UNDERSTANDING LONG-TERM ENERGY USE AND CARBON DIOXIDE EMISSIONS IN THE USA

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Abstract

We compile a database of energy uses, energy sources, and carbon dioxide emissions for the USA for the period 1850-2002. We use a model to extrapolate the missing observations on energy use by sector. Overall emission intensity rose between 1850 and 1917, and fell between 1917 and 2002. The leading cause for the rise in emission intensity was the switch from wood to coal, but population growth, economic growth, and electrification contributed as well. After 1917, population growth, economic growth and electrification pushed emissions up further, and there was no net shift from fossil to non-fossil energy sources. From 1850 to 2002, emissions were reduced by technological and behavioural change (particularly in transport, manufacturing and households), structural change in the economy, and a shift from coal to oil and gas. These trends are stronger than electrification, explaining the fall in emissions relative to GDP.

Key words

Carbon dioxide emissions, decomposition, environmental Kuznets curve, USA, history

1. Introduction

Energy is at the core of some of the greatest environmental and geopolitical challenges of our time. Cheap and plentiful energy – deemed necessary for our current standard of living – can at the moment only be supported by oil and coal, which pollutes the air, changes the climate, and, in the case of oil and gas, comes from unstable regions. Besides stimulating less polluting energy sources, it is important to improve the overall energy efficiency of the economy through technological, behavioural and other changes. For that, one needs to understand how and why energy use has changed in the past. This paper contributes to that.

Figure 1 illustrates the history of US energy use in the period 1850-2000. The carbon dioxide (CO_2) intensity of the economy and the CO_2 emissions per person are shown as a function of per capita income. The CO_2 intensity rose steeply until an average annual income of about

$5,000 per person was reached, and has gently declined ever since. The CO_2 emissions per capita rose steeply until some $5,000/capita, more gently till $19,000/capita, and have been roughly stable since then. Explaining this pattern is crucial for projecting the future.

There is a rich literature on energy use and CO_2 emissions. This paper relates to two broad fields. First, there is the environmental Kuznets curve (EKC) literature, pioneered by Grossman and Krueger (1995). In this literature, people statistically relate some indicator for environmental quality or resource use to per capita income. EKCs have been found for a range of substances and issues, but not for energy and carbon dioxide emissions. We deviate from this literature in a three ways. We look at a single country (the USA) rather than a group of countries, but we look at a much longer period (1850-2000). This has been done for Sweden (Lindmark, 2002) and for all countries (Lindmark, 2004), but not in much detail. We mix observations and model results. We look at overall energy use and carbon dioxide emissions, but break these down in their constituents as well.

This paper is therefore also related to the decomposition literature (Ang and Zhang, 2000). That literature breaks down the changes in an indicator, say carbon dioxide emissions, to its constituent changes, say fuel mix, conversion efficiency, structure of production and international trade, behavioural change, and end-use efficiency. We deviate from the typical decomposition paper by looking at a much longer period (accepting a less detailed decomposition in return) and by supplementing observations with model data.

The results of our work can be used to improve the projections of future energy use. It is important to know the size of the challenges ahead. It is also important to know what technological and behavioural changes can reasonably be expected to alter future energy use, and what further changes need to be induced by policy interventions.

In Section 2, we take a closer look at previous papers. In Section 3, we present the data and discuss its basic features. Section 4 presents the model, its calibration, and the first results. Section 5 decomposes the trend in CO_2 emissions into its constituent trends. Section 6 shows a counterfactual history, freezing parts of the economy and the energy sector in 1917, the year emission intensity peaked. Section 7 discusses and concludes.

2. Previous studies

Grossman and Krueger (1995) and Selden and Song (1994) pioneered the study of the Environmental Kuznets Curve (EKC), but did not look at CO_2 emissions. Arrow *et al.* (1995) give an overview of the reasons why one might expect to observe an EKC. Andreoni and Levinson (2001) provide an elegant analytical model of the EKC. See Stern (2004) for a recent literature review. Selden *et al.* (1998) is one of the few EKC paper that decomposes changes in emissions (but not CO_2).

Based on a panel-data analysis of 130 countries for 1951-1986, Holtz-Eakin and Seldon (1995), find an EKC for CO_2 emissions per capita. They did not include a cubic term, however. Shafik (1994) did, for a panel of 149 countries for 1960-1990, and finds no evidence of an EKC. In a graphical analysis, Unruh and Moomaw (1998) find an EKC for CO_2 emissions per capita for 12 developed countries for 1950-1992. More recently, people have used ever more complex statistical methods for roughly the same data, but without finding qualitatively different results (Galeotti and Lanza, 1999; Halkos and Tsionas, 2001; Bertinelli and Strobl, 2004; Martinez-Zarzoso and Bengochea-Morancho, 2004; Bradford *et al.*, 2005; Liu, 2005; Vollebergh *et al.*, 2005; Dijkgraaf and Vollebergh, in press). Note that an EKC for CO_2 emissions *per capita* does not imply an EKC for CO_2 emissions.

The above studies are all on a national basis. Working with data for 1960-1999, Aldy (2005) finds different EKCs for per capita CO_2 emissions for different US states. Kahn (1998) finds an EKC in micro-data for vehicle emissions in California. Based on a sample of five countries for the 1990s, Lenzen *et al.* (2006) find no evidence of an EKC for energy use by households; instead, energy use increases monotonically with income and expenditure. They do find that this relationship is different for different countries.

Rothman (1998) argues that changes in emissions need to be understood in terms of changes in consumption patterns, and that such analysis should include domestic production as well as imports and exports. Kahn (2003) shows that the energy intensity of US imports has converged with the energy intensity of US production, which suggests that the trade effect is small. Nonetheless, Suri and Chapman (1998) find that the inclusion of international trade alters the EKC for per capita energy use in an analysis of 33 countries for 1971-1991.

Kriström and Lundgren (2005) regress CO_2 emissions on per capita income and its square, like most other EKC studies. They restrict the analysis to one country (Sweden) but include data from 1900 to 1999. They find strong evidence for an EKC, with emissions peaking in the early 1970s. Lindmark (2002) finds a similar result for Sweden for the period 1870-1997. Structural changes in the economy are implicitly included, but not explicitly because of data limitations.

Lindmark (2004) uses CO_2 and income data for a large number of countries for the period 1850-2000. He finds clear evidence for an EKC between CO_2 intensity and per capita income, with some countries turning at $5000 (this includes the USA; see Figure 1)[1], some at $10,000 and some at both. His data do not allow him to explore the underlying relationships. Our study does that, but only for the USA. For this, we rely on decomposition.

Lorna Greening (2004; Greening *et al.*, 1997, 1998, 1999, 2001) sets the empirical standard for the index decomposition of trends in CO_2 emissions for OECD countries, including the USA. Her analyses are limited to the period since 1970. Davis *et al.* (2002) decompose US energy use and carbon dioxide emissions for the period 1986-2000. They find that weather may have contributed to the recent acceleration of decarbonisation. Casler and Rose (1998) use *structural* decomposition for the US for 1972-1982; they ascribe most of the observed changes in CO_2 emissions to fuel switching and energy efficiency. The relatively short period in these seven studies is no exception. Indeed, the 124 decomposition studies surveyed by Ang and Zhang (2000; see also the earlier survey in Huntington, 1989) cover the last 40 years when detailed data were available. Golove and Schipper (1998) go back furthest (for the USA), to 1958.

There are a few studies of historical developments of energy. Most focus on a specific subject, such as light (Nordhaus, 1997; Fouquet and Pearson, 2006) or prices (Fouquet and Pearson, 2003). Other studies are more descriptive (Fouquet and Pearson, 1998; Grübler, 1998; Smil, 1994). This paper is comprehensive and analytical.

3. Data

Marland *et al.* (2005; see also Andres *et al.*, 1999) report carbon dioxide emissions from fossil fuel use (for coal, oil and gas), gas flaring and cement production for 1800-2002. Note that the emission data are constructed from fossil fuel production data for the earlier years (Etemad *et al.*, 1991), and only corrected for international trade as of 1850 (based on Schurr *et al.*, 1960).

[1] Schurr *et al.* (1960) and Schurr (1984) also noted this. Indeed, Sun (1999) criticizes EKC studies of CO_2 for overlooking what had been long known in energy economics. De Bruyn *et al.* (1998) and Foccaci (2003) find declining CO_2 intensity for selected OECD countries for the last 40 years, and some evidence for an EKC.

See Figure 2. Note that we only consider emissions from fossil fuel consumption; cement production (not energy-related) and gas flaring (production, not consumption) are omitted, as are emissions from changes in land use. Coal was the dominant source until 1945. In 2002, 42% of CO_2 emissions was from oil, 36% from coal, and 22% from gas.

Figure 2 also has our alternative estimates of carbon dioxide emissions. For this, we used the average emission coefficients for the last fifty years (1953-2002) of Marland *et al.* (2005). In this period, their emission coefficients vary slightly because of statistical errors. Before 1950, however, variations are larger and trends appear; before 1900, variations are substantial. Our estimates of carbon dioxide emissions are not necessarily better than those of Marland *et al.* (2005) – or worse, for that matter – but they are fully consistent with our energy data.

A number of sources are available for primary energy consumption by source. EIA (2005) is recent, up-to-date and high quality, but extends back to 1949 only. Liesner (1987) goes back further, but is not comprehensive, while Schurr *et al.* (1960) goes back further still and is reasonably comprehensive.[2] See Table 1. Schurr *et al.* (1960) and EIA (2005) overlap for the period 1949-1955. Differences are small, but there nonetheless. We therefore converted the data of Schurr *et al.* (1960) to index numbers and used those to extrapolate the EIA (2005) data for 1850-1949. Figure 3 shows the results. Primary energy consumption increased from 3 Quad BTU in 1850 to 100 Quad BTU in 2004. Wood dominated in 1850, coal in 1910; oil and gas reached their maximum share in 1970 but are still the most important energy sources today. In 2002, 39% of primary consumption was oil, 24% gas, 22% coal, 8% nuclear, 3% hydro, leaving 3% for all other sources of energy.

