The Costs Reduction Effects of Ending the U.S. Crude Oil Export Ban[1]

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ABSTRACT

In reaction to the oil crisis of the mid-1970s, the U.S. government imposed a ban on crude oil exports. This ban was largely symbolic until the "shale revolution" essentially doubled U.S. production of crude oil after 2010. However, this new U.S. light crude oil production growth was not well matched with the existing capacities of domestic refineries, many of which were configured to process heavier crude oil streams. Once the crude oil export ban was lifted at the end of 2015, U.S. light crude oil could be processed by non-U.S. refineries, and in turn this better enabled U.S. refineries to optimize their operations using a diverse crude mix. Examining the attributes of "crack spreads", which are a proxy for the amount that refiners receive to refine crude oil into finished petroleum products, we analyze the impacts of ending the ban on both light and heavy crude oil value chains. We find that the end of the export ban reduced the crack spread on light crude oil by nearly $8.00 per barrel, while also reducing the crack spread on heavy crude oil by nearly $9.00 per barrel. Together these generated average annual savings of nearly $50 billion per year between 2016 and 2021. Notably, the results are consistent with the hypothesis that ending the crude oil export ban reduced refinery costs, rather than creating a more competitive market that lowered refining margins.

I. Introduction

In 1975, amid deep concern about the security of supply of oil, the Energy Policy and Conservation Act (EPCA) became law. Part of this Act prohibited the export of crude oil from the United States. At the end of 2015, after 40 years, the export ban was repealed. This work examines the gain to the U.S. economy from the repeal of the export ban in the form of lower refinery costs.

When the export ban was passed, the U.S. was the world's largest crude oil importer,[2] therefore banning exports was largely symbolic. By 2015, however, U.S crude oil production

[1] This examination of the economic benefits to lifting the U.S. crude oil export ban is the authors' own initiative and is not a function of the American Petroleum Institute (API).
[2] International Energy Agency World Energy Balances (2021) report that in 1975 the U.S. imported nearly five million barrels per day (mb/d) of crude oil. Japan (4.4 mb/d) was second, and Germany (2.1 mb/d) was a distant third.

had nearly doubled to 9.4 million barrels per day (mb/d) from 5.0 mb/d in 2008, and U.S. proven non-producing reserves of crude oil and condensates also nearly doubled over the same period.[3] With this rapid and historically unprecedented increase in U.S. crude oil production and reserves due to the "shale revolution", the crude oil export ban became a binding constraint. In essence, the export ban prevented different streams of crude oil from going to refineries that were best configured to process them. Thus, the 2015 action could have been expected to have reduced refining costs. To date, however, there has been no estimate of the level of the reduction of those costs.

Section II presents background on the beginning of the oil export ban in 1975 and its ending 40 years later in 2015. Section III examines the combination of refining and economic issues that are relevant to the oil export ban. Section IV explains our econometric strategy, data sources, and focus on "crack spreads" – the difference in prices between the inputs into a refined oil product and the outputs. Section V presents the results of our study. Section VI contains our conclusions. Our main finding is that allowing better alignment of the crude oil streams with refineries reduced U.S. refining costs by nearly $50 billion per year between 2016 and 2020.

II. The Crude Oil Export Ban – In the 1970s and the 2010s.

A, The Change in U.S. Crude Oil Production

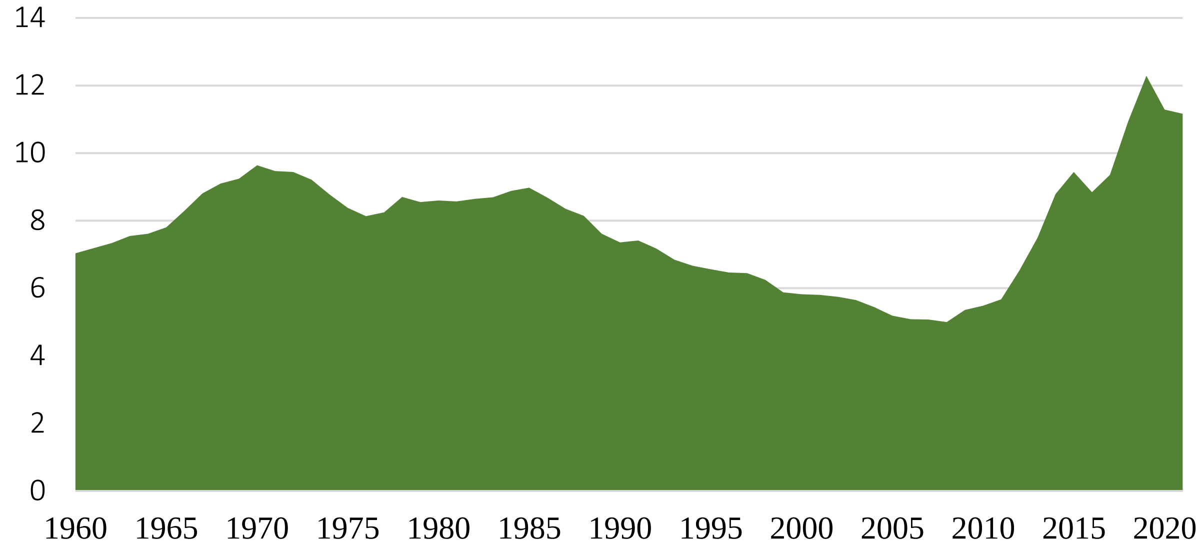
The energy shock of 1973-1974 gave impetus to a variety of new energy policies. One of these was a ban, with some exceptions for Canada,[4] on exports of crude oil from the U.S. (Note that exports of refined petroleum products were permissible.) In retrospect, at least, it appears that this ban was meant to be symbolic. At a time when the U.S. was the world's largest crude oil importer (IEA 2021), the crude oil export ban had little effect. There was no rationale to export oil from the United States, as the relevant prices implied that it was economic to import oil. This situation persisted for over 30 years. By 2008, U.S. oil production had fallen by about half from its level in 1970. Throughout this period, the export ban was likely a non-binding constraint.

