Prices, Income and Energy Demand

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ABSTRACT
This chapter covers what we have learned from economic studies that model the derived demand of energy-using services like space conditioning, lighting, mobility and industrial production. We report the range of estimated income and price elasticities—i.e., the percent change in energy demand that corresponds to a one percent change in that corresponding variables' level—for several aggregations of energy use: total energy consumption, road transport (gasoline and diesel), residential consumption (particularly electricity) and industry consumption (particularly electricity). While summarizing the literature, we focus on answering two important energy demand questions: (i) is the income elasticity of energy demand less than unity? and (ii) are income and price elasticities different across income levels? Additionally, we consider whether demand responses could have been larger due to the oil price shocks in the 1970s than in later years. The chapter concludes with some discussion of policy implications and avenues for future work.

Keywords: price and income elasticity estimates; OECD and non-OECD countries; energy and electricity demand; energy intensity.

1. Introduction

Can the world economy continue to grow while simultaneously reducing its dependence on energy sources that emit large amounts of greenhouse gas emissions? That challenge remains paramount over the next several decades for a range of different country experiences. Our chapter focuses upon what can be learned from economic studies about the energy consumption trends after the 1973 oil price shock. The past by no means dictates the future, as the penetration of new technologies and business strategies like shared mobility are beginning to materialize. Nevertheless, a careful reading of the past trends and of the factors causing them provides a useful benchmark that will continue to help shape future trends.

World energy use grew more slowly than world economic activity since 1971 due to the combination of higher energy prices, energy-saving technical progress, and shifts towards less energy-intensive economic activities. Figure 1 depicts key world energy and real GDP trends on a per-capita basis over the 1971-2014 period as measured by the World Bank's *World Development Indicators*. Each trend/series is indexed by setting its 1971 level equal to unity. Both fossil fuel (dashed black line) and total energy (solid black line) per-capita use rise more slowly than the real per-capita GDP trend (line with circle markers), while electricity use (gray line) rises more rapidly. The trend towards more electrification has been a long-run phenomenon. Through 2014, the trends for fossil fuel and total energy have been reasonably similar, although there has been a greater shift away from fossil fuels in more recent years that are not yet included in the World Bank series.

Figure 1

In contrast to these gradually rising trends, the average price for all commercial energy forms fluctuated substantially more without a dominant trend over this period. Figure 1 also includes price as a dotted line, but it is important to recognize that its scale is plotted along the right-hand axis. If the price line's scale were plotted along the left-hand axis, prices would have no long-term trend relative to the other variables. This series is the cross-country average of the real energy price data from Liddle and Huntington (2020a) that is used in the more detailed results considered in later sections. The average energy price rose through the 1970s as Middle Eastern oil supply disruptions made oil supplies scarcer and more expensive. After reaching a peak in 1982, energy prices subsided for more than two decades before rising beginning in 2004. By 2014, the average energy price was only 9.5% higher than its 1971 level compared to the 2014 GDP level, which was 65% higher than in 1971. Nearly half the years (21) were marked by energy price declines. Thus, energy consumption during this period was responding to relatively steady long-term economic growth (with occasional recessions), but also to fluctuating energy prices that rose very little over the long term.

Electricity, petroleum, natural gas and coal are the primary energy sources, and their prices followed different patterns and displayed some important regional differences. Electricity prices tend to vary substantially across countries—both in terms of the levels of price and the trends over-time; however, in most countries, industrial prices are lower than residential prices. Road fuel prices are highly correlated and tend to move together with international oil prices. Yet, those prices can differ substantially across countries—mostly because of differences in taxes; but, typically, diesel is priced less than gasoline/petrol. Until around 2008, crude oil prices and natural gas prices moved in tandem; however, since 2008, the two prices have largely decoupled.

The demand responses to real energy prices and income (as measured by real GDP) discussed in this chapter will be based upon the best available techniques for evaluating these responses in many countries over multiple decades. As a useful benchmark for framing the discussion of detailed results in this chapter, consider a very simple curve-fitting exercise on the World Bank data (i.e., Figure 1) for per capita total energy and per capita GDP with the additional information about energy prices. When global energy demand per capita is regressed as a simple static function of real energy prices and real world GDP per capita, we observe that energy demand increases by 0.66 percent when income (GDP) increases by one percent and decreases by 0.34 percent when real energy prices increase by one percent.[1] Both responses are significantly different from zero at the one percent level.

Rather than improve this equation with further refinements, we will instead draw upon a rich and growing literature on estimates that incorporate and adjust for dynamic responses, the vast heterogeneity across individual countries, possible unit root trends, and the likely cross-sectional dependence between countries. Nonetheless, these simple global responses suggest that total energy consumption responds inelastically to both price and income,[2] but that the (absolute value) response to income may be approximately twice its price counterpart. This benchmark serves as a useful guide for evaluating responses derived from more detailed studies. They underscore the importance of tracking both price and income effects when evaluating energy consumption trends rather than focusing upon either factor alone. Later sections will

[1] This illustrative equation is:

$$\text{ln\_energy} = -0.34\ \text{ln\_price} + 0.66\ \text{ln\_gdp} - 0.04\ \text{post-shock}$$
$$\qquad\qquad(3.64)\qquad\qquad(26.17)\qquad\qquad(3.05)$$

Root MSE=0.026; Durbin-Watson =0.687

where the prefix ln_ refers to the natural logarithm, and all variables are expressed as indices where 1971 equals 100. Post-shock adjusts the intercept to incorporate the long-term effect of structural shifts caused by the oil price shocks during the 1970s. It equals 1 after 1982 when energy prices reached their maximum level and 0 otherwise. The t-statistics shown in parentheses are adjusted for heteroskedasticity and hence are more efficient with smaller confidence limits than otherwise. But clearly the error term appears to be serially correlated as revealed by the reported Durbin-Watson statistic that is well below 2.

[2] Inelasticity exists when the percentage change in energy demand is less in absolute terms than the percentage change in either price or income.

explore the extent to which these general conclusions remain intact with more detailed techniques that account for the substantial heterogeneity in the various responses by country. For exposition reasons only, the discussion will focus on the average response across all countries in total or within a group (like developed or developing countries). These averages represent typical responses, but the actual response within any one country may vary considerably from these estimates.

