# PART I

# CAUSES AND CONSEQUENCES OF ENVIRONMENTAL PROBLEMS

# 1. The development of global $CO_2$ emissions

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## 1. INTRODUCTION

Carbon dioxide ($CO_2$) emissions are the main cause of global warming and play the central role in discussions on climate change mitigation. The problem can be visualized by three trends depicted in Figure 1.1. Since 1960, global $CO_2$ emissions have increased from 10 Gt per year to 35 Gt in 2019 (solid line in Figure 1.1). This massive rise is mainly due to two factors: the increase in the earth's population from 3 billion to 7.7 billion in 2019, and the strong economic growth of most nations in the past 60 years. Parallel to the increase of emissions which result mainly from burning fossil fuels for heating, transportation and energy production, the concentration of $CO_2$ molecules in the atmosphere as measured by parts per million (ppm) increased (dotted line in Figure 1.1). Fortunately, not all emissions end up in the atmosphere. A very large amount (54 percent: see Friedlingstein et al., 2020) of it is absorbed by the earth's ecosystem, particularly by plants, oceans and soil. But the emission levels exceeded the absorption capacity of the earth such that the concentration of $CO_2$ in the atmosphere increased as well from 317 ppm in 1960 to 411 ppm in 2019. This increase is much slower than one would expect, which is due to the greening of the planet (Zhu et al., 2016). The third trend shows the development of emission levels net of population growth. The curve for per capita emissions goes up if the increase in wealth (and therefore consumption) increases more strongly than population growth. And this is what happened on average during the last 60 years: wealth and consumption of every individual on earth increased on average, resulting in an increase in the per capita emission levels from 3 tons per year per person in 1960 to 4.6 tons per year and person in 2019. This trend is not linear, and for the period between 1980 and 2000 it is flat because the increase in population was stronger than in wealth, resulting in stable per capita emissions.

The interesting and important question is how many anthropocentric emissions the earth can deal with. How many emissions are acceptable? This question was more or less explicitly answered by the Paris Agreement in 2015, where the world community agreed to limit the average global warming to 1.5 to 2 degrees Celsius. According to an estimate by the Intergovernmental Panel on Climate Change (IPCC) this target implies approximately 30 Gt of anthropogenic $CO_2$ per year (Friedlingstein et al., 2014; IPCC, 2014; Meinshausen et al., 2009). Given that the world population will increase to approximately 10 billion by 2050 (UN, 2015) the two-degree target would allow emissions of 3 tons per person and year. In 2019 the world average per person was 4.6 tons. Hence, the average per capita emissions have to decrease by one third per capita in order to limit global warming to a maximum of 2 degrees.

Figure 1.2 depicts the production-based per capita emissions by country. We ranked the top 10 countries with the largest emissions as well as the 10 countries with the lowest emissions in 2019. Some countries at the top of the distribution have very small populations and were treated as statistical outliers, and accordingly are not shown in Figure 1.2. Also, most African countries have very small emission levels and were grouped into one category (Africa),

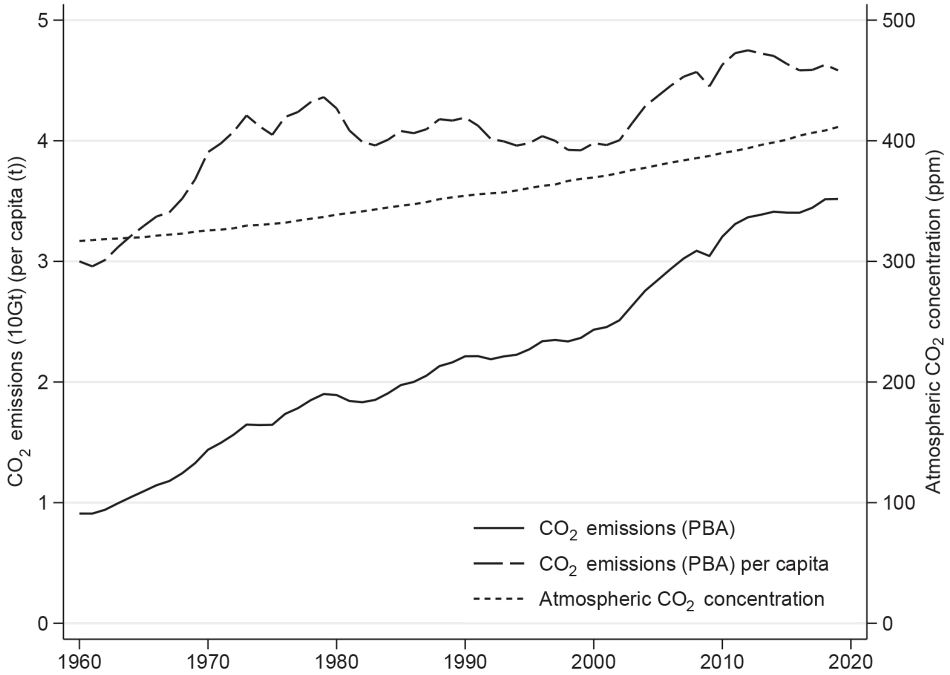
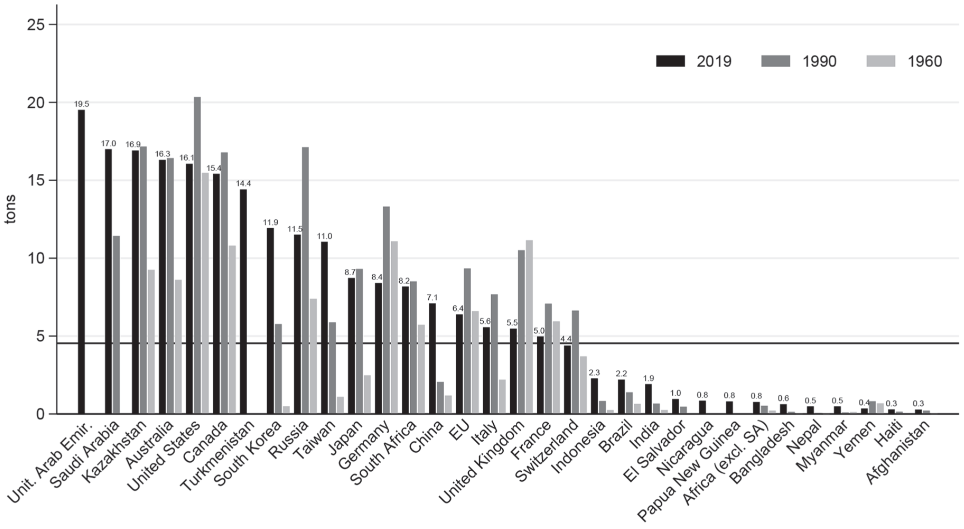


