DEPARTMENT OF ECONOMICS
JOHANNES KEPLER UNIVERSITY OF LINZ

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by

Jochen Güntner

Michael Irlacher

Peter Öhlinger

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Johannes Kepler University of Linz
Department of Economics
Altenberger Strasse 69
A-4040 Linz - Auhof, Austria
www.econ.jku.at

jochen.guentner@jku.at

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Jochen Güntner† Michael Irlacher‡ Peter Öhlinger§

JKU Linz JKU Linz, CESifo JKU Linz

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Abstract

Motivated by the European Union's debate on sanctioning crude oil imports from Russia, we estimate the elasticity of substitution between different crude oil types. Using European data on country-level crude oil imports by field of origin, we argue that crude oil is not a homogenous good and that the relevant substitutability for analyzing the impact of trade sanctions must account for the quality of different oil types in terms of their API gravity and sulfur content. Our results suggest that, by neglecting these differences in quality, standard estimates significantly underestimate the production disruptions in crude oil refining resulting from sanctions.

Keywords: Crude Oil Trade, Elasticity of Substitution, Refinery Economics, Sanctions

JEL Codes: F14, F51, L71, Q37, Q41

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†Johannes Kepler University (JKU) Linz, Altenberger Straße 69, Linz 4040, Austria. E-mail address: jochen.guentner@jku.at

‡Johannes Kepler University (JKU) Linz, Altenberger Straße 69, Linz 4040, Austria. E-mail address: michael.irlacher@jku.at

§Corresponding author. Johannes Kepler University (JKU) Linz, Altenberger Straße 69, Linz 4040, Austria. E-mail address: peter.oehlinger@jku.at

1 Introduction

Following the Russian Federation's invasion of Ukraine, many countries, including the European Union (EU), have adopted trade-related sanctions against Russia covering both exports and imports of thousands of goods and services.[1] However, it was primarily the debate of oil and gas sanctions that attracted widespread attention by the media and policy makers. This is due to the EU's reliance on Russian fossil fuels and vulnerabilities of the European transport infrastructure. Yet, political considerations regarding the economic viability of sanctions hinge on the volume of energy imports that must be replaced and the substitutability of Russian oil and gas imports, whether through direct replacement or alternative energy sources. A crucial aspect that has been ignored in the debate of sanctions against Russia are disparities in quality between and within different types of crude oil.

In this paper, we use comprehensive country-level data on EU crude oil imports to show that the elasticity of substitution among crude oil types is much lower than suggested by previous studies. While crude oil is commonly regarded as a standardized commodity, we show that, in reality, it is far from homogenous, owing to the variability in its chemical composition in two key dimensions. In particular, our data contains detailed information on the density (i.e. low or high API gravity) as well as the sulfur content (i.e. "sweet" or "sour") of oil varieties across different fields of origin. This allows us to group crude oils by their chemical composition into technically heterogeneous oil types and to disentangle the elasticities of substitution within and between these types. We use these insights to inform the public debate on the potential consequences of sanctioning foreign crude oil imports.

Building on the methods of Feenstra (1994) and Broda and Weinstein (2006), our estimates suggest that the substitutability between types is much lower than within types.[2] This

[1]Council Regulation (EU) No 833/2014 (link), documents the introduction of restrictive measures against Russia since the annexation of Crimea in 2014. The list comprises of sanctions targeted at particular Russian individuals, firms, and organizations, a.k.a. 'smart sanctions', as well as comprehensive trade and financial restrictions (Draca et al., 2022).

[2]It is important to note that Broda and Weinstein (2006) do not distinguish between intermediate and final products when quantifying the welfare gains from a larger set of varieties. Given that crude oil is used almost exclusively as an intermediate input in the refining process rather than consumed directly, sanctions

has implications for evaluating the economic costs of sanctioning oil imports. Russian Urals, in particular, serves as an important medium-sour benchmark for the European crude oil market that is more technically challenging and thus more expensive to replace. A deviation from optimal crude slates (i.e. a removal of Russian crude oil) leads to distortions in production in a highly relevant sector of the economy. This is consistent with the idea of Ossa (2015) that some industries are critical to the functioning of the economy and therefore have greater welfare impacts when their trade is halted. While the energy component accounts for 7–8% of the consumer price index in the U.S., European countries consistently surpass 10% and reach weights of up to 15% in the overall consumption basket. Accordingly, the surge of energy prices in 2022 contributed to long-term records of headline CPI inflation in Europe as well as the associated losses of purchasing power and consumer welfare. Back-of-the-envelope calculations, in which we allow for different elasticities within and between crude oil types, indicate up to three percentage points higher disruptions in production compared to a standard CES production function.

This paper contributes to the existing literature in several dimensions. The main contribution is to acknowledge the fact that crude oil varies in its chemical composition and, hence, its quality. Bachmann et al. (2022) argue that, given the size of the global crude oil market, it should be relatively easy to find alternative suppliers. While we agree that a reallocation of crude oil trade flows may be more easily implemented than a reallocation of natural gas trade flows, Bachmann et al. (2022) and others ignore the fact that not all oil types are alike. We provide new estimates of the elasticity of substitution across different crude oil types that explicitly account for their chemical composition. Given the importance of the elasticity of substitution for both the welfare gains from globalization and the welfare losses from sanctions (see, e.g., Broda and Weinstein, 2006, Crozet and Hinz, 2020), our empirical results matter for an informed debate about sanctioning Russian crude oil and

impair the "ideal set" of a refinery's crude slate — the mix of crude oils used by refineries as an input in the production process — and thus consumer welfare indirectly through higher prices of refined petroleum products. In this particular context, the potential welfare effects of sanctions refer to higher output prices due to a shrinking set of available inputs in refining.

other commodities with similar characteristics.

The prior articles most closely related to our study are Balistreri et al. (2010) and Farrokhi (2020). Building on the model in Anderson and van Wincoop (2003), Balistreri et al. (2010) estimate the Armington elasticities for six crude oil types classified by API gravity and sulfur content. Rather than quantifying elasticities of substitution *between types*, the authors focus on the elasticities of substitution *within types*.[3] However, what arguable matters for quantifying the losses from sanctions is the difficulty or ease of substituting medium-sour Russian Urals with light sweet North Sea Brent in the refining process. Moreover, the model of Anderson and van Wincoop (2003) estimates the same elasticity of substitution for *all countries*, abstracting from cross-country heterogeneity. We are able to recover *country-specific* elasticities of substitution between different types of crude oil. Our results suggest substantial heterogeneity between countries. Given that countries differ with regard to their transport and refining infrastructure, this seems economically plausible.[4,5]

Farrokhi (2020), on the other hand, develops a detailed multi-country general equilibrium model that includes the global sourcing behavior of refineries and downstream industries. In this model, the gains from trade are higher compared to benchmark models. However, the sizable estimates of Farrokhi (2020) are due to the fact that downstream industries have difficulties in substituting crude oil with other production factors or intermediate products rather than the elasticity of substitution of refining inputs.

Our work also contributes to the growing literature on the relation between quality and the gains from trade. A recurrent issue in international trade is the lack of objective quality

[3]For instance, Balistreri et al. (2010) are concerned with the difficulty of substituting light sweet crude from one region with light sweet crude from another region.

