

OIL INTENSITY: THE CURIOUSLY STEADY DECLINE OF OIL IN GDP

BY CHRISTOF RÜHL AND TIT ERKER SEPTEMBER 2021



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EXECUTIVE SUMMARY

Oil is the largest primary fuel, and the trajectory of oil consumption is of great concern and consequence for economic, political, and, not least, for climate change reasons. Anticipating oil prices and production from year to year is not easy; identifying even basic ingredients of aggregate demand and supply schedules, such as price or income elasticities, is notoriously difficult. It's an additional challenge to model the structure of a market that sometimes appears to be highly cartelized, and at other times populated by a large flock of peaceful price takers.

But a remarkably steady metric—and possible tool for projecting consumption into the future—has been identified in this paper: oil intensity. Oil intensity is the volume of oil consumed per unit of gross domestic product (GDP). Measured simply in barrels per dollar, it is often viewed as a broad measure of oil efficiency; it certainly demonstrates the importance of oil in a society.

The efficiency of oil use has improved, in other words oil intensity has declined, over the years and decades. In 1973, for example, when oil intensity was at its zenith, the world used a little less than one barrel of oil to produce \$1,000 worth of GDP (2015 prices). By 2019 (the last data set before Covid) global oil intensity was 0.43 barrel per \$1,000 of global GDP—a 56% decline. Oil has become a lot less important and humanity has become more efficient in making use of it.

What is worth a closer look, and is the focus of this paper reporting on oil and gas related research at Columbia University's Center on Global Energy Policy, is the pattern by which this progress has been achieved. Since 1984, oil intensity has fallen every year in an almost perfectly linear fashion: the amount of oil used per dollar of global GDP has dropped by roughly the same amount each year. Wars and revolutions, booms and busts, OPEC successes and failures, and every other monumental event in the last 35 years left their imprint on oil markets but didn't alter oil intensity's steady, downward crawl. This kind of regularity is very rare in any long-time trend, in economics or in energy.

Although oil intensity isn't a new topic, an attempt to explain its curiously consistent downward progress—or even any discussion about it—is hard to find in the literature. For this paper, the authors explain the trend and cross-validate its predictive potential before delving into possible reasons behind the linear decline in oil intensity. It finally extrapolates what such a continuing trend might mean for oil consumption and policies around it going forward. Key findings of this research include the following:

• The amount of oil needed to produce \$1,000 worth of global GDP (0.43 barrel in 2019) has fallen by just under 0.01 barrel each year for the last three and a half decades. The predictive power of this linear approximation was tested by running regressions on overlapping windows of at least 20 years of data from 1984 to 2017. Comparing the resulting near-term demand forecasts against actual demand for years in this period,



the average error was 1.7% to 5.1%—strikingly reliable, especially over the longer time horizons.

- These steady volumetric improvements in the oil intensity metric are possibly the result of a shift in the composition of oil demand from intermediate to final consumption. The typically single-fuel appliances associated with final consumption (such as a car or new boiler) restrict inter-fuel substitutability and price elasticity, whereas for intermediate consumption (such as in a power plant or a petrochemical factory), there can be greater allowance for fuel-switching. Globalization has helped to spread the efficiency gains in end-user appliances quickly and evenly around the world.
- The time trend also reflects a gradual regime change from a supply- to a demandconstrained global oil market. In percentage terms, oil intensity first declines at rates lower than global GDP growth, allowing global oil demand to rise. Over time, given its linear functional form, the rate of intensity decline will accelerate to outpace the rate of global GDP growth, in which case global oil demand would peak and start to decline.
- While it is conceivable that relative price changes could break the trend, by reconfiguring the degree of substitutability embodied in the capital stock, so far neither shale oil (accelerating oil demand) nor the energy transition (decelerating it) have had this effect. For now, the linear trend holds.
- A key ramification for policy makers is that the less scope for fuel substitution in final goods (the lower the price sensitivity of demand), the higher any enacted carbon price would have to be to dent oil consumption.

INTRODUCTION

Oil markets are notoriously difficult to model.¹ They are complex and volatile and at the same time of vital importance to the economy. Despite this importance, it is hard to find a simplified, common narrative connecting different phases of their historic development, much less a generally accepted model of lasting empirical relevance.

This void has many good reasons. Oil prices and production are subject to idiosyncratic and hard-to-model parameters, often interlocking with what they are supposed to explain (e.g., increasing returns in production or, on the demand side, feedback loops with the economy). These interdependencies make it hard to identify even basic ingredients of aggregate demand and supply schedules such as, notoriously, price or income elasticities. Finally, it is hard to model the structure of a market that sometimes appears to be highly cartelized and at other times populated by a large flock of peaceful price takers.

"Too many moving parts" is a most fitting description.

All the more surprising, then, how in the midst of all these moving parts, a stable trend stands out. Oil intensity—that is, oil consumed per unit of economic output—has declined steadily over many decades, with remarkable regularity and in almost perfectly linear fashion.

The following paper investigates this time trend. We revisit the historic context in which it first emerged (part 2), examine the reasons for its stability (part 3), and explore whether this trend can be exploited to improve our understanding of longer-term oil market developments (part 4).



A VERY STABLE RELATIONSHIP

Oil remains the largest primary fuel, moving into pole position in 1964, almost 60 years ago. Like the consumption of all other commercially traded fuels, global oil consumption continues to rise in absolute terms²—by 6 percent per year since records exist (1870), 1.2 percent p.a. since 1973, when its share in global primary energy peaked, and 1.6 percent over the last 10 years. Its market share in the global primary energy mix, however, has fallen from 50 percent in 1973 to 33 percent in 2019 and continues to decline (Figure 1).³

Analytically, oil consumption growth is a function of price and income changes. The literature has long emphasized the relative price inelasticity of demand, especially in the short term. The extent to which oil price fluctuations may impact GDP growth adds a curious identification problem to income elasticities. However, the attempts at estimating with great accuracy functional elasticities, which are recognized as unstable over time and space, may not be the only strategy to gain insights into the future path of production and consumption. A bird's-eye, macro view of changes in the ratio of aggregate oil consumption and global income generation provides a surprisingly constructive addition.



Figure 1: Primary fuel shares and global oil demand, 1965–2019

Source: BP, Statistical Review of World Energy, 2020, <u>https://www.bp.com/en/global/corporate/energy-</u> economics/statistical-review-of-world-energy.html.



