critical role. Commodity price volatility has also been identified as a major source of resource curse in resource-rich countries (Van der Ploeg and Poelhekke (2009)). Volatile terms of trade can suppress productivity growth, even in the presence of large capital accumulations.

Investment on downstream might be a potential remedy for the resource curse if it helps oil-rich countries alleviate some of the negative features of exporting crude oil. Merener and Steglich (2017) consider the role of price correlation to gauge the price performance of diversified economies and conclude that diversified commodity producing countries face a significantly lower risk than specialized producers. Borensztein et al. (2013) quantify the welfare gains of hedging against the commodity price risk for commodity-exporting countries and highlight the first order effect of reducing precautionary saving. Van der Ploeg and Venables (2011) discuss policy options for spending resource revenues. Export diversification is a key suggestion to reduce the magnitude of the resource curse. Herzer and Nowak-Lehnmann D (2006) and Bertinelli et al. (2009), among others, empirically examine the export diversification structure of resource-rich countries and conclude that considerable welfare can be gained if these countries move toward an optimal export portfolio. Alwang and Siegel (1994)) evaluate the usefulness of portfolio models in advising export diversification policies for resource-rich countries. Labys and Lord (1990) use portfolio optimization techniques to determine the optimal export diversification strategy for Latin American countries. Massol and Banal-Estañol (2014) apply an optimization model to identify the optimal downstream investment for gas-rich countries. Cherif and Hasanov (2013) model the consumption, saving, and investment decisions of oil-exporting countries and show that a sizable precautionary saving is optimal for such economies.

A variety of strategic motives and efficiency reasons (e.g., transaction costs, property rights, agency models) are offered for vertical integration and have been extensively discussed in the industrial organization (IO) literature (see Carlton (1979), Lieberman (1991) and Joskow (2012)). Suzuki et al. (2011) provides an interesting rationale for partial vertical integration when small suppliers have a superior ability to absorb demand shocks. Also, Aïd et al. (2011) and Léautier and Rochet (2014) discuss the risk-reduction incentives of vertical integration. However, some insights of that literature are not directly applicable to the oil industry. Crude oil has no economic substitute. Therefore, the downstream of the oil industry is not making a strategic choice of input, and there is little room for the upstream monopolist to influence the downstream decisions. This eliminates strategic considerations that are typical in the IO literature.

Levin (1981) and Barrera-Rey (1995) study the effect of vertical integration on the performance of oil companies and find no impact on the profitability but a small effect on risk

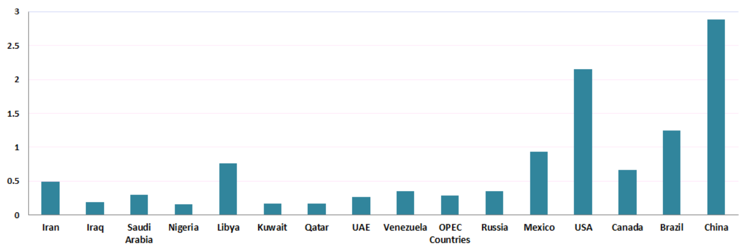


Figure 1: Refining Capacity to Crude Oil Production Capacity. Data Source: IEA

reduction. Norton (1993) shows that vertical integration reduces systematic risks for refinery companies. The optimal hedging strategy for refiners has been studied by several papers (e.g. Sykuta (1996), Sukcharoen and Leatham (2017)). Alexander et al. (2013) criticize the merits of the standard mean-variance optimization methods for determining the optimal hedging policy. Our paper differs from this literature by focusing on the profitability of the upstream rather than the profitability of the refinery. Moreover, we pose the problem from a macro policy-making perspective.

3. Motivating Facts

3.1. Refining Capacity of OPEC Members

Major oil producing countries are diverse regarding the ratio of their upstream and downstream capacities. Figure 1 shows the ratio of the domestic refining capacity to oil production capacity of countries[6].

As the first stylized fact, we observe a significant degree of heterogeneity among the major oil-producing nations. We also note that due to large domestic consumption levels, non-OPEC oil producers (e.g., USA) tend to have a much larger ratio of downstream to upstream, compared to OPEC members[7].

[6]A limitation of the table is that it only contains domestic refining capacity. Oil producing countries may also own refineries overseas.

[7]The refinery industry is complex and highly capital intensive. Financial constraints of oil-producing countries may have played a role in the observed weak vertical integration.

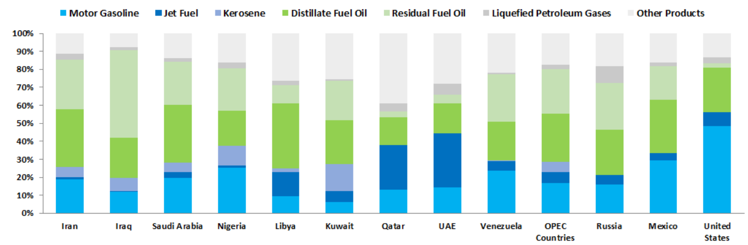


Figure 2: Relative Share of Different Refined Products in the Production Portfolio. Data Source: IEA

To better understand the output structure, Figure 2 shows the refining output basket for several countries (including major OPEC members). The plot suggests that OPEC countries' production capacities are typically not targeted toward high value-added products such as gasoline and jet fuel[8].

3.2. Historical Price and Margin Trends

Figure 3 shows the time-series of real prices of crude oil as well as the real crack spread. While crude oil price takes a wide range of values (and also seem to behave close to a random walk pattern), crack spreads show a low-volatility mean-reverting behavior staying in a more limited range[9]. We will report the detailed statistical analysis of these patterns in Section 6.

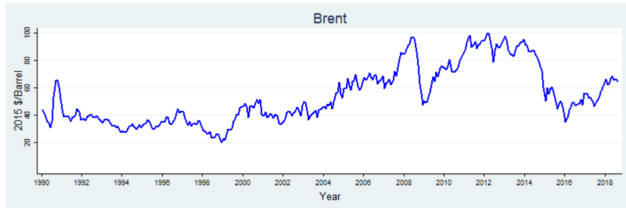
3.3. New Risks: Climate Change and Shale Revolution

Two major developments in the petroleum sector: 1) advances in production methods for unconventional oil and gas, such as shale oil, 2) negotiations over global climate policy, which may transform petroleum related geopolitics. We will discuss both effects on the context of our model.

