The Economic Cost of CO_2 Emission Cuts

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, Pennsylvania, July 24-26, 2011

Abstract

We follow Schmalensee, Stoker, and Judson (1998) to forecast CO_2 emissions based on the environmental Kuznets curve (EKC). Our findings suggest that the EKC will not lead to significant decreases in CO_2 emissions even by 2050 for countries with the highest incomes. Therefore, mandatory emissions cuts are required to limit climate change. In the same spirit of Horowitz (2009) and Ng and Zhao (2010), we then use a reduced-form approach to estimate the economic costs of mandatory emission cuts. Based on our parameter estimates, we find that a 25% mandatory deduction in CO_2 emissions from 1990 will lead to a 5.63% decrease in the combined GDP of the 19 OECD countries, and a 40% deduction will result in a 12.92% loss in income (holding other relevant variables constant)! Our estimates are substantially higher than those in Paltsev, Reillya, Jacobya, and Morris (2009) and Dellink, Briner and Clapp (2010), and suggest that the economic cost to limit climate change as envisioned in the Copenhagen Accord may be substantial and more research should be done before mandatory emission cuts are implemented.

Keywords: Environmental Kuznets Curve; Carbon Dioxide Emissions; Economic Cost; Climate Change

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1. Introduction

The international community has agreed on the Copenhagen Accord that “climate change is one of the greatest challenges of our time.” (page 5) The scientific view is that CO_2 emissions are its major driving force (IPCC, 2007). We ask two related questions in this paper. First, to limit climate change, do countries have to implement mandatory CO_2 emission cuts? Second, if mandatory cuts are required, what are the economic costs of such cuts?

The first question is motivated by the voluminous literature on the environmental Kuznets curve (EKC).[1] The EKC predicts that emissions will decrease with income in the long run. Therefore, if the EKC is strong enough, mandatory emission cuts may not be necessary. Otherwise, mandatory cuts are required. Then, a natural and important question arises: what are the economic costs of mandatory emission cuts? To answer this question, we need to study a reverse EKC. That is, we need to investigate how emissions and emission cuts affect income (not how income affects emissions as in the EKC studies).[2] If the adverse impact of emission cuts on income is small, it may be sensible to make significant cuts, vice verse. The importance of this question is manifested in the disagreements at the 2009 United Nations Climate Change Conference in Copenhagen

[1] See for instance Grossman and Krueger (1991, 1995), Shafik and Bandyopadyay (1992), Holtz-Eakin and Selden (1995), Galeotti and Lanza (1999), Dijkgraaf and Vollebergh (2001), Dasgupta et al. (2002), Martinez-Zarzoso and Bengochea-Morancho (2004), Stern (2004), Galeotti, Lanza, and Pauli (2006), Vollebergh, Melenberg and Dijkgraaf (2009), and Stern (2010) among others.

[2] There is a huge literature on the relationship between energy consumption and economic growth. See Ozturk (2010) for a comprehensive review. We in this paper instead focus on the relationship between emission cuts and income.

(Müller 2010) and the 2010 State of the Union Address by United States President Barack Obama (State of the Union Address Library 2010).[3]

Numerous studies have produced long-run forecasts of CO_2 emissions. See IPCC (2007) for a survey. Majority of these studies use structural simulation models. Such an approach assumes "business as usual", which, as Schmalensee, Stoker, and Judson (1998) (SSJ) indicate, does not describe the dynamic nature of the world economy. They therefore employ a reduced-form approach based on the EKC, which essentially assumes "change as usual" and may be a better description of the dynamic world economy. SSJ find that the IPCC's emission projections depart substantially from past trends.[4]

In this paper, we follow SSJ and project CO_2 emissions based on the EKC with the 19 OECD countries' data from 1980 to 2007. In this regard, the first contribution of the paper is to update SSJ with more recent data. Consistent with SSJ, we find that IPCC (2007)'s new emissions forecasts still depart from past trends substantially. However, what we emphasize in this paper is that the EKC (which is discussed extensively in the literature) will not lead to significant decreases in CO_2 emissions even by 2050 for countries with the highest incomes. Therefore, mandatory emissions cuts are required to limit climate change.

[3] The significance of this question is also emphasized in a Wall Street Journal article, in which Robert Stavins from Harvard University and Steven Hayward from the American Enterprise Institute for Public Policy Research debate whether carbon emission cuts can hurt economic growth (Wall Street Journal 21 September 2009).

[4] Furthermore, as Campbell and Diebold (2005) point out, successful modeling and forecasting does not necessarily require a structural model, and in the last several decades statisticians and econometricians have made great strides in the nonstructural modeling and forecasting of time series trend, seasonal, cyclical, and noise components.

There is also a lot of research on economic costs of mandatory emission cuts (see IPCC, 2007). Most studies rely on structural models to assess the impact of emissions cuts. For instance, Paltsev, Reillya, Jacobya, and Morris (2009) use the MIT Emissions Prediction and Policy Analysis (EPPA) model; Dellink, Briner and Clapp (2010) employ the OECD's ENV-Linkages model. The structural approach has one major challenge in its complexity. The possible pathways through which emissions may affect economic outcomes are numerous and, even if each pathway could be understood, how they interact and aggregate to determine macroeconomic outcomes raises additional difficulties. In contrast, the cross-sectional relationship between emissions and income motivates a simple reduced-form approach. Two noteworthy recent examples of using reduced-form approach in the global warming literature are Horowitz (2009) and Ng and Zhao (2010).

