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Oil Trade and Climate Policy

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Abstract

It has been argued that a depletable resource owner might optimally increase near-term supply in response to environmental policies promoting the development of alternative resources, which might render climate policy ineffective or even counterproductive. This paper empirically confirms this prediction using data on crude oil exports from OPEC to OECD countries between 2001-2010 in a gravity framework. It documents that oil exporters decrease prices and increase quantity of oil exports in response to increases in R&D intensity on renewable energy technologies in importer countries. We further show that (i) these findings are mainly driven by the exporters with higher dependence on oil revenues; (ii) the Armington elasticity of oil is about 2.4; and (iii) exports of coal, which is in abundant supply, are not significantly affected by the changes in R&D intensity of importer countries. Besides having important implications for the effectiveness and design of climate policy, these results underscore the role of dependence on oil revenues of the oil exporters and economic/political diversification incentives of the importer countries in the oil markets.

JEL-Code: F100, Q400, Q500.

Keywords: climate policy, oil trade, gravity equation, Green Paradox.

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1 Introduction

The sustainability of long-run development has been threatened by the extensive use of fossil fuels and associated greenhouse gas emissions, which continue to grow and increased to above 39 percent over the preindustrial level by the end of 2010 (IPCC, 2011). Under the business-as-usual scenario, climate-model projections reflect a significant increase in global mean temperature by the end of the century which poses great risks of abrupt and irreversible changes in human and natural systems (IPCC, 2014). Renewable energy, as a substitute for fossil fuels, has been considered as a key element in the transition to a sustainable economy and mitigating climate change. The global renewable energy investment has risen 600 percent from 2004 to 2011 and reached to 279.4 billion US dollars while global R&D spending on renewable energy increased 136 percent within the same period reaching 9.7 billion US dollars in 2011. Despite the increasing role of renewable energy in climate change policies to reduce fossil fuel consumption, a well-known result in the theoretical literature states that owners of a non-renewable resource may optimally increase short-term extraction in anticipation of declining demand in the future due to the development of alternative resources. This counteracting impact of promoting alternative energy sources has been an important theme in the debates on the design and effectiveness of climate policies.

In this paper, we investigate the impact of renewable energy development on the supply behavior of oil rich countries by first deriving a gravity equation for oil trade incorporating the effects of climate policy. Then, we test whether the changes in R&D intensity on renewable energy technologies in importer countries induce systematic changes in the supply behavior of the exporters using trade flows from OPEC to OECD countries between 2001 and 2010.[1] Our empirical analysis shows that oil exporters decrease prices and increase the quantity of oil exports in response to an increase in the intensity of R&D on renewable energy technologies in importer countries. The effects are statistically and economically significant, robust to various concerns and are not driven by the endogeneity of the R&D effort. These findings are in line with the pessimistic predictions in the literature and have important implications for the effectiveness and design of climate policies. Our results also reveal important characteristics of crude oil trade, which constitutes almost 10 percent of

[1] Throughout the paper we use exporter (importer) and OPEC (OECD) countries interchangeably.

global merchandise trade. In particular, we find that the Armington elasticity of crude oil is about 2.4, which implies that crude oil from different source countries is not treated as homogenous.

The growing need to mitigate the use of fossil fuels and associated carbon emissions go hand in hand with the accumulating experience on the difficulty in the implementation of optimal environmental policies. Existing policies might suffer from two issues, which attenuate or might even reverse the intended effects on carbon emissions. The *carbon leakage* on the spatial dimension might arise due to the lack of coordinated global action and imperfect regional coverage of existing treaties such as the Kyoto Protocol and it refers to the relocation of production and emissions from regulated to unregulated markets (see Copeland and Taylor (2005)). While the strength of carbon leakage has been a debated issue,[2] more recent studies document that it is sizable (e.g. Aichele and Felbermayr (2012)). Unfortunately, solving substantial coordination issues might still not be a remedy when the policies fail to take the incentives of the supply side into account. It is natural that a decline in the price of alternative energy technologies might depress current prices and increase consumption. Recently, Sinn (2008) has argued that a rapidly increasing carbon tax might create incentives for the resource owners to increase near-term extractions to avoid future declines in their profits. This intertemporal leakage, which is also known as the *green paradox*, has been argued to emerge in different settings by numerous studies (see Eichner and Pethig (2011); Hoel (2011); Gerlagh (2011); and Van der Ploeg and Withagen (2012) among others).

Despite the high academic interest and its frequent presence in policy discussions, the empirical evidence on the intertemporal leakage is scarce. To our knowledge, Di Maria, Lange, and Van der Werf (2013) is the only study testing the validity of the green paradox hypothesis. Using a unique dataset on coal deliveries to U.S. power plants, the authors estimate the changes in the price, quality and quantity of the coal supply between the announcement of the Acid Rain Programme in 1990 and its implementation in 1995.[3] Their

[2] The predictions mostly come from computable general equilibrium models, therefore vary in a considerable range due to the differences in modeling choices or parameter restrictions (cf. Bernstein, Montgomery, and Rutherford (1999); Babiker (2005); and Elliott, Foster, Kortum, Munson, Cervantes, and Weisbach (2010)).

[3] While scarcity of the resource is at the core of the literature on the green paradox, Smulders, Tsur, and Zemel (2012) show that it might arise even without scarcity due to implementation lags.

results indicate that coal prices significantly declined in the interim but coal consumption was largely unaffected. Unlike oil, which is the focus of our study, coal is an abundant resource as reflected in its very high reserve-to-production (R/P) ratio of 241 years for the U.S. and 118 years for the whole world in 2010.[4] This nuance creates important differences in the supply behavior of resource owners as we show in the empirical analysis.

Studying the impact of climate policies on the supply behavior of oil rich countries in an international setting has various advantages. First, we use data on oil exports from OPEC to OECD countries which constitute a sizable share of total world oil production. According to the figures of the U.S. Energy Information Administration (EIA), OPEC member countries produce about 40 percent of the world's crude oil and export about 60 percent of the total petroleum traded internationally. Second, the use of bilateral trade data enables us to make use of the spatial variation in environmental policies across different importer countries by controlling for exporter-year fixed effects. By doing so, we can control for exporter-time specific shocks such as discoveries of new reserves, changes in the regulatory environment or any type of macroeconomic shock within and outside the oil industry which can affect the export decisions of oil rich countries. Third, the panel dimension of our data allows us to include bilateral fixed effects in our estimations which can control for the effects of all relevant time-invariant factors specific to a particular trade linkage, e.g. bilateral long-term agreements, geographic, political and cultural proximity of trading parties, on the relationship between the climate policy and oil trade. Fourth, having data on different exporter countries, we are able to examine the role of various economic and institutional factors on the relationship between environmental R&D and oil supply. Therefore, it is possible to identify relevant dimensions which should be incorporated to the models investigating the effects of environmental policies on the supply behavior of the resource owners.

Our results reveal that OPEC countries lower the price and increase the quantity of oil exports when importer countries increase their intensity of R&D activities on renewable energy technologies. Furthermore, we show that the exporter countries which are more dependent on oil revenues are more likely to increase oil supply in response to the anticipation of future demand reduction. To check whether our results are driven by the reallocation of demand from coal to oil and whether the scarcity of the resource affects

[4]Source: BP Statistical Review of World Energy June 2011 through CESifo Dice.

the supply behavior of oil exporters, we replicate our analysis focusing on the coal trade. Despite the differences in the data and methodology, our results on coal trade are similar to the findings of Di Maria, Lange, and Van der Werf (2013) in the sense that following an increase in the intensity of R&D on renewables in importer countries, prices decline but the export quantity does not change significantly for coal. Our results are robust to the presence of alternative explanations, relaxation of various modeling assumptions used to derive the gravity equation and possible issues regarding our choices on the treatment of the data such as the effects of the outliers. Falsification tests show that once R&D on renewable energy technologies is replaced by R&D effort in other industries, the results disappear. We also show that these results are not driven by endogeneity issues by employing R&D on defence and aerospace industries as instruments for R&D on renewable energy technologies. Finally, we provide evidence that the effects of climate policy on the aggregate oil production of exporter countries are similar to the ones observed in the bilateral trade flows.

The rest of the paper is organized as follows. The next section describes the data used in the study. Section 3 derives a gravity equation incorporating the effects of climate policy for oil trade and explains the empirical methodology. Main results are presented and discussed in Section 4, followed by robustness tests and additional analysis in Section 5. Section 6 concludes.