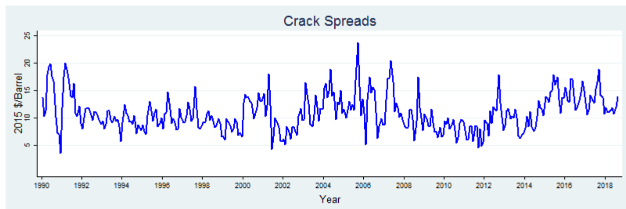
The majority of shale oil reserves have been developed only in the past few years, and particularly in the United States. The United States has increased shale oil production by

[8]Additional analysis also showed that OPEC countries' refining output baskets are biased toward their domestic consumption (as opposed to being export-oriented).

[9]A mean-reverting process can also take a wide range of values if the volatility parameter is sufficiently large. In the case of crack spreads, the volatility is small.



(a) Crude Oil Prices



(b) The Refinery Profitably Measure

Figure 3: Crude Oil Prices versus the Refinery Profitably Measure (both in 2015$).

180% from 2010 to 2013 (Lemons (2014)). This development resulted in a reduction in the price of natural gas, reduced oil imports and a reduction in the price of WTI crude oil relative to Brent crude oil. Since the majority of OPEC oil are inexpensive to produce, OPEC would continue to play a pivotal role in world oil supply under a lower price scenario, whereas it would be the most expensive unconventional oil and gas developments that would be canceled. However, OPEC would lose its market power above the cost levels for producing unconventional oil and could be selling at lower prices than during the first two decades of this century. Though the downward price pressure exerted by unconventional oil is restricted by the high cost of producing unconventional resources, that cost could change as technologies evolve. (Overland (2015)).

When it comes to climate change policies, OPEC countries typically do not welcome the idea of establishing a more stringent and more comprehensive climate policy. They tend to consider it as a potential threat to their oil export revenues, and possibly even their statehood (Bradshaw (2010)). To counter or mitigate potential risks of a more stricter global climate policy, some OPEC countries have been investing in renewable energy to diversify their economic base away from oil (Overland (2015)). Loulou et al. (2008) examine scenarios of introducing stronger climate-change targets and their impact on the OPEC countries. They find that while OPEC's export volumes would remain relatively stable under such scenarios, their profit margins would be lowered. However, if OPEC countries (especially the arid countries of the Middle East) see climate change as a serious threat to their environment, agriculture, ecology and water supply, they may start joining the global efforts (Brown and Crawford (2009)).

4. Theoretical Analysis

We build two stylized theoretical models (one static and one dynamic) to better identify the relationship between various underlying factors and the optimal degree of vertical integration. Key notations are introduced and summarized in Table 1. Our first model borrows insights from the portfolio theory literature; however, since it is applied to physical assets (as opposed to traded assets), the results for financial portfolios are not applicable to this case; thus, we need to set up the problem and derive the results.

5. Summary of Notations

5.1. Basics Assumptions and Components of Model

The oil-producing economy is endowed with a large reserve of natural resources (crude oil) sold in international markets at an exogenously specified random price P. The constant cost of extracting a barrel of oil is θ, resulting in $P_t - \theta$ unit of net revenue from each barrel of crude oil.

5.1.1. Stochastic Processes

The price of crude oil and the level of crack spreads (i.e refining margins) are both identically and independently distributed (i.i.d). random variables defined by the following equations:

Notation	Interpretation	Remark
$U(X)$	Utility of the social planner	Mean-variance specification
γ	Degree of risk-aversion	$\gamma = 3$ is a typical assumption.
ω	Degree of vertical integration	Control variable of the model
K_U	Level of upstream investment	Endogenous
K_D	Level of downstream investment	Endogenous
$I_1(K_U)$	Upstream investment cost function	$I_1^{'} > 0$, $I_1^{''} > 0$
$I_2(K_D)$	Downstream investment cost function	$I_2^{'} > 0$, $I_2^{''} > 0$
$\overline{I}$	Total investment budget	Exogenous
θ	Cost of extraction	Assumed to be zero
σ_R	Variance of total revenues	
P	Spot price of crude oil	Random variable
C	Current level of refining margins	Random variable
$\overline{P}$	Baseline level of crude oil	Random variable
$\overline{C}$	Baseline level of refining margins	Random variable
σ_U	Volatility of i.i.d shocks to upstream	
σ_D	Volatility of i.i.d shocks to downstream	
$\overline{C}$	Long-run level of refining margins	= \$4.32
μ_P	Drift of crude oil process	= 0.006
μ_C	Mean-reversion rate of refining margins	= 0.28
σ_P	Volatility of crude oil price process	0.09
σ_C	Volatility of refining margins process	= 2.52
r	Discount rate	= 0.05 per year
V	Present value of oil revenues	Closed-form solution
Y	Present value of refining revenues	Closed-form solution
ϵ	Sensitivity of revenue value to spot values	Closed-form solution

Table 1: List of Variables and Notations

$$
\begin{cases} P = \overline{P} + \epsilon_P \\ C = \overline{C} + \epsilon_C \end{cases} \tag{1}
$$

where $\overline{P}$ and $\overline{C}$ represent the base level of crude oil price and crack spreads and ϵ_P, and ϵ_C are normally distributed mean-zero shocks to the baseline levels with variances σ_U and $\sigma_D, respectively.$

5.1.2. Preferences

We represent the CARA preference of the risk-averse social planner over a random revenue X by a reduced-form mean-variance model

$$
U(X) = \mathbb{E}(X) - \frac{\gamma}{2}\text{Var}(X) \tag{2}
$$

where γ is the parameter of risk-aversion.

5.1.3. Investment Costs

The country faces a total investment budget constraint of $\overline{I}$, which can be allocated to build upstream and downstream capacities. The cost of K_U and $K_D = \omega K_U$ units of upstream and downstream capacity are given by two functions, $I_1(K_U)$ and $I_2(K_D)$, respectively. The simplified investment budget constraint is capturing frictions such as the limited pledgeability (i.e., the collateral value) of a country's energy sector assets, the capacity of the domestic financial system, and the risk diversification motives of international lenders. Due to these frictions, the country can only raise a total of $\overline{I}$ units of capital. The budget constraint imposes the standard condition of $I_1(K_U) + I_2(K_D) \leqslant \overline{I}$.

