U.S. Carbon Emissions, Technological Progress and Economic Growth Since 1870

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Abstract

The long-term U.S. experience emphasizes the importance of controlling for electrification and other major technology transformations when evaluating the growth of carbon emissions at different stages of development. Prior to World War I, carbon emissions grew faster than economic growth by 2.3% per year. As electricity use expanded and steam engines became much larger, carbon emissions began to grow slower than economic growth by 1.6% per year. Adjusting for this technological shift, an expanding economy continues to increase carbon emissions by about 9 percent for each 10 percent faster growth. There is little evidence for a decline in this elasticity as the income level rises. These results suggest that the United States today will need to find additional policies to curb carbon emissions if it wishes to prevent any further increase in its per capita emissions and its per capita economy grows by more than 1.8 percent per year.

Keywords: Global climate change; Economic growth

JEL classification: O40; Q21

Introduction

Economic development transforms societies and their carbon dioxide emissions in important ways. The early stages are often characterized by dependence on activities and technologies that are relatively carbon intensive. Economic maturation reduces this trend, as slowing rates of urbanization and energy commercialization reinforce the effect of compositional shifts within the economy that move resources to less-carbon intensive activities. Some mature economies may even show a reversal in the trend, where per capita emissions have already peaked and begin to decline as the economy grows.[1]

These trends have very significant policy implications for efforts to control worldwide emissions. Fears of potential climate warming have led many countries to consider policies for limiting the growth in carbon dioxide and other greenhouse gas emissions to a previous year's level.[2] Over time, economic growth will cause the gap between projected future emissions without any policy intervention and the lower targeted levels to grow. This widening gap between actual and targeted emissions will require increasingly more costly policies if countries are to remain committed to current protocols for limiting climate change.

The current international protocol (established in Kyoto in 1997) restricts carbon dioxide emissions in industrialized countries but allows emissions to grow unconstrained in developing countries. If mature economies have already reached their maximum carbon emissions levels, a commitment to an international agreement like the Kyoto protocol would not be as burdensome for these few industrialized countries as is sometimes feared, although total emissions would continue to grow with population even if per capita emissions did not. Soon after President Bush was elected, the

United States decided that it would not commit to its targets contained in the Kyoto protocol. In place of its Kyoto commitments, the Bush Administration recently proposed that the country should meet a target based upon a historical benchmark for carbon intensity rather than carbon levels. However, the United States' reluctance to join the protocol or to adopt its own intensity target would not seriously affect world emissions levels if economic maturation caused richer countries to reach beyond their peak carbon emissions levels. More disturbing perhaps would be that developing countries are not required to restrict their greenhouse gas emissions under any proposed international climate change agreements. Thus, these agreements would not affect emissions growth in those countries that are expected to contribute the most to the problem over the coming decades.

Nakicenovic (2002) has documented the basic trends relating past emissions with economic growth with very illuminating charts that underscore the dramatic shifts from coal and oil as industrialized economies have matured. Although these great energy transformations are widely acknowledged within the research and policy community, there have been limited efforts to quantify these developments and understand possible causes. Several specific issues include: when did the process begin, what conditions ushered in the new trends, and what can be said about future trends given this past experience.

The analysis in this paper evaluates the US experience with per capita carbon emissions, economic growth, and technical progress since 1870 to help understand that country's historical experience and its prospects for controlling emissions in the future as the economy grows.[3] Trends within the United States are important, because the country remains the largest emitter of carbon on a per-capita basis. Moreover, its historical experience may have some interesting insights for countries currently transforming their economies through increased industrialization and economic restructuring. Although the US experience must be applied judiciously to these newly developing countries, due to a different set of available technologies than in the past and other leap-frogging effects, these trends may provide a useful benchmark for initial inquiry into the problem.

Although future research on more developed and developing countries will be important and useful, there are reasons for proceeding slowly on the issues being addressed in this paper. Perhaps reflecting the resource intensity of the country, the US historical experience is particularly well documented with relatively high quality data for almost 130 years. This long period allows an analysis of a single country through the development process. When multiple countries are collectively analyzed, there is a strong tendency to pool the data and to assume that all countries are locked into similar trends or responses. This seems highly unrealistic. Countries have different economic structures, adopt new technologies at different times, experience different prices and may respond to prices in very different ways. In addition, the temptation to pool developed and developing countries should be vigorously avoided, because their structures are considerably different.

Our goals are threefold: (1) estimate the response of carbon emissions to economic growth, (2) estimate the effect of technological progress on carbon emissions, and (3) determine the year when the technological progress effects began to change and discuss the changed conditions during that transition period. The next section discusses the data and tests the stationary properties of the different variables. Regression analysis is conducted on the full 1870-1998 data and results are presented in Section 3. In order to incorporate the possible influence of energy prices, the data set is limited to the 1890-1998 period. Section 4 evaluates these results. Recent analysis has shown that oil and energy demand may respond differently to price increases than to price decreases. Section 5 discusses the tests to account for this asymmetry in responses. Implications of the analysis are evaluated in section 6.