*Figure 1.1 The development of global $CO_2$ emissions*

*Source:* Data source is the US National Oceanic & Atmospheric Administration (2021) for atmospheric carbon dioxide concentration, Global Carbon Atlas (Friedlingstein et al., 2020) for production-based accounting (PBA) of anthropogenic carbon dioxide emissions, and the World Bank (2021) for the world population.

without South Africa. Furthermore, emission levels are also shown for groups of countries such as the EU, since they form a political union with respect to climate policy.

Figure 1.2 shows the country ranking with respect to $CO_2$ per capita emissions in 2019. As can be seen, the variation is very large. Countries at the top, such as the USA, emitted 16.1 tons in 2019, making the US one of the biggest polluters in terms of per capita $CO_2$ emissions. Figure 1.2 also depicts the trend by showing emission levels for 1960, the start of our data, and for 1990, which serves as a benchmark in the Kyoto Protocol. The development for the US reveals that emission levels were already very high in 1960 (15 tons p.c.), reached 20 tons in the 1990s, and are still among the highest in 2019. In comparison, emission levels in the EU are 6.4 tons. Figure 1.2 also reveals that the EU made some progress in reducing emissions, since emission levels dropped from 9 tons in 1990 to 6.4 tons in 2019, a decrease of almost 30 percent. At the bottom of the distribution are mainly poor countries in Africa, Asia and Latin America. India, which is a large player due to its population size, has per capita emissions of only 1.9 tons, and African countries (excluding South Africa) have on average emissions of less than 1 ton per capita. The global average was 4.6 tons in 2019 (solid line in Figure 1.2), which demonstrates that the world is still far away from the 3 tons that are presumably compatible with limiting climate change. For countries at the top of the distribution, sustainable



*Note:* The figure shows the top 10 and bottom 10 countries, G7, and BRIICS members with respect to carbon dioxide emissions per capita following production-based accounting (PBA) ranked by 2019. Excluded are some countries from the top of the distribution with a very small population size (Qatar, Trinidad and Tobago, Kuwait, Brunei Darussalam, Bahrain, and Mongolia).
*Source:* Data source is the Global Carbon Atlas (Friedlingstein et al., 2020).

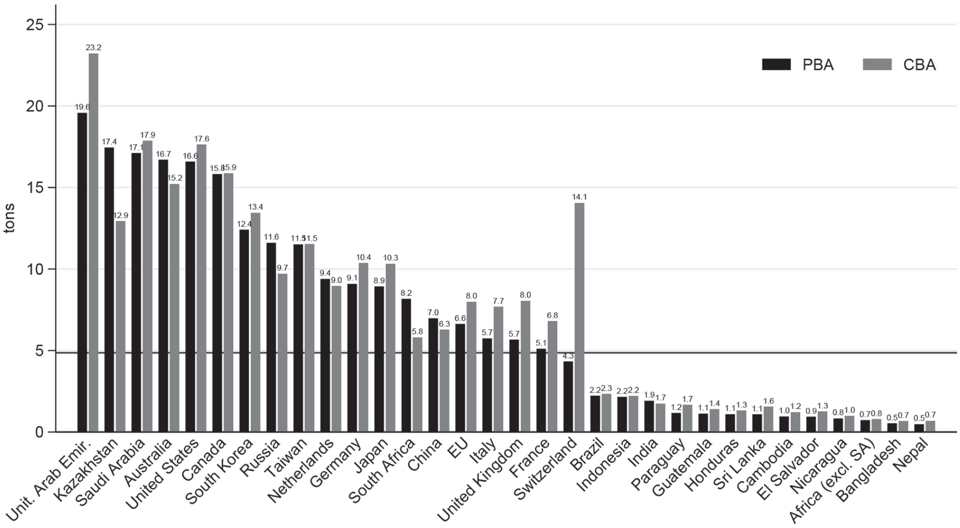
*Figure 1.2* *$CO_2$ emissions per capita (PBA) in international comparison 1960, 1990 and 2019*

emission levels are a long way off, and even the EU has to cut emissions by half in order to reach sustainable levels.

Another big player in terms of total $CO_2$ emissions is China. In fact, China overtook the USA in total emissions. Its per capita emissions reached 7.1 tons and the trend shows a steep increase from 1 ton in 1960, 2 tons in the 1990s to the level of 7.1 tons in 2019. Hence, China has caught up with the EU and there is no indication so far that this trend will reverse.

Recently, a discussion on the accounting schemes of $CO_2$ emissions has emerged. Some authors suggest that production-based accounting is misleading, since many rich countries relocate $CO_2$ intensive industries into poor countries, because they have less strict emission controls. Therefore, rich countries look better than they really are, since they have relatively low emission levels but reimport $CO_2$ emissions through the import of products. Hence, these authors suggest that a fairer accounting should not only include the emissions that are produced in a given country, but should also include the emissions contained in imports (Liu, 2015; Zhang and Fang, 2019; but see also Franzen and Mader, 2018, 2020). To take a look at the empirical validity of this argument, Figure 1.3 displays a comparison of production-based (PBA) and consumption-based (CBA) accounting of emission levels. Inspection of Figure 1.3 reveals a few interesting facts.