2 Data

The dataset includes bilateral oil trade between OPEC and OECD countries, R&D spending on renewable technologies in OECD countries and the standard determinants of bilateral trade employed in the empirical gravity literature. Oil trade data are compiled from the United Nations Commodity Trade Statistics Database (UN-Comtrade). The commodity under consideration is "Crude Petroleum" (SITC Rev. Code is 3330). We use the data reported by the importer countries due to higher data quality, and subtract the re-exports which are exports of foreign goods imported previously. For the determinants of bilateral trade such as bilateral distance, common language, common border, or colonial history, we employ CEPII database (Mayer and Zignago, 2011). As a proxy for the anticipation of improvements in renewable energy technologies, we use the data for total

R&D spending on renewable energy technologies provided by the International Energy Agency (IEA). Furthermore, in order to investigate the effect of R&D subsidies, we also use the R&D spending on renewables only by the government. The GDP and population data, as well as the data for our other control variables are from the World Development Indicators provided by the World Bank. Table 1 presents the summary statistics for the main variables used in the empirical analysis.[5]

Table 1: Descriptive Statistics

	Units	Mean	Median	St. Dev.	Min.	Max.	Obs.
Trade quantity	Tons(mln)	56.476	14.599	121.245	0.000	865.250	1285
Trade value	US$(bln)	21.189	4.917	50.907	0.000	553.618	1292
GDP exp.	US$(bln)	1.438	1.122	1.195	0.047	5.396	1257
GDP imp.	US$(bln)	23.174	9.518	34.822	0.533	147.203	1293
Oil rev. exp.	US$(bln)	0.479	0.299	0.520	0.019	3.060	1257
Distance	km.	6346.303	5063.601	3981.868	697.690	17901.582	1293
R&D spending	US$(mln)	5380.649	46.896	17509.382	0.000	134826.000	1292
Government R&D	US$(mln)	4776.860	41.100	15269.621	0.000	116800.438	1292

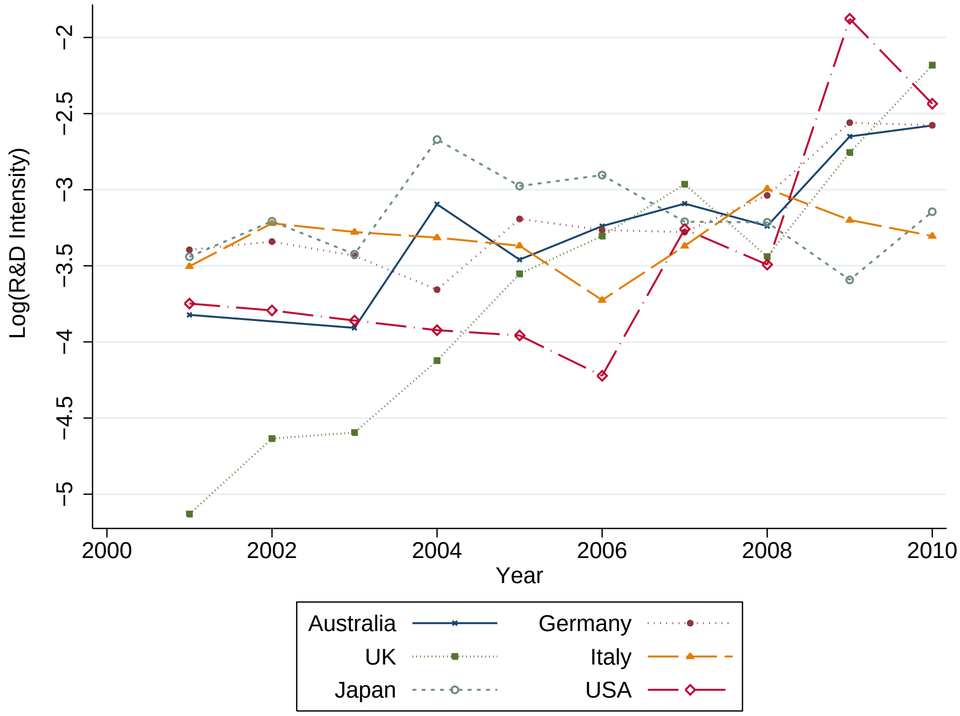
Note: Descriptive statistics are for the period 2001 - 2010. In our sample, importers are OECD countries and exporters are OPEC countries.

In this paper, we mainly investigate the effects of R&D intensity of oil importing countries in renewable energy technologies on oil trade. We define R&D intensity as the ratio of R&D spending on renewable energy technologies to GDP. Since, R&D spending does not directly translate into productivity gains due to the uncertainties inherent in the R&D process and the sluggish diffusion of new technologies into the production practices, it is unlikely to trigger immediate substitution possibilities on the demand side. Instead, we expect that any immediate effect of R&D spending should be due to its anticipated effect on future oil demand, which might be consistent with the results in the theoretical literature that in response to the anticipation of future advances in alternative sources, resource owners might optimally increase near term oil supply.

Figure 1 presents the evolution of R&D intensity on renewable energy technologies for Australia, Germany, Italy, Japan, United Kingdom and the United States in the sample period. It is seen that while there is a general upward trend, the heterogeneity across countries is clearly visible and R&D intensity on renewables exhibits sizable variation across countries and time, which we exploit in the empirical analysis.

[5]A detailed description of the data sources and variable descriptions is given in the data appendix.

Figure 1: R&D Intensity on Renewable Energy Technologies



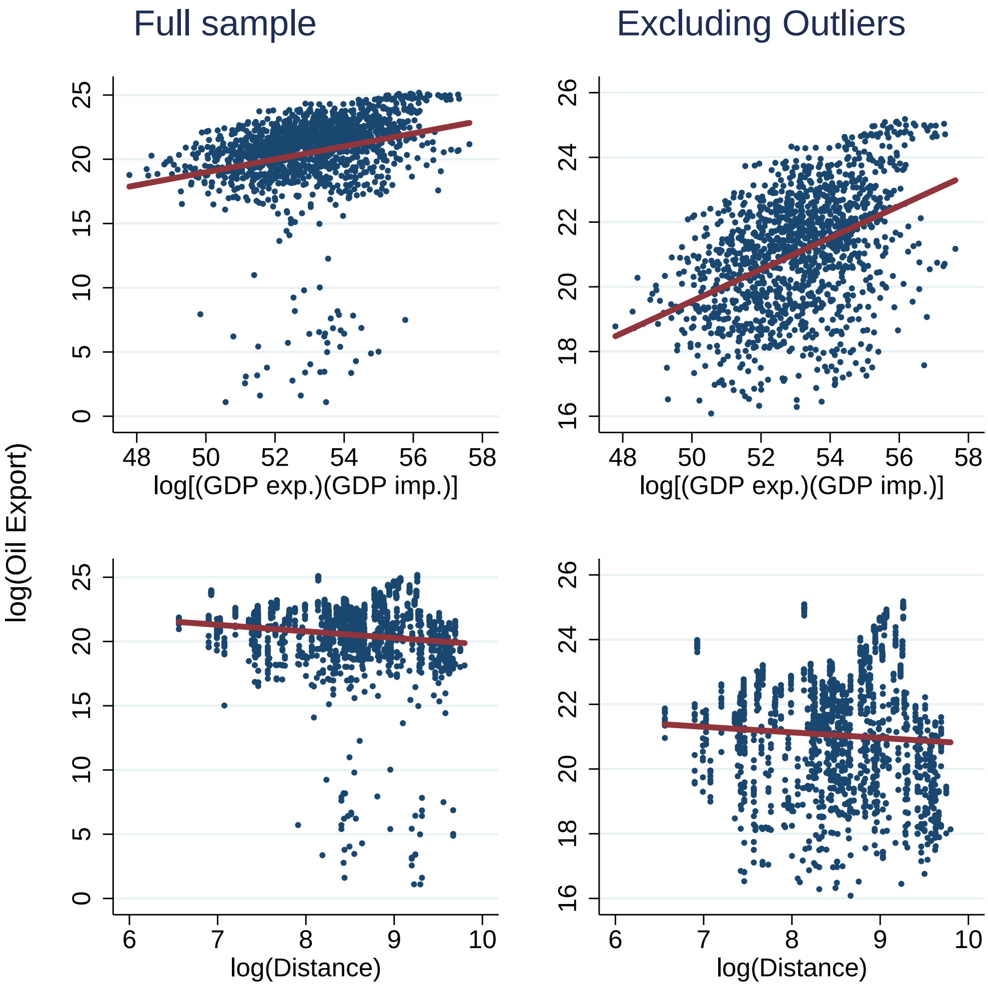
In Table 1 and in our baseline regressions, we exclude observations with missing trade values which are generally treated as zero trade in the cross-sectional analysis in the literature. Therefore the minimum values of zeros for the trade variables reflect the rounding of very small values. In our preferred specification, we control for country pair fixed effects, hence the possible selection issue due to the country pairs which do not trade at all in the sample period are controlled for. A substantial part of the remaining zeros are likely to be due to missing observations, and low or irregular frequency of delivery.

3 The Gravity of Oil Trade

3.1 A First Pass

Inspired by the Newton's law of gravitation, Tinbergen (1962) introduced the gravity model of bilateral trade where the trade flow is positively related to the economic size of the partner countries and inversely related to the distance between pairs. The gravity model has been the workhorse model in the empirical international trade literature in

Figure 2: Gravity of Oil Trade



order to analyze the effects of trade related policies, and it reveals one of the strongest correlation in the empirical economics (Leamer and Levinsohn, 1995).

Figure 2 illustrates the fundamental components of the gravity model for oil trade. The left panel uses full sample, while the right panel excludes the low value observations. In the upper panel we see a clear positive correlation between the oil trade flow and interacted economic size of the trading countries. The lower panel illustrates the negative correlation between trade flow and distance. These correlations seem to be not affected by the inclusion of the observations with low trade values. We provide additional tests addressing the effects of outliers on the parameter estimates in Section 5.3.1.

