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Crude oil footprint in the rapidly changing world and implications from their income and price elasticities

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ABSTRACT

Oil demand's income and price elasticities are important behavioral parameters for policy making. Despite its popularity in research, few studies investigated the elasticities of consumption-based oil demand, i.e., the amount of crude oil required to meet a nation's final demand regardless of the location of extractions, namely the oil footprint. Here we quantified the oil footprint of 49 countries/regions from 1995 to 2017 and estimated the elasticities of oil footprints using the panel Autoregressive Distributed Lag model. The results reveal the oil connections among countries hidden in the non-oil trade: the United States, China, and Japan imported a large amount of virtual oil embodied in the commodities and services, while Canada and Russia are the dominant suppliers. The elasticity estimations on 30 OECD countries show that oil footprints are more responsive to income increases in the long run than their short-run counterpart, with the elasticities around 0.75 and 0.48, respectively. Tariffs on oil products might not curb the oil footprint as the price elasticities are not robustly significant or negative. Moreover, the divergent elasticities of oil footprint by consumption categories highlight that more attention should be paid to the surge of oil demand embodied in construction, manufactured products, and services.

1. Introduction

Oil is one of the dominant energy sources in the modern economy and the strategic resource involving energy rights, geopolitical patterns, and economic trends (Costantini et al., 2007; Zhou et al., 2020). In a rapidly changing world, the focus on the oil industry has shifted from the concerns for insufficient supply caused by resource depletion to the uncertainty of demand and price under the intertwined impacts of the global pandemic, climate change mitigation, and increasingly frequent geopolitical conflicts (Brandt et al., 2018). The disturbances in crude oil demand and oil prices, especially those following the COVID-19 epidemic and the Russia-Ukraine war, remind policymakers and investors that the oil market plays a crucial role in reflecting the health of the global economy (Considine et al., 2021).

Oil demand's income and price elasticities denote their responsiveness to economic growth and price fluctuation and are important behavioral parameters for predicting the demand trend. The forecast of these indicators supports decisions on refinery investment and policymaking concerning energy security, climate change, and international trade (Dahl, 2012; Ghoddusi et al., 2021). A large number of studies have estimated the income and price elasticity of oil or oil product demand in various countries and regions and gained fruitful findings on this topic (e.g., (Baranzini and Weber, 2013; Bhattacharyya and Blake, 2009; Labandeira et al., 2017; Liddle and Huntington, 2020a; Sa'ad, 2009; Yousaf Raza and Lin, 2021). However, almost all of them focused on the income and price elasticities of domestic use of crude oil or oil product (Polemis, 2006); few studies investigated the elasticities of a country's actual oil demand driven by its final demand.

The actual oil demand, which is the amount of crude oil required to meet a nation's final demand regardless of the location of extractions, namely oil footprint, has been proven different from direct oil flows and domestic use (Wang and Jiang, 2019; Wang and Yang, 2020). It equals

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the crude oil extraction to satisfy the final demand of a country, excluding the oil consumption embodied in downstream products outsourced and consumed in other countries, and including those embodied in the imported products. Wu and Chen (2019) found that the global volume of oil embodied in trade is twenty percent larger than that in oil exploitation, and the role of the trade of non-oil goods in the global oil balance is comparable to that of the direct oil trade. Li et al. (2021) analyzed the time-series evolution characteristics of the global oil supply chain during 2000–2015 and pointed out that considering virtual oil flows embodied in the international trade of non-oil products (e.g., rubber, plastic, synthetic fiber, cosmetics and so on) greatly changes the perception of global oil supply chain and use patterns. Given these insights, investigating the elasticities of the footprint will assist with a more accurate forecast of countries' actual oil demand and better decisions on policymaking and investment.

Here enabled by the combination of a multi-regional input-output database (EXIOBASE 3.8.1) (Stadler et al., 2021) and crude oil production data from the International Energy Agency (IEA) (IEA, 2022b), we depict the oil footprint of 49 countries, territories, and regions in the past 23 years (1995–2017). The quantification of oil footprint is similar to the recent literature that examines consumption-based rather than territory-based environmental and resource footprints (Dorninger et al., 2021; Wiedmann and Lenzen, 2018; Zheng et al., 2018). We further employed the panel Autoregressive Distributed Lag (ARDL) model to estimate the oil footprints' income and price elasticities in 30 OECD countries where the oil price data are available. The findings generate new insights on energy-involving policies and investment decisions, facilitate a more comprehensive understanding of the global oil market, and help enhance the prediction and adaptation abilities in the rapidly changing world.

2. Literature review

2.1. Debates on oil demand prediction

In terms of future oil demand predictions, researchers and investors haven't reached a consensus (Kilian, 2022). A stream of arguments acknowledges that oil demand will change under the climate change vision, but not enough to shake up the industry (Spencer Dale and Fattouh, 2018). They claim that the low-carbon transition from fossil fuels to renewable energy will take a long time, like all previous transitions. The lock-in effect of infrastructure committed that oil and other fossil fuels would not be squeezed out in the short term. At the same time, the construction of emerging infrastructure needed for the energy transition still depends on fossil fuels such as oil (Smil, 2016). Although the demand for oil as fuels in transportation, heating, and industry will decrease in the future along with full electrification and energy substitution, non-fuel use is hard to be substituted in the short term. Unless consumers compromise their lifestyles, the growing demand for petrochemicals (especially plastics) from the emerging middle-class will continue driving the oil demand increase (IEA, 2018).

By contrast, the opponents argue that there are indeed historical examples of rapid energy transitions, such as the quick transition from coal to natural gas in the United Kingdom (UK), the rise of nuclear power in France, and the retirement of coal in Ontario, Canada (Wilson and Staffell, 2018). Besides, even if the physical energy infrastructure changes slowly, financial parameters and investors' confidence change very quickly and may broadly accelerate the evolution of oil demand. Especially when the economic cost of renewable energy is dramatically declining (BP, 2021; IRENA, 2020), the investors' confidence and behaviors could subvert.

The divergent arguments imply the considerable uncertainties in the future of the oil industry. Some studies predict that oil demand has collapsed, and an early peak of the industry is coming. For example, British Petroleum (BP) 's Energy Outlook presented scenarios with harsh climate policies, in which the global oil demand peaked in 2019 and would never fully recover from the fall caused by Covid-19 (BP, 2020). However, as the OPEC forecast, global oil demand will grow until around 2040 and is unlikely to fall sharply (Wang, 2020). A better understanding of actual oil demand driven by a country's final demand and its composition relating to different consumption categories could lower the prediction uncertainties.

2.2. Elasticity estimates of oil demand

Income and price elasticities are two critical parameters in the oil demand prediction, which describe the response of producer and consumer behaviors to affluence changes and price fluctuations. The estimates of these two parameters have been a welcoming research topic (Huntington et al., 2019; Moore, 2011; Raghoo and Surroop, 2020; Ziramba, 2010). Previous studies have focused on the domestic consumption of crude oil or oil products and found that the elasticity varies considerably across countries, fuel types, data frequency, and even estimation methods (Ajanovic et al., 2012; Labandeira et al., 2017). For example, Dahl (2012) reviewed 240 studies and found that the price elasticity estimates from models for gasoline range from less than −1.63 to positive values, with a median of −0.34; those for diesel fuel range from less than −0.67 to positive values. Huntington et al. (2019) studied five countries (i.e., China, Brazil, India, Mexico, and Russia), and reported the averages of short and long-run price elasticities for oil demand around −0.15∼−0.07, and the averages of short and long-run income elasticities for oil demand around 0.39–0.50. Liddle and Huntington (Liddle and Huntington, 2020b) assembled a wide panel dataset of energy consumption and prices for 37 OECD and 41 non-OECD countries and found that most evidence supports the income elasticity is less than unity (i.e., 0.7) and the price elasticities was insignificant.

