Energy Transitions and Technology Change: "Leapfrogging" Reconsidered

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Abstract

Innovations in energy production, conversion and efficient use create opportunities for low-income nations to skip or "leapfrog" over older technologies that dominated the development paths of today's industrialized countries. Nonetheless, countervailing trends, policy choices, or institutional features may hinder the ability of low-income countries to take advantage of these opportunities. Understanding the relationship between economic growth, energy consumption, and pollution provides an important guide for forecasting energy use and environmental impacts. Some prior research suggests that the energy intensity of economic growth is higher for today's developing countries than developing countries of the past. I assemble an unbalanced panel of energy consumption for 124 countries, extending as far back as 1861 for some countries; this long time series allows me to analyze changing relationships between energy use and economic growth at a timescale more appropriate for the long-term nature of energy investment. Using methods consistent with prior research, but a longer time series, I find evidence that the energy intensity of economic growth is in fact lower for today's developing countries. In ongoing research, I analyze how the relationship among economic output, energy use, and pollution has changed over time, as well as heterogeneous institutional, financial and environmental factors that predict greater or lesser energy intensity with respect to economic growth.

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1 Introduction

The recent rapid growth in many emerging economies comes with opportunities for better living conditions, increased investments in human capital, self-sustaining economic growth, and greater global prosperity. Energy consumption is foundational to this economic growth, yet over a billion people still lack access to electricity, and many more are served by underpowered or unreliable energy systems. Over the coming decades, energy systems for both generation and consumption will be built to accommodate the needs of these populations, even as they continue to grow. Indeed, Wolfram et al. (2012) forecast that nearly all of the growth in energy demand in coming decades will arise from the developing world. Meanwhile, technological innovation creates opportunities for “leapfrogging” in energy systems—that is, the use of modern technologies in emerging economies that were not available to today’s industrialized countries at the comparable time of their development. Leapfrogging opportunities may exist in interrelated areas that affect the efficiency of energy transformation, the carbon intensity of energy generation, and the energy intensity of economic growth (van Benthem, 2015).

Researchers have pointed out actual or potential technology leapfrogging in various domains (e.g. Goldemberg, 1998; Smil, 2010; Amankwah-Amoah, 2014), with the most notable example being cellular telephone networks that allow developing countries to skip over fixed-line technology. In the energy domain, researchers have documented leapfrogging in the adoption of solar electricity generation technologies in rural areas, ethanol production in Brazil, and biomass cookstoves in China (Goldemberg, 1998), adoption of energy-efficient appliances and fuel-efficient vehicles (van Benthem, 2015), and elsewhere.

At the same time, institutions may hinder the ability of countries to take advantage of these opportunities. Large entrenched industries, often with strong political and economic ties to central governments, may take strategic actions to block or slow the growth of potential competitors (Pearson, 2014). Government planners who wish to utilize the best modern technology may withdraw their support for incremental steps. Unreliable energy grids may create incentives for private firms or capital-rich house-holds to build redundant energy generation systems that, in turn, operate less efficiently due to lower economies of scale. Studies of technological change, including numerous examples from the energy sector, suggest widespread change often takes many decades (Rosenberg, 1972; David, 1990; Grübler et al., 1999; Hall, 2004; Smil, 2010).

This paper contributes to the understanding of technological evolution in the energy sector by exploring the extent to which the energy intensity of economic growth has changed across countries over many decades. I test for evidence of "leapfrogging" in the overall amount of energy used and the intensity of energy used to generate a given change in economic output. This first step builds on recent research by van Benthem (2015); I expand on that analysis by incorporating a longer time series of energy consumption for industrialized countries and by including energy used in energy conversion and distribution, rather than just consumption by end users. Next, I test for evidence of leapfrogging in the carbon intensity of economic output and growth. Finally, I explore the heterogeneity in relationships between economic output, energy use, and pollution, identifying institutional, financial and environmental factors that correlate with different countries' experiences with energy leapfrogging.

2 Energy consumption, economic growth, and technology

Research on economic and energy history shows that energy intensity of economic growth varies with the income level (van Benthem, 2015). At the lowest levels of economic development, the energy intensity of economic growth is relatively low, while in the "takeoff" or middle-income period energy intensity increases. In later phases of development, especially as economies transition to more service-based sectors, the energy intensity of economic growth tends to decline once again.

2.1 Empirical analysis: Energy and development

A large literature in economics explores cross-sectional differences in energy use and energy intensity of economic growth.[1] Several authors have used panel econometric methods to study these phenomena (e.g., Medlock and Soligo, 2001; Judson et al., 1999; Galli, 1998; van Benthem and Romani, 2009). In general these studies find strong evidence of non-linearity in the relationship between income and energy demand, reflecting the effects of structural economic changes and adoption of new technologies during the course of development. For instance, Galli (1998), studying ten Asian developing countries, finds evidence of declining energy intensity as nations become wealthier. Judson et al. (1999) analyze the relation of growth to energy consumption in different sectors for a panel of 123 countries, and find different patterns for household use (increasing over most of the income range), transportation (increasing over all of the income range), and industrial sectors (an inverted U shape over the income range).

A recent panel analysis (van Benthem, 2015) tests for energy leapfrogging in both levels of energy use for a given level of income, and intensity of economic growth. This analysis takes advantage of a proprietary dataset with information on energy consumption and GDP distinguished into eight sectors, spanning 76 countries with up to 46 years for some countries (1960-2006). The author finds no evidence that today's developing countries experience economic growth with lower energy use or energy intensity than did developing countries in the past. He does, however, find evidence of household-level adoption of energy-efficient appliances and vehicles. He reconciles these observations by noting the combination of industrial outsourcing to

[1] Interest is hardly confined to economics; many historians, for instance, have reflected on decadal energy transitions in regions or individual countries.

less-developed countries, and more energy-intensive consumption by households and public institutions at an earlier stage of development—along the lines of a technology rebound effect. However, the detailed data are available only for a relatively small set of industrialized countries (twelve). This is because IEA data on energy consumption start in 1960, and by this time many industrialized countries had per capita income greater than $10,000, which is too high to be relevant for the tests used (i.e., because the tests compare today's industrialized countries at a time when they had per capita income less than that amount). Thus, one drawback to this analysis is that the conclusions may be due partly to peculiar characteristics of the small set of industrialized countries available for comparison.

2.2 Institutions, policy, and technological change

Widespread technological change, especially when it involves large capital investments, can be a slow and gradual process, particularly due to (1) the co-evolution of long-lived technological systems or clusters; (2) dynamic competition between technologies rather than a smooth progression from identifiably "old" to identifiably "new" technologies; and (3) nonlinear patterns of technology adoption with respect to income. These factors suggest reason to be cautious in interpreting the results of panel studies depending on the timeline used for the analysis.