First of all, the world's average per capita must be the same for both accounting schemes. This is the case for the data we use, the Global Carbon Atlas: both averages are 4.9, as indicated by the solid line in Figure 1.3. Second, some rich countries do have more per capita

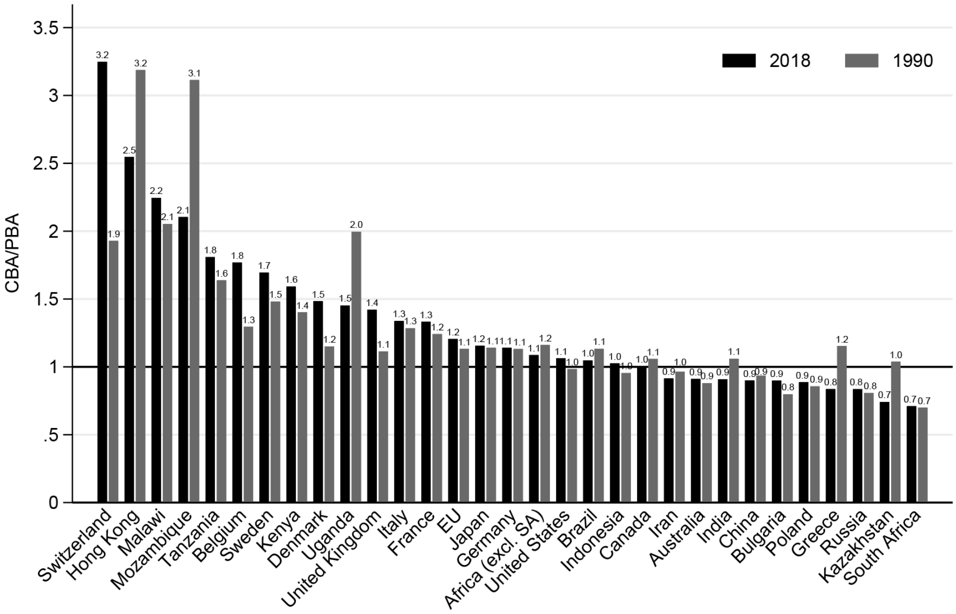


*Note:* The figure shows the top 10 and bottom 10 countries, G7, and BRIICS members with respect to production-based accounting (PBA) and consumption-based accounting (CBA) of carbon dioxide emissions per capita. Excluded are some countries from the top of the distribution with a very small population size (Qatar, Trinidad and Tobago, Kuwait, Brunei Darussalam, Bahrain and Mongolia). The solid line indicates the average of the countries with both, reported CBA and PBA emissions (mean = 4.9 tons).
*Source:* Data source is the Global Carbon Atlas (Friedlingstein et al., 2020).

*Figure 1.3 $CO_2$ emissions per capita in international comparison 2018: PBA vs CBA*

consumption-based emissions as compared to production-based emissions. Particularly, this is the case for Switzerland. The country ranks among the top countries in terms of GDP per capita and has very low PBA (4.3 tons p.c.). However, its CBA is 3.3 times as large (14.1 tons p.c.). Hence, the consumption of $CO_2$ emissions of inhabitants of Switzerland is much larger than is indicated by its PBA. A different example is China. The country had 7 tons in PBA in 2018 and only 6.3 in terms of CBA, indicating that some of the countries' $CO_2$ emissions are due to exports. However, on average the countries' differences between PBA and CBA are small and, more importantly, not related to GDP, and the correlation is r = 0.9. In other words, there are also many poor countries that have higher levels of CBA than PBA, and a detailed analysis of the ratio of CBA to PBA shows that this ratio is not driven by GDP (Franzen and Mader, 2018, 2020). Thus, the thesis that China's $CO_2$ emissions are high because China is the workbench of the world is not true. China is exporting a lot of products but it also has high imports. On average a switch of accounting schemes does not profit poor countries and it does not make rich countries look worse. The finding that countries' wealth is on average not related to the ratio of CBA to PBA can also be demonstrated by a simple country ranking in terms of the ratio of CBA to PBA. If the ratio is larger than 1, a country has more CBA than PBA and the opposite is true for ratios below 1. Figure 1.4 presents such a ranking and reveals that besides some rich countries, many poor countries have ratios exceeding 1.

The rest of this chapter proceeds in two further steps. In the next section, we present the statistical analysis of the drivers of national $CO_2$ emissions. We use the latest available data



*Note:* The figure shows the top 10 and bottom 10 countries, G7, and BRIICS members with respect to the ratio of consumption-based accounting (CBA) to production-based accounting (PBA) of carbon dioxide emissions (CBA/PBA).
*Source*: Data source is the Global Carbon Atlas (Friedlingstein et al., 2020).

*Figure 1.4 The ratio of CBA vs PBA of $CO_2$ emissions per capita in international comparison: 2018 vs 1990*

containing 186 countries with yearly reported $CO_2$ levels starting in 1980 through 2019 provided by the Global Carbon Atlas (Friedlingstein et al., 2020). Because of its longitudinal structure the data is suitable for investigating the causal influence of some key variables by calculating fixed effects estimates. We then extend the model by incorporating new variables into the analysis, which have been discussed lately in relation to $CO_2$ levels such as the extent of foreign trade, or energy prices (Dietz et al., 2010; Franzen and Mader, 2016; Jorgenson and Clark, 2011; Rosa and Dietz, 2012; Rosa et al., 2015; Sarkodie et al., 2020; Xia et al., 2020). Finally, the main results are summarized and discussed in the last section.