Despite the variations in the quantified results, some consensus has been achieved: 1) Both income elasticities and price elasticities have larger long-term elasticity coefficients than short-term elasticity coefficients, implying that oil (product) demand is more responsive to changes in income and prices in the long term (Cooper, 2003a; Sita et al., 2012). 2) Oil demand is more sensitive to changes in income than to price variations (Liddle and Huntington, 2020b). The former reported in many studies are inelastic or close to unity, while the latter have deficient elasticity, both in the short and long term, generally in the range of −0.3∼−0.1 (Eleyan et al., 2021). 3) The income elasticity has been declining (Eleyan et al., 2021), which is positive for climate change as it implies that the oil intensity decreases with economic growth.

The methods to obtain the above findings are diverse in previous studies. The model specifications evolve from static equation and partial adjustment method (Cooper, 2003a) to error correction and cointegration techniques for analyzing time-series data (Akinboade et al., 2008). Recently, the use of ARDL Error Correction Model (ARDL-ECM) in elasticity estimation has gained popularity as it allows simultaneous assessment of short- and long-run elasticities (Raghoo and Surroop, 2020).

3. Methodology

3.1. Oil footprint quantifications

Combining the crude oil production data and the multi-regional input-output table, we quantified the oil footprint of 49 countries, territories, and regions during 1995–2017 (Table A1 lists the full name of the samples) by applying the Leontief demand-pull model (Eq. (1)).

$$OF^r = S \times (I - A)^{-1} \times Y^r \tag{1}$$

where OF^r represents the oil footprint by country r. S is the physical amount of crude oil extraction per monetary output. I refers to the identity matrix and A is the technical coefficient submatrix. $(I - A)^{-1}$ represents the Leontief inverse matrix which captures both direct and indirect economic inputs to satisfy one unit of final demand in monetary value. Y^r is the final demand of country *r*. It is worth noting that the estimates in this study only capture the annual oil flow from production to consumption while ignoring the changes in the oil stocks (Kilian and Murphy, 2014).

3.2. Empirical estimation models

We employed the panel ARDL model (Pesaran et al., 1999) to estimate the long-run and short-run dynamic relationships between a country's oil footprint and socioeconomic drivers. We adopt this model for three reasons. First, unlike static models that capture the intermediate-run elasticities, ARDL is a dynamic model that provides short- and long-run relationships among variables. Second, the ARDL model is suitable even if the sample size is small. Third, the ARDL model is valid for non-stationary variables, as well as for a mixture of variables that are stationary at level (known as I(0) variable) and those which are non-stationary at level but are first-difference stationary (known as I(1) variable), fitting the situation of our sample data well (see more details in section 3.3.2 unit root tests).

The model estimated has the form of an ARDL(p,q,r) model (Eq. (2)):

$$\ln OF_{i,t} = a_i + \sum_{j=1}^{p} \gamma_{i,j} \ln OF_{i,t-j} + \sum_{j=0}^{q} \theta_{i,j} \ln GDP_{i,t-j} + \sum_{j=0}^{r} \delta_{i,j} P_{i,t-j} + e_{it} \tag{2}$$

where $\ln(OF_{i,t})$ is the logarithmic form of per capita oil footprints for country *i* in year t; $\ln(GDP_{i,t})$ denotes the logarithmic form of affluence, indicated by per capita GDP at purchasing power parity (2017 constant international dollars); $P_{i,t}$ is the real index of oil product prices for industry and households (2015 = 100); a_i is the group-specific effect and e_{it} is the error term. The optimal lag orders (p, q, r) are selected according to the Bayesian Information Criterion (BIC).

If the variables are cointegrated, the model can be reparametrized into the error-correction model:

$$\Delta \ln OF_{i,t} = a_i + \varphi_i \left(\ln OF_{i,t-1} - \beta_1 \ln GDP_{i,t-1} - \beta_2 \ln P_{i,t-1} \right) + \sum_{j=1}^{p-1} \gamma^{*}_{i,j} \Delta \ln OF_{i,t-j} + \sum_{j=0}^{q-1} \theta^{*}_{i,j} \Delta \ln GDP_{i,t-j} + \sum_{j=0}^{r-1} \delta^{*}_{i,j} \Delta \ln P_{i,t-j} + e_{it} \tag{3}$$

where β_1 and β_2 are the long-run coefficients of the explanatory variables on per capita crude oil footprint and φ_i is the error-correcting speed of adjustment term. This parameter is expected to be significantly negative under the prior assumption that the variables show a return to long-run equilibrium. $\gamma^{*}_{i,j}$, $\theta^{*}_{i,j}$, and $\delta^{*}_{i,j}$ are the short-run coefficients. Δ reflects the first difference operator, which means the series of changes from one period to the next.

For comparison, we also estimated the income and price elasticities of per-capita domestic oil use on the same sample. The cointegration tests (see more details in section 3.3.2) didn't reject the null hypothesis of no cointegration at a 10% confidential level, indicating the error-correction model is unsuitable. Thus we estimate the short-run elasticities using the First Difference (FD) model:

$$\Delta \ln DU_{i,t} = a_i + \sum_{j=1}^{p-1} \gamma'_{i,j} \Delta \ln DU_{i,t-j} + \sum_{j=0}^{q-1} \theta'_{i,j} \Delta \ln GDP_{i,t-j} + \sum_{j=0}^{r-1} \delta'_{i,j} \Delta P_{i,t-j} + e_{it} \tag{4}$$

where $\ln(DU_{i,t})$ is the logarithmic form of per capita domestic oil use for country *i* in year *t*.

3.3. Data and tests

3.3.1. Data sources

The EXIOBASE database (Stadler et al., 2021) describes the world economy regarding the production, consumption, and trade of 200 commodities between and among 44 countries/territories and 5 regions. The production, import, export, and domestic use data of crude oil by country are referenced from the IEA Oil Information database (IEA, 2022b). Crude oil production is defined as the quantities of oil extracted from the ground after removing inert matter or impurities, including all crude oil, NGL, condensates, and other hydrocarbons (including the receipts of additives). The crude oil prices are indicated by the real index of oil product prices for industry and households (2015 = 100), which are referenced from the IEA Energy Prices database (IEA, 2022a). It is worth noting that the availability of price data across countries is the main factor constraining the sample size since the price data only cover the OECD countries. Thus the panel data analysis dataset of oil footprint is unbalanced, covering 30 countries from 1995 to 2017 (Table A2). The data of per capita GDP and population are sourced from World Bank Development Indicators (The World Bank, 2017). Table 1 provides the descriptive statistics of the variables used in the basic model.

3.3.2. Unit root tests

As Table 2 shows, we employed two methods to test the stationary of the variables: the Im–Pesaran–Shin (IPS) test (Im et al., 2003), and the Fisher-ADF test (Choi, 2001). Both test methods have the null hypothesis that all the panels contain a unit root. The tests show that per capital oil footprint (*ppof*) is stationary, while there is some doubt about the existence of a unit root for the three independent variables. Regarding the first difference of the variables, the tests show all of them are stationary.

3.3.3. Cointegration

We performed the cointegration tests using the Pedroni (1999) and Westerlund (2005) methods (Table 3). Both tests reject the null hypothesis of no cointegration at 5% for Eq. (3), supporting the use of ARDL and interpreting the coefficients of the variables in levels as the long-run impact on the dependent variable. However, when per-capita domestic oil use is used as the dependent variable, the Westerlund test doesn't reject the null hypothesis of no cointegration at a 10% significance level.