Emissions and Economic Growth Data

The analysis focuses upon total carbon emissions and real U.S. gross domestic product on a per capita basis and on real energy (i.e., fuel and power) and coal prices. The sample dates from 1870 for carbon emissions and GDP and from 1890 for real prices. The data sources are described in the data appendix.

Initial unit root tests on these data suggested that both series might not be stationary. Augmented Dickey-Fuller tests did not reject the null hypothesis at the 5% level that unit roots existed. Table 1 summarizes these tests and their significance levels as well as the number of lags that appeared optimal. However, both series appear to have important shifts in their trends that need to be controlled when testing for unit roots. Perron (1989) has discussed the problems with the economic data and the tendency of its level and rate to change with certain discrete events. Figure 1 shows that real per capita GDP dips immediately after the 1929 depression and begins to increase more strongly in the late 1930s. Figure 2 shows that per capita carbon emissions begin a much slower growth around 1920. Figure 3 and 4 emphasize the energy price shocks after 1972 that dominate the trends in real fuel and power and real coal prices.

We conducted a procedure developed by Perron to estimate a test-statistic for unit roots given that the series had a break in both its constant and trend.[4] The test does not impose the breakpoint *a* *priori* but rather estimates it from the series' distribution. The new test-statistics are reported in Table 2. None of these series appear to have unit roots, as the test-statistic for each series exceeds the critical value provided by Perron. His critical values depend upon the ratio of the years prior to the break and the total sample. This value, λ, ranges from a low of 37% for carbon emissions and 53% for GDP to a high of 76% for the two energy prices. The test estimates that the break point for carbon emissions occurs in 1917, that for gross domestic product occurs in 1938, and those for energy and coal prices in 1972.

Estimating the 1870-1998 Carbon Emissions-GDP Relationship

The absence of unit roots in these two series suggests that we can obtain meaningful estimates from applying standard econometric techniques. Figure 4 shows that the trend between carbon emissions, plotted on the vertical axis, and real GDP, plotted on the horizontal axis, is clearly not constant. Around the breakpoint for carbon emissions (1917), proportional growth in the economy begins to produce sharply lower growth in carbon emissions. This result suggests strongly for the need to consider allowing for a break in the relationship between emissions and economic growth.

The form of this relationship is critical for future discussions about US climate change policy and its impact on world emissions. If the income elasticity declines as the income level increases, U.S. emissions may eventually peak and stabilize. On the other hand, if technological progress leads to future reduction in carbon intensity, independent of the level of income, its effect will be more complex. More rapid autonomous technological progress will reduce carbon dioxide emissions, but this effect may be offset either partially or completely by rapid economic growth.

Resolving this issue requires a structured and methodical approach for considering the alternatives. Initially, the analysis focuses on the longer, 1870-1998 horizon in order to establish the basic relationship between emissions, technological progress and economic growth. In the following section, it incorporates energy prices by evaluating the somewhat shorter, 1890-1998 period. In each case, we develop a general specification before reducing parameters to reach a more simplified equation.

The general specification for the 1870-1998 period without energy prices is:

$$\ln C = \beta_0 + \beta_1 \ln Y + \beta_2 T + BREAK * (\beta_3 + \beta_4 \ln Y + \beta_5 T) + \mu$$

where C represents per capita carbon emissions, Y refers to per capita real gross domestic product, T is a time trend, BREAK is a dummy variable that equals one if the year occurs after the breakpoint and zero otherwise, and μ denotes the disturbance term.

Although it appears that the carbon emissions path began to separate from the economy's growth path about the time that carbon emissions experienced its break over time (1917), it was decided to test for when this break occurred. Ordinary-least squares produced a result with significant and logical estimates but the Durbin-Watson statistic fell below the lower end for rejecting autocorrelation. We used a Hildreth-Lu specification to estimate an autocorrelation coefficient and to adjust the equation for biases created by this problem.

We initiated the break in 1890 and tested whether the pre- and post-break coefficients were significantly different from each other. We evaluated multiple Chow (1960) tests by escalating each time the breakpoint one year. The sequence of Chow tests for each breakpoint is shown in Figure 5.

Its maximum is reached in 1913 with a value of about 20, which exceeds the criteria for significance (Andrews 1993 and Andrews and Ploberger 1994). Following the Andrews-Quandt procedure, we conclude that a statistically significant break occurs in 1913.

Table 3 summarizes the coefficients (and standard errors in the second row) of the basic equations in moving from the general unrestricted specification of equation (1) to more restricted formulations. The first equation includes break terms for the constant and both independent variables. The second equation eliminates the constant and income after the break. The post-1913 constant should be removed, because Figures 2 and 3 do not reveal a sharp upward or downward jump in per-capita emissions or GDP in 1913, although the trend with time is changing. The post-1913 income variable appears to add very little explanatory power. Finally, in the third numerical column, the final equation eliminates the post-1913 time trend, resulting in an equation without any breaks.