Therefore, in this paper, different from previous studies, we employ a reduce-form approach to estimate the economic costs of emission cuts. Such an approach may also be more consistent with historical experience in the SSJ sense. In this regard, this is the second contribution of the paper. We start by deriving a CO_2-income relationship based on a Cobb-Douglas type production function, which captures the standard economics idea that income in the long run depends on technology and factors of production. Since energy is a factor of production, CO_2 emissions associated with energy use becomes a determinant of income in the long run. Our economic model enables us to identify relevant economic variables in our empirical regression model. We then estimate our empirical model for the 19 OECD countries in a panel framework.

The Copenhagen Accord envisions that global warming should be limited to 2°C, which may require a 25% to 40% GHG emission reduction from 1990 levels by 2020 for

Annex I countries (IPCC, 2007). Based on our parameter estimates, we find that a 25% mandatory deduction in CO_2 emissions from 1990 will lead to a 5.63% decrease in the combined GDP of the 19 OECD countries, and a 40% deduction will result in a 12.92% loss in income (holding other relevant variables constant)! Our estimates are substantially higher than those in Paltsev, Reillya, Jacobya, and Morris (2009) and Dellink, Briner and Clapp (2010),[5] and suggest that the economic cost to limit climate change as envisioned in the Copenhagen Accord may be substantial and more research should be done before mandatory emission cuts are implemented.

The remainder of the paper is organized as follows: Section 2 examines the EKC in the 19 OECD countries. Section 3 studies the impact of mandatory emission cuts on income. Section 4 concludes the paper with a brief summary.

2 CO_2 emission forecasts based on the EKC

Data

In this paper, we focus on 19 high-income OECD countries. There are three reasons. First, since they have similar levels of technology, the income-emission model we develop in Section 3 is applicable. Second, these 19 countries' combined CO_2 emissions (according to our calculations) are 49% of the world CO_2 emissions in 1980 and 35% in 2007, which manifest their importance in climate change policy discussion. Third, the EKC suggests that emissions will decrease when income is high. Therefore, focusing on the countries with the highest incomes will enable us to estimate the

[5] For instance, Dellink, Briner and Clapp (2010) find that the economic cost of the Copenhagen Accord pledges is about 0.3% of GDP for both Annex I countries.

maximum deductions in emissions that the EKC may bring about. Our 19 countries do not include Germany, because its emissions data are not available until 1991. But in the robustness check section, we show that including Germany in the more recent sample period will not change our results qualitatively.

We obtain macroeconomic data used in this study from the Penn World Tables.[6] The CO_2 emissions data are from the US Energy Information Administration (http://www.eia.doe.gov/environment.html). Since the emissions data start in 1980 and the macroeconomic data from the Penn World Tables end in 2007, our sample period covers the period from 1980 to 2007. Table 1 contains summary statistics of the variables used in this paper.

A reduced-form approach based on the environmental Kuznets curve

Most previous studies use structural models to produce long-run forecasts of CO_2 emissions, which often depart substantially from past trends. Therefore, in this paper, we follow SSJ and employ a flexible reduced-form approach based on the EKC. The EKC hypothesis postulates an inverted U-shaped relationship between (logarithm of) levels of emissions of wastes per capita and (logarithm of) income per capita. That is, at low income levels, emissions are hypothesized to increase with income but at a slower pace; beyond a critical income level, emissions are conjectured to decrease as income further

[6] Data comes from Alan Heston, Robert Summers and Bettina Aten, Penn World Table Version 6.3, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, August 2009.

increases. Brock and Taylor (2010), among others, explain why, in theory, income may affect emissions in such a way.[7]

Empirically, researchers usually use the following reduced-form quadratic regression model to capture the EKC idea (i.e. SSJ; Stern, 2004 among others).

$$Log(\frac{E_{it}}{P_{it}}) = a_i + b_t + c_1 \log(\frac{GDP_{it}}{P_{it}}) + c_2 \left(\log(\frac{GDP_{it}}{P_{it}}) \right)^2 + e_{it} \quad (1)$$

where E_{it} is emissions, P_{it} is population, GDP_{it} is the total income measured by real Gross Domestic Product (GDP), a_i and b_t are country and year fixed effects, and ε_{it} is the error term capturing the effects of all other variables.

To visualize the EKC, Figure 1 presents the scatter graphs of the logarithm of real GDP per capital and that of CO_2 emission per capita for five major OECD countries as well as for 19 OECD countries as a whole from 1980 to 2007. The horizontal axis measures the log of real GDP per capita, while the vertical axis measures the log of CO_2 emissions per capita. An inverted U-shaped relationship seems to exist.

We next empirically estimate Equation (1) in a panel framework as in most EKC studies. The main purpose is to utilize the EKC parameter estimates to project emissions by 2050 as in SSJ. If the autonomous deductions in emissions due to the EKC are close to the target in popular proposals such as the Copenhagen Accord, mandatory emission cuts may not be necessary; on the other hand, if the projected reductions are still fall short of the target significantly, mandatory emissions cuts may have to be implemented. Panel A of Table 2 reports the fixed-effects panel regression results for the sample period from

[7] See Kijima, Nishide, and Ohyama (2010) for an excellent review.

