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Source: *The Energy Journal*, Vol. 28, No. 1 (2007), pp. 91-111
Published by: International Association for Energy Economics
Stable URL: http://www.jstor.org/stable/41323084
Accessed: 21-07-2016 20:55 UTC

Energy and Carbon Dynamics at Advanced Stages of Development: An Analysis of the U.S. States, 1960–1999

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This paper explores the relationships among per capita income, energy consumption, and carbon dioxide (CO_2) emissions by focusing on a set of economies at advanced stages of development, the U.S. states. Energy consumption and emissions grew 50–60 percent on average over the 1960–1999 period. The states' per capita energy consumption and emissions have grown on average 2 percent annually. The energy consumption income elasticity is positive but decreasing in income, although energy production takes an inverted-U shape, reflecting the electricity imports among high income states. The standard CO_2 measure, corresponding to energy production, is characterized by an inverted-U environmental Kuznets curve. Adjusting emissions for interstate electricity trade yields an emissions-income relationship that peaks and plateaus. The carbon intensity of energy declines with income for total energy consumption and the industrial, residential, and commercial sectors.

1. INTRODUCTION

This paper explores the relationships among per capita income, energy consumption, and carbon dioxide (CO_2) emissions by focusing on a set of economies at advanced stages of development, the U.S. states. Understanding energy-emissions-income dynamics at an advanced stage of development may provide insights for national-level dynamics as more countries develop and attain higher incomes. An assessment of state-level energy consumption and CO_2 emissions is of interest in its own right as a number of states have initiated action on energy

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Acknowledgments: This research was supported by the Repsol-YPF/John F. Kennedy School of Government Energy Policy program, the U.S. Environmental Protection Agency's STAR program, the Switzer Foundation, and the Udall Foundation. Three anonymous referees and seminar participants at the University of Kentucky and Resources for the Future provided valuable comments on earlier drafts. Any errors that remain are solely the responsibility of the author.

and CO_2 regulatory policies. This analysis illustrates the broad determinants of states' CO_2 emissions and provides some sense of the feasibility of state efforts to limit emissions. Finally, an assessment of the U.S. states can complement analyses of U.S. national-level energy consumption and CO_2 emissions.

This analysis builds on papers that explore questions of energy-income and emissions-income relationships. Several papers express per capita energy use as a quadratic function of per capita income (and other covariates). Galli (1998) examines the energy-income relationship for 10 Asian economies over the 1973–1990 period and finds that energy consumption per capita first increases and then decreases with per capita incomes. For a set of 28 countries, Medlock and Soligo (2001) estimate a concave energy-income relationship and find that, among major sectors, per capita industrial energy use declines first, followed by the residential and commercial buildings sector, and finally by the transportation sector. Accounting for the effects of manufacturing and trade on energy use, Suri and Chapman (1998) find that per capita energy follows an inverted-U shape, although the peak is beyond the maximum income in their sample of 33 countries. Judson et al. (1999) employ piecewise linear spline income functions to estimate more flexible energy-income relationships at both the economy and sector level for 123 countries. They find that per capita energy consumption increases with income, but at a declining rate, and that the transportation sector's share of energy consumption increases with income while the household's share declines with income.

Darmstadter (2001) uses the Kaya Identity to decompose U.S. CO_2 emissions by population growth, per capita income growth, the energy intensity of output, and the CO_2 intensity of energy. He finds that the U.S. energy intensity of output and the CO_2 intensity of energy both declined over time, but at rates insufficient to offset income and population growth. Holtz-Eakin and Selden (1995) provide the first environmental Kuznets curve (EKC) analysis of CO_2 per capita using a large international data set, and find an inverted-U emissions-income relationship. Schmalensee et al. (1998) employ similar methods as Judson et al. (1999) and find that per capita emissions peak at about $10,000 (1985$). Aldy (2005) estimates inverted-U EKCs for state-level per capita CO_2. After adjusting emissions for interstate electricity trade, he finds that the peak in the inverted-U occurs at higher incomes and per capita emissions decline modestly after the peak than with the standard pre-trade CO_2 measure.

Rothman (1998) focuses on the effect of trade in the distinction between the location of consumption and the location of production and notes the shortcomings in most EKCs in this respect. Suri and Chapman (1998) find that trade can influence the shape of their estimated energy-income function because industrialized countries have increased their imports of energy-intensive goods. Aldy (2005, 2006a) shows that interstate electricity trade can affect estimated emissions-income relationships and the convergence in per capita emissions.

To complement this literature, this empirical analysis focuses on state-level energy consumption and CO_2 emissions over the 1960–1999 period. Investigating the energy-emissions-income dynamics of a set of advanced economies follows in the spirit of Barro and Sala-i-Martin (1992), who study the economic convergence dynamics of the states in order to better understand convergence and growth in the broader world. This paper makes several contributions to the literatures on energy- and emissions-income elasticities and energy policy debates. First, it provides the initial characterization of state-level energy dynamics through Kaya Identity analysis and regression analysis based on flexible piecewise linear and cubic spline income functions. Energy consumption has grown about 2 percent annually over 1960–1999 and the income elasticity of energy consumption is always positive but decreasing with income. Second, it employs a novel data set of state-level CO_2 emissions constructed by the author to explore the emissions-income relationship. CO_2 emissions have also grown about 2 percent per year as population and income growth have outpaced the declining energy intensity of output and the modest change in the carbon intensity of energy. The standard CO_2 per capita measure follows an inverted-U emissions-income relationship. Third, it illustrates the effects of interstate electricity trade on energy-income and emissions-income relationships. Accounting for interstate electricity trade shows that per capita energy production follows an inverted-U shape with respect to income, similar to the form for the standard measure of CO_2. Adjusting the emissions measure for electricity trade produces a peak and plateau emissions-income relationship instead of the inverted-U. Finally, it illustrates how sectoral energy consumption increases vary with income in transportation, industrial, residential, and commercial building sectors.

Section 2 describes the data used in the analysis, including a detailed discussion of the construction of the state-level CO_2 data. The third section decomposes the growth in energy consumption and emissions through the Kaya Identity for a variety of sectors of the economy. Section 4 presents energy-income and emissions-income elasticities estimated through flexible piecewise linear and cubic spline regressions, with a focus of the effects of electricity trade on these estimated relationships. The final section concludes with policy implications and ideas for future research.