Shown below the second and third equations are F-test statistics that reject that specification if it exceeds the critical value for the constraints and degrees of freedom for the unconstrained specification. Observation of these values indicates that one can reject the specification that includes the constant and income after the break but not the specification that includes the trend after the break. Thus, the break focuses primarily upon the trend rather than income per capita in these equations.

The income elasticities in Table 3 remain consistently at 0.9 before and after the break. These results cast doubt upon specifications that impose a nonlinear response where the income elasticity declines as incomes increase. This procedure is done frequently because it is relatively easy to implement, but it should be done based upon formal testing of the linear and nonlinear specifications.

The nonlinearity specification was tested more formally by estimating regression equation specification error tests based upon the errors from the equation shown in column (2) of Table 3. When squared income is introduced into the RESET equation explaining the residual, the F-statistic for this variable was 0.52, indicating that the linear specification could not be rejected.

A second test based upon the forecasting properties of the two different specifications confirmed the linear form. Our preferred equation represented in column 3 of Table 3 was estimated through 1990, and the coefficients were used to project values for per capita carbon emissions between 1991 and 1998. The root mean square (RMS) percent error was 1.48%. A similar procedure that used income, income squared and time (but not time after the 1913 break) as independent variables produced a slightly higher RMS percent error of 2.48%.

Offsetting the income effect is a time trend that moves the economy away from carbon use at a rate of 1.6% per year (=.023-.039) after the year 1913. Thus, economic growth will raise emissions if it exceeds 1.78% p.a. (= 1.6%/0.9); otherwise, per capita carbon emissions will decline.

Estimating the 1890-1998 Carbon Emissions-GDP Relationship

A shorter time horizon covering the 1890-1998 period allows the analysis to incorporate the effect of energy prices into the previous equation. The left-side set of columns of Table 4 shows the responses when real total fuel and power prices are included, while the right-side set of columns indicates the responses when real coal prices are included. Coal prices may be individually important because that fuel accounts for considerably more carbon emissions per British thermal unit of energy than do other energy sources.

Table 4 shows coefficients that are broadly consistent with the previous estimates, although energy prices are not significant. The income elasticity remains at 0.9 before and after the break. F-tests again indicate that the middle column in each set is preferred. The time trend increases per capita emissions by +2.2% per annum before 1913 and decreases them by 1.6% per annum after 1913. Thus, the shorter time horizon or the inclusion of energy prices has not changed the estimated coefficients.

Regardless of the specification, the economic and technological factors incorporated by the time trend have changed substantially over the full horizon. Prior to 1913, this trend increased carbon use, much as it appears to do today in many developing countries.[5] After 1913, carbon use declines with time if GDP does not change.

Decomposing Energy Prices

The disappointing result for fuel and coal prices prompted alternative specifications. Gately and Huntington (2002) have shown that oil and energy demand in many countries may respond asymmetrically to energy price increases and decreases. The source of this asymmetry can be either induced technological change or irreversible responses due to sunk investments. When energy prices rise, consumers and firms choose automobiles, airplanes and other energy-equipment that not only reduce energy intensity but also embody major changes in their performance. When prices fall, consumers and firms cannot simply return to yesterday's older equipment, because it is no longer available. In addition, some retrofitting (like home insulation) and other energy-saving adjustments are too expensive to reverse, and hence represent sunk costs, if energy prices should begin to fall.

Since carbon emissions are so closely tied with energy use, these same dynamics might be operating in this analysis.

Gately and Huntington separate the response to energy prices into three separate price components: the highest maximum level, price cuts below the historical peak, and price recoveries rising back towards the peak. The alternative specification in this paper follows a similar conceptual approach by including three separate energy price series. P_{max} equals the real fuel and power price if it is a historical maximum; otherwise, it is zero. P_{cut} equals the real fuel and power price if is declining; otherwise, it is zero. And finally, P_{rec} equals the real fuel and power price if it is recovering back towards but still below its historical maximum; otherwise, it is zero. When summed, these price series equal the original price series. Note that carbon emissions should be inversely related to positive energy price increases (P_{max} or P_{rec}) or to negative energy price decreases (P_{cut}).[6]

Inclusion of these decomposed price series did not improve the equation's fit and resulted in statistically insignificant price coefficients. As a result, there seems to be little reason to include either the original energy price variables or their decomposition in these relationships.[7]

Implications

The major transformation away from carbon intensity in the United States occurred prior to World War I rather than after the 1973-74 oil price crisis. Per capita carbon dioxide emissions grew by 4.2% per year between 1870 and 1913 and by 0.6% per year between 1913-1972, while it decreased by 0.2% per year since 1972. Meanwhile, real per-capita gross domestic product grew by 2.2% per year during the 1913-1972 period and by 2.0% per year over the other periods.