1980 to 2007. As we can see, c_1 and c_2 have expected signs and are statistically significant at the 1% level.

Projected CO_2 emissions by 2050

To project future emissions by 2050 based on the EKC, we use a similar approach as in SSJ. First, we obtain the scenarios for GDP and population growth for OECD countries used by IPCC from Special Report on Emissions Scenarios (2000) (SRES). Table 3 summaries the IPCC’s assumptions. Four scenario "families", A1, A2, B1, and B2, are considered by IPCC. The A1 scenario family describes a future world of rapid economic growth and convergence among regions, and low population growth. The A2 scenario family describes a heterogeneous world with slow convergence and high population growth. The B1 scenario family describes a convergent world with the same low population growth as in the A1 storyline and an emphasis of global solutions to economic, social, and environmental sustainability. The B2 scenario family describes a world with moderate population growth, intermediate levels of economic development and an emphasis of local solutions to economic, social, and environmental sustainability.

Second, we project the emissions per capita by 2050 for each country in each scenario based on the panel parameter estimates in Panel A of Table 2 and the economic growth assumptions in Table 3. To do so, we need to project the time effects. One approached used by Holtz-Eakin and Selden (1995) is to set the time effect at its value in the last year of the sample, while another approach suggested by SSJ is to model it as a deterministic trend model. We first follow SSJ and estimate a linear time trend model over the entire sample from 1980 to 2007. The results are reported in Panel B of Table 2.

The linear trend is significant at the 10% level. However, a close examination of the time effects in Figure 2 suggests that the time effects in 1980 and 1981 may be outliners. We therefore re-estimate the time trend model over 1981 to 2007 and 1982 to 2007. As we can see, excluding the first two observations will eliminate the significance of the time trend. Therefore, we follow Holtz-Eakin and Selden (1995) and set the time effect at its value in the last year of the sample (i.e. 2007).

Finally, we project the total emissions of 19 countries in each scenario based on their projected emissions per capita (from Step 2) and the population growth assumptions from Table 3. The projected total emissions as well as historical emissions for the 19 OECD countries in each scenario are depicted in Figure 3. For comparison, we also include the IPCC projections. The horizontal axis indicates time, while the vertical axis measures the total emissions as a percentage of 1990 emissions. E is the historical emissions, IPCC is the IPCC projections, and EKC is the projections based on the EKC.

As we can see, the IPCC projections often depart from past trends substantially. In contrast, the reduced-form approach based on the EKC seems to produce the projections that are more consistent with past trends. Which projections are more accurate is not the focus of this paper. Instead, what we emphasize is that emissions in any case will not likely to decrease significantly below 1990 levels by 2020 if mandatory emission cuts are not implemented.

The Copenhagen Accord envisions that global warming should be limited to 2°C, which may require a 25% to 40% GHG emission reduction from 1990 levels by 2020 for Annex I countries (IPCC, 2007). However, based on the IPCC and EKC projections, emissions by 2020 will instead be about 20% above 1990 levels regardless of which scenario we look at and regardless of which approach we use. Therefore, our analysis suggests that the EKC (which is discussed extensively in the literature) will not lead to significant decreases in CO_2 emissions by 2020 and countries have to implement mandatory emission cuts to limit climate change.

There may be some econometrics problems when Eq. (1) is estimated in a regular panel framework. For instance, Stern (2004) emphasizes that emissions and income may have unit roots and the correlation from Eq. (1) may be spurious if these two variables are not cointegrated. We think that econometrics specifications should be based on theory not diagnostic tests. Since a lot of theories (i.e. Brock and Taylor, 2010) suggest that there is a long term EKC relationship, it may be plausible to estimate the Eq. (1) in a regular panel framework. Furthermore, our focus is not the EKC itself but emission projections. If the EKC relationship were weaker after we took into account all the econometrics problems as Stern (2004) indicates,[8] it would suggest even more aggressive mandatory reductions in emissions. In this sense, our analysis serves as a lower-bond for the need of mandatory reductions in emissions, and provides a motivation to study the cost of mandatory emission cuts.

3 Costs of mandatory emissions cuts

Methodology

There is a lot of research on economic costs of mandatory emission cuts. Most studies rely on structural models to assess the impact of emissions cuts. The structural approach has one major challenge in its complexity. In contrast, the cross-sectional

[8] See also Stern and Common (2001) and Perman and Stern (2003).

relationship between emissions and income motivates a simple reduced-form approach. Two noteworthy recent examples of using reduced-form approach in the global warming literature are Horowitz (2009) and Ng and Zhao (2010). Therefore, in this paper, different from previous studies, we employ a reduce-form approach to estimate the economic costs of emission cuts.

We start by deriving a CO_2-income relationship based on a Cobb-Douglas type production function, which captures the standard economics idea that income in the long run depends on technology and factors of production. Since energy is a factor of production, CO_2 emissions associated with energy use becomes a determinant of income in the long run.[9] More specifically, we consider the following production function[10]:

$$GDP_{it} = e^{\varepsilon_{ti}} A_{it} L_{it}^{\alpha} K_{it}^{\beta} EC_{it}^{\gamma} \tag{2}$$

where GDP_{it} is the real Gross Domestic Product (GDP), A_{it} represents technology, K_{it} represents capital, L_{it} stands for labor, and EC_{it} is energy consumption of country i in year t, respectively. ε_i captures the effects of all other variables, and $\alpha,\ \beta,\ \gamma < 1$. This model augments the standard Cobb-Douglas production function by taking into account a fact that energy is a factor of production required to produce output.