2. Basic model for deriving energy income and price elasticities

Empirical applications have long recognized that energy use is a derived demand for meeting a range of energy-using services like space heating, mobility and production of products like steel or vehicles. These choices comprise two distinct and separate decisions about energy use: (1) the purchase of new equipment to replace old equipment or expand activities, and (2) its utilization rate. The capital-stock-utilization framework (Fisher and Kaysen, 1962) explicitly represents the normal energy usage associated with specific energy-using technologies and equipment for a particular vintage or year when the equipment is purchased. Utilization rates may vary in the short run as income, price and other economic and demographic factors change.

As conceptually appealing as this approach is, collecting the appropriate energy equipment data for even one country can be a monumental task. As a result, most empirical applications follow the lines suggested by the flow-adjustment model (Houthakker and Taylor 1970) that incorporates the stocks of capital implicitly but that maintain the distinction between short- and long-run effects. This framework assumes that consumers have a long-run desired flow of energy consumption that they want to reach if all equipment could be turned over immediately. In the short run, they can adjust only partially to the difference between desired and actual flows.

The standard energy demand model for empirical applications is:

$$ln\ E_{it} = \alpha_i + \beta_i^1 ln\ Y_{it} + \beta_i^2 ln\ price_{it} + \varepsilon_{it} \quad (1)$$

where subscripts *it* denote the *i*th cross-section and *t*th time period, *E* is energy consumption per capita, *Y* is income or GDP per capita, and *price* is energy price.[3] Both price and income are expressed in real terms by adjusting for any price inflation over time. If the variables are in logged form (as in Equation 1), the estimated betas can be thought of as elasticities, i.e., they represent the percent change in energy demand that corresponds to a one percent change in the corresponding variables' level (either income or price). One expects a positive relationship between income and energy consumption and a negative relationship between energy price and energy consumption.[4] If the variables in Equation 1 are in logged level terms, one would typically interpret the estimated betas as long-run elasticities.

To incorporate the gradual adjustments imposed by new capital stocks/technologies gradually replacing older vintages and to estimate short-run and long-run effects simultaneously, one could make Equation 1 dynamic. The simplest dynamic model, the partial adjustment model, adds a lag of the dependent variable:

$$ln\ E_{it} = \alpha_i + \beta_i^1 ln\ Y_{it} + \beta_i^2 ln\ price_{it} + \beta_i^3 ln\ E_{it-1} + \varepsilon_{it} \quad (2)$$

Because adjusting to changes in income or prices takes time, one expects short-run elasticities to be smaller in (absolute) magnitude than long-run elasticities. In principle the difference between the long-run and short-run would represent the time it takes for the (relevant) capital stocks to

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[3] There is a large literature that examines the directions of causality between energy consumption and economic growth, i.e., the idea that energy could cause GDP too. However, a meta-study that examined that literature, Bruns et al. (2014), could only establish a robust genuine effect from GDP to energy use when prices were included, i.e., the direction of causality represented in Equation 1.

[4] There are many complexities in measuring the energy price elasticity accurately. EMF4 Working Group et al (1981) provides a comprehensive discussion of the major problems, including adjustments for the heterogeneity of fuel types and whether prices are measured on the wholesale or retail level.

turnover/be replaced. In applied work, β^1 and β^2 from Equation 2 are considered short-run elasticities (as opposed to in Equation 1), and the long-run elasticities for income and price, respectively, are calculated from the following transformations:

$$\frac{\beta^1}{(1-\beta^3)} \text{ and } \frac{\beta^2}{(1-\beta^3)} \quad (3)$$

The data used in Equations 1 and 2 could be macro, country-level (or in the case of the US or China, for example, state or provincial level), or it could be micro-level data, e.g., from households or firms. In the macro case, the observations would most likely be annual (or, perhaps, quarterly); whereas, in the micro data case, the observations could be much more frequent, such as monthly or weekly.

The data also could be based on end-use sector, e.g., residential, industry or transport, or based on fuel type, e.g., electricity or natural gas. Indeed, because energy services differ and their substitution possibilities differ, estimated elasticities for various end-uses are typically different.

Occasionally one augments Equations 1 or 2 with the price of an alternative fuel to estimate a cross-price elasticity (e.g., Alberini et al. 2011). In such cases, one expects the cross-price elasticity to be positive. While such cross-price elasticities can be useful for policy makers, they are most commonly not considered unless the analyst adopts a systems approach.[5] In addition to data availability restrictions, there is evidence that fuel switching without changing equipment is rare (e.g., Steinbuks 2012), because, for example, some services can be performed only by electricity; likewise, vehicles use either gasoline or diesel, and stoves/furnaces use either

[5] Two popular system approaches are the Almost Ideal Demand System (AIDS) used by Schmitz and Madlener (2020) and the translog cost estimation used by Griffin and Gregory (1976) and Pindyck (1979). Many recent estimates do not use a systems approach, however, due to data limitations, and because this method often sacrifices degrees of freedom to achieve greater flexibility.

electricity or natural gas. Over time, homeowners and industry can substitute between energy forms by replacing their capital stock. Espey and Espey (2004), in their meta-study on residential electricity demand, found that the omission of substitute fuels did not have a significant impact on short-run price elasticities, or long-run income elasticities but did result in significantly lower long-run price estimates and short-run income estimates.

Data availability also often constrains the inclusion of other possible explanatory variables. Some of the typical additional variables (depending on the model and data aggregation) are: vehicle stocks for road transport consumption (Karathodorou et al. 2010; Liddle 2012), weather controls for residential consumption (e.g., Eskeland and Mideksa 2010; Liddle and Huntington 2020c), demographic characteristics (age, household size) for household, micro-data (e.g., Alberini et al. 2011), dwelling size for residential consumption and household data (e.g., Alberini et al. 2011), and urban density for city-level (cross-sectional) data (e.g., Karathodorou et al. 2010; Liddle 2013). Ultimately, to maximize time observations and/or cross-sections, the reduced form model (e.g., Equations 1 and 2) tends to be the most popular.

Another variable that is sometimes included (for which data availability is rarely a constraint) is share of people living in urban areas or urbanization. Urbanization is clearly an *indicator* of modernization, development and progress (as is wide-spread electrification), but urbanization is unlikely a *catalyst* for any of them (Henderson 2003). Furthermore, in addition to the fact that urbanization and GDP per capita are highly correlated, introducing urbanization to the right-hand-size of Equation 1 or 2 can lead to misspecification, because there is more evidence that electricity consumption Granger-causes urbanization than the other way around (Liddle and Lung 2014).