2. ENERGY, EMISSIONS, AND INCOME DATA

2.1 Energy

The Energy Information Administration (EIA) compiled state-level energy consumption by fuel type and sector for 1960–1999 as a part of the State Energy Data System (EIA 2001b). These estimates include consumption of petroleum products, natural gas, coal, and renewable fuels for the transportation, industrial, residential, and commercial sectors. The SEDS also provides data on the consumption of electricity generated from fuel oil, coal, natural gas, nuclear power, and renewables and interstate electricity trade. All energy measures used in this analysis are presented in British Thermal Units (BTUs).

2.2 Carbon Dioxide

I have constructed state-level CO_2 emissions estimates based on the fossil fuel combustion data for 1960–1999 from EIA (2001b).[1] I converted energy consumption to CO_2 emissions using national sector- and fuel-specific emissions factors provided by EIA (2001a, Appendix B). A total of 51 fuel-sector measures allowed for precise matches of fuel-sector emissions factors to sector-specific fuel consumption. Refer to Lutter (2000), Marland et al. (2003), and Blasing et al. (2004, 2005) for similar applications of this approach.

I undertook two checks to assess the plausibility of constructing state-level CO_2 emissions in this manner. First, I constructed national estimates from the state-level CO_2 emissions values and compared these with the Marland et al. (2003) and EIA (2001a) national estimates. Over the period 1960–1999 period, my constructed annual national values differ on average 1.9 percent from the Marland et al. estimates (6.0 percent maximum annual differential) and 2.0 percent from the EIA estimates (4.8 percent maximum annual differential). To provide some context, a comparison of the EIA and Marland et al. data sets arrives at similar differences: an average difference of 1.7 percent with a 4.5 percent maximum annual difference.

Second, I compared my data set with a state-level CO_2 emissions data set published after I began this research project. The Blasing et al. (2004, 2005) data set is constructed from the same source file as mine (EIA 2001b), so the comparison can assess only differences in the methods used in constructing CO_2 from fossil fuel consumption. Blasing et al. note that their aggregate national values differ from other national values (e.g., Marland et al. 2003) "by around 2 percent." I have replicated the cubic spline regression presented in Figure 4 and find that the estimated EKCs are very similar for both the Blasing et al. and my data sets.[2]

My constructed CO_2 data set represents emissions associated with producing all goods and services in a given state, so we can also denote them *production* CO_2 emissions. The standard measure of CO_2 emissions, this is comparable to the national measures used to develop greenhouse gas commitments under the Kyoto Protocol. In the presence of interstate trade, the emissions intensity of a state's production may differ from the intensity of this state's consumption. Some states may specialize in carbon-intensive production and export a substantial share of this output, while others may specialize in carbon-lean production for export.

To illustrate the potential role of trade in measuring CO_2, a second emissions data set was constructed to account for interstate electricity trade. To

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[1] All statistical analyses presented in this paper exclude Alaska, Hawaii, and Washington, DC. EIA (2001b) does not provide energy use data for Washington, DC. The analyses omit Alaska and Hawaii because they differ along several dimensions from most of the continental United States (e.g., weather-related energy demand, population density) and because they do not engage in interstate electricity trade.

[2] Additional details comparing the two data sets are available from the author upon request.

construct this post-electricity trade CO_2 data set, I started with the production CO_2 data set. Then, I calculated the annual average carbon-intensity of each state's electricity sector. For a state that is a net exporter of electricity in a given year, the carbon emissions associated with the exported electricity (reflecting the state's average electricity carbon intensity) are deducted from that state's total emissions for that year. For a net importer, that state's emissions are augmented based on the average carbon intensity of electricity imports.[3] Since this modified measure reflects post-trade emissions and attempts to approximate for *consumption* emissions, as opposed to the production or standard measure of emissions, I refer to it as consumption CO_2 throughout this analysis.

A second reason for referring to this measure as consumption CO_2 is that it corresponds to end-use energy consumption measures. For example, a state's industrial sector energy consumption includes that sector's electricity consumption. If this state is an electricity importer, then some of the industrial sector energy consumption is associated with CO_2 emissions in electricity-exporting states. Sectoral CO_2 values presented below are this consumption CO_2 measure to ensure comparability with the sectoral energy consumption data.

2.3 Income

I use the Bureau of Economic Analysis (BEA 2000) state personal income series as my income measure.[4] This series has been used in EKC, emissions convergence, and economic growth papers (e.g., Aldy 2005, 2006a; and Barro and Sala-i-Martin 1992). BEA also provides the annual population data used to construct per capita estimates.

3. ENERGY AND EMISSIONS DECOMPOSITIONS

To provide an initial illustration of state-level energy consumption and CO_2 emissions, I have estimated annual mean per capita measures and their associated 95 percent confidence intervals. Figure 1 shows how energy consumption per capita has increased on average 50 percent since 1960. In 1999, the average state-level per capita energy consumption was 379 million BTUs. The confidence interval is fairly tight, with the 1999 95 percent interval ranging between 1.33 and 1.61 times the 1960 per capita level. Because of a number of short-term declines, 1999 energy consumption was only slightly higher than in 1973. These short-term declines likely reflect the effects of high energy prices and slow or negative economic growth.

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[3] This average intensity of imports is a national average; it reflects the average intensity of electricity generation for all states that export electricity in that year. Although the carbon-intensity of the marginal power source for electricity would be preferable, it is difficult to determine what constitutes the marginal source in each state.

[4] These were converted to constant-year (1999) dollars based on the national CPI-Urban deflator.

Figure 2 depicts a similar trend in production (standard) CO_2 emissions for the states. Per capita emissions grew faster than per capita energy consumption, although emissions declined in many of the same years as energy use. By 1999, per capita CO_2 – at 6.6 tons of carbon – was on average 1.64 times greater than it was in 1960. The confidence interval is much wider by the 1990s for CO_2 per capita than for energy consumption per capita, reflecting how some states have differed in their use of various fossil fuels and the effects of interstate electricity trade.