More formally, Table 2 presents a series of gravity regressions for oil trade.[6] The first

[6]While the gravity model is traditionally estimated using cross-sectional data using extensive control

Table 2: Gravity of Oil Trade

	Dependent variable: Oil exports ($ln(Q_{ijt})$)					
	(1)	(2)	(3)	(4)	(5)	(6)
GDP exp.	0.625***	1.040**	0.967**	0.718**	0.757**	
	(0.109)	(0.482)	(0.467)	(0.330)	(0.377)	
GDP imp.	0.843***	0.884	0.725	0.495		0.501
	(0.055)	(0.670)	(0.612)	(0.407)		(0.600)
Distance	-0.791***		-2.510***			
	(0.105)		(0.246)			
CEPII pair-controls	Yes	No	Yes	No	No	No
Exporter effects	No	Yes	Yes	Yes	Yes	Yes
Importer effects	No	Yes	Yes	Yes	Yes	Yes
Time effects	Yes	Yes	Yes	Yes	Yes	Yes
Pair effects	No	No	No	Yes	Yes	Yes
Exporter time eff.	No	No	No	No	No	Yes
Importer time eff.	No	No	No	No	Yes	No
Adjusted R^2	0.14	0.38	0.43	0.79	0.82	0.79
AIC	6580.8	6194.4	6081.8	4516.4	4345.6	4745.1
BIC	6673.9	6442.6	6361.1	4578.5	5049.1	5338.9
Observations	1303	1303	1303	1303	1303	1351

This table shows the effects of fundamental factors in a gravity model on oil exports. All variables are in logarithms. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

regression is comparable to the general approach of using cross-sectional data by only controlling for time dummies and a set of controls which are generally employed in the literature. The results are in line with the expectation that economic size is positively and distance is negatively correlated with trade. The following regressions include controls for different combinations of exporter fixed effects, importer fixed effects, common time effects, pair specific effects, exporter-time effects, and importer-time effects. The general finding is that GDP of the exporter and distance between trading countries are significantly correlated with trade, while importer GDP is no longer significant with these additional controls. As a whole, these results indicate that the gravity model seems to be a convenient framework in order to analyze the effects of various policies and factors on the oil trade.

3.2 Gravity and the Climate Policy

A substantial literature has developed various theoretical explanations for the gravity model.[7] However, our analysis deviates from the standard practices in the literature in two ways. First, we focus on a particular good rather than the total or average bilateral trade between country pairs. Second, we are interested in the quantity of oil exports rather than its value since the ultimate aim is to contribute to the understanding of the relationship between climate policy and environmental degradation. Hence, to guide our empirical analysis, evaluate the possible effects of these two deviations from standard practices, and incorporate the impact of R&D intensity on the supply decision of oil exporters, we present a simple derivation of our estimating equation for the case of oil trade.

The world economy consists of I oil exporting countries and J importer countries. The aggregate product of country j is produced out of energy (Z) and a composite input (M)

variables, the more recent literature focuses on the proper specification of the gravity model with panel estimation techniques. Mátyás (1997) suggests to use exporter, importer, and time dummies which are referred as the main effects. A more common approach is to control for fixed effects of the trading-pairs as suggested by Hummels and Levinsohn (1995). Indeed, Egger and Pfaffermayr (2003) show that omission of the pair effects might lead to biased estimates, and suggest employing both time and pair effects. As a further step, Baltagi, Egger, and Pfaffermayr (2003) point out the importance of controlling for the importer and exporter specific time effects.

[7]See among others Anderson (1979); Bergstrand (1985); Deardorff (1998); Eaton and Kortum (2002); Anderson and Van Wincoop (2003); Baldwin and Taglioni (2006). For recent surveys, see Anderson (2010); De Benedictis and Taglioni (2011).

according to a Cobb-Douglas production function:

$$Y_{jt} = Z_{jt}^{\theta} M_{jt}^{1-\theta}, \ \ 0 < \theta < 1 \tag{1}$$

where θ is the expenditure share of energy in total GDP, j denotes the importer country and t represents time. Energy, on the other hand, can be produced out of various resources including crude oil. To focus on the changes in oil consumption, we define a composite resource (X) being an imperfect substitute for oil (Q) in the energy production function which takes the standard CES form:

$$Z_{jt} = \left(\alpha_j^{\frac{1}{\sigma}} X_{jt}^{\frac{\sigma-1}{\sigma}} + \gamma_j^{\frac{1}{\sigma}} Q_{jt}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \quad \sigma > 0 \tag{2}$$

where σ is the elasticity of substitution between crude oil and the composite resource, α_j and γ_j are non-negative weights which sum up to 1. Hence, the expenditure on oil in importer country j is given by:

$$E_{jt}^{o} \equiv P_{jt}^{o} Q_{jt} = \gamma_j \left(\frac{P_{jt}^{o}}{P_{jt}^{z}} \right)^{1-\sigma} E_{jt}^{z} \tag{3}$$

where P_{jt}^{o} is the price of the oil basket, P_{jt}^{z} is the energy price and $E_{jt}^{z} = P_{jt}^{z} Z_{jt}$ is the level of energy expenditure in importer country j.

Crude oil is generally considered to be a homogenous good whose price differs across regions only due to the variation in oil taxes or time-invariant factors such as transportation costs or quality. In a unified global oil market, what matters for the oil price determination would be only the aggregate demand and supply (Nordhaus, 2009). However, there are various reasons why the importers may choose to diversify the oil supply and behave “as if” crude oil from different source countries are differentiated. Probably the most important and recently obvious of them is the international politics. In a recent article, Mityakov, Tang, and Tsui (2013) show that U.S. oil imports are significantly affected by international politics and American firms diversify their oil imports significantly away from political opponents of the United States. Another prominent explanation for the observed behavior of oil importers is related to the short and medium-run technological constraints which introduce imperfect substitution among oil products across different sources as in Salant and Gaudet (2014). Given these rationales and the sizable variation in oil prices which can not be explained solely by transportation costs or time-invariant exporter or importer characteristics, we employ the usual “Armington” assumption that goods are differentiated with respect to the origin which yields the following CES demand schedule:

$$V_{ijt} \equiv p_{ijt}Q_{ijt} = \left(\frac{p_{ijt}}{P^o_{jt}}\right)^{1-\varepsilon} E^o_{jt} \tag{4}$$

where V_{ijt} is the value of oil exports, $\varepsilon > 1$ is the Armington elasticity, p_{ijt} is the c.i.f (cost, insurance, and fright inclusive) price of crude oil and the oil price index in importer j is given by:

$$P^o_{jt} = \left(\sum_{i\in I} (p_{ijt})^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}. \tag{5}$$

Price differences across importer countries are partly explained by bilateral frictions (τ_{ij}) which constitute the time-invariant component such as transportation costs. Furthermore, we introduce a new component determined by the importer specific R&D intensity (i.e. share of corresponding spending in the nominal GDP of the importer country) on green alternatives (s_{jt}) which possibly changes over time. We assume that current prices are influenced by the anticipation of future demand reductions proxied by the R&D intensity on renewable energy technologies of the importer country in the previous year to be in line with the lag structure in the empirical analysis.[8] Briefly

$$p_{ijt} = p_{it}\tau_{ij}s^{\beta}_{jt-1}, \tag{6}$$

where β is the elasticity of oil price with respect to R&D intensity in the importer country, which we aim to estimate in our empirical analysis. A negative estimate for β, i.e. a negative coefficient on logged R&D intensity in a pricing equation, implies that exporters decrease oil prices in response to the policies promoting alternative resources in the importer countries.

Using (1), (3) and (6) in the demand equation (4) and noting that total oil revenues of exporter i is $Y^o_{it} = \sum_{j\in J} V_{ijt}/\tau_{ij}$, we find the value and quantity of exports from source i to country j:

$$V_{ijt} = \gamma_j\theta \left(\frac{\tau_{ij}s^{\beta}_{jt-1}}{P^o_{jt}}\right)^{1-\varepsilon} \frac{Y^o_{it}}{\Omega_{it}} \left(\frac{P^o_{jt}}{P^z_{jt}}\right)^{1-\sigma} E_{jt}, \tag{7}$$

$$Q_{ijt} = \gamma_j\theta \left(\tau_{ij}s^{\beta}_{jt-1}\right)^{-\varepsilon} \left(\frac{Y^o_{it}}{\Omega_{it}}\right)^{\frac{\varepsilon}{\varepsilon-1}} \left(\frac{P^o_{jt}}{P^z_{jt}}\right)^{1-\sigma} \frac{E_{jt}}{(P^o_{jt})^{1-\varepsilon}}, \tag{8}$$

[8] All the results presented in this paper are valid when the level of R&D spending is used instead of its intensity. We report the corresponding baseline results in the Appendix and the additional analysis is available upon request from the authors.

where E_{jt} is the nominal GDP of importer j and Ω_{it}, which can be considered as the market potential of exporter i, is given by:

$$\Omega_{it} = \sum_{j \in J_i} \left(\tau_{ij}^{-\varepsilon} s_{jt-1}^{\beta(1-\varepsilon)} \right) \frac{E_{jt}^o}{\left(P_{jt}^o\right)^{1-\varepsilon}}. \tag{9}$$

Taking the logarithm of both sides of (8), we obtain the logged quantity of oil exports:

$$ln(Q_{ijt}) = -\varepsilon ln(\tau_{ij}) - \sigma\beta ln(s_{jt-1}) + \frac{\varepsilon}{\varepsilon - 1} ln(Y_{it}^o) - \frac{\varepsilon}{\varepsilon - 1} ln(\Omega_{it}) + ln(E_{jt}) + u_j + u_{ijt} \tag{10}$$

where $u_j = ln\left(\gamma_j\right) + ln\left(\theta\right)$ and $u_{ijt} = \left(\frac{\varepsilon-\sigma}{1-\varepsilon}\right) ln \left(\sum_{i\in I} \left(p_{it}\tau_{ij}\right)^{1-\varepsilon}\right) + (\sigma - 1)\, ln(P_{jt}^z)$.

Equation (10) constitutes the main relationship which we estimate in the empirical analysis and presents the relevant factors which might bias the estimates of R&D intensity if omitted. In our analysis, nominal GDP of the importer country (E_{jt}) is directly controlled for and the weights of the crude oil in energy (γ_j) together with the share of energy expenditure in total GDP (θ) are captured by the importer fixed effects. We control for the time-invariant determinants of oil prices (τ_{ij}) by the proxies available in the literature such as population-weighted distance between trading partners, common language or border or by controlling for bilateral fixed effects in our preferred specification. For Y_{it}^o, we control for total oil revenues of exporter countries. Finally, the time-varying market potential (Ω_{it}) is captured by exporter specific time fixed effects.