The investment cost functions are assumed to be continuous, increasing, and *convex* in $K_{U,D}$ (see Ghoddusi et al. (2017) for a detailed discussion of the implications). Following the standard merit-order assumption of natural resource economics, the convexity of the investment cost function captures the decreasing return to scale or the increasing cost of exploiting new reserves[10].

5.1.4. Investment Policy

The oil-rich country decides on the optimal degree of vertical integration, ω, defined as $\omega = \frac{K_D}{K_U}$, as the main control variable. The country chooses ω once and forever. Since restructuring is very difficult in the case of physical assets, we assume that the government makes a one-shot perpetual decision based on the expected behavior of the upstream and downstream, i.e., the problem can be solved as a static one-period problem.

5.2. Static Model

The model takes into account the randomness in crude oil prices and refining margins (i.e., crack spreads). We use this simple model to generate some insights regarding the risk-mitigating incentives of vertical integration.

5.2.1. Objective Function

The objective of the social planer is to maximize the expected utility through choosing an optimal level of vertical integration ($0 \leqslant \omega = \frac{K_D}{K_U}$)[11]:

$$\begin{cases} \max_{K_U, K_D} Z = \mathbb{E}[U(K_U, K_D)] \\ \text{s.t.} \\ I_1(K_D) + I_2(K_U) = \overline{I} \end{cases} \tag{3}$$

For given levels of K_U and K_D the total revenue R of the country is given by:

[10] The merit-order model of resource extraction and production suggests that the country first starts extracting from the most efficient reserve and then moves to less efficient ones. This can be translated into the increasing marginal cost of building an extra unit of capacity, which is captured through the convex form of investment functions.

[11] One key difference between solving the optimal portfolio problem for physical and financial assets is that, unlike financial portfolios, the investment on physical assets can not short positions.

$$R = \underbrace{[P-\theta]K_U}_{\text{Upstream Revenue}} + \underbrace{K_D C}_{\text{Downstream Revenue}} = K_U[P-\theta+\omega C] \tag{4}$$

The variance of the revenue process is given by:

$$\sigma_R^2 = K_U^2\sigma_U^2 + K_D^2\sigma_D^2 + 2K_UK_D\text{Cov}(\epsilon_C, \epsilon_P) \tag{5}$$

Plugging the explicit values into the objective to the objective function (Eqaution 2) and setting up the Lagrangian function results in:

$$\mathcal{L} = K_U[\overline{P}-\theta] + K_D\overline{C} - \frac{\gamma}{2}K_U^2[\sigma_U^2 + \omega^2\sigma_D^2 + 2\omega\text{Cov}(\epsilon_C, \epsilon_P)] - \lambda[I_1 + I_2 - \overline{I}] \tag{6}$$

After some algebra the (first order) optimality conditions can be written as:

$$\begin{cases} \frac{\partial\mathcal{L}}{\partial K_U} = 0 \Rightarrow \overline{P} - 2\gamma[K_U\sigma_U^2 + K_D\sigma_{D,U}] = \lambda I_1'(K_U) \\ \frac{\partial\mathcal{L}}{\partial K_D} = 0 \Rightarrow \overline{C} - 2\gamma[K_D\sigma_C^2 + K_U\sigma_{D,U}] = \lambda I_2'(K_D) \end{cases} \tag{7}$$

where $\sigma_{D,U}$ is the correlation between the profitability of the upstream and downstream segments. The optimality conditions suggest that the marginal cost of investing an extra unit of capacity in each sector must be equal to the marginal benefit (i.e., sales price) corrected for the disutility of risk.

While a risk-neutral planner (i.e., when $\gamma = 0$) will most likely choose a corner solution, a risk-averse planner will be encouraged to choose an interior solution. If the social planner is risk-neutral or if both crude oil and refining margins are deterministic (i.e. no randomness), the optimal conditions simplify to $\frac{\overline{P}}{\overline{C}} = \frac{I_1'(K_U)}{I_2'(K_D)}$. In this case, the optimal degree of vertical integration will be determined by pure return on investment (ROI) considerations. If the convexity of investment function is sufficiently weak (i.e., the investment cost is near linear), this first-order condition (FOC) will likely result in a corner solution in which the investment will be allocated to the sector with the highest ROI (most likely the upstream sector for OPEC countries).

However, once the risk-aversion is introduced, the *hedging* value of diversification through downstream investment will be added to optimally conditions of the investment as shown in Equation 8.

$$\frac{\overline{P} - 2\gamma[K_U\sigma_U^2 + K_D\sigma_{D,U}]}{\overline{C} - 2\gamma[K_D\sigma_D^2 + K_U\sigma_{D,U}]} = \frac{I_1^{'}(K_U)}{I_2^{'}(K_D)} \tag{8}$$

The solution of Equation **??** (the model with a risk-averse social planner) will encourage an interior solution, in which positive investment will is possible to be observed in both sectors.

5.2.2. Comparative Statics

To better understand the behavior of the problem we consider the differential changes in the utility of the planner when resources are moved from one sector to another. The comparative static of a constrained optimization problem can be derived from applying the insights of the Envelope theorem to the Lagrangian problem. The fact that $I_{1,2}$ are continuous, monotone, and convex and appear on the numerator and denominator of the fraction, makes the comparative static of marginal changes rather straightforward. Motivated by industry information, we assume that building one unit of upstream is more expensive than a unit of refinery capacity, $K_U > K_D$.

For a given level of K_U and K_D a total differentiation of the budget constraint suggests that at the margin, an extra unit of downstream investment causes a $\frac{I_2^{'}(K_D)}{I_1^{'}(K_U)}$ reduction in the capacity of upstream. The country loses $\frac{I_2^{'}(K_D)}{I_1^{'}(K_U)}(P - C)$ units of revenue for each extra unit of capacity installed in the downstream. However, the utility may improve because of risk-reducing features of diversification.

The key driver of the result is that variance of the revenues is *convex* in the level of capacity of the respective sector (K_U^2 and K_D^2)

A marginal reduction of upstream capacity reduces $2K_U\sigma_P^2$ units of upstream risks and increases the other two terms by $2K_D[\sigma_C^2 + \sigma_{U,D}^2]$. If $K_D << K_U$ (little capacity in the downstream) or if $\sigma_D < \sigma_U$ (lower relative volatility of refining margins), the total volatility is reduced.