IEA (2005) reports final energy consumption by sector for 1960-2002. Note that this is direct consumption only; for example, the energy used for producing fertiliser is attributed to manufacturing rather than to agriculture (e.g., Cleveland, 1995). IEA (2005) also has "unspecified" consumption; there are simultaneous shifts in "unspecified" and "agriculture" and in "unspecified" and "residential", so we ascribed most of "unspecified" to these two sectors. Final energy consumption can also be constructed from EIA (2005) data, but agriculture is grouped with manufacturing. We are not aware of earlier data for final energy consumption by sector. Figure 4 shows the results. Final energy consumption rose by 92% between 1960 and 2002. Energy consumption by the transport sector rose fastest (172%), followed by services (156%). Residential energy consumption rose by 61%, and manufacturing by 38%. Agricultural energy consumption fell by 33%. In 2002, 42% of all energy consumption was in transport, 26% in manufacturing, 18% in residential, 13% in services, and 1% in agriculture. In 1960, primary energy consumption was 46% larger than final energy consumption; in 2002, this had risen to 66% with growing electrification. See Figure 7.

The sectoral composition of gross domestic product can be found in Mitchell (1998) from 1869 onwards. We add "industry" and "construction", and "transport and communication" and "commerce". WRI (2005) reports the sectoral composition for 1971-2001. For the overlapping years, the two data-sets agree. We use WRI (2005) as the data are reported annually. We assume that there was no sectoral change between 1850 and 1869, and that 2002 equals 2001. See Figure 5. In 1869, 58% of the US economy was in services, 24% in agriculture, and 21% in manufacturing. In 2001, services had risen to 75%, and manufacturing to 23%, while agriculture had fallen to 2%.

Population and GDP are taken from Maddison (2003). Between 1850 and 2002, the US population rose 12-fold, from 23 million to 288 million. GDP rose 217-fold, from $43 billion

[2] Schurr *et al.* (1960) omit wind, water and animal power.

to $9.2 trillion. Consequently, GDP per capita went up 18-fold, from $1,800 to $32,000 per year.

4. The model

The main purpose of this paper is to explain the trends in energy use and carbon dioxide emissions. The growth of the population and the economy only partly explain the increase in energy use and carbon dioxide emissions. Energy supply, the structure of the economy, technology and behaviour all changed. We have data on the first two components, but unfortunately cannot separated technological from behavioural change.

For the period 1960-2002, we have data on both energy consumption by sector, and the share of this sector in the economy. This defines the sectoral energy intensity, trends in which capture technological and behavioural change. In order to extrapolate this to the period 1850-1960, we first constructed a statistical model of the sectoral energy intensities. For agriculture, manufacturing and services, the energy intensity follows an exponential trend, attenuated by price changes (from Schurr *et al.*, 1960, and EIA, 2005). For transport and residential, energy intensity follows price and per capita consumption expenditures (from Liesner, 1987, and BEA, 2005). Parameters were fitted by minimum least squares,[3] where the observations are sectoral final energy consumption for 1960-2002, and primary energy consumption for 1850-2002. The ratio of primary and final energy consumption follows an exponential trend, the parameters of which are fitted in the same procedure.

This model performs rather poorly. This may be because 40 years of data is too few from a 150 year period. The model may also be too crude. For instance, the manufacturing sector has changed in many ways, the results of which cannot be captured by a single exponential trend.

Therefore, we constructed a second model, in which the energy intensities vary from year to year, but cannot deviate more than 2%[4] from the energy intensity of the previous year. The wedge between primary and final energy use still grows exponentially with time. The results for this second model are shown in Figures 4, 7 and 8.

When there are observations (whole period, primary energy; 1960-2002, final energy), confidence intervals are based on the model error. For 1850-1959, for final energy, model errors follow from the model error of primary energy attributed to the sectors in proportion to their share in primary energy. For final energy, the number of degrees of freedom is equal to the number of observations minus one plus the number of times the energy intensities changes the maximum of 2%; for primary energy, two additional parameters were estimated for the wedge between primary and final energy.

Figure 4 shows final energy consumption per sector. The model adequately reproduces total energy consumption, the sectoral composition, and some the variability. The fit is not perfect however.

Figure 7 shows observed and modelled energy intensities. Except for agriculture, the model is very reasonable for 1960-2002. Before that, an interesting pattern emerges. The energy intensity of transport and services is roughly flat. Agricultural energy intensity gently slopes down. The energy intensity of manufacturing increases until 1920, decreases until 1945, increases until 1965, and then decreases again. Residential energy use per capita falls most

[3] The model is non-linear. We used GAMS (REF) to minimize the sum of squared residuals. Most of the variables have exponential trends. We therefore minimized the sum of squared residual relative to the observations. If not, the estimation would secure a good fit in recent years only.
[4] Experiments show that 1% is too restrictive to guarantee a good model fit, while 3% has a fit that is too good, and wild behaviour by parameters.

rapidly, but at a decelerating pace. Between 1900 and 1910 and between 1960 and 1970, however, residential energy use per capita increases rapidly. Changes in residential energy use dominate the trend in the overall energy intensity of the economy. The early dominance of residential energy use is consistent with the early dominance of fuel wood.

Figure 8 shows final and primary energy use. The model reproduces the observations fairly well, and the extrapolation of the wedge between primary and final energy use is consistent with the observations for 1960-2002. It is also consistent with Schurr *et al.* (1990), who report that electricity was hardly used in the USA before 1900.

5. Decomposition

Having build the database and filled in the gaps with the model described above, we now turn to decomposing the "observed" trends. We split the period 1850-2002 into three periods: 1850-1917, 1917-1960, and 1960-2002. The energy intensity of the US economy reached its maximum in 1917. Sectoral energy consumption data begin in 1960.

We split the change in carbon dioxide emissions into six components, viz. changes in:

1. Population;
2. Per capita income;
3. Energy intensity;
4. Conversion efficiency (the ratio of primary and final energy consumption);
5. Fossil / non-fossil mix (the ratio of fossil and total primary energy use); and
6. Fossil fuel mix (the ratio of carbon dioxide emission and fossil primary energy use).

These are all single indicators, except for the energy intensity. We decompose changes in the energy intensity into changes in the structure of the economy and changes in the sectoral energy intensity due to technological and behavioural change. We use the Törnqvist index (or multiplicative, arithmetic mean Divisia index; see Hoekstra and Van der Bergh, 2003) for this. If I_t denotes the energy intensity at time t, then

(1) $$I_t = \sum_i I_{t,i} S_{t,i}$$

where S_i is the share of sector i in total production. The Törnqvist decomposition has that

(2a) $$\frac{I_t}{I_0} = D_S D_I D_R$$

where

(2b) $$D_S = \exp\left(\sum_i \omega_i \ln \frac{S_{i,t}}{S_{i,0}}\right)$$

(2c) $$D_I = \exp\left(\sum_i \omega_i \ln \frac{I_{i,t}}{I_{i,0}}\right)$$

(2d) $$\omega_i = 0.5\left(\frac{E_{i,0}}{E_0} + \frac{E_{i,t}}{E_t}\right)$$

and E denotes energy use. D_R is a rest term, that equals the interaction between D_I and D_S; the interaction effect is small in the application below. We refer to D_S as the structural effect, and to D_I as the effect of technology and behaviour.

Note that we have only energy consumption for transport and residential, but no date on their share in the economy; energy intensity cannot be defined. Therefore, we ascribe all changes in energy consumption in these sectors to "technology and behaviour". As a result, "structure" is means "structure of production (excl. transport)".

Table 2 shows the results. Between 1850 and 1917, CO_2 emissions increased 82 fold, or 6.7% per year. The largest contributor with a factor 12.5 is the switch from fuelwood to coal. This is somewhat dampened (a factor 0.95) by the introduction of oil and gas, which have lower emission coefficients. Population (4.4), income (2.9) and electrification (1.3) are smaller contributors. An increase in energy efficiency reduced emissions growth by a factor 0.4. Table 3 further details the changes in energy efficiency. In production, efficiency decreased by a factor 1.2, most of which was structural change (from agriculture to manufacturing). Transport efficiency fell by a factor 1.3, or 0.4% per year. The increase in energy efficiency is entirely due to the residential sector, which improved at 2.3% per year. The share of residential in final energy use fell from 80% in 1850 to 40% in 1917.

Between 1917 and 1960, the growth in CO_2 emissions was much slower: 1.3% per year. Population growth decelerated, but economic growth accelerated. The biggest contribution to the deceleration, however, was that most traditional fuels had already been replaced by fossil fuels; wood-to-coal still contributed a factor 1.1 to emissions growth over the period. Electrification contributed a similar factor; electrification was slower between 1917 and 1960 than between 1850 and 1917. The replacement of coal by oil and gas reduced emissions by a factor 0.75, which is considerably faster than in the previous period. Increases in energy efficiency again did most to slow the growth of emissions; at 1.4% per year, this was faster than in the previous period (1.3%). In this period, production and transport became more energy efficient, not less as in the previous period. Production efficiency improved by a factor 0.77, largely because of technological change. Transport efficiency improved by 1.2% per year, while improvements in residential energy use accelerated to 2.9%.

Between 1960 and 2002, the growth in CO_2 emissions accelerated again to 1.7% per year. Population growth decelerated further (a factor 1.6), but income growth accelerated again (2.8). Electrification gathered pace again (1.1), and power production switched back to coal (1.0). The introduction of nuclear power and, to a lesser extent, renewables reduced the growth in CO_2 emissions by a factor 0.9. Increases in energy efficiency dampened emissions growth by a factor 0.5, which is again faster than in the previous period. Production efficiency increased by 2.1% per year, one third of which was structural change. Transport efficiency increased by 0.9% per year, and residential efficiency by an annual 2.1%. By 2002, residential energy use was only 18% to final energy use, while transport had risen to 42%, up from 8% in 1850.

Figure 9 shows the results of decomposing CO_2 trends on an annual basis. Note that the data were smoothed by the 11-year running mean. The broad features are obviously as described above, but additional details emerge. CO2 emissions fell during the Great Depression, largely because of economic shrink. World War II saw a rapid rise of emissions, again largely because of economic growth. Technological change accelerated in World War II and again after during the 1970s and 1980s (because of the oil crises). There were also periods, notably the 1900s when the economy became less energy efficient.

6. Virtual wedges

Pacala and Socolow (2004) introduce “wedges” to discuss policies to reduce future CO_2 emissions. Each wedge represents a specific set of technologies that reduce or avoid emissions. Emission reducing technologies that would be adopted without climate policy can be dubbed “virtual wedges”. Figure 10 shows the virtual wedges for the period 1917-2002.

We cumulatively decomposed CO2 emission trends, with 1917 as the base year; 1917 was the year in which emission intensity peaked. Over this period, emissions were reduced by changes in the fossil fuel mix, in the structure of the economy, and in technology and behaviour. Figure 10 shows what the emissions would have been, had these parameters stayed at their 1917 values.