[4]It is important to note that our estimates of the elasticity of substitution based on price and quantity data reflect both the economic and technical substitutability of different crude oil types. The former captures price differentials, while the latter captures quality differentials as well as refinery characteristics.

[5]The refining landscape is an important determinant of crude oil trade flows. In the U.S., for example, the domestic production of light sweet crude oil led to a significant decline in imports of light sweet crude oil in 2020, whereas there still is robust demand for heavy crude oil. Refineries that invested in complex refining units predominantly process imported heavy crude oil, as the benefits of processing higher quality crude oil as an input are more than offset by the price premium on light over heavy crude oil types (see U.S. Energy Information Administration, 2020).

measures for many products. Accordingly, Khandelwal (2010) and Feenstra and Romalis (2014) resort to price and quantity data in order to proxy for product quality. Crozet et al. (2012) focus on a particular, arguably less important market and firm-level trade data to investigate the influence of quality on trade. In this context, the objective measurement of crude oil quality based on its API gravity and sulfur content seems particularly appealing and important when discussing the impact of sanctions. Economic studies on sanctions commonly rely on official trade data, such as the United Nations COMTRADE database (see, e.g., Afesorgbor, 2019, Crozet and Hinz, 2020, Fuchs and Klann, 2013). While allowing for an increasingly disaggregated analysis, such data sets lack a meaningful quality dimension, which arguably matters for the welfare gains from trade as well as the welfare losses due to sanctions. Thus, our research augments the growing body of literature on the relationship between quality and trade, while simultaneously linking it to the study of sanctions.

The rest of the paper is organized as follows. Section 2 briefly discusses refinery economics and the importance of crude oil quality. Section 3 presents the data and some preliminary results. Section 4 describes our econometric approach. Section 5 presents our main results and illustrates the implications of crude oil sanctions for production when accounting for quality. Section 6 concludes.

2 Refinery Economics

In this section, we provide a simplified description of the refining process in order to illustrate the importance of the quality of crude oil as an input in the production of refined petroleum products. In the next paragraph we explain the economic intuition. The interested reader is encouraged to explore the more technical explanation that follows.

From an economic perspective, it is sufficient to understand that crude oil quality matters because "light" (i.e. high API gravity) crude oil yields a larger share of high-value refined products and because removing sulfur — the most common impurity of crude oil — is costly. A profit-maximizing refinery tries to minimize the costs of its intermediate inputs, while maximizing the output share of refined products that are currently in high demand. Moreover, the equipment installed or layout of a refinery determines the range of crude oil slates it can process.

From a technical perspective, petroleum refineries transform crude oil into refined products that are used as transportation fuels (kerosene, diesel, gasoline), heating oil, bitumen, and petrochemical feedstock. When crude oil enters the refinery, it is desalted, heated, and separated into different fractions in the distillation column. The distillation unit determines the volume a refinery can process, as all crude oil needs to go through the distillation step. The resulting proportions of each fraction depend on the crude oil quality — mainly its density, which is measured by API gravity. The higher the quality of the crude oil, the higher the yield of premium distilled products such as gasoline. As a result, low-quality crude oil trades at a discount in global markets.

To increase the output share of high-margin products, such as gasoline or diesel, refineries aim at upgrading low-value fractions in the conversion process by the use of cokers, alkylation, reforming or some kind of cracking unit.[6] Although the construction of cracking and coking units is costly, Gary et al. (2020) points out that their installation greatly increases the efficiency and flexibility of a refinery with regard to processable crude slates. Simple refineries without conversion units (a.k.a. topping refineries) are much more restricted with respect to the slates they can process. Given that they produce a large share of low-margin heavy fuel oil, these refineries are less common today and mainly used in remote areas for the production of industrial fuels or to prepare feedstocks for petrochemical industry.[7]

The last refining step discussed here is desulfurization. Due to environmental regulations and for technical consideration, crude oil impurities in general need to be removed in the refining process. The most common impurity in crude oil is sulfur, which causes oxidation

[6]For details on this step of the refining process, the interested reader is referred to Gary et al. (2020).

[7]Favennec (2022) estimates that the costs of building a new complex refinery with a capacity of 160,000 b/d in Europe in 2022 would be approximately $6 billion, while a simple refinery (i.e. just distillation column) with a capacity of 100,000 b/d would cost about $3 billion.

and reduces thus the lifespan of a refinery. Removing sulfur is costly for a refinery, as it requires high temperature and pressure as well as the use of hydrogen. For both technical and cost reasons, refineries therefore prefer crude oil slates with low sulfur content.

The above description, although simplified, emphasizes that crude oil is not a homogenous input in the refinering process. On the one hand, sulfur impurities are costly to remove and accelerate attrition. On the other hand, higher-density crude oil yields a large share of low-margin refined products from distillation and must therefore be upgraded, which is costly and requires the installment of a conversion unit. For example, recent crude assays by BP (2023) indicate that distillation of Iraqi Basrah Heavy (23.7° API gravity) yields 57.2% of low-value residual fuels, whereas distillation of the global benchmark Brent crude (38° API density) yields only 39.7% of residual fuels.

3 Data and Preliminary Evidence

We use data from the European Commission's (EC) Crude Oil Import Register (COIR), which mandates EU member countries to report their crude oil imports by field of origin.[8] The data are available on a monthly basis for January 2013 through December 2019. Due to the volatility of crude oil imports at the monthly frequency and to facilitate a comparison with estimates of substitution elasticities for crude oil in the existing literature, the data is time-aggregated to annual frequency.[9]

With regard to measuring quality, the COIR data comes along with a key advantage over standard trade data. EU countries are mandated to report their crude oil imports by field of origin along with its defining characteristics, in particular its API gravity and sulfur content. Where quality information is missing, we obtain supplementary information from various sources, such as the McKinsey Energy Insight and the Energy Information

[8]Details are described in the (COUNCIL REGULATION (EC) No 2964/95).

[9]It is important to note that the prices reported in the EC's COIR are Cost, Insurance, and Freight (CIF) prices. Accordingly, our estimates of substitution elasticities reflect the quality dimension of crude oil as well as a country's geographical location and the transport infrastructure in place.

Administration.[10] However, quality assignment is not perfect, as some imports are classified as *Other Crude Oil from Country X*. The most critical case in terms of volume is Russia, where countries either report imports of *Urals* or *Other Russian Crude Oil*. Labeling all *Other Russian Crude Oil* as Siberian Light Sweet — the second largest type produced in Russia — would result in unreasonably high imports of the latter. According to Adolfsen et al. (2023) and Heussaff et al. (2023), the main type of crude oil exported from Russia to the European Union is Urals. We therefore assume that *Other Russian Crude Oil* comprises of 70% Urals and 30% Siberian Light Sweet crude oil — the two types' approximate shares in Russian production. This might be considered a conservative approach. Our results remain qualitatively unchanged without this assumption.

So far, we have not shown the economic importance of crude oil quality and transportation infrastructure in the refining process. Table 1 reports the coefficient estimates of a hedonic pricing model, where we regress the import price of crude oil on quality characteristics and observables that are typically included in gravity models of international trade. Based on the refinery economics in Section 2, all else equal, higher API gravity should be associated with a higher crude oil price, as lighter crude oil yields a larger share of high-value refined products. Conversely, higher sulfur content should be associated with a lower crude oil price, as removing impurities is costly for refineries. Including time, importer, and exporter fixed effects, the respective coefficient estimates reported in Table 1 have the expected signs, are highly statistically significant and economically relevant.[11] Moreover, there is strong evidence of a role for transport infrastructure and geographical distance, as crude oil tends to be significantly cheaper when imported via pipelines and more expensive when the field of origin is located further away. Note that, once we control for crude oil quality and mode of transport, geographical distance is only statistically significant at the 10% level.