The U.S. "shale revolution" changed this calculus. Technological advances in directional drilling were combined with advanced imaging and hydraulic fracturing to enable economical production of crude oil from a variety of "plays" across the United States. In particular, crude oil was developed in the Bakken formation in North Dakota and Montana; the Eagle Ford in Texas, Anadarko in Oklahoma and Texas; the DJ Niobrara in Colorado, Wyoming, Kansas and Nebraska; and the Permian Basin in Texas and New Mexico. (See, for example, Gong 2021.)

[3] See U.S. Energy Information Administration (2022), Crude Oil Production (eia.gov) and U.S. Proved Nonproducing Reserves (eia.gov), accessed Feb. 6, 2022.

[4] As Brown et. al. (2014) described, the 1975 EPCA Act prohibited the export of U.S.-produced crude oil and natural gas but enabled permits for limited exemptions of U.S crude oil exports including those to Canada.

Figure 1
U.S. crude oil production, 1960-2021
Million barrels per day (mb/d)



Sources: EIA and API

As indicated in Figure 1, U.S. production of crude oil peaked at 9.6 mb/d in 1970 and then declined steadily to 5.0 mb/d in 2008. The U.S. was consistently the world's largest crude oil importer, and its crude oil imports more than doubled over time to roughly 10 mb/d in the 2005-2008 period. As global oil supply struggled to keep pace with strong demand, oil prices rose to over $130 per barrel (nominal) in mid-2008, which helped spur the shale revolution. As the shale revolution progressed, U.S. crude oil production more than doubled over the next decade and reached as high as 13.0 mb/d in Nov. 2019 (U.S. Energy Information Administration 2022).

Crude oil, however, must both reach a refinery and be processed to be useful for end-use consumption. As Agerton and Upton (2019) discuss, both transportation and refining capacities posed problems for these new sources. As discussed below in Section III, U.S. refineries were generally not configured to refine as much light oil as was newly being produced across the U.S, especially in the Midwest. As a result, light oil in the midwestern U.S. sold at substantial discounts to other many other global and regional crude oil grades.

In a world without an export ban, these light crude oil streams could have been exported to more appropriate refineries in places like the Asia Pacific or Latin America, which historically had an abundance of distillation capacity designed to process light crudes. However, the export ban forced this oil to be refined in the United States, where refineries generally were configured to process only so much of the growing light crude stream.

As U.S. production rose, the price difference between domestic and international crude oil grew to unprecedented levels. At one point in September 2011, the most widely cited U.S. crude benchmark, West Texas Intermediate (WTI), traded at a $29.70 discount to the main international benchmark, Brent crude from the North Sea. WTI crude oil, which has a lighter API gravity than Brent crude and therefore requires less processing to be made into refined petroleum products, historically commanded a price premium over the heavier Brent crude.

However, WTI crude oil traded at persistent price discounts to Brent after the onset of the shale revolution.[5] Medlock (2015, 11) reports that the discount averaged over $10 per barrel between 2010 and 2014. This discount spurred a debate over its causes and whether it could be eliminated by removing the export ban.

B. Expected Impacts of Ending the Export Ban

As WTI crude oil continued to trade at a large and persistent discount to Brent crude, calls arose to end the export ban. Consequently, there were a series of studies in 2014 and 2015 that attempted to evaluate the impact of lifting the crude oil export ban. Essentially, these studies assumed that the price discount for U.S. light crude oil would disappear after the lifting of the crude oil ban, which in turn could motivate even greater crude oil production in the United States. Ending the export ban was not expected to have any adverse impact on consumers, however, since the prices of refined petroleum products are established by global markets. (See Medlock, 2015 at 4-8 for a summary of these studies.) For example, Medlock (2015) found that eliminating the export ban could increase the price of light crude streams (which encompassed between 80 and 90 percent of domestic production) in the United States by approximately $8.00 per barrel, while having no impact on consumer prices. Medlock (2015) also suggested that ending the export ban would not have any impact on the level of heavy crack spreads.

The economic rationale for this anticipated price decrease was essentially that the export ban created monopsony power for refineries, as domestic sources of crude were not allowed to reach potentially competitive refiners overseas.[6] This situation could be lucrative for domestic refiners. As Medlock (2015, 21) described, "refiners that normally process light crude oil earn tremendous rents when the domestic light crude price is discounted, while refiners of heavy crudes would see little to no tangible benefit from the current policy."[7] The implication of this theory is that ending the export ban could result in reduced light oil refining spreads, higher light crude oil prices, but have no impact on heavy oil processing costs. (Rosenfeld et. al., 2014, and Baron et. al., 2014, take similar approaches.)

By contrast, in a study sponsored by the American Petroleum Institute, Vidas et. al. (2014) focused on the increased cost of refining that was created by forcing U.S. crude oil streams into refineries configured to process heavy crude. According to this approach, the export ban increased the costs of refining light crudes as suboptimal refining processes were being used. Additionally, the costs to refine heavier crude streams were estimated to have increased since refiners could not achieve the same economies of scale when utilizing lighter crude streams.

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[5] Between 1987 and 2009, WTI crude oil spot prices averaged $1.41 per barrel (nominal) more than those of Brent crude, but since 2009 Brent prices exceeded those of WTI every year, averaging $6.40 per barrel higher. See U.S. Energy Information Administration (2022).