[9] Coondoo and Dinda (2002) find that for developed countries the causality between income and emission runs from emission to income.

[10] See Choinière and Horowitz (2006) for another application: they investigate the relationship between income and temperature using a Cobb-Douglas production function with temperature added as an input along with physical and human capital. Temperature lowers the marginal product of physical and human capital in their model.

Given the technology level at a point in time, there is a direct linear relationship between energy consumption and CO_2 emissions.[11] That is, $EC_{it} = c_{it} E_{it}$, where E_{it} again represents corresponding CO_2 emissions. Furthermore, let d_{it} represent the labor participation ratio and P_{it} be population. Then we have,

$$GDP_{it} = c_{it}^{\gamma} d_{it}^{\alpha} e^{\varepsilon_{it}} A_{it} P_{it}^{\alpha} K_{it}^{\beta} E_{it}^{\gamma} \qquad (3)$$

To get income per capita, we divide both sides by P_{it} . We further assume that the production function exhibits constant returns to scale (i.e. $\alpha + \beta + \gamma = 1$). Then we get

$$\frac{GDP_{it}}{P_{it}} = c_{it}^{\gamma} d_{it}^{\alpha} e^{\varepsilon_{ii}} A_{it} \left(\frac{K_{it}}{P_{it}} \right)^{\beta} \left(\frac{E_{it}}{P_{it}} \right)^{\gamma} \qquad (4)$$

Taking log on both sides, we have

$$\log\left(\frac{GDP_{it}}{P_{it}} \right) = \log(c_{it}^{\gamma} d_{it}^{\alpha} A_{it}) + \beta \log\left(\frac{K_{ti}}{P_{it}} \right) + \gamma \log\left(\frac{E_{it}}{P_{it}} \right) + \varepsilon_{it} \qquad (5)$$

Data on c, d and A are usually not available in practice. But if we focus on the countries with similar technology, it may be plausible to assume that c and A are the same across countries at a point in time and therefore $\log(c_{it}^{\gamma} A_{it})$ may be modeled by a time effect. The labor participation ratio may be country specific and change very slow over time. Therefore, it may be modeled by a country effect. That is, for countries with similar technology, we may have.

$$\log\left(\frac{GDP_{it}}{P_{it}} \right) = \mu_i + \tau_t + \beta \log\left(\frac{K_{ti}}{P_{it}} \right) + \gamma \log\left(\frac{E_{it}}{P_{it}} \right) + \varepsilon_{it} \qquad (6)$$

Eq. (6) can then be estimated in a panel framework.

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[11] See Pereira and Pereira (2010).

The EKC suggests that energy and therefore CO_2 emissions will become less important in the production function. To allow this nonlinearity, we include a quadratic term in our empirical model.

$$\log\left(\frac{GDP_{it}}{P_{it}}\right) = \mu_i + \tau_t + \beta \log\left(\frac{K_{ti}}{P_{it}}\right) + \gamma \log\left(\frac{E_{it}}{P_{it}}\right) + \delta\left(\log\left(\frac{E_{it}}{P_{it}}\right)\right)^2 + \varepsilon_{it} \qquad (7)$$

We focus on Equation (7) to estimate the reverse EKC relationship between income and CO_2 emissions. Since our model applies to countries that are homogenous in terms of technology, we focus on 19 high-income OECD countries and exclude Mexico, South Korea, Turkey, Greece, Spain, Portugal, and Eastern European countries which have substantial lower incomes. Since the Penn World Tables do not provide data for capital per person, we use investment share of GDP as a proxy for capital per person. Intuitively, a country that invests more in capital should have higher capital per person.

Empirical Results

We estimate Equation (7) with a fixed-effects panel regression. The coefficient estimates and the adjusted R^2 are reported in Panel A of Table 4. The estimated coefficient on the linear component of emissions is equal to 1.45 (t = 7.68), while that on the quadratic term is -0.27 (t = -6.71). The negative coefficient on quadratic term is consistent with the idea of the EKC.

We next estimate the costs of mandatory emission cuts. In the same spirit of Horowitz (2009), we measure the cost of an emission cut as the impact of a certain percentage decrease in emissions on the combined GDP of all 19 OECD countries (holding other relevant variables constant). Specifically, we use the coefficient estimates in Panel A of Table 4 to calculate the effect of a certain percentage decrease in all emissions on the combined GDP of all 19 countries in our sample (holding other relevant variables constant). To be comparable with the emission cuts required to limit climate change suggested by IPCC (2007), we look at the costs of emission cuts that are 20%, 25%, 30% 35% and 40% below 1990 levels. The results are reported in Panel B of Table 4.