Oil intensity is defined as oil consumed per unit of economic output (or income or GDP) and measured best in barrels (bbl) per dollar. Just as with GDP, it can be studied from the income or the expenditure side. Oil intensity is often viewed as the broadest efficiency measure we have—a gauge of the economic importance of oil (it is the inverse of oil productivity, after all). Effectively, it is the result of multiple influences, including changes in end-user preferences, technical efficiency improvements, and changes in the structural composition of the economy, such as industrialization or urbanization.

The Linear Time Trend of Oil Intensity

The key observation motivating this paper is that oil intensity on a global scale has for many decades exhibited linear improvements (declines) year after year. The unceasingly regular decline of oil consumption in global GDP has been accompanied by convergence of oil intensity across major consuming countries.

The regularity of this time trend is startling. At a global level, oil intensity starts to decline in roughly constant annual increments from 1984 onward, after a decade of high price and consumption volatility. In retrospect, the global oil economy at this point appears to have settled into a new modus operandi, of which the time trend we are discussing is a key indicator. The trend has stayed intact ever since, running silently and rather neglected in the background.⁴ The linear decline continued through the only other period of comparable price volatility, after the turn of the millennium when, in contrast to the 1970s, oil consumption remained relatively insensitive to price volatility. At first glance, prices do not seem to be the main driver of the oil intensity trend, an issue we will come back to.

Panel (b) in Figure 2 illustrates the linear decline of oil intensity from 1984 until 2019. The data for this period transform into an almost perfect straight line with an impressive statistical fit (R^2 of 0.99). The time trend itself depicts constant volumetric declines per unit of GDP over the entire period. In numbers, the regression tells us that it took on average 0.0095 barrels (1.5 liters or 0.4 US gallons) less to produce \$1,000 worth of global GDP (in 2015 prices)—year after year, for the last three and a half decades, with very high regularity.⁵





Figure 2: Global oil intensity and time trend

Source: BP, Statistical Review, 2020; Oxford Economics, Global Economic Databank, June 2020, <u>https://www.oxfordeconomics.com/Global-Economic-Databank</u>; World Bank, World Bank Data, 2020; authors' calculations.

One of the first questions when encountering this linear rate of decline will be whether it would withstand disaggregation to the region or country level. However, this time trend does not depend on data manipulation or source, is not a statistical fluke, and is robust.⁶ It can be replicated for regions and countries. Individual characteristics or deviations displayed on that level are consistent with the explanation for the trend's existence we will advance below (see appendix). The same is true if it is broken down by sector. The trend shows the highest explanatory power in retail-based final consumption sectors such as transport or residential use and less in lumpy intermediate segments such as industry and petrochemicals.⁷

There are fluctuations around the trend over time, of course, but they tend to be limited in scope and duration. For instance, we have seen a significant deceleration in the incremental annual decline in oil intensity (i.e., a flattening of the curve) during the years 1991–97 and an even more pronounced deceleration from 2001–4.⁸ However, in both instances this was reversed by a subsequent acceleration in the oil intensity decline (i.e., a steepening of the curve), with a record improvement after the second episode.

This is an important point because, had the data shown the increments declining in step with the decline in oil intensity over time, it would have been an indication of oil intensity improvements following an exponential, rather than a linear, trend. So far this has not been the case; we have seen oscillations instead. In other words, the trend was stable as periods of relatively slower decline were alternating with and reversed by periods of faster intensity decline. The duration of deviations in either direction has been four to eight years in the past, and the amplitude was between 1 and 2 percent of the oil intensity level (or 0.005 to 0.010





barrels per \$1,000 of GDP) before the financial crisis in 2008-9 (Figure 3).

Figure 3: Global oil intensity deviations from the linear trend, 1984-2019

The most pronounced slowdown in the rate of oil intensity decline has happened more recently, namely since the financial crisis in 2008–9, and throughout the high and low price periods since then. Although this moderation stands out in terms of depth and duration, it seems already obvious that it will be reversed by the impact of the COVID-19 pandemic, which hit global oil demand much harder than global GDP. Regardless, the current deviation is of interest because it appears to be linked to the US shale "revolution," which could bring it much closer to the possibility of a structural break in the system than previous episodes (discussed below).

Like most economists would when catching sight of a linear time trend, we harbor lingering suspicions about Stein's law and hence performed due diligence by applying an exponential trend to the data as well.⁹ The statistical fit turns out to be literally almost identical, with the flattening of the curve since 2009 also following a significant acceleration in intensity declines in the period 2005–8.¹⁰ However, for regions, like the EU or the OECD, in which the regular oil intensity decline is most advanced and where decline rates have already surpassed GDP growth and have translated into declining oil demand, the linear trend is the better fit.¹¹ That statistical fit, the observed episodes of reversed deviations from (oscillation around) the trend, and not least our understanding of the reasons for a linear time trend led to the conclusion that oil intensity declines have been linear and to the adoption of the linear trend as the most appropriate specification.

The predictive power of this linear approximation confirms the exceptional data fit. Out-ofsample forecasts 1 and up to 14 years ahead, based on overlapping windows of at least 20 years of data (from 1984 to 2003, 1984 to 2004, and up to the 1984 to 2017 window), have an average



Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.

error of 1.7 to 5.1 percent (increasing with the length of the forecast period). In absolute terms, this is equivalent to an average root mean squared deviation of 0.008 barrels per \$1,000 for all 15 1-year-ahead out-of-sample oil intensity forecasts for the years 2004, 2005, 2006,...,2018 and up to 0.022 barrels per \$1,000 for the three 14 years ahead out-of-sample forecasts.¹² It is a truly extraordinary performance, especially over the longer horizons—even more so in the case of the EU and the OECD, two regions where oil demand has been declining for some time and where forecasting accuracy starts to improve over longer horizons (see appendix 3 for details).

It bears repeating just how extraordinary the consistency and the ex post predictive power of this linear trend are. Thirty-five years is a long time, with price booms and busts, OPEC successes and failures, wars, revolutions, the rise of China, and the dissolution of the Soviet Union all exerting their influence on the global market for oil. Without much deviation, the constant declines in oil consumption per unit of GDP have been sustained through all of it.

It was not always like that, however.

How Did This Trend Emerge?

Historically, oil intensity has been rising during the years after World War II, with the share of oil in the global energy mix increasing fast. Oil became the largest fuel in 1964 and continued to globalize, on the back of large finds in the Middle East. Based on economic competitiveness—that is, a competitive relative price for superior energy density and convenience properties—it substituted for other fuels, specifically coal, in power generation, space heating, and industrial applications. The rise of oil was of course propelled forward by the global rollout of a transport sector based on the internal combustion engine; but it was not confined to new applications.

