Energy content of world trade

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Abstract

This paper constructs a comprehensive dataset of oil and total energy embedded in world trade of manufacturing goods for 73 countries from 1978 to 2000. Applying the data to debates on the dependency on foreign energy sources makes clear that achieving complete energy independence in the foreseeable future is unlikely to be feasible and may not be desirable. Applying it to the discussion of environmental Kuznets curves (EKC)s highlights an important distinction between production and consumption of energy. Richer countries use relatively less energy in their industrial production yet still consume relatively large amounts of energy indirectly. A further investigation largely excludes structural shifts of production in and out of the manufacturing sector as an explanation for the downward-sloping portion of the EKC. Country-level analyses add caveats but show tentative support for the cross-country conclusions.

1. Introduction

The United States imports around 10 million barrels of oil per day. This number is widely known. It is also of much concern in the policy community. “Energy independence” has been buzzword in Washington since the 1970s. The Council on Foreign Relations (CFR) Independent Task Force Report on the “National Security Consequences of U.S. Oil Dependency” identified it as one of the main myths. In the foreseeable future, the United States will depend on imported oil, “barring draconian measures” (CFR, 2007) that, in any case, would be ill advised. More importantly, even if the United States becomes “energy independent” in the sense conveyed in the report and in much of the policy discussion, it would still depend on imported oil through its trade in manufacturing goods.

In 2000, the United States imported 0.8 million barrels of oil per day embedded in imported manufacturing goods. The number increases to 2.4 million barrels of oil-equivalent energy when accounting for all energy sources (compared to 13.2 million barrels of oil-equivalent energy imported directly). These embedded energy numbers are not officially calculated and do not register in the policy discussion on energy dependency. Section 2 of this paper focuses on this dataset, which accounts for how much oil and energy are embedded in world trade and lays out possible policy implications.

Using detailed data on the energy content of world trade and given a high correlation between energy use and CO2-emissions, we can reexamine a well-known and much-discussed relationship between growth and the environment in Section 3. The environmental Kuznets curve (EKC) postulates an inverse-U relationship between pollution and per-capita income. At low levels of development, pollution increases with income at an ever-decreasing rate until the relationship reverses at high levels of development. Pollution now decreases with income (Fig. 1). Described in theory and supported by anecdotal evidence, broad cross-country empirical studies provide a mixed picture.

Grossman and Krueger (1995) and Selden and Song (1994) were the first to find cross-country EKCs, but subsequent studies have cast doubts on the general conclusions. Harbaugh et al. (2002) reexamine the evidence and find that the results are highly sensitive to covariates and sample size and ultimately conclude, “that there is little empirical support for an inverted U-shaped relationship between several important air pollutants and national income.” Dijkgraaf and Vollebergh (2005) also challenge

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Fig. 1. Common theoretical explanation of observed environmental Kuznets curve (EKC) patterns.

Fig. 2. Trade allows a discrepancy between environmental Kuznets curve (EKC) associated with consumption and the actual environmental impact from production.

The existence of an EKC for CO₂ emissions, which had previously been shown by Schmalensee et al. (1998). Cole (2003) provides a notable recent exception. He finds support for robust cross-country EKCs for several common pollutants. Brock and Taylor (2004) provide a well-grounded theoretical explanation for the EKC and successfully test the predicted convergence in pollution across OECD countries. Panayotou (2000) and Smulders (2000) offer surveys of the theoretical explanations driving the EKC. Others have looked directly at the energy-income relationship, which ought to be similar to patterns observed for CO₂ emissions (Galli, 1998; Suri and Chapman, 1998; Medlock and Soligo, 2001; Judson et al., 1999, Richmond and Kaufmann, 2006).⁴

Trade complicates the basic EKC-story. It enables countries to produce in different sectors than they consume. Suri and Chapman (1998), for example, find that richer countries are increasingly importing more energy-intensive products. Including trade also enables a separation of production and consumption EKCs. Potentially harmful effects from energy-intensive goods accrue at the point of production. Consuming these goods releases no further significant quantities of pollution (Fig. 2). We may, therefore, expect to find EKCs for production of energy, but perhaps none for consumption.

We will differentiate between production and consumption EKCs in Section 3. Following Aldy (2005, 2007), who focuses on CO₂ emissions in the United States and inter-state electricity trade, we calculate consumption of oil and total energy in manufacturing using net factor trades combined with readily available production figures. Subsequently, we will focus on structural shifts in and out of the manufacturing sector and largely exclude them as potential drivers of the EKC. Lastly, we will analyze the EKC more closely using country-level time series econometric techniques. But first, a closer look at the dataset of factor trades in oil and energy.

2. Direct and embedded energy imports

The market for oil – and energy in general – is globally integrated along two dimensions. Two-thirds of the world’s oil extracted each day crosses an international border before it is consumed as a primary energy source. Supplies of oil are concentrated in relatively few countries. Five countries hold more than 60 percent of the world’s proven oil reserves; the top twenty hold 95 percent.⁶ This enormous supply concentration is the root of most national security concerns in the context of energy markets.