To assess the major determinants of energy use and CO_2 emissions, the Kaya Identity can be used to decompose emissions (or energy use) into the effects of four drivers: population, per capita income, the energy intensity of output, and the carbon intensity of energy. This approach can illustrate whether changes in CO_2 emissions reflect decarbonization of energy (declining carbon-energy ratio) or improvements in energy efficiency, or simply changes in economic growth or population growth. The Kaya Identity for CO_2 emissions is given by

$$CO_2 = Population \bullet \left(\frac{Income}{Population}\right) \bullet \left(\frac{Energy}{Income}\right) \bullet \left(\frac{CO_2}{Energy}\right) \tag{1}$$

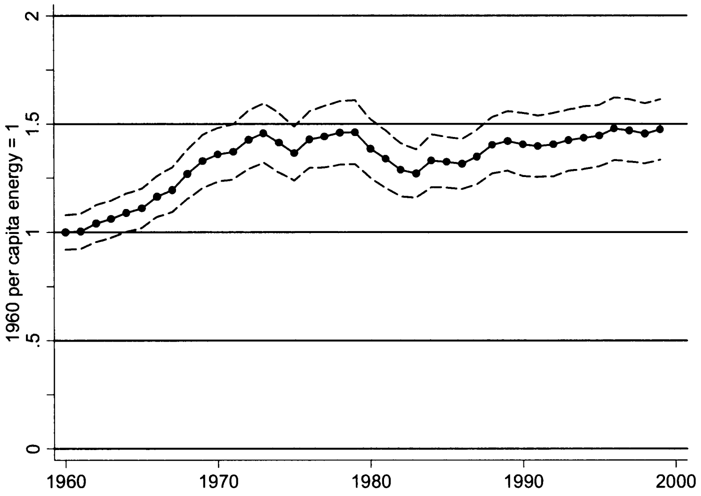
and a comparable equation for energy consumption is given by

$$Energy = Population \bullet \left(\frac{Income}{Population}\right) \bullet \left(\frac{Energy}{Income}\right). \tag{2}$$

To illustrate the trends in emissions and energy use, I have modified these two equations to present average growth rates (and associated standard deviations) for the states over 1960–1999 in Tables 1 and 2. For the small changes over time in these measures, the growth rates of the drivers are approximately additive with respect to the growth rates for emissions and energy. Previous analyses of this type used standard measures of energy consumption and CO_2 emissions. Since the standard CO_2 measure corresponds to the production of electricity (pre-trade) while the energy consumption data correspond to the consumption of electricity (post-trade), this may yield a biased characterization of decarbonization of energy. All analyses presented in Tables 1 and 2 are based on the consumption CO_2 measure, with discussion of how the choice of emissions measure influences the results.

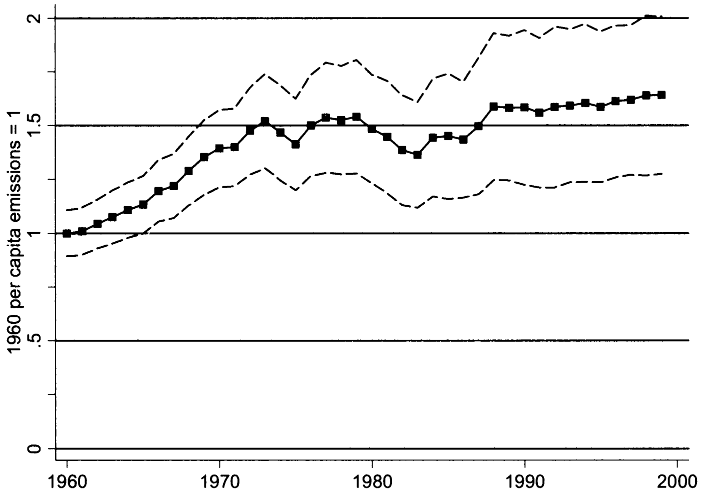
In Table 1, Panel A, the average CO_2 growth rate of 2.0 percent is slightly less than the energy consumption growth rate of 2.1 percent. This reflects the small change in the CO_2 intensity of energy (last column). The growth in income per capita is 2.1 percent, population grew 1.1 percent, and the energy intensity of output declined by 1.2 percent annually. Some of the decline in energy intensity of output reflects a transition from more energy-intensive economic activity (e.g., manufacturing) to less energy-intensive activity (e.g., services). The average manufacturing share of state income declined by nearly half from 20.1 to 11.5

Figure 1. States' Energy Consumption Per Capita, 1960–1999



Notes: Annual unweighted mean energy consumption per capita for the continental 48 states for all sources of energy presented in solid line. Dashed lines represent the annual 95 percent confidence interval. Constructed by author with data from EIA (2001b).

Figure 2. States' Carbon Dioxide Emissions Per Capita, 1960–1999



Notes: Annual unweighted mean production carbon dioxide emissions per capita for the continental 48 states presented in solid line. Dashed lines represent the annual 95 percent confidence interval. Constructed by author with data from EIA (2001a, 2001b).

Table 1. Economy-Wide Energy Consumption and CO_2 Emissions Decompositions of Average State Growth Rates

	CO_2	*Energy*	*Population*	$\frac{Income}{Population}$	$\frac{Energy}{Income}$	$\frac{CO_2}{Energy}$
A. By Sample						
Full Sample	0.020	0.021	0.011	0.021	-0.012	-0.00091
1960-1999	(0.011)	(0.0088)	(0.0090)	(0.0031)	(0.0045)	(0.0040)
Slow Growth States	0.0075	0.012	0.0054	0.020	-0.014	-0.0043
1960-1999	(0.0056)	(0.0050)	(0.0034)	(0.0021)	(0.0037)	(0.0031)
Fast Growth States	0.032	0.029	0.018	0.020	-0.0097	0.0035
1960-1999	(0.011)	(0.011)	(0.014)	(0.0034)	(0.0060)	(0.0036)
B. By Period						
Full Sample	0.042	0.041	0.013	0.036	-0.0076	0.00078
1960-1973	(0.017)	(0.013)	(0.0098)	(0.0077)	(0.0089)	(0.068)
Full Sample	0.00023	0.0032	0.011	0.012	-0.020	-0.0029
1973-1986	(0.015)	(0.011)	(0.010)	(0.0065)	(0.012)	(0.086)
Full Sample	0.017	0.018	0.0093	0.016	-0.0077	-0.00060
1986-1999	(0.012)	(0.0088)	(0.0089)	(0.0030)	(0.0063)	(0.0079)

Notes: States' average growth rates and their associated standard deviations in parentheses are presented. Estimated using author's consumption CO_2 emissions data constructed using EIA (2001a, 2001b), energy consumption data from EIA (2001a), and income and population data from BEA (2000). Slow growth states correspond to the 10 states with slowest CO_2 growth rates and fast growth rates correspond to the 10 states with fastest CO_2 growth rates for economy-wide fossil fuel CO_2 emissions over 1960–1999.

percent over the 1960–1999 period. In contrast, the average services share of state income increased from 28.7 to 35.6 percent over this period.[5] The state average growth rates presented in Table 1 are not weighted by states' populations, so they will differ from national averages. For example, national-level CO_2 emissions grew 1.7 percent annually and energy use grew 1.9 percent annually over this period. The national-level growth rates in population, income per capita, and the energy-intensity of output are virtually identical to the average growth rates among the states. The lower national-level growth rates for emissions and energy use reflects the faster rates of decline in the carbon intensity of energy in more densely populated states.