In Equations 1 and 2, we have suggested the structure of the data contains observations from both different cross-sections and different time periods; however, this need not be the case. The data could be time series data (from a single country) or pure cross-sectional data (taken at a single time observation). Time series are useful to model dynamics and to distinguish between long-run and short-run effects. Cross-sections are commonly thought of as producing long-run estimations, but using such data runs a heightened risk of missing variable misspecification (since countries may differ in ways that are not controlled for). Panel data involves a combination of these two extremes, i.e., several cross-sections observed at more than one time period (and as such, panel data can control for slow moving, country-specific factors). Long panel data are comprised of individual time series that are "stacked" upon one another. Such long panels may be considered the preferred construct for macro models that are based on annual data (provided that enough cross-sections and time observations are available, say, at a minimum 20 of each). Liddle and Huntington (2020a and 2020b) go into detail on the important statistical issues to consider in using long panels, as well as on the advantages and pitfalls of several estimators that are typically employed. (See Miller and Alberini 2016 for a discussion of statistical/modeling issues that are pertinent for micro data.)

When combining data from different countries, earlier studies often assumed that each nation's response was the same as that for other nations.[6] Later studies replaced this assumption with specifications that allowed a different response for each nation.[7] A related issue sometimes arises when a country's experience is related to what happens in other countries. This cross-sectional dependence can be due to global shocks like widespread economic recessions or world

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[6] Fixed and random effects estimations based on panel data are common methods for implementing this approach.

[7] A widely used technique adopting this approach is the mean group estimation on panel data.

oil price shocks, as well to pervasive phenomena like the very similar GDP growth rates within OECD countries.

Meta studies of energy demand papers have shown that differences in cross-sectional and temperate aggregation matter in terms of the magnitudes of the estimated elasticities. National level data often provide more inelastic (i.e., smaller absolute) price elasticities than less aggregated household data (Halvorsen and Larsen 2013; Labandeira et al. 2017; Miller and Alberini 2016; Zhu et al. 2018). Espey and Espey (2004) determined that studies using monthly data found significantly more elastic (i.e., larger) long-run price estimates than those using yearly data. Labandeira et al. (2017) reported that price elasticities were larger in (absolute) magnitude on average when based on cross-sections than on panels, which themselves, produced larger in magnitude elasticities than those based on individual time series data.

In terms of the income elasticity, studies using cross-sectional data tended to estimate higher elasticities, but panel vs time-series data did not have an impact on long-run estimates (Espey and Espey 2004; Havranek and Kokes 2015; Zhu et al. 2018). Zhu et al. (2018) found that annual data produced larger long-run elasticity estimates for residential electricity than monthly data, but there was no difference in short-run estimates; by contrast, Havranek and Kokes (2015) determined that the sampling frequency of the data did not matter for gasoline demand. Lastly, Zhu et al. (2018) claimed that using macro or micro/survey data had no impact on short- or long-run income elasticity estimates.

3. State of knowledge on income and price elasticities of energy demand

In this section we provide the reader with an overview of the income and price elasticity results from energy demand analyses. Our main purpose is to provide a range and reasonable mean for income and price elasticities at several levels of energy use: economy-wide, total energy consumption, road transport (gasoline and diesel), residential consumption (particularly electricity) and industry consumption (particularly electricity). While we do not provide a comprehensive review of this extensive literature, we do believe the following discussion covers the definitive, current state of knowledge for two important energy demand questions: (i) is the income elasticity of energy demand less than unity, and (ii) are income and price elasticities different across income levels? Additionally, we consider several possibilities for why the demand response to price increases and decreases could differ from each other (often referred to as asymmetric responses), and whether the responses could have been larger due to the oil price shocks in the 1970s than in later years.

The energy price shocks during the 1970s caused widespread unemployment and made the existing capital stock obsolete in many developed economies. In response to these conditions, early cross-country studies focused on the response to major price shifts and on whether energy and capital were substitutes for or complements of each other. Pindyck (1979) and Griffin and Gregory (1976) evaluated nine and ten developed economies, respectively, to demonstrate that the long-run substitution opportunities between energy and the capital stock were more extensive in cross-country studies than those found in studies of a single economy, and that the price elasticity of energy demand might be larger than supposed.[8] During the 1990s and later, research interests shifted towards understanding the long-run implications for energy consumption in response to sustained economic growth, particularly outside the OECD.

While perhaps not obvious, the issue of whether the income/GDP elasticity of energy demand is less than one is of import, because in such a case, energy intensity (energy

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[8] Both studies found a long-run price elasticity of about -0.8 for the manufacturing sector, which is larger than what most later cross-country studies reveal. However, both studies used a methodology that holds fixed the real prices of labor and capital, while the later studies reviewed below do not control these non-energy factor prices.

consumption divided by GDP) will fall with economic growth (or increases in GDP). Falling energy intensity is of interest for two reasons. First, several countries/groups of countries have targets/goals for lowering intensity-based indicators (energy intensity, carbon intensity). For example, several countries, as part of the Paris Agreement on climate change, have committed to reduce their emissions intensity; among the countries to set intensity-based targets are China, India, Malaysia, and U.S. Several other countries have set goals to reduce emissions below a business-as-usual (growth) scenario, including Indonesia, Thailand, and Republic of Korea. (Indonesia has a goal to lower its macro energy elasticity of GDP, too.) In addition, the APEC economies have an aspirational goal of lowering APEC aggregate energy intensity by 45% from 2005 levels by 2035; and the ASEAN countries have a goal of lowering energy intensity by 20% from 2005 levels by 2020 and 30% by 2025. However, if the appropriate GDP elasticity is less than unity, intensity will fall in an economic-growth, business-as-usual situation, thereby making the target considerably less stringent.