An important point to note is that we do not include importer specific time fixed effects in the regressions to be able to estimate the impact of R&D intensity on oil supply. Hence, the energy price index in the importer country (P_{jt}^z) appears in the error term and might introduce a bias which is proportional to the share of oil in energy expenditures. We control for this potential bias by using the energy price index provided by IEA in Appendix C. We show that energy price index is insignificant, and none of our results are affected when the energy price index is included in the estimations. There might be an additional source of bias if p_{it} is also affected by the climate policy of an importer country, i.e. when there is spatial leakage. We address these issues in Section 5.2.2, where we employ instrumental variables estimations and show that the IV estimate of σ is similar to the baseline value hence these potential biases are negligible.

Next, we assess the impact of R&D intensity on oil prices. Since oil prices are observable in the case of oil trade, possibly with sizable measurement errors, it is possible to separately identify the elasticities of oil price and trade with respect to the R&D intensity on renewable energy technologies. Taking the logarithm of both sides of (6) and eliminating p_{it}, we obtain

$$ln(p_{ijt}) = \frac{1}{1-\varepsilon} ln(Y_{it}^{o}) - \frac{1}{1-\varepsilon} ln(\Omega_{it}) + ln(\tau_{ij}) + \beta ln(s_{jt-1}). \quad (11)$$

Expression (11) guides our price regressions and shows that an OLS estimation where logged oil prices are regressed on logged R&D intensity controlling for exporter specific time fixed effects for Y_{it}^{o} Ω_{it} and bilateral fixed effects for τ_{ij} yields consistent estimates for β.

4 Results

This section presents the results from estimation of different versions of equations (10) and (11) where we investigate whether R&D intensity on renewable energy technologies by importer countries has a systematic effect on the quantity and price of oil exports.

4.1 Oil Exports

Table 3 presents our baseline regressions which corresponds to equation (10). In the first three columns, the main variable of interest is the importer's R&D on renewable energy. Regression (1) only controls for the main effects and a series of control variables from the CEPII dataset to control for time-invariant trade frictions. In regression (2) we use pair specific dummies in order to control for time-invariant factors specific to each trade linkage. In column (3), we further include exporter specific time effects which capture exporter-time specific shocks such as discoveries of new reserves, changes in the regulatory environment or any type of macroeconomic shock within and outside the oil industry which can affect the export decisions of the exporter countries. In all regressions, one year lagged R&D intensity has a positive and significant effect on the oil exports. The estimated elasticity ($\sigma\beta$) is sizable by being above 0.27 in all regressions. In our preferred specification including the exporter-time fixed effects, which also yields the most conservative estimate, the elasticity of quantity of oil exports to R&D intensity on renewable energy technologies is 0.273. These results are in line with the green paradox hypothesis that producers might bring the oil extraction forward in response to the anticipation of a decrease in the costs of producing renewable alternative energy sources.

Table 3: R&D on Renewable Energy and Oil Exports

Dependent variable: Oil exports ($ln(Q_{ijt})$)						
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.346***	0.303**	0.273**			
	(0.132)	(0.127)	(0.114)			
Government R&D $ln(s^g_{jt-1})$				0.371**	0.363**	0.335**
				(0.166)	(0.160)	(0.142)
Oil revenues $ln(Y^o_{it})$	1.532**	1.180*		1.528**	1.182*	
	(0.655)	(0.606)		(0.654)	(0.604)	
GDP imp. $ln(GDP_{jt})$	0.649	0.802*	0.899	0.681	0.841*	0.929
	(0.491)	(0.482)	(0.653)	(0.497)	(0.489)	(0.656)
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.39	0.77	0.77	0.39	0.77	0.77
AIC	4933.8	3625.9	3812.5	4933.6	3623.0	3809.4
BIC	5135.4	3686.4	4335.7	5135.2	3683.5	4332.5
Observations	1143	1143	1187	1143	1143	1187

This table shows the effects of the R&D intensity on renewable energy technologies in importer countries on the quantity of oil exports, see equation (10). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

The regressions from (4) to (6) replicate the previous estimations by using government R&D spending on renewable energy instead of total spending. The findings are in line with the results in the first three columns. An interesting point is that the estimated effect of the government effort is larger compared to the total spending which also includes the spending by the private sector. This result is intuitive in the sense that government spending may reflect a higher commitment to the goal of reducing the costs of renewable energy production and therefore might be a stronger signal for the producer countries.

4.2 Oil Prices

Next, we investigate the effect of the R&D spending on oil prices and present estimations of several versions of equation (11) in Table (4). In these estimations, we use the unit

Table 4: R&D on Renewable Energy and Oil Prices

	Dependent variable: Oil price ($ln(p_{ijt})$)					
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	-0.082***	-0.093***	-0.094***			
	(0.029)	(0.032)	(0.034)			
Government R&D $ln(s^g_{jt-1})$				-0.119***	-0.132***	-0.137***
				(0.041)	(0.046)	(0.049)
Oil revenues $ln(Y^o_{it})$	-0.019	-0.036		-0.019	-0.037	
	(0.103)	(0.115)		(0.102)	(0.114)	
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.47	0.45	0.38	0.48	0.45	0.38
AIC	1458.7	1320.8	1629.1	1454.1	1315.6	1623.4
BIC	1649.5	1376.1	2140.1	1644.9	1370.8	2134.4
Observations	1121	1121	1164	1121	1121	1164

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the oil price of exporters countries, see equation (11). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

value of the trade flow which is equal to the reported value of trade flow divided by traded quantity. In contrast to the common idea of a unique worldwide oil price, the unit values of oil trade flow exhibit considerable variation across space and over time.[9] The estimated elasticity of oil price with respect to R&D intensity is negative, statistically significant at 1 percent and economically important. Using the estimate from our preferred specification, column 3 of Table 4, together with the findings in the quantity regression, we find that $\beta = 0.094$ and the implied elasticity of substitution between crude oil and other energy resources is 2.90, i.e. $\sigma = 2.90$. In line with the previous results, the estimated effect of the government R&D spending is larger compared to the total spending. Therefore, these results might reflect the mechanism that oil exporters decrease the prices and increase oil supply in response to the anticipation of future demand reductions reflected in the R&D effort on renewable alternatives in the importer countries, consistent with the green paradox hypothesis.

[9]While it is plausible that some of the variation stems from measurement error, we should note that the effects of measurement errors or practices specific to exporter-year pairs and bilateral trade linkages are controlled for when the corresponding fixed effects are introduced.

5 Robustness Tests and Additional Analysis

In this section, we assess the sensitivity of the baseline results in three dimensions and provide estimates of the Armington elasticity of crude oil. First, we test the robustness of our results to the presence of alternative explanations and also conduct falsification tests using R&D effort which are not directly related to the energy markets. Second, we relax some of the modeling assumptions used to derive the gravity equation and assess the sensitivity of the findings to the violation of these assumptions. Third, we consider possible issues regarding the econometric choices and issues in the main analysis such as the effects of outliers on the estimates or different estimation techniques. Fourth, we provide two estimates of the Armington elasticity of crude oil by: (i) using data on oil prices and (ii) estimating the quantity equation without pair fixed effects and controlling for importer-year specific effects. Finally, we provide suggestive evidence on the effects of R&D decisions of importer countries on the aggregate oil production of the oil exporters.

5.1 Alternative Explanations

In this part, we investigate the robustness of the baseline results to the possible effects of two alternative explanations: demand relocation from coal to oil and comovement between R&D spending on renewables and fuel taxes. Then we present falsification tests using R&D effort on activities which are not directly related to the energy markets instead of renewable energy technologies to show that the baseline findings are indeed driven by the efforts to promote alternative energy sources.

5.1.1 Coal Trade

An alternative explanation for our baseline findings might be related to the effects of R&D activities on the demand for other energy resources. Namely, the primary effect of an increase in the R&D spending on renewable energy technologies might be to depress demand for coal and trigger substitution of coal with oil. Such a change in the composition of fossil fuel demand can plausibly rationalize the positive effect of R&D intensity on the quantity of oil exports. Although it is difficult to explain declining prices with the relocation of demand towards oil, we explicitly assess the plausibility of this explanation by investigating if there are systematic changes in coal demand in the importer countries in response to changes in the intensity of R&D on renewable technologies. This additional test also enables us to assess the empirical importance of a fundamental element in the theoretical explanations for the intertemporal leakage, namely the scarcity of the nonrenewable resource. Reflected in its higher reserves-to-production ratio, coal is a more abundant natural resource compared to oil. Since coal exports are not concentrated in a handful of countries as in oil trade and OPEC countries, in particular, have an almost negligible share in coal exports, we consider the trade flows from all source countries to the OECD members.

The results, presented in Tables 5 and 6, indicate that while coal prices decrease due to higher R&D intensity on renewables, the traded quantities do not change significantly which are both consistent with the findings of Di Maria, Lange, and Van der Werf (2013). First, these results support the idea that scarcity of the nonrenewable resource might have a crucial role in the occurrence of intertemporal leakage. Second, it shows that our results are not driven by demand side effects, in particular by the substitution between oil and coal that might be triggered by the changes in R&D intensity on renewable energy technologies in importer countries.

