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Abstract

We consider per-capita carbon dioxide emission trends in 16 early developed countries over the period 1870-2028. Using a multiple-break time series method we find more evidence for very early downturns in per-capita trends than for late downturns, during the oil price shocks of the 1970s. Only for two countries do downturns in trends imply downward sloping stable trends. We also consider trends in emission composition and find little evidence for in-sample peaks for emissions from liquid and gaseous fuel uses. These results lead us to reject the oil price shocks as events causing permanent

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breaks in the structure and level of emissions, a conclusion often made in analyses using shorter postwar data.

1 Introduction

While consequences of the climate warming remain highly uncertain, most scientists find it likely that emissions of Carbon Dioxide (CO_2) and other greenhouse gases contribute to the warming. The rising atmospheric concentration of CO_2 is generally viewed as the most important cause for the greenhouse effect. Economic actions that seek to reverse the "business-as-usual" trend of CO_2 emissions may prove to be very costly: according to an overview of estimates produced by thirteen research teams, the implementation of relatively modest reduction targets may generate significant annual costs ([28]; see also [17]).

Because of these characteristics, there has been a considerable recent interest in projecting the development of global CO_2 emissions to the future. The econometric approach has been to model similarities across countries using reduced-form models estimated with cross-national panel data on CO_2 emissions and indicators of economic development ([25], [24], [11], [10] [23]). The global projections are then based on the assumption that development in developing countries brings about the emission pattern estimated for the developed countries. Much of the focus has been on a pattern called "inverted U" relationship between emissions and income levels. The relationship is interesting because it implies that future reduction in emissions might follow as a by-product of economic growth.

This paper *is not* about the "inverted U". Rather than testing hypotheses about global similarities in emission-income patterns, we choose a much simpler objective: What are the historical trends in per-capita emissions from fossil fuel burning for those countries which have the longest industrial history? To put this question to perspective we note that per-capita emissions from solid-fuel burning, while still significant, are currently below the levels reached close to 100 years ago in many early developed countries. The (nontrivial) national emission histories are thus much longer than the postwar period used in previous studies focusing on the "inverted U".[1] In fact, for most developed countries the national time series of CO_2 emissions from fossil fuel combustion can be extended to the early stages of industrial revolution. Using such data over the period $1870-1998$ for 16 early developed countries we address the phases of per-capita emission development by identifying stable historical trends and structural breaks in trends with time-series methods.

One hypothesis is that early industrialized countries have had three phases in their emission development. The first phase was that of fast growth of per-capita emissions, as early industrialization and development in general was so heavily using coal. The second phase was characterized by less growth due to the shift from solid to non-solid fuels (from coal to oil and gas). This diversification in national fuel compositions was partly induced by local but CO_2-related pollution problems and technological progress associated with the demand for higher energy density fuels.[2] The third phase followed the oil price shocks of the 1970s

[1] These studies consider reduced-form relationships with a wide country coverage, so that it would be hard to extend the data period beyond the postwar era without loosing the country coverage or quality of the data for economic variables. We focus on a subset of countries having a reasonably good statistical basis for the pre-1950 period for the variables we use, so that it makes sense to consider the longer period 1870-1998. Edmunds and Reilly [22] also have a similar historical perspective but a shorter post-energy crises period.

[2] The shift from solid to liquid fuels is an example of the trend toward "Decarbonization", claimed to have been ongoing for the last 200 years [2]. For example, burning wood releases about 10 carbons per hydrogen

which permanently changed the structure of emissions from fossil fuels and possibly led to downward sloping per-capita emission trends.

We find evidence for very early downturns in stable per-capita trends, during the first decade of 20th century, for a group of industrial first movers. This is consistent with the above hypothesis. However, we find relatively little evidence for late downturns, during the oil price shocks of the 1970s, which contradicts the above three-phase pattern. Only for two countries do downturns in trends imply downward sloping stable trends. To understand what causes the early downturns in trends we consider trends in emissions from two sources: from (i) solid and (ii) liquid and gaseous (non-solid) fuels burning. Changes in emission composition indicate shifts in national fuel composition. In fact, this shift is related to the early downturns, since all stable trends for emissions from solid-fuels burning have very early structural breaks and trends in several countries have been downward sloping for a period close to century long. The emission composition also indicates why the oil price shocks of the 1970s cannot be viewed as events causing general downturns in per-capita emissions: there are signs of temporary substitution away from liquid to solid fuels during the 1970s, so that the overall emission levels do not experience large shocks causing general downturns in long-run trends.[3]

atom. This ratio is: one- or two-to-one for coal; one-to-two for oil; and one-to-four for natural gas [2]. So, the trend implies that the use of an energy unit produces more water and less CO_2.

[3] That trends are upward-sloping does not, of course, contradict the "Inverted U" hypothesis. What is new here is that our approach puts little weight on the emission peaks of the 1970s which are necessarily important for reduced-form estimations using postwar or shorter data. We find more evidence for structural breaks occurring early and potentially relating to shifts from solid (coal) to liquid (oil) fuels than for breaks occurring late and relating to shifts permanently away from oil.

Our testing procedures follow the general theme of the literature started by Nelson and Plosser [18] in that we identify stable trends in CO_2 series which emissions tend to revert to.[4] In our case, the trend function has potentially multiple data-dependent (endogenous) structural breaks, a possibility necessarily needed since the data spans over a century and extraordinary periods such as the World Wars and oil price shocks. Getting an idea of the time-series properties of the emissions is essential for both understanding their historical behavior and forecasting, and, therefore, we start our analysis by unit root tests, taking the possibility of structural breaks into account. Although we do not want to project national emissions very far to the future without having a structural model, we do project our series through 2028 for two reasons.[5] First, forecasts provide a consistency check for the estimated historical break-structure.[6] Second, forecasts can be used to discuss whether per-capita emissions have already peaked or if such peaks can be expected in the near future. Using this reasoning we find that the early in-sample peaks for emissions from solid-fuels burning for the first-movers in industrial development are the true peaks for emission from this source. However, we find no such in-sample peaks in non-solid-fuel emissions for all but one country.