## 2. DRIVERS OF $CO_2$ EMISSIONS

The differences displayed in Figure 1.2 raise the question of what is causing them. Past research has focused on the famous IPAT formula (Commoner et al., 1971; Ehrlich and Holdren, 1970, 1971), which specifies that the environmental impact of a country is a function of population size, wealth and technology. The basic assumptions of the IPAT formula and its statistical interpretation (STIRPAT) have been confirmed by older studies using cross-sectional data analysis (Dietz and Rosa, 1997; Rosa et al., 2004; York et al., 2003) as well as by more recent studies that use methodologically more advanced statistical methods exploiting the longitudinal data structure (Cole and Neumayer, 2004; Jorgenson et al., 2014; Liddle, 2015; Poumanyvong and Kaneko, 2010). Newest results from the latter line of research estimate that a 1 percent increase in population increases $CO_2$ emissions by roughly 1 percent (Liddle, 2014). Additionally, a 1 percent increase in wealth (measured by the purchasing power parity (PPP) of GDP per capita) increases $CO_2$ emissions in the range of 0.57 to 0.97 (Liddle, 2015). Furthermore, some prior studies incorporate the energy intensity of the industrial sector and the share of non-fossil fuels of energy production as indicators of a country's technology. As energy intensity increases by 1 percent per GDP of output (measuring higher inefficiency), $CO_2$ emissions increase by 0.31 percent, and $CO_2$ is reduced if a country has a larger proportion of non-fossil energy production (Liddle, 2015). Hence, also new results using longitudinal statistical analysis confirm the assumptions specified by the IPAT formula that population, wealth and technology are the important drivers of national $CO_2$ emissions.

For our statistical analyses we compiled data from newest available sources (see Table 1A.1 in the Appendix for a complete description of all variables). Most importantly, we used the Global Carbon Atlas (GCA), which contains yearly information on $CO_2$ emissions from 1960 to 2019 for 186 countries. However, country numbers are reduced due to missing data in some covariates or due to statistical outliers (a detailed list of the countries included can be obtained from the authors). Information on countries' population size is taken from the World Bank (WB). Data on GDP (converted into PPP) is obtained from the International Monetary Fund (IMF). The IMF data has the advantage of providing PPP GDP information for every country starting 1980 onwards. In comparison, data from the World Bank starts in 1990 and would restrict the observation period to 30 years. Information on the share of electricity production from renewable sources is gathered from the International Energy Agency (IEA). Data on import and export rates and information about countries' GDP share of industry or service is taken from the World Bank (WB).

We estimate the effects via a standard fixed effects (FE) panel regression model in which the yearly changes of $CO_2$ emissions (from the mean) are regressed on the yearly changes in the independent variables (Brüderl and Ludwig, 2015; Wooldridge, 2010). The model can be written as:

$$y_{it} - \bar{y}_i = \left(\boldsymbol{x}_{it} - \bar{\boldsymbol{x}}_i\right)\beta + \boldsymbol{Z}_t\gamma + \varepsilon_{it} - \bar{\varepsilon}_i \tag{1.1}$$

$y_{it}$ denotes the (natural logarithm of) $CO_2$ per capita of country $i$ in year $t$. $\bar{y}_i$ denotes the countries' average for the whole observation period. $\boldsymbol{x}_{it}$ denotes the vector of all exogenous variables for country $i$ in time $t$, and $\bar{\boldsymbol{x}}_i$ the averages for the whole observation period. $\boldsymbol{Z}$ is a vector of dummy variables which controls period effects for all countries. It takes the value ~~of~~ for the given year and zero otherwise for all $t \neq 1$. $\varepsilon_{it}$ refers to a country's time varying stochastic error term. For statistical purposes and for ease of interpretation we took the natural logarithm of all exogenous variables. The fixed effects model given in equation (1.1) has the advantage of taking only the within country variations into account. Any unobserved between country differences, therefore, cannot bias the estimation. Under the assumption that $\boldsymbol{x}_{it}$ and $\varepsilon_{it}$ are not correlated (strict exogeneity) a fixed effects model is an adequate statistical tool to estimate the unbiased causal effect of the independent variables $\boldsymbol{X}$ on $Y$. The assumption is

*Table 1.1* *Country and year fixed effects regressions of PBA of $CO_2$ emissions (per capita)*

| Model | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Dependent Variables | $CO_2$ | $CO_2$ per capita | | | |
| Population | 1.05*** | | | | |
| | (0.10) | | | | |
| GDP per capita | 0.84** | 0.62*** | 0.68*** | 0.55** | 0.49*** |
| | (0.28) | (0.16) | (0.19) | (0.19) | (0.09) |
| GDP per capita squared | −0.02 | −0.01 | −0.02 | −0.01 | |
| | (0.02) | (0.01) | (0.01) | (0.01) | |
| Imports | | | 0.02 | 0.05 | −0.11 |
| | | | (0.03) | (0.04) | (0.09) |
| Exports | | | −0.04 | −0.04 | 0.05 |
| | | | (0.04) | (0.03) | (0.06) |
| Industry | | | 0.05 | 0.05 | −0.04 |
| | | | (0.03) | (0.05) | (0.17) |
| Services | | | −0.06 | −0.07 | −0.12 |
| | | | (0.05) | (0.07) | (0.25) |
| Electricity Production from Renewable Sources | | | | −0.10*** | −0.07** |
| | | | | (0.02) | (0.02) |
| Energy Prices | | | | | −0.18** |
| | | | | | (0.06) |
| n × T | 6659 | 6659 | 5296 | 3524 | 831 |
| n | 186 | 186 | 176 | 133 | 39 |
| adjusted $R^2$ within | 0.40 | 0.28 | 0.22 | 0.34 | 0.49 |

*Note:* * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.
PBA = production-based accounting.
Unstandardized regression coefficients with standard errors in brackets. All standard errors are clustered by country and year, and therefore robust with respect to autocorrelation. All effects can be interpreted as elasticities because all variables are logged. All variables are described in Table 1A.1 in the Appendix. Model 5 excludes GDP p.c. squared, because its inclusion leads to severe misspecification bias, since the relationship is all linear.

violated if there are measurement errors in $\boldsymbol{x}_{it}$ , unaccounted period effects (external shocks), or omitted variables that are correlated with $Y$ and $\boldsymbol{X}$, such as heterogeneous trends. We account for possible period effects by including the yearly time dummies ($\boldsymbol{Z}$) into the analyses.

