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Toxic Income as a Trigger of Climate Change

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Abstract: The rate of CO_2 emissions concentration in the atmosphere increases the likelihood of significant impacts on humankind and ecosystems. The assumption that permissible levels of greenhouse gas emissions cannot exceed the global average temperature increase of 2 °C in relation to pre-industrial levels remains uncertain. Despite this uncertainty, the direct implication is that enormous quantities of fossil fuels have, thus far, wrongly been counted as assets by hydrocarbon firms as they cannot be exploited if we want to keep climate under certain control. These are the so-called "toxic assets". Due to the relationship among CO_2 emissions, GDP, energy consumption, and energy efficiency, the concept of toxic assets can be transferred to toxic income, which is the income level that would generate levels of CO_2 emissions incompatible with keeping climate change under control. This research, using a simulation model based on country-based econometric models, estimated a threshold for income per capita above which the temperature limit of 2 °C would be surpassed. Under the business as usual scenario, average per capita income would be $14,208 (in constant 2010 USD) in 2033; and under the intervention scenario, which reflects the commitments of the COP21 meeting held in Paris in December 2015, the toxic revenue would be $13,433 (in constant 2010 USD) in 2036.

Keywords: climate change; CO_2 emissions; toxic income; contraction and convergence; Paris agreement; intended nationally determined contributions (INDC)

JEL Classification: Q43; Q54; Q57

1. Introduction

There is a high degree of scientific consensus regarding to the level of global warming that is causing climate changes. Global mean temperature rise, due to CO_2 and other greenhouse gases (GHG) concentration levels in the atmosphere, should not exceed 2 °C from pre-industrial times. The agreement on this value was reached at the Conference of the Parties (COP) 16, held in Cancún in 2010 [1]. This political target was established based on several studies [2,3], which had calculated the first estimation of the emission reductions needed. That threshold has been subject to some criticism and revision, even by the very same authors that helped to define it. To keep the temperature below 2 °C [1–4], the emission reduction in 2020 was estimated to be around 25–40% comparing to 1990 baseline levels, and 50–80% for 2050. One of the reasons for this skepticism is the high level of uncertainty involved to reduce emissions [5]. Scientists also estimate the critical threshold for CO_2 concentration levels in the atmosphere to be within 450 and 500 ppm of CO_2 based on the 2 °C

rise [2] (parts per million (ppm) is the ratio between the number of molecules in a gas and the number of molecules in dry air [6]). Above this level, impacts on global climate regulation would be irreversible. These approaches have also been contested by some authors [7] who doubt the usefulness of the concept of climate stability. Only a holistic approach (economic, social and environmental) in the international context can avoid the major ecological disaster humanity has been facing in the last centuries, originated by global warming and climate change.

The level of CO_2 emissions, and therefore the concentration in the atmosphere, depends on energy consumption, mostly composed of fossil fuels. Since energy consumption is strongly linked to economic growth and Gross Domestic Product (GDP), as shown by several studies [8–11], the existence of a critical threshold for greenhouse gases in the atmosphere could imply the existence of a critical level for fossil fuels and therefore, for income. Above that level, we would interfere with climate regulation.

One could argue that the link between energy consumption and GDP alone is not enough, as the world could change its energy mix towards low-carbon options. In fact, there is an ongoing debate about this issue. On the one hand, there are economies decarbonizing prior to 1990, although at only 0.3% per year [12]. This is the case for China and some other economies. A structural decomposition analysis for China found that the country had reduced carbon intensity especially due to structural changes in the economy and through the substitution of energy sources [13]. However, total emissions kept growing in the analyzed period. The same approach was used for the Baltic countries, finding improvements only in carbon intensity but not in total carbon emissions [14]. This optimism is shared by other authors who assert that well-being could be decoupled from energy consumption and carbon emissions [15].

On the other hand, some authors [16] show how carbon emissions have been rising by more than 2% per year since 1990, and the carbon intensity reductions, agreed in the Copenhagen pledges, would easily be surpassed by GDP growth rates. South Korea is a great example of a fast-growing country increasing its carbon intensity [17]. Some other authors [18] are skeptical about decarbonization approaches and question some of the assumptions made in mitigation models, which tend to discontinue the relation between energy consumption and GDP, i.e., leapfrogging. The authors, however, point out that historical and current trends do not support those assumptions, making leapfrogging less likely.

Decarbonization is needed, but it will be costly [19] and it should go along demand-side measures such as establishing caps for energy consumption [20]. However, despite the literature discussed above and the ongoing discussions in policy and academic forums, nowadays the world is not experiencing a process of decarbonization, as shown in Figure 1.
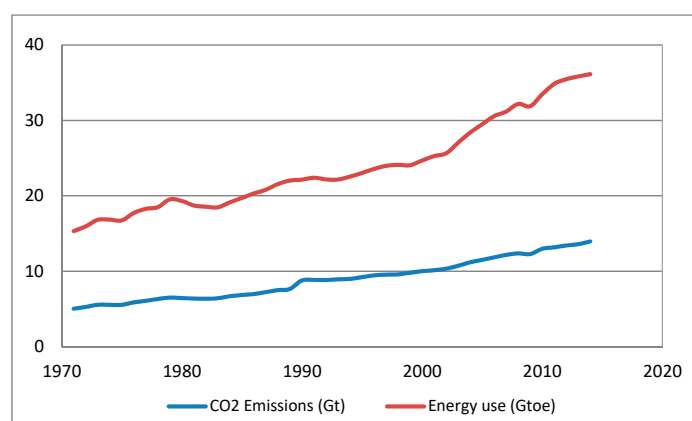
Figure 1. Global carbon emissions and primary energy, 1971–2013. Source: [21].