[4] To this end we use Dickey-Fuller type unit root tests [5], [6], allowing for the possibility of structural breaks in trend first introduced by Perron [19] and further developed by Zivot and Andrews [29] and Vogelsang and Perron [27] among others.

[5] By the nature of the climate change, only very long-term projections are of ultimate interest. For example, the MIT-EPPA model, which is a computable general equilibrium model, is used to produce projections through 2100 (for the EPPA model, see Babiker el al. 2001). The time series approach cannot compete with these projections, so we focus on the historical trends and use forecasts only for the purpose specified below.

[6] We will compare our projections with those published by the U.S. department of energy (doe). Our projected total emission trends are roughly consistent with the U.S.doe projections.

This leads us to finally rule out the oil price shocks of the 1970s as events causing permanent changes in the overall per-capita emission trends.

The rest of the paper is organized as follows. The next section discusses the data and general characteristics of CO_2 series. Section 3 introduces the econometric methodology, discusses the problems related to breakpoint selection, and explains our operational testing procedures. Section 4 presents the empirical results for total and solid-fuel emissions. Using the estimated models for each series, section 5 introduces the projections for total, solid-, and non-solid-fuel emissions. Section 6 concludes.

2 Per-Capita CO_2 Series 1870-1998

We use the emission data provided by the U.S. Department of Energy through its Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory (CDIAC) [16]. An observation is an annual number giving national emissions in metric tons of carbon from fossil-fuel burning, cement manufacturing, and gas flaring. The vast majority of annual emissions come from two sources, from solid and liquid and gaseous (non-solid) fuel uses.[7] For a country i, burning of a given fuel in year t is

$$\begin{aligned} \text{burning}_{it} &= \text{production}_{it}\text{+imports}_{it}\text{-exports}_{it} \qquad (1) \\ &\quad \text{-bunkers}_{it}\text{-changes in stocks}_{it} \end{aligned}$$

[7] We will consider the total emissions and solid-fuels emissions separately. The number for non-solid-fuel emissions is the residual and therefore will not be explicitly presented. Solid fuels include different varieties of coal and coke, and peat. Non-solid fuels include crude and processed oils, natural gas liquids, and natural gas.

which is then multiplied by fuel-specific oxidization and carbon content coefficients (see Andres et al. [1]).[8] The emission data period is 1751-1998 but we work with shorter period $1870-1998$ because (i) this improves the quality of the data,[9] and (ii) at 1870 most of the 16 countries we consider had entered the industrial era.[10] The source of the population data is Maddison [15]. By and large, both data sets reflect the present national boundaries.[11] Using

[8] The first three numbers on the r.h.s. of (1) are from historical energy production and fuel trade statistics. The last two are available only for the postwar period. The omission of the last two numbers for the pre-1950 period is not a source of large errors because these numbers are significant only for the postwar period.

[9] We are aware of two studies addressing the quality of CDIAC numbers. First, Kunnas and Myllyntaus [13] reconstructed the Finnish numbers using domestic statistics and found no great discrepancies (they do find differences by changing the coverage of emissions). Second, the Swedish series was reconstructed by Kander [12]. For the postwar period, her series is systematically at a lower level than the CDIAC series, but both have the same pattern. This indicates potentially large errors in cumulative national emissions. This error should not affect our qualitative conclusions. In general, our hypothesis is that the pre-1950 data is more accurate for small countries importing most of their fuels than for large countries producing from own reserves (historical trade records are more precise than production records). If there is a systematic error of neglecting early production, this should only reinforce our conclusions regarding early rather than late downturns in trends.

[10] We excluded Norway because we suspected a data problem. We included Austria despite the huge territorial changes due to Ausria-Hungary dual monarchy (1867-1918) since per-capita numbers remain reasonable.

[11] Territorial changes require a number of adjustments. The population series for Germany was constructed as follows. Using Maddison [15] we obtain population estimates for an area that corresponds to the 1989 borders of the Federal Republic. For 1946-1998 we added the population of the GDR territory, and for 1870-1945 we assumed that the proportion of the population in the GDR territory remained constant (38 percent). Thus, both the population and the CDIAC emission data reflect the present territory of Germany.

these two data sets we construct the per-capital series which we transform into logarithms.[12]

The logarithms of national per-capita emissions are graphed in fig. 1 which makes two points clear. First, and not surprisingly, national emissions from fossil-fuel burning at 1870 indicate the stage of industrial development. Therefore, the early levels are highest for the U.K., Belgian, German and the U.S. series; the ranking of emissions at 1870 follows rather closely the income-level ranking provided, for example, by Maddison [15]. The second descriptive feature is that some early developed countries reached their current per-capita emission levels surprisingly early, during the first decades of the 20th century. Solid-fuel uses are responsible for the early emissions. Per-capita emissions from these sources are shown in fig. 2 which illustrates that solid-fuel emissions have not only reached high levels early but also potentially peaked very early. This is confirmed by Table 1 showing the historical peaks for each series in figs. 1-2. The table shows also the peaks for the difference between total and solid-fuels emissions representing emissions from non-solid-fuel uses.[13]

$$[Figs.1-2]$$

We can now restate the question for our research more precisely. In view of fig.1, does it seem plausible that the oil price shocks of 1970s or perhaps earlier extraordinary events have caused permanent downturns in national per-capita emission trends? What is the exact timing of these potential structural breaks? To answer this question we will construct time-

[12] The CDIAC data set includes per-capita emissions only for the period 1950-1998. To avoid inconsistencies between the population estimates, our per-capita numbers for the period 1950-1998 are based on the Maddison's population data. We compared our per-capita numbers with those of the CDIAC and found no significant discrepancies.