Global oil intensity peaked in 1973, the same year oil's share in global primary energy reached its zenith (at 50 percent). At that time, it took just under 1 barrel (159 liters, or 42 US gallons) of oil—0.97 barrels, to be precise—to support the generation of \$1,000 worth of global GDP (in 2015 dollars)—a number that helps to appreciate the prominence of oil in contemporary debates of economic performance (Figure 2a).

The time when oil rapidly permeated the nooks and crannies of the global economy came to an end with the two oil crises in the 1970s.

After the Iranian Revolution, as real crude prices reached levels unrivaled for the next three decades, oil intensity went into a tailspin for a few years. Oil retreated from applications where it faced competition from other fuels, which now had become relatively cheaper and less prone to the threat of supply disruptions and associated price volatility. Oil use declined "under the boiler" and especially in power generation; its concentration in transport increased significantly. The steep decline of oil intensity coincides with a steep decline in fuel market share, both lasting until 1984 when the new regime of a secular trend decline in oil intensity sets in.

By 2019, oil consumption per \$1,000 of global GDP was down to 0.43 barrels (68 liters, or 18 US gallons), a decline of 56 percent since oil intensity had peaked 46 years earlier (and still a number giving pause for thought). More than half (61 percent) of this achievement has been attained after the earlier period of high prices and rapid oil demand decline—that is, after 1984—as a result of the steady oil intensity declines embodied in the new time trend.



What matters here, of course, is less the observation that oil intensity has declined over time but the regular pattern that has been marking this decline. A new regime with income and demand growth moving in lockstep has asserted itself. With it, the relationship between prices and demand also changed.

The 1970s and early 1980s have been a period of great volatility of price and quantity adjustments in global oil markets, with (political) disruptions triggering huge price movements and price movements triggering swift demand adjustments (and a lagged supply response). Until the mid-1980s, global demand and therefore oil intensity mirrored price fluctuations during the years of turbulence as one would expect—dropping after price spikes and rising after prices fell or stabilized. After that, oil intensity continued to decline, despite a drop in oil prices: between 1980 and 1985, oil intensity declined by 15 percent, while real oil prices dropped by more than 40 percent.

An important component of this transition is how the interaction between the price of oil and oil intensity changed. With low and declining real oil prices until the early 1970s, oil intensity had increased; during and after the first two oil price shocks, oil intensity dropped precipitously. From the mid-1980s on, when oil intensity embarked on its newly found steady course, the umbilical link to prices seems to have become undone (Figure 4).



Figure 4: Global oil intensity and real oil price, before and after 1985

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.



When the price volatility of the 1970s returned on a comparable scale decades later, with the run-up of prices in the first decade of the new millennium and the shale oil induced price collapse from 2014, oil intensity declines showed little perturbation. The standard explanation for the difference is that the price volatility was caused by supply disruptions in the first and by increasing demand in the second instance and that price and income elasticities therefore have been affected in different ways.¹³

Viewed from the macro perspective of oil intensity, however, there is more to this asymmetric reaction than different price triggers alone. In both instances, not only oil intensity but the share of oil in global primary energy behaved very differently—volatile in the 1970s and gradually continuing to decline in the 2000s. A bigger transition was afoot. Had oil markets become less flexible—that is, less prone to interfuel substitution than they used to be? If so, why would that be?

Oil Demand

The new configuration after the turbulent 1970s was not lost on contemporary observers.

The beginning of the secular trend in regular oil intensity declines coincides with years of weak demand and falling oil prices. It puzzled observers why the demand response to falling prices was so sluggish.¹⁴ In standard economic theory, the demand reaction to falling or rising energy (or oil) prices would have been symmetric, with capital, labor, and energy close substitutes and their configuration (or "technology") flexible and driven by relative prices. The lack of a more enthusiastic demand response to falling and stagnating oil prices in the 1980s and 1990s, in contrast to the decline in demand following the price spikes in the 1970s, did not fit into this picture.

One popular attempt at explaining the data was the hypothesis of an asymmetric response of oil demand to price movements: once high prices had triggered efficiency gains, either baked into the capital stock ("isolating the attic") or directly incentivizing technology (a more efficient car engine), these gains would to an extent persist and not go away in response to a fall in the relative price of oil.¹⁵ The result would be a ratchet effect for oil demand that, with halfway steady GDP growth, should leave oil intensity improving in steps: high price periods would meet elastic oil demand and lead to irreversible declines in oil intensity, whereas for low price periods the predicted oil intensity adjustments would be disproportionally small.¹⁶

Not everyone was convinced. There is a discord between the practical appeal of an idea such as efficiency gains being irreversible (unlearning, we like to think, is hard to do) and the tenets of standard economic theory. To the extent that efficiency gains are the result of extensive investments in response to a shift in the relative price of oil (the famous isolation of the attic), they will depreciate and wither away eventually—that is, not be replaced over time once the initial price trigger has been removed. To the extent that they reflect endogenous technological change triggered by price movements (e.g., a more efficient car engine following an oil price increase), other parts of the economy will catch up to neutralize the comparative advantage of this innovation over time, once the underlying structure of relative prices has been restored—that is, the original incentive removed. Hence, in the long term, there should be no ratchet effect in the data.



Yet, there was no denying that oil intensity fell continuously, with GDP growth in the 1980s outpacing oil demand growth, despite a declining relative price for oil. Prices low and falling, demand growth stalling despite reasonable GDP growth, oil intensity steadily improving—it must have seemed as if market demand was doomed *and* as if there was a missing ingredient for economic modeling to fit the data. It may be obvious in retrospect (as with so many good ideas) to identify oil-saving technological change as the most trustworthy guide out of the analytical impasse. To incorporate a time trend of oil conserving technology that was independent of price would allow the coexistence of positive oil demand growth with declining oil intensity into the future, without compromising long-term price effects.

Hogan (1993) estimates a number of aggregate oil demand specifications, symmetric and asymmetric. He encapsulates the general conclusion, with the winner to emerge from his exercise a reduced form model that combines symmetric price reactions and an oil-conserving technology trend which is not price dependent.¹⁷ "Apparently," the author notes with slight disbelief when inspecting modeled long-term intensity estimates, "there should be a significant further reduction [of] oil intensity over the 1990s, independent of price, even though there will be continuing growth in total oil demand." Which, of course, is exactly what has happened.

This was perhaps the high point in a debate that subsequently petered out gradually, just as the oil markets themselves lost much of their luster and excitement throughout the 1990s. Oil markets remained subdued until catching analysts by surprise again, first by the lack of economic impact of sky-high prices in the 2000s and then by shale oil. As to the economic debate, variables such as oil intensity lost their place in the sun as attention turned inward, toward exercises driven by data availability and increasingly divorced from the macroeconomic narrative of the day.