Second, there has long been a belief that energy intensity follows an inverted-U shaped path with GDP per capita, in which resource use per unit of GDP falls once an economy passes some threshold level of GDP per capita. The expectation is that energy intensity initially rises as low-income countries increase their industrial bases and then declines over time as countries undergo a sectoral shift from energy-intensive, heavy industry to light industry, and ultimately to the (even) less energy intensive service sector. In other words, the income elasticity of energy consumption is greater than unity when an economy is on the left-hand-side of that inverted-U shaped, energy intensity-GDP path; whereas, the income elasticity of energy consumption is less than unity when an economy is on the right-hand side of the inverted-U. So, an elasticity of less than one marks a country's transition into a more dematerial or relative-decoupling state.

3.1 Macro- or economy-wide income and price elasticities

Popular questions in energy economics include (i) estimating the relationship between economic development and energy demand, i.e., the macro-energy-GDP elasticity—the percentage change in energy consumption associated with a 1% change in GDP, and (ii) determining whether that relationship changes as levels of development. Previous panel estimations of a nonlinearly changing macro-energy elasticity of GDP include Galli (1998), Medlock and Soligo (2001), Richmond and Kaufmann (2006), van Benthem and Romani (2009), and van Benthem (2015). In addition to analyzing data that had both time series and cross-sectional dimensions, these papers considered both GDP and energy prices.

Galli analyzed 10 developing Asian countries, including Korea and Taiwan, over 1973-1990. Medlock and Soligo compiled data from 28 countries, of which seven were non-OECD (Brazil and six Asian countries), over 1978-1995. Richmond and Kaufmann (2006) considered data from 16 OECD countries, spanning 1978-1997. The dataset van Benthem and Romani analyzed contained 17 developing countries (including Israel and Korea)—for which individual country, end-use prices were available—and spanned 1978-2003. The individual country, end-use price data that van Benthem (2015) used ran from 1978-2006 and included observations from 58 countries. It appears that only the Galli and Richmond and Kaufmann datasets were balanced and sourced from public energy price data.

In addition to using a standard demand-type model in which energy consumption per capita is a function of GDP per capita and real energy price (i.e., Equation 1), Medlock and Soligo (2001), van Benthem and Romani (2009), and van Benthem (2015) employed the partial adjustment mechanism (i.e., Equation 2); whereas, Galli (1998) estimated an error correction model. Richmond and Kaufmann (2006) only estimated static models. To capture potential nonlinearities, all five papers added a GDP per capita squared term (van Benthem and Romani included price squared as well, and Richmond and Kaufmann included semi-log and double-log specifications as alternatives to the GDP per capita quadratic). In addition, van Benthem (2015) estimated a linear model across several income bands.

All papers uncovered evidence of a nonlinear relationship between energy consumption and GDP, e.g., significant coefficients for both GDP and GDP squared (although, for Galli, those coefficients were insignificant when the country responses to GDP were allowed to differ from each other through a technique called the mean group estimator). However, the shapes of the GDP-energy relationship were not always the same. Richmond and Kaufmann (2006) rejected an inverted-U-type relationship between income and energy use when real oil prices were included, but claimed their results suggest "diminishing returns." Galli (1998) and Medlock and Soligo (2001) estimated inverted U-shaped relationships (i.e., the GDP term was positive while the GDP squared term was negative), as did van Benthem (2015) for income in the $10,000-$40,000 range. In contrast, van Benthem and Romani (2009) estimated U-shaped relationships (i.e., a negative GDP coefficient but a positive GDP squared one), as did van Benthem (2015) for GDP per capita less than $10,000 (where the linear GDP term was insignificant). The van Benthem and Romani result of an increasing income elasticity appears to have been caused by observations from income levels less than $5,000 since a subsequent regressions based on income levels between $5,000-$10,000 produced an inverted-U shaped relationship.

For a linear model, Galli estimated long run income and price elasticities of 1.18 and -0.32, respectively. Also, country-specific income elasticities were typically above unity for the developing Asian countries that Galli analyzed; yet, the forecasts implied that nearly all the countries considered would have an elasticity below unity today because the projected income levels would be substantially higher than the historical levels used in the estimation equation. In their linear model, van Benthem and Romani (2009), also considering developing countries, found substantially different GDP and price elasticities of 0.64 and -0.55, respectively (although, that regression does not include time effects, which are demonstrated to be significant). Another (van Benthem and Romani) regression that was based on a $5,000-$10,000 income band and that included GDP squared (but not price squared) produced a much lower price elasticity of -0.11. Richmond and Kaufmann (2006) calculated a panel average income elasticity of 0.33 for OECD countries (an F-test rejected homogenous or equal slopes for all nations). Van Benthem (2015) often estimated a GDP elasticity that was near unity for less developed countries and sometimes found that the elasticity varied across income bands (in such cases it was higher at lower incomes).

So, this earlier work found that the GDP elasticity varied with income and was (typically) near one when averaged across all (considered) developing countries, except for Richmond and Kaufmann (2006)—whose data was OECD only—and who found an average income elasticity of well below one. However, the estimates in these previous studies revealed very different patterns about when the response to income would begin to decline. Moreover, they assumed that income responses changed only gradually as the economy became more developed and per-capita income advanced.

Recognizing that the vastly different experiences of developing economies may be due to other factors, Gately and Huntington (2002) offered a very different approach by selecting different groups of countries based upon their economic growth patterns as well as their dependence upon oil exports. They also cast attention to many more countries than other studies discussed above. Their sample covered 96 nations over the 1971-97 period and represented energy costs with oil prices. Their estimates for long-run income elasticity of energy were (i) about 0.6 for the OECD countries, (ii) about 1.0 for Non-OECD countries whose income was growing steadily by at least two percent annually,[9] (iii) about 0.5 for Non-OECD oil importers with slow and uneven income growth, and (iv) substantially above unity for oil-exporting developing economies. The rather sharp differences among the income elasticities for these groups underscore that results will be very dependent upon which developing countries are included or excluded from a particular study. Their estimates for long-run price elasticity of energy were about -0.25 for the OECD countries, but below or about -0.1 for the various Non-OECD country groups.[10]

In a more recent paper, Czereklyei et al. (2016), applied static (and linear) models to a cross-sectional approach and, like the Gately-Huntington study, considered a large number of countries. Czereklyei et al. uncovered a stable relationship between energy use and income over 1971-2010, and found an energy elasticity of income less than unity (i.e., around 0.7) by comparing five cross-sectional regressions (of 99 countries) taken at ten-year intervals. However, Czereklyei et al. did not account for energy prices, and considering whether cross-sectional estimations vary over time assumes independence both over time and across units (Smith and Fuertes 2016).