5.1.2 Fuel Taxes

When the aim is to estimate the impact of changes in climate policy in importer countries such as R&D spending on renewables, it is not possible to control for the time-varying importer fixed effects. This constraint might raise the concern that omission of other policy tools yields biased estimates since it is plausible that various policy changes towards the same aim are executed simultaneously and therefore correlated. Among these, end-use fuel taxes might be a particular concern which might influence the quantity and price of oil exports and exhibit significant co-movement with the R&D spending on renewables even after controlling for time-invariant importer specific effects. The direction of the bias due to the omission of fuel taxes, however, depends on the relationship between these taxes and the dependent variable and also whether R&D and fuel taxes are substitutes or complements from the perspective of governments. To investigate the effects of the changes in taxes on our baseline estimates, we employ fuel tax data provided by the International Energy Agency (IEA), namely diesel taxes for industry sector, and explicitly include them

Table 5: R&D on Renewable Energy and Coal Exports

	Dependent variable: Coal exports					
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.091	0.074	0.075			
	(0.072)	(0.070)	(0.075)			
Government R&D $ln(s^g_{jt-1})$				0.116	0.109	0.108
				(0.074)	(0.073)	(0.078)
Coal revenues $ln(Y^c_{it})$	-0.008	-0.004		-0.008	-0.004	
	(0.009)	(0.007)		(0.009)	(0.007)	
GDP imp. $ln(GDP_{jt})$	1.015**	0.906**	0.590	1.003**	0.895**	0.579
	(0.422)	(0.429)	(0.442)	(0.421)	(0.428)	(0.442)
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.60	0.84	0.86	0.60	0.84	0.86
AIC	24995.0	19183.0	18920.4	24994.1	19180.0	18916.9
BIC	25310.0	19261.7	21325.1	25309.1	19258.7	21321.7
Observations	5227	5228	5273	5227	5228	5273

This table shows the effects of R&D intensity on renewable energy technologies importer countries on the quantity of coal exports. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: R&D on Renewable Energy and Coal Prices

	Dependent variable: Coal price					
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	-0.060**	-0.043*	-0.049**			
	(0.026)	(0.022)	(0.025)			
Government R&D $ln(s^g_{jt-1})$				-0.070**	-0.053**	-0.057**
				(0.027)	(0.023)	(0.026)
Coal revenues $ln(Y^c_{it})$	0.011***	0.009***		0.011***	0.009***	
	(0.003)	(0.003)		(0.003)	(0.003)	
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.36	0.58	0.61	0.36	0.58	0.61
AIC	13287.8	10128.2	9937.5	13285.7	10125.8	9935.1
BIC	13596.2	10200.4	12335.7	13594.1	10197.9	12333.3
Observations	5227	5228	5273	5227	5228	5273

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the quantity of coal prices. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

in our estimating equations (10) and (11). The results for the quantity and price of oil exports are presented in Tables 7 and 8, respectively. The results confirm our baseline findings that R&D intensity on renewables decreases oil prices and increases the quantity of oil exports and the coefficient estimates are close to the baseline estimations.

Given the relevance of fuel taxes as a climate policy tool and the interest in the literature on relationship between various forms taxes and resource extraction, it is worthwhile to elaborate on the estimated impact of fuel taxes on oil trade. Our findings show that end-use fuel taxes do not have a significant impact on the price of imported oil in all specifications as seen in Table 8 whereas they depress oil consumption unless we control for exporter-specific time fixed effects. Furthermore, the estimated impact of fuel taxes decreases once pair fixed effects are controlled for in the quantity regressions. This observation shows that average (over time) fuel taxes constitutes a non-negligible share of the time-invariant bilateral frictions between trading partners and R&D on renewables is negatively correlated with the unobserved bilateral trade frictions, a relationship which is already apparent in the main results where the coefficient estimate of R&D intensity decreases when we control

Table 7: Oil Trade: Controlling for Fuel Taxes

Dependent variable: Oil exports ($ln(Q_{ijt})$)						
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.276**	0.312**	0.299**			
	(0.139)	(0.144)	(0.129)			
Government R&D $ln(s^g_{jt-1})$				0.299	0.385**	0.367**
				(0.181)	(0.185)	(0.160)
Fuel tax $ln(\tau^f_{jt-1})$	-1.701**	-1.159*	-0.705	-1.748**	-1.181*	-0.731
	(0.807)	(0.632)	(0.735)	(0.787)	(0.622)	(0.717)
Oil revenues $ln(Y^o_{it})$	1.584**	1.184*		1.580**	1.182*	
	(0.701)	(0.631)		(0.699)	(0.626)	
GDP imp. $ln(GDP_{jt})$	2.282**	2.058**	1.967*	2.345**	2.120**	2.016**
	(1.015)	(0.869)	(1.007)	(1.010)	(0.866)	(0.998)
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.39	0.77	0.77	0.39	0.77	0.77
AIC	4519.8	3363.8	3523.0	4519.7	3360.7	3519.7
BIC	4712.6	3428.0	3996.2	4712.4	3424.9	3993.0
Observations	1035	1035	1077	1035	1035	1077

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the quantity of oil exports controlling for fuel taxes in the importer countries ($ln(\tau^f_{jt-1})$), see equation (10). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Oil Prices: Controlling for Fuel Taxes

	Dependent variable: Oil price ($ln(p_{ijt})$)					
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	-0.093***	-0.102***	-0.104***			
	(0.034)	(0.037)	(0.037)			
Government R&D $ln(s^g_{jt-1})$				-0.136***	-0.146***	-0.151***
				(0.047)	(0.052)	(0.054)
Fuel tax $ln(\tau^f_{jt-1})$	0.088	0.100	0.064	0.070	0.082	0.049
	(0.077)	(0.088)	(0.154)	(0.075)	(0.086)	(0.150)
Oil revenues $ln(Y^o_{it})$	-0.027	-0.045		-0.027	-0.044	
	(0.109)	(0.120)		(0.108)	(0.119)	
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.46	0.43	0.36	0.46	0.44	0.36
AIC	1431.5	1304.2	1589.9	1426.7	1298.8	1584.1
BIC	1619.3	1363.5	2058.2	1614.5	1358.1	2052.4
Observations	1035	1035	1077	1035	1035	1077

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the quantity of oil prices controlling for fuel taxes in the importer countries ($ln(\tau^f_{jt-1})$), see equation (11). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

for the pair fixed effects in Table 3.

5.1.3 Falsification Tests

A natural concern might be that the results, albeit being quite robust, are not driven specifically by the climate policies aiming to reduce demand for fossil fuels but by other mechanisms which might be related to R&D effort in general and assumed away in this paper. In such a case, omission of such factors might lead to biased inference to the extent that various dimensions of R&D activities are correlated with the R&D on renewable energy technologies. One way to address this issue is to conduct falsification tests by using other measures of R&D intensity which are not directly related to the energy markets and check whether a similar relationship appears also for those "irrelevant" variables.

Table 9: Falsification Tests: Total R&D and Oil Exports

Dependent variable: Oil exports ($ln(Q_{ijt})$)						
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.069	-0.848*	-0.691			
	(0.553)	(0.449)	(0.440)			
Government R&D $ln(s^g_{jt-1})$				-0.362	-0.385	-0.265
				(0.377)	(0.315)	(0.315)
Oil revenues $ln(Y^o_{it})$	1.525**	1.014*		1.593**	1.056*	
	(0.656)	(0.580)		(0.663)	(0.592)	
GDP imp. $ln(GDP_{jt})$	0.550	1.272*	1.346	0.926	1.109	1.165
	(0.768)	(0.686)	(0.878)	(0.757)	(0.684)	(0.865)
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.39	0.79	0.79	0.39	0.79	0.79
AIC	4914.9	3494.8	3683.6	4836.2	3444.0	3627.0
BIC	5116.4	3555.3	4206.1	5036.9	3504.2	4147.4
Observations	1137	1137	1180	1116	1116	1156

This table replicates the baseline quantity estimations by using R&D on all activities instead of on renewable energy technologies and reports the results of this falsification test. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Accordingly, we replicate the baseline quantity and price estimations by replacing the

Table 10: Falsification Tests: Total R&D and Oil Prices

	Dependent variable: Oil price ($ln(p_{ijt})$)					
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.100	0.125*	0.122			
	(0.070)	(0.076)	(0.080)			
Government R&D $ln(s^g_{jt-1})$				0.090*	0.096*	0.059
				(0.047)	(0.050)	(0.056)
Oil revenues $ln(Y^o_{it})$	-0.040	-0.049		-0.042	-0.049	
	(0.106)	(0.118)		(0.107)	(0.121)	
Main effects	Yes	Yes	Yes	Yes	Yes	Yes
CEPII pair-controls	Yes	No	Yes	Yes	No	Yes
Pair effects	No	Yes	Yes	No	Yes	Yes
Exporter time eff.	No	No	Yes	No	No	Yes
Adjusted R^2	0.46	0.43	0.36	0.46	0.42	0.35
AIC	1455.4	1319.1	1632.7	1447.0	1312.1	1620.4
BIC	1649.9	1374.0	2145.0	1640.8	1366.7	2130.9
Observations	1080	1080	1122	1063	1063	1102

This table replicates the baseline price estimations by using R&D on all activities instead of on renewable energy technologies and reports the results of this falsification test. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

R&D on renewable energy technologies with the R&D intensity on different aspects of the economy which are not specifically related to the energy markets. Similar to the baseline estimations, we also construct corresponding variables using only governmental effort. For the sake of brevity, we report the results using total R&D effort in Tables 9 and 10.[10] The results presented in Tables 9 and 10 show that total R&D effort does not have a systematic effect on the quantity of imports or oil prices. Hence, it is indeed the actions promoting the development of alternative energy sources which drive the robust relationships documented in the baseline analysis.