[13] Emissions from cement manufacturing are insignificant and can be ignored here.

series representations for each total and solid-fuel emission series with potentially multiple structural breaks. The representations will help to understand historical emission patterns for these series and also for the residual, non-solid-fuel emission series. The representations will be used in analyzing whether the historical peaks in Table 1 will be exceeded in the near future.[14]

[$Table$ 1]

3 The Econometric Methodology

The econometric problem is that of choosing between two competing models, both of which are conceivable representations of the per-capita CO_2 series, $\{y_t\}_1^T$, for a given individual country. Under the null hypothesis, the series is a unit root process. Under the alternative hypothesis, the series is stationary around a deterministic trend function. The behavior of the series is thus very different under the null and alternative hypotheses, and the unit root test can be seen as a pretest for determining the significance of structural breaks. In addition, the unit root test improves the predictive accuracy of emission projections (see, e.g., Diebold and Kilian [7]). Our purpose is to identify those series which can be represented by a stationary and piecewise linear trend function where breaks are endogenously determined by the data. To make this target entirely clear, consider fig. 3 which depicts the U.S. per-

[14] We emphasize that we do not have a structural explanation for the patterns we produce. Our results will indicate interesting across-country differences which may be used later to formulate structural hypotheses. For example, the substitution between emissions from solid and non-solid fuel uses is likely to depend on national coal reserves, share of exports, or on national fuel composition in general.

capita emissions and a linear trend function with three breaks. We will explain the testing procedure in detail below, but fig. 3 illustrates the general idea: we seek to piece together linear trend segments with data-dependent lengths. The hope is that the estimated trend function identifies the critical phases in historical emissions development and that the trend works well also after the data period.

$[Fig.3]$

3.1 Unit root testing with one break

We consider the following additive outlier (AO) model

$$y_t = \mu + \beta t + \gamma DT_t + z_t, \quad t = 1, 2, ..., T \tag{2}$$

where $DT_t = 1(t > T_b)(t - T_b)$, $1 < T_b < T$ is the break date, and $1(\cdot)$ is the indicator function. z_t is an ARMA$(p + 1, q)$ process $A(L)z_t = B(L)e_t$ where $e_t \sim iid(0, \sigma^2)$. Lag polynomial $A(L)$ can be factored as $A(L) = (1 - \alpha L)A^*(L)$ and the pth order polynomial $A^*(L)$ and $B(L)$ have all roots outside the unit circle. The initial value y_0 is assumed to be a fixed constant. In unit root testing the null hypothesis can thus be expressed as $H_0 : \alpha = 1$ while the alternative hypothesis is $H_1 : |\alpha| < 1$. The magnitude of the potential trend break is measured by parameter γ. As mentioned above, no level shifts are allowed for. There is no particular reason to expect them and their inclusion in the model can reduce the power of the unit root test if none really are present.

The additive outlier model implies a sudden break in contrast to the so called innovational outlier (IO) model where the break evolves slowly over time. We prefer the AO model here because the main emphasis is on the potential trend break due to, for example, the oil price shock whose effect on the trend of the series can be expected to be abrupt in the annual data we use. The lag length p also turns out to be unity in all cases so that the difference between the two specifications is expected to be minor.[15]

In testing for a unit root it will be assumed that a break in trend can only occur under the alternative hypothesis of stationarity. Hence, we are interested in finding out whether shocks to the carbon dioxide series are permanent or whether the series can be characterized as having temporary shocks fluctuating around a broken deterministic trend function. This assumption could, of course, be tested using a test for a break that is valid under both hypotheses, but such a pretest is likely to distort the size of the actual unit root test, and therefore, we have not taken this route.[16]

For a given known break date we could use the two-step procedure of Perron[19]. First, the series y_t is detrended by running the following OLS regression

$$y_t = \mu + \beta t + \gamma DT_t + \widetilde{y}_t.$$

Then, the unit root test statistic is obtained as the t statistic testing for $\alpha = 1$, $t_{\widehat{\alpha}}$, in the

[15] The finite sample simulations of Vogelsang and Perron (1998) suggested that if the magnitude of the shift is suspected to be large (here we expect the slope of the trend to turn from positive to negative), the AO model is preferable to the IO model in terms of the size of the unit root test. Also, it can be shown that the correct break date is estimated asymptotically correctly using the procedure we employ below in the AO model (2) but not in the corresponding IO model (see, Vogelsang and Perron (1998)).

[16] We experimented with one such test, namely the Sup WD_T^1 test of Vogelsang (1997), as a preliminary check for a significant break, and it indicated no evidence for breaks in any of the series. However, for persistent but stationary series the test is conservative and may not be very powerful.

regression

$$\widetilde{y}_t = \alpha \widetilde{y}_{t-1} + \sum_{i=1}^{k} c_i \Delta \widetilde{y}_{t-i} + u_t.$$

However, for CO_2 series it is difficult to ascertain what exact event is a reasonable breakpoint, so we cannot assume knowledge of the break date. Also, estimating this date is of interest in its own right. Several break date estimators in a model like (2) have been introduced. Because we expect the break to be such that it turns the deterministic trend from positive to negative, the natural estimator is based on minimizing t_γ, the t statistic of γ over all possible break dates. This estimator selects the date corresponding to the most negative value of t_γ, thus maximizing the probability of a turn in the trend. Vogelsang and Perron [27] have shown that in our setup this estimator selects the correct break date asymptotically, contrary to some other popular estimators such as the one based on minimizing t_α. The asymptotic null distribution of the test statistic is derived by Vogelsang and Perron [27] who also tabulate some critical values.