National energy consumption arises from the net effect of countless individual and institutional actors representing households, firms, and governments. Some of the energy-using technologies in which these actors invest have relatively short useful lives, on the order of a few years, while other technologies are useful for several decades. For instance, household appliances may last as little as three to five years; motor vehicles on the order of ten to fifteen years. Industrial capital assets frequently produce value for thirty years or more.[2] Grübler et al. (1999) document diffusion

[2]Institutions and policies may have much longer-lasting consequences, such as urban development that is oriented around mass transit versus private vehicles.

processes for about 25 energy-using or energy generation technologies and note a range of diffusion rates, depending on the relative advantage of the new technology, the degree of interdependence with other technologies, and the degree to which the new technology is complementary within existing technology ecosystems or requires the development of new infrastructure. David (1990) echoes the theme of the slow evolution of technological and economic ecosystems in documenting the slow diffusion of electric dynamo technology. Given that energy infrastructure frequently requires large capital investments, has a long useful life, and is integrally embedded within technological ecosystems, longer-duration studies of the relationship of energy consumption and economic growth may reveal insights not otherwise available.

Furthermore, when technological change involves the displacement of one technology by another, that displacement need not occur quickly or in a uniform direction. For instance, writing about the transition from sail-powered ships to steamships, which involved the use of auxiliary sails on steamships and auxiliary engines on sailing ships, Rosenberg (1972) cautions against the interpretation of technological change as "historical foreshortening" and notes that a careful analysis would describe invention and technological change as "a gradual process of accretion" and "a cumulation of minor improvements." This is especially true when users and manufacturers of older technologies are able to improve the efficiency of the old technology in the face of competition from substitutes—the so-called "last gasp" phenomenon—but can also arise from setbacks in the development of newer technologies, or from political-economic interactions in which bureaucracies or other institutions grow up around certain industries and then act, strategically or otherwise, to slow the innovation or adoption of new technologies (e.g., see Pearson, 2014).

The nonlinear relationship between household income and adoption of energy technologies, well documented in Wolfram et al. (2012) and Gertler et al. (2016), also suggests advantages to longer-run analysis, since relationships based on medium-run trends may not hold at longer time scales. Taken together, these three aspects of technological change imply that long-run analyses of technological change may reveal insights that medium-run analysis may not.

3 Data

I assemble a panel dataset of energy consumption, energy-related carbon emissions, population, GDP, and an index of real oil prices for 124 countries, with coverage for as long as 153 years for some countries. The next two subsections describe the sources for this dataset, and Section 3.3 provides a summary of the coverage of this panel.

3.1 Energy consumption and emissions

I use two measures of energy consumption. The first is total final consumption (sometimes abbreviated TFC), which represents energy consumption by end users, including households and industries. The second is TFC plus energy used in transformation from primary to secondary sources (e.g., the transformation of coal or natural gas into electricity), energy used by energy-producing industries (e.g., to produce coal from source rock), and losses during energy transmission and distribution. I call this total energy use (TEU).[3] In 2013, the components of TEU outside of TFC—energy used to extract, convert, and distribute energy—accounted for one-third of global consumption (IEA, 2015a).

My data on energy consumption come from several sources. The bulk of the data are from the International Energy Agency (IEA), which draws on national statistical organizations, international agencies, and other sources to compile energy consumption (and other) statistics. The IEA Extended Energy Balances series (IEA, 2015a) provides information for countries on the supply and consumption of energy, tabulated over about 60 generation sources ("products" in the IEA jargon) and 90 use

[3] My TEU measure differs from the International Energy Agency's "Total Primary Energy Supply" in that I exclude non-energy uses of fossil fuels, such as the production of petrochemicals, lubricants or tar.

categories ("flows").

The earliest energy consumption data from IEA (2015a) are available for countries in the Organization for Economic Cooperation and Development (OECD) from as early as 1960, and non-OECD countries from as early as 1971. However, as of 1960 many industrialized countries had per capita income greater than 10,000 USD. Thus, a data series using only IEA data may not provide an adequate number of points of comparison. To address this concern, I incorporate data from Unger and Thistle (2013) for Canada, and Kander et al. (2014) for eight European countries (France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom). The start years for these countries vary, but in all cases annual energy consumption is available by 1861. In addition, I incorporate data on historical energy consumption in the USA starting in 1900 (Schurr et al., 1960; EIA, 2016). Appendix A provides additional details about combining the energy consumption data series.

Table 1 provides summary statistics for average energy use over time for different groups of countries. As expected, both energy consumption and carbon emissions are higher for countries with higher levels of income.[4] However, Table 1 also provides suggestive evidence that other factors besides income affect energy consumption and emissions. For example, comparing both 2013 TEU per capita, and 2013 TFC per capita, between OECD and non-OECD countries at income levels in the $20,000-$30,000 and over $30,000 ranges shows that non-OECD countries have substantially greater total energy use within the same income range. This suggests institutions may moderate the relationship between economic activity and energy use, perhaps by influencing the abilities of governments, firms or households to adopt energy-efficient technologies. A similar relationship holds for carbon emissions between these comparison groups. For lower levels of income (e.g., $10,000-$20,000), OECD countries use greater amounts of energy and emit more carbon from energy uses.

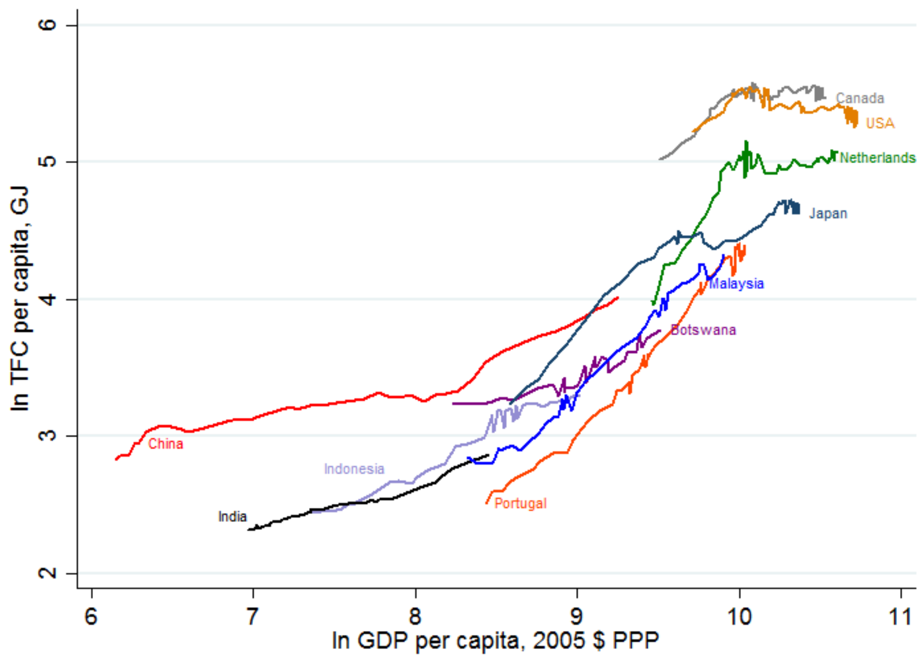
[4]The relatively high figure for TEU per capita in 1960 for "OECD countries with income between $10,000 and $20,000" is attributable to the fact that data are available for only two countries in this category in 1960 (Poland and Turkey), so the average is more sensitive to outliers.