The long-run cost of carbon-intensive coal and fossil fuel was not a primary cause for this declining carbon intensity. In the years immediately preceding World War I, coal and fuel and power prices were not trending upward, although both prices were volatile and coal strikes threatened energy supply disruptions in much the same way that oil embargos operate in today's economy. The prices of coal and fuel and power had their most dramatic upsurge between 1920 and 1922, well after the shift away from carbon intensity had begun, according to this analysis. Oil was replacing coal in some important applications, but long-run prices were not yet favoring oil over coal.

Instead, the U.S. economy during this transitional period appeared to be experiencing rapid technological progress for reasons other than the long-run cost of carbon-intensive fuels. This period around World War I was characterized by the rapid replacement of steam engines by electric power. Electricity increased its share of total energy use in the manufacturing sector from 18.7% to 50.2% between 1909 and 1919 (Du Boff 1966). The expansion of electric power had dramatic effects on the costs of operating industrial facilities and in increasing firms' flexibility to change their factories and produce new products (Schurr *et al*, 1960). This period experienced increasing trends in output per manhour, output per unit of capital and output per unit of total factor productivity (Du Boff 1966).

During this transitional period, there was a temporary reduction in energy use and a long-run shift away from coal, a very carbon-intensive fuel source. Both fuel and coal use per capita reached their local maximums in 1913. Energy use per capita recovered through the 1913-1918 period and eventually surpassed its 1918 peak by the beginning of World War II (1941). After a brief recovery, coal use per capita attained its global historical maximum five years later in 1918, before declining permanently. An important sector that used coal was pig-iron production, which peaked in 1916.

It is important to incorporate these technological progress trends when estimating the effect of income or GDP on carbon emissions based upon the long-term U.S. historical experience since 1870. During the early years before 1913, carbon emissions grew faster than economic growth by 2.3% per year. In later years, carbon emissions grew slower than economic growth by 1.6% per year. Empirical studies should *not* ignore these critical shifts in technological progress. If they do, they will tend to find a nonlinear specification between carbon emissions and income, when a better specification would allow for shifts in technological progress.

If carbon emissions are a nonlinear function of income, richer countries will eventually emit fewer emissions when their economies grow. The implication of these trends is that richer economies may be able to grow their way out of the climate change problem. On the other hand, the implications are quite different if carbon emissions instead reflect major shifts in technological progress caused by electrification and adoption of other critical technologies. These developments will reduce carbon dioxide emissions, but this effect may not be sufficient to offset the influence of rapid economic growth.

The estimates in this study show that an increase of 10 percent in the U.S. economy's size will expand carbon emissions by 9 percent, holding constant the time trends that control for technological progress. When combined with these technological trend effects, these results imply that per capita carbon emissions will decline if today's economy fails to grow by 1.8 percent per year on a per-capita basis. Otherwise, they will increase. There appears to be no indication that per capita economic growth had any different effect on per capita carbon emissions before 1913 than after that date. Economic growth's elasticity was remarkably similar at 0.9 in both periods. This result suggests that the U.S. income elasticity for carbon emissions does not decline at higher income levels. Economic growth in a more mature U.S. economy does not reduce per capita carbon emissions relative to its situation earlier in the development process. RESET tests and in-sample forecasting confirm this conclusion by failing to reject the assumption of linearity in the emissions-GDP relationship.

These results question some previous studies that pool country data (e.g., Schmalensee *et al* and Holtz-Eakin and Selden). The pooled analyses incorporated the combined effects of technological progress and of prices, which are unavailable for many countries, through a dummy variable for each year. By necessity, the coefficient for each year is restricted to be the same for all countries.[8] This restriction will not be correct if technological progress and energy prices have dissimilar effects in different countries.

It is highly unlikely that technological progress will operate uniformly in each country. Technologies will penetrate some countries considerably more quickly than others (Comin and Hobijn, 2004). Countries with different economic structures, climates, dependence upon private transportation and urbanization rates are likely to experience different technology trends. Technical progress may be encouraging shifts away from carbon-intensive activities in countries at more advanced stages of development and towards carbon-intensive activities in countries with less development, in much the same way that was observed for the United States at different periods in this study.

Countries may also differ in their response to price changes because energy prices do not move similarly across countries due to local market conditions, taxes and subsidies, or because countries respond differently to any given energy price change. Gately and Huntington (2002) estimated significantly different responses for developed countries than for developing countries as well as equally significant differences among different groups of developing countries. Hopefully, future efforts in using pooled data will work towards resolving some of these important issues and testing the robustness of the results derived from this long-run historical path for an important industrialized country.

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Appendix: Data Sources

Carbon Dioxide - "Global, Regional, and National Annual CO2 Emissions from Fossil-Fuel Burning, Cement Production, and Gas Flaring: 1751-1998 (revised July 2001)" by G. Marland, T.A. Boden, and R.J. Andres. Report NDP-030. Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, TN. Oak Ridge website at http://cdiac.esd.ornl.gov/ndps/ndp030.html.