Volatility. We can see that if the volatility of the upstream sector is large, if the volatility of downstream is small, or if the covariance between the cash-flows of upstream and downstream is small or negative, the incentive to invest in the downstream is larger.

$$\frac{\partial \omega}{\partial [\frac{\sigma_U}{\sigma_D}]} > 0 \tag{9}$$

The term $\gamma K_U^2 \sigma_D \sigma_U \sigma_{D,U}$ represents an additional hedging value when $\sigma_{D,U}$ is negative.

$$\frac{\partial \omega}{\partial \sigma_{U,D}} < 0 \tag{10}$$

Source of Crude Oil Price Fluctuations: Demand/ Supply Shocks. A key parameter of the model is $\sigma_{U,D}$, the correlation between movements of crude oil prices and refining margins. To open up the black box of $\sigma_{U,D}$ Ghoddusi et al. (2018) provide a structural model of the refining margins dynamics. Their results show that the correlation of crude oil prices and crack spreads can be negative or positive, depending on the source of crude oil price shocks. If crude oil prices are driven down by favorable supply shocks (i.e., a shift of the supply curve to the right/left), crack spreads and crude oil prices move in opposite directions. Whereas, when crude oil price is driven by demand shocks (i.e., the shift of the demand curve to the right/left), crack spreads and crude oil prices move in the same direction. We discuss two examples of sources of supply and demand shocks.

Shale Revolution. The refinery sector will provide a better hedging for their economy if the oil price is low because of a positive supply shock such as shale revolution or OPEC's decision not to cut production; a chief example of it would be the 2014-2017 episode.

Climate Change. On the other hand, if the oil price is low due to the global recession and low demand, the refinery margins would also be low, and hedging will not be very effective. The overall decision depends on the historical magnitude of demand and supply shocks.

Source of Shock	Correlation of Crude Oil Prices and Refining Margins	Implications for Vertical Integration
Shocks mainly to the supply of crude oil (e.g. shale technology)	Negative	Larger degree of vertical integration
Shocks mainly to the demand for refined products (e.g. climate change)	Positive	Smaller degree of vertical integration

Table 2: Effect of Crude Oil Shocks on Vertical Integration. The table suggests that vertical integration is more attractive when the source of threat is from the supply side (e.g. shale) than the demand (e.g. climate change).

Level of Crude Oil Prices. As we see in Figure 3, when crude oil prices are high, the relative size of crack-spreads to crude oil prices are small. Thus, if it is expected that oil prices will remain high, the relative attractiveness of the refinery sector would be lower. This negative correlation is not only a statistical artifact, but in agreement with economic intuition if one considers an increasing marginal cost of refining in a merit-order type model[12]. If oil prices are high due to adverse supply shocks, demand for refined products and also the capacity utilization of the refinery sector will be low (under the usual ceteris paribus clause). This lower capacity utilization will lower the crack spreads of refined products, as less efficient

[12]A merit-order model suggests that the industry will use the most efficient production units first and then, as demand increases, will utilize less efficient production units. The price of the good will be determined by the production cost of the marginal producer, and some Ricardian rent will accrue to all production units before the marginal one.

refinery units will not run and the efficiency rent accruing to efficient units will be lower. Conversely, low oil prices caused by favorable supply shocks (e.g., post-2015 situation) trigger a high refined products demand and consequently higher refining margins.

$$\frac{\partial \omega}{\partial [\overline{P} - \overline{C}]} < 0 \tag{11}$$

Extraction Costs. Countries differ significantly concerning their crude oil production costs. If the production costs of crude oil are high, ceteris paribus the net margin of a high-cost country would be lower, compared to the profit margin of a low-cost country. The higher the extraction cost of crude oil, the higher the relative importance of the crack-spreads. Thus, it is expected that high-cost countries would have a higher incentive to invest in the downstream sector. This result partially explains why countries like US and Brazil build large refinery capacities; whereas, low-cost Persian Gulf countries such as Iran and Saudi Arabia focus more on building crude oil extraction capacity.

$$\frac{\partial \omega}{\partial \theta} > 0 \tag{12}$$

Degree of Risk-Aversion. The benefit of hedging is higher for a risk-averse agent. If the agent is completely risk-neutral, the hedging benefits of the downstream investment disappear, and the only relevant factor would be the excess return in this sector. We see that under the realistic assumption of $\overline{P} > \overline{C}$ a lower risk-aversion parameter shifts the optimal portfolio to investment toward the high-return sector.

$$\frac{\partial \omega}{\partial \gamma} > 0 \tag{13}$$

5.3. Dynamic Model: Serial Correlation in Shock

One key extension of the previous model is to consider the case when the planner is concerned with the expected present value of future revenues *over a time period* (as opposed to a single period only). The i.i.d nature of shocks to stochastic processes in the previous model makes a dynamic analysis unnecessary because the dynamic problem is just a sequence of similar static problems. However, once a serial correlation in price/margin processes is introduced, a dynamic analysis is required.

In a realistic scenario, with the possibility of inter-temporal transfers (i.e., borrowing and saving), the government spending of the OPEC country is bounded by its total lifetime budget. In a framework similar to the spirit of the Ricardian equivalence in macroeconomics, the present value of all government spending cannot be larger than the present value (PV) of revenues from the upstream and downstream sectors. For simplicity, assume there are no other revenue sources such as taxes.

However, the critical point is that the expected PVs of revenues from the upstream and downstream sectors (given the information set and current prices at every moment) are themselves random variables. The annual export revenue from one year to another year may change as a function of the latest realization of volatile spot prices and refining margins.

To shed a light on this matter, we derive explicit solutions for the present value of revenues from those sectors and compare their time dynamics and volatility. The general problem can be formulated as:

$$X = \mathbb{E}[\int_t^{t+T} x_s e^{-r(s-t)} ds] \tag{14}$$

where x_s is a stream of instantaneous random revenues and X is the expected present value of revenues over the next T periods. To make the analysis of the closed-form solutions more elegant, we let $T \to \infty$, which is a harmless assumption when discount rates are sufficiently large.