[6] Alternatively, the embargo could have created profits for refiners because the supply curve for refining light crude was highly inelastic. With increases in demand would likely have come large increases in prices and resulting profits. This condition would have the same implications for the end of the embargo as a monopsony situation.

[7] Medlock (2015, 21) points out that in the long run this price differential and the resulting rents to light crude refiners would have induced investment in light crude refineries.

Vidas et. al. (at 14, 79) concluded that ending the export ban would cause average U.S. refinery margins (across both light and heavy crudes) to decline by $1.50 to $2.85 per barrel in constant 2011 dollars, which equates to $1.88 to $3.50 per barrel in 2022 constant dollars. If realized, this could amount to a substantial amount of money. Based on the quantities of light and heavy crude oils refined in the U.S. and holding these margin differences constant in real terms after the export ban was lifted at the end of 2015, this could have translated into average annual cost reductions of $11 billion to $21 billion in 2022 constant dollars. An implication of this approach is that ending the export ban could reduce refinery margins on both light and heavy crude streams.

There is only limited literature evaluating the effects of ending the export ban. Melek and Ojeda (2017, 66) report that the Brent-WTI and Brent-Louisiana Light price spreads declined in 2016, after the export ban was eliminated. Agerton and Upton (2019), however, suggest that any pricing differentials inside the United States were due to pipeline and transportation constraints rather than any mismatch between refiners and crude oil grades. Rushlow and Bauer (2021) found that WTI and Brent crude oil prices were not cointegrated prior to 2016 but were cointegrated after that date. This implies that the end of the export ban may have served to integrate the midwestern U.S. crude oil supplies with global markets, which in turn suggests that lifting the crude oil export ban eliminated an important barrier to trade.[8]

III. Background on Refinery Challenges in the United States

A. The refinery problem

While crude oil is a global commodity, almost no one consumes crude oil directly. It must be refined into fuels, feedstocks, materials, and other final products. This means that physical characteristics – such as where oil is produced versus where there is refining or manufacturing plants, or the location of the greatest consumer demand – affect its usefulness and therefore value.

As highlighted in Section II, oil is not a homogeneous product. In particular, crude oil can have different densities and sulfur levels. These two factors (among others) determine the types of equipment and processing needed to refine any particular type of oil. The American Petroleum Institute (API) and National Institute of Standards and Technology (NIST) have adopted a standard to measure the density of oil, based on the density of water. Water is rated 10 on the API gravity scale. Therefore, any crude stream with an API measure greater than 10 will float. High API gravity measures (above 35) indicate that a particular crude is “light”, while lower API gravity measures indicate that the oil is “heavy.” In addition, crudes with sulfur contents of less than 1.0 percent are referred to as “sweet”, while crudes with higher sulfur

[8] Towards the end of 2021, during a period of high oil prices, there were calls to reestablish the export ban. See the discussion in Golding and Kilian (2022).

contents are referred to as "sour." (See, for example, Bordoff and Hauser (2014, 22-24) and Melek and Ojeda (2017, 52)).

For example, crude oil from hydraulically fractured wells in the Bakken formation typically has an API gravity of 40 to 45 degrees and a sulfur content below 0.2 percent (see S&P Global 2022 at 17). Such crudes are therefore "light and sweet". Similarly, sweet crudes produced in the Eagle Ford field in Texas typically have an API gravity of over 45 degrees. (See Energy Information Administration 2017 for state comparisons)

As with crude oil streams, refineries also have different characteristics. (See Foreman 2018.) In general, refineries match their processing capabilities with types of crude oils from their supply streams that enable them to make high-value motor fuels and other petroleum products in a cost-effective manner. Refineries also serve niche product markets for chemicals, petrochemical feedstocks, lubricants, waxes and materials for roads and roofs. Heavier crude oil contains more complex molecules, which make it better for producing many of these niche products. However, turning heavy oil into high-quality products also requires more advanced molecular processing than is possible with simple refining or distillation.

Consequently, refining heavy oil requires substantial capital investments in additional refining processes, such as cracking or coking, or what the industry refers to as "complexity."[9] With the requisite additional investment and processing cost, heavy oil crude typically has been priced less than light crude oil. In 2021, for example, Bloomberg data show that Western Canadian Select (WCS) heavy oil averaged around $55 per barrel, while West Texas Intermediate (WTI) light crude oil averaged just over $68 per barrel. The $13 per barrel premium of WTI over WCS, the light-heavy crude oil price differential, reflects the additional processing and transportation costs to convert heavy crude oil into refined products.

Refineries are capital intensive and time consuming to build. The complexity of a refinery has historically been measured by the Nelson Complexity Index (NCI), which compares the capital investment of processes installed across refineries globally. The heavier or sourer a crude oil stream is, the more complex it is to refine. Accordingly, complex refineries offer flexibility to process a broader range of crude oils, but also require higher capital investments. Although the data on individual refinery complexity are proprietary, Eni (2021 at 83) summarizes the NCI across regions for 2015 and 2020. In 2020, the average NCI across the world was about 9.6. The average NCI in North America was relatively higher at 11.6, indicative of the region's more complex refining capacity. By contrast, the average NCI in Central and South America was relatively low at 8.0, reflecting the predominance of simpler crude oil distillation capacity in these regions.

Essentially, many refineries in Texas, Louisiana and across the midcontinent U.S. were configured to refine the heavy and sour grades of crude oil that historically came from conventional U.S. oil production as well as Canada, Mexico, the Gulf of Mexico and Venezuela

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[9] McKinsey (2022) defines complexity as a quantitative measure of how much high-value conversion capacity a refinery has installed relative to its distillation capacity. A complex refinery has relatively more high-value conversion units.