Table 1: Summary statistics for energy use and carbon emissions

Measure (per capita)	Year	OECD 10-20k	OECD 20-30k	OECD >30k	non-OECD <10k	non-OECD 10-20k	non-OECD 20-30k	non-OECD >30k
TFC	1960	33.3	24.9	88.8				
(GJ)	1971	41	63.9	133.7	14.4	26.4	25.8	76.3
	2013	65.2	84.9	158.7	21.8	51.7	142.1	196.2
TEU	1960	45.7	29.5	116.8				
(GJ)	1971	54	84.8	165.9	17.1	35.4	46.6	152.5
	2013	98.8	119.9	218.5	29.3	69.7	157.2	335.5
CO_2	1960	3.5	1.9	9.7				
(metric	1971	3.9	5.8	11.6	0.4	1.9	2.9	8.3
tons)	2013	6.3	6.6	9.4	1.4	3.9	10.1	19.3

Dataset includes 34 OECD and 90 non-OECD countries.
Income levels are per capita in 2013, measured in 2005 USD at purchasing power parity. Data are available for most OECD countries from 1960, and for most non-OECD countries from 1971.
Source: IEA (2015a, 2015b).

Figure 1: Energy transitions for select countries, 1960-2013



Studies of economic growth and energy use show that predominantly agricultural societies use relatively low levels of energy. With industrialization and increased urban settlement, energy demand increases, then levels off as the economic base becomes more organized around services, manufacturing is often outsourced to other countries, and more efficient energy technologies are deployed, either due to technological advance or economies of scale (Smil, 2010). Figure 1 shows, for a few countries, the resulting S-shaped relationship between energy consumption and economic growth. If technology leapfrogging does result in lower energy consumption for a given quantity of economic growth, the S-shaped curves shown in Figure 1 should be flatter for countries that develop later in time.[5]

To the extent that energy from low-carbon sources supplies a relatively small part of most countries' energy needs, the relationship between carbon emissions and

[5]The relationship between TEU and economic growth, though not shown, looks substantially similar for this subset of countries.

economic growth follows a similar pattern. This observation runs counter to earlier theoretical predictions and some empirical findings that economic growth eventually leads to lower levels of emissions (e.g., the "Environmental Kuznets Curve" literature). With increased development of renewable energy along with other non-fossil sources such as nuclear fission, some countries may eventually be able to achieve economic growth without increased carbon emissions. Similar to the comment above, to the extent that countries can take advantage of technology leapfrogging opportunities in energy efficiency or in low-carbon generation, curves illustrating this relationship would be flatter for countries that develop in later periods.

3.2 Prices, GDP, and emissions

Data on energy-related carbon dioxide (CO2) emissions come from IEA (2015b), which provides that information for the same years as the energy consumption metrics.[6] Data on population and Gross Domestic Product (GDP) are from the World Bank's World Development Indicators, supplemented by data from the International Monetary Fund's International Financial Statistics and from Maddison (2010). The latter source provides all of the GDP and population data prior to 1960, which is the start year for data from the World Development Indicators. I use the purchasing power parity (PPP) measure of GDP, which facilitates cross-country comparisons by accounting for differences in relative price levels.

Following van Benthem (2015), I construct a real oil price index using oil price data from the BP Statistical Review of World Energy, converted into country-specific indexes using inflation and exchange rate data from the World Development Indicators (from 1960 onward) and Bordo (2015) (1861-1959 for countries with energy consumption data over that period). The oil price index provides a country-specific measure of price variability over time, compared to the world oil price from the BP

[6] In a future draft, I plan to calculate carbon emissions for the pre-1960 energy consumption series using the same methodologies as in IEA (2015b).

Statistical Review.[7]

3.3 Summary of panel data

The full panel consists of energy consumption, population, GDP, and real price data for 124 countries, starting as far back as 1861 and extending to 2013. This includes 43 countries classified by the World Bank as high-income (per capita income greater than 12,745 USD in 2013), 36 as upper-middle income (income between 4,126 and 12,745 USD), 31 as lower-middle income (income from 1,046 to 4,125 USD), and 14 as low-income (income below 1,046 USD). The panel begins in 1861 for Canada and eight European countries, in 1900 for the USA, in 1960 for most remaining OECD countries, and in 1971 for most of the non-OECD countries. For a few countries, coverage begins in a different year; the main exceptions are former Soviet republics and certain Eastern European countries, for which coverage begins in 1990.

For the initial exercise of comparing my results to those of van Benthem (2015), I use that paper's definition of developing and industrialized countries. In this framework, "developing" countries are those with per capita income of 10,000 USD or below in 2013 (in 2005 USD PPP), and "industrialized" countries are those with per capita income of 15,000 USD or greater. These classifications are also in rough accordance with the World Bank income groups. Under this classification system, my panel includes 53 developed countries, 52 developing countries, and 19 countries in an intermediate range.

4 Empirical methods and results

In documenting the empirical analysis, I begin with an exploration of the relationship between energy consumption and income level for developed and developing countries,

[7] I am grateful to Arthur van Benthem for sharing detailed calculations for his construction of a real price index, as well as data on historical exchange rates and consumer price indices.