4. Results

4.1. Evolution of oil footprint 1995–2017

From 1995 to 2017, the world has observed an overall increasing trend in crude oil consumption, from 3.3 to 4.5 billion tons of oil equivalent (toe) (Fig. 1a). More specifically, we found that the oil footprint in developing countries, such as China and India, has increased rapidly. China's crude oil footprint grow considerably by four times, from 151.7 to 751.6 million toes, accounting for half of the global increase. India's crude oil footprint grow by almost five times, from 44.9 to 263.5 million toes, accounting for 19% of the global increase. By contrast, some developed countries, such as the United States (USA) and Japan, showed a shrinking trend in the crude oil footprint. The crude oil footprint in the USA peaked at 1.1 million toes in 2004 and decreased by 7% from 2004 to 2017. The oil footprint in Japan shows a fluctuating decreasing trend, with a decrease rate of 16% in the past two decades. Despite the contrary direction of the oil footprint trend in developed and developing countries, the per-capita footprints in developing countries are still dramatically lower than those in developed countries. In 2017, the national average per capita footprints varied from 0.2 toe/y in India and Indonesia to 5–6 toe/y in Malta and Norway.

The gaps between a country's crude oil footprint and its domestic use represent the net exports or imports of crude oil embodied in the commodity and service. From 1995 to 2017, the USA, EU, China (after 2009), and Japan were the primary importer of embodied oil, while India and Russia were the dominant suppliers (Fig. 1b). We also see some interesting transitions in the import/export trend of crude oil and embodied oil. For example, driven by the increasing final demand, the USA and China transit from net exporters of embodied oil to net

Table 1
Variables definition and descriptive statistics.

Variable name	Definition	Obs.	Mean	Std. Dev.	Minimum	Maximum
ppof	Oil footprint per capita (ton)	670	2.0	1.8	0.1	29.6
ppdu	Domestic use of crude oil per capita (ton)	670	1.6	1.2	0.0	5.9
ppgdpppp	GDP per capita, PPP (constant 2017 international $)	670	40994.1	17752.5	10949.7	120648.0
realpriceindex	Real index of oil product prices for industry and households, 2015 = 100	670	94.1	17.0	25.5	152.3

Table 2
Stationarity tests of the variables in levels and in first differences.

Variable	IPS		Fisher-ADF	
	Trend	Constant	Trend	Constant
ln(*ppof*)	0.0000	0.0000	0.0000	0.0000
ln(*ppdu*)	0.0224	0.0001	0.6990	0.0000
ln(*ppgdpppp*)	0.0000	0.9004	0.8562	0.0000
realpriceindex	0.4705	0.0000	0.9974	0.0000
△ln(*ppof*)	0.0000	0.0000	0.0000	0.0000
△ln(*ppdu*)	0.0000	0.0000	0.0000	0.0000
△ln(*ppgdpppp*)	0.0000	0.0000	0.0000	0.0000
△*realpriceindex*	0.0000	0.0000	0.0000	0.0000

Notes: the numbers in the table present the p values of the tests. Δ reflects the first difference operator.

Table 3
Cointegration tests.

	ln(*ppof*) as dependent variable		ln(*ppdu*) as dependent variable	
	Trend	No trend	Trend	No trend
Pedroni test				
Modified Phillips-Perron t	0.0011	0.0000	0.0112	0.1093
Phillips-Perron t	0.0000	0.0000	0.0000	0.0034
Augmented Dickey-Fuller t	0.0000	0.0000	0.0000	0.0002
Westerlund test				
Variance ratio	0.0014	0.0105	0.3780	0.1554

importers in 1999 and 2009, respectively. Although the net imports of embodied oil in the USA are shrinking, its final demand was still dependent on other countries' crude oil consumption until 2017. The EU has transitioned from a net embodied oil exporter to a net importer in 1999 and back to a net exporter in 2015. Before 1999, it provided oil products and exported embodied oil thanks to its strong refining capacity. Between 1999 and 2015, the older installations and less adaptability of European refineries led to declining competitiveness compared to the rapid capacity additions in Asia and the relatively low cost in the USA, so crude oil footprint exports declined and entered a period of net imports. After 2015, with industry consolidation, Europe again showed a net crude oil footprint export trend.

Comparing the embodied oil imports/exports with the direct crude oil trade, we can classify the countries into four categories (Fig. 1c, and see more details in Table A1). Countries in category one are net exporters of crude oil in apparent trade but net importers of embodied oil. For example, the UK before 2005 was one of such countryies that extracted a large amount of crude oil but had the limited refining capacity to meet its great final demand. Thus it exported crude oil and imported crude oil products, leaving part of the oil refining and production abroad. With the decrease in crude oil production amount, the UK became a net importer of crude oil after 2005; meanwhile, it was still the net importer of embodied oil. Countries in category two include the EU (1999–2014), the USA (after 1999), China (after 2009), Japan, Australia, and Switzerland. These countries not only imported crude oil directly but also imported embodied oil through commodity and service trade. Especially in China (since 2009) and Japan, these two countries have net imported millions of tonnes of crude oil directly, and the net imports of embodied oil were large too, accounting for 5%–45% and 19%–75%, respectively as the direct imports. Countries in category three are net importers of crude oil but net exporters of embodied oil, including the EU (before 1999 and after 2015), China (before 2009), and India (2000–2016). In India, up to 60% of its domestic use of crude oil was embodied in the commodity to meet the final demand of other countries (Table A3), accounting for 84% of its apparent crude oil imports. The number in China (before 2009) and the EU (before 1999 and after 2015) are mainly 1%–15% (Table A3). Countries in these categories are more like transit points, producing imported crude oil to oil products and then exporting them abroad. The last type incorporates countries that are net exporters of both crude oil and embodied oil. Examples of such countries are Canada and Russia, which have abundant oil resources and sufficient refining capacity to support other countries' demands.

4.2. Linking oil footprint with final demand

Fig. 2a and Fig. 2b provide a global overview of the final users and final consumption categories responsible for the oil demand. On a worldwide scale, 52%–65% of the oil demand is driven by household consumption, 7%–9% is related to government consumption, and 27%–39% is related to the capital formation (i.e., investment) from 1995 to 2017. Although the oil demand driven by household consumption accounts for the largest proportion, its proportion shows a slightly decreasing trend in this period, from 60% in 1995 to 56% in 2017. By contrast, the oil demand driven by capital formation shows an increasing trend, especially from 2001 to 2013 (+66%).

Regarding the various consumption categories, the oil used by mobility (gasoline, diesel, kerosene, and other oil fuels directly used in the land and air transportation by residents and the government) is the dominant category driving the oil demand, which is in accordance with our common sense. However, it is not as crucial as we probably perceived since it only accounts for 26%–36% of the total. Oil footprint driven by shelter use followed, accounting for 16%–22% of the total. The oil footprints driven by shelter use (e.g., lighting, cooking, heating, etc.) are mainly related to fuel combustion in households or power plants. Service operates nearly 20% of the oil demand, in which "health and social work services" and "public administration and defense services, compulsory social security services" dominant by 8%. Crude oil demand driven by service is usually in the form of naphtha-made plastics and oil fuels powering trucks and trains that move commodities. The consumption of construction and manufactured products also plays a significant role in crude oil demand, which causes 10%–14% of the oil footprint. Oil footprints driven by these categories are often embodied in a wide range of products, such as insulation, paint, asphalt, and other petrochemical products, and the fuel consumption by freight transportation for moving these commodities. Food, clothing, and trade are the minor contributors to the oil footprint (less than 6%), which mainly happens in the supply chain.