However, there was a clear understanding by the early 1990s of how a growing economy over the long term could reconcile demand growth and oil intensity decline (and why oil intensity was declining less than GDP was growing), based on an exogenous series of oil-saving technological changes.¹⁸ The analytical insights of the debate would allow a forecast of the direction of the future path of oil intensity. But to tame quantity adjustments by adding irreversible exogenous efficiency improvements is not the same as to rule out that symmetric price responses might increase oil intensity again. The second half of our puzzle, the fact that oil intensity declines turned out to be not only relentless but regular, was not something anyone had on the radar at that time.

Today, there seems to be no choice but to find an explanation for the regularity of the time trend if the goal is to improve our understanding of the path of oil consumption.



WHAT EXPLAINS THE LINEAR TREND?

It is not one but three questions that need an answer. First, what explains the linearity of the observed path of oil intensity over the last few decades. Second, why the two most volatile oil price periods in living memory had such a profoundly distinct impact on real variables, including on oil consumption. And third, what, if anything, this regime change can teach us about a future in which people may actively desire to switch away from oil consumption.

Derived Demand

Oil demand is derived. There is no direct utility from consuming oil. To benefit from its use requires a parallel investment in appliances. For final consumption demand, these appliances will enable consumers to derive the services oil provides—a car for transport or a boiler for space heating. Alternatively, for production purposes, capital goods are required to convert oil from an intermediary input into a final good or into another intermediary, such as plastic or power.¹⁹

Conceptually it pays to distinguish end-user appliances that enable final consumption (the household car or boiler) from capital goods that absorb oil as an intermediary input in producing something else (a power plant or a petrochemical factory). A second distinction will be useful for our purposes, namely that between single- and multifuel appliances—that is, between appliances (or systems) that allow for fuel switching and substitution across fuels and those that do not.

Appliances of all sorts imply sunk costs. Single-fuel appliances diminish the price elasticity of oil demand directly: the higher the ratio of fixed to variable cost, with oil the variable component, the less will variations in fuel prices affect the cost of the service provided.²⁰ This same principle should apply for final consumption and for intermediate use. Conversely, the option of fuel substitution increases the price elasticity of oil demand. Note that fuel switching may be due to multifuel appliances (dual fired power plants or, if batteries lived up to expectations, hybrid cars) or to the possibility of fuel switching by switching between appliances with different input fuels in systems with built-in redundancy (e.g., if a power system for security reasons offers the option to switch between oil fired and other power stations).²¹

Traditionally, final demand and the consumer appliances it is associated with have been more likely to consist of single-fuel devices, whereas capital goods, which use oil as an intermediary input, are more likely to allow for fuel substitution, especially if policy issues such as energy security, the environment, or industrial planning are involved.²² Newer and more efficient technologies tend to favor single-fuel specialization as well.

Our first proposition, on the impact of derived demand on global oil intensity, would thus be the following: over time, as income levels rise, the share of oil used in final consumption, and therefore in conjunction with single-fuel appliances, increases. As a result, oil price elasticity diminishes. This has been the case on a global scale since the 1980s.²³





Figure 5: Global share of oil in primary energy and share of oil used for final consumption

In this reasoning, as the lion's share of oil consumption shifts toward final consumption, the increased efficiency of end-user devices will eventually slow the growth of oil in the economy, the dwindling options for fuel substitution will stabilize the share of oil in the fuel mix, and both will lower the price elasticity of oil. Oil consumption growing faster than GDP (oil intensity rising), then oil consumption growing but slower than GDP (oil intensity falling), and finally, the point from which the intensity decline starts to outpace GDP growth and oil demand starts to decline—these have been the thresholds oil intensity had to cross in regions where the full process has already played itself out.

Globalization

Globalization itself is another factor encouraging both regularity and direction of travel for the trend toward lower global oil intensity. Accelerating international competition and the growing "flow of everything" (trade, investment, people and capital) across borders have bolstered the uniform spread of technology over the last four decades, including efficiency improvements embodied in machinery. Figure 6, representing 47 percent of global consumption in 2019, illustrates the convergence of oil intensities across the most important oil consumers, which mirrors deeper economic integration as well as intensifying global competition. However, conversion of oil intensity across countries with different income levels is not easily depicted in the data because sheer scale effects will outweigh the diffusion of oil-conserving efficiency improvements especially in periods of rapid industrialization.²⁴



Source: BP, Statistical Review, 2020; IEA, "Oil total final consumption by sector," 2020, <u>https://www.iea.</u> <u>org/data-and-statistics/charts/oil-total-final-consumption-by-sector-1971-2018</u>; author's calculations.



Figure 6: Oil intensity convergence across the three largest consumers, 1965–2019

Note: Quantities are in bbl per \$1,000 of GDP (in 2015 prices) except where otherwise specified. Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.

It may appear that speed and reach of the diffusion of technological change embodied in mechanical devices should be the same for end-user appliances and for capital goods, which would imply that globalization would not affect the scope for fuel substitution determined by the share of these devices. However, the data suggest otherwise. As discussed above and shown in Figure 5, the share of oil used in final consumption has indeed increased steadily since the 1980s—and it stands to reason that the diffusion of appliances for retail consumption with shorter life cycles (vehicles for transport or home appliances for residential consumption) has been faster and more uniformly distributed than the, even on a global scale, lumpier infrastructure equipment required to use oil as an intermediary input (industry and power generation). Shorter life spans for equipment and regular turnover cycles will both accelerate and smoothen the diffusion into a more uniform distribution over time, especially in the thick markets for common devices such as cars.

A number of subordinate reasons support the argument: the global retail market for applications is competitive also because it is for the most part private, with consumers meeting profit-maximizing suppliers, whereas the use of oil as an intermediary, from power generation to oil intensive industries, in particular in producer countries, is more likely to encounter governmental interference. Second, "strategic" industries, of which the latter



group is often considered a part, often come with a degree of redundancy reflecting security concerns, not economics; third, the shorter life span and turnover period of end-user appliances should encourage a uniform spread of efficiency improvements; finally, it is easier to pass on the cost of slow innovation to customers in oligopolistic and capital intensive (and sometimes government controlled) industries; investments in these industries may be "lumpy" even on a global scale, and measured oil intensity declines therefore more discretionary. All of this indicates that globalization accelerates and smooths the diffusion of oil-conserving end-user appliances, reinforcing the trend toward a smooth, regular oil intensity decline over time.

A second testable proposition would be that globalization encourages a uniform spread of efficiency improvements across countries. It should therefore promote convergence of oil intensity across countries, with improvements fastest and smoothest in end-user appliances. Convergence is visible for three large oil-consuming economies since the 1980s.