Second, oil crosses borders embedded in manufacturing goods. In 2000, global trade in manufacturing goods accounted for 2.9 million barrels of oil per day, compared to 33.2 million barrels of oil per day traded directly. This calculation of oil used in industry includes oil used as a direct input in manufacturing processes. It does not account for indirect oil used, for example by labor. Table 1 lists oil and energy import figures for the United States. The table includes direct imports and contrasts them with oil and energy embedded in manufacturing imports. It also presents net import figures. The United States is a large net importer, yet some oil and other energy is also re-exported. This holds particularly true for oil and energy embedded in exports. On net, the United States imports 0.4 million barrels of oil embedded in trade per day, while the total figure for embedded imports amounts to 0.8 million barrels in 2000. This last figure is the salient number for energy security considerations, where the entire dependence on foreign oil is more relevant than “net dependence,” imports minus exports.

Appendix A describes the data sources. We employ oil, coal and gas consumption data for industry and the total economy as well as their exports and imports and make two assumptions about crude oil use.

First, we assume that the ratio of crude use to total energy use in manufacturing for country \( c \) and time \( t \), \( \text{oil} / \text{e}_{ct} \), is the same as in the overall economy, indicated by \( T \) for total, \( \text{oil} / \text{e}^T_{ct} \). This assumption enables us to calculate total oil use in the manufacturing sector:

\[
\text{oil}_{ct} = \left[ \frac{\text{oil}}{\text{e}^T_{ct}} \right] \text{e}_{ct},
\]

subsequently presented in units of barrels per capita per day and referred to as \( \text{oil}^\text{prod}_{ct} \), used in parallel with \( e^\text{prod}_{ct} \). For later use, we can split up \( \text{oil}^\text{prod}_{ct} \) and \( e^\text{prod}_{ct} \) into intensities per unit of manufacturing output and manufacturing output, \( y_{ct} \), in million 2000 US dollars:

\[
\text{oil}^\text{prod}_{ct} = \frac{\text{oil}}{y} \text{e}_{ct}, \quad e^\text{prod}_{ct} = \frac{e^\text{prod}}{y} \text{e}_{ct},
\]

where \( y_{ct} \) figures come directly from UNIDO’s Industrial Statistics Database aggregated across industrial sectors. It is unclear which bias this assumption introduces, if any. While it is true that instead of using crude oil directly, industry often relies on other fuel sources, it is unclear where the offsets occur.

⁴ EKC hypotheses are often tested for both aggregate and per capita pollution and emissions. Grossman and Krueger (1995), for example, analyze aggregate figures; Selden and Song (1994) focus on per capita values. We will discuss the distinction further in Section 3.

⁵ Schmalensee et al. (1998) calculate a correlation of 0.9974 between CO₂ emissions and total energy use for a large panel of 141 countries between 1950 and 1990.

⁶ The five countries with the largest reserves are Saudi Arabia, Canada, Iran, Iraq, and Kuwait. They are also the only ones with reserves above 100 billion barrels. (Oil and Gas Journal 2005; also see EIA, 2006; CFR, 2007.)
However, Kellogg also finds that the absolute magnitude of the assumption may underestimate the energy content of trade. This conjecture for coal. If this is the overwhelming effect, the energy content suggests that poorer countries may export particularly energy and pollution-intensive products. Kellogg (2007) confirms this hypothesis for manufacturing jobs. Rather, it is competing with Mexico, a country like China is not directly competing with the United States than competition based on energy-intensity. In particular, a market is relatively global compared to markets for labor. We would expect that most trade be driven by wage differentials rather than competition based on energy-intensity. In particular, a country like China is not directly competing with the United States for manufacturing jobs. Rather, it is competing with Mexico, Malaysia and other lower-wage producers, which employ similarly high-energy intensive technologies. If this effect dominates, this assumption is unlikely to introduce any significant bias.

Lastly, we calculate oil and energy use in consumption of manufactured goods by subtracting net manufacturing exports from production figures:

\[ o_{i,ct}^{\text{cons}} = o_{i,ct}^{\text{prod}} - o_{i,ct}^{\text{X}} - o_{i,ct}^{M} \]

\[ e_{i,ct}^{\text{cons}} = e_{i,ct}^{\text{prod}} - e_{i,ct}^{X} - e_{i,ct}^{M} \]

Throughout the paper, we frequently refer to both \( o_{i,ct}^{\text{cons}} \) and \( e_{i,ct}^{\text{cons}} \) by the abbreviation \( E_{ct} \), where \( i \in \{\text{cons,prod}\} \), and normalize all quantities to units of barrels of oil per capita per day. The complete dataset for all 73 countries in the sample spanning the years 1978 through 2000 is available on http://gagner.com/research/energy_trade.

Others have worked on similar energy trade datasets, most notably Hertwich and Peters (2009), which focuses on cross-national and cross-sectional data. Wyckoff and Roop (1994) calculate the energy content of imports using a methodology analogous to this analysis, with the goal of imputing carbon contents and the possibility for emissions leakage in a Kyoto-style climate change agreement. Their analysis focuses on one year between 1984 and 1986 for each of six countries: Canada, France, Germany, Japan, the United Kingdom and the United States. See also Machado et al. (2001), who calculate the energy content of trade for Brazil in 1995, and Kellogg (2007), who calculates detailed factor trades in coal for 64 sectors in 17 countries for the years 1985–1997.