Energy - Data for 1949-current year reported in US Energy Information Administration, Annual Energy Review 2000, Washington, DC. Series were extended back with Historical Statistics of the United States. This procedure provided a reasonably good fit between the two series. Historical data are slightly smaller probably because they exclude nuclear. EIA website at http://www.eia.doe.gov/emeu/aer/contents.html.

Population – Bureau of Economic Analysis for 1949-current year from website at: http://www.census.gov/population/estimates/nation/popclockest.txt. Data series was extended back with Historical Statistics of the United States.

GDP per capita – Real GDP per capita are billions of 1987 dollars per person. BEA website provides GDP for 1929-current year, which is divided by population. Series extended back by the growth rate in per capita GDP data from Jones (1995). The Jones data was developed by Andrew Bernard and is reported at http://elsa.berkeley.edu/~chad/TimeEGM.asc.

Prices - Real energy and coal prices are in 1982 dollars. All prices are deflated by producer price index for all products. Price index for 1929 - current year is reported in BLS website. BLS website at http://www.bls.gov/ppi/home.htm. Series was extended backwards using Historical Statistics of the United States. Klemmer and Kelley (1998) find that the BLS data on producer price index for energy products track other energy price data like those reported by the EIA pretty well.


Figure 1. GDP (1987$ per capita)
35000
30000
25000
20000
15000
10000
5000
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

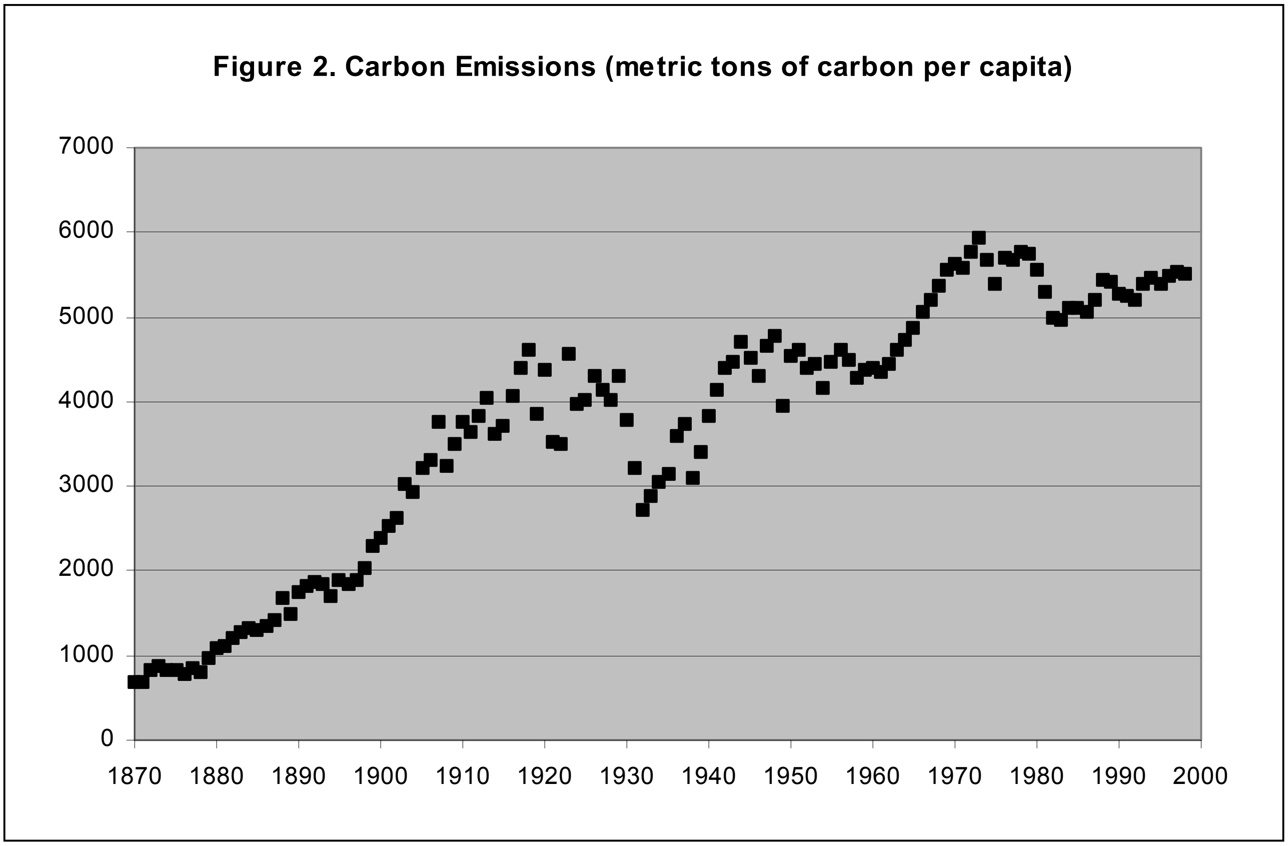
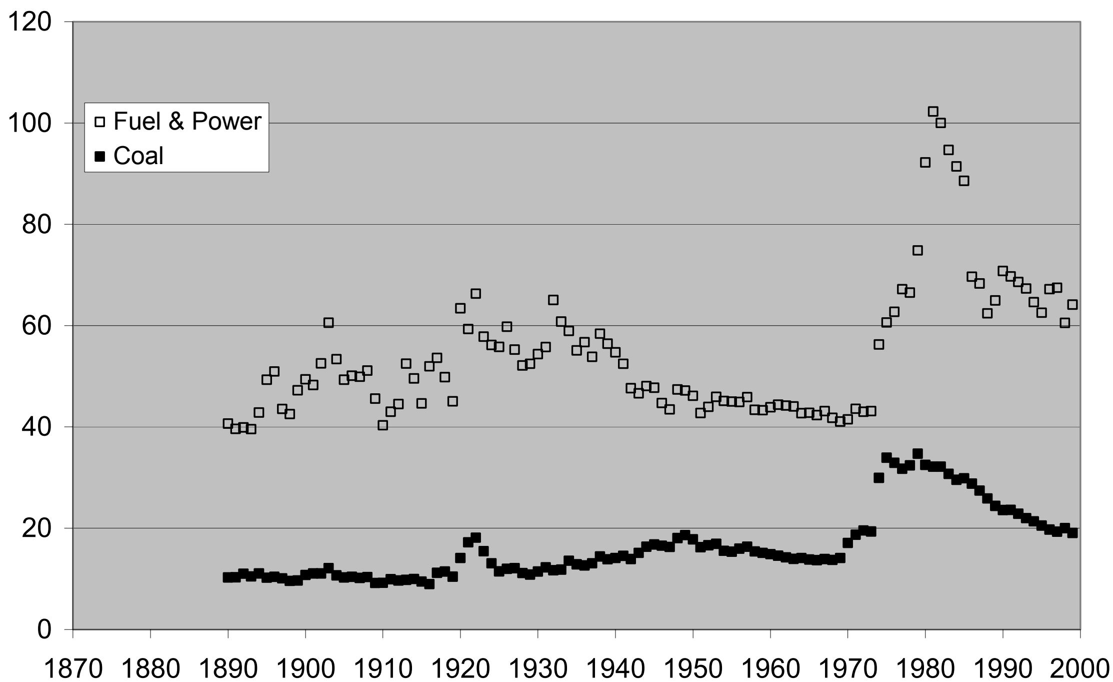