At the national scale, the consumption categories confirm the general patterns that households and mobility dominate the oil consumption, while enormous spatial heterogeneity exists (Fig. 2c and d). The share of oil footprint driven by investment is generally more significant in developing economies, such as China, Indonesia, and India, yet an exception exists in Norway. The share of oil footprint driven by shelter consumption in Norway is as large as 71%. In China, service and construction play incredibly significant roles in oil footprint, accounting for

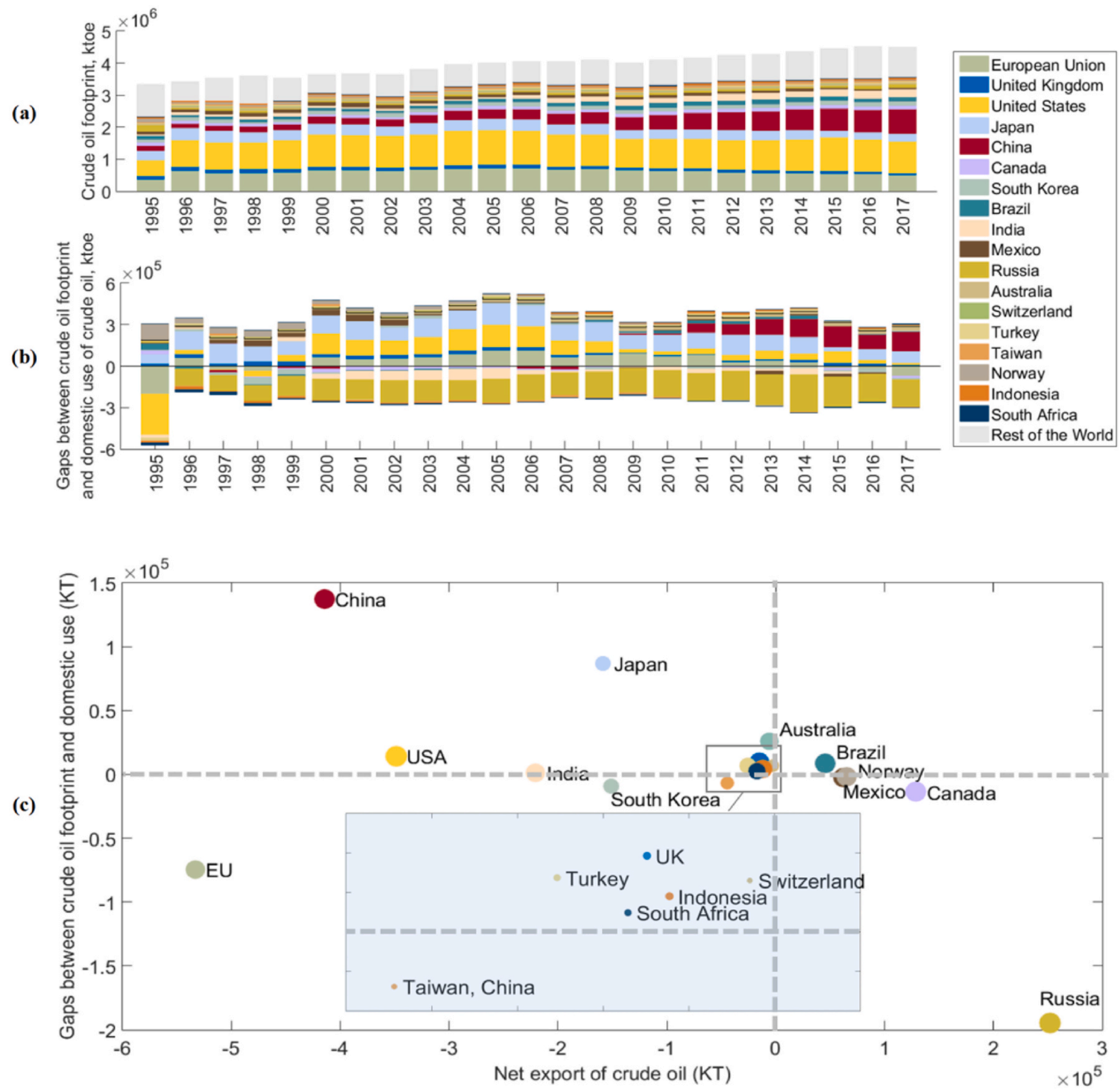

Fig. 1. The evolution of crude oil footprint (a), embodied oil imports (b) during 1995–2017, and the comparison between embodied oil imports and direct oil imports in 2017 (c). Crude oil footprint refers to the amount of crude oil required to meet a nation's final demand regardless of the location of oil extractions. Embodied oil imports refer to the gaps between a country's crude oil footprint and its domestic use of crude oil, in which negative values indicate embodied oil exports. The area of the markers in panel (c) is proportionate to the natural log form of crude oil production.

32% and 31% of the total, respectively, which even exceed mobility (accounting for 17%). In Indonesia, shelter and construction cause the most oil footprint, accounting for 32% and 21%, respectively, while mobility only accounts for 19%. In Norway, the largest consumption category is shelter (60%), followed by mobility (13%).

4.3. Drivers of the oil footprint evolution

A panel data analysis is employed to investigate the income and price elasticities of oil footprint in 30 countries where oil price data are available. In the long run, the income elasticity of oil footprint is 0.747 (Column II in Table 4, $0.747 = 0.207/0.277$), suggesting a significantly positive correlation between oil footprint increase and economic growth. When time trends and prices are controlled, every 1% increase in per capita GDP is associated with a 0.75% increase in per capita oil footprint. Without holding the time trend, the long-run income elasticity turns out to be insignificant. This variation is explainable as the time trend captures the impact of technology improvement, efficiency enhancement, and renewable substitution on curbing oil demand, which might offset the positive effects of economic growth. The significantly negative time trend coefficient ($0.046 = -0.0128/0.277$) supports such conjecture, showing that the per capita oil footprint decreases by 4.6% annually. With regard to the price elasticity, whether the time trend is controlled or not also matters. With the time trend and per capita GDP controlled, the long-run price elasticity is positive but not stably significant when a sub-sample is used (Table A4). If mixed with the effects of time trend, the price elasticity is significantly negative at -0.0091 (Column I in Table 4, $-0.0091 = -0.00173/0.190$), indicating a unit incline in the real price index of oil products links with a 0.91% decrease in per-capita oil footprint. The negative coefficient is expected and can be explained as price incline links with less oil demand, probably enabled by the technology improvement, efficiency enhancement, and energy substitution.