5.2 Modeling Assumptions

In this part, we assess the possible impacts of relaxing some of the modeling assumptions used to derive the estimating gravity and price equations, (10) and (11), and test the sensitivity of the main results. In the previous section, we already take a step towards this direction by allowing for demand leakages between oil and coal markets. In the following, we consider also the substitution between domestic use and exports. In doing so, we investigate the plausibility of the implicit assumption that the effect of R&D on renewable energy on the supply behaviour does not exhibit any heterogeneity across exporter countries. Another assumption relates to the exogeneity of R&D spending on renewables, which we address by conducting instrumental variables estimations where R&D spending on defence and aerospace industries which are not directly related to the energy markets are used as instruments for R&D on renewable energy technologies.

5.2.1 Dependency on Oil Revenues

In the existing literature it has been the common practice to investigate the supply behavior of scarce resource owners in a partial equilibrium setting. While being natural for many cases, in our setting this modeling choice assumes away an important trade-off faced by the resource owners who might optimally divert oil supply to domestic use rather than trading them in international markets. In particular, a relative decline in the export price

[10] Various estimations using different types of R&D activity, e.g. R&D on pharmaceutical and defense industries, yield similar results. The data employed in the falsification tests use gross domestic expenditure on R&D in various sectors divided by the GDP of the importer country. The data are taken from "the main science and technology indicators database" of OECD.

of crude oil relative to the marginal revenue productivity of energy in the domestic economy is expected to increase the share of domestic consumption in the total oil extraction. If relevant, this mechanism makes it harder to find evidence in favor of the green paradox in our setting, especially for countries having better substitution possibilities. Hence, we might expect the observed effect to be stronger for countries with a larger share of resource sector. Similarly, the exporters relying more on oil revenues will be more vulnerable to changes in oil demand in their trading partners, which might make it possible to find a larger effect of demand reduction policies on oil exports. In both cases, it is predicted that oil exports of the countries with a higher share of oil revenues in the overall economy are likely to be more responsive to the changes in demand conditions in importing countries.

Table 11: The Role of Oil Dependency: Above Median

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.372**		-0.092*	
	(0.180)		(0.047)	
Government R&D $ln(s^g_{jt-1})$		0.463**		-0.130*
		(0.224)		(0.068)
GDP imp. $ln(GDP_{jt})$	1.392	1.427		
	(1.064)	(1.069)		
Adjusted R^2	0.74	0.74	0.32	0.32
AIC	1933.6	1930.5	910.2	908.1
BIC	2156.0	2152.9	1128.2	1126.1
Observations	578	578	578	578

This table shows the effect of R&D intensity on renewable energy technologies in importer countries on the exported quantity and price of oil for the exporter countries with an above median dependency on oil revenues. The dependency on oil revenues is measured by the oil-rents-to-GDP ratio in 2000. All variables are in logarithms. Robust standard errors clustered at the bilateral level in parenthesis. Controls include bilateral and exporter-time fixed effects. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

To investigate this possibility, we group OPEC countries into two categories using the share of oil rents in total GDP in 2000. The countries having an above median oil-rents-to-GDP ratio is considered to be highly dependent on oil revenues and vice versa.[11] The

[11] The median oil-rents-to-GDP ratio is 33.8 percent in 2000.

Table 12: The Role of Oil Dependency: Below Median

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.176		-0.093**	
	(0.139)		(0.046)	
Government R&D $ln(s^g_{jt-1})$		0.202		-0.137**
		(0.170)		(0.066)
GDP imp. $ln(GDP_{jt})$	0.420	0.440		
	(0.777)	(0.779)		
Adjusted R^2	0.80	0.80	0.46	0.46
AIC	1868.9	1868.5	714.2	710.5
BIC	2107.1	2106.7	948.0	944.3
Observations	609	609	609	609

This table shows the effect of R&D intensity on renewable energy technologies in importer countries on the exported quantity and price of oil for the exporter countries with a below median dependency on oil revenues. The dependency on oil revenues is measured by the oil-rents-to-GDP ratio in 2000. All variables are in logarithms. Robust standard errors clustered at the bilateral level in parenthesis. Controls include bilateral and exporter-time fixed effects. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

baseline year is selected to be just before our sample period starts so that the grouping is not endogenous to subsequent changes in R&D policies in importer countries but at the same time it can reflect the actual ranking of countries in the period we investigate. Then we replicate our analysis for countries with above median and below median oil dependency, separately. The results are presented in Tables 11 and 12 for oil trade and oil price, respectively. The results reveal that while the increase in the R&D intensity in importer countries leads to price declines in all exporters, only the ones with higher oil dependency respond by significantly increasing the quantity of exports, which is consistent with the expectation. This finding highlights an important source of heterogeneity in the supply behavior of oil exporters in response to the climate policy.

5.2.2 Endogeneity

In setting up the pricing equation (6), R&D on renewables are assumed to be exogenously determined by the importer countries. However, one might expect a positive correlation between R&D spending and oil prices, since the government of an oil importing country might increase the spending on renewable energy R&D in order to reduce its oil dependency when oil price rises. If this is the case, our estimated coefficients would be biased towards zero, hence the true effect might be even larger than the ones reported in the baseline findings. In order to control for such an endogeneity problem that may arise from possible feedback effects from oil prices to R&D spending, we use one year lagged R&D spending on renewable energy technologies throughout the paper. Unfortunately, using lagged R&D might not be sufficient to eliminate these concerns since it is not unlikely that oil importing countries anticipate the evolution of future oil prices. In this respect, we use R&D intensity on various activities which are not directly related to the energy markets, such as R&D on defence and aerospace industries, as instruments for R&D on renewable energy energy technologies. The downside of this approach is that these variables are only available for a subset of country-year pairs and almost 30 percent of the observations are lost. Still, it might be valuable to compare the estimates from IV regressions and the baseline findings, to assess the direction of the bias on the reported estimates.

The second stage results of IV estimations are presented in Table 13 (see Appendix D for the first stage results). An important point is that these instruments satisfy the exclusion restriction, i.e. they are uncorrelated with the error terms in the second stage,

Table 13: R&D on Renewables and Oil Trade: IV Estimations

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	1.885**		-0.811***	
	(0.735)		(0.304)	
Government R&D $ln(s^g_{jt-1})$		1.680***		-0.707***
		(0.606)		(0.264)
GDP imp. $ln(GDP_{jt})$	1.157	0.960		
	(1.139)	(1.057)		
Overidentification: Hansen-J Test	0.123	0.474	0.437	0.719
Joint significance of instruments: F Stat.	14.438	21.855	14.068	19.555
Observations	798	798	798	798

This table reports the effects of R&D intensity on renewable energy technologies in importer countries on the quantity and price of oil exports using R&D intensity on defence and aerospace industries as instruments for the R&D intensity on renewable energy technologies. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

and weak instrumentation issue seems to be mild given the F-statistics in the first stage. It is seen that the IV estimate for the impact of R&D intensity on oil prices (β) is larger in absolute terms relative to the baseline values, while the implied elasticity of substitution between crude oil and other energy inputs (σ) is still about 2.32 (=1.885/0.811), which is similar to the baseline estimate. When the impact of government R&D is considered, the implied σ values are about 2.4 and almost identical in the baseline and IV regressions. This shows that possible endogeneity of R&D activities on renewable energy technologies works against documenting the intertemporal leakage in the pricing equation as expected. Although IV estimations reveal that the sign of β is robust to endogeneity concerns, robust inference about the magnitude of the point estimate would require stronger instruments. Hence, the exact magnitude of the elasticity of oil prices with respect to the R&D intensity in the baseline estimations should be considered as a lower bound.

5.3 Treatment of Data

In this part, we test the robustness of the baseline results to the choices on the econometric model and sample construction. Namely, we investigate the effects of outliers, and estimating coefficients of interest with different estimation techniques.

5.3.1 Outliers

In this section, we repeat our baseline analysis by conducting quantile regressions and trimming the observations which fall in the upper and lower first or fifth percentile of the distribution in order to check robustness of our results to the outliers.

In the median regression, the most common form of quantile regression, the hypothesized relationship is summarized with the conditional median function, instead of the conditional mean function as in standard linear regression methods. Median regression is appealing for being more robust to outliers and handling non-standard distribution of regression errors. Although the quantile regression methods are well-developed, applying quantile regressions in a panel setting is not straightforward. First of all, introducing dummy variables for the fixed-cross section specific effects is not appropriate due to the incidental parameters problem (See Koenker (2004) among others). Secondly, the standard transformations applied in standard linear regressions to eliminate fixed effects do not work in case of quantile regression, since this approach requires the expectation operator to be linear, which is not the case for quantile regression. For these reasons, we employ the panel quantile estimator by Canay (2011). The identifying assumption in Canay (2011) is that fixed effects are treated as location shifters. In our case, this means that the effect of the bilateral dummies, for example distance, is the same at every point of the conditional distribution of the oil trade, an assumption which is in line with the pricing equation of oil exporters (6). Canay (2011) estimator eliminates the fixed effects in a first stage estimation as time dimension goes to infinity. The parameter of interest is then identified in the second stage for a fixed time dimension.

We replicate the baseline specifications with median regression and present the results for controlling for pair-fixed and common time effects in Table 14.[12] The results document that oil prices decline and quantity of exports increases in response to increases in R&D intensity on renewables and show that the baseline findings are not driven by the outliers in the sample.[13] The coefficient estimates are highly significant, and their size are close

[12]The results are valid for all specifications and robust to the control of exporter-time fixed effects; however, employing exporter specific time effects may not be appropriate since this introduces a large number of dummy variables in the second stage.