In 2002, the USA emitted 5.7 Pg CO_2 from fossil fuel use. With the 1917 mix of coal, oil and gas, this would have been 7.5 Pg CO_2. With the 1917 economic structure on top, this would have been 8.5 Pg CO_2. With 1917 technology and behaviour, this would have been 30.2 Pg CO_2. So, market forces abated 24.5 Pg CO_2. This may be ground for optimism: Substantial emission abatement is possible. This may also be ground for pessimism: Abatement is already very substantial, but needs to be further accelerated.

We split the contribution of technology and behaviour into the five energy sectors, on the basis of their respective emission intensity trends and their share in final energy consumption. Transport contributed most (9.2 Pg CO_2), followed by manufacturing (7.0 Pg CO_2). The contributions of services (2.3 Pg CO_2), residential (2.1 Pg CO_2)[5] and agriculture (1.0 Pg CO_2) were much less.

Figure 10 repeats this exercise with 1954 and 1973 as the base year; 1954 was the year that the share of manufacturing in US production peaked; 1973 saw the first oil crisis. Had 2002 had the 1954 fuel mix, emissions would have been 5.8 Pg CO_2 rather than 5.7 Pg CO_2. Fixing the structure of the economy would have added a further 1.0 Pg CO_2. Frozen technology and behaviour would have added an additional 5.7 Pg CO_2, 2.4 Pg CO_2 in transport, 1.9 Pg CO_2 in manufacturing, 0.7 Pg CO_2 in residential, 0.6 Pg CO_2 in services and 0.1 Pg CO_2 in agriculture.

Freezing the 1973 fuel mix would have reduced 2002 emissions by 0.2 Pg CO_2. A fixed structure of the economy would have added 0.6 Pg CO_2. Frozen technology would have further increased emissions by 4.7 Pg CO_2, 2.0 Pg CO_2 in transport, 1.5 Pg CO_2 in manufacturing, 0.7 Pg CO_2 in residential, 0.5 Pg CO_2 in services and 0.1 Pg CO_2 in agriculture.

Changes in technology and behaviour, particularly in transport and manufacturing, have therefore been the main drivers of changes in the carbon intensity of the US economy since 1917.

7. Discussion and conclusion

In this paper, we compile a database of energy uses, energy sources, and carbon dioxide emissions for the USA for the period 1850-2002. We use a model to extrapolate the missing observations on energy use by sector. Overall emission intensity rose between 1850 and 1917, and fell between 1917 and 2002. The leading cause for the rise in emission intensity was the switch from wood to coal, but population growth, economic growth, and electrification contributed as well. After 1917, population growth, economic growth and electrification

[5] This assumes that final energy use per capita in 2002 were as it was in 1917. One can interpret this as “frozen technology”, that is, poorly insulated houses with terribly inefficient heating. One can also interpret this as if energy demand has an income elasticity of one, that is, modern houses but much larger and filled with appliances that are always on.

pushed emissions up further, and there was no net shift from fossil to non-fossil energy sources. From 1850 to 2002, emissions were reduced by technological and behavioural change (particularly in transport, manufacturing and households), structural change in the economy, and a shift from coal to oil and gas. These trends are stronger than electrification, explaining the fall in emissions relative to GDP.

This paper goes beyond the environmental Kuznets curve literature in that it looks at a longer time-period, and in that it decomposes the EKC into its constituent trends. The decline in CO2 emission intensity since 1917 is driven by market forces in the energy sector, by the development of the economy, and by technological and behavioural change. Opening the black box of the EKC allows for improved policy advice and better future projections.

This paper goes beyond the decomposition literature in that it looks at a longer time period, partially by virtue of complementing observations with model data. This allows us to put recent trends in an historic context.

Future research should improve on the work presented here. Crucially, earlier data on energy use by sector are needed – if not a complete time series, then some data points to constrain the model before 1960. Early accounts of US energy use including wind, water and animal power would be welcome. Also, energy use in transport and households need to be split into activity levels (e.g., miles travelled) and energy intensities. These three points are the major shortcomings of this study. Replication of the current study for other countries would shed light on the question which of the features found here are specific to the USA, and which are universal.

For climate policy, the following results emerge. Firstly, the USA started its transition to a more energy- and carbon-extensive economy at around $5000 per person per year. Much of South America and Southeast Asia is already past that level, and China is getting there rapidly. These countries may mimic the US trajectory or, with the help of modern technologies, decarbonise faster. Secondly, on a pessimistic note, trends in the US have been fairly constant over the period 1917-2002. This suggests that there a deeper cause, which may be hard to beat should the USA decide to reduce its carbon dioxide emissions more rapidly. Thirdly, on an optimistic note, the US has been through two major energy transitions in the last 150 years without economic crises. This suggests that the USA can repeat this trick in the current century.

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References

Aldy, J.E. (2005), ‘An Environmental Kuznets Curve Analysis of US State Level Carbon Dioxide Emissions’, *Journal of Environment and Development*, **14** (1), 58-72.

Andreoni, J. and A. Levinson (2001), ‘The Simple Analytics of the Environmental Kuznets Curve’, *Journal of Public Economics*, **80**, 269-286.

Andres, R.J., D.J. Fielding, G. Marland, T.A. Boden, N. Kumar and A.T. Kearney (1999), ‘Carbon Dioxide Emissions from Fossil Fuel Use: 1751-1950’, *Tellus*, **51B**, 759-765.

Ang, B.W. and F.Q. Zhang (2000), ‘A Survey of Index Decomposition Analysis in Energy and Environmental Studies’, *Energy*, **25**, 1149-1176.

Arrow, K.J., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C.S. Holling, B.-O. Jansson, S. Levin, K.-G. Mäler, C. Perrings and D. Pimentel (1995), ‘Economic Growth, Carrying Capacity, and the Environment’, *Science*, **268**, 520-521.

BEA (2005), *US Economic Accounts*, Bureau of Economic Analysis, US Department of Commerce, http://www.bea.doc.gov/

Bertinelli, L. and E. Strobl (2004), *The Environmental Kuznets Curve Semi-Parametrically Revisited*, CORE Discussion Paper **2004/55**, Universite Catholique de Louvain.

Bradford, D.F., R.A. Fender, S.H. Shore and M. Fender (2005), ‘The Environmental Kuznets Curve: Exploring a Fresh Specification’, *Contributions to Economic Analysis and Policy*, **4** (1), 5.

Casler, S.D. and A.Z. Rose (1998), ‘Carbon Dioxide Emissions in the US Economy’, *Environmental and Resource Economics*, **11** (3-4), 349-363.

Cleveland, C.J. (1995), ‘The Direct and Indirect Use of Fossil Fuels and Electricity in USA Agriculture, 1910-1990’, *Agriculture, Ecosystems and Environment*, **55**, 111-121.

Davis, W.B., A.H. Sanstad and J.G. Koomey (2002), ‘Contributions of Weather and Fuel Mix to Recent Declines in US Energy and Carbon Intensity’, *Energy Economics*, **25**, 375-396.

De Bruyn, S.M., J.C.J.M. van den Bergh and J.B. Opschoor (1998), ‘Economic Growth and Emissions: Reconsidering the Empirical Basis of Environmental Kuznets Curves’, *Ecological Economics*, **25** (2), 161-175.

Dijkgraaf, E. and H.R.J. Vollebergh (in press), ‘A Test for Parameter Heterogeneity in CO2 Panel EKC Estimations’, *Environmental and Resource Economics*.

EIA (2005), *Historical Data Overview*, Energy Information Agency, US Department of Energy http://www.eia.doe.gov/overview_hd.html

Foccaci, A. (2003), ‘Empirical Evidence in the Analysis of the Environmental and Energy Policies of a Series of Industrialised Nations, During the Period 1960-1997, Using Widely Employed Macroeconomic Indicators’, *Energy Policy*, **31**, 333-352.

Galeotti, M. and A. Lanza (1999), ‘Richer and Cleaner? A Study on Carbon Dioxide Emissions in Developing Countries’, *Energy Policy*, **27**, 565-573.

Golove, W.H. and L.J. Schipper (1998), ‘Long-Term Trends in US Manufacturing Energy Consumption and Carbon Dioxide Emissions’, *Energy*, **21** (7/8), 683-692.

Greening, L.A. (2004), ‘Effects of Human Behaviour on Aggregate Carbon Intensity of Personal Transportation: Comparison of 10 OECD Countries for the Period 1970-1993’, *Energy Economics*, **26** (1), 1-30.

Greening, L.A., W.B. Davis and L. Schipper (1998), ‘Decomposition of Aggregate Carbon Intensity for the Manufacturing Sector: Comparison of Declining Trends from 10 OECD Countries for the Period 1971-1993’, *Energy Economics*, **20** (1), 43-65.

Greening, L.A., W.B. Davis, L. Schipper and M. Khrushch (1997), ‘Comparison of Six Decomposition Methods: Application to Aggregate Energy Intensity for Manufacturing in 10 OECD Countries’, *Energy Economics*, **19** (3), 375-390.

Greening, L.A., M. Ting and W.B. Davis (1999), ‘Decomposition of Aggregate Carbon Intensity for Freight: Trends from 10 OECD Countries for the Period 1971-1993’, *Energy Economics*, **21** (4), 331-361.

Greening, L.A., M. Ting and T.J. Krackler (2001), ‘Effects of Changes in Residential End-Uses on Aggregate Carbon Intensity: Comparison of 10 OECD Countries for the Period 1970 through 1993’, *Energy Economics*, **23** (2), 153-178.

Grossman, G.M. and A.B. Krueger (1995), ‘Economic Growth and the Environment’, *Quarterly Journal of Economics*, **60** (2), 353-375.

Grübler, A. (1998), *Technology and Global Change*, Cambridge University Press, Cambridge.

Halkos, G.E. and E.G. Tsionas (2001), ‘Environmental Kuznets Curves: Bayesian Evidence from Switching Regime Models’, Energy Economics, **23**, 191-210.

Hoekstra, R. and J.C.J.M. van der Bergh (2003), ‘Comparing Structural and Index Decomposition Analysis’, *Energy Economics*, **25**, 39-64.

Huntington, H.G. (1989), ‘The Impact of Sectoral Shifts in Industry on US Energy Demands’, *Energy*, **14** (6), 363-372.

Etemad, B., J. Luciani, P. Bairoch and J.-C. Toutain (1991), *World Energy Production 1800-1985*, Librairie Droz, Geneve.