In the short run, economic growth also positively affects oil footprint increase with the time trend controlled, although the magnitude is lower than its long-run counterpart. A 1% increase in GDP growth rate is associated with a 0.48% increase in oil footprint growth rate. Moreover, the economic growth also has a two-year lagged positive effect on the oil footprint increase. The short-run price elasticity is insignificant, suggesting that an increase in oil product price doesn't have a temporal

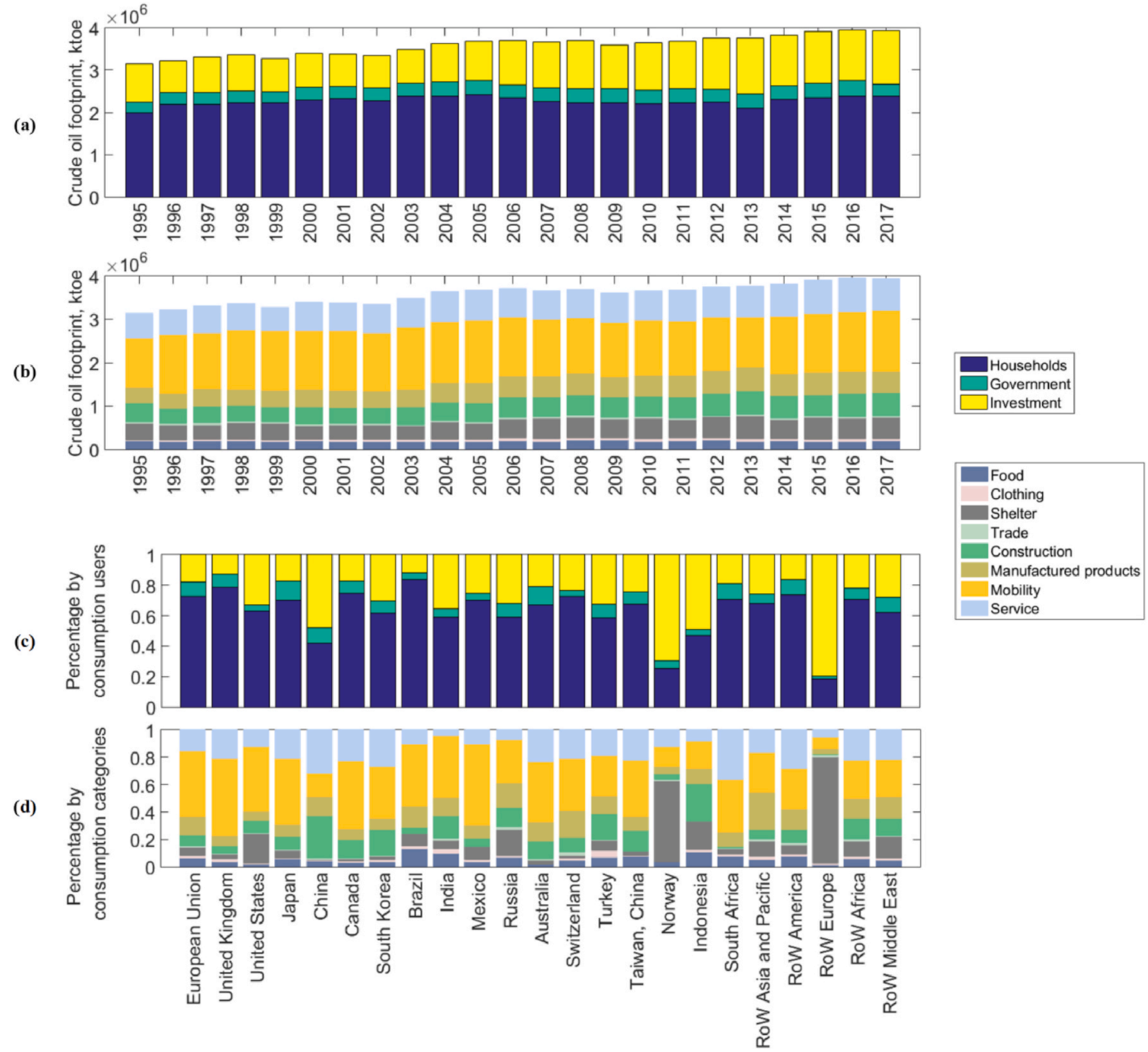

Fig. 2. Crude oil footprint and the percentage structure for different consumption users and categories. Panels (a) and (b) show the global oil footprint trend by consumption users and consumption categories. Panels (c) and (d) show the percentage of oil footprint by different consumption users and consumption categories in 2017.

demand-side impact. The coefficient for the error correction term is significantly negative as expected, which means that the deviations of short-term oil footprint from the long-term equilibrium are corrected in the next period.

For comparison, we also estimated the income and price elasticities of per-capita domestic use of crude oil in the same sample countries (Column III in Table 4). Since the null hypothesis of no cointegration is not rejected, we only estimate the short-run income and price elasticities using the FD model (Column III in Table 4). The results show that domestic oil use is more responsive to income changes than oil footprint in the short run, with an inelastic income elasticity around 0.632 and a positive price elasticity around 0.00252. The lack of a long-run equilibrium relationship, however, suggests that in our sample, income changes have little effect on domestic oil use in the long run. More comparisons between our findings and previous ones are presented in Table A5.

4.4. Additional tests on the elasticity

Breaking down the oil footprint into consumption- and investment-driven ones, we found that income and price elasticities vary by use purposes (Table 5). In the long run, the consumption-driven oil footprint is income elastic, while the investment-driven one is inelastic. Every 1% increase in per capita GDP is associated with a 1.43% increase in consumption-driven oil footprint and a 0.69% increase in investment-driven oil footprint in the long term. That implies oil demand by final consumption increases more rapidly than economic growth, while investment-driven oil demand is less responsive. Regarding the price elasticity, the opposite situation appears. Consumption-driven oil footprint has few responses to price changes, while investment-driven ones are more responsive. Every one-unit increase in the real index of oil product price is associated with a 0.98% increase in investment-driven oil footprint. In the short run, the consumption-driven oil footprint is insensitive to price and income, but the investment-driven one is positively correlated with both. The short-term income elasticity of investment-driven crude oil demand is particularly prominent, with a high elasticity coefficient of 2.19. That means that investment-driven crude oil demand has increased at a rate more than twice the per capita GDP growth rate.

Moreover, we found that the reactions of oil footprint driven by various consumption categories to changes in income and price are also differentiated. In the long run, oil footprints driven by clothing consumption, construction, manufacturing products, mobility, and services are elastic with respect to income. Their income elasticity appears to be between 1.16 and 3.35, indicating that oil demand by these categories, either in the forms of fuel oil or petrochemicals, increases more rapidly

Table 4
Income and price elasticities of oil footprint and domestic oil use.

	ln(*ppof*)		ln(*ppdu*)
	ARDL(3,2,2)	ARDL(3,2,1)	FD
$\ln(ppof)_{t-1}$	−0.190***	−0.277***	
$\ln(ppgdpppp)_{t-1}$	**−0.0597**	**0.207****	
$realpriceindext_{t-1}$	**−0.00173*****	**0.000958****	
$timetrend_{t-1}$		**−0.0128*****	
$\triangle\ln(ppof)_{t-1}$	−0.282***	−0.243***	−0.185*** #
$\triangle\ln(ppof)_{t-2}$	−0.0869***	−0.0887***	
$\Delta\ln(ppgdpppp)_t$	0.468	0.484*	0.632*
$\Delta\ln(ppgdpppp)_{t-1}$	0.621***	0.453**	
$\Delta realpriceindex_t$	0.000463	0.00122	0.00252*
$\Delta realpriceindex_{t-1}$	0.00249***		
Sample size	580	580	581
R^2	0.276	0.309	0.083
AIC	−747.3	−774.5	−440.6
BIC	−708	−735.2	−427.5

Notes: # this is the coefficient of $\Delta\ln(ppdu)_{t-1}$. *ppof* denotes oil footprint per capita. *ppdu* is the domestic use of crude oil per capita. *ppgdpppp* is GDP per capita, PPP (constant 2017 international $). *realpriceindex* denotes the real index of oil product prices for industry and households, 2015 = 100. $\triangle$ is the first difference operator. The preferred ARDL model is selected by the BIC. Coefficients in bold are not long-run elasticities but $-\varphi_i\beta_1$ as Eq. (3) indicates. Long-run elasticities β_1 is the coefficients divided by $-\varphi_i$. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

than affluence accumulation. In terms of the magnitude of effects, affluence increases exert greater influence on oil footprint driven by construction, followed by clothing, manufactured products, services, and mobility. Oil footprint driven by food consumption is moderately income inelastic, implying the nature of necessity goods. Regarding the price elasticity, only are the oil footprints driven by clothing, shelter, and manufactured products responsive to price changes but not at all for other categories. In the short term, the income elasticity of oil footprint driven by clothing, construction, and manufactured products varies from 1.016 to 2.039, and neither of the consumption categories is significant in price elasticity at a 5% confidential level.