[13]The pseudo R^2, presented for quantile regressions, belongs to second stage regression for which the effect of bilateral fixed effects has already been partialled out in the first stage. Therefore, the R^2's are

Table 14: Median Regressions

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.269***		-0.084***	
	(0.020)		(0.004)	
Government R&D $ln(s^g_{jt-1})$		0.328***		-0.119***
		(0.020)		(0.004)
Oil revenues $ln(Y^o_{it})$	1.169***	1.167***	-0.049***	-0.051***
	(0.023)	(0.023)	(0.004)	(0.004)
GDP imp. $ln(GDP_{jt})$	0.805***	0.846***		
	(0.014)	(0.014)		
Pseudo R^2	0.57	0.58	0.72	0.71
Observations	1143	1143	1143	1143

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the quantity and price of oil exports using median regression, see equations (10) and (11). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

to those obtained in the OLS estimations.[14]

As the second robustness check for outliers, we repeat our baseline regressions by excluding the upper and lower first percentile data and report the results in Tables 15 and 16, respectively. The lower fifth percentile also excludes the observations corresponding to the relatively lower export levels observed in the scatter plots presented in section 2. Noting that the results are robust for all specifications in our baseline regressions, we only report the results of the most extended specification including bilateral and exporter-year fixed effects for the sake of brevity. The estimated impact of R&D on renewable alternatives is significant in all specifications, confirming the baseline findings on the positive (negative) effect of the R&D intensity on the quantity (price) of oil exports.

smaller compared to the baseline regressions.

[14] A further advantage of quantile regression is that it enables us to analyze the effect of R&D intensity at different quantiles of the trade distribution, not just at the conditional mean. We replicate the analysis for oil trade for different quantiles. The results are in line with the baseline findings and estimated elasticities are close to the baseline estimates in magnitude. The results are available upon request.

Table 15: Excluding First Percentile Outliers

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.351**		-0.114***	
	(0.136)		(0.043)	
Government R&D $ln(s^g_{jt-1})$		0.380**		-0.150***
		(0.159)		(0.055)
GDP imp. $ln(GDP_{jt})$	1.103	1.165		
	(0.788)	(0.798)		
Adjusted R^2	0.75	0.75	0.35	0.35
AIC	3504.6	3502.9	1582.3	1577.3
BIC	4007.5	4005.8	2080.2	2075.2
Observations	1074	1074	1074	1074

This table shows the impact of R&D intensity on renewable energy technologies on the quantity and price of crude oil exports by excluding the observations falling in the upper and lower first percentiles in the distribution of the dependent and independent variables. The first two columns , respectively. The dependent variable is the quantity of oil exports and all variables are in logarithms. Robust standard errors are clustered at the bilateral level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 16: Excluding Fifth Percentile Outliers

	Trade		Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.454**		-0.174**	
	(0.183)		(0.075)	
Government R&D $ln(s^g_{jt-1})$		0.430**		-0.208**
		(0.198)		(0.087)
GDP imp. $ln(GDP_{jt})$	0.352	0.387		
	(0.901)	(0.911)		
Adjusted R^2	0.74	0.74	0.31	0.32
AIC	2557.2	2558.7	1305.7	1301.4
BIC	2992.9	2994.4	1736.6	1732.3
Observations	842	842	842	842

This table shows the impact of R&D intensity on renewable energy technologies on the quantity and price of crude oil exports by excluding the observations falling in the upper and lower fifth percentiles in the distribution of the dependent and independent variables. The first two columns , respectively. The dependent variable is the quantity of oil exports and all variables are in logarithms. Robust standard errors are clustered at the bilateral level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.4 Armington Elasticity of Crude Oil

Armington elasticity captures the degree of differentiation among crude oil from different source countries and the strength of diversification incentives of importers due to economic as well as political factors. A possible way to estimate the Armington elasticity (ε) is to use the information on prices directly. Taking the logarithm of the quantity of exports, we obtain

$$ln\left(Q_{ijt}\right) = -\varepsilon ln\left(p_{ijt}\right) + u_{jt} \tag{12}$$

where $u_{jt} = (\varepsilon - 1)\, ln\left(P^{o}_{jt}\right) + ln\left(E^{o}_{jt}\right)$. Hence, ε can be estimated by regressing logged quantity of oil exports on logged prices controlling for importer-year fixed effects. An alternative way is to expand equation (12) one step further and estimate equation (10) by regressing logged quantity of oil exports on logged distance conditional exporter-year and importer-year fixed effects. To the extent that distance captures the bilateral resistance between the trading partners, the coefficient on logged distance yields an estimate of ε.

Table 17: Armington Elasticity (ε)

Dependent variable: Oil exports		
	(1)	(2)
Price	-2.079*	
	(1.096)	
Distance		-2.363***
		(0.213)
Exporter-year FE's	No	Yes
Importer-year FE's	Yes	Yes
Adjusted R^2	0.32	0.43
Observations	1434	1434

This table shows the estimates of the Armington elasticity. Columns 1 and 2 provide the estimation results of equations (12) and (10), respectively. The dependent variable is the quantity of oil exports and all variables are in logarithms. Robust standard errors are clustered at the importer-year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 17 presents the corresponding results. The first column reports the results of estimating equation (12) whereas Column 2 corresponds to equation (10) controlling for the relevant fixed effects. Although both methods yield similar values for ε, it is seen that using price data directly leads to higher standard errors, probably due to higher noise in prices, for the estimate and one cannot reject a fairly wide range of parameter values. For this reason, we opt to use the estimate on logged distance, which is estimated with higher precision and implies that $\varepsilon = 2.363$.

5.5 Aggregate Consequences: Total Oil Production

A sizable share of the world oil production takes place in the OPEC countries which are substantially export oriented. Therefore, it is natural to investigate the green paradox in case of oil production in an international trade setting. The gravity model is a convenient tool by allowing for extensive controls for both the supply and demand side. However, the preponderance of the theoretical literature on extraction of nonrenewable resources concentrates on the total production rather than the trade flows. For this reason, we also investigate the effect of R&D intensity of the OECD countries on the total oil production of the OPEC countries. This requires to construct an exporter specific measure of renewable R&D intensity in the importer countries. While there is no theoretical prior guiding the aggregation of R&D intensities across importer countries, a natural way to begin with is using the trade shares. We construct the effective R&D intensity as the average renewable R&D intensity of the importer countries weighted by the trade shares of the exporter country with the importers:

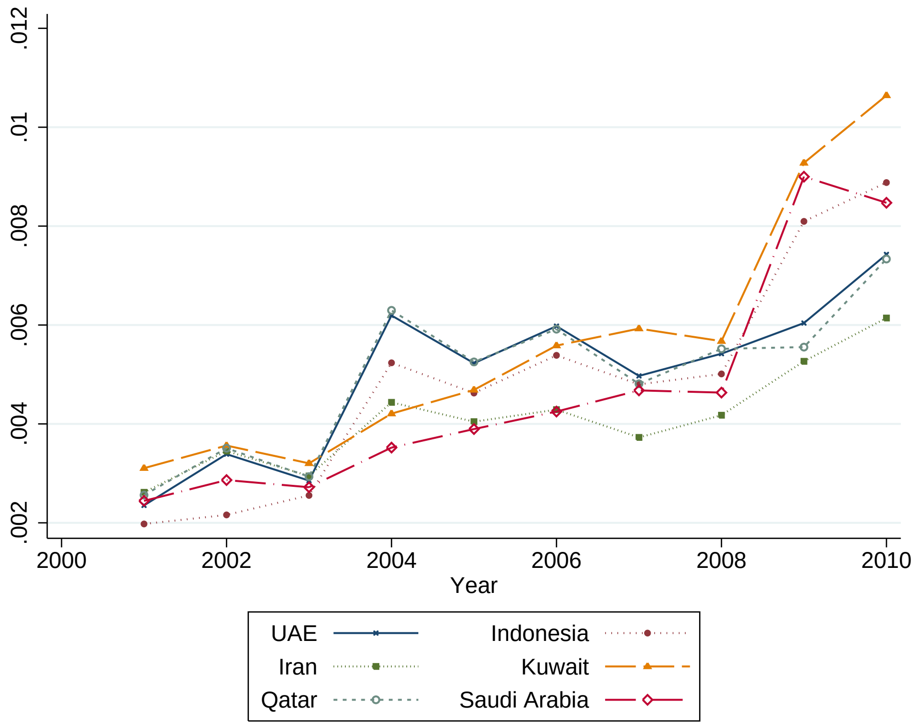
$$S_{it} = \sum_{j \in J} \frac{Q_{ijt}}{\sum_{k \in J} Q_{ikt}} S_{jt} \tag{13}$$

where Q_{ijt} is the quantity of exports from country i to importer country j as above and S_{jt} is the level of R&D intensity in an importer country at time t.[15] As in the bilateral-level estimations, we have two different measures of R&D intensity computed using total or government R&D spending only. Figure 3 shows the evolution of effective R&D intensity faced by 6 oil-exporting countries from 2001 to 2010 in percentage points.

The bilateral level estimations in Section 5.2.1 reveal an important source of heterogeneity due to the degree of oil dependence of exporter countries. We estimate the impact of the effective R&D measure on the total oil production for these two sets of countries. The first set corresponds to all OPEC countries while the second includes the ones with

[15] The results are intact when value shares are used instead of quantity shares.

Figure 3: Effective R&D on Renewable Technologies at the Exporter Level



an above median dependency on oil revenues in 2000, which corresponds to an oil-rents-to-GDP ratio of 33.8 percent. Given the baseline findings on the differential response of countries with higher dependency on oil revenues, it might be expected that country level estimations will exhibit a similar pattern.