[10] For details on the data preparation, see Appendix A.

[11] Comparing Brent crude (38° API gravity, 0.4% sulfur content) and Basrah Heavy (23.7° API gravity, 4.12% sulfur content), for example, the latter trades at an average discount of 6.69$/bbl in our sample.

	Dependent variable:
	CIF price ($/bbl)
Typical API gravity	1.051***
	(0.081)
Typical API gravity (squared)	−0.014***
	(0.001)
Typical sulphur content	−0.952***
	(0.104)
Volume (1000 bbl)	−0.00001
	(0.00002)
Pipeline connection	−1.764***
	(0.237)
Distance	0.0001*
	(0.0001)
Constant	96.85***
	(1.507)
Observations	15,213
R^2	0.982
Adjusted R^2	0.982
Residual std. error	3.282 (df = 15,076)
F statistic	6,186*** (df = 136; 15,076)
Fixed effects:	Time, Importer, Exporter
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 1: Hedonic Pricing Model

4 Econometric Approach

4.1 Estimating the Elasticity of Substitution

To estimate the elasticity of substitution between different crude oil types, we apply the econometric approach proposed by Feenstra (1994) and refined by Broda and Weinstein

(2006).[12] We use this method for two reasons. First, it is widely used in empirical work (see, e.g., Goldberg et al., 2010, Imbs and Mejean, 2017, Redding and Weinstein, 2020). Second, it allows for heterogeneity in the substitution elasticity across countries. In contrast to Feenstra (1994) and Broda and Weinstein (2006), who are interested in estimating an exact aggregate price index to study the gains from trade due to a larger set of varieties, we focus on estimating the elasticity of substitution between imported varieties of the same good. Feenstra et al. (2018) refers to this as the *micro-elasticity* of substitution, i.e. the elasticity of substitution between several foreign goods. Given that the econometric approach is described in detail in Feenstra (1994) and Broda and Weinstein (2006), we limit the discussion to an intuitive explanation of the model and defer its formal derivation to Appendix B.

Feenstra's method uses a GMM identification via heteroskedasticity of supply and demand shocks, which goes back to the standard identification problem. Given data on prices and quantities but no additional information on external shocks, supply and demand elasticities cannot be identified uniquely.[13] Feenstra (1994) recognizes that by adding another dimension to the data, namely differences in varieties, we obtain a panel data set, which allows estimating supply and demand elasticities. Intuitively, one can estimate a hyperbola of optimal supply and demand elasticities for each variety. Assuming that the elasticity of substitution is constant across varieties and that the same holds for the supply elasticity, the true estimator is given by the intersection of the hyperbolas.[14] A sufficient condition for the applicability of Feenstra's method is that the hyperbolas are not the same across varieties. It can be shown that the curve for each variety depends on the variances and covariances of supply and demand shocks, which in turn depend on macroeconomic fluctuations. As long

[12]See Hillberry and Hummels (2013) for a critical discussion of the methodology. Soderbery (2010) shows that the estimator suffers from small sample bias, which is less relevant for estimating substitution elasticities, given that the structural form eliminates most of the bias. In later work, Soderbery (2015) improves the estimation method and proposes a LIML estimator that corrects for small sample bias and constrained search inefficiencies. Imbs and Mejean (2015), on the other hand, show that the estimator suffers from heterogeneity bias when sector level data is aggregated. However, this also applies to the alternative approach proposed by Caliendo and Parro (2015).

[13]See Leamer (1981) for a formal derivation of this result.

[14]Feenstra (2010) and Broda and Weinstein (2010) discuss the econometric approach in greater detail, including a graphical representation of the "estimator".

as some of the economies that a country imports from face different macroeconomic shocks, efficient estimates can be obtained.

4.2 Definition of Goods and Varieties

While applying Feenstra's method, we depart from the original Armington (1969) assumption that different varieties of the same good are identified by their countries of origin.[15] To gauge the effects of sanctioning oil imports from Russia or other major oil-exporting countries on production, we instead define different varieties of the good crude oil by its objectively measurable chemical composition. Following Broda and Weinstein (2010), we then estimate the between-product elasticity of substitution between these heterogeneous crude oil types.

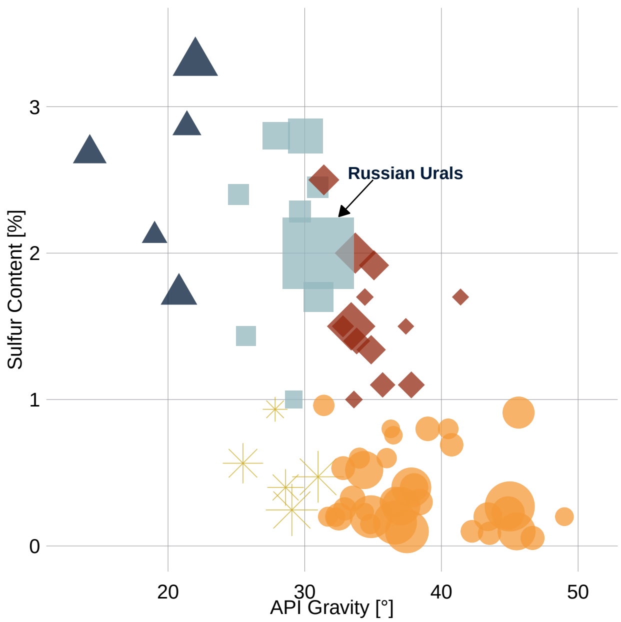
We measure crude oil quality along the two dimensions discussed in Section 2, that is API gravity and sulfur content. To categorize similar crude oil types, practitioners usually differentiate between light, medium, and heavy as well as sweet and sour crude oil, where light indicates a low density (i.e. high API gravity) and sweet indicates low sulfur content.

Figure 1 illustrates different aggregation methods using the COIR data set. Panel (a) depicts Euro Area crude oil imports over the entire sample period by field of origin. Accordingly, each symbol refers to a specific oil field, while the size of the symbol indicates the volume of crude oil imported from this field. Naïvely applying Feenstra's method to the disaggregated data addresses the question how easily crude oil imports from any field can on average be replaced by crude oil imports from any other field.