(Bordoff and Hauser 2014). By comparison, many refineries in the northeast U.S., Hawaii, and Alaska have crude distillation capabilities configured to process the light and sweet crude oil.

The shale revolution thus created a mismatch with the large and rapid crude oil supply growth, which was almost entirely light and sweet crude oil, with the configurations of nearby refineries to process that crude. Consequently, within refining system limitations, the crude oil export ban forced relatively more of the new light sweet crude oil production to be processed in refineries that were historically geared towards a heavier crude slate. If lifting the crude oil export ban helped refineries to optimize their operations and production, there could be a measurable impact on refinery costs.

IV. Estimation Strategy and Data

Our basic hypothesis is that lifting the U.S. crude oil export ban helped to alleviate refinery market imbalances that had occurred due to a combination of the shale revolution and the export ban. As the shale revolution accelerated, light oil became abundant and increasingly discounted below international oil prices, which provided economic incentives to process more of it. However, for a refinery to process more light oil than its designed capacity could require additional capital investments or, alternatively, result in an under-utilization of its capacity to process heavier grades of crude oil.

According to our hypothesis, the benefit of ending the export ban was to reduce refinery costs by ending this mismatching of light oil being refined in refineries designed for heavy oil. We measure this potential positive impact to ending the export ban by examining the drivers of refining crack spreads, which measure the difference between the value of the refined products produced and the crude oil inputs that went into those products. A crack spread can therefore be seen as a measure of the cost to refine crude oil into finished products.[10]

While configurations differ across refineries, a common refining strategy is to turn three barrels of crude oil into two barrels of gasoline and one barrel of distillates (which include diesel and jet fuel). The difference in prices per barrel, which equates to (2/3) * price of a barrel of gasoline + (1/3) price of a barrel of distillates – price of a barrel of crude oil, is often referred to as the "3:2:1 crack spread."[11]

Crack spreads are specific to the regional refinery location, configuration and crude oil input. We are particularly interested in the comparing U.S. Gulf Coast 3:2:1 crack spreads based on West Texas Intermediate (WTI) crude oil and, alternatively, Western Canadian Select (WCS) crude oil, which is the main benchmark for imported Canadian heavy and sour crude oil

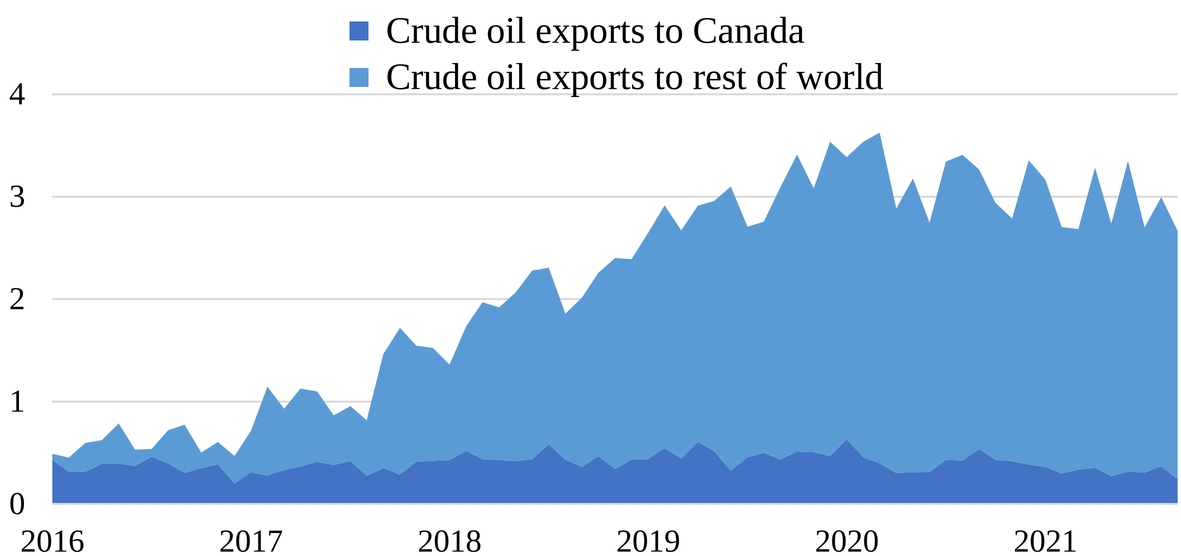
[10] The crack spread also serves as the basis for financial derivatives that are widely available through global exchanges. Refiners commonly use crack spread futures contracts to hedge the difference between their output prices and input costs (see CME Group 2021).

[11] See, for example, Chicago Mercantile Exchange, "Hedging the Crack Spread," Introduction to Crack Spreads - CME Group, viewed 6 Jan 2022.

that is blended and priced at Edmonton, Alberta.[12] In this analysis, we econometrically analyze these U.S. Gulf Coast crack spreads as reported by Bloomberg: (1) LIGHTSPREAD, the WTI crude oil 3:2:1 crack spread; and (2) HEAVYSPREAD, the WCS crude oil 3:2:1 crack spread.[13] The data on the crack spreads are in logged constant 2021 dollars per barrel, each as reported by Bloomberg, while the refined product prices employed in the LIGHTSPREAD variable are the prompt month futures prices for U.S. Gulf Coast 87 octane regular motor gasoline and a low-sulfur distillate product in No. 2 heating oil. The HEAVYSPREAD includes the identical motor gasoline prices, but since processing heavy oil yields a greater share of distillates the formula utilizes the price of ultra-low sulfur diesel fuel in lieu of No. 2 heating oil, also based on a U.S. Gulf Coast location and prompt month futures prices.