The results are presented in Table 18 and are line with the bilateral level estimations. In the first 2 columns, we report the results for the whole OPEC sample. The coefficient of the effective R&D intensity is insignificant and even negative. In stark contrast, for the OPEC countries with an above median oil-rents-to-GDP ratio, the estimated effects are significant and positive despite the low number of observations (see columns 3 and 4 in Table 18). The effect of government R&D spending is larger compared to the total spending, consistent with the baseline findings, which possibly shows that government spending reflects a stronger commitment to reduce the costs of renewable energy production and is a stronger signal for the exporter countries. The results also reveal that the effectiveness of R&D activities on renewable energy technologies depend crucially on the dependency of oil-rich countries on oil revenues, which seems to be a crucial element to understand the link between climate policies and the supply behavior of the resource owners.

Table 18: Oil Production - Exporter Level

Dependent variable: Total oil production				
	All OPEC		Above Median	
	(1)	(2)	(3)	(4)
Effective R&D S_{it-1}	-0.074		0.230*	
	(0.076)		(0.101)	
Effective Gov. R&D S^g_{it-1}		-0.159		0.394*
		(0.174)		(0.187)
Year effects	Yes	Yes	Yes	Yes
Adjusted R^2	0.238	0.241	0.212	0.209
AIC	-195.1	-195.7	-85.1	-84.9
BIC	-166.0	-166.6	-71.9	-71.7
Observations	136	136	67	67

This table presents the affects of effective R&D intensity on total oil production. The first two columns show the estimates for the whole sample of OPEC countries while the last two replicate the analysis only for exporter countries with above median oil dependency. Exporter and time fixed effects are included in all specifications. Robust standard errors clustered at the exporter level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

6 Conclusion

This paper investigates the relationship between the climate policies promoting renewable alternative technologies for fossil fuels and the supply behavior of oil exporters. Using data on crude oil exports from OPEC to OECD countries between 2001-2010 in a gravity framework, we document that oil exporters lower prices and increase quantity of oil exports in response to increases in R&D intensity on renewable technologies in importer countries. These findings are robust to controlling for an extensive set of factors including exporter-year specific shocks and bilateral fixed effects. We also show that (i) this relationship is mainly driven by the exporters with higher dependence on oil revenues; (ii) the Armington elasticity of oil is about 2.4 which is lower than commonly expected; and (iii) exports of coal, which is in abundant supply, are not significantly affected by the changes in R&D intensity of importer countries.

An important implication of these results is that demand reduction policies might lead to increases in near term supply, which might render the climate policy ineffective or even counter-productive. Hence, climate policy design should also take this strategic response of resource suppliers into account. More importantly, it is documented that the strength of the supply-side reaction depends on a specific supplier characteristic, namely the dependency of the resource rich countries on oil revenues. This result also calls for more detailed analysis of supplier characteristics which might be decisive on supply behavior, not only at country level but also at the local supplier level for other resources which are operated in more decentralized markets.

Another implication of the results is that crude oil from different source countries is not treated as homogenous goods given the finding that the Armington elasticity is about 2.4. This finding demonstrates that taking economic and political diversification incentives of the importer countries into account might enrich the understanding of the impact of various policies on the oil market.

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A Data Appendix

Table 19 presents the data sources, measurement unit, and definition of all the variables employed throughout the paper.

B R&D Spending without Normalization

In the main text we present the results from using R&D intensity which is R&D spending normalized by the nominal GDP of the importer country. Table 20 is a summary table replicating our baseline regressions with the most extensive control set without normalizing R&D spending with GDP. In the first two columns we replicate quantity regressions, and the last two columns present the price regressions, which yield similar results to our baseline regressions. The robustness tests and the additional analysis where we employ the level of R&D spending are available upon request from the authors.

C Controlling for Energy Price Index

In section 3.2, it is shown that omitting the energy price index might introduce a bias on the coefficient estimate of the climate policy variable which is proportional to the expenditure share of oil in total energy production. To address this issue and assess the magnitude of this bias in practice, we include the logarithm of the energy price index in the importer country (P^z_{jt}) compiled from the International Energy Agency (IEA) in the baseline quantity regression. The results, reported in Table 21, show that the energy price index is itself insignificant in all specifications and the coefficient on the R&D intensity is only marginally affected.

D IV Estimations: First stage results

Table 22 presents the first stage results of the IV estimations presented in section 5.2.2, where R&D intensity on renewables is regressed on R&D intensity on defence and aerospace industries. The partial correlations of these instruments with R&D intensity on renewables are strong and highly significant. The F-statistics revealing the joint significance of the

Table 19: Data sources and variable definitions

Data source	Variable	Units	Definition
Commodity Trade Statistics Database (UN)	Oil Trade - Quantity	Tonnes (mln.)	Crude Petroleum (SITC Rev. Code is 3330) trade flows. Re-exports are substracted.
	Oil Trade - Value	US$(bln.)	Crude Petroleum (SITC Rev. Code is 3330) trade flows. Re-exports are substracted.
Gravity Database (CEPII)	Distance	km.	Simple shortest distance between most populated cities.
	Common Borders	Dummy	(=1) if neighbors.
	Common Official Language	Dummy	(=1) if the official language is the same.
	Common Spoken Language	Dummy	(=1) if the same language is spoken by more than 9% of the population in both countries.
	Colonial History	Dummy	(=1) if ever have colonial relationship.
	Common Colonizer	Dummy	(=1) if ever both countries are colonized by the same country.
	Current Colony	Dummy	(=1) if there is a current colonial relationship.
	Colonial History post 1945	Dummy	(=1) if there has been a colonial relationship since 1945.
	Common Colonizer post 1945	Dummy	(=1) if there has been a common colonizer since 1945.
	Same Country	Dummy	(=1) if countries were or are the same countries.
World Development Indicators (World Bank)	GDP	US$(bln.)	Gross domestic production in current U.S. dollars, converted from domestic currencies using single year official exchange rates.
	Population	-	Mid-year values of counts of all residents.
	Oil Rents	% of GDP	Quantity extracted is multiplied by the difference between the price of a commodity and the average cost of producing it.
Energy Statistics (International Energy Agency)	Total R&D Spending	US$(bln.)	Total R&D spending on renewable energy sources.
	Government R&D Spending	US$(bln.)	Government R&D spending on renewable energy sources.
	Fuel Tax	US$/litre	Automobile diesel fuel tax for the industry.
DICE Database (CESifo)	Oil Production	Tonnes (mln.)	Annual extracted tonnes of oil.
Constructed Variables	R&D Intensity	-	R&D Spending / GDP
	Oil Price (Unit Value)	(mln.)US$/tonnes	Traded Value / Traded Quantity
	Oil Revenues	US$(bln.)	Oil Rents of GDP * GDP /100

Table 20: Baseline Regressions with R&D Spending

	Oil Trade		Oil Price	
	(1)	(2)	(3)	(4)
R&D $ln(s_{jt-1})$	0.274**		-0.099***	
	(0.113)		(0.036)	
Government R&D $ln(s^g_{jt-1})$		0.333**		-0.142***
		(0.139)		(0.051)
GDP imp. $ln(GDP_{jt})$	0.835	0.851		
	(0.645)	(0.643)		
Adjusted R^2	0.77	0.77	0.38	0.38
AIC	3812.4	3809.3	1628.3	1622.3
BIC	4335.6	4332.5	2139.4	2133.4
Observations	1187	1187	1164	1164

This table shows the effects of R&D spending on renewable energy technologies in importer countries on the quantity and price of oil exports, see equation (10). Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

instruments is higher than 10, which is the rule of thumb to reject a weak instrumentation issue.

Table 21: R&D on Renewable Energy, Oil Exports, and Energy Price Index

Dependent variable: Oil exports						
	(1)	(2)	(3)	(4)	(5)	(6)
R&D $ln(s_{jt-1})$	0.282*	0.274*	0.241**			
	(0.151)	(0.139)	(0.122)			
Government R&D $ln(s^g_{jt-1})$				0.322*	0.329*	0.299**
				(0.180)	(0.167)	(0.149)
Oil revenues $ln(Y^o_{it})$	1.521**	1.174*		1.519**	1.177*	
	(0.667)	(0.614)		(0.666)	(0.612)	
GDP imp. $ln(GDP_{jt})$	1.115**	1.041*	1.057	1.153**	1.081**	1.085
	(0.541)	(0.536)	(0.700)	(0.548)	(0.544)	(0.704)
Energy Price Index $ln(P^z_{jt})$	1.185	0.197	0.193	1.346	0.367	0.332
	(0.941)	(0.911)	(0.975)	(0.901)	(0.878)	(0.955)
Adjusted R^2	0.39	0.77	0.77	0.39	0.77	0.77
AIC	4745.6	3493.2	3685.1	4745.1	3491.0	3682.5
BIC	4940.4	3558.2	4208.5	4939.9	3555.9	4206.0
Observations	1090	1090	1134	1090	1090	1134

This table shows the effects of R&D intensity on renewable energy technologies in importer countries on the quantity and price of oil exports controlling for energy price index in the importer country, see equation (10) and compare with Table 3. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 22: IV Estimations: First Stage Results

Second stage equation:	Quantity		Price	
Dependent variable: R&D Intensity on Renewables	Total	Government	Total	Government
R&D on defence	0.104***	0.087***	0.098***	0.076***
	(0.029)	(0.024)	(0.027)	(0.021)
R&D on aerospace	-0.169***	-0.226***	-0.164***	-0.218***
	(0.038)	(0.037)	(0.039)	(0.038)
Overidentification: Hansen-J Test	0.123	0.474	0.437	0.719
Joint significance of instruments: F Stat.	14.438	21.855	14.068	19.555
Observations	798	798	798	798

This table reports the first stage results from IV estimations of effects of R&D intensity on renewable energy technologies in importer countries on the quantity and price of oil exports using R&D intensity on defence and aerospace industries as instruments for the R&D intensity on renewable energy technologies. Robust standard errors clustered at the bilateral level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.