More recently still, Liddle and Huntington (2020a) assembled a dataset of energy consumption and prices for 37 OECD and 41 non-OECD countries and estimated dynamic

[9] Their fast-grower group included 14 developing countries whose average annual growth in per-capita income exceeded two percent: South Korea, Thailand, Malaysia, Tunisia, Syria, India, Sri Lanka, Egypt, Colombia, Israel, Singapore, Malta, Morocco, and Bangladesh. They excluded two other developing countries that also experienced this rate of income growth: China due to its size and unique characteristics and Indonesia because it is an oil exporter.

[10] This study also controlled for asymmetric responses to oil price movements and is discussed further in section 3.2.

demand equations using a statistical method that allowed for different responses across countries and accounted for that dependence over time and across units. Liddle and Huntington calculated a long-run GDP elasticity of approximately 0.7 that was likely (even if not at the 95% level of certainty) below unity. They found no evidence that the elasticity varied systematically according to GDP per capita/level of development, in considering, e.g., (i) country specific estimations by sample average GDP per capita, or (ii) partitions of the dataset by OECD status or upper-middle- and lower-middle-income level. Hence, they concluded that energy intensity will fall with economic growth—because the GDP elasticity of energy is less than one, not because the elasticity changes with economic growth. Liddle and Huntington calculated a price elasticity of -0.27 for OECD/high-income countries and a very small and highly statistically insignificant price elasticity for non-OECD/middle-income countries.

3.2 Asymmetric and dissimilar demand responses

The mean price and income elasticities discussed in the previous subsections are useful reference points for understanding the approximate size of the responses to price and GDP. One should not view these responses as being the same for all countries or for all years. The previous sections have discussed the possibility that the demand response to GDP may change as the economy becomes more developed. This section considers the possibility that the demand response to price may change as the underlying conditions shift.

One can differentiate between two types of adjustments: dissimilar and asymmetric responses. Dissimilar impacts may be expected if the nature of an energy price increase changes or when the underlying economic conditions are different. The direction of the price change is not the distinguishing feature. Asymmetric impacts, however, occur when energy price increases have stronger effects on energy consumption than do energy price decreases. If consumers confront adjustment costs whenever energy prices change unexpectedly, these costs reinforce the reduction in energy consumption when prices rise but operate counter to the expected increase in energy use when prices decline. Although they are different concepts, asymmetric and dissimilar responses are often discussed together.

During 1973-74 and 1979-80, energy price shocks rocked the world economy and induced major structural changes. Higher prices, lower economic activity, the replacement of residual fuel oil within the electric generation sector, and more stringent energy policies on vehicle and equipment efficiency combined to reduce the growth in oil use sharply from its pre-1970 trend. When oil prices retreated from these higher levels, beginning in 1982 and particularly after 1986, petroleum demand did not expand nearly as rapidly as it had declined when oil prices rose during the 1970s (Huntington 1994).

There exists a voluminous literature (e.g., Dargay 1992; Walker and Wirl 1993; Dargay and Gately 1995, 1997, 2010; Gately and Huntington 2002; Huntington 2010) on the oil demand adjustment during and immediately after this (1970s) period. A common approach decomposed oil prices into three components: a price maximum since the beginning of an analysis, cumulative price increases, and cumulative price decreases. The first component largely captures the effect of oil price trends over the 1970s, and these articles justify its use on these grounds. When data is not available to measure price changes until 1979, as is often the case in the empirical literature, applying price maximums makes little sense unless the researcher can document that these periods, when prices were reaching their maximum level, had important structural changes.

The demand response to price changes that were reaching their maximum through the 1970s were significantly larger in absolute terms than their counterparts after 1980. Within the

OECD, the long-run oil consumption response when prices were reaching their maximum was -0.64, but was about half that effect for prices that occurred after that period (Gately and Huntington 2002). The comparable effects for OECD energy consumption were -0.24 and about -0.1. This effect was more dramatic for oil use than for energy consumption, and for the OECD countries than for the developing countries.

More recently, Adeyemi et al. (2010) analyzed 17 OECD countries and failed to find price asymmetries at the panel level, but did find such effects for about half of the countries at the individual level. More recently still, Liddle and Sadorsky (2020) considered panels of 91 OECD and non-OECD countries and determined that there was evidence of short run income asymmetry in all country groups (but no such long-run asymmetry). They found that GDP decreases have a larger impact on (short-run) energy consumption than increases in GDP by a factor of approximately two to one. Liddle and Sadorsky found some evidence of asymmetric long run price effects for OECD countries only (i.e., those countries for which their data stretched back to the 1960s-70s).

These results were often discussed as revealing asymmetric responses because oil prices increased during the 1970s but declined during much of the 1980s. This response, however, may have less to do with the direction of the oil price change and may instead simply reflect a smaller demand response that occurred after the 1970s. This interpretation is supported by several studies (Ryan and Plourde 2002; Hughes et al. 2008) that compare different periods directly. Moreover, studies (e.g., van Benthem and Romani 2009; Liddle and Huntington 2020b) conducted for periods that excluded the 1970s often do not find asymmetric responses. Similarly, studies (e.g., Huntington 2010) that include the 1970s, but also control for the experiences of the 1970s, often find similar effects for price increases and decreases after the 1970s.

3.3 Sub-sector income and price elasticities

While end-use energy demand has been a particularly well-studied area, many analyses have focused on single countries (despite the advantage of cross-country panels). So, surveys and meta-studies of this literature have been both common and helpful. Indeed, surveys of earlier econometric estimates (Dahl and Sterner 1991; Graham and Glaister 2004; Huntington et al. 2019) and meta-analyses seeking to explain the range of results across different studies (Brons et al. 2008; Espey and Espey 2004; Havranek et al. 2012; Havranek and Kokes 2015; Labandeira et al. 2017; Zhu et al. 2018) have played important roles in assessing/summarizing previous work and informing policy developers. Collectively, they have revealed reasonable estimates of the likely mean and range of responses to prices and income.