3.2 Unit root testing with multiple breaks

Above we described the case of one potential break in the deterministic trend. In practice it is likely that multiple such breaks have occurred. However, directly extending the framework to the case of an unknown number of breaks at unknown dates is complicated, and to our knowledge, such tests have not been presented.[17] To tackle with the problem of multiple breaks we employ the following sequential procedure. Model (2) is first estimated with data from the entire sample period to obtain the estimate for the break date T_b and the unit root

[17]Lumsdaine and Papell [14] introduced unit root tests in the case where the number of structural breaks is known to be two, but they only explicitly considered models including level shifts as well.

test statistic. If the break is estimated relatively early in the sample, a new search over the period from $T_b + 1$ until the end of the sample is conducted to obtain another break date T_b and unit root test statistic for this subsample period. This may be repeated if the new break date lies near T_b so that enough observations are available to still expect reasonable power in the unit root test.

The series is deemed stationary if the unit root test rejects (at the 10% level) in the entire sample because in this case the test is most powerful and expected to reject even if additional breaks were introduced. On the other hand, if only one break near the end of the sample period is detected and the unit root test fails to reject, the series can rather safely be deemed a unit root process. It turns out that in addition to these two clear cases, there are some series for which the unit root null is not rejected in any of the subsample periods. These cases are problematic because it is possible that a unit root test simultaneously taking multiple breaks into account, would reject the unit root hypothesis. Nevertheless, in these cases we shall conclude that the series is a unit root process.

Having estimated all the breaks, we estimated for each stationary series an AO model for testing the significance of the breaks (if any) and for forecasting. In specifying the model we started out by estimating an AO model including all the estimated breaks and tested the significance of each of them individually using a t-test. If some of the breaks were not individually significant (at the 10% level), the least significant break was dropped and the model was reestimated. This procedure was then repeated until all the included breaks were significant. The ensuing model was used for forecasting, while the forecasts for the $I(1)$ series were computed from autoregressive models estimated for the difference.

4 Empirical Results

4.1 Total Emissions from Fossil-Fuel Uses

The main empirical result is that we find no general evidence for structural breaks causing downward-sloping per-capita emissions during or after the oil-price shocks of the 1970s. We find clear evidence for such late breaks only for the U.K. and Sweden and some evidence for Belgium and Denmark. All the remaining structural breaks in stable trends are very early downturns in the (positive) slope of the trend: Austria 1907, Denmark 1904, Germany 1900, U.K. 1901, U.S. 1908. A stable trend function without breaks can be found for Finland, Italy, and the Netherlands.[18]

[*Table* 2]

To see how these conclusions were reached, consider table 2 which presents the unit root tests and estimated break dates for the total emission series. The table shows all the estimated breaks but only breaks in stationary series are relevant.[19] The series for the 10 countries mentioned above are stationary.[20] However, not all of the breaks in the stationary

[18]Since we generally reject structural breaks related to the oil price shocks, it should be emphasized that our sequential method is not unfair to breaks occurring late in the series. First, a break in the 70s has a chance to be chosen in each consecutive estimation. Second, serious loss of power is not expected in subsample tests either because only relatively large subsamples are considered.

[19]Under the null hypothesis, a large shock is a realization from the tail of the distribution for the data-generating process.

[20]For these 10 countries, the unit root hypothesis is rejected in the entire sample at the 10% significance level. For the French series the break point is estimated near the end of the series and the test does not reject, so that the series can relatively safely be concluded to be I(1). Hence we are left with five somewhat problematic series (namely those of Austria, Canada, Japan, New Zealand, and Switzerland) for which the

series are statistically significant. This was to be expected because our procedure assumes that in each subsample period there is one break but there is no reason for this assumption to be true. Their individual significance was tested in an AO model as described above.[21] It turns out that the series of Finland, Italy and the Netherlands have no significant breaks, whereas those of Denmark and the UK have two and the rest one significant trend break.

An interesting question relating to the significant breaks is whether they indicate a turn in the trend from upward to downward sloping. This can be examined by computing confidence intervals for the sum of the coefficient of the linear trend and the trend break dummies. Such 90% confidence intervals are presented in Table 4. If the confidence interval includes only negative values, there is strong evidence for a downturn causing a downward sloping trend. With the exception of the U.K. series, negative values are included only in the confidence intervals corresponding to breaks occurring in the 70s which points towards the oil price shocks. However, there is strong evidence for a downward sloping trends only for the U.K. and Sweden as these are the two countries with confidence intervals containing purely negative values corresponding to the 1974 break for the UK and the 1976 break for Sweden. In contrast, the results indicate no turn in the trend of the series of Australia, Germany and the USA.

$[Table 4]$

unit root null cannot be rejected in any of the subsample periods, but as discussed above, they will be classified as I(1).

[21] Under stationarity, standard asymptotic theory should apply, and hence, the t-statistics are compared to critical values from the standard normal distribution.

4.2 Emissions from Solid-Fuel Uses

The results for the solid-fuel series are presented in Tables 3 and 5. The main result is that most breaks occur relatively early and that there are much stronger early changes in the slopes of the stable trends than in the case of the total emissions series. The lack of general evidence for late breaks in total and solid-fuel emissions suggests that there is no general evidence oil-price shock related break for the difference of the two series neither, e.g., for the emissions from liquid and gaseous fuel uses.[22]

Using the same method as above, the clearly stationary solid-fuel series are those of Australia, Belgium, Finland, Germany, Italy, Japan, New Zealand, Sweden, and the UK, while the rest are deemed unit-root processes. The following countries experience downturns twice and clearly have downward sloping post-break(s) trends: Germany (1909, 1987), New Zealand (1899, 1947), and the U.K. (1955, 1993). Belgium (1937) and Sweden (1911) both have one clear structural break and a negative post-break trend. Thus, for these five countries we can rather safely conclude that the decline of emissions from solid-fuel uses has started early. For Italy the break occurs early, in 1904, but it merely flattens the trend; there is no evidence for either downward or upward sloping post-break trends. For Australia (1908), Japan (1976), and Finland (no break) the trend remains upward-sloping throughout the sample period. Thus, for these four countries there is no evidence for a decline of solid-fuel emissions.