### 2.1. Direct and indirect dependency on foreign energy sources

The extent of the present dataset and the inclusion of both direct and embedded energy flows ought to enable a better-informed energy security debate. For one, the focus on embedded energy content highlights the misconception that energy independence is possible or even desirable. Short of cutting off all world trade, the United States will always depend on foreign energy sources through table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Oil Imports</th>
<th>Net oil imports</th>
<th>Energy imports</th>
<th>Net energy imports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct</td>
<td>Embedded</td>
<td>Direct</td>
<td>Embedded</td>
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<tr>
<td>1978</td>
<td>6.75</td>
<td>0.34</td>
<td>6.67</td>
<td>0.21</td>
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<tr>
<td>1979</td>
<td>6.82</td>
<td>0.32</td>
<td>6.75</td>
<td>0.11</td>
</tr>
<tr>
<td>1980</td>
<td>5.51</td>
<td>0.28</td>
<td>5.43</td>
<td>0.05</td>
</tr>
<tr>
<td>1981</td>
<td>4.61</td>
<td>0.28</td>
<td>4.57</td>
<td>0.08</td>
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<tr>
<td>1982</td>
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<td>0.30</td>
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</tr>
<tr>
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<td>3.57</td>
<td>0.34</td>
<td>3.55</td>
<td>0.19</td>
</tr>
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<td>1984</td>
<td>3.68</td>
<td>0.39</td>
<td>3.67</td>
<td>0.23</td>
</tr>
<tr>
<td>1985</td>
<td>3.42</td>
<td>0.40</td>
<td>3.40</td>
<td>0.24</td>
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<td>4.39</td>
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<td>4.38</td>
<td>0.24</td>
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<tr>
<td>1987</td>
<td>4.86</td>
<td>0.43</td>
<td>4.84</td>
<td>0.25</td>
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<tr>
<td>1988</td>
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<td>0.43</td>
<td>5.15</td>
<td>0.22</td>
</tr>
<tr>
<td>1989</td>
<td>5.94</td>
<td>0.46</td>
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<tr>
<td>1991</td>
<td>5.88</td>
<td>0.45</td>
<td>5.87</td>
<td>0.23</td>
</tr>
<tr>
<td>1992</td>
<td>6.26</td>
<td>0.46</td>
<td>6.25</td>
<td>0.24</td>
</tr>
<tr>
<td>1993</td>
<td>6.91</td>
<td>0.52</td>
<td>6.91</td>
<td>0.27</td>
</tr>
<tr>
<td>1994</td>
<td>7.26</td>
<td>0.56</td>
<td>7.25</td>
<td>0.30</td>
</tr>
<tr>
<td>1995</td>
<td>7.36</td>
<td>0.61</td>
<td>7.36</td>
<td>0.35</td>
</tr>
<tr>
<td>1996</td>
<td>7.78</td>
<td>0.63</td>
<td>7.73</td>
<td>–</td>
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<tr>
<td>1997</td>
<td>8.49</td>
<td>0.71</td>
<td>8.40</td>
<td>0.43</td>
</tr>
<tr>
<td>1998</td>
<td>8.91</td>
<td>0.75</td>
<td>8.81</td>
<td>0.46</td>
</tr>
<tr>
<td>1999</td>
<td>8.92</td>
<td>0.74</td>
<td>8.81</td>
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<tr>
<td>2000</td>
<td>9.30</td>
<td>0.80</td>
<td>9.25</td>
<td>0.42</td>
</tr>
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</table>

its imports of manufacturing goods, even if it were possible to limit direct energy imports.

Other more intricate implications focus on political realignments of U.S. trading partners and potential leverage of the United States, given its overall trade relationships. CFR (2007) highlights Chinese bilateral oil deals as an illustration of political interventions in oil markets. The present data allow us to quantify the energy link between the United States and China in more detail. In the next section will take a closer look at other implications arising from direct energy imports.

Table 2
Oil and energy imports from China to the United States (million barrels of oil and oil-equivalent per day) and oil and energy import intensities for imports from China and all imports (barrels of oil and oil-equivalent per million dollars of imports in 2000 dollars).