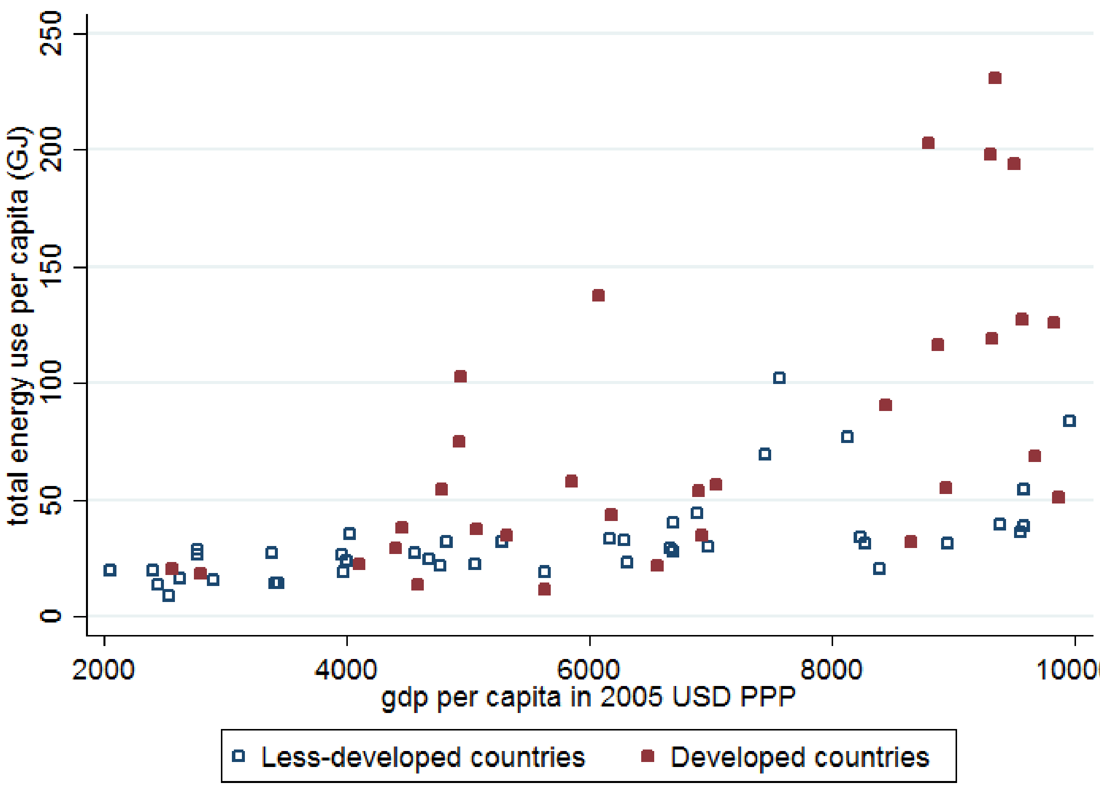
comparing the ratio of energy demand to GDP per capita between those two groups. I then analyze the energy intensity and carbon intensity of GDP growth, and look for evidence of technology leapfrogging. I also explore the heterogeneity in energy intensity and carbon intensity of income growth across countries and over time, with an eye toward discerning what characteristics or institutions explain the most variation in the energy intensity of growth in different countries.

4.1 Levels

As an initial exploration of the relationship between energy consumption and income, I compare energy consumption per capita with GDP per capita between industrialized countries at the time of their development, and developing countries in 2013. Figure 2 provides a graphical overview of this relationship for countries in the range of 2,000 to 10,000 USD GDP per capita. Hollow squares in the figure show less-developed countries as of 2013, and solid squares show the developed nations of 2013 at an earlier stage in their development. This includes the earliest year with IEA data on total energy consumption for which today's developed nations had income per capita below 10,000 USD (1960 for most OECD countries, 1971 for most non-OECD countries, and between 1991 and 1993 for five countries in the former Soviet Union or Yugoslavia). It also includes six additional countries that had income per capita above 10,000 USD by the start of the IEA data series, but for which the other sources noted above provide pre-1960 data on energy consumption. For these countries (Canada, Germany, Netherlands, Sweden, USA, and United Kingdom), Figure 2 shows energy use and GDP in 1925.

Figure 2 provides suggestive evidence that less-developed countries today may be achieving higher income at a lower level of energy use than industrialized countries did at a comparable time of their development. Many of the solid squares (developed countries) exhibit relatively high levels of energy use for their level of economic development, higher than many of the hollow squares (developing countries). While

Figure 2: Total energy use per capita versus GDP for developed countries historically and developing countries in 2013



suggestive, this figure uses only a portion of the data available, since each country is represented only once, and for an arbitrary year.

For a more rigorous analysis, I estimate the quantitative relationship between per capita energy consumption (and, separately, emissions) and GDP, plus a dummy variable for today's less-developed countries. For each dependent variable I use four alternative specifications of the relationship: two in levels and two in logs, and with a linear and a quadratic specification on the income term. Thus, for instance, the specification for energy consumption in logs with a quadratic income term is

$$\ln EC_{it} = \alpha_0 + \alpha_1 \ln GDP_{it} + \alpha_2 (\ln GDP_{it})^2 + 1(LDC_i) + \epsilon_{it}, \tag{1}$$

where EC_{it} is energy consumption in country i in year t; GDP_{it} is gross domestic product per capita; and $1(LDC_i)$ is an indicator equal to one if country i is a less-developed country in 2013. I estimate this equation for country-years in which GDP per capita is between 2,000 and 12,000 USD, corresponding to the World Bank definitions of middle-income countries.

In terms of the energy-income relationships illustrated in Figure 1, the specification (in logs) forces the paths of less developed countries to be parallel to those of industrialized nations but, through the use of a dummy variable for less developed countries, permits a different intercept. A negative coefficient for the dummy variable would imply that the developing nations of today are experiencing higher income at a lower level of energy consumption compared to previous cohorts of developing countries—that is, to today's industrialized countries during the time of their development.

Table 2: Per capita energy use and carbon emissions for developing & developed countries

	DV: Total energy use per capita (GJ)				DV: CO_2 per capita (metric tons)			
Variable	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
$1(LDC_i)$	-21.44^{***}	-21.9^{***}	-0.5^{***}	-0.49^{***}	-1.1	-1.05	-0.37	-0.35
	(7.02)	(7.12)	(0.13)	(0.13)	(0.8)	(0.81)	(0.24)	(0.24)
GDP_{it}	0.007^{***}	0.011^{**}			0.0005^{***}	0.0003		
	(0.001)	(0.004)			(0.0001)	(0.0003)		
$(GDP_{it})^2$		2.9×10^{-7}				1.3×10^{-8}		
		(3.3×10^{-7})				(2.0×10^{-8})		
$\ln(GDP_{it})$			0.78^{***}	0.25			1.43^{***}	0.28
			(0.09)	(2.39)			(0.17)	(4.42)
$(\ln GDP_{it})^2$				0.03				0.07
				(0.14)				(0.26)
Constant	17.52^{**}	8.72	-2.82^{***}	-0.58	0.28	0.66	-11.69^{***}	-6.89
	(7.24)	(10.49)	(0.77)	(10.02)	(0.91)	(0.93)	(1.54)	(18.76)

N=2,563 (total energy use) or 1,809 (energy-related CO_2) country-year observations.
Standard errors, clustered at the country level, in parentheses.
*** $p < .01$, ** $p < .05$, * $p < 0.10$.
Similar to Figure 2, the results focus on country-years where GDP per capita is between 2,000 and 10,000 USD.

Table 2 presents the results of this analysis. For both total energy use and energy-related carbon emissions, the coefficient on the LDC dummy is negative in all specifications, supporting the notion that some form of technology leapfrogging is occurring in energy efficiency and perhaps also in the carbon intensity of energy generation. At similar income levels, today's developing countries consume about 49 percent less energy (about 21 GJ less) than did today's industrialized countries during their economic development. Also, at similar income levels, today's developing countries produce about 35 percent less carbon than did today's industrialized countries when they were developing.

With the longer data series, the finding on energy use is opposite to that of van Benthem (2015); in a similar analysis, but with a smaller set of countries and a shorter time period, that study found developing countries using 19-20 percent more energy than developed countries when they had similar income levels. One explanation is that the longer time series allows more time for technological change to take effect, and also allows the use of a larger set of comparison countries—especially industrialized countries.