[$Tables$ 3 and 5]

[22] We do not analyze the series for emissions from non-solid fuels directly, because in most cases the series are too short for our method.

5 Forecasts

We project the national per-capita series through 2028 for two reasons.[23] First, the forecasts depend on the historical break structure estimated above, meaning that by comparing the forecasts with those published elsewhere we obtain a rough consistency check on the estimated break structure. Second, forecast can be used to discuss whether the historical peaks in Table 1 will remain as peaks or if the true peaks can be expected in the near future.

[*Table* 6]

Table 6 shows our estimates for per-capita emission peaks over the period $1870 - 2028$. In view of the Table 6 and the fact that the post-break trends are downward sloping, we can rather safely conclude that total per-capita emissions have in-sample peaks for Sweden (1970) and the U.K. (1913). Note, however, that despite of the overall decline, non-solid-fuel emissions are expected to have a peak relatively late (2015) in the U.K. Our forecasts suggest that also Austria, Belgium and Denmark have in-sample peaks for the total per-capita emissions.[24] The historical emission peaks for the remaining 14 countries will be exceeded in the near future, according to our analysis. In contrast, for most countries, solid-

[23] Forecasts for both the "total" and "solid" series were computed either from autoregressions for the difference or stationary AO models, depending on whether the series was deemed I(1) or I(0). For those I(0) series in which no significant breaks were detected, the model, of course, reduces to a regular autoregression. The Bayesian information criterion (BIC) selected one lag in each case. The stationary AO models were formulated sequentially by dropping the insignificant breaks one at a time, as described above (see, p. 13). In other words, these models include the breaks in Tables 3 and 5 that are significant at the 10% level at least.

[24] However, the post-break trend for Austria and Denmark is positive, so the conclusion depends on the length of the projection period.

fuel emissions have early peaks in the sample, implying that it is the non-solid fuel use that is driving the total. The group of countries with early peaks includes all of the first-movers in industrialization.

Figures 4-5 show the total per-capita emissions, our projections of these series through 2028, and the forecasts published by the U.S.d.o.e. [8] (dots at years 1998, 1999, 2005, 2010, 2015, 2020) for 6 countries. The two sets of projections do not exactly coincide but are reasonably consistent with each other.[25]

[$Figs.$ 4-5]

6 Conclusion

One of the most pressing global climate policy issues is the future development of greenhouse gas emissions. Even the most intelligent emission forecasts have to be based on historical emission patterns. The history, which is extended to the future by projection-models, typically covers the period after the Second World War. However, the history of economic development based on the carbon-intensive energy use is considerably longer than the post-war period: for some early industrialized countries, historical per-capita emissions peaked already before the history of a typical projection-model started. In this paper we attempted to understand the basic trends in the development of carbon-intensive energy use, with a long historical perspective.

To the above end, we addressed the properties of the historical time series for per-capita

[25] The U.S.doe forecasts are available also for Japan and the Netherlands. We excluded the comparisons with these two countries because the 1998 levels of the series are different in the two data sets.

CO_2 emissions in major developed countries. We used econometric approach to find "stable phases" for per-capita emission development. We found evidence for a two-phase pattern: the initial fast growth during the early industrialization followed by an early downturn to a period of less growth in per-capita emissions. Only for *two* countries could we find clear evidence about a third phase characterized by declining per-capita emissions. A similar two-phase pattern applies for emissions from solid-fuel burning, for most early industrialized countries, with the difference that emissions from this source seem be on a declining path. The results imply that emissions from liquid and gaseous fuels are mainly responsible for the historical and future growth in emissions; the oil price shocks of the 1970s did not cause general downturns in long-run trends for these emissions. The estimated two-phase pattern for per-capita emissions can be seen as partial "decarbonization" of per-capita energy use. The process has been important in slowing down the rate of increase in emissions, but there is little historical evidence that it could reduce future per-capital emissions.

While the finding that many of the per-capita emission series are nonstationary may seem confusing, it should be noted that the result does not rule out an equilibrium relationship between CO_2 emissions and economic variables. It is quite possible that there exists a reduced-form long-run relationship between the levels of emissions and income per capita, as assumed by the literature on the "Inverse U". For nonstationary series the existence of such a relationship would mean cointegration [9]. The present analysis is a first step toward cointegration analysis, because a long-run relationship between these variables makes sense only if their time-series properties are known to be similar (the series must be integrated of the same order). However, given that most of the emission series were deemed stationary, cointegration is not meaningful for them, and alternative long-run equilibrium concepts should be entertained. One possibility would be to consider nonlinear models and test for common nonlinearities (see, e.g. Bierens [4]). Our results about differences in the properties of national CO_2 series indicate potential differences for the nature of national long-run relationships across countries.

References

[1] Andres, R.J., D.J. Fielding, G. Marland, T.A. Boden, N. Kumar, and A.T. Kearney, Carbon Dioxide Emissions from Fossil-Fuel Use, 1751-1950, *Tellus* **51B**, 759-765 (1999).

[2] Ausubel, J.H., Where is the Energy Going, *The Industrial Physicist* **1**,16-19, February (2000).

[3] Babiker, M.H., J.M. Reilly, M. Mayer, R.S. Eckaus, I.S. Wing, R.C. Hyman, The MIT Predictions and Policy Analysis (EPPA) model: Revisions, Sensitivities, and Comparisons of Results, Report 71, MIT Joint Program on the Science and the Policy of Global Change, Cambridge MA (2001).

[4] Bierens, H.J., Nonparametric Nonlinear Cotrending Analysis, With an Application to Interest and Inflation in the United States, *Journal of Business and Economic Statistics* **18**, 323-337 (2000).

[5] Dickey, D. A., and W.A. Fuller, Distribution of the Estimators for Autoregressive Time Series with a Unit Root, *Journal of the American Statistical Association* **74**, 427-431 (1979).