Our data begin in 2008, when the establishment of reported transaction prices for WCS crude oil enabled Bloomberg to begin reporting the heavy crack spread, and end in September 2021, giving 157 monthly observations once we account for the lag structure. We estimate our regressions using seemingly unrelated regression (SUR) as well as generalized linear model (GLM) maximum likelihood estimation (Hardin and Hilbe, 2018).

Figure 2. U.S. crude oil exports (million barrels per day, mb/d)



source: EIA

Central to our estimation strategy is the amount of crude oil exported from the U.S. to countries other than Canada. As shown in Figure 2, U.S. crude oil exports to the world grew from negligible levels at the beginning of 2016 to more than three million barrels per day at the end of 2019 but slipped in the wake of the 2020 COVID-19 recession. Presumably, the more oil

[12] See Argus (2022). "Argus Americas Crude," Methodology and Specifications Guide, viewed 6 Jan 2022. Western Canadian Select is Canada's largest heavy crude oil stream, comprised of bitumen, conventional oil, synthetic crude, and condensate.

[13] Bloomberg L.P. (2022). Western Canada Select crude oil (WCS) FOB Hardisty AB spot. 5/1/08 to 9/30/21. Retrieved 23 Dec 2021 from Bloomberg terminal.

exported, the greater the gains from trade by matching oil to refineries. Any savings resulting from the end of the export ban will thus be a function of the amount of oil exported. We therefore calculate a variable OILEXPORT as equal to the natural log of U.S. crude oil exports to countries other than Canada in thousand barrels per month after the end of the export ban in 2015, 0 otherwise.

We also have a set of explanatory variables that describe refinery operating costs and activities. These include REFCAP, the natural log of average capacity refining of the refineries across the U.S. Gulf Coast lagged by one month in thousands of barrels per day, acquired from the Energy Information Administration (EIA).[14] We expect the coefficient on this variable to be positive, as the size of refineries allows them to take advantage of economies of scale that increase refining margins and crack spreads, other things being equal. (See Hibdon and Mueller, 1990).

Additionally, from EIA and the API Monthly Statistical Report (MSR),[15] we measure U.S. refinery throughput based on the gross inputs into crude distillation units (INPUTS), lagged by one month; this corresponds with greater refined product production in the past month and therefore should lower the current period's output value and correspond with a negative estimated coefficient and narrower crack spread, other things being equal.

FUTURES is the crude oil futures price expectation, measured by the natural log of the ratio of the twelve-month futures price of WTI crude oil to its prompt month futures price, sourced from CME Group via Bloomberg. If crude oil is expected to increase in price (i.e., a higher value of the ratio), this should correspond with higher prospective input costs and therefore a lower crack spread and a negative estimated coefficient in the current period, other things being equal.

CRUDESTOCKS is the natural log of level of crude oil stocks in thousand barrels in the United States (excluding the Strategic Petroleum Reserve), lagged by one month, as acquired from the API Monthly Statistical Report. A greater abundance of crude oil stocks last month should correspond with relatively lower refiner crude oil acquisition costs and therefore a larger crack spread in the current period other things being equal, implying a positive estimated coefficient.

HENRY HUB is the logged natural gas price at Henry Hub, Louisiana, in constant 2021 dollars, lagged by one month, as reported by the U.S. Energy Information Administration.[16] As the main U.S. refinery energy input for processing, increased natural gas prices could raise operating costs, widen the difference between output values and input costs, and correspond with a wider crack spread and positive estimated coefficient in a competitive and closed U.S. market, other things being equal. Alternatively, as refined product prices are primarily set by global markets, increased U.S. natural gas prices could raise operations costs for U.S. refiners but not

[14] U.S. Energy Information Administration (2022).

[15] American Petroleum Institute (2021).

[16] U.S. Energy Information Administration (2022).

necessarily affect output values. Consequently, it is possible that increased natural gas prices could reduce U.S. refining margins and correspond with a narrower crack spread as well as a negative estimated coefficient, other things being equal.

LIGHTMHEAVY is the natural log price of the price differential between light WTI and heavy WCS crude oil, expressed in constant 2021 dollars per barrel and lagged by one month. To the extent that refiners have both simple crude oil distillation capacity as well as conversion units, including varieties of thermal cracking and coking, the relative prices of light and heavy crude oil present opportunities to optimize profits by switching crude streams, given overall refinery production and logistical constraints. Specifically, if light oil became relatively more expensive last month, we would expect refiners to switch towards running relatively less expensive heavier crude oil this month, other things being equal. By way of illustration, if the relative price of WTI crude oil rose last month relative to that of WCS, then the value of LIGHTMHEAVY will increase and refineries will have an incentive to substitute towards heavier crude streams. This would correspond with a lower crack spread for light oil and a higher crack spread for heavy oil. Thus, we expect the coefficient on LIGHTMHEAVY to be negative for the light crack spread and positive for the heavy crack spread.

We note, however, that the switching ability and therefore the estimated coefficients may not be symmetric. For example, WCS is a blend of bitumen, conventional oil, synthetic crude and condensate (Oil Sands Magazine 2016) that must be processed using thermal cracking or coking. Thus. some lighter crude streams are generally part of processing heavy crude. However, the converse is not true. Refinery capacity to distill light oil is not capable of breaking down molecules of heavy crude oil. Consequently, we expect the LIGHTMHEAVY price differential could be more important to the HEAVYSPREAD than it would be to the LIGHTSPREAD equation.

Next, in the same manner that past crude oil CRUDESTOCKS could relate to current input prices, we employ past distillate stocks (DISTSTOCKS) as an indicator of potential value. Distillates represented 30.6 percent of Gulf Coast refinery output over the sample period from May 2008 to Sep. 2021, according to EIA.[17] If distillates/diesel fuel as in higher supply last month, the output value of diesel fuel could decrease in the current month, which would reduce the crack spread and thus we expect a negative estimated coefficient.