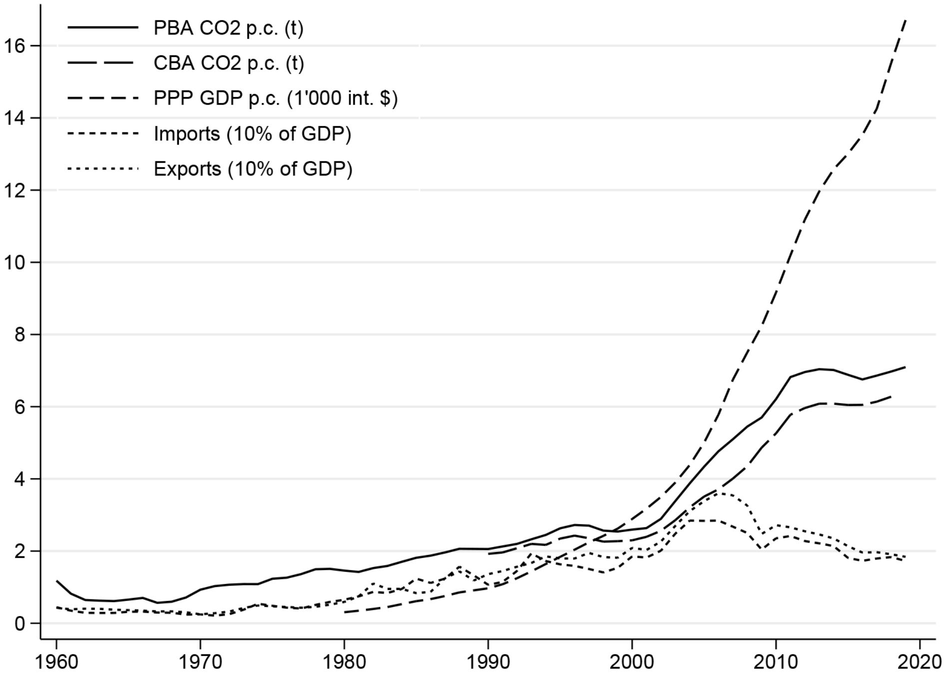
We begin our analyses by first estimating the effect of countries' population growth and wealth increase (PPP of GDP) on $CO_2$ levels. The results show (see Table 1.1, Model 1) that a 1 percent increase in population is related to a 1.05 percent increase in $CO_2$ emissions. This result is not very surprising and closely replicates former studies (Liddle, 2015; Franzen and Mader, 2016). A population estimate of 1 percent suggests that $CO_2$ emissions are simply proportional to population size. A quadratic population term (not shown in Table 1.1) is statistically not significant, suggesting that there are neither exponential nor marginal decreasing effects of population (for similar results see also Jorgenson and Clark, 2010).

Similar in size is the effect of wealth as measured by countries' GDP on $CO_2$ emissions. The estimation suggests that a 1 percent increase in wealth is almost proportionally related to $CO_2$ emissions, that is, it increases emissions by 0.84 percent. Furthermore, the model includes a quadratic term of wealth. This effect is practically zero, suggesting that wealth is linearly related to emissions. Hence, we do not observe an Environmental Kuznets Curve (EKC) with respect to $CO_2$ emissions. In difference to other pollutants, $CO_2$ emission do not decrease with increasing $CO_2$. Both variables, population and wealth, almost explain half (40 percent) of the variation of GDP emissions. This demonstrates how important these determinants are.

The proportionality of the population effect suggests that models of $CO_2$ emissions are better specified by using emissions per capita instead of total country level emissions, because this incorporates population into the dependent variable and thereby circumvents potential problems of multicollinearity. For instance, countries with large populations are often developing countries, and this status can be related to both $CO_2$ levels (e.g. by outdated technology) and GDP. The estimates would therefore be biased due to an omitted variable problem. The results of a model using the $CO_2$ emissions per capita are displayed in Model 2 of Table 1.1. The results suggest that every increase in GDP per capita by 1 percent increases $CO_2$ emissions by 0.6 percent. Again, the quadratic term of logged GDP is practically zero, suggesting that the effect of wealth on $CO_2$ is linear and not reversely U-shaped as suggested by the EKC, which confirms former findings (Aslanidis and Iranzo, 2009; Azomahou et al., 2006; Cavlovic et al., 2000; Jorgenson, 2012; Jorgenson and Clark, 2012; Liddle, 2015; Wagner, 2008; Wang and Su, 2020).

Next, we are concerned with extending the IPAT formula and the analyses of prior studies by taking further possible causes of $CO_2$ emissions into account. One argument often heard in the debate is that some developing countries have high emission rates because they have become industrial production sites of the world. Hence, $CO_2$ emissions are created in developing countries, but the goods are consumed in the affluent nations (so-called pollution-haven hypothesis) (Chichilnisky, 1994; Jorgenson, 2012). To test this argument, we take the countries' export and import activities into account. Furthermore, we also incorporate countries' economic structure measured by the share of GDP due to industrial production or the service sector as compared to the agricultural sector. The results of this extension are presented in Model 3 of Table 1.1. Surprisingly, our results suggest that the amount of international trade is not related to the countries' per capita $CO_2$ emissions. The effect of imports as well as the effect of exports (both measured as percentages of GDP) is practically zero. This is a surprising result and in contradiction to the pollution-haven hypothesis. In theory, imports should decrease production-based emissions, because countries with high imports of products or services do not need to produce them within the country. Exports, in contrast, should increase production-based emissions. However, the empirical evidence suggests that neither imports nor exports affect the $CO_2$ emission level of countries. We also combined import and export rates into a variable measuring the percentage of foreign trade relative to a country's GDP. However, also the percentage of foreign trade does not produce any significant result in our model (not shown). This finding can also be demonstrated with respect to China. Figure 1.5 shows that GDP and $CO_2$ per capita have been rising steeply in China since 2005. However, both import and export rates have been falling during the same time period. Hence, exports are not the main driver of $CO_2$ levels in China (see also Arto and Dietzenbacher, 2014). We also find no reliable evidence regarding an economy's share of the industrial or service sector with respect to GDP, suggesting that a shift to the service sector does not go hand-in-hand with reductions of $CO_2$ per capita, as often assumed.