4.2 Intensity of economic growth

The analysis of levels of energy demand for a given income level indicates some support for the occurrence of technology leapfrogging, but a more meaningful analysis would identify the relationship between growth rates of economic activity and energy consumption (or carbon emissions). The time-invariant features of individual countries such as climate or hydroelectric potential affect overall levels of energy demand or carbon emissions, but a key question regarding technology change is whether the next increment of economic growth requires the same proportional increase in energy consumption for today's developing countries as it did for developing countries in the past.

What follows in this section, including the buildup of estimating equations and justification for the approach, hews closely to the analysis of van Benthem (2015). As noted previously, that paper is the most recent and thorough analysis of the possibility of technology leapfrogging in energy systems, and I intentionally set out to replicate the approach with a more expansive dataset and considering a larger range of dependent variables, before analyzing the sources of heterogeneity.

Prior literature (van Benthem, 2015; van Benthem and Romani, 2009; Medlock and Soligo, 2001) considers the relationship between economic growth, energy consumption, and prices using the following specification:

$$\ln EC_{it} = \alpha_0 + \alpha_1 \ln GDP_{it} + \alpha_2 (\ln GDP_{it})^2 + \alpha_3 \ln p_{it} + \theta_i + \lambda_t + \epsilon_{it}, \quad (2)$$

in which EC_{it} and GDP_{it} are defined as in equation (1), p_{it} represents energy prices (the real oil price index discussed in Section 3), and θ and λ represent country and year fixed effects. Country-specific fixed effects allow for time-invariant differences in country-level energy use, such as due to climatic differences. Time fixed effects allow for trends in technological capability or macroeconomic shocks that affect energy consumption over and above the effect of GDP and energy prices.

Equation (2) implicitly assumes that energy consumption responds immediately to the effect of prices and income growth, regaining a long-term equilibrium with no lag in response. In reality, when households, firms and governments make decisions about capital stock, those decisions are responsive to prices and income growth over longer periods of time. Incorporating a lagged term of energy consumption in the right-hand side allows the short-run response to differ from that in the long run:

$$\ln EC_{it} = \alpha_0 + \alpha_1 \ln GDP_{it} + \alpha_2 (\ln GDP_{it})^2 + \alpha_3 \ln p_{it} + \gamma \ln EC_{i,t-1} + \theta_i + \lambda_t + \epsilon_{it} \quad (3)$$

In equation (3), γ represents the speed of adjustment. The short-run response of energy consumption to prices is still measured by α_3, and response to income growth is still calculated as $\alpha_1 + 2\alpha_2 \ln GDP$. The long-run responses are measured as the short-run responses divided by $(1 - \gamma)$.

Equation (3) still has limitations, however. Among the most important is that it restricts the fitted relationship to be quadratic, whereas the true relationship may be more complex. Again following van Benthem (2015), I code a series of dummy variables that split the sample into several income bands based on GDP per capita. I choose these bands to match the 2015 study: per capita income under 3,500 USD; from 3,500 to 10,000 USD; from 10,000 to 20,000 USD, 20,000 to 30,000 USD, and over 30,000 USD (note that in both the 2015 paper and this paper, income is measured in 2005 USD at purchasing power parity). These are in rough accordance with the World Bank classifications of low, middle, and high income countries, although with additional break points within the high income countries. I also code dummy variables that correspond to the classification of countries as being developed or less-developed as of 2013 (i.e., today's developing countries and developing countries of the past).

By interacting these dummy variables with each other and with the explanatory variables, I can distinguish the long-run responsiveness of energy consumption (or carbon emissions) to income growth for the developing countries of today and of the past. In the equation that follows, $1(B_n)$ is an indicator variable with value one if GDP_{it} is within the income band, and zero otherwise. Similarly, $1(LDC_i)$ is an indicator variable with value one if country i is a less-developed country in 2013 (and zero otherwise), and $1(IC_i)$ is defined similarly but for industrialized countries. The equation I estimate is as follows:

$$
\begin{aligned}
\ln EC_{it} = \ & \beta_0 \\
& + 1(LDC_i)[\Sigma_n \beta_{1n,LDC} \ln(GDP_{it}) 1(B_n) + \beta_{2n,LDC} \ln(P_{it}) 1(B_n) \\
& + \Sigma_n \gamma_{n,LDC} \ln(EC_{i,t-1}) 1(B_n)] \\
& + 1(IC_i)[\Sigma_n \beta_{1n,IC} \ln(GDP_{it}) 1(B_n) + \beta_{2n,IC} \ln(P_{it}) 1(B_n) \\
& + \Sigma_n \gamma_{n,IC} \ln(EC_{i,t-1}) 1(B_n)] \\
& + \theta_i + \lambda_t + \epsilon_{it}
\end{aligned}
\tag{4}
$$

If technology leapfrogging has occurred, in a way that reduces the energy intensity of growth for today's developing countries, this would correspond to a finding that the long-run responsiveness differs between the LDC parameters and the IC parameters over the same income range. I focus particularly on the income band from 3,500 to 10,000 USD, which encompasses the "takeoff" period of economic development, the period of rising energy intensity according to historical studies, and approximately matches the World Bank classification for middle-income countries. Thus, I test whether $\frac{\beta_{1,LDC}}{(1-\gamma_{LDC})}$ is equal to $\frac{\beta_{1,IC}}{(1-\gamma_{IC})}$. If the former term is lower, this would suggest that today's developing countries are developing with lower energy intensity.

Table 3 presents the results of estimating equation (4) and calculating long-run responses. As expected, the long-run response of energy consumption to real energy price is generally negative (or zero). It may seem curious at first that the long-run response of consumption to real energy price is positive and significant for industrialized countries at the highest income level; however, this may be caused by the fact that some industrialized countries are also net energy exporters, so when the real energy price increases their energy consumption also increases because households and other users can afford to use energy less efficiently. Perhaps surprisingly, in most specifications the energy intensity of GDP growth does not decline with higher levels of income (e.g., in column 1, within industrialized countries the magnitudes of the coefficients on $\ln GDP$ are about the same for higher income levels as they are for lower income levels). This runs counter to the historical observation that energy intensity declines for higher income levels, and may be due to the relatively low threshold for the highest category of income; however, this puzzle warrants further investigation.

The main question of interest is whether the long-run response of energy consumption to economic growth is lower for today's less-developed countries (second row of coefficients in Table 3) than for today's industrialized countries when they were at similar levels of income (third row of coefficients). The last row in the table provides the results of this test, which suggests that there is some form of technological advance that has allowed less-developed nations to grow with lower energy intensity than in the past. The result is weakly statistically significant but stable across specifications.