[6] Dickey, D. A., and W.A. Fuller, Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root, *Econometrica* **49**, 1057-1072 (1981).

[7] Diebold, F.X. and L. Kilian, Unit root tests are useful for selecting forecasting models, *Journal of Business and Economic Statistics* **18**, 265–273 (2000).

[8] The U.S. Department of Energy, Energy Information Administration, Office of Integrated Analysis and Forecasting, *International Energy Outlook* (2001).

[9] Engle, R., and C. W. J. Granger, Cointegration and Error-Correction: Representation, Estimation, and Testing, *Econometrica* **55**, 251-276 (1987).

[10] Grossman, G.M., and A.B. Krueger, Economic Growth and the Environment, *Quarterly Journal of Economics* **110**, 353-377 (1994).

[11] Holz-Eakin, D., and T. M. Selden, Stoking the Fires? CO_2 and Long-run Growth, *Journal of Public Economics* **57**, 85-101 (1995).

[12] Kander, A., Economic Growth, Energy Consumption, and CO_2 Emissions in Sweden 1800-2000. Lund Studies in Economic History 19. Lund University (dissertation).

[13] Kunnas, J., and T. Myllyntaus, CO_2 Emissions from Fossil Fuel Burning - Comparative Case Studies on Austria, Denmark, Finland, Sweden and Switzerland, 1800 -1998, $XXIX$ Symposium of the International Committee for the History of Technology, ICOHTEC, Granada, Spain, June 24-29 (2002).

[14] Lumsdaine, R.L., and D.H. Papell, Multiple trend breaks and the unit-root hypothesis, *Review of Economics and Statistics* **79**, 212–218 (1997).

[15] Maddison, A., Monitoring the World Economy 1820-1992, Development Centre Studies, OECD (1995).

[16] Marland, G., T.A. Boden, R. J. Andres, Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn.,U.S.A. (2000).

[17] McKibbin, W. J., and P.J. Wilcoxen, The Role of Economics in Climate Change Policy, *Journal of Economic Perspectives* **16**, 107-129, Spring (2002).

[18] Nelson, C. R., and C. I. Plosser, Trends and Random Walks in Macroeconomic Time Series, *Journal of Monetary Economic*s **10**, 139-162 (1982).

[19] Perron P., Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis, *Econometrica* **57**, 1361-1401 (1989).

[20] Perron P., Testing for a Unit Root in a Time Series with a Changing Mean, *Journal of Business and Economic Statistics* **8**, 153-162 (1990).

[21] Perron, P. and T.J. Vogelsang, The great crash, the oil price shock, and the unit root hypothesis: Erratum, *Econometrica* **61**, 248–249 (1993).

[22] J. Edmunds, and J. Reilly, Global Energy: Assessing the Future, Oxford University Press (1985)

[23] Schmalensee, R., T. Stoker, and R. Judson, World Carbon Dioxide Emissions: 1950-2050, *The Review of Economics and Statistics* **80**, 15-27 (1998).

[24] Selden, T. M., and D. Song, Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions? *Journal of Environmental Economics and Management* **27**, 147-162 (1994).

[25] Shafik, N., Economic Development and Environmental Quality: An Econometric Analysis, *Oxford Economic Papers* **46**, 757-773 (1994).

[26] Vogelsang, T.J., Wald-type tests for detecting breaks in the trend function of a dynamic time series, *Econometric Theory* **13**, 818–849 (1997).

[27] Vogelsang, T.J. and P. Perron, Additional tests for a unit root allowing for a break in the trend function at an unknown time, *International Economic Review* **39**, 1073–1100 (1998).

[28] Weyant, J. and Hill P., Introduction and Overview, *The Energy Journal*, Kyoto Special Issue, iv-xliv (1999).

[29] Zivot E., and D. W.K. Andrews, Further Evidence on the Great Crash, the Oil-Price Shock, and the Unit-Root Hypothesis, *Journal of Business and Economic Statistics* **10**, 251-270 (1992).

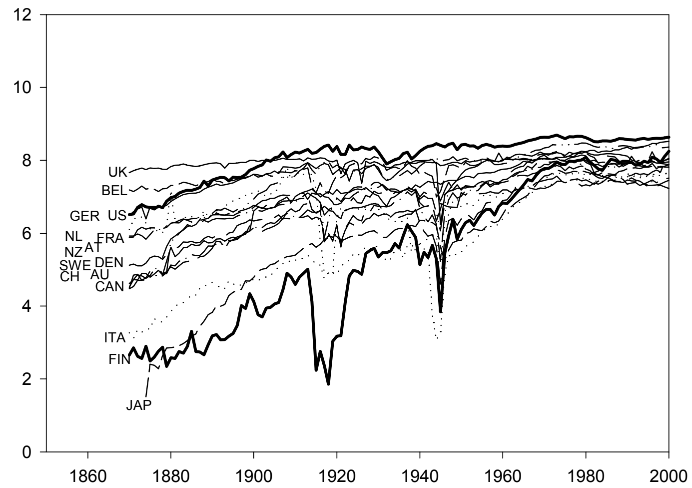

Figure 1: Logarithm of "per-capita CO_2" from fossil fuel burning over 1870-1998 for Australia, Austria, Belgium, Canada, Denmark, France, Finland, Germany, Italy, Japan, Netherlands, New Zealand, Sweden,Switzerland, United Kingdom, United States.