Following Rosa and Dietz (2012) (see also Rosa et al., 2015) we extend the model further by incorporating indicators of environmental policies. Environmental policies can more or less directly intervene with regard to energy supply and energy consumption. The supply side is often influenced by encouraging (and subsidizing) electricity production by renewable



*Source:* Data source for $CO_2$ is the Global Carbon Atlas (GCA), for GDP the International Monetary Fund (IMF), and for foreign trade the World Bank (WB).

*Figure 1.5 Comparison of trends in $CO_2$ emissions, GDP and foreign trade for China*

resources, for example electricity produced by water, solar, wind or biomass. We integrated the percentage in electric energy supply produced by renewable sources. As expected, the results indicate that every increase of 1 percent reduces the per capita $CO_2$ emissions by 0.10 percent. This substitution effect of non-renewable electricity production by renewable sources is surprisingly small. However, the result replicates former findings (Franzen and Mader, 2016; York, 2012). One reason for this might be that renewable energy sources are very volatile, depending on weather conditions such as wind, sunshine, or water supply. Supposedly, high volatility reduces the substitution effect, particularly if storage capacity or smart grids are not available. Moreover, electricity production consists generally only of a small fraction of the total energy consumption, and accordingly can also provide only a small reduction in emissions.

An often used instrument for reducing emissions is the price mechanism, and many countries tax oil and electricity in order to encourage reduction efforts. Internationally comparable energy price time series are hard to find in international statistics and are only available for OECD countries. This reduces the number of countries for this analysis to 39. The results are displayed in Model 5 of Table 1.1 and show that an increase in energy prices by 1 percent reduces $CO_2$ emissions by 0.18 percent. Also, this effect is small and far from proportional. One possible interpretation is that the elasticity of the price effect depends on the substitutability of energy. Prices are expected to have only small effects if the substitutability is low. This seems to be the case for the overall energy demand. Price elasticities can be low for two reasons. On one hand increases in prices are often soon compensated by increases in wealth. On the other hand it is often difficult for consumers to substitute the consumption of energy, for example to avoid heating oil or gasoline in the short run. In the long run, heating systems or modes of transportation can be subject to change to other and more efficient technologies or changes in the mode of transportation. A further reason might be that many energy prices, particularly the oil price, are volatile. High volatility makes it hard for consumers to adapt persistently to energy-reducing life styles.

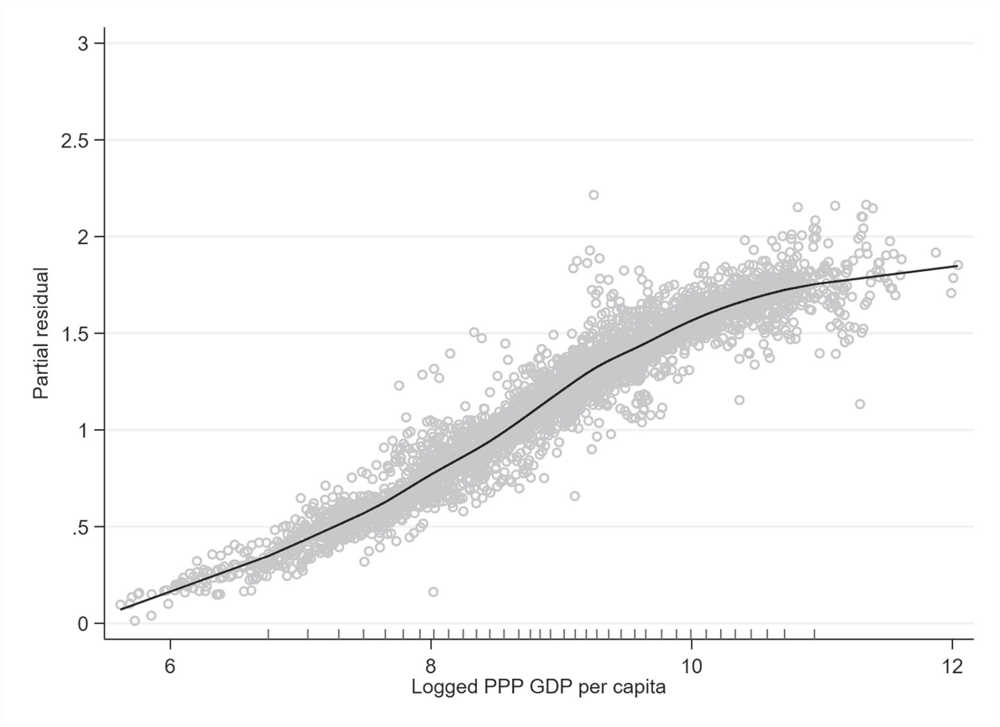
Many studies that investigate the drivers of $CO_2$ emissions include the energy used to produce a unit of GDP (energy intensity) or fossil fuel consumption in the regression model. $CO_2$ emissions are of course not caused by GDP itself, but by the energy used to produce the GDP. Hence, fossil fuel consumption is a mediator for the GDP effect. Since we are interested here in the total effect of GDP, we did not include fossil fuel consumption. The problem with energy intensity is that it does not capture only the carbon content of energy use but also the general efficiency of an economy. Hence, in this chapter we limit the analysis to the more straightforward modeling of the total effect of GDP. This total effect on $CO_2$ emissions can be visualized more thoroughly by taking a look at the countries' residuals obtained from the fixed effects panel regression by using penalized splines as suggested by Ruppert et al. (2003). Such an analysis is depicted in Figure 1.6.

In contrast to the results depicted in Table 1.1, the plotting of the residuals suggests that the effect of GDP on emission levels is not linear but decreases with higher GDP. However, this diminishing effect of GDP is based on relatively few observations, which is the reason why the quadratic term of GDP in Table 1.1 is not statistically significant. Hence, there is some indication that the emission intensity of wealth is diminishing, even though this finding is statistically unreliable.

Next, we investigate whether the findings presented so far change if the dependent variables are not production-based $CO_2$ emissions but consumption-based emissions per capita. The results of this analysis are depicted in Table 1.2. First, an analysis of countries' total CBA demonstrates that population size is again linearly related to CBA emissions, as in the analysis using PBA.