In the 44 years period from 1971 to 2014, the link between energy use and carbon emissions has remained close. In the period 1971–1980, world energy consumption increased, on average, at 2.4% per year, while CO_2 emissions increased at a yearly rate of 2%. Despite of the advances in energy efficiency and in the share of renewable sources, CO_2 emissions have increased in relative terms with respect to

energy consumption. This result is in line with the work of some authors [22] who found that a scenario of no climate change or no technology transfer fits better with historical trends for India, the USA and Europe. Therefore, by considering the link between energy and carbon emissions, as well as between energy consumption and GDP as stated above, this research did not enter the discussion of decarbonization directly, but included it in two ways: (i) by considering the improvements in energy efficiency that can come with the transfer of technology; and (ii) by accounting for recent voluntary commitments, the so-called Intended Nationally Determined Contributions (INDC), presented in the Paris Agreement in the COP21 that took place in Paris in December 2015.

This research relied also on the approach of contraction and convergence (C&C), introduced in 1996 by Aubrey Meyer at the Global Commons Institute in the UK [23–25]. The main idea of the approach is that we could consider the atmosphere as global commons to which every individual would have the same right of access. That would imply having the same right to emit greenhouse gases. Under this approach, global emissions should be distributed among countries in a per capita egalitarian way, taking as a reference one base year, for instance 2014. The goal would be that emissions per capita would be equal for all countries in a target year, for example 2050. This would imply that countries with emission levels above their target would need to reduce their levels, so that every country would converge to the equal per capita level defined for the final year.

Due to the relation between CO_2 emissions, GDP, energy consumption and energy efficiency, a certain level of income could be understood as toxic when it is accompanied by a level of CO_2 emissions incompatible with keeping climate change under certain control.

This new concept is regarded as useful for understanding human-nature relations. Moreover, it helps in understanding income inequality among nations. To test the concept, a simulation model was designed that estimates, under certain assumptions or parameters, the year in which toxic income would be reached. This exercise is not exempt from limitations, the main one being that the level of uncertainty increases as the period simulated increases. However, this limitation is only relative in the sense that the interest does not lie on the particular value for toxic income but on its dynamics over time.

Toxic Income

Conventional economic theory asserts that one of the main goals of economic policy is to increase the income level [26]. For instance, the axiom of non-satiation preferences assumes that more is better; but this is not necessarily true, as higher consumption levels imply higher environmental impacts, as in the case with CO_2 emissions. Under this consideration, one could ask if a particular level of income could be considered "toxic" in the sense that it could induce to CO_2 emissions incompatible with climate regulation.

According to accounting rules, oil companies usually record among their assets oil and coal reserves valued at market prices. This helps companies to increase their total assets: the more reserves a company has, the wealthier that company is. However, what would happen if all those reserves were extracted and burnt?

One of the clearest and most updated answers to that question is found in [27]. According to the authors, maintaining temperature rise below 2 °C implies that we have to keep in the ground one third of current oil reserves, half of natural gas reserves, and 82% of coal reserves until year 2050. The implication of this is that hydrocarbon companies are accounting in their books some toxic assets, and therefore their balances can be questioned [28].

When speaking of income, we are referring to a distribution of per capita income, since not all countries have the same levels of per capita income, and even within each country disparities on income arise. Future income distribution depends on the different growth trajectories of each country. In a simplified way, the fastest-growing countries are the upper-middle income countries, followed by the low-middle income countries, with high-income and low-income countries lagging behind. These different rates of growth are modifying the distribution of (toxic) income.

Generally speaking, increases in economic income might be harmful for the environment, but there are actions of effective decarbonization and distributive improvements. Other factors that affect the determination of toxic income are energy efficiency (GDP/energy consumption) and carbon intensity (CO_2 emissions/GDP). Both variables are closely related to the degree of technological development of a country and the economic structure of a country, as shown, for instance, by York et al. [29]. In a very simple way, with more technology we can find less energy consumption and less CO_2 emissions in relative terms. Similarly, in a very simplified way, we can say that industrial economies have higher levels of emission of pollutants than agrarian or services economies. Of course, we have to consider the levels of affluence or intensity of consumption. The Jevons' paradox also works here, i.e., efficiency improvements can lead to a reduction in prices and, therefore, to an increase in consumption that ends up with higher total levels of consumption (and emission of pollutants) per capita [30].

Finally, the uncertainty mentioned above about the critical thresholds of CO_2 concentration of greenhouse gases (GHG) (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) induces a high degree of uncertainty in the distribution of toxic revenue.