Figure 2. Carbon Emissions (metric tons of carbon per capita)
7000
6000
5000
4000
3000
2000
1000
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

Figure 3. Real Energy Prices (1982 cents)



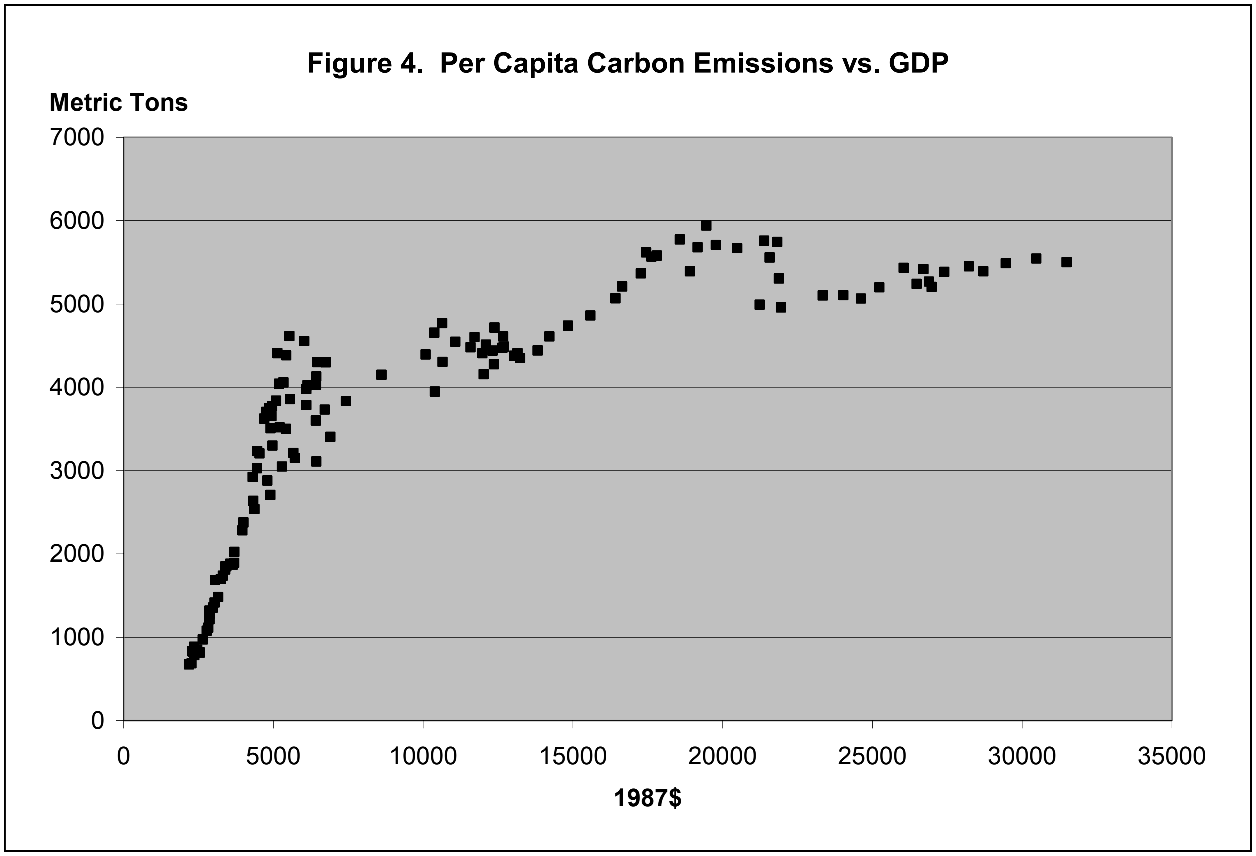


Figure 4. Per Capita Carbon Emissions vs. GDP
Metric Tons
7000
6000
5000
4000
3000
2000
1000
0
0
5000
10000
15000
20000
25000
30000
35000
1987$

Figure 5. Chow Test Sequence as a Function of Breakdate

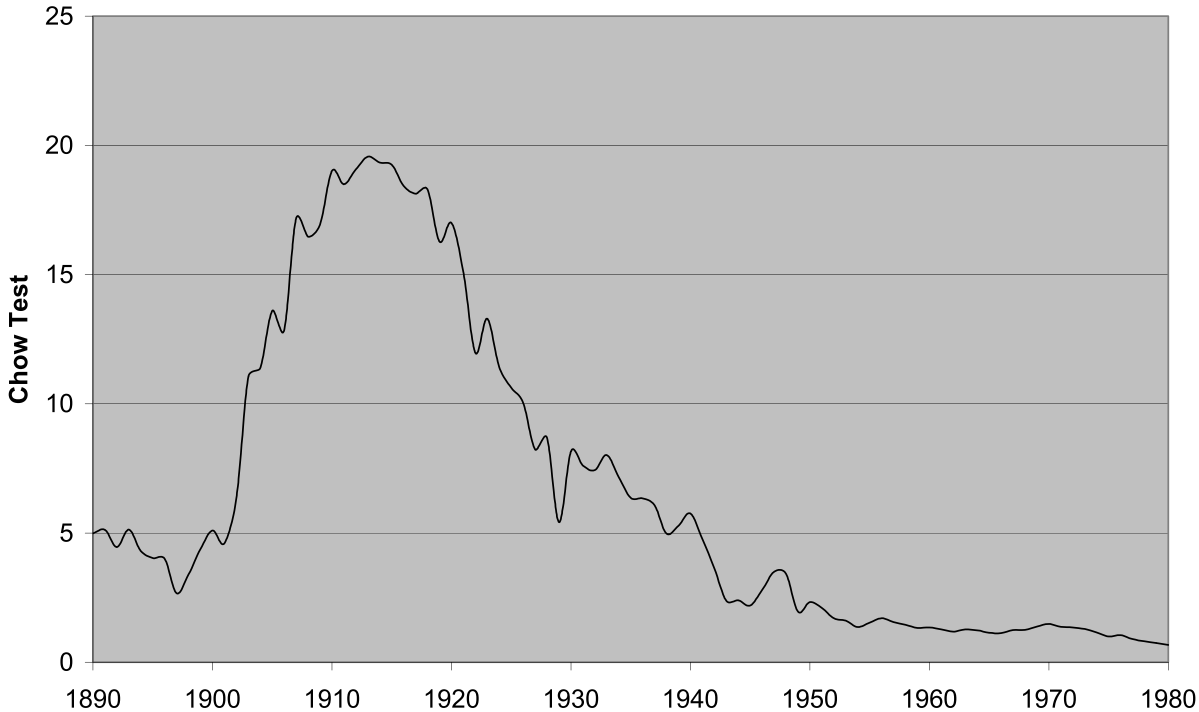


Table 1. Augmented Dickey-Fuller Tests

Variable	Period	Statistic	P-values	Lags
Per Capita Carbon	1870-1998	-3.34	6.0%	10
Per Capita GDP	1870-1998	-3.05	12.0%	3
Coal Price	1890-1998	-3.21	8.3%	6
Energy Price	1890-1998	-2.24	46.7%	2

Table 2. Perron Tests for Databreak in Series

Variable	Period	Statistic	Breakdate	Lags	Relative Break	Significance
Per Capita Carbon	1870-1998	-4.53	1917	8	0.367	2.5%
Per Capita GDP	1870-1998	-5.56	1938	2	0.531	1.0%
Coal Price	1890-1998	-5.46	1972	3	0.759	1.0%
Energy Price	1890-1998	-4.47	1972	0	0.759	2.5%