5.3.1. Stochastic Processes:

A critical component of our analysis is the time-series behavior of crude oil price and crack spread processes. A well-accepted view in the literature suggests that the price of crude oil is close to a unit-root process (i.e., non-stationary); whereas, crack spreads follow a stationary process. This view will be re-confirmed in Table 3 of the next section. Crude oil price follows a Geometric Brownian Motion (GBM) process represented by the following continuous-time stochastic differential equation (SDE):

$$\frac{dP}{P} = \mu dt + \sigma dW \tag{15}$$

The SDE governing the mean-reverting crack-spreads is given by[13]:

$$dC = (\overline{C} - C)\mu dt + \sigma_C dW_C \tag{16}$$

5.3.2. Present Value of Upstream Activities

Following standard steps (e.g., Dixit (1993)) the expected present value of all future oil revenues will be given by

$$V_t = \mathbb{E}_t \int_t^{\infty} [P_s - \theta] e^{-r(s-t)} ds = \frac{P_t}{r - \mu} - \frac{\theta}{r} \tag{17}$$

From Equation 18 it is clear that the expected present value of oil revenue is in a one to one relationship with the spot price of oil. If crude oil prices follow a GBM process, the current price level is the best predictor of all future prices. Thus, the latest realized spot price contains the richest information set regarding expected future prices, and the value of the resource asset is highly sensitive to fluctuations in spot prices. Absent extraction costs

[13] Ghoddusi et al. (2018) provide a theoretical model to explain why in in equilibrium input prices can be close to random walk but refining margins can be stationary and mean-reverting.

(i.e., assuming $\theta = 0$)[14], the relative volatility of the total oil revenue to crude oil prices will be given by:

$$\xi_{\text{Oil Revenue}} = \frac{\sigma_P}{\sigma_P} = 1 \tag{18}$$

This result suggests that the volatility of the *revenue* process is as large as the volatility of the spot prices of crude oil.

5.3.3. Present Value of Downstream Activities

Under the mean-reverting crack spread process, the present value of the downstream revenues is given by:

$$Y_t = \int_t^{\infty} \mathbb{E}_t(C_s) e^{-r(s-t)} ds = \underbrace{\frac{\overline{C}}{r}}_{\text{Perpetual value of long-run equilibrium price}} + \underbrace{\frac{(C_t - \overline{C})}{r + \mu_C}}_{\text{Correction for current deviation}} \tag{19}$$

If the current crack spread is below its long-run mean, the term $\frac{C_t - C_0}{r + \mu_C}$ will be negative, reducing the present value compared to the perpetual case. However, if it is positive the term $\frac{C_t - C_0}{r + \mu_C}$ becomes positive and increases the present value compared to the perpetual case.

The dynamics of the downstream value can be written as:

$$d\text{Y} = \mu_C(\frac{\overline{C}}{r} - Y_t) + \frac{\sigma}{r + \mu_C} dW_C \tag{20}$$

$$Y_t = \frac{\overline{C}}{r} - \frac{\overline{C}}{r + \mu_P} + \frac{C_t}{r + \mu_C} = \frac{\frac{\mu_C}{r}\overline{C} + C_t}{r + \mu_C} \Rightarrow dV = \frac{dC_t}{r + \mu_C} \Rightarrow \frac{dV}{dC} = \frac{1}{r + \mu_P} \tag{21}$$

The value is a function of the weighted sum of current and long-run crack spreads:

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[14], In reality, the marginal extraction cost for the majority of OPEC members is very small. Thus, it is innocent to assume $\theta = 0$ as an approximation.

$$\xi_{\text{Refinery Revenue}} = \frac{dV}{dC}\frac{C}{V} = \frac{1}{(r+\mu_C)}\frac{(r+\mu_C)C_t}{\frac{\mu_C}{r}\overline{C}+C_t} = \frac{C_t}{\frac{\mu_C}{r}\overline{C}+C_t} \tag{22}$$

Since $\overline{C} > 0$ the denominator is always larger than numerator and as a result $0 < \xi_{\text{Mean-reverting}} < 1$. When $\mu_C \to 0$ (i.e. random walk) the effect of $\overline{P}$ vanishes and $\xi \to 1$. On the other end, when $\mu_P \to \infty$ (i.e. i.i.d distribution of prices) $\xi \to 0$. The limiting case of the independently and identically distributed refining margins ($\mu_P \to \infty$), which was discussed in the static model, suggests that the expected present value of refining profits will be a *constant* number despite the fact that each period's margin can be very volatile!

We also see that a higher discount rate and a lower mean-reversion rate increase the sensitivity of the revenue value to the transient fluctuations of refining margins. When the $\mu_C > r$ condition holds, the weight of the long-run refining margins is bigger and when $\mu_C < r$ the weight of current margins dominates. One can easily see that a smaller μ_C or a larger r dilute the impact of $\overline{C}$ compared to C_t.

In summary, this important result suggests that the volatility of the *revenue* process in the downstream is always smaller than the volatility of spot refining margins. On the other hand, the volatility of the revenue process in the upstream sector is as volatile as the underlying spot prices.

6. Empirical Analysis

In this section, we analyze the main indicators of the downstream sector's economic performance to produce a few key empirical results.

6.1. Data

We download monthly data on wholesale spot prices of Brent crude oil, NY gasoline, and NY heating oil from the Energy Information Administration (EIA). The dataset covers 1987/05 - 2018/12 (382 monthly observations) on spot prices of fuels. We also obtain capacity utilization data from BP's Energy Outlook (2017) report. The refining capacity, production, domestic consumption, and export data are all from EIA.

All price variables are converted to 2015$ values, and the analysis is conducted using real variables. Unless otherwise mentioned, the reader should assume that presented variables are in real terms.

The price of crude oil basket exported by the member states of OPEC (e.g., OPEC basket, Iran light and heavy, Dubai) is only available since 2003; whereas, Brent data is available since 1987. To have a larger sample, we choose to work with Brent crude oil and US NY Harbor refined products prices as *proxies* for characterizing the performance of a representative downstream industry. Using Brent as a proxy is an innocuous assumption that increases the power of statistical tests without inducing a bias. As a robustness test, we did compare the behavior of Brent and OPEC basket over the 2003-2018 period and find a negligible difference between the two price series throughout the 2003-2018 sample. Thus, the analysis using Brent can be confidently considered representative for OPEC countries too.