The rest of Panel A illustrates the effects of these major drivers of energy consumption and emissions for a sample of the 10 states with the lowest CO_2 growth rates (slow growth) and a sample of the 10 states with the highest emissions growth rates (fast growth) over the period of 1960–1999. The slow growth states had a CO_2 growth rate (0.75 percent) one-fourth the rate of the fast growth states

[5] The services estimate reflects a broad categorization of services to include income in BEA-identified sectors of services, retail, wholesale, and financial activities. The manufacturing estimate reflects only the BEA-identified sector of manufacturing.

Table 2. Sectoral Energy Consumption and CO_2 Emissions Decompositions of Average State Growth Rates, 1960-1999

	CO_2	*Energy*	*Population*	$\frac{Income}{Population}$	$\frac{Energy}{Income}$	$\frac{CO_2}{Energy}$
A. Transportation Sector						
Full Sample	0.019	0.023	0.011	0.021	-0.0090	-0.0039
	(0.0083)	(0.0077)	(0.0090)	(0.0031)	(0.0057)	(0.0025)
Slow Growth States	0.012	0.014	0.0054	0.020	-0.011	-0.0027
	(0.0067)	(0.0066)	(0.0034)	(0.0021)	(0.0066)	(0.00052)
Fast Growth States	0.024	0.029	0.018	0.020	-0.0098	-0.0044
	(0.010)	(0.0081)	(0.014)	(0.0034)	(0.0074)	(0.0039)
B. Industrial Sector						
Full Sample	0.015	0.016	0.011	0.021	-0.016	-0.0013
	(0.015)	(0.012)	(0.0090)	(0.0031)	(0.0090)	(0.0065)
Slow Growth States	-0.00050	0.0067	0.0054	0.020	-0.019	-0.0072
	(0.0089)	(0.0096)	(0.0034)	(0.0021)	(0.0086)	(0.0042)
Fast Growth States	0.032	0.026	0.018	0.020	-0.013	-0.0057
	(0.014)	(0.014)	(0.014)	(0.0034)	(0.0099)	(0.0053)
C. Residential Sector						
Full Sample	0.025	0.020	0.011	0.021	-0.012	-0.012
	(0.015)	(0.011)	(0.0090)	(0.0031)	(0.0048)	(0.0077)
Slow Growth States	0.012	0.010	0.0054	0.020	-0.015	0.0018
	(0.0075)	(0.0046)	(0.0034)	(0.0021)	(0.0043)	(0.0058)
Fast Growth States	0.042	0.030	0.018	0.020	-0.0089	0.012
	(0.018)	(0.015)	(0.014)	(0.0034)	(0.0046)	(0.012)
D. Commercial Sector						
Full Sample	0.031	0.032	0.011	0.021	-0.0073	-0.00091
	(0.014)	(0.010)	(0.0090)	(0.0031)	(0.0058)	(0.0085)
Slow Growth States	0.017	0.022	0.0054	0.020	-0.0038	-0.0051
	(0.0073)	(0.0061)	(0.0034)	(0.0021)	(0.0056)	(0.0055)
Fast Growth States	0.045	0.039	0.018	0.020	0.00023	0.0063
	(0.016)	(0.012)	(0.014)	(0.0034)	(0.0084)	(0.0077)

Notes: States' average growth rates and their associated standard deviations in parentheses are presented. Estimated using author's consumption CO_2 emissions data constructed using EIA (2001a, 2001b), energy consumption data from EIA (2001a), and income and population data from BEA (2000). Slow growth states correspond to the 10 states with slowest CO_2 growth rates and fast growth rates correspond to the 10 states with fastest CO_2 growth rates for economy-wide fossil fuel CO_2 emissions over 1960–1999.

(3.2 percent). This substantial difference primarily reflects the faster population growth rates (0.54 percent versus 1.8 percent) and the decarbonization of energy in the slow growth states (–0.43 percent) in contrast with the carbonization of energy in the fast growth states (0.35 percent). Per capita income growth rates are virtually the same among the fast and slow growth states, and the slow growth states have more rapid declines in energy intensity. Failing to account for electricity trade would yield a faster rate of decarbonization of the slow growth states (–0.81 percent) and a faster rate of carbonization for the fast growth states (0.93 percent).

These growth rates mask considerable variation over the sample period. Panel B of Table 1 shows the Kaya Identity annual growth rates for the pre-oil shock period (1960–1973), the period of high oil prices (1973–1986), and the post-oil shock period (1986–1999). The emissions and energy consumption growth rates before 1974 were faster than the negligible growth during the oil shock period or the modest growth in the post-oil shock period. The lower CO_2 and energy use growth rates during the second period reflected a substantial decline in economic growth (income per capita grew 2.4 percentage points slower) and a steep decline in the energy intensity of output. The oil shocks clearly sent signals to reduce energy consumption and reallocate capital to less energy-intensive sectors, and the productivity slowdown starting in 1973 translated into slower income growth. The emissions and energy growth rates of 1.7 percent and 1.8 percent in the 1986-1999 period reflects primarily the faster rate of income growth and slower rates of decline in energy efficiency. Decarbonization of energy does not appear to be a major factor in any period – the rate of decline never fell below –0.3 percent.

There is also considerable variation across the states. Some states experienced per capita energy consumption growth of about 1/3 of 1 percent annually as others experienced growth rates of nearly 5 percent. This difference is more pronounced in the 1986–1999 period, when some states had negative energy use per capita growth rates and other states had growth in excess of 5 percent per year. In addition, the states vary in terms of their rates of decarbonization of energy. The large standard deviation relative to the average growth rate for the full sample carbon-energy ratio reflects the divergence between slow emissions growth states (annual rate of change of –0.4 percent) and fast growth states (annual rate of change of 0.4 percent). This increased dispersion in the carbon intensity of energy, especially relative to the much smaller dispersion in income per capita growth rates, is also evident in the divergence in per capita carbon dioxide emissions among the states over the 1960–1999 period (Aldy 2006a).