This finding is counter to that of van Benthem (2015), who found no significant change using the same empirical test (but a smaller set of countries and years). As with other differences in findings, the difference may arise from several sources. In Table 3 the measure of energy use (total final consumption by end users) is the same as in van Benthem (2015), so that is not the source of the different result. One likely cause is that I use a longer time series and a broader set of countries, which may better capture the time scale necessary for widespread technological change. However, where that paper had data on energy consumption and GDP at the country-sector-year level, I have data only at the country-year level. Thus, there may be sectoral shifts in economic activity that I do not capture. In this sense, the 2015 paper suggests an absence of energy leapfrogging within sectors (e.g., leapfrogging is not resulting in more energy-efficient manufacturing or transportation in developing countries), while this paper suggests leapfrogging is occurring within countries (perhaps as a combination of sectoral shifts and leapfrogging over a longer time period). In the absence of sector-level data, I cannot distinguish how much of the difference arises from sectoral shifts and how much from the longer time horizon. However, if agents can take advantage of more free trade or other institutions that facilitate sectoral shifts even as

Table 3: Long-run response of total final consumption to income and price, by income group and development status

Variable	Income band (USD $k)	Country group	(1)	(2)	(3)	(4)	(5)
ln(GDP)	0-3.5	LDC	0.49***	0.52***	0.52***	0.25***	0.25***
			(0.07)	(0.08)	(0.09)	(0.09)	(0.09)
	3.5-10	LDC	0.50***	0.52***	0.52***	0.88***	0.94***
			(0.06)	(0.08)	(0.08)	(0.12)	(0.12)
	3.5-10	IC	0.60***	0.64***	0.61***	1.06***	0.94***
			(0.08)	(0.10)	(0.11)	(0.22)	(0.30)
	10-20	IC	0.64***	0.67***	0.64***	0.68***	0.71***
			(0.09)	(0.12)	(0.13)	(0.17)	(0.17)
	20-30	IC	0.62***	0.63***	0.69***	0.23	0.25
			(0.09)	(0.12)	(0.13)	(0.32)	(0.32)
	> 30	IC	0.49***	0.52***	0.50***	0.83***	0.83***
			(0.06)	(0.09)	(0.09)	(0.27)	(0.27)
ln (p)	0-3.5	LDC	-0.01	0.06	0.03	0.03	-0.02
			(0.05)	(0.06)	(0.06)	(0.08)	(0.10)
	3.5-10	LDC	-0.12***	-0.07**	-0.06**	-0.07***	-0.08***
			(0.04)	(0.03)	(0.03)	(0.02)	(0.02)
	3.5-10	IC	-0.12**	-0.04	-0.01	-0.02	-0.02
			(0.05)	(0.04)	(0.04)	(0.03)	(0.03)
	10-20	IC	-0.10*	0.02	0.06	-0.08	-0.08
			(0.05)	(0.07)	(0.08)	(0.22)	(0.23)
	20-30	IC	0.10***	0.13***	0.12***	0.08**	0.09**
			(0.03)	(0.02)	(0.02)	(0.04)	(0.04
	> 30	IC	-0.01	0.06	0.03	0.03	-0.02
			(0.05)	(0.06)	(0.06)	(0.08)	(0.10)
Time fixed effects			no	λ_t	$\lambda_t \times (LDC, IC)$	$\lambda_t \times 1(B_n)$	$\lambda_t \times (LDC, IC) \times 1(B_n)$
Income coefficient (LDC-IC) within 3.5-10k USD income band			-0.09*	-0.12*	-0.09	-0.19	0
			(0.06)	(0.06)	(0.07)	(0.17)	(0.32)

Results of estimating Equation 4 with dependent variable log of total final consumption per capita.
Standard errors, clustered at the country level, in parentheses.
Includes country fixed effects. N=3,969 country-year observations.
$^{***}p < .01, ^{**}p < .05, ^{*}p < 0.10$.

they allow income growth, then this may be sufficiently informative for policymakers and others interested in recognizing and facilitating leapfrog opportunities.

I run the same test for total energy use and for energy-related carbon emissions. Table 4 presents the results of this test for total energy use, presenting results only for comparisons of developing and industrialized countries in the 3,500-10,000 USD income band (however, the estimation strategy is the same as that shown in equation (4) and Table 3). The results suggest weak evidence of leapfrogging in total energy use: perhaps surprisingly, weaker than in total final consumption. Since the difference between the two series amounts to energy industry own use and energy losses in transformation and distribution, this suggests that there has been more leapfrogging in end-user consumption than in these segments. Indeed, an analysis of own use and transformation losses separately might suggest the energy intensity of these losses has increased for today's developing countries, which is a surprising result given advances in technology for the production of energy. One possible explanation is that energy sources are becoming harder to access (e.g., oil exploration in more remote areas, coal seams deeper underground).

Table 5 provides results of the same test, using per-capita energy-related carbon emissions as the dependent variable. There is weak evidence for "carbon leapfrogging," with the magnitudes of coefficients for developing countries slightly smaller than for developed countries (but not significantly so). The responses shown in Table 5 are a composite of the energy intensity of income and the carbon intensity of energy consumption; thus, they partly reflect the same trends as in Table 4. The responses are also consistent with the observation that, with a few notable exceptions (like China), most developing countries have invested relatively little in low-carbon generation sources.

Table 4: Long-run response of total energy use to income

Variable	Income band (USD $k)	Country group	(1)	(2)	(3)	(4)	(5)
ln (GDP)	3.5-10	LDC	0.59***	0.54***	0.56***	0.83***	0.80***
			(0.07)	(0.08)	(0.08)	(0.11)	(0.11)
	3.5-10	IC	0.62***	0.62***	0.61***	0.87***	0.90***
			(0.06)	(0.07)	(0.08)	(0.11)	(0.17)
Time fixed effects			no	λ_t	$\lambda_t \times (LDC, IC)$	$\lambda_t \times 1(B_n)$	$\lambda_t \times (LDC, IC) \times 1(B_n)$
Income coefficient (LDC-IC) within 3.5-10k USD income band			-0.03	-0.08*	-0.05	-0.04	-0.1
			(0.04)	(0.04)	(0.04)	(0.08)	(0.20)

Results of estimating Equation 4 with dependent variable log of total energy use per capita. (A subset of parameter estimates are shown here.)
Standard errors, clustered at the country level, in parentheses.
Includes country fixed effects. N=4,586 country-year observations.
$^{***}p < .01, ^{**}p < .05, ^{*}p < 0.10$.

Table 5: Long-run response of CO_2 emissions to income

Variable	Income band (USD $k)	Country group	(1)	(2)	(3)	(4)	(5)
ln (GDP)	3.5-10	LDC	1.11***	1.05***	0.87***	1.07***	0.98***
			(0.18)	(0.19)	(0.18)	(0.22)	(0.24)
	3.5-10	IC	1.06***	1.08***	1.09***	1.21***	1.40***
			(0.14)	(0.17)	(0.20)	(0.23)	(0.32)
Time fixed effects			no	λ_t	$\lambda_t \times (LDC, IC)$	$\lambda_t \times 1(B_n)$	$\lambda_t \times (LDC, IC) \times 1(B_n)$
Income coefficient (LDC-IC) within 3.5-10k USD income band			0.05	-0.04	-0.22	-0.15	-0.42
			(0.20)	(0.20)	(0.22)	(0.22)	(0.40)

Results of estimating Equation 4 with dependent variable log of carbon emissions per capita. (A subset of parameter estimates are shown here.)
Standard errors, clustered at the country level, in parentheses.
Includes country fixed effects. N=3,969 country-year observations.
$^{***}p < .01, ^{**}p < .05, ^{*}p < 0.10$.