THE TREND IN LONG-TERM PERSPECTIVE

Structural Change

The path of economic development displays a common pattern of structural change, which is connected to energy intensity in an unambiguous fashion: as economies industrialize—that is, as their dominant economic activity shifts from agriculture to industry—primary energy intensity rises. And as they switch from industrial to the dominance of service sector activities, energy intensity falls. There are only a handful of easily explainable exceptions to this general rule.²⁵

In a first approximation (i.e. keeping the fuel mix constant), this would imply that oil intensity first rises and then falls as economies industrialize and mature. Unfortunately, the fuel mix is unlikely to stay constant during transformations of this scope and magnitude. But there are two other data points which can serve as handrails.

First, as economies mature there is scope for the composition of oil consumption itself to change. For example, the share of oil for intermediate use (power and industry) may be rising during the period of industrialization. To the extent this intrafuel adjustment does take place, it will enlarge the playing field for interfuel competition later.

These changes operate through changing the stock of mechanized consumer devices and capital goods. Under the common, sensible assumption of irreversible putty-clay technology, investment in highly specific appliances cannot easily be converted back to other uses. To what an extent the capital stock changes (and how fast it can turn over) depends on actual as well as expected relative fuel prices over the lifetime of new equipment.

In principle, the scope for relative prices to change the capital stock is vast: we have seen the surge of oil in industry and in power generation when oil, able to compete on price, penetrated the global economy for the first time in the 1950s and 1960s. China's industrialization proceeded with a greatly decreased demand for oil in key sectors; and the dissolution of the Soviet Union has demonstrated how deep modern energy systems can be cut (to the bone) if the set of relative prices suddenly changes. In all cases, though, the price elasticity of oil has fallen once income levels allowed for a rise in the share of oil destined for final consumption (and with lower substitutability). The reason why the impact of relative price changes on the composition of the capital stock is sparingly documented and often difficult to trace in the data is the obvious one: changes in relative prices exert their influence only over the long term, and they need to be accompanied by durable changes in expectations for the capital stock to become malleable.

Second, the link between changes in a country's sectoral composition and the rise and decline of primary energy intensity may be unambiguous, but no single fuel needs to mimic this pattern with accuracy. Oil intensity in particular is likely to "overshoot" as final consumption in transport and residential use—that is, the less price sensitive and less substitutable part of total oil consumption—continues to expand with income growth, which will rise even after the economy has embarked on its transition toward the service sector.



The rise of the service sector decreases primary energy intensity. But the share of oil in the fuel mix, and in principle even oil intensity, may continue to rise for a while longer as the share of nonsubstitutable consumer appliances in total oil consumption increases. During this transition, oil demand becomes less sensitive to price changes. At the end of it will be the point at which GDP growth outpaces oil demand growth, and oil intensity will start to decline. And eventually, if the trend continues, the oil intensity of GDP will decline faster than GDP grows and translate into falling oil demand.

The exact interaction between intrafuel shifts impacting the substitutability of oil demand, changes in the economy's fuel mix, and the ultimate translation into oil and energy intensities forms a complicated web. But disentangling it (to the extent possible on a conceptual level) leads to a number of conclusions. First, global oil intensity has declined as a larger share of global GDP has moved from industry into services. Second, the scope for interfuel substitution baked into the capital stock diminishes as the capital stock responds to the demands of higher income levels. Third, oil demand growth will stabilize as a consequence. Through the microcosm of many developing economies, the linear trend in oil intensity has been sustained.

Regime Change

It now becomes clearer why the impact of high and volatile prices on global economic activity as well as on oil demand has been so substantially different after the turn of the millennium, from the last comparable high price episode in the 1970s.²⁶ The two oil price shocks in the 1970s ushered in a global recession; but neither the oil price spikes in the run-up to the financial crisis 2008 nor the high-price period of 2011-14 has been blamed for an adverse impact on global economic performance.

The standard explanation of course is that both events were triggered by completely different circumstances, and this is correct.²⁷ The price spike in the 2000s and its long run-up were the result of rapidly growing demand from booming economies, especially in the developing world, whereas the price shocks in the 1970s were sudden, disruptive, and caused by politically motivated supply side events.

Behind the obvious loom the vast structural changes that have taken place in between these episodes, roughly three decades apart. They can now be condensed into three data points. These are of wider interest because they do not only explain what did not happen in the 2000s but what may be in store when the energy transition starts to interfere with oil prices and consumption.

First, the role of oil in the global economy has changed in ways that are likely to become irreversible, especially if they are explored and exploited by future energy policy: oil has simply become a less important component of the economy, globally as well as in most economic jurisdictions. This is of course the very essence of arguing that oil intensity has declined by almost two-thirds and that systematic and endogenous reasons for this decline can be identified, which are likely to shape the future of oil in the economy even more than they have shaped the past. With oil needs per unit of economic output so much lower, price changes in the precious commodity will have a lower impact—not only on inflation but on real variables such as income, employment, and productivity.



Second, oil remains the largest fuel globally, but its share is declining. Given the rather inexorable way in which this decline is likely to proceed if the current regime does not change (which is possible, caused for example by a long period of low relative oil prices and sustained expectations of more thereof) and assuming continued economic growth, peak oil demand is a serious prospect. Driven by the adjustments discussed above, this would change oil markets further and in particular in areas not addressed here, namely on the supply side. A shrinking global market is unlikely to leave space for the role OPEC has played over the entire period from the end of the old regime in the 1970s to the dusk of the present one.²⁸

Third are changes in the composition of oil demand, namely the shift to end-user demand and the associated loss of substitutability. Just as a lower share of oil in the economy will lessen the impact of higher oil prices on the economy, so a higher share of final consumption in total oil consumption will lessen the price impact on total oil demand. This may make price spikes more likely but limits their impact for any given magnitude. If oil demand has become less price elastic, and even more so in countries with higher per capita incomes, some of the more interesting implications concern the intent of making oil more expensive, by carbon pricing or taxation, to curtail its use. Without loosening the current tight link between final consumption services and nonsubstitutability—that is, without widening the scope for substitution for final consumption services (to use the hybrid car example again) this may be a tall order, with oil demand much less affected than other fuels by a uniform carbon price across the entire economy.²⁹

Resource Abundance

As noted earlier, global oil intensity declines have slowed down since 2009. The relationship of this deceleration to oil prices is ambiguous, the link to the slowdown in income growth after the global financial crisis less so. However, although the intensity slowdown has been noted in most countries or regions, it appears to have been driven to a considerable extent by the United States and in the wake of the shale "revolution"—which will make for an interesting test case.