5. Discussion

5.1. Oil connections among countries are more than direct trade but include virtual flows

A country's real crude oil demand does not only occur in its own country but may also be implicitly transferred to other countries through being embedded in the international trade. In this study, we first find that the crude oil footprint of developed countries is on a downward trend while developing countries are on an upward trend, which may be related to the rising consumption of the growing middle-income groups in developing countries. We also found the role some main economies played in the supply chain of embedded crude oil is divergent from that in the apparent trade. Some countries with high oil demand, such as China, the United States, and Japan, are not only direct importers of crude oil but also greatly dependent on foreign supplies of embedded oil. In contrast to these countries, major oil producers such as Russia and Canada net export both crude oil and embedded oil. This implies that in the event of geopolitical conflicts, such as the recent Russia-Ukraine war, the commodity trade sanctions that the West has launched against Russia will cause harm to the oil industry both directly and indirectly, e.g., jeopardizing Russia's crude oil industry through virtual flow changes and causing supply insufficiency to meet other countries' final demand. A comprehensive analysis of direct trade and virtual flow is useful for a more comprehensive understanding of each country's position and role in the global crude oil market and provides insights for designing trade policy and energy security strategy.

Table 5
Income and price elasticities of oil footprint driven by different consumption categories using ARDL-ECM estimations.

	I	II	III	IV	V	VI	VII	VIII	IX	X
	ln (OF_{cons})	ln (OF_{inv})	ln (OF_{food})	ln ($OF_{clothing}$)	ln ($OF_{shelter}$)	ln (OF_{trade})	ln ($OF_{construction}$)	ln ($OF_{manufacture}$)	ln ($OF_{mobility}$)	ln ($OF_{service}$)
$\ln(ppof_k)_{t-1}$	**−0.268*****	**−0.409*****	**−0.236*****	**−0.386*****	**−0.476*****	**−0.427*****	**−0.487*****	**−0.255*****	**−0.424*****	**−0.272*****
$\ln(ppgdpppp)_{t-1}$	**0.382****	**0.284***	**0.172***	**1.048*****	**−0.3**	**0.00339**	**1.632*****	**0.575*****	**0.492*****	**0.359****
$realpriceindext_{t-1}$	**0.000176**	**0.00401*****	**−0.000368**	**0.00289****	**0.00429****	**−0.00101**	**0.00208**	**0.00272*****	**0.000112**	**0.000515**
$timetrend_{t-1}$	**−0.0155*****	**−0.0164*****	**−0.00877*****	**−0.0186*****	**−0.0155****	**−0.0220*****	**−0.0381*****	−0.0183***	−0.0179***	−0.0156***
$\Delta\ln(ppof)_{t-1}$	−0.234***	−0.173***	−0.311***	−0.144	−0.167**	−0.209**	−0.268***	−0.206***	−0.220***	−0.169***
$\Delta\ln(ppof)_{t-2}$	−0.0772**	−0.021	−0.112***	0.0567	−0.0312	−0.0556	−0.0945***	−0.100***	−0.0272	−0.0862*
$\Delta\ln(ppdu)_{t-1}\ln(ppgdpppp)_t$	0.225	2.186***	0.0649	2.039***	−0.568	0.551	1.673*	1.935***	1.016**	−0.262
$\triangle$ *realpriceindex*$_t$	−0.000083	0.00453***	−0.000729	0.00132	0.00583	−0.00345*	0.000761	0.000737	0.00127	−0.000166
N	580	580	580	580	580	580	580	580	580	580
R^2	0.27	0.353	0.253	0.281	0.319	0.311	0.368	0.271	0.344	0.222
AIC	−619.7	−11.72	−317.2	215.2	706.5	392	621.7	−158.6	−60.08	−249.3
BIC	−584.8	23.19	−282.3	250.1	741.4	426.9	656.6	−123.7	−25.18	−214.4

Notes: *ppof* denotes oil footprint per capita. *ppdu* is the domestic use of crude oil per capita. *ppgdpppp* is GDP per capita, PPP (constant 2017 international $). *realpriceindex* denotes the real index of oil product prices for industry and households, 2015 = 100. $\triangle$ is the first difference operator. The preferred ARDL model is ARDL(3,3,1) for all types of oil footprints, selected by the Bayesian Information Criteria (BIC). Coefficients in bold are not long-run elasticities but $-\varphi_i\beta_1$ as Eq. (3) indicates. Long-run elasticities β_1 is the coefficients divided by $-\varphi_i$. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

5.2. Oil footprint is more responsive to income increases than price changes in the long tun

In terms of income elasticity, domestic crude oil use is more sensitive to economic growth in the short term, but the country's real crude oil footprint is not growing as fast as domestic use. This suggests that some of the oil demand increase may support final consumption in other countries. In the long term, the crude oil footprint increases significantly with economic growth, but on the same sample, there is no evidence that this positive correlation also exists for domestic oil use.

Regarding price elasticities, the insignificant long-run and positive short-run price elasticities in oil footprint with the time trend held imply that tariffs on end-use oil products would not be a viable tool to promote a reduction in a country's real oil demand. Excessive prices, such as pollution fees or carbon tax due to strict environmental regulations, increase production costs and discourage investment and production in the domestic crude oil industry. In this case, oil-intensive industries might be outsourced to other countries, which provide more trade comparative advantages and economic profits (Li et al., 2022), and the real oil demand of the country might not decrease as much as the domestic use does.

Another interesting finding is that the time trend, which incorporates the combined impacts of technology improvement, efficiency enhancement, and energy substitution, matters for estimating income and price elasticities. When the time trend is controlled, affluence accumulation has a significant positive effect on oil footprint in both the long and short term; otherwise, the income elasticities are insignificant. This is probably because the positive impact of economic growth is offset by the negative effect of technology and energy substitution progress. This effect also exists for price elasticity. In the long run, the oil footprint is positively correlated with price changes when the time trend is controlled, while the opposite is true (i.e., negative correlation) without controlling. For robustness check, we performed the regression on a subsample between 1995 and 2015 (Table A4), confirming that these conclusions remain robust after changing the sample size. The most straightforward implication of this finding is that addressing the factors captured by the time trend might facilitate the decoupling of oil footprint from economic growth or enable the price tools to effectively curb oil demand.

5.3. More mitigation effort should be put into other oil use than transportation fuels

The high income elasticity of oil footprint driven by clothing, construction, manufactured products, and services predicts the surge of oil demand in these categories emanating from economic growth. It alerts the policymakers that curbing the oil demand in the carbon-constrained world should not only focus on direct fuel oil use by mobility but also on managing the oil demand hidden in the products and services for other purposes. However, the task is challenging, as embodied oil use is primarily in the forms of petrochemical refining & processing products, which have fewer substitutions than fuel oil. New production technologies that use advanced biofuels, hydrogen, and synthetic fuels, the application of negative emission technologies, such as carbon capture and natural carbon sinks, and the reuse of petrochemical products are thus suggested to strengthen the mitigation efforts in the oil industry.

The variances in the elasticities of the oil footprint driven by different consumption categories also imply that investors should pay attention to the structural changes in oil demand and make rational investment decisions. Although oil demand will not be phased out completely from the economy in the short run due to the use of petrochemical products, the industry's production structure would be substantially different or even subvert to match the demand changes.