6.2. Descriptive Statistics

Table 3 provides basic descriptive statistics of crude oil, major refined products, and also various measures of the spread between refined products and crude oil (to be used as proxies for the profit margin of the downstream sector). It is well-known that crude oil price series are non-stationary and the typical descriptive statistics (e.g., variance) for a non-stationary process are not well defined. We report these values only to provide a comparison between the behavior of crude oil prices and refining margins *within* the sample of 1990-2018. Therefore, the statistics should not be interpreted as the moments of the data-generating process (which does not exist) but should be read as sample statistics.

Our choice of the refining margin is motivated by the famous 1-2-3 crack spread, defined as the difference of three units of Brent crude oil, two units of NY harbor gasoline and one unit of heating oil. One can debate the choice of the weights of the crack spreads (e.g., using a 2-3-5 crack spread) or even including the value of other refined products in the measure. However, the overall behavioral patterns reported in this section will not change.

Price	Mean	Median	Standard Deviation	Skewness	Kurtosis	ADF t-Statistic	Unit-Root
Brent	54.03	47.92	20.90	0.61	2.20	-1.89	Yes
NY Gasoline	64.94	61.80	20.12	0.37	2.03	-2.47	Yes
Heating Oil	64.73	60.14	22.67	0.53	2.20	-1.94	Yes
Jet Fuel	65.48	59.20	23.53	0.52	2.09	-2.06	Yes
Gasoline - Brent	10.91	10.40	4.58	0.62	3.71	-8.28***	No
Heating Oil - Brent	10.71	10.38	4.11	0.88	3.93	-5.35 ***	No
Jet Fuel - Brent	11.35	10.32	4.78	1.89	10.02	-5.63***	No
Crack Spread	10.84	10.35	3.26	0.68	3.51	-8.16***	No

Table 3: Descriptive Statistics of Original Prices

6.3. Empirical Analysis

This section provides a few empirical results regarding the relationship between crude oil prices and downstream metrics of profitability.

6.3.1. Average Level of Value-Added

Given its competitive industrial organization, the refinery industry produces a *normal* economic profit consistent with other competitive industry performances.[15] To provide a better understanding of the profit margins in this industry, we plot the histogram of monthly net refining margins for a representative refinery of North America in Figure 4.

The net refining margin is obtained after subtracting refining costs from crack spreads. The operational expenses of the refining vary between \$4-\$7 depending on the region and

[15] In the economics literature, the expression "normal profit" refers to the case where all production factors receive their equilibrium market rate. In other words, there is no rent accruing to the owners of the capital assets.

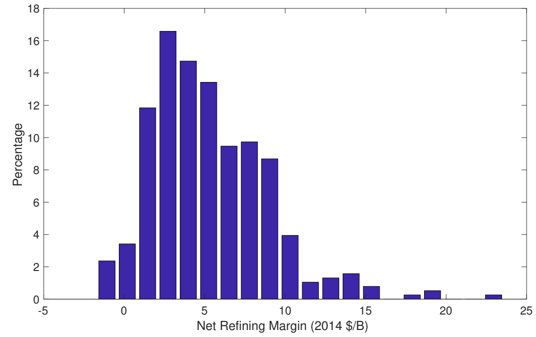


Figure 4: Histogram of Net Profit Margins (2015$). We subtract a 5$/b refining cost from crack spreads to produce net refining margins. Number on bars show the percentage of observations.

the production technology[16]. We choose 5$/b as the baseline refining cost[17].

From the numbers displayed on the histogram, one can infer a small range (between 0-$10) for the typical margin of value-added in the downstream sector. Industry reports on refining margins (e.g., BP Statistical Review of World Energy[18]) also provide very similar results that support our calculations; average refining margins in different regions are typically around 5$/b. The average refining margin can be contrasted to the upstream revenue: considering a recent historical average 55$/b crude oil price and an average 5$/b-10$/b production costs for OPEC countries, they make a net 45$/b-50$/b revenue from the upstream sector. Thus, the net margin of upstream is between 5 to 10 times larger than the net refining margin.

To better understand the dynamics of the gap between crude oil and crack spread margins, Figure 5 shows the difference between crude oil and refining margins. The plot shows the additional revenue per unit of capital in the upstream versus the downstream.

Empirical Result 1. OPEC countries on average earn much bigger rents in the upstream sector, compared to the potential value-added in the refinery sector.

[16] https://www.iea.org/media/omrreports/Refining_Margin_Supplement_OMRAUG_12SEP2012.pdf
[17] https://iea-etsap.org/E-TechDS/PDF/P04_Oil%20Ref_KV_Apr2014_GSOK.pdf
[18] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/oil/refining.html

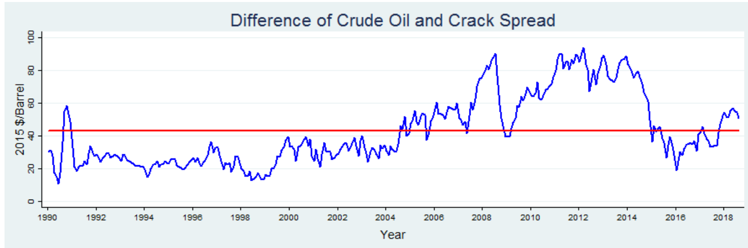
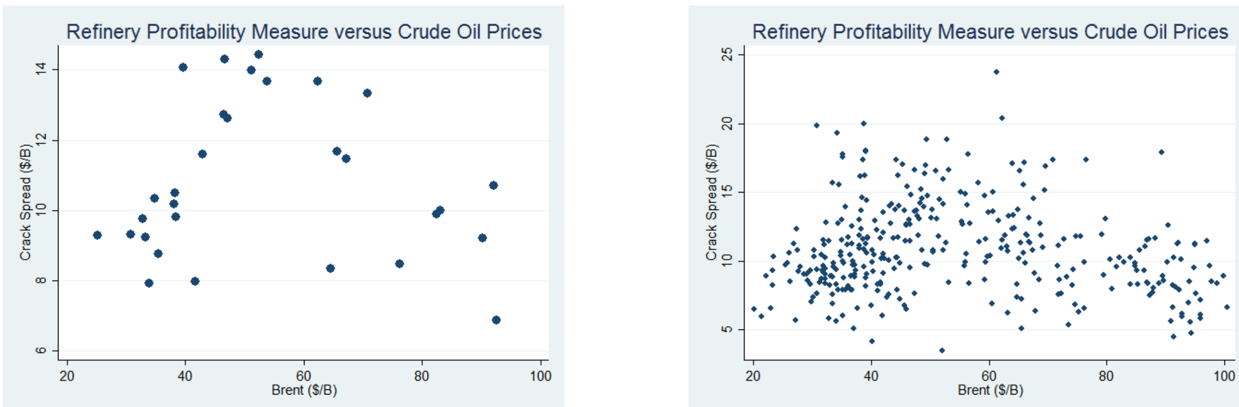


Figure 5: The Gap Between Crude Oil Price and Crack Spreads. The red line is the historical average of the gap.