The pace of oil intensity declines in the rest of the world has fallen by 20 percent since 2009, to an annual average of 0.008 barrels per \$1,000. In the United States, the pace of the decline over the same period halved, to 0.006 barrels per \$1,000 p.a. The US moderation (and global difference) is even more striking for the period after 2012, after US shale oil production was in full swing (Figure 7).³⁰ Is this heralding a trend break on a global scale, or will it become part of the oscillations discussed earlier?





Figure 7: Global and regional oil intensity deviations from the linear trend line, 1984–2019

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.

The jury is out. However, the ongoing episode highlights two important insights: first, the crucial role that not only relative prices but expectations—of prices and resource availability—play in determining the configuration between final and intermediate uses of oil, which ultimately determines the path of oil intensity; second, the ability of expectations and relative prices to reconfigure the capital stock effectively and in unexpected ways. The data indicate that the deceleration in US oil intensity declines was not based on a simple, price induced reversal of oil consumption back into areas where it can compete with other fuels (such as substitution in power generation). Instead, it was driven by an increase in final oil consumption—mostly by an immense increase in the share of less fuel efficient CUVs (crossover utility vehicles), pickup trucks, and SUVs in the US car fleet—that is, by a simple switch of appliances within final consumption.³¹ The effect was massive enough to allow for an uptick in the share of oil in US primary energy consumption.

The rise of tight oil production (and the lowering of its production cost) has been a monumental moment in global oil markets, and it has been well publicized. The price impact, however, was global rather than local. Moreover, the price decline caused by shale oil was late (second half of 2014) and muted, courtesy initially of numerous supply disruptions and later of the formation and activities of OPEC+.



What did change dramatically was the US position in global oil markets as the country moved from the world's largest oil importer to an exporter (since 2020) in just a few years. It is fair to say that the rapid rise of shale production and its bright future has completely changed perceptions of energy security and resource scarcity among US consumers. Given the absence of a more tangible price impact and the estimated low price elasticity of consumer demand, it will have been that change in long-term expectations that caused the switch in the car fleet enabling the rapid adjustment of consumption patterns.³²

No matter whether shale oil will be sufficient to move the dial on the long-term trend in global energy intensity, the episode already should provide food for thought for the energy transition—in many ways shale's antidote, as an attempt to reverse current consumption patterns and to accelerate the oil intensity trend decline.



CONCLUSION

Oil markets are hard to model; it is true. Like the global economy and global energy markets of which they are a part, they do exhibit patterns of systematic structural adjustment and reconfiguration. Such patterns are traceable and may form a narrative which can be checked for coherence; it is from these narratives that we hope to find a window into what the future may hold.

Oil markets, we have argued, have experienced regime change over the course of a long and protracted transition. This process is far from complete. Over the last four decades, markets have reconfigured from intermediating a supply constrained, highly versatile, and competitive commodity into allocating a commodity that is demand constrained, highly specialized, and concentrated in its applications. We have traced this reconfiguration by putting a spotlight on oil intensity: first growing and volatile, as global oil consumption growth outpaced GDP growth; next, declining and regular, but with oil demand still rising, as increasing specialization ensures the rate of oil intensity decline remains below GDP growth; and in the future, if the narrative holds, with the decline in oil intensity continuing to accelerate in relative terms until it outpaces GDP growth, which means oil demand will have to shrink. We are in stage two of this development. Note the obvious, however: oil intensity is just one parameter in a much bigger universe of change. In particular, we have not investigated the supply side at all.³³

Nevertheless, this focus allows for a number of conclusions. Two of them are of particular importance in linking this analysis to broader oil market developments.

There is first the intriguing question of how far the claim of a linear time trend for oil intensity is to be trusted: Should it be applied as a forecasting tool? "Tool" may sound ambitious, but we certainly believe it is a useful rule to base estimates on. Given the track record (although replicated ex post) as well as the consistency of the narrative, the presumption of a continuation of the linear trend should indeed put it on a par with other, more traditional concepts. That means it can be used, for example, to calculate how much oil demand will be lost if global GDP returns to pre-COVID (i.e., 2019) levels only in 2021 or 2022 or to estimate global peak oil demand.

The second relates to energy policy and the energy transition. In many discussions, oil is being singled out, typically in its most protected habitat, transport, as a fuel that needs to be eliminated from the global fuel mix and replaced because of its greenhouse gas emissions. The attempt to break oil's monopoly by deploying technological alternatives that allow for substitution, especially electric vehicles, has started. Here is not the place to comment on this idea's technical and environmental merits. However, it is widely undisputed that goodwill, subsidies, and regulation alone will not be enough to decarbonize the global transport sector and that a carbon price would at least be helpful in this regard.

To tease oil out of its most privileged application with the help of a carbon price may become a tall order. To be precise, the analysis gives a dual perspective on transport and the energy



transition. Price sensitivity has diminished, and so any carbon price would have less impact on oil in transport than on other fuels with more scope for substitution. To open up options to substitute away from oil (such as the electric car) will become crucial for any decarbonization strategy targeting final oil consumption. This creates a little bit of a "chicken and egg" problem if alternatives are unknown or have to be subsidized. Assuming that, to minimize the social cost of decarbonization, the principle of a uniform carbon price across the economy is maintained (and quantity targets eschewed), the less scope for fuel substitution there is, the higher the carbon price necessary to dent oil consumption. In itself, however, this is just a variant of a more general conclusion of this analysis, namely that the scope for price volatility has become larger and the scope for volume volatility has become smaller over time.

So far, the energy transition has had no discernible effect on global oil markets, disruptive or otherwise. The gains in oil conservation from the shift toward final demand have been endogenous, as was the retreat of oil from (now sometimes more carbon intensive) intermediary sectors. We have seen how relative price changes can have an impact on the configuration of the capital stock and of appliances. In transport, it will take a very large adjustment—of prices or of substitutes.



APPENDIX

Global, OECD, and Non-OECD Oil Intensity and Share of Oil in Primary Energy



Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.





Figure A2: Share of oil in total primary energy consumption, 1965–2019

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations.



Figure A3: Global share of oil used in transport and for residential use (final consumption), 1971–2018

Source: IEA, "Oil total final consumption by sector," 2020, <u>https://www.iea.org/data-and-statistics/charts/</u> oil-total-final-consumption-by-sector-1971-2018.



Model Specification

The econometric analysis of the time trend of oil intensity is based on time series data from 1984 to 2019 (BP Statistical Review of World Energy 2020 and Oxford Economics Global Database June 2020).