Fouquet, R. and P.J.G. Pearson (1998), ‘A Thousand Years of Energy Use in the United Kingdom’, *Energy Journal*, **19** (4), 1-41.

Fouquet, R. and P.J.G. Pearson (2003), ‘Five Centuries of Energy Prices’, *World Economics*, **4** (2).

Fouquet, R. and P.J.G. Pearson (2006), ‘Seven Centuries of Energy Services: The Price and Use of Light in the United Kingdom (1300-2000)’, *Energy Journal*, 27 (1), PAGES NOT GIVEN

IEA (2005), *World Energy Statistics and Balances*, International Energy Agency http://hermia.sourceoecd.com/vl=6413579/cl=13/nw=1/rpsv/statistic/s35_about.htm?jnlissn=16834240

Kahn, M.E. (1998), ‘A Household Level Environmental Kuznets Curve’, *Economics Letters*, **59**, 269-273.

Kahn, M.E. (2003), ‘The Geography of US Pollution Intensive Trade: Evidence from 1958 to 1994’, *Regional Science and Urban Economics*, **33**, 383-400.

Kriström, B. and T. Lundgren (2005), ‘Swedish CO2 Emissions 1900-2100 – An Exploratory Note’, *Energy Policy*, **33**, 1223-1230.

Lenzen, M., M. Wier, C. Cohen, H. Hayami, S. Pachauri and R. Schaeffer (2006), ‘A Comparative Multivariate Analysis of Household Energy Requirements in Australia, Brazil, Denmark, India and Japan’, *Energy*, **31**, 181-207.

Liesner, T. (1989), *One Hundred Years of Economic Statistics – A New Edition of* Economic Statistics 1900-1983 *Revised and Expanded to 1987*, Facts on File, New York.

Lindmark, M. (2002), ‘An EKC Pattern in Historical Perspective: Carbon Dioxide Emissions, Technology, Fuel Prices and Growth in Sweden, 1870-1997’, *Ecological Economics*, **42**, 333-347.

Lindmark, M. (2004), ‘Patterns of Historical CO_2 Intensity Transitions among High and Low Income Countries’, *Explorations in Economic History*, **41**, 426-447.

Liu, X. (2005), ‘Explaining the Relationship between CO_2 Emissions and National Income – The Role of Energy Consumption’, *Economics Letters*, **87**, 325-328.

Maddison, A. (2003), *The World Economy: Historical Statistics*, OECD, Paris.

Marland, G., T.A. Boden and R.J. Andres (2005), 'Global, Regional and National CO2 Emissions' in *Trends: A Compendium of Data on Global Change*, Oak Ridge National Laboratory, Oak Ridge. http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm

Martinez-Zarzoso, I. and A. Bengochea-Morancho (2004), 'Pooled Mean Group Estimation of an Environmental Kuznets Curve for CO_2', *Economics Letters*, **82**, 121-126.

Mitchell, B.R. (1998), *International Historical Statistics: The Americas 1750-1993*, 4th Edition, Stockton Press, New York.

Nordhaus, W.D. (1997), 'Do Real Output and Real Wage Measures Capture Reality? The History of Light Suggests Not", in R.J. Gordon and T.F. Bresnahan (eds.), *The Economics of New Goods*, University of Chicago Press for National Bureau of Economic Research, 29-66.

Pacala, S.W. and R.H. Socolow (2004), 'Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technology', *Science*, **305** (5685), 968-972.

Rothman, D.S. (1998), 'Environmental Kuznets Curves – Real Progress or Passing the Buck? A Case for Consumption-Based Approaches', *Ecological Economics*, **25**, 177-194.

Schurr, S.H. (1984), Energy Use, Technological Change, and Productive Energy – An Economic-Historical Interpretation', *Annual Review of Energy*, **9**, 409-425.

Schurr, S.H., C.C. Burwell, W.D. Devine Jr. and S. Sonenblum (1990), *Electricity in the American Economy – Agent of Technological Progress*, Electric Power Research Institute / Greenwood Press, New York.

Schurr, S.H., B.C. Netschert, V.F. Eliasberg, J. Lerner and H.H. Landsberg (1960), *Energy in the American Economy 1850-1975 – An Economic Study of its History and Prospects*, Resources for the Future / Johns Hopkins Press, Baltimore.

Selden, T.M., A.S. Forrest and J.E. Lockhart (1998), 'Analysing the Reduction in US Air Pollution Emissions: 1970-1990', *Land Economics*, **75** (1), 1-21.

Selden, T.M. and D. Song (1994), 'Environmental Quality and Development – Is There a Kuznets Curve for Air Pollution Emissions?', *Journal of Environmental Economics and Management*, **27**, 147-162.

Shafik, N. (1994), 'Economic Development and Environmental Quality – An Econometric Analysis', *Oxford Economic Papers*, **46**, 757-773.

Smil, V. (1994), *Energy in World History*, Westview Press, Boulder.

Suri, V. and D. Chapman (1998), 'Economic Growth, Trade and Energy: Implications for the Environmental Kuznets Curve', *Ecological Economics*, **25** (2), 195-208.

Stern, D.I. (2004), 'The Rise and Fall of the Environmental Kuznets Curve', *World Economics*, **32** (8), 1419-1439.

Sun, J.W. (1999), 'The Nature of CO_2 Emission Kuznets Curve', *Energy Policy*, **27**, 691-694.

Sun, J.W. (2000), 'Is CO_2 Emission Intensity Comparable?', *Energy Policy*, **28**, 1081-1084.

Unruh, G.C. and W.R. Moomaw (1998), 'An Alternative Analysis of Apparent EKC Transitions', **25**, 221-229.

Vollebergh, H.R.J., E. Dijkgraaf and E. Melenberg (2005), *Environmental Kuznets Curves for CO_2: Heterogeneity versus Homogeneity*, CentER Discussion Paper **2005-25**, University of Tilburg.

WRI (2005), *EarthTrends – The Environmental Information Portal*, World Resource Institute http://earthtrends.wri.org/

Table 1. Data: Coverage and sources.

Variable	Coverage	Period	Source
Energy			
Primary energy consumption	Coal, oil, gas, hydro, wood	1850-1955	Schurr *et al.* (1960)
Primary energy consumption	Coal, oil, gas	1900-1987	Liesner (1989)
Primary energy consumption	Coal, oil, gas, nuclear, hydro, other; Industrial, commercial, transport, residential	1949-2004	EIA (2005)
Primary energy consumption	Coal, oil, gas, nuclear, hydro, other	1960-2002	IEA (2005)
Final energy consumption	Coal, oil, gas, electricity, other; Agriculture, manufacturing, services, transport, residential	1960-2002	IEA (2005)
Population			
Size	-	1850-2003	Maddison (2003)
Economy			
GDP		1850-2002	Maddison (2003)
Structure of GDP	Agriculture, manufacturing, construction, transport and communication, commerce	1869-1993	Mitchell (1998)
Structure of GDP	Agriculture, manufacturing, services	1971-2001	WRI (2005)
Emissions			
Carbon dioxide	Coal, oil, gas, flaring, cement	1800-2002	Marland *et al.* (2005)

Table 2a. Change in carbon dioxide emissions and its constituents.

	1850-1917	1917-1960	1960-2002
Carbon dioxide emissions	82.15	1.76	2.02
Fossil fuel mix	0.95	0.75	1.02
Fossil / non-fossil fuel mix	12.51	1.08	0.92
Conversion efficiency	1.34	1.08	1.13
Energy intensity	0.41	0.53	0.48
Income per capita	2.91	2.16	2.50
Population	4.40	1.74	1.59

Note: Multiplicative decomposition.

Table 2b. Annual rates of change (%) in carbon dioxide emissions and its constituents.

	1850-1917	1917-1960	1960-2002
Carbon dioxide emissions	6.70	1.29	1.65
Fossil fuel mix	-0.08	-0.64	0.04
Fossil / non-fossil fuel mix	3.79	0.18	-0.20
Conversion efficiency	0.43	0.18	0.29
Energy intensity	-1.32	-1.43	-1.69
Income per capita	1.58	1.76	2.15
Population	2.20	1.27	1.09

Note: Additive decomposition: growth rates do not add up because of interaction effects.

Table 3a. Change in energy intensity and its constituents.

	1850-1917		1917-1960		1960-2002	
Energy intensity	0.41		0.53		0.48	
Production	1.18		0.77		0.41	
Structure		0.97		0.96		0.73
Technology and behaviour		1.23		0.79		0.54
Interaction		1.00		1.01		1.04
Transport	1.30		0.60		0.68	
Residential	0.20		0.28		0.40	

Note: Additive decomposition for production/transport/energy using the weights of Table 3c. Multiplicative decomposition of production into “structure” and “technology and behaviour”.

Table 3b. Annual rates of change (%) in energy intensity and its constituents.

	1850-1917		1917-1960		1960-2002	
Energy intensity	-1.33		-1.43		-1.69	
Production	0.25		-0.60		-2.06	
Structure		-0.05		-0.09		-0.72
Technology and behaviour		0.30		-0.53		-1.43
Interaction		0.00		0.02		0.08
Transport	0.39		-1.16		-0.89	
Residential	-2.32		-2.89		-2.09	

Note: Growth rates commensurate with Table 3a.

Table 3c. Sectoral share (%) of final energy consumption.