(a) Annual Observations

(b) Monthly Observations

Figure 6: Crack Spreads versus Crude Oil Prices

6.3.2. Relationship between Crude Oil and Crack Spreads

Figure 6 shows the scatter plot of the crack spreads against the level of crude oil prices, using annual and monthly data.

The visual inspection suggests no relation between the level of crude oil prices and crack spreads. To test the relationship more formally, we run the following simple regressions on the level and the first-difference of the two variables[19].

$$C_t = \alpha_1 + \alpha_2 P_{Ct} + \epsilon \tag{23}$$

[19]Note that the regression is not subject to the spurious regression problem because refining margins are stationary.

$$\Delta C_t = \beta_1 + \beta_2 \Delta P_{Ct} + \epsilon \tag{24}$$

Table 4: Relationship between crack spreads and crude oil prices

Variables	C_t	ΔC_t
P_{Ct}	-0.0170**	
	(0.00839)	
ΔP_{Ct}		-0.0578
		(0.0351)
Constant	11.76***	0.00358
	(0.485)	(0.138)
Observations	344	343
R-squared	0.012	0.008

*** and **: indicate 1% and 5% significance level.
Standard errors are in parentheses.

Results reported in Table 4 suggest a weak negative relationship between the magnitude of crack spreads and the level of crude oil prices. The relationship between *changes* (i.e., first difference) of the two variables is statistically insignificant.

The negative correlation of crack spreads and crude oil prices, as well as the zero correlation of changes, justify using the refinery industry as a hedging mechanism for oil-producing countries. Note that the refining process (aka cracking) is energy intensive and higher natural gas prices will reduce the real level of crack spreads. We assume a constant level for processing costs. If one takes into account the higher processing costs during high crude oil prices, the negative relationship between crude oil price and net crack spreads will become even larger and provides stronger support for the hedging argument.

To further investigate the connection between crude oil and crack spreads, we divide the full sample to six five-year sub-samples and estimate the correlation within each sub-sample. Figure 7 shows time-varying correlation of the two series. We observe that in the late 1980s

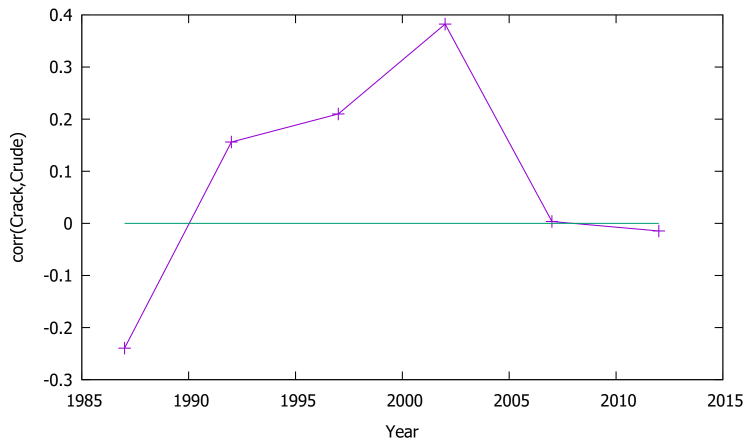


Figure 7: Time-Varying Correlation of Crude Oil Prices and Crack Spreads. Each bar shows the estimated correlation for a 60-month window starting by that year.

the correlation was negative; however, since then the correlation is either positive or near zero. The recent patterns of near-zero correlation are not ideal for hedging because a negative correlation could even provide a more effective hedge; however, even a near-zero correlation provides support for a hedging argument because the combination of two assets with zero correlation will significantly reduce the overall risk of revenue portfolio.

A positive correlation in the 1980s is consistent with a supply driven market in our theoretical analysis. However, the more demand-driven market in recent years has changed the correlation to a negative. The demand volatility is combined with a new supply-side shock (the shale revolution) in recent years; the net effect causes the correlation to become near zero.

Empirical Result 2. The identified pattern of co-movement between crude oil prices and crack spreads supports a hedging view to downstream investment.

6.3.3. Degree of Mean-Reversion in Crack spreads

The different time-series behavior of crude oil prices and refinery markups, shows in Figure 3, is an important feature to consider. The results of multiple unit-root tests reported in 5, almost unanimously, support the view that prices (crude oil and refined products) contain unit-roots and are *non-stationary* ; whereas, measures of spread are *stationary* [20].

Time-Series	ADF	ADF	DF-GLS	DF-GLS	Phillips-Perron	Phillips-Perron	Zivot-Andrews
	Trend	No-Trend	Trend	No-Trend	Trend	No-Trend	Break (Trend)
Brent	-1.890	-1.312	-1.810	-0.746	-2.540	-1.729	-3.674
NY Gasoline	-2.471	-1.557	-2.332	-0.941	-2.833	-1.760	-3.695
Heating Oil	-1.938	-1.217	-1.774	-0.709	-2.586	-1.652	-3.674
Jet Fuel	-2.059	-1.450	-2.020	-0.766	-2.591	-1.785	-3.751
Gasoline - Brent	-8.280***	-6.816***	-8.194***	-5.869***	-8.223***	-6.669***	-7.445***
Heating Oil - Brent	-5.347***	-3.760***	-4.388***	-3.757***	-5.318***	-3.513***	-5.479***
Jet Fuel - Brent	-5.628***	-4.555***	-5.499***	-4.030***	-5.254***	-3.979***	-4.049
Crack Spread	-8.155***	-5.530***	-7.416***	-4.989***	-8.035***	-5.038***	-6.964***

Table 5: Unit-Root Tests. Three stars demonstrate the rejection of the null hypothesis of unit-root at 99% confidence. We do not observe contradictory results between different tests. All tests fail to reject the existence of unit root in the first four time series; whereas, the unit-root hypothesis is rejected for the last four series.

Empirical Result 3. Refining margins are mean-reverting; whereas, crude oil prices contain a unit root.