Global oil intensity is calculated as

$$Oilint_{t} = \frac{Oil_{t}}{GDP_{t}}$$

where

Oilintt global oil intensity in year t in barrels of oil equivalent (bbl) per \$1,000 of global GDP in 2015 constant prices and exchange rates; and

Trendt time trend where year 1984 = 0, up to year 2019 = 35.

$$Oilint_t = c + \beta Trend_t + \epsilon_t$$

where

Oilintt global oil intensity in year t in barrels of oil equivalent (bbl) per \$1,000 of global GDP in 2015 constant prices and exchange rates; and

Trendt time trend where year 1984 = 0, up to year 2019 = 35.

In addition to the linear trend model, we estimated logarithmic trend model with oil intensity expressed in natural logarithms. Table A1 reports the results.

Table	Λ1-	Global	oil	intoncity	trond	in	linoar	and	logarithmic	tormc_	-roarossion	roculte
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	Linear trend specification: Oilint _t = c+ β Trend _t + ϵ_t	Logarithmic trend specification: Ln(Oilint) _t = c + β Trend _t + ϵ_t			
Sample 1984-2019		1984-2019			
Constant	0.746 t = 295.5 (P = 0.000)	-0.270 t = -72.1 (P = 0.000)			
Trend	-0.00954 t = -76.9 (P = 0.000)	-0.01664 t = -90.5 (P = 0.000)			
Observations	36	36			
R ²	0.994	0.996			

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; authors' calculations in EViews.



Table A2 reports the comparison of both trend specifications for the OECD and the EU—two economic blocks in which oil demand has peaked. For these more mature economies, the linear trend specification exhibited the better fit.

	Linear trend speci Oilint _t = c+β Trend _t	fication: + ε _t	Logarithmic trend specification: Ln(Oilint) _t = c + β Trend _t + ϵ_t		
	OECD	EU	OECD	EU	
Sample	1984-2019	1984-2019	1984-2019	1984-2019	
Constant	0.651 t = 206.3 (P = 0.000)	0.525 t = 207.8 (P = 0.000)	-0.397 t = -42.5 (P = 0.000)	-0.606 t = -63.2 (P = 0.000)	
Trend	-0.00906 t = -58.4 (P = 0.000)	-0.00780 t = -62.8 (P = 0.000)	-0.01889 t = -41.1 (P = 0.000)	-0.02061 t = -43.7 (P = 0.000)	
Observations	36	36	36	36	
R ²	0.990	0.991	0.980	0.983	

Table A2: OECD and EU oil intensity trend in linear and logarithmic terms—regression results

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations in EViews.

Cross-Validation: Rolling Window Forecasts of the Linear Trend Specification

In a first step, we evaluate the predictive power of our linear specification for the global, the OECD, and the EU oil intensity model. The three regressions were run on 15 overlapping samples (so-called training periods), starting with period 1984–2003 and up to 1984–2017, in annual increments. Based on the estimated coefficients, we made out-of-sample forecasts from 1 year ahead up to 14 years ahead, which we compared to the actual oil intensities, to calculate root mean squared deviations (RMSDs).

For example, based on the 1984–2003 training period (of 20 years), we estimated the linear time trend coefficient, which was then used to generate forecasts from 1 and up to 14 years ahead (i.e., for years 2004, 2005, and up to 2017). We repeated the same procedure for the 1984–2004 training period, based on which we generate forecasts from 1 and up to 14 years ahead (i.e., for years 2005, 2006, and up to 2018). The same exercise is repeated for all overlapping windows up to the 1984–2017 training period, which is only used to generate two forecasts 1 and 2 years ahead (since our data series ends in 2019). We generated 15 1- and 2-year ahead forecasts, 14 3-year-ahead forecasts, and so on, up to 3 14-year ahead forecasts.

We calculated the corresponding RMSDs and expressed them in relative terms, compared to the actual average oil intensity over the corresponding forecasting periods.





Note: The charts show average root mean squared deviations over different forecast horizons as a fraction of average oil intensity.

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations in EViews.

Cross-Validation: Comparison of the Linear and Logarithmic Model Specification

Similar to the rolling window exercise in appendix 3, we compared the predictive power of the linear and the logarithmic specification for the global, the OECD, and the EU oil intensity model. The six regressions were run on 15 overlapping samples starting with the period 1984-2003, up to the period 1984-2017, in annual increments.

We compared the predictive power of the linear and logarithmic specification for all 15 regressions for 1 to 14 forecast years ahead (or lags) for the global and each regional pairs. The first step in this exercise was the same as in appendix 3. In the second step, we compared the difference between the root mean squared deviations (RMSDs) for each forecast period (1 to 14 years ahead) between the two regression specifications, normalized by the mean intensity over the forecast period.

Figure A4 summarizes the results, whereby a negative difference indicates that the linear specification has a better predictive power (i.e., lower normalized RMSDs).

The results are consistent with the more general R² results: for global oil intensity, the logarithmic specification exhibits slightly better predictive power at all forecast legs; for the OECD and the EU, the linear trend specification shows a significant forecasting advantage.

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Figure A4: Rolling window forecast comparison with actuals

Figure A5: Cross-validation results comparing linear and logarithmic specifications



Note: The charts show the difference between the linear and logarithmic relative average root mean squared deviations over different forecast horizons.

Source: BP, Statistical Review, 2020; Oxford Economics, Data Bank, 2020; World Bank, Data, 2020; authors' calculations in EViews.