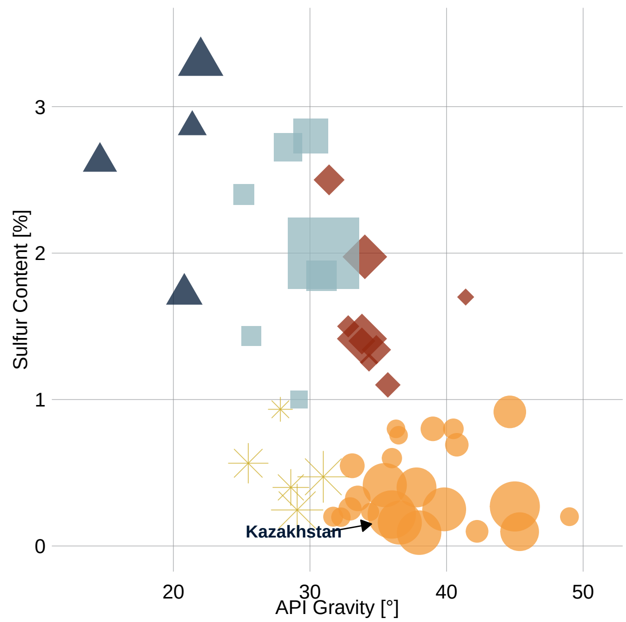
Following Armington (1969) and Feenstra (1994), we can aggregate crude oil imports by country of origin, as in Panel (b). Different varieties of crude oil are then defined at the country level. Given that more than one oil field may be located on the same country's territory, the number of varieties decreases relative to Panel (a).

In the spirit of Blonigen and Soderbery (2010), we can also differentiate goods at a more granular level. For example, we can classify light sweet crude oil as a separate good and

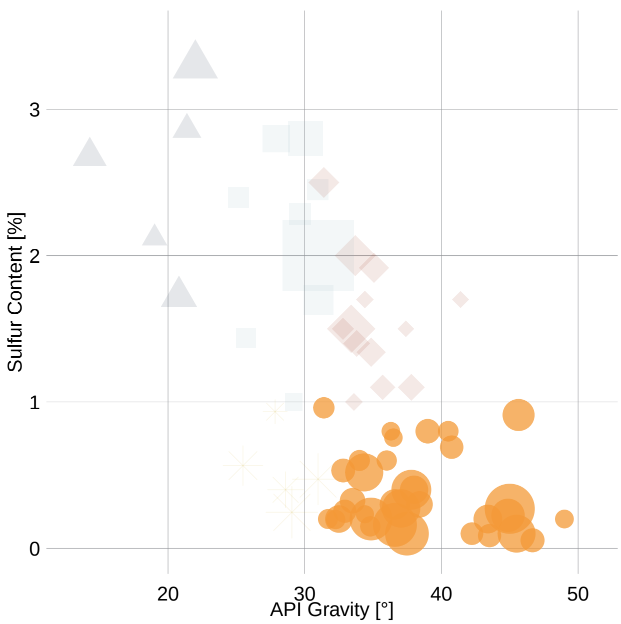
[15] For example, French, German, and Japanese cars are different varieties of the same good both in Armington (1969) and in Feenstra (1994).



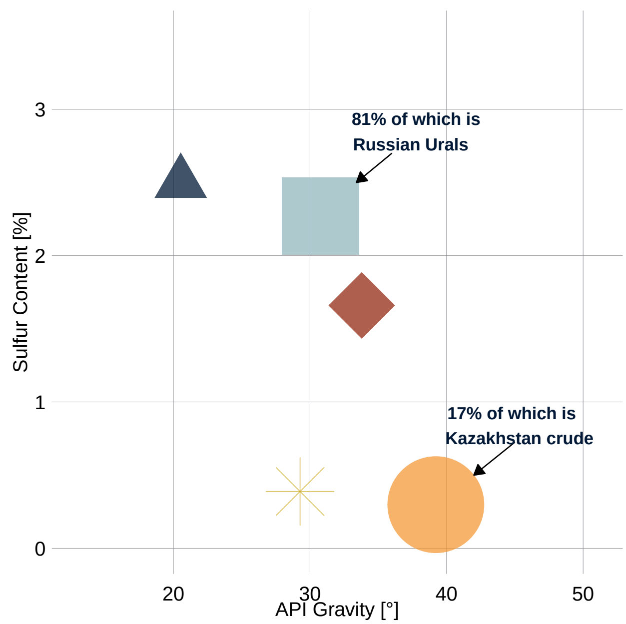
(a) Crude Oil Imports by Oil Field



(b) Crude Oil Imports by Country of Origin



(c) Light Sweet Crude Oil Imports



(d) Crude Oil Imports by Oil Type

Figure 1: Different Product/Variety Specifications for Euro Area Crude Oil Imports

define different varieties of light sweet crude oil by their fields of origin, which may be located in different countries. This is shown in Panel (c). Broda and Weinstein (2010) refer to this as the "within-product elasticity of substitution".[16]

Panel (d) depicts our own definition of varieties based on the chemical composition of different crude oil types. Rather than differentiating varieties of the heterogeneous good crude oil by their countries or fields of origin, we aggregate crude oil imports into five economically meaningful types, which arguably reflect their quality and have different physical properties in the refining process. In contrast to Panel (c), which speaks to the within-type elasticity of substitution, this allows addressing the question how easily one can replace imports of medium-sour crude oil (indicated by the light-blue square) by imports of light sweet crude oil (indicated by the orange circle), for example. In light of the recent debate on sanctions, this seems to be the relevant elasticity of substitution to gauge how costly it is to replace Russian Urals — a medium-sour type, for which there are few within-type substitutes available — by other crude oil types.[17] Or, as Broda and Weinstein (2006) put it:

> "Presumably we care more about the different varieties of fruits than about varieties of apples." (p. 545)

5 Results

5.1 Elasticities of Substitution

Following Feenstra's methodology, we estimate the substitution elasticity of crude oil for the aggregation methods shown in Figure 1. Table 2 reports the estimated elasticities of the panel data estimation for three different specifications of crude oil varieties by oil field, country of origin, and oil type, respectively, for selected EU countries in the COIR data set.

[16]Building on the model of Anderson and van Wincoop (2003), Balistreri et al. (2010) estimate the (within) Armington elasticity for six different crude oil types.

[17]The only quantitatively relevant alternative for medium-sour crude oil is Arab medium crude oil from Saudi Arabia.

Country	Oil Field	Country of Origin	Oil Type
	5.58	**5.61**	**2.77**
Austria	(0.45)	(0.34)	(0.86)
	$[5.38, 5.80]$	$[5.39, 5.87]$	$[2.72, 2.83]$
	112	**16.4**	**9.64**
Belgium	(95.3)	(1.45)	(2.56)
	$[-124, 158]$	$[10.6, 34.8]$	$[9.07, 10.3]$
	80.0	**30.9**	**3.94**
France	(104)	(8.94)	(1.91)
	$[-223, 222]$	$[20.9, 106]$	$[3.72, 4.19]$
	62.6	**18.8**	**5.83**
Germany	(34.7)	(7.34)	(4.19)
	$[-795, 1321]$	$[13.6, 25.6]$	$[4.91, 7.03]$
	1537	**30.0**	**6.13**
Italy	(65570)	(6.00)	(2.12)
	$[NA, NA]$	$[25.5, 36.5]$	$[5.93, 6.34]$
	36.0	**36.2**	**4.19**
Euro Area	(7.33)	(12.9)	(1.12)
	$[-49.2, 235]$	$[28.0, 50.5]$	$[3.49, 5.10]$

Notes: Standard errors in parentheses. 95-percent confidence intervals in brackets. Confidence intervals are calculated using the confidence ellipse around θ_1 and θ_2 (see Appendix B). Based on the classification by country of origin, Broda and Weinstein (2006) estimate an elasticity of substitution for U.S. crude oil imports of **17.1**.