	1850	1917	1960	2002
Production	11.5	33.5	49.5	40.7
Agriculture	7.3	8.5	2.9	1.0
Manufacturing	2.1	17.6	36.8	26.4
Services	2.0	7.5	9.9	13.2
Transport	8.1	26.1	29.5	41.8
Residential	80.5	40.4	21.0	17.6

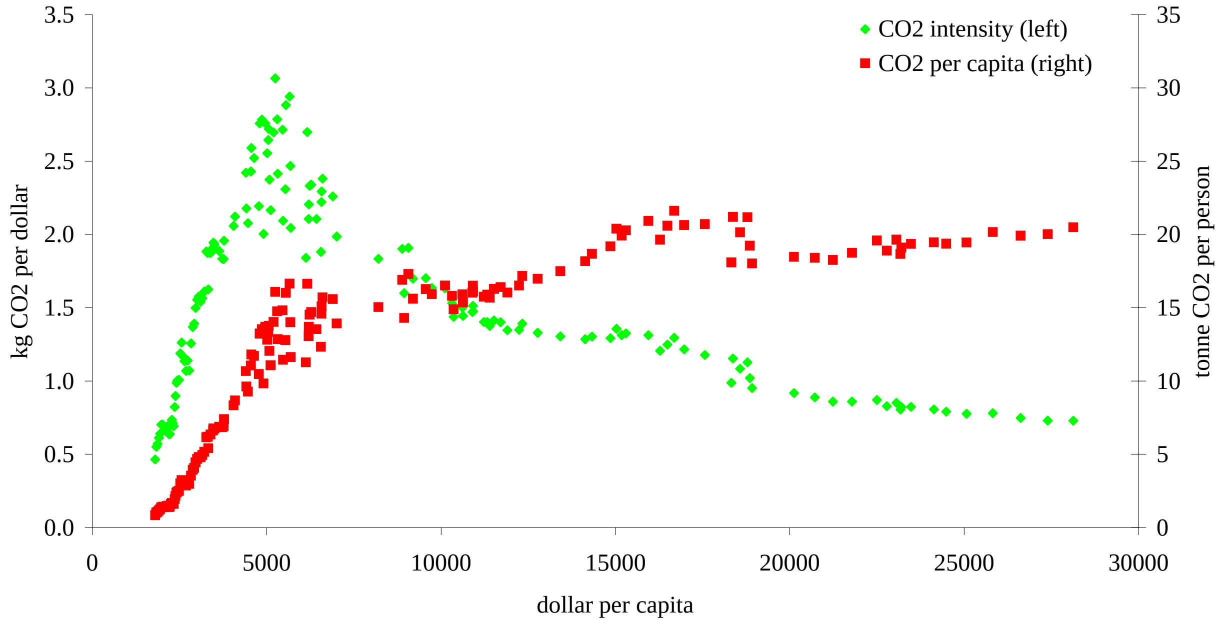


Figure 1. The CO_2 intensity of the economy and the CO2 emissions per capita as a function of per capita income, USA, 1850-2004.

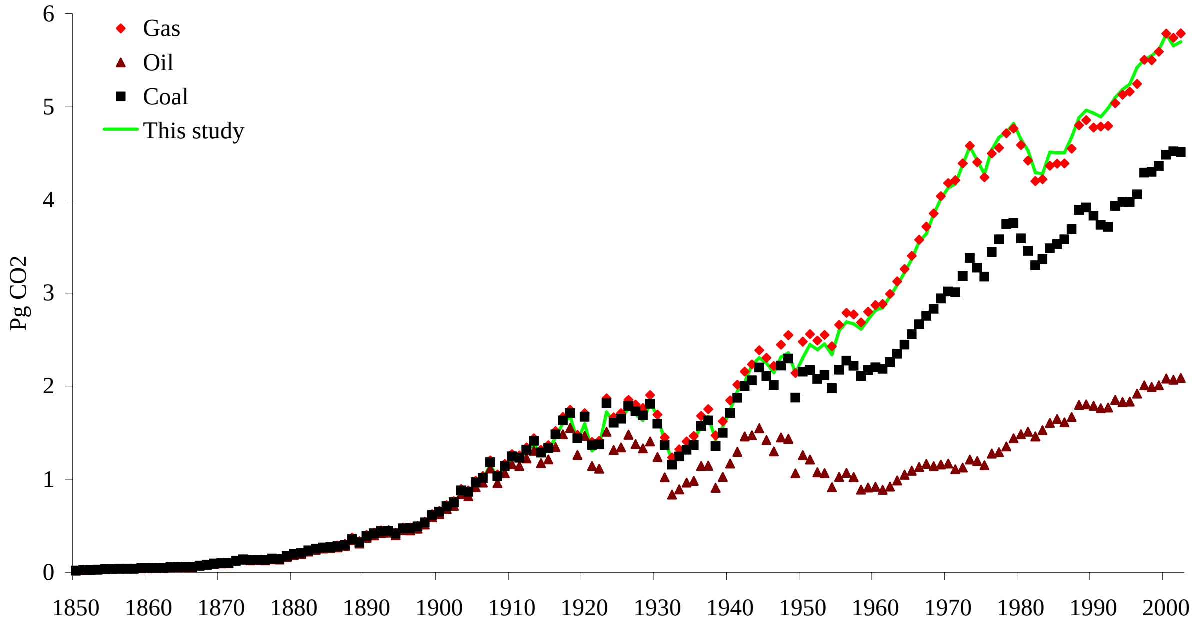


Figure 2. Carbon dioxide emissions by source, as “observed” (symbols); and in total, as modelled (solid line).

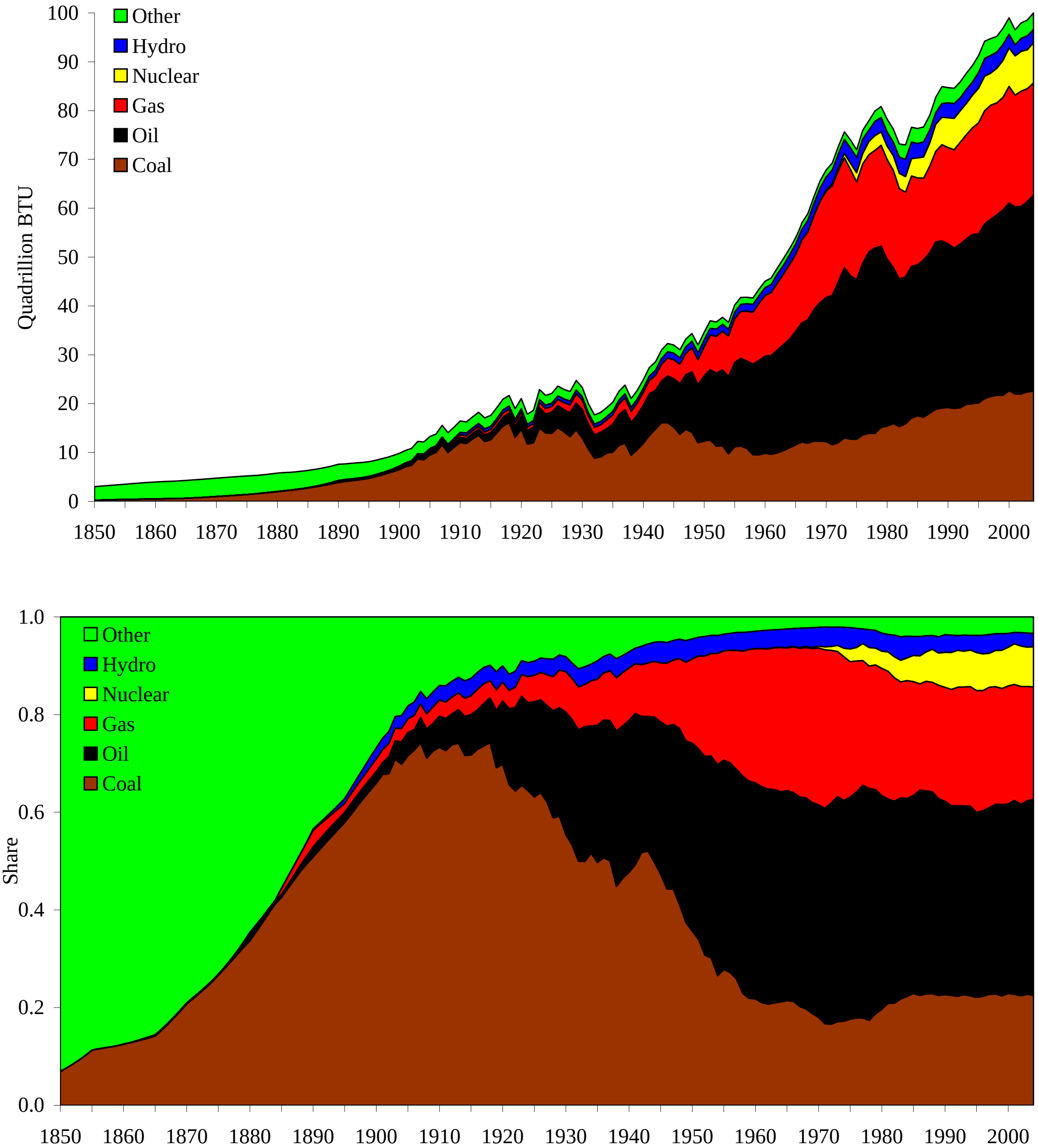
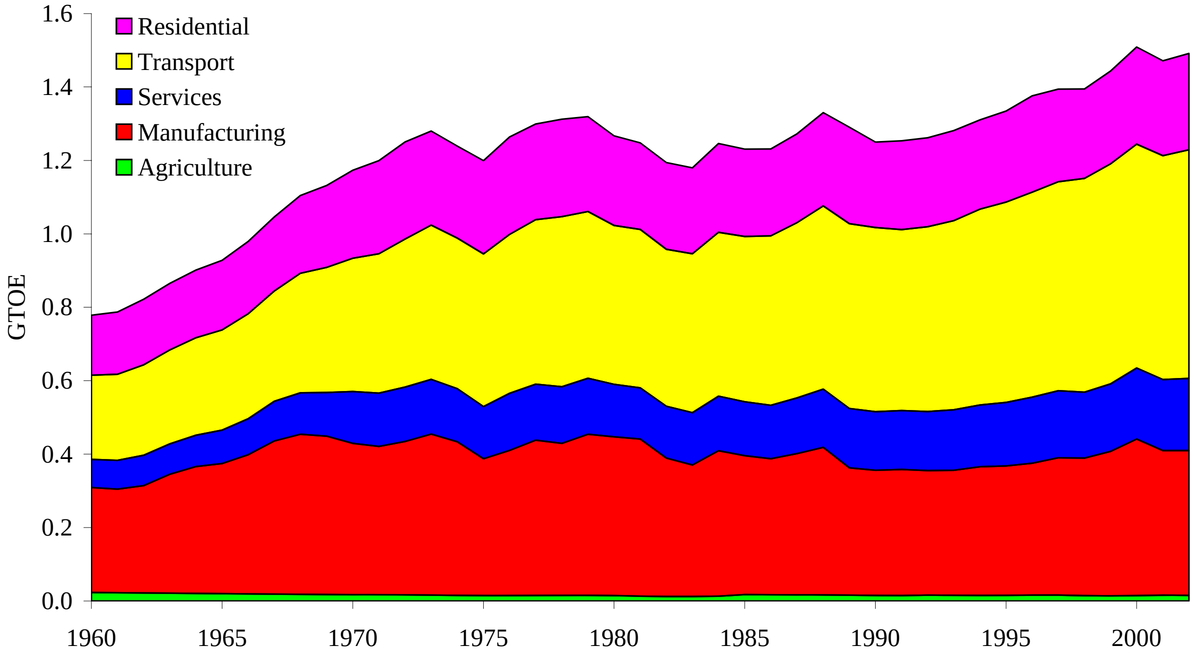


Figure 3. Primary energy consumption by source, USA, 1850-2004; total (top panel) and shares (bottom panel).