Finally, we include in some of our regressions a monthly time trend (TREND) to represent advances in refinery technology and supply chains that lowered costs. We note, however, that the correlation between the time trend and the amount of oil exports is positive and very high (0.88). This correlation arises in large part because our data set only begins in 2008, when data on the heavy crack spread was first reported. Areas in which U.S. refinery and petrochemical operations have historically advanced include increased integration[18] as well as

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[17] U.S. Energy Information Administration (2022).

[18] See, for example, Gelder (2021).

digitalization and advanced analytics to improve control systems and optimize supply chains (Angnihotri 2018).

There are reasons, however, to suspect that the has not been much in the way of technological cost reductions in recent years. As Iplik et. al. (2020) discuss, much of the fundamental reaction process development for cracking dates from the 1960s and 1970s; catalyst research and the vast majority of automation, optimization, and control research date back to the 1980s and 1990s; and most research over the past 30 years focused on process improvements. Consequently, it is not clear from reviewing the literature that substantial technological advances other than in integration, digitalization and control systems could be measurable for the U.S. refining industry. If this is the case, given the econometric results below, it suggests that our regressions including TREND in the specification could underestimate the gains from the ending of the crude oil export ban.

We also include a set of macroeconomic variables, along the lines of Ewing and Thompson (2018, 204-205). CPI represents the consumer price index, acquired from the U.S. Bureau of Labor Statistics. Ewing and Thompson found that crack spreads tended to increase in response to unexpected increases in price inflation. We therefore expect the estimated coefficient on CPI to be positive.

RISKSPREAD measures the default risk premium as a difference in interest rates between high-yield corporate bonds and the federal funds rate. The higher RISKSPREAD, the higher are borrowing costs and the expected level of corporate defaults. As Ewing and Thompson (at 205) note, the expected impact of this on crack spreads is unclear. However, RISKSPREAD has historically risen during periods of economic weakness that could correspond with lower prices and refining margins/crack spreads. Thus, our expectation is that the coefficient on this variable will be negative.

GROWTH is the one-month lagged difference in industrial production, as reported by the Federal Reserve Board. As the economy grows, various utilization rates and input prices may rise, likely resulting in an increase in costs across the economy. Therefore, the coefficient on GROWTH is expected to be positive.

Table One gives the definitions, expected coefficients and summary statistics for the variables used in the regressions in Section V.

Table One. Variables Used in Regressions, Expected Coefficients, and Summary Statistics

Variable Name	Variable Definition	Expected Coefficient	Mean	Std. Dev.
Dependent Variables				
LIGHTSPREAD	Log of the light oil crack spread		2.6586	0.5182
HEAVYSPREAD	Log of the heavy oil crack spread		3.553	0.3404
Policy Variable				
OILEXPORT	Log of U.S. crude oil (non-Canadian) exports	Negative	4.5125	5.2684
Cost Variables				
REFCAP	Log of average crude distillation unit capacity per refinery	Positive	5.0915	0.07
FUTURES	Log of the ratio of 12-month to prompt month futures prices	Negative	0.0197	0.0849
CRUDESTOCKS	Log of crude oil stocks	Positive	12.8829	0.1795
DISTSTOCKS	Log of distillate stocks	Negative	11.8573	0.1165
INPUT	Change in log of gross inputs to Gulf Coast crude distillation units	Negative	0.0001	0.0408
HENRY HUB	Change in log of Henry Hub spot price	Unclear	-0.0601	0.6864
LIGHTMHEAVY	Log of light crude price minus heavy crude price	Negative on LIGHTSPREAD; Positive on HEAVYSPREAD	2.873	0.3835
TREND	Time trend	Negative	82.5	47.4868
Macroeconomic Variables				
CPI	Consumer Price Index	Positive	5.4711	0.0672
RISK SPREAD	Change in risk spread of corporate bonds	Negative	-0.0524	2.2158
GROWTH	Change in industrial production	Positive	0.0001	0.0156

V. Results

A. Econometric Estimates

As discussed in Section II, the literature had two different sets of hypotheses about the impact of ending the crude oil export ban. One set implied that ending the export ban would eliminate the monopsony power of U.S. refineries that process crude oil. This would increase the price of light crude oil streams, but not change the price of refined oil. This would imply a decrease in the crack spread for light oil, but not for heavy oil. Alternatively, the second set implied that ending the export ban could reduce costs, thereby reducing the crack spread for both heavy and light crude streams.