Table 2: Elasticities of Substitution for Different Product/Variety Specifications

In the *Oil Field* column, we distinguish varieties by their fields of production, at the most granular level available in the COIR data set, and estimate elasticities of substitution across all oil types. While it is difficult to form priors on the values of the substitution elasticities, given the granularity of varieties, we would expect these estimates to be higher than for the other two levels of aggregation. Except for Austria, our estimates indeed tend to be very high and, considering the confidence bands, imprecisely estimated.

Using Feenstra's original approach and distinguishing crude oil varieties by their countries rather than fields of origin, our point estimates tend to drop significantly, albeit not for all countries in our sample.[18] These values are directly comparable with estimates previously reported in the literature. Applying the same definition of varieties to U.S. crude oil imports,

[18]The complete list of country estimates is shown in Appendix C. We also provide coefficient estimates of the within-product elasticities of substitution in Appendix D.

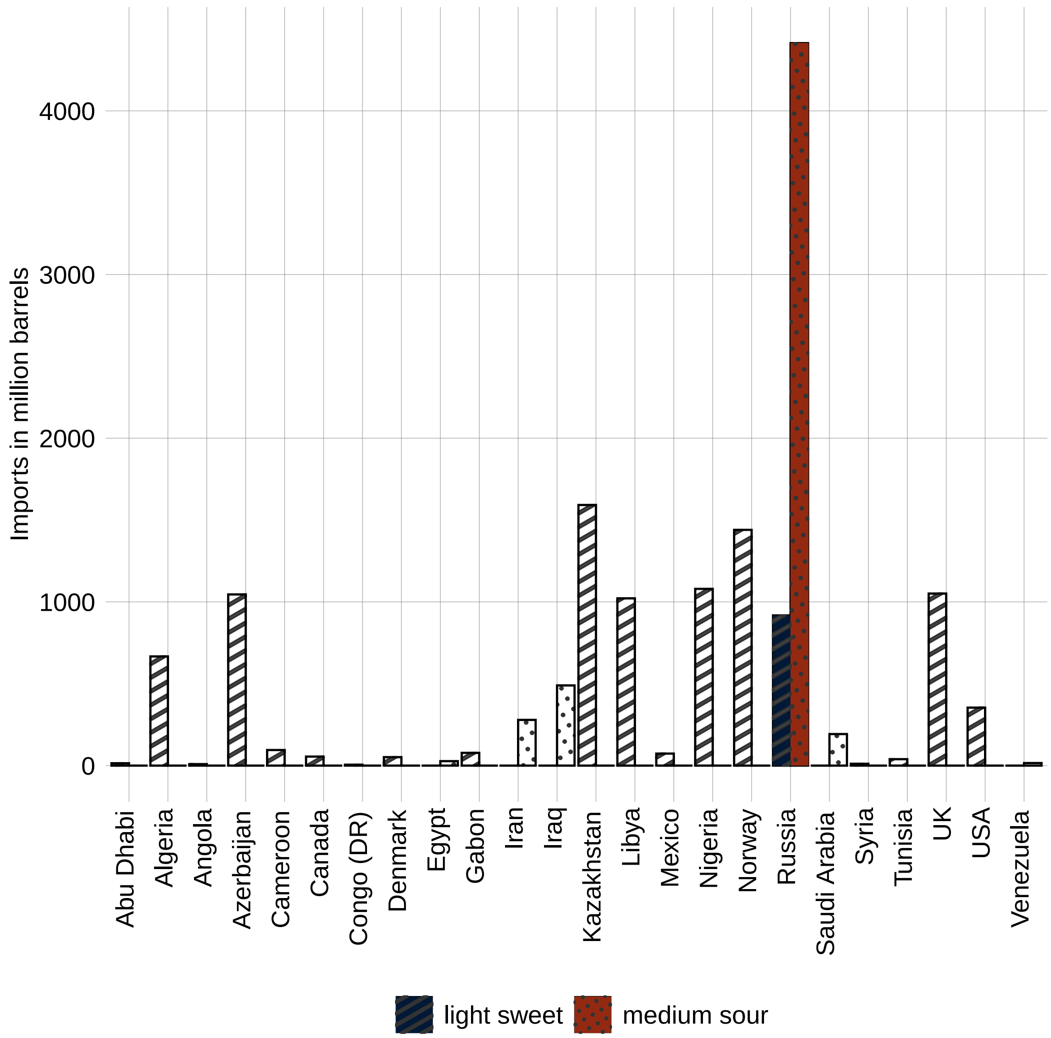


Figure 2: Distribution of Euro Area Imports for the Two Most Common Crude Oil Types

Broda and Weinstein (2006) obtain an estimate of 17.1 for the elasticity of substitution. Using a different estimation method, Farrokhi (2020) estimates a trade elasticity for crude oil of 19.77. Both estimates are close to our estimates based on COIR data.

Considering our specification of crude oil types in the third column, the estimated elasticities of substitution are even lower.[19] Estimates of the order in the third column of Table 2 suggest potentially non-trivial welfare effects of an expansion or shrinkage of this set. Given that Russian Urals accounts for the vast majority of medium-sour imports in the COIR data

[19]Based on a CES representation of household preferences, estimates above 10 or 20 are generally considered high (Broda and Weinstein, 2006), implying limited welfare effects of a change in the set of available varieties.

set (see Figure 2), some EU countries would effectively lose access to this crude oil type, if Russian pipeline imports were banned, as well. Assuming that the crude slate of refineries in the EU was conditionally optimal before the adoption of sanctions, as they benefited from cheap Russian crude oil, the former would be confronted with a narrower set of varieties or higher costs of importing Saudi Arabian medium-sour crude oil via vessels. In either case, this leads to higher costs due to a sub-optimal crude slate or more costly transport over longer distances (see Table 1). Depending on the market power of refineries, the sanctions-induced increase in production costs compresses profit margins of refineries in the EU or is passed on to industry and consumers via higher producer and retail prices.

5.2 Implications for the Evaluation of Sanctions

In this section, we discuss the implications of our approach compared to Feenstra's method. In particular, we show that the conclusions of the two approaches may differ substantially and what this depends on. Our exercise is inspired by the production theory of Ethier (1982), who assumes that downstream producers — in our case refineries — prefer a larger variety of inputs to enhance their productivity.[20] In line with our previous approach, we modify the functional-form assumptions in Ethier (1982) and allow for a nested-CES type production function, where we distinguish the substitutability of crude oil varieties *within* and *between* nests, and each nest corresponds to an oil type. The final output in country c's oil sector is a nested constant-elasticity-of-substitution (nested-CES) aggregate of oil varieties:

$$Y_c = \left[\sum_{g=1}^{G} \left(\sum_{j=1}^{J_g} q_{gj}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{(\sigma-1)} \frac{(\gamma-1)}{\gamma}} \right]^{\frac{\gamma}{\gamma-1}} \tag{1}$$

where q_{gj} denotes the processed quantity of oil variety $j \in J_g$ in oil type (nest) $g \in G$. With this formulation, individual oil varieties can in principle be more substitutable within the

[20]Note that this is very closely connected to the "love of variety" approach introduced in a consumption context by Dixit and Stiglitz (1977).