The Copenhagen Accord envisions that global warming should be limited to 2°C, which may require a 25% to 40% GHG emission reduction from 1990 levels by 2020 for Annex I countries (IPCC, 2007). Based on our parameter estimates, we find that a 25% mandatory deduction in CO_2 emissions from 1990 will lead to a 5.63% decrease in the combined GDP of the 19 OECD countries, and a 40% deduction will result in a 12.92% loss in income (holding other relevant variables constant)! Our estimates are substantially higher than those in Paltsev, Reillya, Jacobya, and Morris (2009) and Dellink, Briner and Clapp (2010), and suggest that the economic cost to limit climate change as envisioned in the Copenhagen Accord may be substantial and more research should be done before mandatory emission cuts are implemented. This is the central finding of our paper.

Robustness checks

There is a large economic literature on trade and economic growth (i.e. Wacziarg and Welch, 2008). We therefore, add the openness indicator from the Penn World Tables to our model. Specifically, we estimate the following panel model.

$$\log\left(\frac{GDP_{it}}{P_{it}}\right) = \mu_i + \tau_t + \phi\log(Open_{it}) + \beta\log\left(\frac{K_{ti}}{P_{it}}\right) + \gamma\log\left(\frac{E_{it}}{P_{it}}\right) + \delta\left(\log\left(\frac{E_{it}}{P_{it}}\right)\right)^2 + \varepsilon_{it} \quad (8)$$

where Open is the openness indicator from the Penn World Tables. The regression results as well as the cost estimates of emission cuts are reported in Panel A Table 5. As we can see, adding the openness indicator does not change our previous findings materially.

Next, we focus a more recent sample period from 1991 to 2007. World economy is dynamic. Therefore, a more recent sample period may be better in terms of predicting impact of emission cuts. 1991 to 2007 is selected because German emissions data become available after 1990. As a result, we also can look at whether our results are robust if Germany is added to our sample. Panel B of Table 5 shows the results when Germany is not included, while Panel C of Table 5 presents the results when Germany is included. As we can see, the economic costs of emission cuts are still substantial even if we focus on the recent period. This finding is not dependent on whether Germany is included or not. Therefore, again, our findings suggest that the economic cost to limit climate change as envisioned in the Copenhagen Accord may be substantial, and more research should be done before mandatory emission cuts are implemented.

4. Conclusion

Climate change is recognized as one of the greatest challenges of our time, and CO_2 emissions are believed to be its major driving force. We ask two related questions in this paper. First, to limit climate change, do countries have to implement mandatory CO_2 emission cuts? Second, if mandatory cuts are required, what are the economic costs of such cuts?

Different from previous studies, we answer these two questions with the reduced-form approaches. Specifically, to answer the first question, we follow SSJ and project

CO_2 emissions based on the EKC with the 19 OECD countries' data from 1980 to 2007. We find that the EKC (which is discussed extensively in the literature) will not lead to significant decreases in CO_2 emissions even by 2050 for countries with the highest incomes. Therefore, mandatory emissions cuts are required to limit climate change.

To answer the second question, we first derive a CO_2-income relationship based on a Cobb-Douglas type production function, which is consistent with the standard economics idea that income in the long run depends on technology and factors of production. We then estimate our empirical model for the 19 OECD countries in a panel framework. Based on our parameter estimates, we find that a 25% mandatory deduction in CO_2 emissions from 1990 will lead to a 5.63% decrease in the combined GDP of the 19 OECD countries, and a 40% deduction will result in a 12.92% loss in income (holding other relevant variables constant)! Our estimates are substantially higher than those in previous studies, and suggest that the economic cost to limit climate change as envisioned in the Copenhagen Accord may be substantial and more research should be done before mandatory emission cuts are implemented.