In addition to informing with regards to the important influence of data characteristics on estimated values, meta-type analyses suggest what data setups are best for analyzing certain questions. While some residential and industry energy demand studies have considered household- or firm-level data, the vast majority of road fuel estimates are based on aggregate level data at the country or sub-national level (Graham and Glaister 2002). Micro data may allow for a more accurate modeling of decisions—particularly for price effects and for short-run effects; however, there is evidence that income effects are more difficult to determine using disaggregated data (Graham and Glaister 2002). Furthermore, micro-based panels are typically short (in terms of time observations), and Havranek and Kokes (2015) argued that it is likely that studies using short series will not be able to observe the full effect of the adjustment to changes in income. Also, Havranek and Kokes (2015) argued that pure time-series analyses—ones that do not include any cross-sectional information—may be biased. Yearly data arguably is more suitable for modeling long-term income adjustments (Dahl and Sterner 1991; Zhu et al. 2018), but monthly data may more accurately measure the demand response to price changes (Espey and Espey 2004; Zhu et al. 2018). Lastly, Liddle and Huntington (2020a)—not a survey or meta-study—argued and demonstrated that employing long-panel data facilitates addressing several key statistical/modeling issues (nonstationarity, cross-sectional dependence, heterogeneity).

Yet, surveys and meta-studies often do not appear to have the resolution/available data to determine whether/how much elasticities vary between OECD and non-OECD countries at the sectoral level; furthermore, after controlling for important modeling and statistical concerns, even general average calculations can be severely affected by a lack of precision. In addition, such analyses rely on data that is of questionable quality. Indeed, Havranek and Kokes (2015) and Havranek et al. (2012) demonstrated the importance of adjusting for publication bias, e.g., researchers self-censor by not reporting economically implausible results. Yet, this bias is not asymmetrical—not all published studies are of the highest quality, at least, not at the highest *current* quality standards. So, after Havranek and Kokes (2015) adjusted for their preferred specifications, their resulting income elasticity estimates were insignificant for both OECD and developing countries.

The above discussion points to the value of studies that analyze a large sample of developed and developing countries. Hence, in the account below, we rely on both surveys and meta-studies and recent results that are based on long-panel, national-level, annualized data.

3.3.1 Transport/road fuels

Road transport is likely the most analyzed sector of energy demand. Indeed, easily more than a dozen surveys or meta-studies have covered or entirely focused on transport demand (by far the most for any energy subsector). Table 1 indicates the average gasoline elasticities reported by several such surveys and meta-analyses (skewed toward the more recent). The long-run income elasticity has ranged from 0.2 to 1.2, and the long-run price elasticity has ranged from -0.3 to -0.9.

Table 1

In a meta-type-analysis,[11] Dahl (2012) analyzed patterns of income and price elasticities for both gasoline and diesel from a database of previous (often country-specific) estimates. For gasoline, she found that price elasticities were higher at higher price levels and were higher at higher income per capita; whereas, income elasticities fell as income increased. For diesel, price elasticities were (similar to gasoline) higher at higher prices but (in contrast to gasoline) were lower at higher income levels. Because Dahl collected substantially less data on diesel estimates, she could not establish a conclusion as to whether income elasticities for diesel were different across income levels.

Estimating panel income and price elasticities for gasoline and diesel is challenging for OECD countries because, beginning in the late-1990s, many/most European governments instituted policies to make diesel passenger vehicles more popular. As a result of these policies, for example, the share of diesel cars in the passenger car fleet for the EU28 increased from 27% in 2005 to over 42% in 2017, and for 10 EU countries diesel cars represented the majority of their fleet in 2017 (data from European Environment Agency). Liddle and Huntington (2020b), considering a 35-OECD country panel, estimated long-run income and price elasticities for gasoline of 0.56 and -0.74, respectively. When they split that OECD panel into (1) the nine non-European countries plus Greece and Slovakia (which all have low diesel penetration rates in their passenger vehicle fleets), and (2) the 24 European countries that have a high degree of diesel penetration in their passenger fleets, the gasoline elasticities were mostly similar. However,

[11]Dahl (2012), Footnote 5, suggested that the statistical test she reported was different from traditional meta-analysis.

substantial differences with regard to diesel were revealed. For the smaller group of countries in which diesel primarily represents freight, the income elasticity was near unity, and the price elasticity was small and insignificant. For the European panel, the income elasticity was 2.1, and the price elasticity was -0.33 (significant, but less than half of that for gasoline). The high income elasticity for Europe is driven by policy preferences and is unlikely to continue substantially into the future.

The Liddle and Huntington (2020b) analysis considered a particularly large group of non-OECD countries (as many as 83 depending on the model). For the non-OECD countries the income and price elasticities were very similar for both gasoline and diesel—around unity for income and -0.25 for price (and statistically significant). In addition, subpanels of these non-OECD countries based on geography and income produced mostly similar coefficients.

So, the recent Liddle and Huntington (2020b) findings supported the Dahl (2012) conclusions that price and income elasticities for gasoline are higher and lower, respectively, at higher levels of income. Since Liddle and Huntington had substantially more information on diesel fuel, their results add clarity to Dahl regarding those previous findings for gasoline. For diesel, the price elasticities may be higher—but are definitely not lower—at higher levels of income. Income elasticities—outside the exception of those many European countries that chose to encourage diesel passenger vehicles—are similar across various income levels.

3.3.2 Residential energy/electricity

Labandeira et al. (2017), a meta-study that collected and aggregated price elasticity estimates from individual studies, reported average short-run and long-run price elasticities for residential energy consumption of -0.22 and -0.62, respectively. That study did not report whether residential price elasticities were different according to development level. They reported a short-run price elasticity for residential electricity of -0.19, but a long-run elasticity for residential electricity appeared to be highly insignificant.

Another recent meta-study, Zhu et al. (2018), that focused only on residential electricity demand, calculated an average long-run price elasticity of -0.58 and an average long-run income elasticity of 0.96. Those average elasticities were similar for both developed and developing countries. However, the individual country responses considered by Zhu et al. ranged from -4.2 to 0.6 for price and from -0.9 to 4.4 for income. (Hence, it is not surprising that Zhu et al. could not determine whether elasticities for developed and developing countries were significantly different.)

A much smaller survey by Huntington et al. (2019) focused specifically on the estimated responses in about a half dozen major industrializing economies (including India, China, and Brazil, among others). These authors derived for residential electricity customers long-run responses to price that averaged -0.49, similar to Zhu et al. (2018), but reported long-run income elasticities that averaged 0.53, i.e., much lower than the average reported by Zhu et al.