same oil type than against other oil types (if $\gamma < \sigma$) or less substitutable (if $\gamma > \sigma$). Our empirical results, however, clearly suggest the former case. This has important implications when analyzing the abrupt stop of oil imports from a certain region as a result of sanctions. The ultimate impact on Y_c depends on whether a representative refinery in country c retains access to close alternative substitutes within the same oil type or whether the imposed sanctions are equivalent to the loss of access to an entire oil type. To fix ideas and focus on the role of changes in the availability of varieties versus oil types, we abstract here from heterogeneity in quantities of oil varieties. This allows us to rewrite Equation (1) as

$$Y_c = G^{\frac{\gamma}{(\gamma-1)}} J^{\frac{\sigma}{(\sigma-1)}} q. \tag{2}$$

Inspecting Equation (2) immediately shows that the elasticity of production with respect to changes in nests (G) or varieties (J) depends on the substituability parameters γ and σ. The respective elasticities are given by $\frac{dlnY_c}{dlnG} = \frac{\gamma}{(\gamma-1)}$ and $\frac{dlnY_c}{dlnJ} = \frac{\sigma}{(\sigma-1)}$, which are only identical for $\gamma = \sigma$. This is the implicit assumption made by Feenstra (1994).[21] In all other scenarios, the results will differ from the case with only one elasticity of substitution, with the deviations increasing in the difference between γ and σ.

In a final step, we apply these theoretical considerations to our data. Table 3 contrasts Feenstra estimates of the CES elasticity based on the *Country of Origin* from Table 2 with our estimates based on a characterization by *Oil Type* and the nested-CES production technology in Equation (1). Column 1 refers to the standard CES case, where σ ($= \gamma$) represents the elasticity of substitution between crude oil imported from different countries. In columns 2 and 3, we report the average within-type elasticity from Table A.2 for the nested-CES case as well as the elasticity of substitution between different crude oil types (γ). In all cases, we find that $\gamma < \sigma$, indicating a lower substitutability between than within nests, and hence a more significant impact on production in case of the removal of an entire oil type.

This can be seen in column 4, where we investigate the hypothetical scenario of a loss

[21] See Appendix E for a formal proof for the case of heterogeneous quantities.

Country	CES σ	Nested CES σ	γ	remove medium-sour imports	remove imports from Russia
Austria	5.6	5.1	2.8	-8.90	-1.46
Belgium	16.4	53.2	9.7	-1.33	-0.78
France	30.9	19.2	3.9	-6.36	-2.97
Germany	18.8	25.5	5.8	-3.71	-2.39
Italy	30.0	79.3	6.1	-3.72	-1.13
Euro Area	36.2	45.8	4.2	-4.74	-1.56

Notes: Content of columns: (2) estimates reported in Table 2 for *Country of Origin*; (3) unweighted mean of the within-type elasticities reported in Table A.2; (4) estimates reported in Table 2 for *Oil Type*. (5) and (6) production differential of standard CES vs. nested CES for two scenarios: (5) countries lose access to imports of medium-sour crude oil; (6) countries lose access to imports of Russian crude oil.

Table 3: Approximation of Production Disruptions

of access to medium-sour crude oil (i.e. a complete nest). This is relevant, as for several countries, a ban of Russian oil comes close to the latter scenario, since Russian Urals accounts for the largest fraction of total medium-sour oil imports.[22] In the final column, we remove crude oil imports (of any type) from Russia. The reported values correspond to differential changes in production in percentage points between the standard CES and the nested-CES case, where we subtract the former from the latter. Accordingly, a negative value indicates that the implied change in production is larger when assuming a nested-CES structure and our estimates for the within- and between-type elasticities, which is always the case. The predicted losses in production from removing all imports of medium-sour crude oil in Euro Area refineries, for example, are 4.74 percentage points larger when accounting for the fact that not all oil types are alike. This pattern of underestimating the disruptions in production from sanctioning Russian oil imports is consistent across both scenarios and for all countries and regions in Table 3.

[22]We find the largest share for Germany, whose imports from Russia account for 93.3% of its total medium-sour oil imports.

Since some of the oil supplied by Russia is Siberian light sweet crude, the difference is smaller in the scenario of a complete halt of Russian crude oil imports. The reduction tends to be smaller for countries that import a lot of medium sour crude oil from Russia and have a low estimated elasticity of substitution.

6 Conclusion

Motivated by the political debate on sanctioning crude oil imports from Russia, we provide novel estimates of the elasticity of substitution across different crude oil types based on an economically meaningful categorization. Rather than considering crude oil as a homogenous good or differentiating crude oil varieties by their countries or fields of origin, we classify crude oil types based on two objective quality characteristics — API gravity and sulfur content. In light of substantially lower estimates of substitution elasticities compared to previous studies, our analysis indicates up to three percentage points larger disruptions of refinery production in case of a complete halt of Russian crude oil imports.

Our empirical estimates also point to heterogeneous effects across EU member countries. Accordingly, the economic cost of sanctioning all crude oil imports from Russia, including pipeline imports, which are exempt from the EU's sanctions currently in place, might not be born equally. The expansion of sanctions against Russia and other commodity exporters has thus important political implications for the EU and energy import-dependent economies.

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Appendix A. Preparation of Crude Oil Import Data

Although the European Commission's template for reporting crude oil imports contains quality measures for most oil fields, there are cases, where this information is missing. In these cases, we supplement the template with data from alternative sources, such as the U.S. Energy Information Administration (EIA) and McKinsey energy insights. Despite the rich details of the published template, it is important to note that certain crude oil imports have been aggregated, resulting in limitations in the assignment of quality measures. For example, published crude oil imports contain "Other Angolan crude oil". Accordingly, we cannot assign a crude oil quality directly. If several crude oil types (including reported quality) are available in the template or from other sources, we use the unweighted mean of all crude oil types from Angola, for example, to approximate average quality. For cases such as "Heavy Canadian crude oil", we calculate the unweighted average of API gravity and sulfur content across all *heavy* Canadian crude oils in the template. Two thirds of the sample can be matched perfectly. Canada and Russia, which we highlight in the main text, account for most of the remaining third.

Appendix B. Empirical Strategy

In this appendix, we describe the estimation procedure of the elasticity of substitution, while skipping the derivation of the exact price index in Feenstra (1994), given that we are not interested in the change of the latter.

Feenstra (1994) generalizes the exact price index of a single good, taking new and disappearing varieties into account. We start our formal exposition with Feenstra's generalized version of the minimum cost function:

$$c\left(\pi_t, \mathbf{I}_t, \mathbf{b}_t\right) = \left[\sum_{i\in\mathbf{I}_t} \left(b_{i,t}\lambda_{i,t-1}/\lambda_{i,t}\right) P_{i,t}^{1-\sigma}\right]^{1/(1-\sigma)}, \tag{A.1}$$

where

$$\lambda_r \equiv \textstyle\sum_{i\in\mathrm{I}} p_{i,r}x_{i,r} / \sum_{i\in\mathrm{I}_r} p_{i,r}x_{i,r} \text{ for } r = t-1, t.$$

In (A.1), i refers to a specific variety in the set I_t available in period t, σ is the elasticity of substitution, and $b_{i,t}$ denotes a variety-specific (random) taste or quality parameter. π_t refers to the exact price index and is equal to the conventional price index $P\left(\mathbf{p}_{t-1},\ \mathbf{p}_t, \mathbf{x}_{t-1}, \mathbf{x}_t, \mathbf{I}\right)$, which ignores new product varieties, times the additional term $\left(\lambda_t/\lambda_{t-1}\right)^{1/(\sigma-1)}$. λ_t denotes the fraction of expenditure on goods available in both periods relative to the expenditure on goods available in period t. p_i and x_i refer to prices and quantities of variety i, respectively. Feenstra (1994) distinguishes varieties by their country of origin, as in Armington (1969).