<table>
<thead>
<tr>
<th>Year</th>
<th>Embedded oil imports from China</th>
<th>Embedded energy imports from China</th>
<th>Oil intensity</th>
<th>Energy intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>All imports</td>
<td>All imports</td>
</tr>
<tr>
<td>1978</td>
<td>–</td>
<td>–</td>
<td>458.7</td>
<td>–</td>
</tr>
<tr>
<td>1979</td>
<td>–</td>
<td>–</td>
<td>409.7</td>
<td>726.8</td>
</tr>
<tr>
<td>1980</td>
<td>0.002</td>
<td>0.014</td>
<td>355.2</td>
<td>711.9</td>
</tr>
<tr>
<td>1981</td>
<td>0.004</td>
<td>0.024</td>
<td>346.7</td>
<td>670.3</td>
</tr>
<tr>
<td>1982</td>
<td>0.005</td>
<td>0.032</td>
<td>392.1</td>
<td>676.6</td>
</tr>
<tr>
<td>1983</td>
<td>0.005</td>
<td>0.034</td>
<td>398.1</td>
<td>790.4</td>
</tr>
<tr>
<td>1984</td>
<td>0.007</td>
<td>0.049</td>
<td>362.1</td>
<td>864.4</td>
</tr>
<tr>
<td>1985</td>
<td>0.007</td>
<td>0.052</td>
<td>349.8</td>
<td>778.5</td>
</tr>
<tr>
<td>1986</td>
<td>0.010</td>
<td>0.073</td>
<td>328.1</td>
<td>778.7</td>
</tr>
<tr>
<td>1987</td>
<td>0.014</td>
<td>0.100</td>
<td>323.8</td>
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<tr>
<td>1988</td>
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<td>0.089</td>
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<td>1989</td>
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<td>0.104</td>
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<td>679.3</td>
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<tr>
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<tr>
<td>1995</td>
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<td>856.4</td>
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<tr>
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<td>0.448</td>
<td>311.4</td>
<td>879.6</td>
</tr>
<tr>
<td>1997</td>
<td>0.072</td>
<td>0.460</td>
<td>324.1</td>
<td>882.1</td>
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<td>0.542</td>
<td>291.3</td>
<td>860.9</td>
</tr>
<tr>
<td>2000</td>
<td>0.105</td>
<td>0.559</td>
<td>279.2</td>
<td>850.8</td>
</tr>
</tbody>
</table>


3. Energy, growth, and trade

The extent of the present dataset allows a reexamination of the energy and income relationship. Environmental Kuznets Curve (EKC) analyses commonly argue that aggregate pollution first increases with rising per capita income and then falls, tracing out an inverse U-relationship. Following Selden and Song (1994), Cole (2000) and Richmond and Kaufmann (2006), among others, this present analysis focuses on per capita figures. This disentangles the effects of energy use per capita and population growth. The EKC story, however, is still the same. Poor countries use little energy per capita. As the economy gets richer, each person’s energy use increases and may ultimately peak before falling for high levels of per capita income. The underlying cause for EKCs can be twofold: structural shifts and technological changes. Structure, in turn, can imply shifts from agriculture to manufacturing and services as well as shifts within manufacturing from clean to dirty sectors, and vice versa. The following analysis conflates both structural shifts and technological changes. We will address this issue in Section 4. First, we focus on overall per capita EKCs.

Aldy (2005, 2007) explores EKCs for CO2 emissions across the continental United States. He groups his analysis by looking at production and consumption EKCs independently. Since U.S. interstate trade data are not available, Aldy focuses on trade in electricity among states. The production of electricity causes CO2 emissions, while its consumption is relatively clean. Aldy hypothesizes that richer states still consume high levels of electricity but purchase it increasingly from relatively poorer states. CO2 emissions associated with production across U.S. states show the typical inverse U-shape; CO2 emissions associated with consumption rise initially but then flatten out and do not decrease for wealthy states.

We adapt Aldy’s methodology to the cross-country energy dataset. Comprehensive production data for oil, oileq|prod and energy, oileq|prod in the manufacturing sector are readily available and have been well studied in an EKC-context.® The dataset of oil and energy embedded in bilateral trade for manufacturing goods

9 See Galli (1998), Medlock and Soligo (2001), and – for the most comprehensive treatment to date – Judson et al. (1999).
allows us to calculate the consumption of oil, \( e_{ct}^{cons} \), and energy, \( e_{ct}^{prod} \), associated with the industrial sector.\(^{10}\) We denote oil use in barrels of oil per capita per day and energy use in barrel-equivalent per capita per day. Subsequently, we will depict both \( o_{ct}^{cons} \) and \( e_{ct}^{prod} \) by \( E_{ct}^{i} \), where \( i \in \{ \text{cons, prod} \} \). We employ a standard EKC framework. We estimate oil and energy use in manufacturing, \( E_{ct}^{i} \), as a function of overall GDP per capita, \( Y_{ct} \), for countries \( c \) and years \( t \) with estimation parameters \( \beta_i \), where \( E_{ct}^{i} \) and \( Y_{ct} \) enter the equation in form of their natural logarithms:

\[
\ln \left( E_{ct}^{i} \right) = \beta_{0}^{i} + \beta_{1}^{i} \ln \left( Y_{ct} \right) + \epsilon_{ct}^{i} + v_{ct}^{i} + u_{ct}^{i} \tag{1}
\]

\( \ln \) for oil and energy associated with both consumption and production. The terms \( v_{ct}^{i} \) and \( u_{ct}^{i} \) are country and year fixed effects,
respectively, and $\varepsilon_{ct}$ is the exogenous error term. The first set of regressions employs quadratic and cubic functional forms, where $F$ represents either a quadratic or cubic function in $\ln(Y_{ct})$. The subscript $k$ in Eq. (1) takes on values from 1 to 2 for quadratic and 1 to 3 for cubic specifications.