Table 3. Carbon Dioxide Emissions and Economic Growth, 1870-1998

	Dependent Variable: Log of Per-Capita Emissions			
Independent Variables	(1)	(2)	(3)	(4)
Constant	**-7.528**	-7.23979	**-7.314**	**-7.274**
	1.764	0.982916	0.626	0.972
Per Capita GDP	**0.928**	**0.928**	**0.901**	**0.932**
	0.230	0.116	0.081	0.114
Trend	**0.023**	-0.003	**0.023**	-0.003
	0.005	0.005	0.002	0.005
Break-Constant	0.358			
	2.132			
Break-GDP	-0.043	-0.002		
	0.250	0.008		
Break-Trend	**-0.038**		**-0.039**	
	0.005		0.001	
Rho	**0.540**	**0.987**	**0.543**	**0.987**
	0.075	0.011	0.074	0.011
Adjusted R-squared	0.991	0.986	0.991	0.986
Durbin-Watson	2.144	2.219	2.145	2.219
df-constraints		2	2	1
df-unconstrained parameters		123	123	125
F-statistic		**38.349**	0.069	**77.909**

Table 4. Carbon Dioxide Emissions, Prices and Economic Growth, 1890-1998

Independent Variables		Dependent Variable: Log of Per-Capita Emissions (1)	(2)	(3)	(4)	(5)	(6)
Constant	Estimate	**-7.043**	**-7.058**	**-7.123**	**-6.796**	**-6.824**	**-6.669**
	Error	1.943	0.744	0.979	1.968	0.671	0.951
		Fuel & Power Prices			Coal Prices		
Energy Price		0.062	0.044	0.082	-0.016	0.027	0.006
		0.132	0.049	0.069	0.206	0.047	0.069
Per Capita GDP		**0.899**	**0.909**	**0.942**	**0.902**	**0.893**	**0.923**
		0.233	0.083	0.109	0.234	0.081	0.109
Trend		**0.022**	**0.022**	**-0.010**	**0.022**	**0.022**	**-0.010**
		0.006	0.002	0.004	0.006	0.002	0.004
Break-Constant		-0.060	- -	- -	-0.017	- -	- -
		2.265			2.240		
Break-Price		-0.019	- -	- -	0.045	- -	- -
		0.142			0.211		
Break-GDP		0.017	- -	- -	-0.010	- -	- -
		0.254			0.254		
Break-Trend		**-0.037**	**-0.038**	- -	**-0.037**	**-0.038**	- -
		0.006	0.003		0.006	0.003	
Rho		**0.586**	**0.585**	**0.964**	**0.578**	**0.577**	**0.963**
		0.080	0.078	0.026	0.080	0.079	0.026
Adjusted R-squared		0.972	0.973	0.960	0.972	0.973	0.960
Durbin-Watson		2.139	2.142	2.250	2.139	2.142	2.250
df-constraints	DFTOP		3	1		3	1
df-unconstrained parameters	DFBOT		101	104		101	104
F-statistic	FSTAT		0.023	**55.430**		0.023	57.294

Footnotes

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[1] After analyzing world emissions trends over the 1950-92 period, Schmalensee et al (1998) have suggested that the richer industrialized nations have already reached their "peaks", where carbon emissions per capita stopped growing. Holz-Eakin and Selden (1995) also find that emissions per capita grow more slowly with higher GDP per capita levels, although they do not find peaking within their data set. Many modeling efforts have established the result that carbon emissions do not grow as rapidly in developed nations with higher income levels as they do in many developing countries (e.g., see the results described in Weyant, 1999). A number of factors contribute to this result, including the shift from energy-intensive manufacturing to lighter manufacturing and services, declining urbanization rates, and fewer opportunities to substitute away from traditional biomass fuels (like firewood).

[2] Manne and Richels (1992), Nordhaus (1994), Weyant (2000) and Intergovernmental Panel on Climate Change (2001) discuss the problem and various strategies for mitigating emissions.

[3] Data on energy prices will restrict the horizon to 1890 and beyond for results incorporating the price effect.

[4] The regressions in this paper were estimated with TSP 4.4. The file, adfbrk.tsp, was used for estimating the breakdates.

[5] Gately and Huntington (2002) discuss the experiences of some developing countries that increase their energy use even though economic conditions are stagnant. The factors explaining energy use are similar to those that explain carbon emissions so that their results are relevant to this discussion.

[6] The Gately and Gately-Huntington analyses defined the price decomposition somewhat differently. Each series was defined as the cumulating change in price from the beginning year of the sample until the current year. This specification causes the energy price term to be highly correlated with the time trend variable, which is not appropriate for our purposes, because we want to measure the separate influence of technological progress, or time.

[7] These specifications produced similar results for different samples: 1913-1998 and 1949-98. Results are available upon request.

[8] Country dummy variables in a pooled specification will adjust for differences in the level of carbon emissions for different countries, but will not control for how emissions change over time in one country relative to another.