Second, the effect of GDP seems to be much stronger than suggested using PBA and has a negative quadratic term. However, the effect sizes become smaller in later models in which further variables are taken into consideration. Hence, the quadratic term is statistically not significant in Model 4 and the size of GDP reduces to levels similar to those when using PBA. What does change are the effects of imports and exports. Models 3 and 4 show that imports increase CBA and exports reduce them as expected by the definition and calculation of CBA. Furthermore, electricity from renewable energy sources as well as prices decrease emissions as in the PBA model (see Model 5). Overall, an analysis of emissions using CBA arrives at very similar conclusions as the analysis using PBA, except for the effects of imports and exports. The effect sizes vary a little between both models (particularly in Model 5) but some variation of effect sizes is of course due to fewer countries when using CBA as a result of data availability.

We performed a number of robustness checks for the models in Tables 1.1 and 1.2. First we recalculated the models using fixed effects (FE) panel regressions with country-specific constants and slopes (FEIS) (Brüderl and Ludwig, 2015) to test the parallel trend assumption,



*Note:* The plot shows the partial residual for every country year (grey circles) and the smoothed mean (black curve) as calculated from the fixed effects regression (Model 4 of Table 1.1) with penalized splines (Ruppert et al., 2003) for logged PPP GDP per capita instead of polynoms. Ticks on the x-axis represent the intervals of the splines.

*Figure 1.6 The effect of GDP on $CO_2$ emissions (PBA)*

as well as first difference and second difference regressions to account for feedback effects (Wooldridge, 2010). Moreover, we tested all parameters for linearity using penalized splines FE models (Ruppert et al., 2003). Furthermore, we ran regressions dropping one country each time to test for statistical outliers. In addition, the robustness of standard errors was checked using non-parametric bootstrapping. None of these checks had any substantial influence on the estimates. Finally, the robustness of all estimates with respect to model specification was assessed using the procedure suggested by Young and Holsteen (2017). The potential influence of omitted variables was examined using the method suggested by Frank (2000). Also, these tests indicate that the models shown in Tables 1.1 and 1.2 are robust. All models and all robustness checks were calculated using the statistical software package STATA 16.1.

## 3. SUMMARY AND DISCUSSION

This chapter investigates the determinants of national $CO_2$ emissions per capita by using more extensive and more accurate data sources than prior studies. The analyses are based on 186 countries for which yearly measurements of $CO_2$ per capita and various covariates exist for

*Table 1.2 Country and year fixed effects regressions of CBA of $CO_2$ emissions (per capita)*

| Model | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Dependent Variables | $CO_2$ | $CO_2$ per capita | | | |
| Population | 1.05*** | | | | |
| | (0.18) | | | | |
| GDP per capita | 1.98*** | 0.87*** | 0.83*** | 0.72** | 0.49*** |
| | (0.37) | (0.23) | (0.21) | (0.22) | (0.11) |
| GDP per capita squared | −0.08*** | −0.03* | −0.03* | −0.02 | |
| | (0.02) | (0.01) | (0.01) | (0.01) | |
| Imports | | | 0.16** | 0.18** | 0.20** |
| | | | (0.05) | (0.05) | (0.06) |
| Exports | | | −0.27*** | −0.25*** | −0.17 |
| | | | (0.05) | (0.05) | (0.09) |
| Industry | | | 0.15 | 0.12 | −0.38 |
| | | | (0.09) | (0.10) | (0.44) |
| Services | | | −0.13 | −0.18* | −0.83 |
| | | | (0.08) | (0.08) | (0.65) |
| Electricity Production from Renewable Sources | | | | −0.09*** | −0.09** |
| | | | | (0.02) | (0.03) |
| Energy Prices | | | | | −0.18*** |
| | | | | | (0.04) |
| n × T | 3371 | 3371 | 3079 | 2559 | 752 |
| n | 118 | 118 | 117 | 110 | 38 |
| adjusted $R^2$ within | 0.44 | 0.16 | 0.22 | 0.24 | 0.31 |

*Note*: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.
CBA = consumption-based accounting.
Unstandardized regression coefficients with standard errors in brackets. All standard errors are clustered by country and year, and therefore robust with respect to autocorrelation. All effects can be interpreted as elasticities because all variables are logged. All variables are described in Table 1A.1 in the Appendix. Model 5 excludes GDP per capita squared, because its inclusion leads to severe misspecification bias, since the relationship is all linear.

the period between 1980 and 2019. First, the descriptive results show that the world is still far away from sustainable emission levels. In 2019 every inhabitant on earth emitted on average 4.6 tons of $CO_2$. Assuming that the world population will reach roughly 10 billion by the middle of the century (and stabilizes thereafter) and given that the atmosphere of the earth can cope with roughly 30 Gt of $CO_2$ emissions, the sustainable per capita emission is about 3 tons per year. Most industrialized countries exceed 3 tons per capita extensively. Even the most sustainable countries in Europe (e.g. France, or Switzerland) still have emission levels of about 5 tons per capita and would need a reduction of around 40 percent to become sustainable with respect to greenhouse gas emissions. Reductions of 40 percent are still very ambitious but appear feasible. Other countries such as the USA, Australia or Canada have emission levels of about 16 tons and would therefore need reductions of about 80 percent. Hence, many countries have a long way to go and will have to take ambitious measures in order to keep the 2-degree goal. The world is still far away from sustainable emission levels and this is particularly true for rich countries.

Second, we analyzed the determinants of emissions by using fixed effects panel regression models. Such models avoid cross-sectional comparisons, which are often biased due to unobserved heterogeneity between the countries. Our analyses replicate former results (particularly

Liddle, 2015; Franzen and Mader, 2016) and show that a country's population size is proportionally related to $CO_2$ emissions. This means that population growth is a major threat for the effort to reduce $CO_2$ emissions. Furthermore, our analyses suggest that the growth of wealth (GDP per capita) is mostly linearly related to growth in $CO_2$ emissions. The estimated elasticity of 0.5 to 0.8 and the penalized splines indicate that the growth of emissions is marginally decreasing at higher levels of GDP. However, increases in wealth are still strongly related to increases to $CO_2$ emissions, particularly for lower GDP ranges as in developing countries.