Table 3 shows results for quadratic and cubic regressions with oil use as the dependent variable. Table 4 repeats the same for total energy use. While quadratic OLS specifications for oil are generally not significant, FGLS specifications in (5)–(6) are highly significant at the one percent significance level and show the expected EKC shape of an inverted-U. Cubic specifications are significant throughout and provide better fits for the data than quadratic functions. Graphical analyses show that they, too, follow inverted-U shapes. Regression results for total energy use are similar, except that in the quadratic FGLS specification, only the slopes are significant. All cubic specifications are once again significant.

Fig. 3 demonstrates a striking relationship prevalent in all specifications. Regressions with production as the dependent variable show more prominently curved U-shape patterns. This relationship holds for both oil and energy. All other specifications follow the same pattern: richer economies produce less oil and energy than they consume embedded in manufacturing goods. Poorer economies produce more than they consume.

The difference between consumption and production of oil is statistically significant. At first glance, we see that predicted consumption peaks are much higher than production peaks. FGLS specifications for oil predict a peak of oil use in consumption at a per capita income of $30,854, with a standard error of $3387). The peak for production occurs at $24,014, with an error of $1771 (Table 3, columns (7)–(8)). The corresponding peaks for total energy are $54,251 for consumption and $39,655 for production, with errors of $11,234 and $4951, respectively. To test the significance of these differences, mirroring Aldy (2005), we create regression results for total energy use.

Table 3 shows results for quadratic and cubic regressions with oil use as the dependent variable: International Energy Agency’s Extended Energy Balances, Feenstra et al.’s (1998) world trade flows dataset, and United Nations Industrial Development Organization’s Industrial Statistics Database. See Appendix A for a detailed description of the data.
Recent developments, particularly in the United States, may account for some of the consumption and production disparities. We now turn to the question of whether underlying structural differences across economies account for the observed overall EKC patterns. This line of research follows a long tradition in the environmental trade literature. Trade influences a country's energy use through three avenues: size of the economy, structural changes and technology. Grossman and Krueger (1993) introduced this classification for identifying the effects of trade on the income distribution in Fig. 3 represents the United States. We also repeat the graphical analysis by employing a cubic spline function of income, \( F[\ln(Yt)] \). This more flexible functional form better approximates the data by not constraining the overall model to a quadratic or cubic forms. We employ spline functions divided into 2 to 12 knots for production and consumption of both oil and energy measures. The resulting figures are sensitive to including the United States, particularly as more knots are added.

### Table 5

<table>
<thead>
<tr>
<th></th>
<th>(1) Oil Quadratic</th>
<th>(2) Oil Cubic</th>
<th>(3) Energy Quadratic</th>
<th>(4) Energy Cubic</th>
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<td>42.34***</td>
<td>49.26***</td>
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<tr>
<td></td>
<td>[29.88***]</td>
<td>[41.25***]</td>
<td>[25.97***]</td>
<td>[29.71***]</td>
</tr>
<tr>
<td>( \chi^2 ) statistic ( H_1 )</td>
<td>35.44***</td>
<td>38.40***</td>
<td>48.61***</td>
<td>57.72***</td>
</tr>
<tr>
<td>( \chi^2 ) statistic ( H_2 )</td>
<td>–</td>
<td>5.22***</td>
<td>–</td>
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<td></td>
<td>[1.96]</td>
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</tbody>
</table>

Sources: International Energy Agency’s Extended Energy Balances, Feenstra et al.’s (2005) world trade flows dataset, and United Nations Industrial Development Organization’s Industrial Statistics Database. See Appendix A for a detailed description of the data. Ordinary least squares (OLS) regressions for consumption and production-based estimations with country and year fixed effects. All test statistics are based on robust simultaneous variance-covariance matrices. [Square brackets] present test statistics for robust errors clustered by country.

*** Indicate significance at the 1% level.
** Indicate significance at the 5% level.
* Indicate significance at the 10% level.

Fig. 4 presents predicted oil use associated with consumption and production from cubic spline regressions with and without the United States. Predicted values come from cubic spline OLS regressions with 12 evenly spaced knots. Sources: International Energy Agency’s Extended Energy Balances, Feenstra et al.’s (2005) world trade flows dataset, and United Nations Industrial Development Organization’s Industrial Statistics Database. See Appendix A for a detailed description of the data.
Differences in energy intensity, $[\text{energy}/y]_{ct}$, now reflect both changes in actual intensity across countries and a particular country’s manufacturing product mix. Take for example two products, steel S and toys T. S is more energy intensive than T. If China and the United States used the same techniques of production for products S and T but China produced more S than T and the United States produced more T than S, China’s aggregate production would appear to be more energy intensive, even though the product mixes account for all of the difference in energy intensity. In reality, we would expect Chinese manufacturing to be more energy intensive than U.S. manufacturing. Nevertheless, we cannot ascribe all of the difference in $[\text{energy}/y]_{ct}$ to techniques, but ought to account for the product mix as well. What we can do is separate large-scale structural movements in and out of manufacturing from product mix and technique effects.