From the minimum cost function in (A.1), we can derive the import demand equation for each variety, which is expressed in first differences of import shares:[23]

$$\Delta \ln s_{i,t} = \phi_t - (\sigma - 1)\Delta \ln P_{i,t} + \varepsilon_{i,t}, \tag{A.2}$$

where $\phi_t \equiv (\sigma-1) \ln \left[c\left(\pi_t, \mathbf{I}_t, \mathbf{b}_t\right)/c\left(\pi_{t-1}, \mathbf{I}_{t-1}, \mathbf{b}_{t-1}\right)\right]$ is a random effect, because b_t is random, and $\varepsilon_{i,t} = \Delta ln(b_{i,t}\lambda_{i,t}/\lambda_{i,t-1})$ appears as an error term.

The export supply equation is given by

$$\Delta \ln P_{i,t} = \psi_t + \rho\varepsilon_{i,t}/(\sigma - 1) + \delta_{i,t}, \quad 0 \leq \rho < 1, \tag{A.3}$$

where ω denotes the inverse supply elasticity (assumed to be the same across countries), $\psi_t = \omega\left(\phi_t + \Delta \ln E_t\right)/(1 + \omega\sigma)$ is a random effect, $\delta_{i,t} \equiv \xi_{i,t}/(1 + \omega\sigma)$ is the error, and $\rho \equiv \omega(\sigma - 1)/(1 + \omega\sigma)$.[24]

Note that ϕ_t and ψ_t depend on time only. It is therefore convenient to define a reference country k and difference Equations (A.2) and (A.3) relative to country k.[25] Accordingly,

$$\tilde{\varepsilon}_{i,t} = \Delta^k \ln s_{i,t} + (\sigma - 1)\Delta^k \ln P_{i,t}, \tag{A.4}$$

$$\tilde{\delta}_{i,t} = (1 - \rho)\Delta^k \ln P_{i,t} - \frac{\rho}{\sigma - 1}\Delta^k \ln s_{i,t}, \tag{A.5}$$

where $\Delta^k x_{it} = \Delta x_{it} - \Delta x_{kt}$, $\tilde{\varepsilon}_{it} \equiv \varepsilon_{it} - \varepsilon_{kt}$ and $\tilde{\delta_{it}} \equiv \delta_{it} - \delta_{kt}$.

To take advantage of the independence of $\tilde{\varepsilon}_{it}$ and $\tilde{\delta}_{it}$, we multiply Equations (A.4) and (A.5) and divide by $(1 - \rho)(\sigma - 1) > 0$ to obtain

$$(\Delta^k \ln P_{it})^2 = \theta_1(\Delta^k \ln s_{it})^2 + \theta_2(\Delta^k \ln s_{it}) \times (\Delta^k \ln P_{it}) + u_{it}, \tag{A.6}$$

where

$$u_{it} = \frac{\tilde{\varepsilon}_{i,t}\tilde{\delta}_{i,t}}{(1 - \rho)(\sigma - 1)}, \quad \theta_1 \equiv \frac{\rho}{(\sigma - 1)^2(1 - \rho)}, \quad \text{and} \quad \theta_2 \equiv \frac{(2\rho - 1)}{(\sigma - 1)(1 - \rho)}.$$

The problem with Equation (A.6) is that the error term, u_{it}, is correlated with the depen-

[23] We use shares $s_{i,t}$ rather than quantities, given that the former are not affected by potential measurement error (Kemp, 1962).

[24] $\xi_{i,t}$ is the random error from the supply equation expressed in quantities rather than shares and assumed to be independent from $\varepsilon_{i,t}$. Hence, $\delta_{i,t}$ and $\varepsilon_{i,t}$ are assumed to be independent.

[25] It is important to note that the estimates are sensitive to the choice of the reference country.

dent variables. By exploiting the panel structure of the data together with the assumption that demand and supply elasticities are constant across varieties, consistent estimates can nevertheless be obtained. The variance of the error term in (A.6) depends on the variety i. Thus, we need to correct for heteroskedasticity in order to obtain efficient estimates.

Appendix C. Complete List of Countries

Country	Oil Field	Country of Origin	Oil Type
	5.58	**5.61**	**2.77**
Austria	(0.45)	(0.34)	(0.86)
	[5.38, 5.80]	[5.39, 5.87]	[2.72, 2.83]
	112	**16.4**	**9.64**
Belgium	(95.3)	(1.45)	(2.56)
	[−124, 158]	[10.6, 34.8]	[9.07, 10.3]
	80.0	**30.9**	**3.94**
France	(104)	(8.94)	(1.91)
	[−223, 222]	[20.9, 106]	[3.72, 4.19]
	62.6	**18.8**	**5.83**
Germany	(34.7)	(7.34)	(4.19)
	[−795, 1321]	[13.6, 25.6]	[4.91, 7.03]
	17.5		**7.11**
Greece	(6.96)		(3.31)
	[15.3, 20.4]		[6.92, 7.30]
	1537	**30.0**	**6.13**
Italy	(65570)	(6.00)	(2.12)
	[NA, NA]	[25.5, 36.5]	[5.93, 6.34]
	1006	**38.0**	
Netherlands	(7078)	(43.5)	
	[NA, 278]	[9.5, 69.6]	
	31.1	**87.8**	**10.9**
Portugal	(10.4)	(60.1)	(2.80)
	[20.7, 317]	[71.3, 114]	[10.2, 11.7]
	50.8	**96.3**	**27.5**
Romania	(53.4)	(192)	(12.4)
	[−2628, 262]	[76.1, 131]	[25.4, 29.9]
	16.5	**31.8**	**3.54**
Spain	(1.90)	(16.1)	(0.74)
	[14.1, 19.9]	[19.2, 126]	[3.33, 3.78]
	111	**51.5**	**2.31**
Sweden	(263)	(7.63)	(0.32)
	[−1090, 774]	[47.5, 56.3]	[2.02, 2.72]
			6.35
United Kingdom			(1.46)
			[6.09, 6.63]
	36.0	**36.2**	**4.19**
Euro Area	(7.33)	(12.9)	(1.12)
	[−49.2, 235]	[28.0, 50.5]	[3.49, 5.10]

Notes: Standard errors in parentheses. 95-percent confidence intervals in brackets. Confidence intervals are calculated using the confidence ellipse around θ_1 and θ_2 (see Appendix B). For some EU member states, such as Hungary and Slovakia, it is not possible to estimate the elasticity of substitution due to a lack of importer variety or missing data. Missing estimates are either due to data constraints or a failure of the algorithm to converge. Using the grid search approach of Broda and Weinstein (2006) to obtain these elasticities instead, the estimates tend to be highly sensitive and are thus not reported.

Table A.1: Elasticities of Substitution for Different Product/Variety Specifications

Appendix D. Estimates of Within-Type Elasticities

The main contribution of our study is the empirical quantification of substitution elasticities between different crude oil types, which is arguably relevant for both the gains from trade with and the costs of sanctions on major crude oil exporters, such as Russia. Turning to estimates of within-type elasticities, we have a strong theoretical prior. From a technical perspective, different crude oils of the same type are "more homogenous" and should thus be easier to substitute. However, the results in Table A.2 are only partially consistent with this prior.