To complement the total CO_2 emissions and energy consumption analyses, I present growth rates for the transportation, industry, residential, and commercial sectors in Table 2. These four panels present similar comparisons of the full sample, the 10 slow growth states in total emissions, and the 10 fast growth states in total emissions. The income and population values used in these tables are the same as in Table 1, Panel A, but the energy and CO_2 emissions data are sector-specific. The transportation sector results in Panel A show that transport emissions (1.9 percent) have grown slightly slower and energy used in transport (2.3 percent) has grown slightly faster than the economy as a whole for the full sample. There are minor differences between the energy intensity and the carbon intensity measures for the slowest and fastest growth states. Virtually the entire difference in emissions between these two sets of states lies in the slower population growth in the lowest 10 states. The similarities in the energy-intensity and carbon-intensity measures reflect the national-level approach to fuel economy and the limited opportunities for adjusting the transport sector's fuel mix. The very modest decline in carbon intensity illustrates the increasing use of ethanol (from zero before 1980 to about 0.5 percent of all transportation fuel in 1999), but the transportation energy and emissions measures do not account for the energy and CO_2 emissions associated with making ethanol.[6]

The industrial sector experienced slower emissions and energy growth than any other major sector of the economy (Panel B). For the full sample, emissions grew 1.5 percent per year and energy consumption grew at 1.6 percent per year. The significant decline in the energy intensity of the industrial sector (–1.6 percent) drove this result. The decline in energy intensity in the low emissions rate states may reflect very slow growth in the industrial sector more so than energy efficiency improvements. Using BEA (2000) data on income by economic sector shows that manufacturing industries grew about 0.3 percent per year for the lowest growth states as the fast growth states experienced annual manufacturing income growth of 3.0 percent.[7]

Panel C presents the residential sector's growth rates. Although residential energy consumption per capita increased 2.0 percent annually for the full sample over the 1960–1999 period, CO_2 emissions grew faster at 2.5 percent per year. The markedly slower energy and CO_2 growth rates in the slow growth states reflects the slower population growth, and to a lesser effect, declining energy intensity. Growing electricity use increased the carbon content of residential energy use and more than offset the shift away from heating oil and towards natural gas. Residential consumption of natural gas – with about 25 percent less carbon per BTU than petroleum products – grew 1.6 percent per year as heating oil consumption declined 2.3 percent annually over the 1960–1999 period.

Commercial energy consumption grew faster than any other sector at 3.2 percent for the full sample, 2.2 percent for the slow growth states, and 3.9 percent for the fast growth states (Panel D). Likewise, this sector experienced faster growth in CO_2 emissions (3.1 percent) than any other sector. The growth in electricity offset the decarbonization associated with the growth in natural gas consumption (3.1 percent per year) and the declines in petroleum product consumption (–0.6 percent per year) and coal consumption (–5.8 percent per year).

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[6] Hill et al. (2006) provide an assessment of the energy inputs and carbon dioxide emissions associated with production of ethanol.

[7] The definition of sectors differs between the EIA and the BEA, so it is not possible to make more exact comparisons between the EIA's industry sector and the BEA economic sectors.

4. ENERGY-INCOME AND EMISSIONS-INCOME RELATIONSHIPS

To further illustrate the energy-income and emissions-income relationships I have conducted regression analysis with flexible income specifications. In the context of energy consumption, these are reduced form Engel curves and in the context of CO_2 emissions, these are environmental Kuznets curves. The general regression specification takes the following forms:

$$\ln(c_{it}) = F[\ln y_{it};\beta] + \alpha_i + \tau_t + \varepsilon_{it} \quad (3)$$

$$\ln(e_{it}) = F[\ln y_{it};\beta] + \alpha_i + \tau_t + \varepsilon_{it} \quad (4)$$

where c_{it} is per capita CO_2 in state i in year t, e_{it} is per capita energy consumption, y_{it} is per capita income, β is a vector of parameters to be estimated, α_i and τ_t are state and year fixed effects, and ε_{it} is the error term.

I characterize the income function in two ways: (1) a piecewise linear spline function, like Schmalensee et al. (1998) and Judson et al. (1999); and (2) a cubic spline function. Regression with a linear spline function yields income elasticity estimates specific to each of a series of income ranges (or spline segments), delineated by analyst-chosen knots or points in the income data. The cubic spline ensures that the estimated function is smooth (twice everywhere differentiable) by fitting cubic functions of income in-between similar analyst-chosen knots in the data. For example, one could choose nine knots in the data, one at each decile in the income distribution. For the piecewise linear spline specification, this would yield 10 income elasticities for the 10 deciles in the distribution. Instead of fitting a linear relationship, the cubic spline functions would fit cubic polynomials for each decile but constrained to be smooth at the knots. I experimented with a variety of specifications, including two to as many as 15 knots for both the piecewise linear spline and cubic spline functions. In all specifications, the locations of the knots were chosen to ensure that the identical number of observations fell in-between each pair of knots. Specification tests were performed to determine the smallest number of knots or segments that could be employed without significantly losing explanatory power in the specification. My spline specifications and specification tests follow the approaches employed in Schmalensee et al. (1998) and Judson et al. (1999).[8]

The cubic spline specifications show substantial differences between the consumption and production measures for both energy and emissions. The piecewise linear spline approach produces income elasticity estimates that facilitate comparisons. To assess whether these differences are statistically meaningful, I specify a 2-equation system of the production and consumption

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[8] Neither the choice of the number of knots nor the locations of the knots appear to have a substantive impact on the shapes of the energy–income and emissions–income relationships estimated with the cubic spline specifications. These additional results are available from the author upon request.

measures of energy (and emissions in an analogous 2-equation system) and test for equivalence of income elasticities for the income ranges under consideration

$$H_0^j;\ \beta_j^{consumption} = \beta_j^{production} \text{ for } j = 1,\ldots, J \text{ number of income ranges} \qquad (5)$$

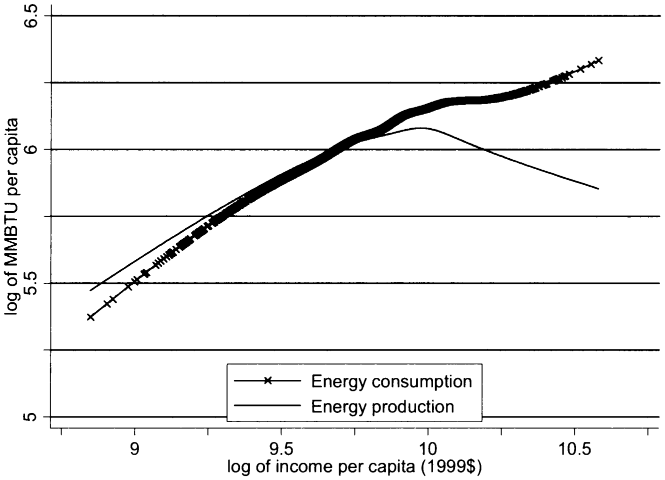
where the β's are the coefficient estimates for the natural logarithm of income for the J spline segments. Rejecting the null hypothesis for a given pair of coefficient estimates indicates that the consumption of energy responds to an increase in income in a statistically different manner than the production of energy for that income range.