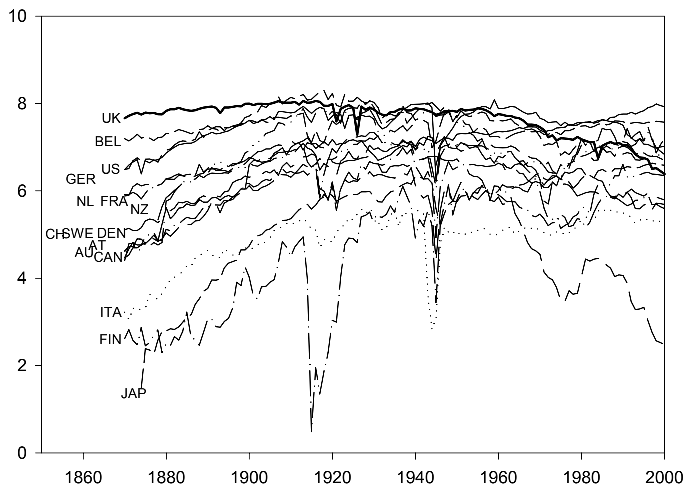

Figure 2: Logarithm of "per-capita CO_2" from solid fuel burning over 1870-1998 for Australia, Austria, Belgium, Canada, Denmark, France, Finland, Germany, Italy, Japan, Netherlands, New Zealand, Sweden, Switzerland, United Kingdom, United States.

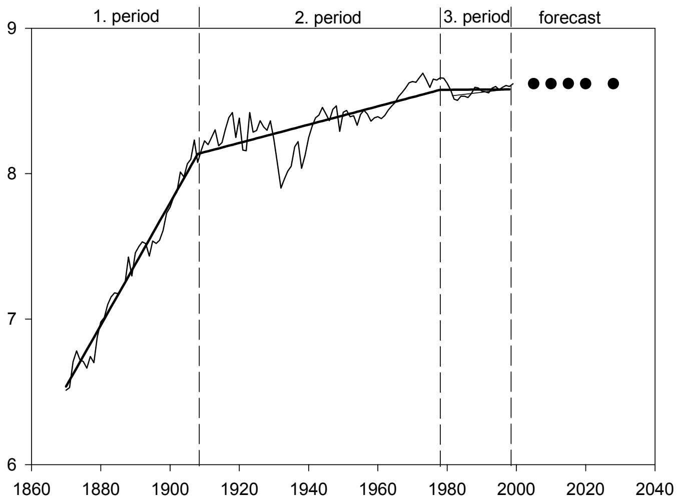

Figure 3: Logarithm of "per-capita CO_2" over 1870-1998 for the United States. The broken trend line is fitted OLS with breaks at 1908 and 1978.

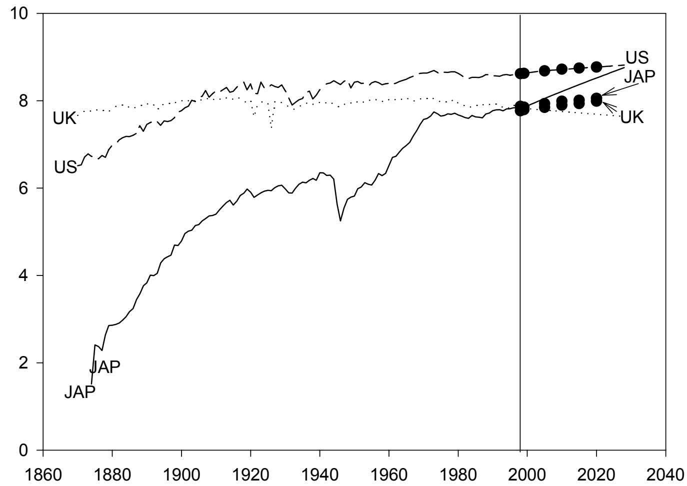

Figure 4: Logarithms of per-capita CO_2 over 1870-1998 and projections through 2028 for Japan, the U.K., and U.S. The U.S. d.o.e. forecasts are dots at 1998, 1999, 2005, 2010, 2015, and 2020.

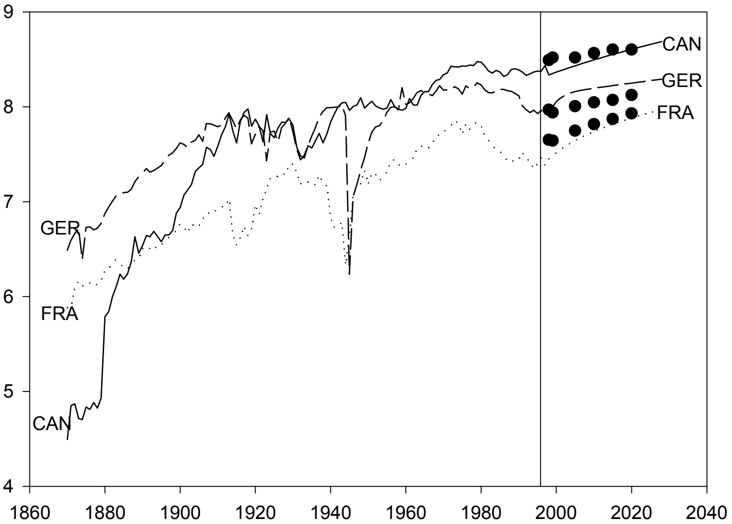

Figure 5: Logarithms of per-capita CO_2 over 1870-1998 and projections through 2028 for Japan, the U.K., and U.S. The U.S. d.o.e. forecasts are dots at 1998, 1999, 2005, 2010, 2015, and 2020.

Table 1: Peak Years for Total, Solid, and Non-Solid Fuel CO_2 Emissions over 1870-1998.

Country	Total	Solid Fuels	Non-Solid Fuels
Australia	1998	1998	1996
Austria	1908	1908	1998
Belgium	1973	1929	1974
Canada	1948	1918	1979
Denmark	1991	1996	1996
Finland	1996	1996	1976
France	1973	1930	1973
Germany	1979	1959	1979
Italy	1998	1985	1998
Japan	1996	1997	1996
Netherlands	1979	1931	1997
New Zealand	1997	1910	1979
Sweden	1970	1937	1973
Switzerland	1973	1939	1985
UK	1913	1913	1996
US	1973	1918	1973

Table 2: Unit root tests for the total emissions series.