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NOTES

- 1. "Oil" in this paper is defined as per the primary data source (BP 2020)—that is, including in-country demand plus international aviation and marine bunkers plus refinery fuel and loss. Biofuel consumption is excluded; derivatives of coal and natural gas are included. All energy data in this paper is "BC" ("before COVID"), up until and including 2019.
- 2. With the possible exception of biomass (wood) and coal. There is no data on commercially traded biomass for energy consumption, and it is too early to tell whether coal consumption has peaked.
- 3. Oil consumption growth was very volatile until after World War II and steadied after the 1960s (1870–1965 = 8.3 percent p.a. vs. 1966–2019 = 2.1 percent p.a.; cf. BP [2011, 2020]).
- 4. The only explicit treatment of reasonably recent vintage we are aware of are Fagan and Duan (2019), Fagan (2020), and Mirzoev et al. (2020). We were unable to replicate the basic oil intensity data cited in Fagan and Dunn (2019) and in Fagan (2020) and therefore their results. The authors did not follow through with a promised explanation despite repeated attempts. Mirzoev et al. (2020) confirm the basic results and observations around the integrity, longevity, and stability of the oil intensity time trend presented here, but the purpose of their publication is not to explain it. The authors infer that the long-term robustness of this time trend may lead to the possibility of estimating future oil demand growth even without recourse to prices—which is a tad further than we would be prepared to go.
- 5. Over the period 1984–2019, oil intensity declined by 1.6 percent p.a., on average.
- 6. On the matter of data sources, we have tested alternative GDP and oil data sources and combinations, including GDP data from the World Bank at constant market exchange rates and at purchasing power parity, and oil consumption from the IEA and BP. In all four combinations, the linear trend performs marginally better than the exponential trend, compared to the data series ultimately reported here (Oxford Economics for GDP and BP for oil demand), a combination chosen for depth, consistency, and timeliness of coverage.
- 7. The residential and transport sectors have an R² of 0.98 and 0.96, respectively, compared to industry and petrochemicals, which have an R² of 0.93 and 0.82, respectively (all over the 1984–2018 period as per IEA 2020 data availability).
- In 1991-97, oil intensity declines flattened to 0.008 barrels (bbl) per \$1,000 p.a., down from 0.011 bbl per \$1,000 p.a. during the preceding seven years, when the long-term oil intensity trend first emerged (1984-90). In 2001-4, incremental oil intensity improvements fell below 0.006 bbl per \$1,000 p.a., compared to 0.010 bbl per \$1,000 during 1984-2000. The subsequent acceleration in 2005-8 saw oil intensity improving by a record 0.016 bbl per \$1,000 p.a.
- 9. The dictum "If something cannot go on forever, it will stop" is referred to as Stein's law



(Samuelson 2013). One could argue, of course, that oil demand will eventually disappear, like firewood did—to stay in the genre, this would be an example from the broader category of "What goes up may always come down, but the reverse is seldom true" (Hogan 1993, 125).

- 10. R² is 0.996 for the exponential trend (i.e., logarithmic specification) and 0.994 for the linear trend specification.
- 11. R² in the linear specification is 0.99 in both cases, whereas with the exponential trend in the logarithmic specification, R² is 0.98 for each of the two groups of countries.
- 12. To put the absolute deviations of 0.008 and 0.022 bbl per \$1,000 into perspective, note the average actual oil intensity level between 2004 and 2018 was 0.487 bbl per \$1,000, and the average actual oil intensity level between 2017 and 2019 (which are the three 14-year forecasts) was 0.435 bbl per \$1,000.
- 13. There is extensive and not always uncontroversial literature on the differences in causes, symptoms, and consequences of oil demand and supply "shocks," including the two episodes referred to in the text. See Blanchard and Gali (2007), Baumeister et al. (2009), and Chain et al. (2014); specifically for the 2000s in the United States, see Hamilton (2009a, 2009b) and Kilian (2009).
- 14. It took nine years for global oil consumption to regain the level of 1979. For real prices (which had reached their apex in 1980), this didn't happen until 2008.
- 15. See Gately and Huntington (2002), Dargay (1992), Gately (1992, 1993), and Dargay and Gately (1994) for the early stages of this discussion.
- 16. In theory, price oscillations would thus drive oil intensity toward zero, which is why slightly more sophisticated versions had to be added.
- 17. Based on the Harvard Oil Market Simulation Model, the estimates were carried out for OECD economies and product prices (as distinct from crude prices). Technological change was exogenous.
- 18. These models would typically use putty clay versions of technological change, with changes in the capital stock irreversible.
- 19. Installations to refine and process crude oil belong in the second category as well. For empirical purposes, we will use the IEA sectoral classification, with transport and residential use representing final consumption and the remainder representing intermediate demand (cf. IEA 2020).
- 20. "Oil" here refers to products, not crude, but empirical studies seem to be doing fine by employing a fixed conversion schedule and taking crude prices as a proxy.
- 21. Close substitutes (e.g., public vs. individual transport) would also fall into this category.
- 22. Also for technical reasons—that is, because they tend to use the heavy end of the barrel.



- 23. Oil demand growth in response to real oil price declines has been declining steadily, from around -0.15 during the 1984-88 oil price decline, to around -0.09 in the 1990s, and down to below -0.07 during the 2014-16 oil price decline.
- 24. The later industrialization has started, for example, the less likely that the initial state has much scope for substituting oil in intermediary uses, such as power or industry. The more elastic the demand for end-user appliances is with respect to per capita income growth, the higher the likelihood that, as GDP grows, the volume demand caused by the sheer number of new appliances outweighs their efficiency improvements in aggregate. Under these conditions, even leapfrogging (resulting, for example, in a new and highly efficient vehicle fleet) may, at least during the initial period of rapid oil demand growth, not show up as the smooth convergence of oil intensity across countries we found with regard to the three large economies depicted in the text.
- 25. The biggest exceptions are large oil producers in the Middle East, where energy intensity continues to rise, regardless of their sectoral composition. Cf. Rühl and Giljum (2011) and Rühl et al. (2012).
- 26. After the first oil price shock in 1973, GDP slowed down to 0.6 percent (1976), from a five-year average of 5.3 percent (pre-1973); similarly for the price shock in 1979-80, from a previous average of 4.3 percent (four years), GDP growth slowed down to 0.4 percent in 1982. After the run-up to higher prices in 2010-11, global growth actually accelerated (to 2.8 percent, from a five-year average of 2.6 percent for 2007-11).
- 27. Cf. the references listed in note 15.
- 28. The argument made in this paper implies that both the likelihood and likely timing of peak oil demand as well as the consequences for the structure of the oil market and the role of OPEC are making their way on the global agenda independent of the Energy Transition.
- 29. Assuming no quantity targets—that is, that the principle is maintained that to minimize the social cost of decarbonization, the price of carbon has to be uniform across all segments of the economy.
- 30. During 2012–19, the US trend flattened to 0.003 bbl per \$1,000 p.a., down from 0.012 bbl per \$1,000 p.a. in the period 1984–2011, compared to 0.008 bbl per \$1,000 from 0.010 bbl per \$1,000 over the same two periods for the rest of the world—a 70 percent reduction in the United States vs. 20 percent in the rest of the world.
- 31. EIA (2018).
- 32. The forward curve appears to support this proposition. The one- and the five-year strip both indicate lower price expectations in reaction to the advent of sizeable tight oil production growth. However, forward curves also have a tendency to move with prompt prices, a tendency that seems to have been left intact by the rise of shale oil.
- 33. The impact of a "demand peak" on today's oil market structure would be dramatic as it would undermine the ability of low-cost producers to raise prices by cutting production and with it, the OPEC edifice that has been with us for so long.