Residential
Transport
Services
Manufacturing
Agriculture
GTOE
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1960
1965
1970
1975
1980
1985
1990
1995
2000

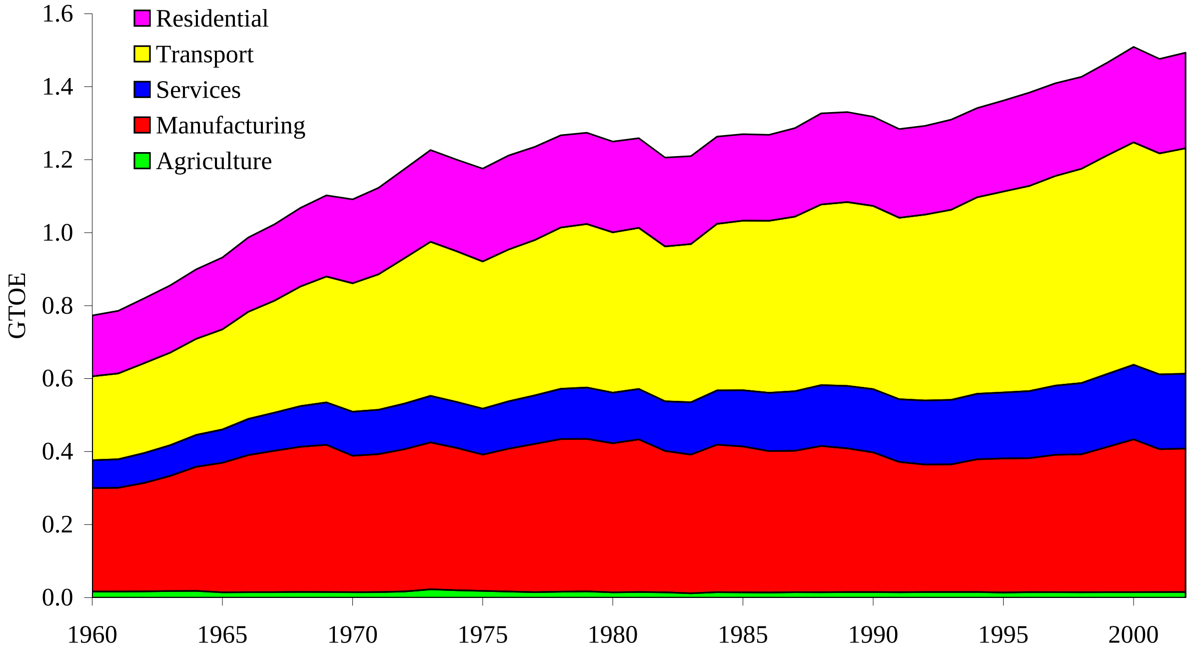


Figure 4a. US final energy use and its composition, as observed (top panel) and as modelled (bottom panel); 1960-2002.

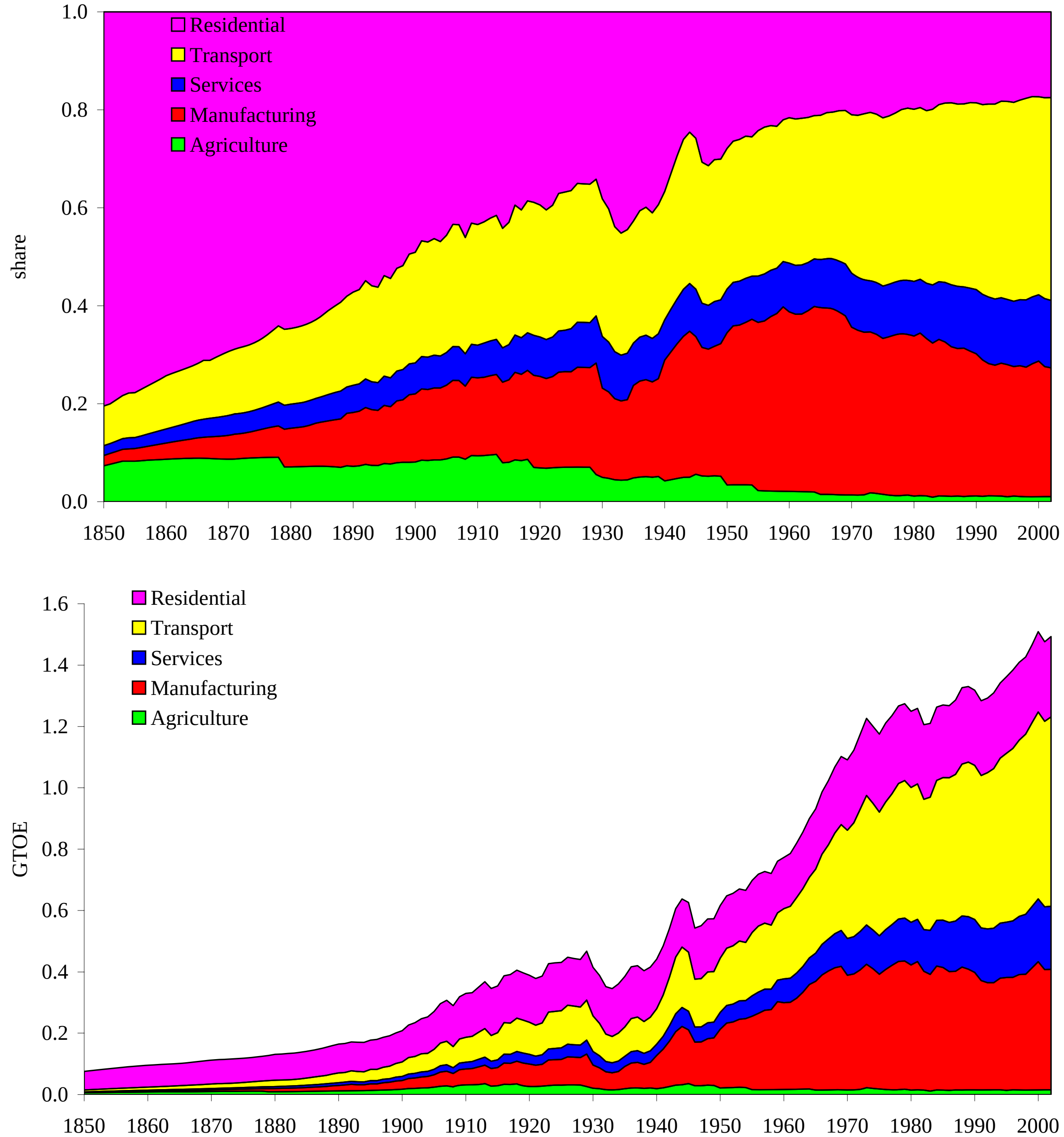


Figure 4b. US final energy use and its composition as modelled totals (top panel) and share (bottom panel); 1850-2002.

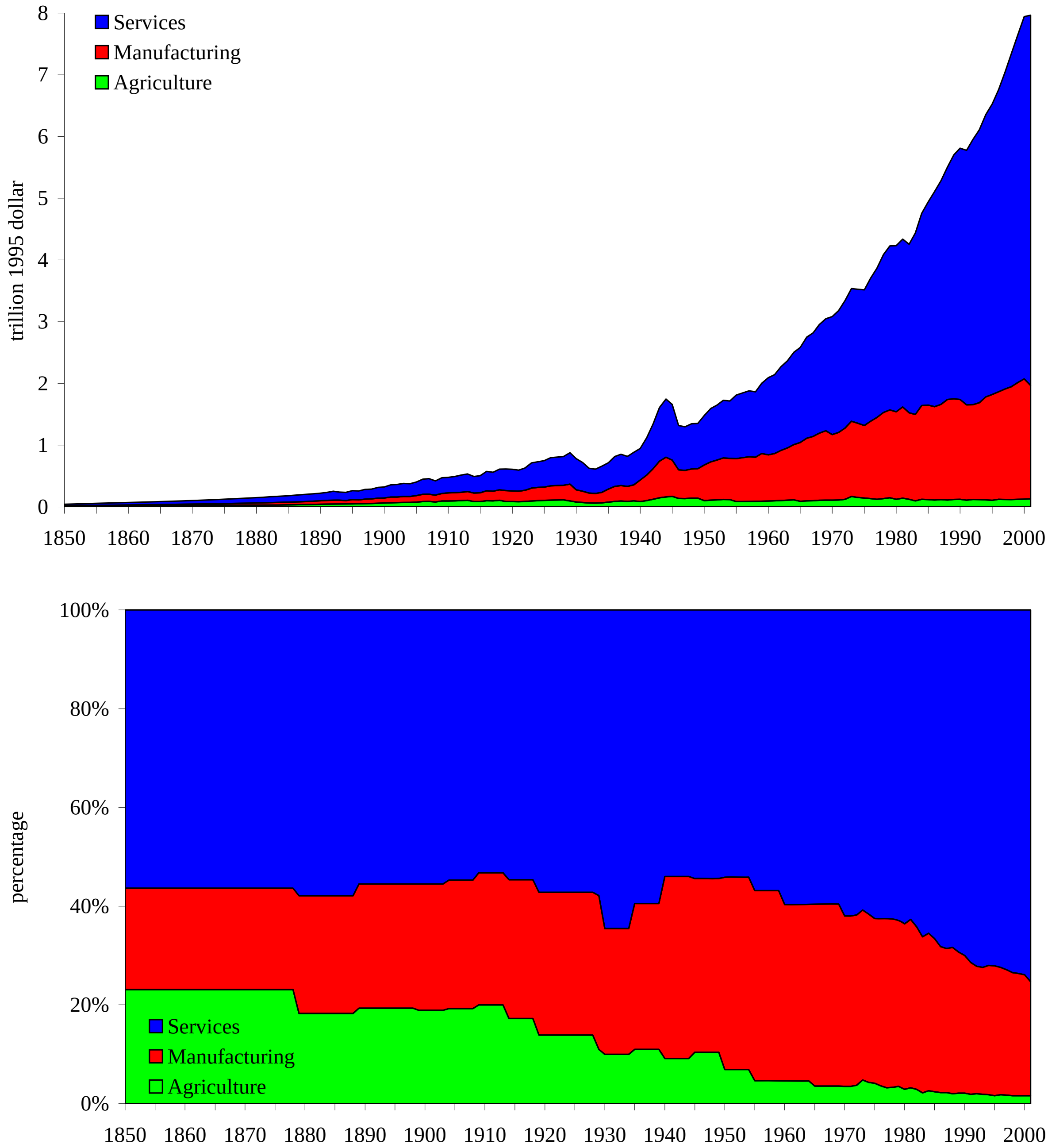


Figure 6. The size and structure of the gross domestic product.