Incorporating state and year effects is important for estimating the energy-income and emissions-income relationships. With the state effects, I can control for the constant or persistent differences among states – such as different energy demands among cold states and warm states – that may be correlated with income. For example, four of the five highest income states in 1999 (Connecticut, Massachusetts, New Jersey, and New York) had higher than average heating degree days. I can control for the effects of technological change and energy price shocks, to the extent that these are common across states, with the year fixed effects.

Figures 3–6 present the results from various cubic spline specifications and Table 3 presents the results from the piecewise linear spline specifications. The estimated energy consumption-income relationship is presented in Figure 3. Energy consumption increases with income for the range of incomes under consideration in this analysis (about $7,000–$39,000 per capita). This differs from the Judson et al. (1999) finding that energy consumption per capita declines at the highest income ranges in their country-level sample and the inverted-U relationships found with the quadratic specifications in Medlock and Soligo (2001) and Galli (1998). Judson et al. note, however, that "the evidence for a negative elasticity at high income levels is, in this sample, less than compelling" (p. 45). The declining income elasticities with income evident in Table 3, column 1 are consistent with the Judson et al. results.

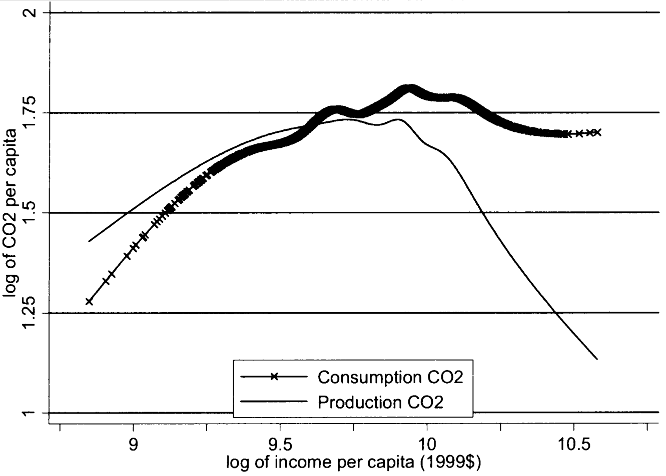
Interstate electricity trade has increased over the sample period. Estimates of states' energy production differ from those for energy consumption by adjusting for net electricity trade. The energy production measure shows a markedly different shape – per capita energy production peaks at about $21,500 per capita. The subsequent decline in energy production per capita falls until the highest income observation has a state per capita energy production commensurate with a state at slightly more than $12,000 per capita income. As states progress to higher income levels, they are relying more on other states to generate the electricity they consume. Future research will explore possible determinants for this relationship. This complements work by Aldy (2005) that showed states with higher historic (lagged) coal production tend to have higher per capita CO_2 emissions. In addition to possible differences associated with incomes between electricity generation and consumption, natural resource-rich states may develop differently from resource-poor states. An extensive literature in economic

Figure 3. States' Production and Consumption Energy-Income Relationships, 1960–1999



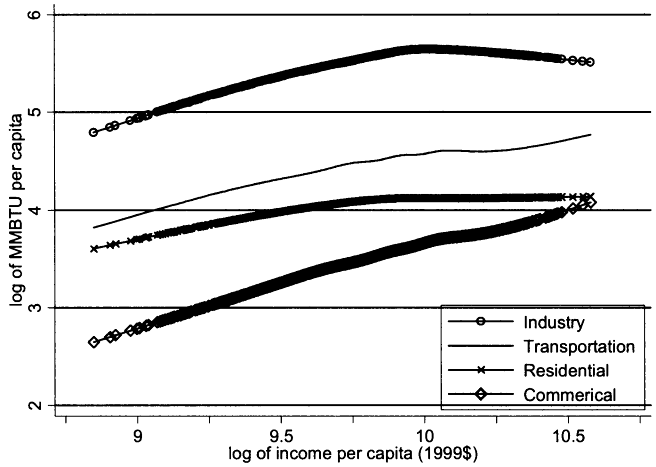
Notes: Functions derived from regressions of the natural logarithm of per capita energy on cubic spline functions of the natural logarithm of per capita income and state and year indicator variables. Based on specification tests, this figure presents the 5-knot cubic spline function for energy consumption and the 8-knot cubic spline function for production. N = 1,920.

Figure 4. States' Production and Consumption CO_2-Income Relationships, 1960–1999



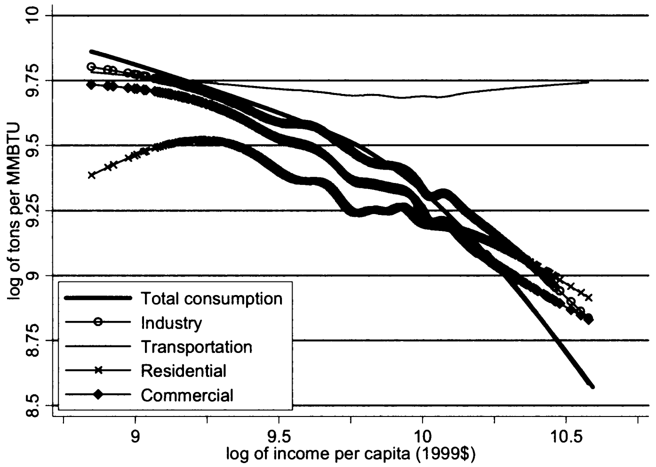
Notes: Functions derived from regressions of the natural logarithm of per capita emissions on cubic spline functions of the natural logarithm of per capita income and state and year indicator variables. Based on specification tests, this figure presents the 11-knot cubic spline function for consumption CO_2 and the 8-knot cubic spline function for production CO_2. N = 1,920.

Figure 5. Sectoral Energy-Income Relationships, 1960–1999



Notes: Functions derived from regressions of the natural logarithm of per capita end-use energy on cubic spline functions of the natural logarithm of per capita income and state and year indicator variables. Based on specification tests, this figure presents the 4-knot cubic spline function for the industrial sector, the 8-knot cubic spline function for the transportation sector, the 3-knot cubic spline function for the residential sector, and the 7-knot cubic spline function for the commercial sector. N = 1,920.