Besides these replications our chapter offers some new and interesting findings. First, we find that a shift from the industrial sector to the service sector is not related to reductions in $CO_2$ emissions as often assumed (e.g. Fourcroy et al., 2012). Second, we show that the share of foreign trade does not determine $CO_2$ levels when PBA is taken into account. This result is surprising since the literature often hypothesizes that some developing countries (e.g. China) have high emission levels because they have become the workbench for more affluent countries. An analysis using CBA does show that imports increase and that exports reduce consumption-based emissions as expected by design. However, we also show that countries with high PBA usually also have high CBA and that switching from one accounting scheme to another does not reveal any new substantial insights. Particularly, the ratio of CBA to PBA is not related to GDP, and the determinants of $CO_2$ emissions are basically the same, irrespective of the accounting scheme.

We also incorporate countries' political effort into our models by taking into consideration the proportion of electricity stemming from renewable resources. Our results suggest that a high proportion of renewable energy production decreases emission levels. Finally, we also show that higher energy prices reduce $CO_2$ emission levels. Both higher consumer prices for fossil fuels and subsidies for renewable energy production are the most important measures of environmental policies. Our analyses demonstrate that they are effective. However, the estimated elasticities of prices and the proportion of renewable energy are surprisingly small, and investigations of why this is the case are fruitful avenues for future research.

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# APPENDIX

*Table 1A.1 Variable description*

| Variable | mean | within ( $\overline{x}_i$ ) | | | between $(x_{it} - \overline{x}_i + \overline{\overline{x}})$ | | | N (n × T) | n | Description | Data Source |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | sd | min. | max. | sd | min. | max. | | | | |
| PBA $CO_2$ (Mt) | 108.15 | 245.36 | -3054.36 | 6688.10 | 445.90 | 0.01 | 4900.15 | 12164 | 213 | PBA $CO_2$ emissions p.c. of fossil fuel use and industrial processes (cement production, carbonate use of limestone and dolomite, non-energy use of fuels and other combustion) attributed to the country in which goods and services are produced. Excluded are: short-cycle biomass burning (such as agricultural waste burning) and large-scale biomass burning (such as forest fires). | GCA |
| PBA $CO_2$ per capita (t) | 4.98 | 3.93 | -44.59 | 75.55 | 7.10 | 0.03 | 52.71 | 12.164 | 213 | | |
| CBA $CO_2$ (Mt) | 228.36 | 236.67 | -2586.91 | 4109.35 | 734.67 | 0.61 | 5846.87 | 3449 | 119 | CBA $CO_2$ emissions p.c. of fossil fuel use and industrial processes attributed to the country in which goods and services are consumed (CBA $CO_2$ = PBA $CO_2$ − $CO_2$ exports + $CO_2$ imports). | GCA |
| CBA $CO_2$ per capita (t) | 6.58 | 2.13 | -9.22 | 31.74 | 6.95 | 0.07 | 33.54 | 3449 | 119 | | |
| Population | 26.11 | 27.79 | -403.93 | 511.94 | 102.01 | 0.01 | 1087.87 | 12019 | 201 | Total population. Unit: 1 million. | WB |
| GDP per capita (1000 | 13.29 | 8.08 | -42.86 | 87.35 | 15.65 | 0.57 | 95.64 | 6853 | 190 | Gross domestic product (GDP) p.c. based on purchasing power parity (PPP). PPP GDP is GDP converted to international dollars using PPP rates. Data are in constant international dollars based on the 2017 International Comparison Program (ICP) round. | IMF |
| Imports | 41.34 | 12.89 | -78.59 | 166.64 | 24.41 | 9.74 | 160.77 | 8217 | 190 | Imports resp. exports of goods and services measured as a share of GDP. Unit: % of GDP. | WB |
| Exports | 35.75 | 12.41 | -87.96 | 133.66 | 27.08 | 0 | 228.99 | 8217 | 190 | | |

| Variable | mean | within ( $\overline{x}_i$ ) | | | between $(x_{it} - \overline{x}_i + \overline{\overline{x}})$ | | | N (n × T) | n | Description | Data Source |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | sd | min. | max. | sd | min. | max. | | | | |
| Industry, value added | 26.77 | 5.95 | -21.36 | 69.31 | 12.37 | 6.50 | 77.10 | 7543 | 195 | Industry corresponds to the International Standard Industrial Classification (ISIC) divisions 10–45. The origin of value added is determined by the ISIC, revision 3. Unit: % of GDP. | WB |
| Services, value added | 50.27 | 6.87 | 9.59 | 109.37 | 12.68 | 29.33 | 89.93 | 7038 | 188 | Services correspond to ISIC divisions 50–99. The industrial origin of value added is determined by the ISIC, revision 3. Unit: % of GDP. | WB |
| Electricity Production from Renewable Sources | 35.05 | 11.09 | -27.30 | 91.28 | 32.41 | 0 | 99.32 | 6012 | 142 | Sources of electricity refer to the inputs used to generate electricity. Electricity production from renewable sources comprise hydroelectric, geothermal, solar, tides, wind, biomass and biofuels.<br>Unit: % of electricity production. | IEA/ WB |
| Energy Prices | 59.23 | 25.84 | -42.18 | 147.84 | 53.32 | 0.08 | 173.04 | 1100 | 39 | Energy prices are consumer prices for the items electricity, gas and other fuels as defined under the Classification of Individual Consumption According to Purpose (COICOP 04.5) and fuel and lubricants for personal transport equipment (COICOP 07.2.2). Data are expressed as index corrected by IMF PPP rates (2015 = 100 for the US). | OECD, IMF |

*Note*: PBA = production-based accounting; CBA = consumption-based accounting; p.c. = per capita; GCA = Global Carbon Atlas; IEA = International Energy Agency; IMF = International Monetary Fund; OECD = Organisation for Economic Co-operation and Development; WB = World Bank.