	$t_{\hat{\alpha}}$	T_b	$t_{\hat{\alpha}}$	T_b	$t_{\hat{\alpha}}$	T_b
Australia	–3.99 [0.062]	1907**	–2.68 [0.492]	1989		
Austria	–2.99 [0.359]	1880	–2.62 [0.515]	1889	–2.53 [0.558]	1995
Belgium	–3.97 [<0.01]	1977+				
Canada	–3.72 [0.110]	1906	–3.21 [0.265]	1981		
Denmark	–4.01 [0.059]	1904**	–4.30 [0.030]	1978**		
Finland	–3.85 [0.085]	1980				
France	–3.38 [0.204]	1978				
Germany	–5.10 [<0.01]	1900**	–4.53 [0.017]	1987		
Italy	–3.97 [0.065]	1883	–3.80 [0.097]	1995		
Japan	–1.98 [0.782]	1902	–1.60 [0.894]	1992		
Netherlands	–4.44 [0.020]	1883	–4.21 [0.038]	1979		
New Zealand	–1.77 [0.851]	1897	–1.57 [0.900]	1904	–2.33 [0.644]	1995
Sweden	–4.41 [0.023]	1976**				
Switzerland	–3.64 [0.131]	1897	–3.19 [0.272]	1990		
UK	–7.38 [<0.01]	1901**	–7.00 [<0.01]	1974**		
USA	–4.52 [0.017]	1908**	–3.43 [0.189]	1978		

Marginal significance levels, computed using the pval program by Timothy J. Vogelsang, in brackets. The lag length k was selected by the BIC criterion. **, * and $^{+}$ denote significance at the 1, 5 and 10% level, respectively.

Table 3: Unit root tests for the solid-fuel series.

	$t_{\hat{\alpha}}$	T_b	$t_{\hat{\alpha}}$	T_b	$t_{\hat{\alpha}}$	T_b
Australia	–3.87 [0.083]	1908**	–2.56 [0.544]	1915	–2.54 [0.549]	1995
Austria	–3.48 [0.172]	1899	–2.83 [0.429]	1991		
Belgium	–4.13 [0.046]	1937**	–3.46 [0.179]	1954	–2.48 [0.577]	1995
Canada	–2.76 [0.457]	1911	–1.64 [0.884]	1918	–1.41 [0.928]	1942
	–1.55 [0.903]	1995				
Denmark	–3.12 [0.305]	1912	–2.50 [0.569]	1930	–2.04 [0.760]	1937
	–1.94 [0.795]	1995				
Finland	–4.37 [0.025]	1952	–3.49 [0.170]	1995		
France	–3.56 [0.150]	1954	–3.03 [0.341]	1982		
Germany	–5.05 [<0.01]	1909**	–4.84 [<0.01]	1987**		
Italy	–6.27 [<0.01]	1904**	–5.54 [<0.01]	1911	–5.41 [<0.01]	1995
Japan	–4.65 [0.012]	1896	–4.45 [0.020]	1914**	–4.13 [0.046]	1921
	–3.98 [0.063]	1995				
Netherlands	–2.54 [0.551]	1931	–1.32 [0.941]	1950	–0.85 [0.978]	1957
	–1.29 [0.944]	1995				
New Zealand	–3.96 [0.066]	1899**	–2.87 [0.409]	1947*	–2.32 [0.646]	1954
	–2.58 [0.531]	1987				
Sweden	–4.06 [0.054]	1911**	–3.55 [0.152]	1934	–2.99 [0.358]	1995
Switzerland	–3.18 [0.277]	1932	–2.51 [0.564]	1956	–1.56 [0.901]	1995
UK	–6.54 [<0.01]	1955**	–3.59 [0.143]	1993+		
USA	–2.80 [0.441]	1908	–2.06 [0.753]	1915	–2.38 [0.621]	1995

See notes to Table 2.

Table 4: 90% confidence intervals for the linear trend after the significant break points for the total emissions series.

	T_b	
Australia	1907	0.0162, 0.02059
Belgium	1977	–0.0243, 0.0040
Denmark	1904	0.0195, 0.0237
	1978	–0.0076, 0.0042
Germany	1900	0.0027, 0.0079
Sweden	1976	–0.0497, –0.0066
UK	1901	–0.0005, 0.0012
	1974	–0.0089, –0.0038
USA	1908	0.0040, 0.0069

90% confidence intervals for the sum of the coefficient of the linear trend and the trend break dummies up to T_b.

Table 5: 90% Confidence intervals for the linear trend after the significant break points for the solid-fuel series.

	T_b	
Australia	1908	0.0081, 0.0126
Belgium	1937	–0.0218, –0.0133
Germany	1909	–0.0049, 0.0003
	1987	–0.0634, –0.0591
Italy	1904	–0.0028, 0.0075
Japan	1976	0.0019, 0.0156
New Zealand	1899	–0.0123, –0.0054
	1947	–0.0281, –0.0074
Sweden	1911	–0.0075, –0.0071
UK	1955	–0.1295, –0.0237
	1993	–0.1195, –0.0127

90% confidence intervals for the sum of the coefficient of the linear trend and the trend break dummies up to T_b.

Table 6: Peak Years for Total, Solid, and Non-Solid Series over 1870-2028.

	Peak Year		
	Total	Solid	Non-Solid
Australia	2028	2028	2028
Austria	1908	1908	2028
Belgium	1973	1929	1974
Canada	2028	1918	2028
Denmark	1996	2028	1996
Finland	2028	2028	2028
France	2028	1930	2028
Germany	2028	1959	2028
Italy	2028	2028	2028
Japan	2028	2028	2028
Netherlands	2028	1931	2028
New Zealand	2028	1910	2028
Sweden	1970	1937	1973
Switzerland	2028	2028	2028
UK	1913	1913	2015
USA	2028	1918	2028