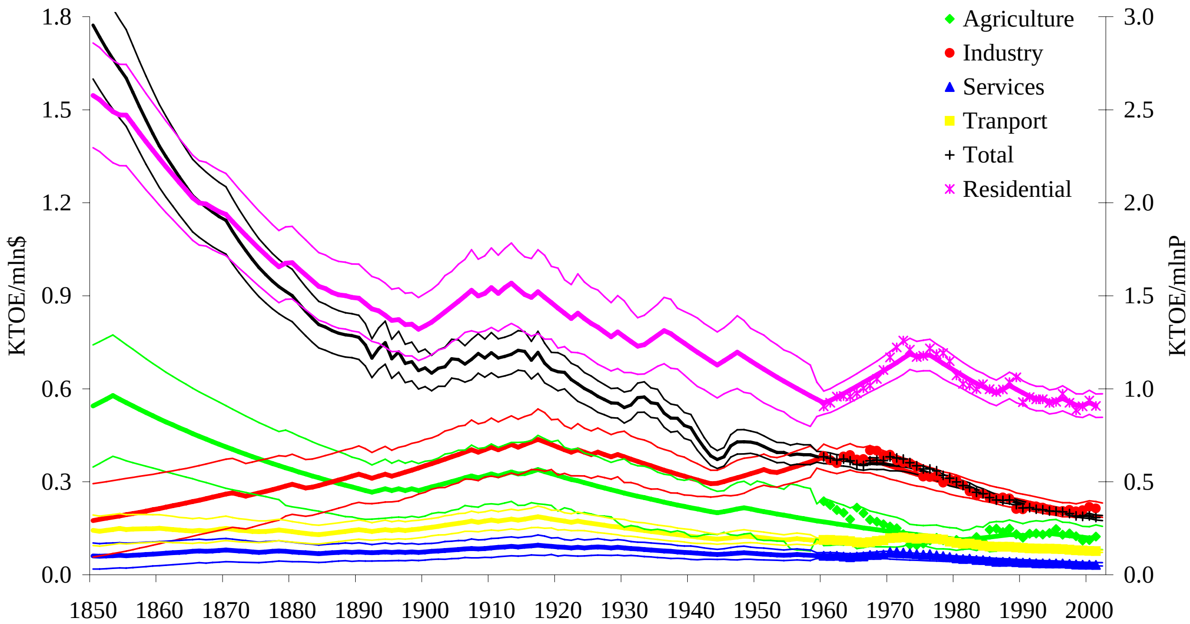


Figure 7. Energy intensity per sector (tonnes of oil equivalent per thousand dollar for all sectors except residential which is in tonnes of oil equivalent per thousand people), as observed (symbols) and as modelled (thick lines; thin lines are the boundaries of the 95% confidence intervals).

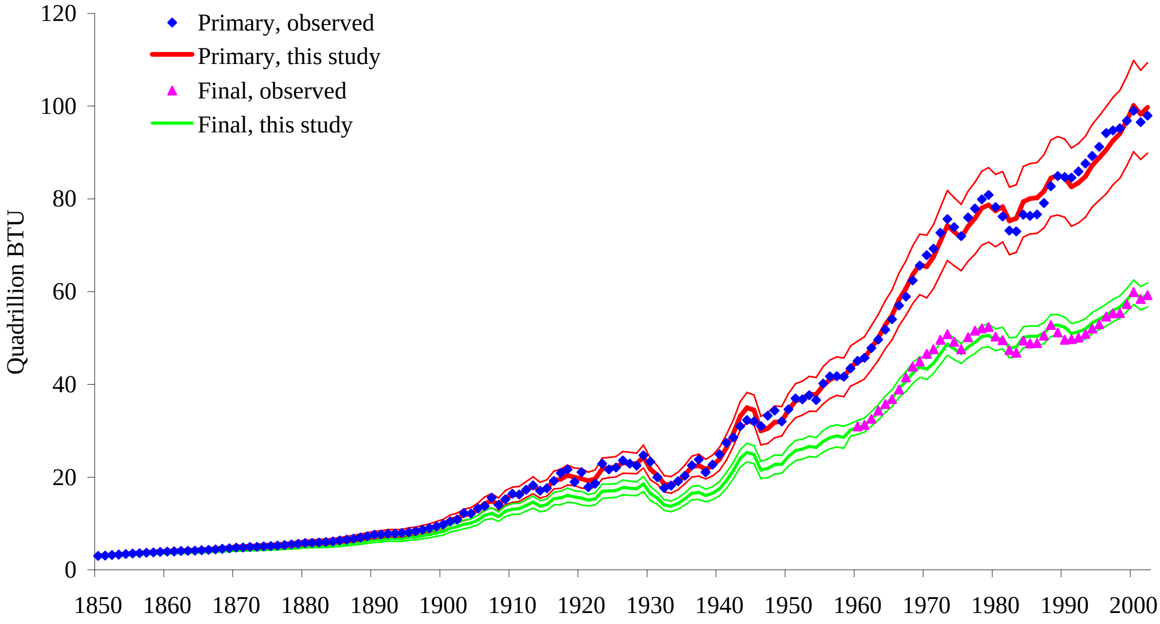


Figure 8. Final and primary energy consumption, as observed (symbols) and as modelled (thick lines; thin lines are the boundaries of the 95% confidence intervals).

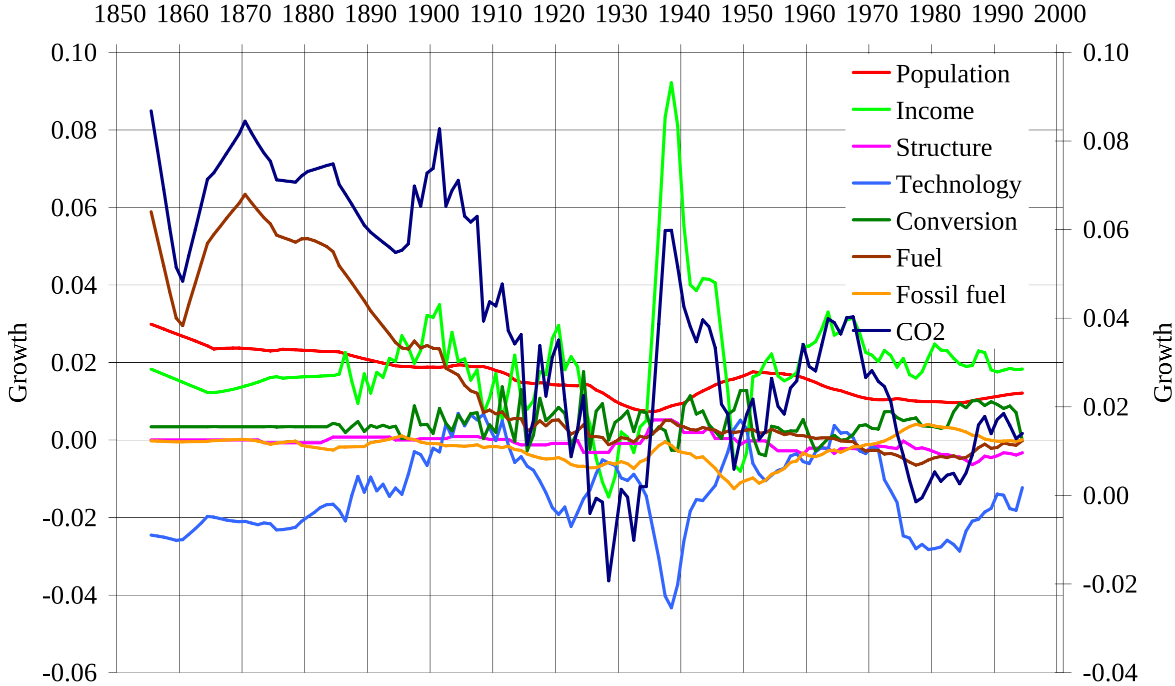
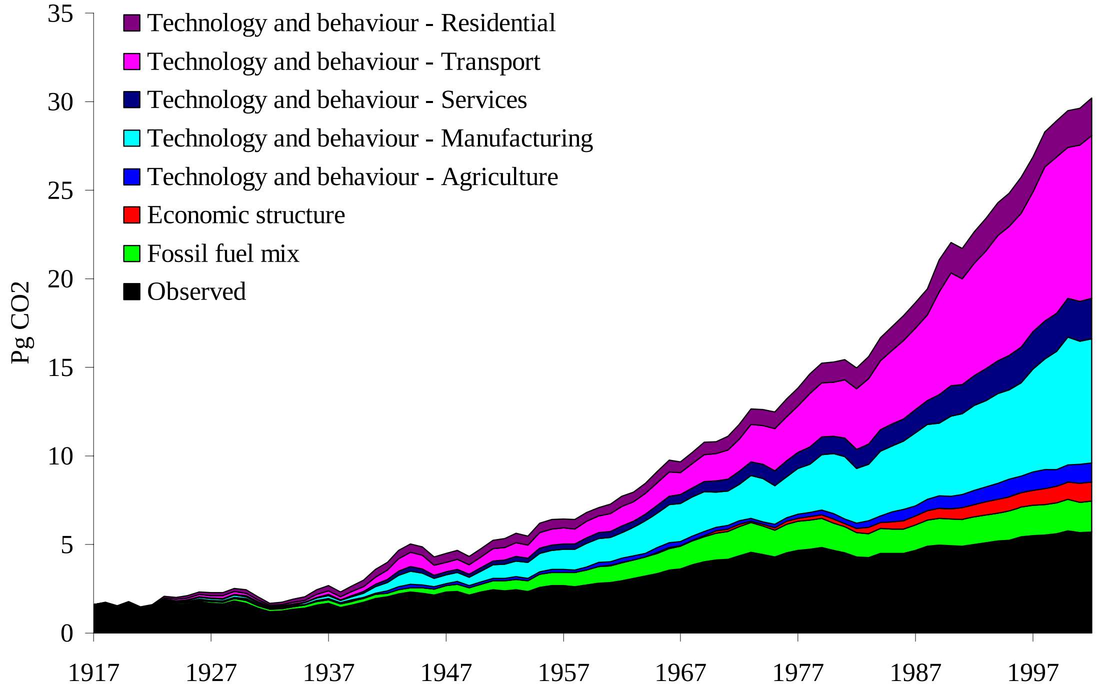
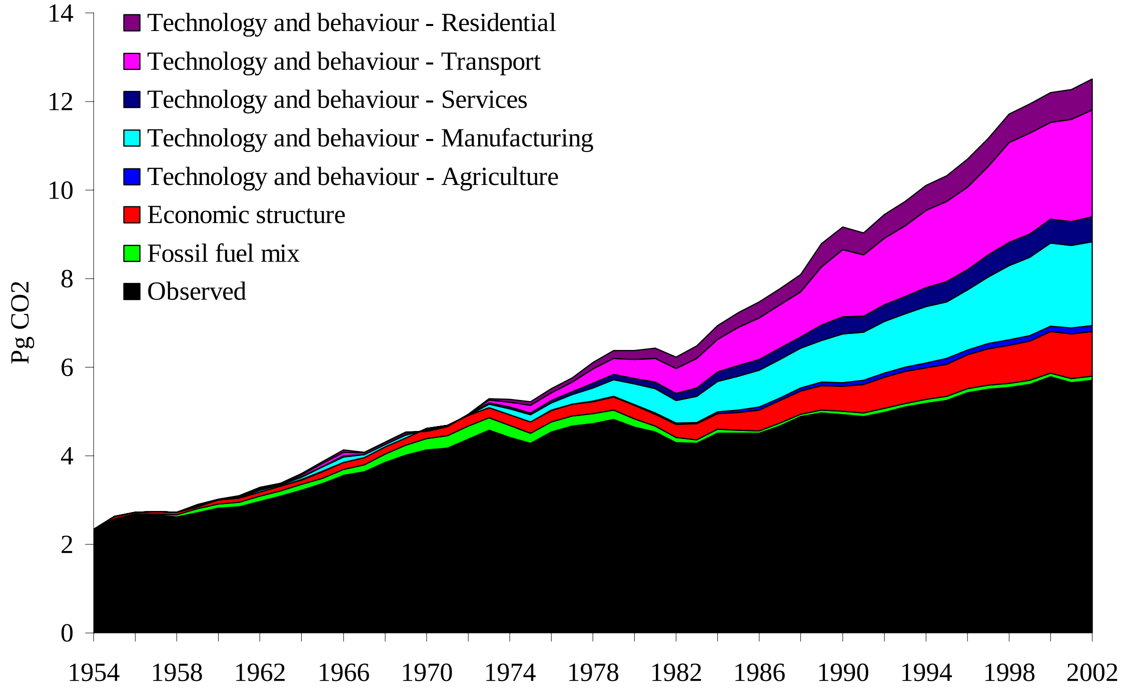