6. Conclusion and policy implications

Combing the oil production data with the MRIO tables, we calculated the crude oil footprint of 49 countries, territories, and regions from 1995 to 2017 and investigated the footprint's income and price elasticities based on ARDL estimation. Comparing a country's oil footprint and domestic use of crude oil, we revealed the role of countries in the oil market, not only in the direct oil trade but also in the virtual flows embedded in other commodities and services. Countries including the United States (after 1999), China (after 2009), and Japan imported a large amount of embodied oil through commodity and service trade. By contrast, Canada and Russia, which have abundant oil resources and sufficient refining capacity, are net exporters of both crude oil and embodied oil. Countries like 27 European countries and South Korea are net importers of direct crude oil but swing between net importers and net exporters of embodied oil back and forth as the refining capacity and the adaptability to the market change. These insights of the embodied oil trade facilitate decisions on refinery investment and policymaking concerning energy security, climate change, and international trade.

Furthermore, the panel data analysis on 30 OECD countries shows that oil footprints are more responsive to income increases in the long run than their short-run counterpart, with the elasticities around 0.75 and 0.48, respectively. With the time trend held, the price elasticity is not stablely significant or negative, implying that tariffs on end-use oil products would not be a viable tool to promote a reduction in a country's real oil demand. However, the negative impacts of time trends on oil footprint indicate that addressing the factors captured by the time trend, including technology improvement and energy substitution, are needed in oil use management. Moreover, the elasticities of oil footprint by consumption categories are divergent. Moreover, the divergent elasticities of oil footprint by consumption categories highlight that policymakers and investors should pay more attention to the oil demand embodied in construction, manufactured products, and services, which are predicted to surge more rapidly than economic growth.

CRediT authorship contribution statement

Xinzhu Zheng: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Visualization. **Ranran Wang:** Conceptualization, Writing – review & editing. **Brantley Liddle:** Data curation, Writing – review & editing. **Yuli Wen:** Writing – review & editing. **Lu Lin:** Writing – review & editing. **Lining Wang:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Table A1
Net export of crude oil versus net import of embodied oil by country.

Country	EU	UK	USA	Japan	China	Canada	South Korea	Brazil	India	Mexico	Russia	Australia	Switzerland	Turkey	Taiwan, China	Norway	Indonesia	South Africa	RoW
1995	38%	55%	73%	-30%	246%	84%	-10%	-178%	76%	6%	12%	-12%	-113%	76%	31%	92%	-22%	94%	23%
1996	-12%	77%	-7%	-61%	338%	4%	-16%	39%	-25%	5%	-107%	-43%	-114%	-71%	17%	26%	-70%	98%	-25%
1997	4%	74%	2%	-61%	101%	13%	15%	-4%	-6%	29%	-92%	-89%	-336%	-28%	-39%	29%	-30%	96%	-16%
1998	7%	106%	8%	-49%	41%	-1%	49%	18%	-2%	45%	-84%	-152%	-294%	0%	-6%	35%	-60%	97%	-1%
1999	0%	71%	-10%	-48%	55%	-29%	33%	35%	-52%	37%	-113%	-76%	-346%	4%	4%	34%	-55%	33%	-15%
2000	-13%	43%	-30%	-59%	32%	-93%	8%	-14%	52%	43%	-109%	-248%	-358%	-19%	-41%	17%	-43%	34%	-25%
2001	-9%	88%	-21%	-66%	4%	-103%	-2%	16%	80%	46%	-95%	-36	-251%	12%	8%	16%	-60%	19%	-22%
2002	-11%	75%	-21%	-45%	7%	-78%	-12%	64%	82%	44%	-88%	-276%	-324%	-5%	16%	17%	-48%	35%	-23%
2003	-12%	103%	-23%	-64%	-1%	-59%	-18%	159%	84%	13%	-67%	-184%	-338%	-22%	21%	17%	-72%	33%	-22%
2004	-16%	11	-28%	-65%	3%	-32%	-4%	46%	84%	9%	-58%	-362%	-224%	-33%	5%	13%	-416%	-7%	-23%
2005	-20%	-520%	-28%	-75%	5%	-23%	-4%	26%	79%	3%	-68%	-188%	-399%	-58%	12%	8%	-84%	9%	-24%
2006	-20%	-259%	-26%	-74%	14%	-22%	-8%	258%	28%	4%	-76%	-192%	-248%	-58%	18%	9%	-75%	-14%	-25%
2007	-12%	-306%	-18%	-55%	15%	-22%	-11%	11	10%	6%	-65%	-250%	-256%	-67%	27%	12%	141	5%	-18%
2008	-15%	-138%	-14%	-71%	1%	-19%	11%	609%	12%	4%	-78%	-243%	-180%	-36%	8%	3%	10	19%	-18%
2009	-18%	-82%	-4%	-60%	-5%	-12%	-3%	177%	2%	-6%	-73%	-393%	-171%	-69%	29%	13%	-174%	15%	-18%
2010	-14%	-85%	-6%	-65%	-4%	-1%	-1%	154%	20%	8%	-78%	-254%	-182%	-53%	17%	4%	-309%	-1%	-15%
2011	-16%	-27%	-9%	-62%	-27%	-8%	13%	161%	17%	16%	-82%	-198%	-233%	-75%	0%	0%	-792%	7%	-17%
2012	-6%	-21%	-9%	-81%	-29%	-11%	5%	212%	10%	3%	-89%	-199%	-353%	-70%	8%	-5%	-371%	-8%	-14%
2013	-8%	-43%	-16%	-62%	-41%	-5%	13%	143	8%	-39%	-96%	-179%	-205%	-55%	-1%	-2%	-156%	0%	-13%
2014	-7%	-63%	-12%	-73%	-43%	-7%	6%	270%	25%	16%	-121%	-160%	-144%	-68%	9%	-1%	-55%	12%	-11%
2015	3%	-161%	-23%	-19%	-45%	-16%	7%	11%	8%	-39%	-89%	-285%	-312%	-25%	1%	-1%	14%	6%	-7%
2016	4%	-140%	-8%	-47%	-28%	0%	16%	2%	1%	-14%	-78%	-489%	-303%	-17%	9%	5%	-68%	30%	-3%
2017	14%	-65%	-4%	-55%	-33%	-11%	6%	18%	-1%	-4%	-77%	-427%	-226%	-27%	16%	-3%	-37%	-14%	-8%

1 Net oil exporter but net importer of embodied oil
2 Net oil importer and net importer of embodied oil
3 Net oil importer but net exporter of embodied oil
4 Net oil exporter and net exporter of embodied oil

Table A2
The country and year samples included in the basic model of panel analysis

Country	The period of sample data
Australia	1995–2017
Austria	1995–2017
Belgium	1995–2017
Canada	1997–2017
Czech Republic	1995–2017
Denmark	1995–2017
Estonia	1997–2017
Finland	1995–2017
France	1995–2017
Germany	1995–2017
Greece	1995–2017
Hungary	1995–2017
Ireland	1995–2017
Italy	1995–2017
Japan	1995–2017
Latvia	1997–2017
Lithuania	2004–2017
Luxembourg	2007–2017
Mexico	1995–2017
Netherlands	1995–2017
Norway	1995–2017
Poland	1995–2017
Portugal	1995–2017
Slovenia	2000–2017
Spain	1995–2017
Sweden	1995–2017
Switzerland	1995–2017

(continued on next page)

Table A2 (*continued*)

Country	The period of sample data
Turkey	1995–2017
United Kingdom	1995–2017
United States	1995–2017

Notes: The availability of the average data of imported crude oil is the main factor constraining the sample size in the fundamental estimation.