Figure 6. Carbon/Energy-Income Relationships, 1960–1999



Notes: Function derived from regression of the natural logarithm of the carbon-energy ratio on cubic spline functions of the natural logarithm of per capita income and state and year indicator variables for total energy consumption and for consumption in each major end-use sector. Based on specification tests, this figure presents the 10-knot cubic spline function for total energy consumption, 4-knot cubic spline function for the industrial sector, the 8-knot cubic spline function for the transportation sector, the 3-knot cubic spline function for the residential sector, and the 7-knot cubic spline function for the commercial sector. N = 1,920.

geography has explored the agglomeration of resource-intensive industries near the location of these resources. The future research will also investigate the possible distinctions between resource-rich and resource-poor states in terms of the energy-intensity and emissions-intensity of their economic growth.

The first two columns in Table 3 illustrate similar results for these two energy measures for the piecewise linear spline specifications.[9] The income elasticities for energy consumption are positive for all eight income ranges, and seven of the eight are statistically different from zero at the 1 percent or 5 percent level. The income elasticities do decline with income over some of the sample range, but rebound in the highest income group (>$31,655). In contrast, the energy production function follows the inverted-U shape depicted in Figure 3 with a decline in energy production starting with the $20,537–$25,497 income range. Tests comparing the income elasticities reveal substantial differences between energy consumption and production starting with incomes of about $16,500. The rows below each pair of income elasticities present the F-statistics for the Wald tests of the null hypothesis of equivalence of elasticity estimates. With F-statistics ranging between 14.92 and 84.21, it is clear that the energy-income relationship differs significantly between consumption and production for the higher incomes in the sample.

The distinction between the location of electricity production and electricity consumption has no real impact on standard analyses of the energy consumption-income relationship because these typically employ a measure of end-use consumption. In contrast, standard EKC analyses of CO_2 per capita use emissions measures based on the geographic location of the fossil fuel combustion. If a lump of coal is burned in a power plant in Kentucky, but this electricity is sent to Ohio, then the CO_2 emissions would be assigned to Kentucky even though the typical measure of end-use energy consumption would assign the electricity to Ohio. Accounting for interstate electricity trade does have a substantial impact in estimating the states' emissions-income relationship. Figure 4 shows that failing to account for electricity trade results in an inverted-U shaped emissions-income relationship – a standard environmental Kuznets curve. Adjusting for interstate electricity trade, and assigning emissions to where the electricity is consumed, results in a very different shape – a peak, a modest decline, and a plateau in per capita emissions for the consumption CO_2 measure.

The last two columns of Table 3 present the results from the emissions-income piecewise linear spline specifications. Only one income range segment has a negative and statistically significant income elasticity for consumption CO_2, and the highest income range has a small elasticity that cannot be discerned from

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[9] Table 3 presents the results for an 8-segment piecewise linear spline. Specification tests for energy consumption could not reject an 8-segment spline, but did reject simpler specifications. To ensure consistency in the comparisons, both 2-system equations were specified as 8-segment spline functions. The explanatory power does not vary substantially across spline specifications. For 8 to 15-segment splines, the R^2s range between 0.9431 and 0.9436 (energy consumption), 0.9277 and 0.9281(energy production), 0.9341 and 0.9346 (consumption CO_2) and 0.9259 and 0.9264 (production CO_2).

Table 3. Estimated Income Elasticities from 8-Segment Piecewise Linear Spline Regressions

Income Range	Energy Consumption		Energy Production	Consumption CO_2		Production CO_2
< \$8,644	1.22		0.51	1.31		0.46
	(0.27)*		(0.37)	(0.38)**		(0.51)
		6.93**			6.59*	
\$8,644 – \$10,732	0.82		0.87	0.60		0.73
	(0.11)**		(0.16)**	(0.16**		(0.21)**
		0.22			0.88	
\$10,732 – \$13,323	0.60		0.50	0.29		0.079
	(0.067)**		(0.094)**	(0.097)		(0.13)
		2.03			6.15*	
\$13,323 – \$16,541	0.64		0.52	0.33		0.20
	(0.054)**		(0.076)**	(0.078)**		(0.10)*
		4.15**			3.20*	
\$16,541 – \$20,537	0.55		0.30	0.26		-0.053
	(0.051)**		(0.072)**	(0.074)**		(0.098)
		23.09**			24.38**	
\$20,537 – \$25,497	0.26		-0.24	-0.15		-0.76
	(0.054)**		(0.076)**	(0.079)		(0.10)**
		81.51**			79.53**	
\$25,497 – \$31,655	0.12		-0.53	-0.35		-1.16
	(0.070)		(0.099)**	(0.10)**		(0.13)**
		84.21**			85.10**	
> \$31,655	0.53		-0.23	-0.089		-1.00
	(0.19)**		(0.27)	(0.28)		(0.37)**
		14.92**			14.18**	

Notes: Dependent variables are natural logarithm of per capita measures listed in the first row. The two energy (CO_2) measures were modeled as a 2-equation system to allow for correlation in the residuals across measures. The table presents the natural logarithm of per capita income coefficient estimates and robust standard errors (in parentheses) for each of eight income ranges (spline segments) in 1999\$. All specifications include year and state indicator variables. Below each consumption-production pair of income elasticities for a given income range are the Wald test statistics for the hypothesis that the pair of elasticities are equal. These statistics are distributed F(1, 1825). *, ** denotes statistical significance at 5 and 1 percent critical levels, respectively. N = 1,920.

zero. This is roughly consistent with the peak, modest decline, and plateau evident in Figure 4. In contrast, income elasticities for the highest three income ranges are negative and statistically significant for production CO_2. With Wald test F-statistics ranging from 14.18–85.10, it is clear that these two emissions-income relationships are statistically different for the four highest income ranges.