4.3 Heterogeneity and robustness

Understanding the heterogeneity across countries (and perhaps time periods of development) would contribute to understanding the effects of technology policies and environmental regulations in developing and developed nations. For instance, Popp (2011) finds that policies in developed countries tend to drive innovation in emissions-reducing technologies, and energy-efficient innovations diffuse to low-income countries regardless of domestic environmental policies, but adoption of other technologies (that do not increase firms' profits) does not increase in the absence of environmental policy. Identifying the net effect of current policies in the aggregate furthers our understanding of how policy in low-income and industrialized countries has affected energy technology innovation and transfer.

A promising research angle would be to pursue further the question of heterogeneous responses, for instance using quantile regression techniques that also account for the panel data structure (Kato et al., 2012; Lamarche, 2010) to analyze energy intensity and carbon intensity of economic growth. In addition to illustrating the heterogeneity across countries, such an approach may also help identify the causes of that heterogeneity. For instance, other researchers have identified various factors that seem to contribute to different responses: the maturity of commercial banking and thus availability of financing for renewable energy technologies (Brunnschweiler, 2010), openness to trade (Lovely and Popp, 2011), natural environmental factors that necessitate more energy use for space conditioning (Smil, 2010), and others. Each of these would suggest a different policy response to maximize potential for technology transfer to reduce the energy intensity of economic growth.

It may also be useful to explore the relationships described in equation (4) through the addition of panel-heterogeneous time trends (Bai, 2009), in addition to the time-invariant country fixed effects and uniform-country time fixed effects. It is reasonable to believe that macroeconomic shocks or technological advance may affect different countries differently, and using heterogeneous time trends provides one way to investigate this heterogeneity. This may also provide some insight on countries' heterogeneous relationships between energy consumption and growth.

Additional insight might be gained by separating out OPEC countries and post-Soviet transition economies. For different reasons, these nations may be outliers in terms of having relatively high energy intensity of economic growth. However, they are generally split between industrialized and developing countries, so special treatment of these observations may not affect the core findings as they relate to leapfrogging.

Finally, it seems useful to explore the effects of using different thresholds to distinguish developed and industrialized nations. The present analysis uses 2013 income levels and follows the thresholds used by van Benthem (2015) to facilitate comparability with that study, but it may be instructive, for instance, to distinguish developed countries based on the era in which their "takeoff" development phase took place (that is, to distinguish countries that developed more recently versus less recently). This would further help to characterize the heterogeneity of nations' experiences, and may clarify the relationship of my findings to those of van Benthem (2015), since that study did not find evidence of leapfrogging for countries that developed earlier (roughly in 1970-2000).

5 Conclusions

With demand for energy services growing rapidly, and especially across the developing world, planners and policy makers rely on accurate quantitative forecasts of energy demand to balance the need to build out energy infrastructure relative to other pressing needs for public investment. A previous paper (van Benthem, 2015) suggests there are important technology rebound effects that may drive today's developing countries to use more energy per unit of economic growth than did developing countries of the past, which bodes ill for forecasters who are assuming some level of energy savings or "leapfrogging" due to the availability of more efficient technologies.

Using a much longer time series and a broader set of countries in the analysis, I offer additional insight and demonstrate that while technology rebound effect may be of concern for some countries, on average it is not, when considering a broader range of developed countries, a longer timeline for analysis, and a more complete set of energy technologies—especially on the generation and distribution side. That is, the forecasting agencies may be correct after all in assuming some level of energy efficiency available to today's developing countries that did not exist in previous decades. That said, the more valuable policy implications may be those that come after continued exploration, including exploration of heterogeneous effects and interactions with historical or current institutions.

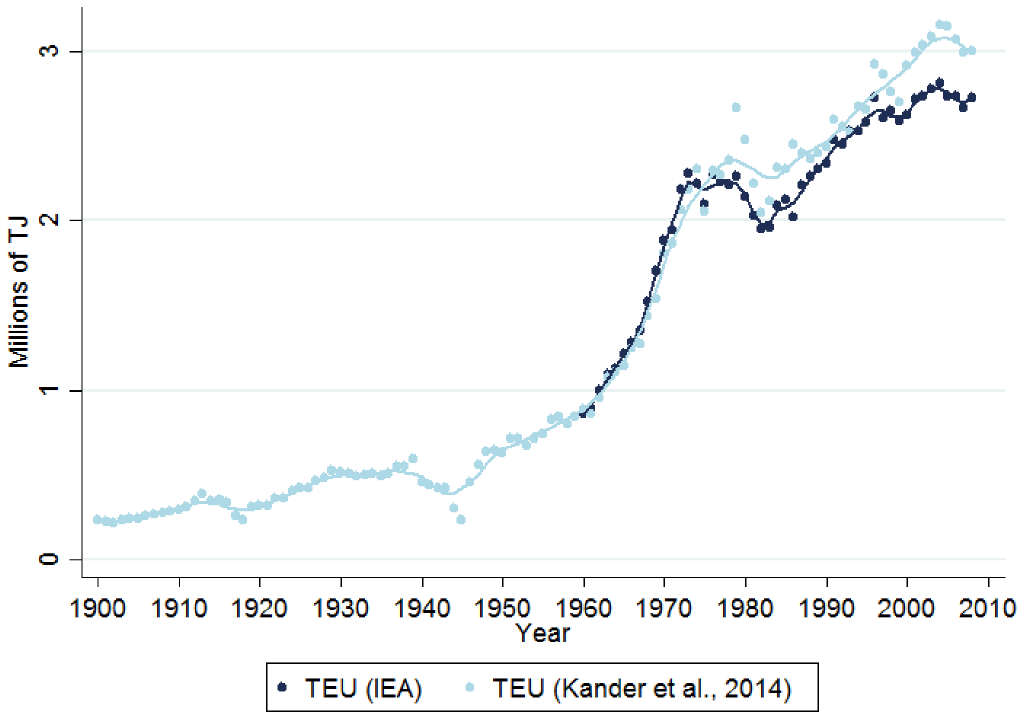
A Appendix: Energy consumption data

I use four sources for energy consumption data prior to 1960. The principal source is Kander et al. (2014), which provides data for eight European countries from 1861-2008. I also obtain data for Canada from 1861-2002 from Unger and Thistle (2013). All of these authors worked together to recover and tabulate historical energy consumption data from each respective country using common methods, including conducting an extensive review to verify comparability across countries. For the USA I use two additional sources, compiled by authors working independently from the European and Canadian group (Schurr et al., 1960; EIA, 2016).