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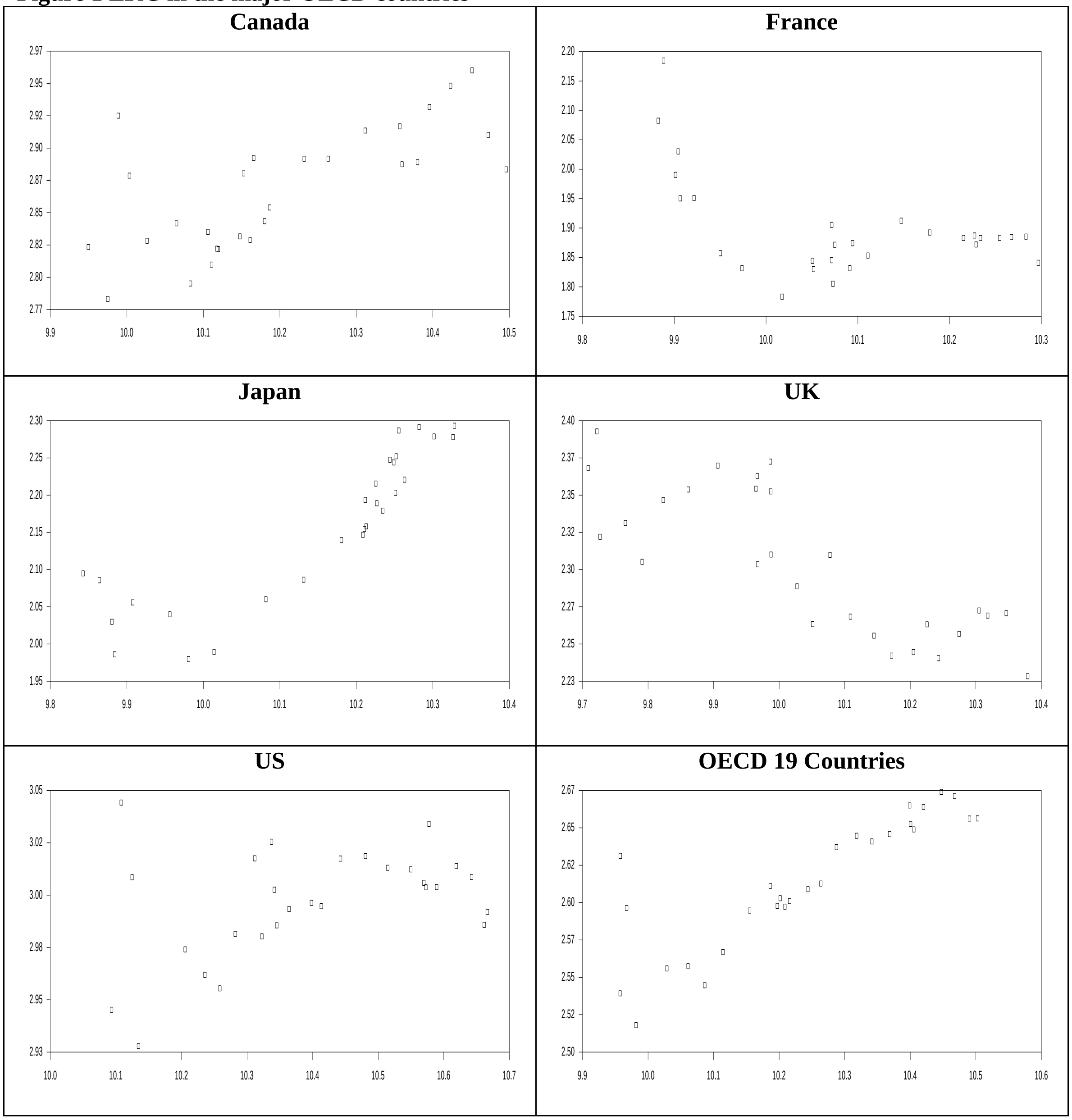
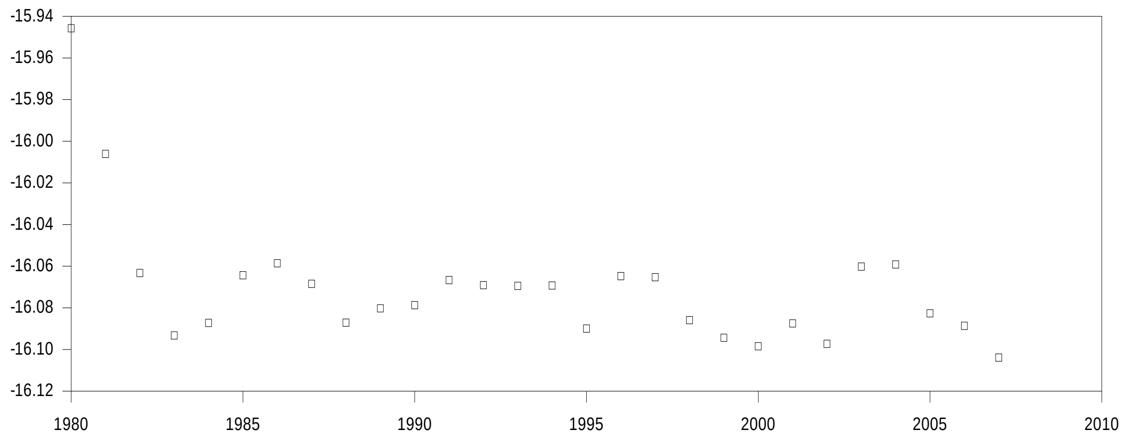
Figure 1 EKC in the major OECD countries