The inverted-U EKC for production CO_2 is consistent with the Schmalensee et al. (1998) results. They estimate a peak in per capita emissions at about \$14,000, and I find a peak of \$16,000.[10] The consumption CO_2 approach does not have an analog at the national level in the literature. These results suggest caution for long-term forecasting, such as in Schmalensee et al. (1998) and Holtz-Eakin and Selden (1995). If trade, whether in electricity or carbon-intensive goods, affects the estimation of national-level EKCs, then using production-based measures instead of consumption-based measures would yield downward biased estimates of long-term emissions as more countries develop.[11, 12]

Figure 5 presents the energy-income relationships for the industry, transportation, residential, and commercial sectors. Industrial energy consumption follows an inverted-U shape, likely reflecting the transition away from manufacturing as economies attain high levels of development. The transportation sector has a fairly steady increase in per capita energy use, reflecting the fairly steady increase in vehicle miles traveled over this period and the fact that there are fewer opportunities to substitute away from transportation uses at high incomes. A concave and flattening out energy-income relationship characterizes the residential sector. The commercial sector has the highest income elasticity among these four major end-use sectors.

These results suggest that transportation and commercial sectors' shares of energy consumption will increase with incomes as the industrial and, to a lesser extent, the residential sectors experience declining shares. This is consistent with the Judson et al. (1999) finding that transportation has an increasing share of energy consumption and industry follows a similar inverted-U shape. The relative shapes of these estimated sectoral functions are fairly similar to the sectoral energy-income profiles constructed in Figure 2 of Medlock and Soligo (2001).

Figure 6 illustrates how the carbon intensity of energy consumption varies with income. Figures 3 and 4 show energy consumption increasing at high incomes and an emissions profile peaking and plateauing at high incomes. These results suggest the decarbonization trends evident in Figure 6. For total consumption and the industrial, residential, and commercial sectors, the carbon content of energy steadily declines with income. Only transportation has experienced a negligible change in the carbon-energy ratio with respect to income.

These substantial declines (with elasticities on the order of –0.3 to –0.4) may initially appear to be inconsistent with the very small growth rates in the carbon-energy ratio presented in Tables 1 and 2. The nature of decarbonization

[10] I have converted the published income at the EKC peak from Schmalensee et al. to 1999 dollars.

[11] The finding of an inverted-U environmental Kuznets curve for production CO_2 is not inconsistent with the finding that the dispersion of per capita CO_2 emissions has increased over time. Refer to Aldy 2006a, 2006b for more details.

[12] The range of income per capita for this analysis (\$6,662–\$39,300 in 1999\$) would include the year 2000 per capita incomes for all developed countries and many middle income countries, such as Argentina, Chile, Czech Republic, Korea, Mexico, and Malaysia, on purchasing power parity terms (Heston et al. 2002). The range of energy consumption per capita for this analysis (162–962 MMBTU) would include the year 2003 per capita energy use values for most developed countries and some middle income countries, such as Czech Republic, Estonia, Korea, and Taiwan (EIA 2005).

differs substantially between the wealthy and less wealthy states. The ten highest income states in 1999 experienced an average rate of change in the carbon-energy ratio of –0.22 percent over 1960–1999. In contrast, the ten lowest income states in 1999 had a 0.11 percent annual growth rate in this ratio. Decarbonization does appear to occur as states achieve higher incomes. This is consistent with the Schmalensee et al. (1998) and Judson et al. (1999) claim that wealthy countries experience a decline in CO_2 per capita because of the transition from coal to natural gas for environmental policy reasons.[13]

Some of this decarbonization may reflect the growing influence of nuclear power in the electricity sector. From 1960–1999, nuclear power grew from a negligible share of the utility sector to nearly one-fifth of all power generation. States with a higher share of nuclear in their power generation mix have lower per capita CO_2 emissions (correlation coefficient of –0.38 in 1999), and higher income states tend to have a higher share of nuclear (correlation coefficient of 0.52 in 1999). The other major non-carbon generation source, hydropower, is associated with lower state per capita emissions (–0.29 correlation coefficient in 1999), but is also modestly associated with lower incomes (correlation coefficient –0.14 in 1999).

5. CONCLUSIONS

This paper provides an evaluation of the energy and emissions dynamics for the U.S. states – a set of economies at an advanced stage of development. The Kaya Identity assessment of the major drivers of energy and emissions shows that population and income growth exceed the reductions in the energy intensity of output and the carbon intensity of energy resulting in average growth rates of about 2 percent for energy and CO_2. Differences in population growth and the change in the energy intensity of output explain most of the variation between slow emissions growth and fast emissions growth states. Differences in the carbon intensity of energy also distinguish slow growth and fast growth states in the residential and commercial sectors.

Regression analyses with piecewise linear spline and cubic spline specifications illustrate how energy and emissions change with respect to income. Energy consumption has a positive but declining income elasticity over the entire income range. CO_2 emissions associated with energy consumption (post-electricity trade measure of emissions) peak and plateau. The difference between these two estimated functions shows the decarbonization of energy evident in high-income states. This EKC for consumption CO_2 differs substantially from the standard inverted-U shape evident with the production CO_2 measure (and the related inverted-U for energy production). Tests of the estimated income elasticities in the piecewise linear spline specifications reveal that the consumption and

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[13] The transition towards natural gas in the electricity sector in the 1990s may have also reflected technological change that improved the heat rates in gas-fired plants and reduced the relative price of natural gas-based electricity.

production profiles are statistically different from each other for both energy and CO_2 starting at about $16,500.

These results can help inform policy-makers on a variety of issues. Understanding how per capita energy consumption changes as economies develop is useful for forecasting future energy demand and this can influence debates on such issues as resource extraction policies, alternative fuels R&D, and energy efficiency standards. The distinction between production and consumption measures of emissions and the role of interstate electricity trade is important in the development of emissions abatement programs. First, it suggests that economies cannot simply grow their way out of pollution. Emissions per capita may appear to decline at high incomes (in the production measure EKC), but that reflects electricity imports more than decarbonization at high income levels. All economies cannot become net importers of electricity in the long term, so an emissions abatement program will be necessary to mitigate climate change risks. Second, the role of trade can influence the design of an emissions abatement policy. This has been noted as the Northeast states move forward with their Regional Greenhouse Gas Initiative and California's consideration of a load-based emissions cap to address the carbon content of imported electricity. Finally, the sector-specific analyses can highlight the opportunities to address fast-growing energy consumption activities.

These policy implications raise issues that merit further research. Additional analysis exploring the causes of the disconnect between electricity production and consumption can be insightful both for policy-makers and for an understanding of energy institutions at advanced stages of development. Perhaps more importantly in the context of country-level emissions trends, future work could assess whether such a disconnect between production and consumption matters for tradable emissions-intensive goods. The relationship between CO_2 emissions and energy suggests that similar work on air pollutant emissions that are also by-products of fossil fuel combustion, such as nitrogen oxides and sulfur dioxide, also could benefit policy-makers.

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