On the one hand, most estimates are in the range of the estimates by oil field and by country from Table 2 and clearly exceed the between-type estimates in the former table. The elasticities in Table A.2 are also consistent with comparable estimates in existing research. In particular, Balistreri et al. (2010) estimate a within-type elasticity of substitution of 32, 15, and 37 for light sweet, light sour, and heavy sour crude oil, respectively. Given that their results build on the empirical approach of Anderson and van Wincoop (2003), however, they cannot account for heterogeneity across countries, which seems to be relevant for our data and sample period.

Country	light sweet	medium sweet	light sour	medium sour	heavy sour	not specified
	7.65			**2.51**		
Austria	(1.7)			(2.0)		
	$[6.9, 8.8]$			$[2.3, 2.8]$		
	83.6			**14.1**	**11.8**	**4.8**
Belgium	(40)			(1.49)	(2.7)	(0.8)
	$[-8760, 2495]$			$[11, 24]$	$[10, 14]$	$[4.5, 5.3]$
	38.8		**16.1**	**6.04**		**15.8**
France	(39)		(2.4)	(1.1)		(2.2)
	$[19, 343]$		$[12, 34]$	$[5.6, 6.7]$		$[15, 17]$
	30.8	**17.8**	**61.3**	**8.65**		**9.0**
Germany	(9.2)	(2.7)	(24)	(6.8)		(27)
	$[24, 46]$	$[13, 46]$	$[36, 411]$	$[7.6, 11]$		$[5.4, 11]$
	12.9	**24.0**	**120**			
Italy	(2.7)	(9.4)	(198)			
	$[11, 16]$	$[23, 26]$	$[-2216, 6579]$			
	37.6	**4.47**	**65.5**	**22.9**	**13.2**	
Euro Area	(8.9)	(1.6)	(29)	(4.8)	(3.2)	
	$[31, 48]$	$[4.0, 5.1]$	$[60, 71]$	$[19, 30]$	$[13, 14]$	

Notes: Standard errors in parentheses. 95-percent confidence intervals in brackets. Confidence intervals are calculated using the confidence ellipse around θ_1 and θ_2 (see Appendix B). Missing values are due to data constraints or a failure of the algorithm to converge. The grid search approach of Broda and Weinstein (2006) has not been applied. Balistreri et al. (2010) estimate an within-type elasticity of substitution of **32**, **15**, and **37** for light sweet, light sour and heavy sour crude oil, respectively.

Table A.2: Within-Product Elasticities of Substitution

On the other hand, our estimates appear to be quite low for some combinations of countries and oil types. While it is difficult to point out the determinants of these counterintuitive cases, they seem to be specific to import partners. Moreover, these exceptions suggest that, from an economic point of view, measures of technical substitutability, such as crude oil quality, must be complemented by economic factors such as transport and refining infrastructure, for example.

Appendix E. Theoretical Derivations

In the main text, we simplified Equation (1) and abstracted from any heterogeneities in quanitities in order to show that the elasticities of production with respect to changes in nests (G) or varieties (J) are only identical in the case of $\gamma = \sigma$. The aim of this appendix is to show that this also holds true when processed quantities may differ across varieties. To do so, we use a continuous-space version of the nested-CES technology given by

$$Y_c = \left[\int_0^G \left(\int_0^{J_g} q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma}{(\sigma-1)} \frac{(\gamma-1)}{\gamma}} dg \right]^{\frac{\gamma}{\gamma-1}} .$$

In a first step, we derive the change in production from a change in the set of available oil types (nests), G, as

$$\begin{aligned}
\frac{\partial Y_c}{\partial G} =& \frac{d}{dG} \left[\int_0^G \left(\int_0^J q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg \right]^{\frac{\gamma}{\gamma-1}} \\
=& \frac{\gamma}{\gamma-1} \left[\int_0^G \left(\int_0^J q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg \right]^{\frac{1}{\gamma-1}} \frac{d}{dK} \left[\int_0^G \left(\int_0^J q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dk \right] \\
=& \frac{\gamma}{\gamma-1} \left[\int_0^G \left(\int_0^J q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg \right]^{\frac{1}{\gamma-1}} \left(\int_0^J q_{gj}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} .
\end{aligned}$$

In a second step, we compute the change in production from a change in the set of available oil varieties, J_g, within an oil type as

$$\begin{aligned}
\frac{\partial Y_c}{\partial J_g} =& \frac{d}{dJ}\left[\int_0^G \left(\int_0^J q_{jg}^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg\right]^{\frac{\gamma}{\gamma-1}} \\
=& \frac{\gamma}{\gamma-1}\left[\int_0^G \left(\int_0^J q_{jg}^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg\right]^{\frac{1}{\gamma-1}} \frac{d}{dJ}\left[\int_0^G \left(\int_0^J q_{jg}^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg\right] \\
=& \frac{\gamma}{\gamma-1}\left[\int_0^G \left(\int_0^J q_{jg}^{\frac{\sigma-1}{\sigma}} dJ_g\right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dk\right]^{\frac{1}{\gamma-1}} \frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}\left(\int_0^{J_g} q_{jg}^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\gamma-\sigma}{(\sigma-1)\gamma}} q_{gJ_g}^{\frac{\sigma-1}{\sigma}}.
\end{aligned}$$

In a final step, we evaluate the latter equation for the case of $\sigma = \gamma$ and compare it to the standard CES case without nests.

$$\begin{aligned}
\frac{\partial Y_c}{\partial J} =& \frac{\gamma}{\gamma-1}\left[\int_0^G \left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}} dg\right]^{\frac{1}{\gamma-1}} \frac{\sigma(\gamma-1)}{(\sigma-1)\gamma}\left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\gamma-\sigma}{(\sigma-1)\gamma}} q_J^{\frac{\sigma-1}{\sigma}} \overset{\sigma=\gamma}{\Leftrightarrow} \\
=& \frac{\gamma}{\gamma-1}\left[\int_0^G \left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{1} dg\right]^{\frac{1}{\gamma-1}} \left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{0} q_J^{\frac{\sigma-1}{\sigma}} \quad \Leftrightarrow \\
=& \frac{\gamma}{\gamma-1}\left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{1}{\gamma-1}} q_J^{\frac{\sigma-1}{\sigma}} \quad \Leftrightarrow \\
=& \frac{\sigma}{\sigma-1}\left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{1}{\sigma-1}} q_J^{\frac{\sigma-1}{\sigma}}.
\end{aligned}$$

As we show in the following, the latter expression is identical to a derivative of a standard CES production function,

$$Y_c = \left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma}{\sigma-1}},$$

with respect to a change in the set of varieties. The respective derivative is given by

$$\begin{aligned}
\frac{\partial Y_c}{\partial J} =& \frac{\sigma}{\sigma-1}\left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{1}{\sigma-1}} \frac{d}{dJ}\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj \\
=& \frac{\sigma}{\sigma-1}\left(\int_0^J q_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{1}{\sigma-1}} q_J^{\frac{\sigma-1}{\sigma}}.
\end{aligned}$$