In addition to working to verify internal consistency, the authors of Kander et al. (2014) also attempted to make their data series consistent with the IEA Extended Energy Balances series, especially through 1970 (personal communication with Astrid Kander). For most countries, the overlap is reasonably good. Figure A.1, for instance, shows both the series from both IEA (2015a) and Kander et al. (2014) for the Netherlands. The data series match almost identically from 1960 through 1971, then diverge, with the IEA series initially slightly higher and then slightly lower than the series from Kander et al. (2014). Nevertheless, the same trends are apparent in both (albeit with somewhat more scatter in the series from Kander et al. (2014)). The comparability of the data series, especially during the period 1960 to 1971, suggests it is reasonable to use the series from Kander et al. (2014) to extend the IEA series backwards.

The series for Germany (Figure A.2) suggests more reason to be cautious in melding the two series. Here, the series match reasonably well from 1970 through 2008, but from 1960 through 1969 the IEA series indicate substantially lower energy consumption, in a way that is discontinuous with both the preceding observations from Kander et al. (2014) and the subsequent observations from IEA (2015a). In Sweden, on the other hand, the series match reasonably well until the late 1970s, at which

Figure A.1: Total Energy Use in the Netherlands: Comparison of IEA (2015a) and Kander et al. (2014)



point the IEA series indicate substantially higher energy consumption, on the order of 30% (Figure A.3).

One reason for the divergence of the two series may be different assumptions regarding the efficiency of conversion for primary electricity sources, including geothermal and nuclear sources (personal communication with Sofia Henriques). In any case, in the regression analyses I include dummy variables to allow for these structural trend breaks (as well as other breaks within the IEA series, such as methodological changes or switches from the use of one national statistical series to another).

Figure A.2: Total Energy Use in Germany: Comparison of IEA (2015a) and Kander et al. (2014)

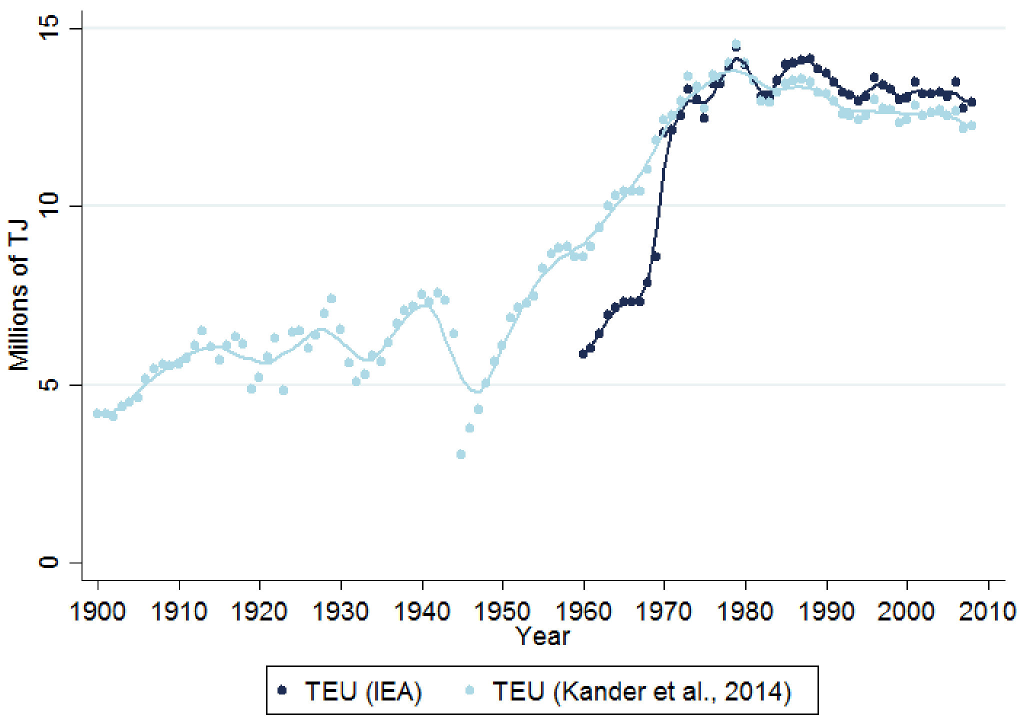
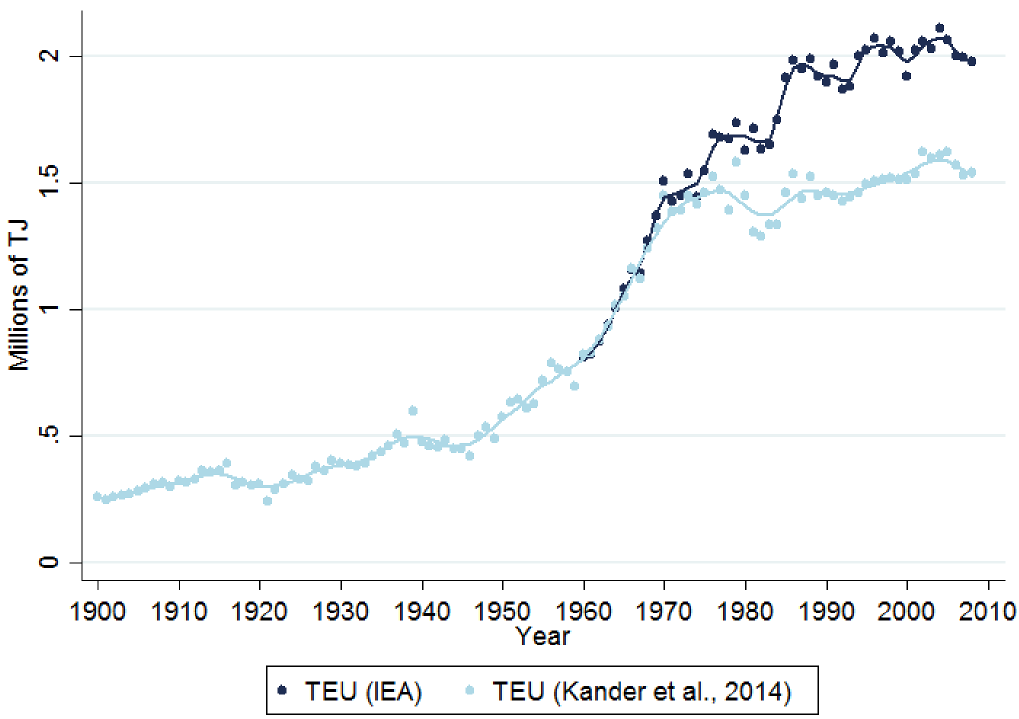


Figure A.3: Total Energy Use in Sweden: Comparison of IEA (2015a) and Kander et al. (2014)



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