Both $y_{ct}$ and intensities, $[\text{energy}/y]_{ct}$, vary by country and year. Fig. 5 depicts oil and energy intensities for China and the United States. China is on average twice as energy-intensive as the United States. The dataset also ascribes it great volatility, while U.S. intensities appear relatively stable. In 1995, the United States used 168 barrels of oil per million U.S. dollars of manufacturing output. This makes it the eleventh lowest of all 73 countries in the sample, but its series is relatively stable compared to most other countries. We can, therefore, focus on one year, for the subsequent analysis: 1995.\(^{14}\)

To disentangle large-scale structural effects on the one hand from product mix and technological effects on the other, we create a composite indicator using U.S. intensities in 1995 for all countries and years:

$$E_{ct} = \left[ \frac{\text{energy}}{y} \right]_{US,95} y_{ct}. \quad (5)$$

This indicator removes any volatility in the product mix and technique factor and ascribes all changes in the data to the country-specific output term. It also removes any underlying time trend in the intensities such as continued increases in energy efficiency over time, a process commonly termed “dematerialization,” or structural changes within manufacturing.\(^{15}\)

We use $E_{ct}$ for $i \in \{\text{cons,prod}\}$ and repeat the analysis in the preceding section. Disregarding the constant term, $[\text{energy}/y]_{US,95}$, the regression for $E_{ct}$ reduces to

$$\ln\{y'_{ct}\} = \beta_0 + \beta F[\ln\{y_{ct}\}] + \nu_t + \nu_{ct}, \quad (6)$$

where all variation in the dependent variable arises from changes in output across countries and time. In short, we test whether income correlates with any systematic changes in the relative size of the manufacturing sector. An EKC-like result would now suggest that structural movements from agriculture to manufacturing and services drive the results presented in Section 3. Differences in technique – oil and energy intensities – and changes in the product mix over time would account for any divergence between the previous results and current ones. Since all variation now arises from output terms common to both oil and total energy, it is no longer necessary to distinguish between the two types of intensities. The only difference will be in the

\(^{14}\)In practice, we could have used any intensity factor for the purpose of the subsequent regression analysis. Since the intensity factor is common to all countries, the results are not sensitive to the intensity used.

\(^{15}\)An alternative indicator would be to use U.S. intensities by year for all countries: $E_c = \{y/y\}_{US,95} y_c$. This measure disentangles cross-sectional structural and intensity effects, but does not accomplish the same along the time dimension. $E_c$ would be the preferred indicator for a cross-sectional analysis focusing on particular years (Cole, 2000).
constant term due to different U.S. intensities. We therefore analyze oil alone.

Table 6 presents the regression output. The most striking observation is that while the results bear with standard EKCs, quadratic regressions are either insignificant or point to increasing U-shaped curves, in contrast to inverse U-shaped EKCs. Moving to cubic functional forms for income improves significance but does not alter the upward-sloping shapes. Only the cubic FGLS specification has peaks of the predicted functional form. Both, however, are around $82,000 and well outside any currently observed income values. Moreover, the two values for consumption and production are practically identical. A graphical analysis confirms these conclusions. Both predicted oil consumption and production curves slope upwards without any sign of turning around (Fig. 6).

Based on the regression analysis presented in Table 6 and comparisons to standard EKC regressions, we can conclude that systematic trends in the size of the manufacturing sector compared to the overall economy cannot account for the observed EKCs in Section 3. Conversely, most of the difference between oil and total energy use in consumption and production must be due to differences in technology and product mix across countries rather than structural changes in and out of the manufacturing sector.

Cole (2000) supports this finding in a similar decomposition analysis by showing that structural changes alone do not account for EKCs. The conclusion may seem to contradict previous findings showing that structural composition of the economy clearly does matter for its fuel mix. Both Judson et al. (1999) and Medlock and Soligo (2001) analyze energy use in industrial, household, transportation and other sectors, and find that energy use shifts between sectors as economies grow. That result still stands. We merely ascribe the particular functional form of the production EKCs primarily to technological and product mix differences across countries and time. Shifts in and out of manufacturing alone do not account for the downward-sloping portion of the EKC.

5. Country-level EKCs

The EKC analysis so far assumed that all countries follow the same path of increased energy use at low levels of development, followed by a flattening and reversal at later stages. Fixed effects allow this relationship to shift across countries and time, but they do not allow for country-specific growth paths. The imposed inverse U-shape is common to all countries. Beginning with List and Gallet (1999), EKC studies have allowed for more flexible specifications across economies. The results have not boded well for simple inverse-U EKC relationships.

Table 6

<table>
<thead>
<tr>
<th></th>
<th>(1) OLS</th>
<th>(2) OLS</th>
<th>(3) OLS</th>
<th>(4) OLS</th>
<th>(5) FGLS</th>
<th>(6) FGLS</th>
<th>(7) FGLS</th>
<th>(8) FGLS</th>
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<tbody>
<tr>
<td>ln(Yct)</td>
<td>-0.42</td>
<td>1.17</td>
<td>-3.80</td>
<td>-1.57</td>
<td>-0.64</td>
<td>-0.35</td>
<td>-0.10</td>
<td>-0.10</td>
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<tr>
<td>ln(Yct)^2</td>
<td>(0.47)</td>
<td>(0.50)**</td>
<td>(4.75)</td>
<td>(5.15)</td>
<td>(4.17)**</td>
<td>(4.18)**</td>
<td>(0.20)</td>
<td>(0.20)***</td>
</tr>
<tr>
<td>ln(Yct)^3</td>
<td>[0.06]**</td>
<td>[0.07]</td>
<td>[0.55]</td>
<td>[0.59]</td>
<td>[0.20]</td>
<td>[0.20]***</td>
<td>[0.04]</td>
<td>[0.04]***</td>
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<tr>
<td>Predicted peak</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>N</td>
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<tr>
<td>Countries</td>
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<tr>
<td>R²</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.10</td>
<td>0.10</td>
<td>0.20</td>
<td>0.20</td>
</tr>
</tbody>
</table>


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** indicate significance at the 1% level.