Table A3
The proportion of a country's net imports/exports of embodied oil in its domestic use

	EU	UK	USA	Japan	China	Canada	South Korea	Brazil	India	Mexico	Russia	Australia	Switzerland	Turkey	Taiwan, China	Norway	Indonesia	South Africa	RoW
1995	-36%	20%	-37%	29%	2%	29%	10%	63%	-32%	5%	7%	3%	113%	-67%	-31%	810%	-13%	-64%	28%
1996	11%	24%	4%	61%	-5%	1%	16%	-14%	12%	5%	-69%	12%	114%	62%	-17%	226%	-37%	-67%	-28%
1997	-4%	22%	-1%	61%	-9%	4%	-15%	1%	3%	32%	-62%	22%	336%	24%	39%	282%	-18%	-70%	-18%
1998	-6%	40%	-4%	49%	-3%	0%	-49%	-6%	1%	49%	-65%	29%	294%	0%	6%	320%	-32%	-68%	-1%
1999	0%	37%	6%	48%	-8%	-9%	-33%	-9%	32%	36%	-85%	24%	346%	-3%	-4%	304%	-28%	-22%	-19%
2000	12%	19%	18%	59%	-9%	-29%	-8%	3%	-35%	50%	-83%	24%	358%	17%	41%	155%	-14%	-23%	-33%
2001	9%	35%	13%	66%	-1%	-30%	2%	-3%	-55%	52%	-79%	43%	251%	-11%	-8%	193%	-17%	-14%	-27%
2002	10%	26%	12%	45%	-2%	-28%	12%	-5%	-56%	51%	-82%	25%	324%	4%	-16%	124%	-10%	-26%	-26%
2003	11%	25%	14%	64%	0%	-22%	18%	-9%	-59%	16%	-76%	30%	338%	20%	-21%	103%	-10%	-27%	-26%
2004	15%	23%	17%	64%	-1%	-12%	4%	-5%	-60%	11%	-73%	56%	224%	30%	-5%	77%	-17%	6%	-30%
2005	18%	28%	18%	75%	-2%	-8%	4%	-1%	-58%	3%	-79%	48%	398%	53%	-12%	38%	-5%	-7%	-31%
2006	18%	28%	17%	74%	-6%	-10%	8%	4%	-21%	5%	-82%	57%	247%	53%	-18%	38%	4%	10%	-34%
2007	11%	23%	11%	54%	-7%	-10%	11%	3%	-7%	7%	-72%	59%	256%	61%	-27%	54%	14%	-4%	-25%
2008	14%	19%	9%	70%	-1%	-9%	-11%	14%	-9%	4%	-77%	65%	180%	33%	-8%	13%	27%	-16%	-24%
2009	16%	9%	3%	59%	3%	-6%	3%	12%	-2%	-5%	-74%	82%	170%	59%	-29%	50%	15%	-13%	-23%
2010	12%	14%	3%	64%	2%	-1%	1%	20%	-16%	8%	-74%	58%	181%	46%	-17%	13%	22%	1%	-19%
2011	15%	8%	5%	62%	15%	-6%	-13%	19%	-14%	15%	-76%	58%	233%	66%	0%	1%	31%	-5%	-23%
2012	6%	8%	5%	81%	16%	-8%	-5%	17%	-8%	2%	-76%	61%	351%	63%	-8%	-12%	31%	6%	-19%
2013	8%	16%	7%	62%	23%	-4%	-13%	15%	-7%	-31%	-80%	66%	205%	48%	1%	-5%	23%	0%	-17%
2014	6%	22%	5%	73%	25%	-6%	-6%	17%	-21%	12%	-88%	59%	143%	59%	-9%	-3%	10%	-10%	-14%
2015	-2%	43%	8%	19%	27%	-14%	-7%	2%	-6%	-35%	-75%	87%	305%	23%	-1%	-4%	-3%	-5%	-9%
2016	-4%	31%	3%	46%	18%	0%	-16%	1%	-1%	-15%	-68%	109%	293%	15%	-9%	15%	11%	-24%	-4%
2017	-13%	15%	1%	54%	22%	-11%	-6%	7%	1%	-5%	-66%	125%	214%	24%	-16%	-7%	8%	11%	-10%

Table A4
Income and price elasticities of oil footprint using sub-sample 1995-2015

	ln(*ppof*)	
	ARDL(3,1,1)	ARDL(3,2,1)
$\ln(ppof)_{t-1}$	−0.245***	−0.319***
$\ln(ppgdpppp)_{t-1}$	**0.087**	**0.358*****
$realpriceindext_{t-1}$	**−0.00202*****	**0.000439**
$timetrend_{t-1}$		**−0.0133*****
$\triangle\ln(ppof)_{t-1}$	−0.177**	−0.135**
$\triangle\ln(ppof)_{t-2}$	−0.0870***	−0.0831***
$\triangle \ln(ppgdpppp)_{t}$	0.409	0.682***
$\triangle \ln(ppgdpppp)_{t-1}$	0.764***	
$\triangle realpriceindex_{t}$	0.000548	0.00103
Sample size	520	520
R^2	0.257	0.271
AIC	−701.8	−711.2
BIC	−667.8	−677.1

Notes: *ppof* denotes oil footprint per capita. *ppgdpppp* is GDP per capita, PPP (constant 2017 international $). *realpriceindex* denotes the real index of oil product prices for industry and households, 2015 = 100. $\triangle$ is the first difference operator. The preferred autoregressive distributed lag (ARDL) model is selected by the Bayesian Information Criteria (BIC). Coefficients in bold are not long-run elasticities but $-\varphi_i\beta_1$ as Eq. (3) indicates. Long-run elasticities β_1 is the coefficients divided by $-\varphi_i$. $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table A5
Summary of selected studies on income and price elasticities on oil demand

Study	Country and time period	Dependent variable	Methodology	Income elasticity		Price elasticity	
				Short-run	Long-run	Short-run	Long-run
Ziramba (2010) (Ziramba, 2010)	South Africa, 1980–2006 with a annually frequency	Imported crude oil	ARDL-ECM	ns	0.429	ns	−0.147
Eleyan et al. (2021) (Eleyan et al., 2021)	BRICS countries, 1990:Q1-2018:Q4 with a quarterly frequency	Oil demand	TVP	–	from −0.646 to 1.193	–	from −0.186 to 0.270
Raza & Lin, 2021 (Yousaf Raza and Lin, 2021)	Pakistan, 1986–2018	Imported crude oil	ARDL-ECM	0.4774	0.2008	0.0854	−0.0406
Raghoo and Surroop (2020) (Raghoo and Surroop, 2020)	Mauritius, 1990 to 2017	Fuel oil demand	ARDL–ECM	0.988	1.193	ns	−0.431
Altinay (2007) (Altinay, 2007)	Turkey, 1980–2005	Imported crude oil	ARDL–ECM	0.635	0.608	−0.104	0.182
Cooper, 2003b (Cooper, 2003b)	23 countries, 1971 to 2000	Crude oil demand	PAM	na	na	from −0.109 to 0.023	from −0.568 to 0.038
Dées et al., 2007 (Dées et al., 2007)	10 regions, 1984:Q1-2002:Q1 with a quarterly frequency	Oil demand	ARDL-ECM	from 0.001 to 0.82	from 0.17 to 0.98	from −0.00 to −0.07	na
This study	30 countries, 1995–2017	Oil footprint	ARDL-ECM	0.742	0.764	ns	0.0016

Notes: ns: not significant at 10% confidential level; na: not applicable; ARDL: Autoregressive distributed lag; ECM: Error correction model; TVP: Time-varying parameter; PAM: Partial Adjustment Model; FD: First Difference Model.

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