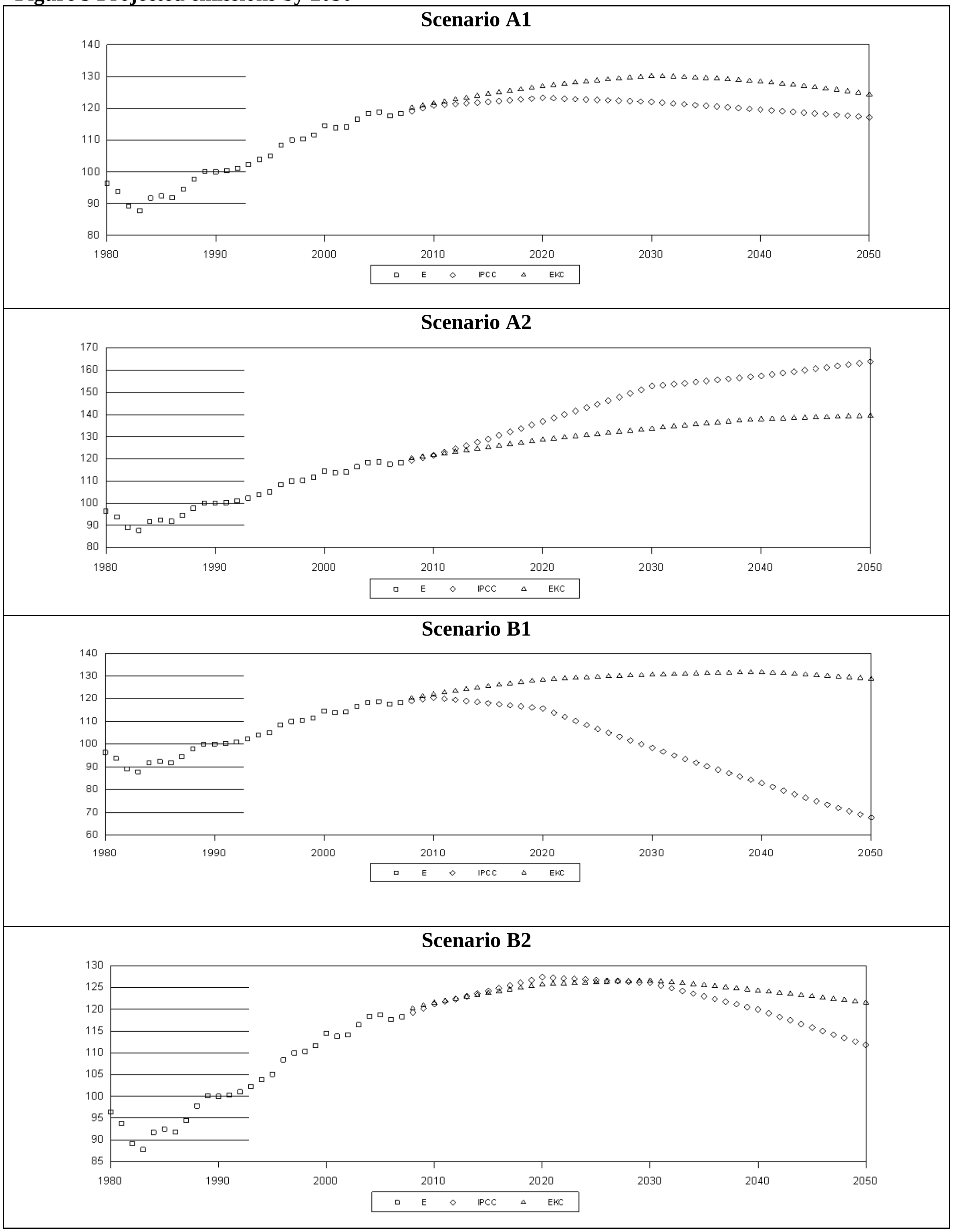
To visualize the EKC, Figure 1 presents the scatter graphs of the logarithm of real GDP per capital and that of CO2 emission per capita for five major OECD countries as well as for 19 OECD countries as a whole from 1980 to 2007. The horizontal axis measures the log of real GDP per capita, while the vertical axis measures the log of CO2 emissions per capita.

Figure 2 EKC Time Effects



Time effects estimates from the EKC panel regression.

Figure 3 Projected emissions by 2050



The projected total emissions as well as historical emissions for the 19 OECD countries in each scenario are depicted in Figure 3. The horizontal axis indicates time, while the vertical axis measures the total emissions as a percentage of 1990 emissions. E is the historical emissions, IPCC is the IPCC projections, and EKC is the projections based on the EKC.

Table 1 Summary Statistics 1980-2007

	GDP Per Capita (Constant Prices: Chain series)	CO2 Emission Per capita	Investment Share
Australia	20647	16.85	30.45
Austria	22206	7.82	28.03
Belgium	20912	13.37	27.27
Canada	21559	17.63	25.98
Denmark	20673	11.56	26.70
Finland	18983	10.37	29.86
France	19464	6.70	25.37
Iceland	22756	9.42	32.81
Ireland	19769	8.41	30.23
Italy	19089	7.26	28.73
Japan	20964	8.68	34.99
Luxembourg	40648	25.31	28.08
Netherlands	21605	14.73	24.85
New Zealand	15444	8.43	25.13
Norway	26052	8.62	32.48
Sweden	20209	7.17	21.44
Switzerland	25303	6.25	31.63
United Kingdom	18943	10.03	20.52
United States	27074	20.02	23.93

Table 1 contains summary statistics of the variables used in this paper.

Table 2 EKC 1980-2007

	Panel A: EKC Panel Estimates		
	c_1	c_2	Adj-R^2
Coefficient	7.89	-0.37	0.95
T-Statistics	9.24	-8.92	
	Panel B: Time Effects		
	1980-2007		
	Constant	Time Trend	Adj-R^2
Coefficient	-12.24	-0.0019	0.23
T-Statistics	-5.84	-1.83	
	1981-2007		
	-13.93	-0.0011	0.16
	-11.27	-1.73	
	1982-2007		
	-14.96	-0.0005	0.06
	-17.96	-1.34	

Panel A of Table 2 reports the fixed-effects panel regression results for the following EKC model.

$$Log(\frac{E_{it}}{P_{it}}) = a_i + b_t + c_1 \log(\frac{GDP_{it}}{P_{it}}) + c_2\left(\log(\frac{GDP_{it}}{P_{it}})\right)^2 + e_{it}$$

where E_{it} is emissions, P_{it} is population, GDP_{it} is the total income measured by real Gross Domestic Product (GDP), a_i and b_t are country and year fixed effects, and ε_{it} is the error term capturing the effects of all other variables. Panel B of Table 2 reports the results when the time effects from the EKC model are regressed on a deterministic time trend.