* indicate significance at the 10% level.
List and Gallet (1999) allow for heterogeneous slopes across states in their analysis of SO₂ and NOₓ emissions within the United States and reject the standard reduced-form model. Aldy (2005) repeats this state-level analysis for CO₂ emissions and United States and rejects the standard reduced-form model. Aldy draws similar conclusions. Perman and Stern (2005) and Dijkgraaf and Vollebergh (2005) employ similar techniques in cross-country analyses and reject homogenous relationships even more decisively. Instead of the reduced-form relationship assumed in Eq. (1), we now allow the constant term and slopes to vary across countries, depicted by the added subscripts on all β coefficients:

\[
\ln (E_{it}^c) = \beta_{0c} + \beta_{1c} \ln (Y_{ct}) + \tau_{1}^{c} + \epsilon_{ct}^{c}
\]

Intercept \( \beta_{00} \) subsumes the previous country fixed effects \( \nu_i \). Otherwise the regression is identical to Eq. (1) with \( \tau_{1}^{c} \) depicting time fixed effects and \( \epsilon_{ct}^{c} \) the exogenous error term. We estimate this relationship for oil and energy in quadratic and cubic specifications and test whether slopes are equal across countries, a requirement for justifying the reduced-form model in Eq. (1):

\[
H_{0}^{2c}: \beta_{k}^{c} = \beta_{k}^{h} \quad \text{for } k = 0, 1, 2, 3, i = \{\text{cons, prod} \}, \text{and all } c = 2, \ldots, 73.
\]

Table 7 reports \( \chi^2 \) test statistics, which overwhelmingly support rejecting the null hypothesis that coefficients across countries are equal. Only cubic energy specifications for consumption do not allow us to reject the null unequivocally, but p-values are still very close to the 10% cutoff. Statistics for oil tend to misrepresent the actual experience of individual countries. Instead we will now focus on country-by-country analyses. As Aldy (2005) observes for U.S. states, country-specific regressions allow us to verify whether countries indeed follow the observed EKC pattern. We would expect poorer economies to show increasing per capita oil and energy use and richer economies to show decreasing trends or inverse U-shaped patterns within their observed levels of income. Most importantly, country-level analysis allows us to employ several time series econometric techniques to verify that any observed relationships are not merely artifacts of spurious correlations.

We conduct two-country-level tests in various specifications and structural forms for the quadratic oil and energy regressions. First, we test for unit roots using augmented Dickey–Fuller tests in connection with the Akaike Information Criterion. We would like to reject these tests to avoid time series data with unit roots. Unfortunately, albeit unsurprisingly, that is only the case for a small fraction of countries. Assuming a model with intercept and trends, 10 of 73 countries have no unit roots in consumption and 13 in production at the 5% significance level. Data for \( \ln (Y_{ct}) \) and \( \ln (Y_{ct})^2 \) have no unit roots in 7 countries each. At the 10% significance level, the numbers are 16, 19, 10, and 9, respectively, barely a quarter of countries in the best scenario. Second, we test whether the data used in country-level regressions are cointegrated. The message here is slightly better. Assuming a model with intercept and an underlying trend, 20 of 73 countries allow us to reject the Engle–Granger test for consumption at the 5% significance level; 22 allow us to do so for production. At the 10% significance level, the numbers increase to 24 and 25 for consumption and production, respectively. The numbers improve for a model assuming intercepts but no time trends. Now tests for 23 countries indicate cointegrated data for consumption regressions and 31 for production regressions at the 5% significance level. The numbers increase to 31 and 39 at the 10% significance level, respectively.

No country allows us to fully reject both tests for no unit roots and no cointegration. Two notable countries are China and the United States. China allows us to reject one test for unit roots in consumption. It also exhibits cointegrated data for consumption, but not for production. The United States allows us to reject one test for unit roots in production assuming no time trends at the 10% level. It also shows cointegrated data for both consumption and production assuming intercepts but no time trends.

We proceed by estimating country-by-country dynamic ordinary least squares (DOLS) regressions with Newey–West standard errors to account for heteroskedasticity and potentially autocorrelated error terms up to a lag of two years:

\[
\ln (E_{it}^c) = \beta_{0c}^{d} + \beta_{1c}^{d} \ln (Y_{ct}) + \sum_{s = -2}^{2} \delta_{s} F [\Delta \ln (Y_{t+s-1})] + \epsilon_{ct}^{c}.
\]

The term \( F [\Delta \ln (Y_{t+s-1})] \) represents in changes in \( \ln (Y_{ct}) \) and \( \ln (Y_{ct})^2 \) with two and one-year lags and leads represented by \( s \) taking on values from –2 to 2. We repeat this analysis for all 73 countries and compare it to DOLS regressions with one-year lags and leads as well as standard country-level OLS regressions. The verdict, while mixed, does show tentative support for previously drawn conclusions.