Figure 9. The 11-year running mean of the annual change in CO_2 emissions and its constituents. The decomposition is as in Table 3; all changes in transport and residential are counted as "technology".


Technology and behaviour - Residential
Technology and behaviour - Transport
Technology and behaviour - Services
Technology and behaviour - Manufacturing
Technology and behaviour - Agriculture
Economic structure
Fossil fuel mix
Observed
Pg CO2
35
30
25
20
15
10
5
0
1917
1927
1937
1947
1957
1967
1977
1987
1997


Technology and behaviour - Residential
Technology and behaviour - Transport
Technology and behaviour - Services
Technology and behaviour - Manufacturing
Technology and behaviour - Agriculture
Economic structure
Fossil fuel mix
Observed
Pg CO2
14
12
10
8
6
4
2
0
1954
1958
1962
1966
1970
1974
1978
1982
1986
1990
1994
1998
2002

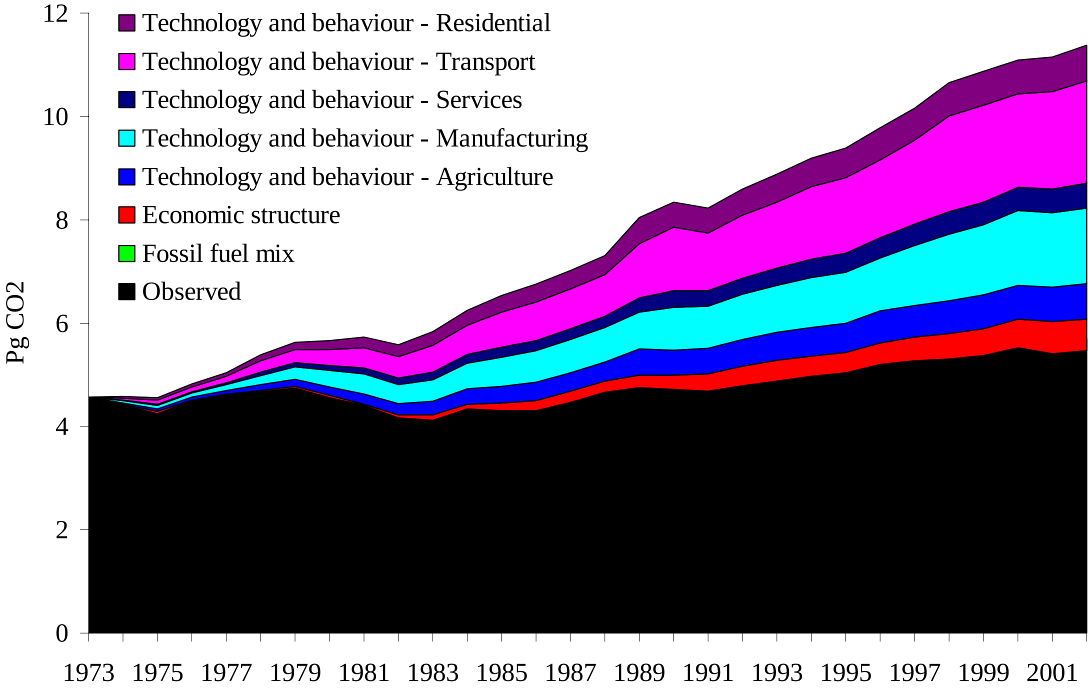


Figure 10. Actual CO_2 emissions and CO_2 emissions had the fossil fuel mix, the structure of the economy, and technology and behaviour been frozen at their 1917 values (top panel), their 1954 values (middle panel) and their 1973 value (bottom panel).

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Tol, R.S.J., S.W. Pacala and R.H. Socolow (2006), *Understanding Long-Term Energy Use and Carbon Dioxide Emissions in the USA*, **FNU-100** (submitted).

Sesabo, J.K, H. Lang and R.S.J. Tol (2006), *Perceived Attitude and Marine Protected Areas (MPAs) establishment: Why households' characteristics matters in Coastal resources conservation initiatives in Tanzania*, **FNU-99** (submitted).

Tol, R.S.J. (2006), *The Polluter Pays Principle and Cost-Benefit Analysis of Climate Change: An Application of* FUND, **FNU-98** (submitted)

Tol, R.S.J. and G.W. Yohe (2006), *The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test,* **FNU-97** (submitted, *Global Environmental Change*)

Berrittella, M., K. Rehdanz, R.Roson and R.S.J. Tol (2005), *The Economic Impact of Water Pricing: A Computable General Equilibrium Analysis*, **FNU-96** (submitted)

Sesabo, J.K. and R. S. J. Tol (2005), *Technical Efficiency and Small-scale Fishing Households in Tanzanian coastal Villages: An Empirical Analysis*, **FNU-95** (submitted)

Lau, M.A. (2005), *Adaptation to Sea-level Rise in the People's Republic of China – Assessing the Institutional Dimension of Alternative Organisational Frameworks*, **FNU-94** (submitted)

Berrittella, M., A.Y. Hoekstra, K. Rehdanz, R.Roson and R.S.J. Tol (2005), *The Economic Impact of Restricted Water Supply: A Computable General Equilibrium Analysis*, **FNU-93** (submitted)

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Ceronsky, M., D. Anthoff, C. Hepburn and R.S.J. Tol (2005), *Checking the price tag on catastrophe: The social cost of carbon under non-linear climate response* **FNU-87** (submitted, *Climatic Change*)

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Rehdanz, K. (2005), *Determinants of Residential Space Heating Demand in Germany*, **FNU-66** (submitted, *Energy Economics*)

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Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of* FUND, **FNU-64** (submitted, *Global Environmental Change*)

Röckmann, C., M.A. St.John, U.A. Schneider, F.W. Köster, F.W. and R.S.J. Tol (2006), *Testing the implications of a permanent or seasonal marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions,* **FNU-63-revised** (submitted)

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Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (submitted)

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Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making,* **FNU-56** (forthcoming, Gössling, S. and C.M. Hall (eds.), Tourism and Global Environmental Change. London: Routledge)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (forthcoming, *Climatic Change*)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54** (submitted)

Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50** (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (forthcoming, *Tourism Management*)

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48** (forthcoming, *Mitigation and Adaptation Strategies for Global Change*)

Erdil, Erkan and Yetkiner, I. Hakan (2004), *A Panel Data Approach for Income-Health Causality*, **FNU-47**

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46** (forthcoming, *Energy Journal*)

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND, **FNU-45** (forthcoming, *Climatic Change*)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport*, **FNU-41** (f*Water Resources Research*, **41** (3), W03003)

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*,**FNU-40** (*Coastline Reports*, Issue 1, pp.213-224.)

Rehdanz, K. and Maddison, D. (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (submitted, *Environmental and Resource Economics*)

Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO_2-abatement with socio-economic inertia and induced technological change*, **FNU-37** (submitted, *Energy Journal*)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism*, **FNU-36** (*Climate Research*, **29**, 255-268)

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)

Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach*, **FNU-34** (submitted, *Climate Research*)

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33** (forthcoming, *Environmental Science and Policy*)

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study*, **FNU-31** (*Global Environmental Change*, **15** (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (*ICES Journal of Marine Science*, **63** (4), 611-625)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (*Ocean & Coastal Management*, No. 48 (2005), pp. 115-159.)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series*, Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (*Integrated Assessment*, **6** (1), 75-82)

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)

Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, **FNU-22** (*Desalination*, **163** (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**

Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics*, **52** 111-125)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (*Energy Policy*, **33** (16), 2064-2074).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (forthcoming, *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists*, **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (*Climate Policy*, **4**, 269-287).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (forthcoming, *Climatic Change*).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (forthcoming, *Environment and Development Economics*).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (*Ecological Economics*, **54**, 397-416).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics*, **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).