A recent assessment of high-income panel estimates of residential electricity demand determined that the income elasticity was always less than one and mostly less than 0.6; and the modal price response (from eight panels total) was between -0.2 and -0.3 (see Liddle and Huntington 2020c, Table 1). In their own analysis, Liddle and Huntington (2020c) considered panels of 26 high-income and 29 middle-income countries (the only non-OECD panel we know of). They estimated long-run income and price elasticities of about 0.6 and -0.2, respectively, for high-income and 0.8 and -0.1, respectively, for middle-income. While the income elasticities for the two groups were not statistically significantly different (but for the high-income group, the elasticity was significantly less than unity), the two price elasticities likely were significantly different. Atalla et al. (2018) similarly found that higher price elasticities (in absolute value) were associated with higher levels of GDP per capita in their study of residential and commercial electricity demand.

3.3.3 Industry energy/electricity

Industry probably has been the least explored demand sector. While there have been several single-country OECD studies on industrial energy demand, there have been particularly few single country middle-income/non-OECD papers—considering only eight different countries in total. Those non-OECD estimated elasticities for both output and price varied considerably—from insignificant to small and significant to relatively large and significant (in absolute value), and that variation occurred among the studies that examined the same country, too (see Liddle and Hasanov 2020, Table 2). While we know of no meta-study specifically focused on industry energy demand, Labandeira et al. (2017) reported average short-run and long-run price elasticities for industry energy of -0.17 and -0.51, respectively. However, that study did not have the resolution to determine whether industry price elasticities differed by development level and, it appears, could not report average industry price elasticities for electricity that were statistically significant.

For high-income panel studies on industry energy/electricity demand, the modal price elasticity (out of six studies) is around -0.2 (see Liddle and Hasanov 2020, Table 1). Not all of those papers estimated output elasticities.[12] Van Benthem and Romani (2009) analyzed a panel of 17 mostly non-OECD countries (only one of two such panel estimates we know of) and estimated a price elasticity for industry energy consumption of -0.07 (that was statistically significant), but they did not estimate an output elasticity.

[12] Since for industry, the demand for energy services are based more on production than income, it is common—but not universal—to consider industry output/value added rather than GDP per capita in the demand estimation.

Recently, Liddle and Hasanov (2020) focused on industry electricity demand and panels of 35 high-income countries and 30 middle-income countries. For the high-income panel, they calculated an output elasticity of 0.5 (that was significantly less than unity) and a price elasticity of -0.25. For the middle-income panel the output elasticity was around 1.2 and was statistically significantly larger than that for the high-income panel. The middle-income price elasticity was highly statistically insignificant.

4. Summary, conclusions, and suggestions for future work

This chapter began with a simple benchmark income elasticity of 0.66 and price elasticity of -0.34 for all energy based upon very aggregate data. Our conclusions concerning the more detailed regional experience for all energy are broadly consistent with these benchmarks. While energy intensity (energy/GDP) will continue to fall with economic growth (the aggregate GDP elasticity of energy demand is around 0.7), energy demand will not decline. Indeed, for middle income/non-OECD countries, demand in several subsectors should rise more or less in concert with income/GDP growth (e.g., road gasoline and diesel, residential and industry electricity). For high-income/OECD countries, price elasticities are typically small, i.e., -0.2 to -0.3. A notable exception to this is road gasoline, for which the price elasticity may be near -1. For non-OECD/middle income countries, price elasticities are often insignificant. Road gasoline and diesel provide an exception, where price elasticities are around -0.25 (relatively small, but statistically significant). Table 2 summarizes the long-run income and price elasticities from recent work that employed the largest samples of data and most comprehensive econometric methods to date.

Table 2

From a policy perspective, these elasticity results suggest that to lower the impact of energy consumption, i.e., climate change/carbon emissions, one needs to focus on decarbonizing electricity generation, and—more challenging—road transport. While there are macro-economic efficiency reasons to have prices reflect external costs, the evidence presented here suggests that only for road gasoline would increased prices lead to substantially reduced consumption.

An important topic for future research will be to understand whether and how demand may respond to different energy price environments. Available estimates are based upon a long-term historical experience in which energy prices have fluctuated greatly on a yearly basis, but there has been no sustained increase in energy prices over multiple decades. The average energy price in 2014 was only 9.5% above the 1971 level; by 2016 this increase had declined to 5.7%. Many policy studies anticipate that sustained higher energy prices on fossil fuels will be required, most likely combined with other policies, to achieve an effective climate strategy. Such sustained long-term energy price increases may induce structural shifts in the economy that reinforce reductions in energy demand that are not picked up otherwise. There appears to be some evidence that the oil price shocks of the 1970s may have been at least twice as effective in reducing petroleum demand as the price changes that occurred in later years.

Data availability is a/the key challenge to overcome to improve understanding of price and income elasticities and of how those elasticities evolve either over time or across development levels. For example, more price data from the 1960s and 1970s would help to determine the extent that price elasticities of demand may have changed in response to the energy crises. More data from low-income countries would further the knowledge of whether/how demand evolves over the development process. Similarly, time series data of capital stocks—e.g., vehicle stocks, appliances—would improve our appreciation of road fuel and residential energy demand.

Also, it may be important to acknowledge the full consequences of oil/energy price changes. As discussed in Section 2, price elasticities are estimated with regression analysis that views prices, GDP and other explanatory factors as exogenous variables that are unrelated to the equation's error term. When supply and demand conditions determine both fuel prices and consumption endogenously, the estimates may be biased below the true value for the demand elasticity of price. This problem will be less severe when prices do not need to rise much to supply additional fuel, i.e., when their supplies are very price elastic. Such supply conditions may apply for a domestic fuel like coal in which additional supplies can be provided with minor or no price adjustments, or for imported oil bought on a global market by one of many nations.