Table Two

Light Crack Spread Regressions

Bold Coefficients Statistically Significant at 5% Level

Regression Type:	SUR		GLM	
With or without time trend:	Time Trend	No time trend	Time Trend	No time trend
Independent Variable	**Coefficient (Standard Error)**			
Policy Variable				
OILEXPORT	**-0.0422** (0.0131)	**-0.0539** (0.0130)	**-0.0407** (0.0137)	**-0.053** (0.0136)
Cost Variables				
REFCAP	**2.324** (0.7078)	**1.8023** (0.7194)	**2.3211** (0.7408)	**1.8346** (0.7490)
FUTURES	**-3.9381** (0.6382)	**-4.7897** (0.5901)	**-3.7414** (0.6671)	**-4.725** (0.6142)
CRUDESTOCKS	**2.7541** (0.4811)	**1.7532** (0.4048)	**2.7167** (0.5035)	**1.7558** (0.4214)
DISTSTOCK	**-0.7622** (0.3489)	**-0.7078** (0.3612)	**-0.7929** (0.3651)	-0.7147 (0.3760)
INPUTS	-1.6896 (0.9027)	-1.3478 (0.9291)	-1.7786 (0.9447)	-1.3893 (0.9674)
HENRY HUB	-0.0833 (0.0432)	**-0.0995** (0.0446)	-0.0838 (0.0453)	**-0.0994** (0.0465)
LIGHTMHEAVY	-0.0307 (0.1008)	-0.0583 (0.1040)	0.0152 (0.1055)	-0.0227 (0.1083)
TIME TREND	**-0.027** (0.0080)		**-0.0271** (0.0083)	
Macroeconomic Variables				
CPI	**12.6322** (4.8859)	**-3.1879** (1.3348)	**12.8372** (5.1032)	**-3.2115** (1.3890)
RISK SPREAD	**-0.0402** (0.0135)	**-0.0404** (0.0140)	**-0.0419** (0.0141)	**-0.0414** (0.0146)
GROWTH	-3.7076 (2.6732)	-5.2766 (2.7105)	-3.2412 (2.7933)	-5.1352 (2.8203)
CONSTANT	**-102.15** (30.3340)	-2.7637 (8.2781)	**-102.55** (31.6949)	-2.8595 (8.6147)

Table Two presents the regression coefficients for the light crack spread equations. The coefficients on the policy variable of interest, OILEXPORT, are negative and significant with 95% confidence in each of the four equations. This implies that the end of the export ban reduced the level of the crack spread for light crude streams, as both sets of theories would imply. The magnitude of these effects will be discussed in part B of this section. Note that excluding the trend variable (TREND) in the specifications increased the magnitude of the OILEXPORT coefficient by over 25 percent.

As expected, the coefficients on refinery capacity (REFCAP), futures prices (FUTURES), and the level of crude oil stock (CRUDE STOCKS) are positive, negative and positive, respectively, and each of these coefficients are statistically significant with 95% confidence. The coefficient on the level of distillation stocks (DISTSTOCKS) is negative, as expected, and statistically significant in three of the four regressions. The coefficient on the variable representing the previous month's gross inputs (INPUTS) has the expected sign, but is not significant.

We hypothesized that the coefficient on the light heavy crude price spread (LIGHTMHEAVY) for the light crack spread regression could be negative, though there were technical reasons why we suspected the coefficient might not be significant. Consistent with this expectation, three of the four regressions coefficient on LIGHTMHEAVY were negative, but none were significant.

The coefficients on the trend variable are significant and negative, as expected. As discussed above, however, there are reasons to believe that technological advancement in the refining industry has been limited, and that this result arises because of the correlation between the trend variable and the policy variable that we use. Thus, the effects of ending the oil export ban may be showing up in the coefficient on TREND.

We expected the coefficients on the price index (CPI) to be positive, which they are in the regressions including a time trend. These coefficients, however, are negative in the regressions without the time trend. We had no prior expected sign on coefficients for the price of natural gas (HENRY HUB). In the regressions, the coefficients have a negative sign and is significant in the estimations without the time trend. The coefficients on the change in risk spread of corporate bonds (RISKSPREAD) are negative and significant as expected. The coefficients on industrial growth (GROWTH) are insignificant.

Table Three presents the regression coefficients on the heavy crack spread. The results are similar in many ways to the light crack spread results, as well as to our expectations. The coefficients on the policy variable of interest, OILEXPORT, are once again negative and significant in each of the four equations. This implies that the end of the export ban reduced the level of the heavy crack spread, consist with the projections of Vidas et al (2014), but not with Medlock (2015). The magnitude of these effects will be discussed in part B of this section. Note that excluding the trend variable TREND from the specifications increased the magnitude of the OILEXPORT coefficient by about 18 percent.

Table Three

Heavy Crack Spread Regressions

Bold Coefficients Statistically Significant at 5% Level

Regression Type:	SUR		GLM	
With or without time trend:	Time Trend	No time trend	Time Trend	No time trend
Independent Variable	**Coefficient (Standard Error)**			
Policy Variable				
OILEXPORT	**-0.0227**	**-0.0265**	**-0.0194**	**-0.0238**
	(0.0063)	(0.0062)	(0.0067)	(0.0065)
Cost Variables				
REFCAP	**0.7090**	**0.5117**	**0.7865**	**0.6161**
	(0.3244)	(0.3262)	(0.3624)	(0.3604)
FUTURES	**-2.5638**	**-2.8397**	**-2.237**	**-2.5814**
	(0.3006)	(0.2720)	(0.3264)	(0.2955)
CRUDESTOCKS	**1.153**	**0.7735**	**1.1185**	**0.782**
	(0.2209)	(0.1841)	(0.2464)	(0.2028)
DISTSTOCK	**-0.4067**	**-0.3923**	**-0.4496**	**-0.4222**
	(0.1607)	(0.1644)	(0.1786)	(0.1809)
INPUTS	-0.6066	-0.4802	-0.7838	-0.6475
	(0.4136)	(0.4211)	(0.4623)	(0.4654)
HENRY HUB	**-0.0435**	**-0.0500**	**-0.0441**	**-0.0495**
	(0.0198)	(0.0202)	(0.0222)	(0.0224)
LIGHTMHEAVY	**0.2285**	**0.2179**	**0.3589**	**0.3457**
	(0.0463)	(0.0471)	(0.0516)	(0.0521)
TIME TREND	**-0.0096**		**-0.0095**	
	(0.0038)		(0.0041)	
Macroeconomic Variables				
CPI	3.9789	**-1.5788**	3.9844	**-1.6363**
	(2.3449)	(0.6230)	(2.4970)	(0.6683)
RISK SPREAD	-0.0046	-0.0048	-0.0086	-0.0084
	(0.0066)	(0.0067)	(0.0069)	(0.0070)
GROWTH	-1.7259	-2.2387	-0.9839	-1.6472
	(1.2702)	(1.2702)	(1.3667)	(1.3570)
CONSTANT	**-31.5725**	3.8227	**-31.4475**	3.465
	(14.4394)	(3.8525)	(15.5083)	(4.1448)

As expected, the coefficients on refinery capacity (REFCAP), futures prices (FUTURES), the level of crude oil stock (CRUDE STOCKS) and the level of distillation stock

(DISTSTOCKS) are positive, negative, positive and negative, respectively. Each of these coefficients is statistically significant.