We would expect a country at the level of development of China to show increasing oil and energy use per capita as its income increases. Similarly, we would expect the United States, a country that has consistently been richer than its trading partners to show decreasing levels of energy use by virtue of being on

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\[16\] Changing the model specifications to one with assumed intercepts but no trends improves the rate of rejection for consumption and production series but worsens those for income and income squared.

\[17\] Full test results are available on http://gwagner.com/research/energy-trade.
6. Conclusion

This article presents a comprehensive dataset of oil and total energy embedded in world trade and analyses its implications for the environmental Kuznets curve (EKC) as well as for energy security and wider policy considerations.

Applying this dataset in the context of environmental or “energy Kuznets curves” allows a separate discussion of energy use in consumption and production. Richer economies use relatively less energy in their industrial production yet still consume relatively large amounts. Trade in energy-intensive goods accounts for the difference. This conclusion points to disconcerting structural shifts as countries develop, which remain hidden in EKC debates that only focus on pollution associated with production. While energy and pollution-intensive production migrates to poorer countries, rich societies do not alter their tastes accordingly. Trade enables richer economies to consume less energy yet still benefit from energy and pollution-intensive production.

Closer examination of structural versus technological shifts paints a slightly more optimistic picture. We can exclude large-scale structural shifts as an explanation for the observed EKC patterns. But given that data for manufacturing are on a country-level rather than further split into particular industries or product categories, we cannot assign the downward-sloping portion of the EKC to technology alone. Structural shifts within manufacturing may account for part of the difference.

Applying this dataset to debates on the dependency on foreign oil shows that the often-cited policy goal of independence from foreign sources of energy is increasingly difficult to achieve, once one considers oil and energy embedded in goods crossing international borders. The flip side of any of these energy security arguments is that indirect dependence on foreign oil through world trade may lessen direct dependency. While ignoring the importance of energy embedded in world trade would be a mistake, equating it with the direct dependency on foreign oil sources would be equally wrong.

Shining a light on embedded energy has much larger policy implications. It is intimately tied to embedded carbon, which raises questions of consumption versus production-based emissions. Currently, responsibility for greenhouse gas emissions more often than not falls on the producer. Most emissions accounting frameworks do not take embedded carbon into account. It is, however, crucial for any discussions of border adjustments and other trade-related implications of domestic climate policy. Embedded carbon and, by extension, embedded energy may well become dimensions through which trade competitiveness gets judged. A key factor is the decoupling of energy and carbon. The energy content of production may increase, while its carbon content will need to fall considerably to avoid the worst consequences of global warming. Countries with abundant, carbon-free energy may experience considerable boosts to energy-intensive exporting sectors.

This dataset and analysis opens avenues for a wealth of future research. First, concerted efforts by researchers or national and international agencies such as the EIA and IEA should provide a reliable stream of annual data on the energy content of trade. Present data limitations force us to assume that exporting industry sectors are as energy intensive as sectors catering to the domestic market. Detailed input/output analyses may account for further indirect oil use, for example by labor employed in the manufacturing sector. This effect will need to be contrasted with direct impacts caused by decreased labor costs in developing manufacturing sectors. This effect will need to be contrasted with direct impacts caused by decreased labor costs in developing industries. This effect will need to be contrasted with direct impacts caused by decreased labor costs in developing countries and the host of implications associated with it. Second, present energy trade data could be expanded to account for the carbon content of trade by using relevant energy-carbon coefficients, with important implications for global climate policy.

Appendix A. Data sources

Feenstra et al.’s (2005) world trade flows dataset comprises bilateral trade data by value for the years 1962 to 2000 covering more than 180 countries and other trading entities. From 1988 to 2000, we use adjusted trade flows for China and Hong Kong to avoid double-counting of Chinese re-exports through Hong Kong. We have removed all trade between the two former German republics and put outside trade into a single German category. Lastly, we have converted the data to 2000 U.S. dollars using GDP deflators generated by the U.S. Department of Commerce’s Bureau of Economic Analysis (BEA).\(^{18}\)

\(^{18}\) Bureau of Economic Analysis Table 1.1.4. Price Indexes for Gross Domestic Product.
The United Nations Industrial Development Organization’s (UNIDO) Industrial Statistics Database supplements the economic data. It provides basic economic figures for 28 industrial sectors across 180 countries from 1963 to 2003. We aggregate across industrial sectors to obtain a panel of industry-wide output data. GDP adjusted by purchasing power parity and population data are taken from the Penn World Table Version 6.1 (Heston et al., 2002).


References


Richmond, Amy K., Kaufmann, Robert K., 2006. Is there a turning point in the relationship between income and energy use and/or carbon emissions? Ecological Economics 56 (2) 176–189.