Table 3 IPCC population and GDP growth assumptions

	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
			Scenario A1		
	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
GDP per capita	0.017	0.016	0.016	0.016	0.016
Population	0.004	0.004	0.004	0.002	0.002
			Scenario A2		
	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
GDP per capita	0.012	0.010	0.010	0.016	0.005
Population	0.005	0.005	0.004	0.005	0.002
			Scenario B1		
	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
GDP per capita	0.020	0.018	0.013	0.011	0.012
Population	0.005	0.005	0.003	0.003	0.001
			Scenario B2		
	2001-2010	2011-2020	2021-2030	2031-2040	2041-2050
GDP per capita	0.019	0.011	0.008	0.009	0.008
Population	0.004	0.003	0.001	-0.001	-0.001

Table 3 summaries the IPCC's assumptions. Four scenario "families", A1, A2, B1, and B2, are considered by IPCC. The A1 scenario family describes a future world of rapid economic growth and convergence among regions, and low population growth. The A2 scenario family describes a heterogeneous world with slow convergence and high population growth. The B1 scenario family describes a convergent world with the same low population growth as in the A1 storyline and an emphasis of global solutions to economic, social, and environmental sustainability. The B2 scenario family describes a world with moderate population growth, intermediate levels of economic development and an emphasis of local solutions to economic, social, and environmental sustainability.

Table 4 Reverse EKC 1980-2007

	Panel A Panel regression results			
	β	γ	δ	Adj-R^2
Coefficient	0.30	1.45	-0.27	0.93
T-Statistics	8.19	7.68	-6.71	

Panel B Economic costs of mandatory emission cuts					
CO_2 Cut	20%	25%	30%	35%	40%
Cost	-4.02	-5.63	-7.59	-9.99	-12.92

We estimate the following model with a fixed-effects panel regression over the sample period from 1980 to 2007. The coefficient estimates and the adjusted R^2 are reported in Panel A of Table 4.

$$\log\left(\frac{GDP_{it}}{P_{it}}\right) = \mu_i + \tau_t + \beta \log\left(\frac{K_{ti}}{P_{it}}\right) + \gamma \log\left(\frac{E_{it}}{P_{it}}\right) + \delta\left(\log\left(\frac{E_{it}}{P_{it}}\right)\right)^2 + \varepsilon_{it}$$

where E_{it} is emissions, P_{it} is population, GDP_{it} is the total income measured by real Gross Domestic Product (GDP), K_{it} represents capital, μ_i and τ_t are country and year fixed effects, and ε_{it} is the error term capturing the effects of all other variables. Panel B of Table 4 reports the economic costs of mandatory emission cuts based on the parameter estimates in Panel A.

Table 5 Robustness checks

Panel A: Add Openness					
	Open	β	γ	δ	Adj-R^2
Coefficient	0.18	0.32	1.51	-0.29	0.93
T-Statistics	4.49	8.82	8.11	-7.18	
CO_2 Cut	20%	25%	30%	35%	40%
Cost	-3.46	-5.01	-6.94	-9.32	-12.23
Panel B: Sample 1991 – 2007 without Germany					
		β	γ	δ	Adj-R^2
Coefficient		0.40	1.18	-0.19	0.96
T-Statistics		10.05	4.83	-3.87	
CO_2 Cut	20%	25%	30%	35%	40%
Cost	-10.07	-12.41	-15.07	-18.14	-21.68
Panel C: Sample 1991-2007 with Germany					
		β	γ	δ	Adj-R^2
Coefficient		0.39	1.17	-0.18	0.96
T-Statistics		10.88	4.94	-3.95	
CO_2 Cut	20%	25%	30%	35%	40%
Cost	-9.03	-11.34	-13.97	-17.00	-20.49

We estimate the following panel model.

$$\log\left(\frac{GDP_{it}}{P_{it}}\right) = \mu_i + \tau_t + \phi\log(Open_{it}) + \beta\log\left(\frac{K_{ti}}{P_{it}}\right) + \gamma\log\left(\frac{E_{it}}{P_{it}}\right) + \delta\left(\log\left(\frac{E_{it}}{P_{it}}\right)\right)^2 + \varepsilon_{it}$$

where Open is the openness indicator from the Penn World Tables, E_{it} is emissions, P_{it} is population, GDP_{it} is the total income measured by real Gross Domestic Product (GDP), K_{it} represents capital, μ_i and τ_t are country and year fixed effects, and ε_{it} is the error term capturing the effects of all other variables.. The regression results as well as the cost estimates of emission cuts are reported in Panel A of Table 5.

We estimate the following model over the sample period from 1991 to 2007.

$$\log\left(\frac{GDP_{it}}{P_{it}}\right) = \mu_i + \tau_t + \beta\log\left(\frac{K_{ti}}{P_{it}}\right) + \gamma\log\left(\frac{E_{it}}{P_{it}}\right) + \delta\left(\log\left(\frac{E_{it}}{P_{it}}\right)\right)^2 + \varepsilon_{it}$$

The regression results excluding Germany are reported in Panel B of Table 5, while those including Germany are presented in Panel C of table 5.