As with the light crack spread, the estimated coefficient on lagged refinery inputs (INPUTS) is negative but not statistically significant. The coefficients on the price of natural gas (HENRY HUB) are negative and significant.

The coefficients on the light minus the heavy crack spread (LIGHTMHEAVY) are positive and significant, as expected. Recall the discussion in Section IV implied that this coefficient would be positive for the heavy crack spread, but not for the light crack spread. The coefficients on the time trend are again negative, though smaller in magnitude than in the light crack spread equation. Once more, the significant coefficients on the price index (CPI) are positive in the regressions with the time trend, but negative without them. The coefficients on RISKSPREAD are negative but not statistically significant. The coefficients on industrial growth (GROWTH) are again negative and insignificant.

We have tested our specifications for omitted variables and, separately, for cointegration. For each of the estimated equations – i.e., light and heavy crack spreads with and without inclusion of a time trend – the Ramsey (1969) regression specification-error test fails to reject the null hypothesis that the model has no omitted variables. Additionally, we tested for cointegration per Engle and Granger (1987) including test statistics and critical values calculated by MacKinnon (1990, 2010) (this can be seen as a robust alternative to the Johansen tests for cointegration) and, for each of the estimated equations, rejected the null hypothesis that the residuals have a unit root, suggesting that the specifications are cointegrated.

B. The Magnitude of the Reduction in Crack Spreads

As Figure 1 indicates, the increase in U.S. exports did not happen all at once. In January 2016, only 60,000 barrels per day of crude oil was exported from the U.S. to countries other than Canada, according to EIA. By the end of 2016, these exports more than quadrupled to 270,000 barrels per day. By December 2017, the exports quadrupled again to about 1.1 million barrels per day. By December 2018, they rose to 2.0 million barrels per day. Since January 2019, these crude oil exports averaged 2.6 million barrels per day despite the 2020 COVID-19 recession.

We calculate the average implied reduction in the level of the crack spread per barrel using the coefficients from the SUR regressions that include the time trend as an explanatory variable. As discussed above, this could underestimate the impact of the end of the crude oil export ban.

Table Four presents the average savings per barrel for the light and heavy crack spreads. In the initial year after the end of the export ban, the estimated savings on the light crack spread were $5.43 per barrel. This rose to over $8 per barrel for next year and was sustained at similar levels between 2018 and 2021.

For the heavy crack spread, which historically has consistently been larger than the light crack spread, the savings averaged over $6 per barrel in 2016, over $8 per barrel in 2017, and almost $9.50 per barrel thereafter.

Table Four

Unweighted Average Cost Reduction in Crack Spread after End of Crude Oil Export Ban Dollars per barrel (2021$)

Period	Impact on Light Crack Spread	Impact on Heavy Crack Spread
2016	$5.43	$6.14
2017	$8.04	$8.35
Jan. 2018 to Sep. 2021	$8.20	$9.47

We then calculate the cost savings per year as a result of the end of the export ban. We do this for the light crack spread by multiplying the savings per barrel times the amount of light oil both refined and consumed in the United States. This works out to a substantial amount. For example, over the period January 2016 to October 2021 the average amount of light crude oil both domestically produced and consumed was approximately 13.2 million barrels per day. We calculate similar numbers for the savings from the reduction in the heavy crack spread, although the amount of heavy oil refined and consumed domestically was only about 20 percent of the level of the light oil refined and consumed domestically.

Table Five

Cost Savings Per Year

Period	Annual Savings on Light Crack Spread (Billion 2021$)	Annual Savings on Heavy Crack Spread (Billion 2021$)	Total Savings (Billion 2021$)
2016	$32.1	$7.7	$39.8
2017	$46.5	$9.9	$56.4
Jan. 2018 to Sep. 2021 (annualized)	$41.7	$9.6	$51.3

Table Five highlights the estimated crack spread savings, which were almost $40 billion in the first year after the end of the export ban, more than $56 billion in 2017, and averaged more than $51 billion per year between 2018 and 2021. The cumulative savings during the period studied were approximately $289 billion.

It would not be appropriate to project these cost savings endlessly into the future. If the export ban had become permanent, U.S. refineries could have gradually adapted to process more of the light crude oil production growth and exported it as refined products. However, it would have taken more than incremental refinery expansions to process a volume anywhere near that of U.S. total crude oil exports, which averaged 2.9 mb/d in 2021. In addition, as discussed above in Section III, investments in new refining capacity are capital-intensive and time consuming.

VI. Conclusion

The shale revolution ended the merely symbolic nature of the crude oil export ban and created a mismatch between refining capacity in the United States and the type of crude oil streams that were available. Our results are consistent with the conclusion of Vidas et. al (2014) that the export ban led to substantial increase in costs and are in contrast with the position of Medlock (2015) that the export ban created monopsony power. Our research indicates that the end of the export ban significantly reduced the crack spreads for both light and heavy crude oil grades in the amount of more than $50 billion per year. Consequently, lifting the crude oil export ban at the beginning of 2016 significantly decreased the cost of refining in the U.S. and had contributed $289 billion in refinery savings to date.

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