6.4. Quantitative Model: Calibration

In order to provide better intuition regarding the relative volatility of crude oil and refining revenues, we calibrate the stochastic processes for the price of crude oil and refining margins using historical data and standard maximum likelihood (ML) techniques.

Table 6 summarizes key parameters. The half-life of the refinery margin process is equal to $\frac{\log(2)}{0.28} \approx 2.5$ months. Assuming a monthly discount rate of 0.4% (apprx 5% p.a), we get $\frac{\mu}{r}\overline{C} = 2.59$ and $\sigma_V = \frac{\sigma_C}{\mu+r} = \frac{2.52}{0.4+0.28} = 3.70$.

The relative volatility of the two total revenues (upstream and downstream) are calculated by estimating $\frac{\text{std}(V)}{\text{mean}(V)}$ for each sector. As expected, the relative volatility of the downstream revenue is one order of magnitude smaller than upstream revenue. Thus, the downstream sector can provide a much more stable long-term revenue (in a total cash-flow sense).

[20] OPEC has some power to determine the time-series behavior of crude oil. If OPEC responds aggressively to demand shocks, the price of crude oil will also be close to mean-reverting.

Entity	Stochastic Process	Key Parameters
Crude Oil Price	$\frac{dP}{P} = \mu_P dt + \sigma_P dW$	$\mu_P = 0.006$, $\sigma_P = 0.09$
Refinery Margin	$dC = \mu_C(\overline{C} - C)dt + \sigma_C dW$	$\overline{C} = \$4.32$, $\mu_C = 0.28$, $\sigma_C = 2.58$
Oil Revenue	$\frac{P_t}{r-\mu} - \frac{\theta}{r}$	$\theta = \$5$, $P_t = \$50$
Downstream Revenue	$\frac{\frac{\mu_C}{r}\overline{C}+C_t}{r+\mu_C}$	$r = \frac{0.05}{12}$, $C_t = 5$

Table 6: Calibrated Processes

Sector	Present Value	Volatility (s.t.d)	$\frac{\text{std}}{\text{mean}}$
Oil revenues	1.34e+04	1.44e+04	1.07
Downstream revenues	650.75	78.38	0.12

Table 7: Relative Volatility of Upstream (Crude Oil) and Downstream (Refining) Revenues

Our results reveal another key challenge to using the downstream sector for hedging purposes: the social-planner is willing to combine the two sectors to benefit from the larger *level* of the present value in the upstream and the lower *volatility* of present value in the downstream. However, this implies hedging a *unit-root* process (i.e., the value of the oil revenues) using a *mean-reverting* process (i.e., the downstream revenue).

In theory, a unit-root process has an unbounded variance and cannot be hedged by a finite variance mean-reverting process. However, if the horizon of the problem is assumed to be finite (e.g., five years), then one can take a pragmatic approach to blend unit-root and mean-reverting assets to minimize the volatility of the overall revenue process.

7. Conclusion

In this paper, we first develop two stylized theoretical models to demonstrate some trade-offs in investment in upstream and downstream. The empirical analysis suggests that though the refining margin is smaller, compared to the large profit margins of the crude oil sector, its hedging value provides some rationale for vertical integration. Moreover, the expected present value of downstream revenues is more predictable than that of the upstream sector.

Downstream investment may include some local spillovers and technology transfer features; however, it is also subject to political economy considerations including empire building by government officials.

If an upstream firm faces substantial volatility in its core business but less or even negatively correlated profits characterize the downstream business, then going downstream can serve as a hedge against the vagaries in the firm's profits[21].

The hedging argument applies to all industries where the margins are negatively correlated with the oil price. Thus, not only refineries (as shown in details in the previous sections) but also energy-intensive sectors such as airlines and metal smelters may offer a hedge. Low energy input costs are good news for all such industries. Therefore, the downstream of the oil sector is not the only option to provide a hedge. Oil producing countries can find several other industries, with zero or even negative correlation to the upstream sector, to diversify their export base.

Our theoretical and empirical analysis of downstream investment have been focused on the hedging perspective. Thus, we had to abstract from many other important aspects in the real world. However, the arguments in favor and against downstream investment are potentially beyond the hedging value. We present a brief list of alternative perspective and metrics as potential research questions to be examined by future research.

Strategic Use and Market guaranty. The ownership of a refinery will provide a guaranteed market for the upstream producer's crude oil. Moreover, through a direct export of refined productions (which is not part of OPEC's mandate), OPEC member states can use their domestic refinery capacity to under-report their oil production numbers.

[21] If the equity of firms are traded in the market firm-level hedging might be socially inefficient or redundant because the investors can always hedge their risk by diversifying their investment.

Security of Supply and Sanctions. One political objective for investing in a downstream industry is to be less exposed to sanctions. There are many examples of this: the most recent example is Qatar facing the risk of a naval blockade. Iran and Russia also want to have a sufficient supply of refined products if they were to face more severe international sanctions. Examples of the past include South Africa, which went so far as to produce gasoline from coal to counter sanctions against the former Apartheid regime. The argument for self-sufficiency in refined products, however, has a political nature. We only note that domestic supply need not deliver refined product at the lowest price (in particular if delivered by a vertically integrated monopoly) nor the intended security of supply. In this paper, we abstract from analyzing such political risks and leave a rigorous analysis of it to future research.

Industrial Organization. our work did not discuss the industrial organization implications of vertical integration for the global energy market (Steele and Daly (1981)). If OPEC members also control the downstream sector, they may consider using their market power differently (c.f. Buehler and Schmutzler (2008)). Future research can also explicitly model the impact of domestic refining capacity on the bargaining power and the behavior of OPEC member countries. Another related extension in this direction is to consider the effect of the downstream investment on the optimal extraction rate of individual countries and also the pricing policies of OPEC.

Optimal Investment Timing. Optimal investment decisions in the upstream and downstream sectors (especially under uncertainty) can be more explicitly modelled. To keep the analysis tractable, we assume several parameters to be exogenous. However, a more detailed optimal investment policy may take into account factors such as mean-reversion in interest rates and building costs, technological development, and the dynamics of carbon taxes. For example, an episode of low-interest rates may encourage oil-producing countries to take advantage of low financing costs and aggressively build new capacities in the downstream sector. Follow-Up research can study the relation between optimal investment in the downstream and the supply side of the capital markets.

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