Many/most macro-level, cross-country studies do not try to control for this (or other/any) endogeneity issue(s), because finding strong and reliable instrumental variables for fuel prices (or GDP) can be quite challenging.[13] For example, instruments that correlate with price difference across panel members may not exhibit as much variation within panel members over-time, in part, because such instruments are based on reserves/endowments or capital stocks—like the share of coal and hydro in the electricity mix or domestic reserves of natural gas; hence, employing such instruments can mean reducing a long panel into a short or purely cross-sectional one. Thus, in choosing to address endogeneity (a single concern), one abandons the ability to address several other important issues (nonstationarity, cross-sectional dependence, heterogeneity, and dynamics).[14] So, improving instrumental variable regression in macro, cross-country panels is a research area under development.

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[13] Micro-level analyses often do address endogeneity; consider, e.g., Miller and Alberini (2016).
[14] Again, these issues are discussed in detail for the macro-panel context in Liddle and Huntington (2020a).

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Table 1. Mean Long-run Elasticity Estimates for Gasoline from Surveys and Meta-Analyses

Study	Income Elasticity	Price Elasticity
Dahl-Sterner (1991)	1.21	-0.86
Graham and Glaister (2004)	0.93	-0.77
Brons et al (2008)		-0.81
Havranek et al (2012)[a]		-0.31
Havranek and Kokes (2015) [a]	0.23	
Labandeira et al (2017)		-0.77
Huntington et al (2019)[b]	0.94	–0.61
Average of studies	0.83	-0.69

Notes: [a] Author-adjusted estimates for publication bias. [b] Study covered major developing countries only. Table adapted from Liddle and Huntington (2020b).

Table 2. Summary of recent large panel estimates of long-run income and price energy elasticities.

Energy end-use	Panel (N)	Income/output	Price
Economy-wide[a]			
	OECD (37)	0.70****	-0.27***
		[0.53 0.88]	[-0.45 -0.098]
	Non-OECD (41)	0.72****	-0.042
		[0.49 0.94]	[-0.11 0.026]
Road gasoline[b]			
	High-income Europe (24)	0.72**	-0.66****
		[0.17 1.27]	[-0.92 -0.40]
	High-income (mostly) non-	0.31	-0.87****
	Europe (11)	[-0.23 0.86]	[-1.23 -0.51]
	Non-OECD (83)	1.00****	-0.25****
		[0.57 1.43]	[-0.36 -0.14]
Road diesel[b]			
	High-income Europe (24)	2.12****	-0.38**
		[1.71 2.54]	[-0.70 -0.066]
	High-income (mostly) non-	0.90*	-0.15
	Europe (11)	[-0.17 1.98]	[-0.39 0.084]
	Non-OECD (76)	1.17****	-0.24***
		[0.60 1.74]	[-0.39 -0.091]
Residential electricity[c]			
	High-income (26)	0.64****	-0.22****
		[0.32 0.95]	[-0.33 -0.10]
	Middle-income (29)	0.81****	-0.083**
		[0.40 1.21]	[-0.16 -0.0023]
Industry electricity[d]			
	High-income (35)	0.46****	-0.25***
		[0.26 0.65]	[-0.39 -0.11]
	Middle-income (30)	1.25****	0.0024
		[0.97 1.54]	[-0.15 0.15]

Notes: ****, ***, **, * indicate statistical significance at the 0.001, 0.01, 0.05, and 0.1 levels, respectively. 95% confidence intervals shown in brackets.

[a] Liddle and Huntington (2020a); [b] Liddle and Huntington (2020b); [c] Liddle and Huntington (2020c); [d] Liddle and Hasanov (2020).

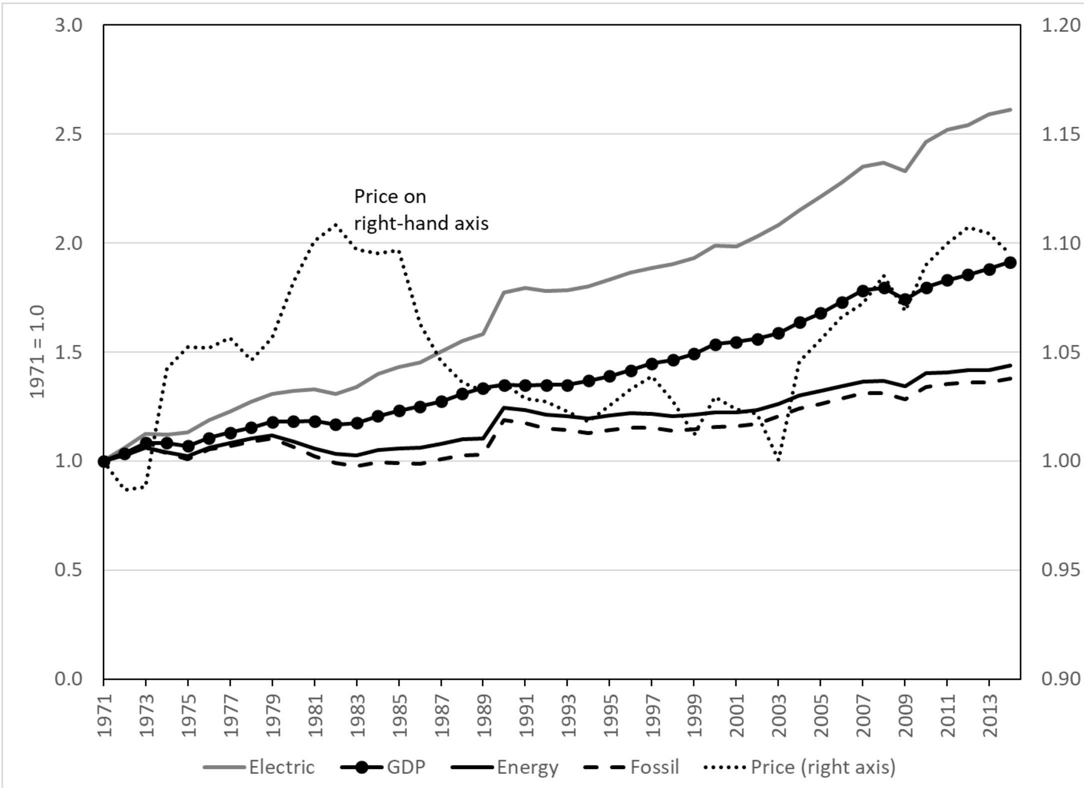

Figure 1. World Energy and GDP Trends, 1971-2014

Sources: World Bank, *World Development Indicators* for GDP and energy consumption and Liddle and Huntington (2020a) for energy price.