Thus, the toxic income would be the per capita income distribution that would generate levels of GHG emissions incompatible with the maintenance of climate change under control. Thus, toxic income depends on the atmospheric concentration of GHG, which depends on population, consumption levels, economic growth trajectories of different countries, energy efficiency, carbon intensity and physical conditions. The toxic income is also a dynamic concept as it depends on the changes in these different variables over time.

2. Data

Data sources used to estimate toxic income are the following: "World Development Indicators" (WDI) database of the World Bank [21]; "World Population Prospects" of the United Nations, Department of Economic and Social Affairs, Population Division [31]; and the European Environment Agency (EEA) [32]. We selected the following series: population [21,31], total and per capita energy consumption, total and per capita CO_2 and GHG emissions, total energy consumption, total and per capita real GDP (base year 2010) [21] and atmospheric greenhouse gas (GHG) concentrations (EEA) [32]. World Bank's income groups were used for grouping countries: low income, middle income (lower and upper) and high income.

Tables 1–5 describe the global framework for the variables mentioned above: population, GDP, CO_2 emissions and energy consumption, grouped by income levels.

Table 1. Population.

Income Group	Number of Countries	Population		Annual Growth Rate 1992–2014 (%)
		2014		
		(Millions)	% Share	
High income	78	1176	16.2	0.7
Upper middle income	56	2541	35.0	0.9
Lower middle income	52	2927	40.3	1.7
Low income	31	625	8.6	2.8
World	217	7269	100.0	1.3

Source: [21].

Table 2. GDP.

Income Group	GDP			Per Capita GDP	
	2014		Annual Growth Rate 1992–2014 (%)	2014	Annual Growth Rate 1992–2014 (%)
	(Trillion US$2010)	% Share		(US$2010)	
High income	48.2	65.5	2.1	40,983	1.4
Upper middle income	19.3	26.2	4.8	7577	3.9
Lower middle income	5.8	7.8	5.0	1968	3.2
Low income	0.36	0.5	3.9	578	1.1
World	73.6	100.0	2.9	10,119	1.5

Source: [21].

Table 3. CO_2 Emissions.

Income Group	CO_2 Emissions			Per capita CO_2 Emissions	
	2014		Annual Growth Rate 1992–2014 (%)	2014	Annual Growth Rate 1992–2014 (%)
	(Gt)	% Share		(t)	
High income	12.9	35.7	0.4	11.0	−0.2
Upper middle income	16.8	46.4	3.7	6.6	2.8
Lower middle income	4.3	11.9	3.1	1.5	1.4
Low income	0.2	0.4	2.4 *	0.3	−0.3 *
World	36.1	100	2.2	5.0	0.9

Source: [21]. * 1998–2014.

Table 4. Energy consumption.

Income Group	Energy Use			Per Capita Energy Use	
	2014		Annual Growth Rate 1992–2014 (%)	2014	Annual Growth Rate 1992–2014 (%)
	(Gtoe) *	% Share		(Toe)	
High income	5.6	42.2	0.8	4.8	0.1
Upper middle income	5.6	42.4	3.3	2.2	2.4
Lower middle income	1.9	14.3	2.6	0.6	0.9
Low income	0.2	1.2	2.9 **	0.4	0.3 *
World	14.0	100	2.1	1.9	0.8

Source: [21]. * toe: Tons of oil equivalent. ** 2000–2014.

Table 5. Energy efficiency (PIB/Energy).

Income Group	Energy Efficiency	
	2014 ($/Koe) *	Annual Growth Rate 1992–2014 (%)
High income	8.62	1.3
Upper middle income	3.42	1.6
Lower middle income	3.04	2.5
Low income	1.28	1.4 **
World	5.27	0.9

Source: [21]. * koe: Kilograms of oil equivalent. ** 1996–2014.

Data in Tables 1–5 present a reality in the world with high levels of inequality in income levels, CO_2 emissions, energy consumption, and energy efficiency, with gaps between countries that seem difficult to reduce. For instance, the high-income group of countries represents 16.2% of world population, while is responsible for 65.5% of world GDP, 35.7% of CO_2 emissions, and 42.2% of energy consumption, and they have an average energy efficiency of 8.62 $/koe. On the other hand, countries of the lower middle income category represent 40.3% of world population, but they only generate 7.8% of world GDP, 11.9% of CO_2 emissions, and 14.3% of world energy consumption, and they do have a much lower energy efficiency at only 3.04 $/koe. In other words, an average citizen of a high income country has an average GDP 20.9 times higher, emits 7.3 times more CO_2, and has an energy consumption eight times higher than an average citizen of a lower middle income country. Moreover, energy efficiency is also 2.8 times higher in high income countries.

Methodology

Even though projections for CO_2 emissions considering a number of future scenarios by the Intergovernmental Panel on Climate Change (IPCC) exist, to estimate toxic income, we need projections that establish a parametric relation between CO_2 emissions, GHGs and income (measured by GDP). This is why econometric models were used to establish the relation between the variables. In a country-base way, the following econometric models were applied:

$$\text{Linear model}: \quad CO2_t = \beta_0 + \beta_1 y_t + \beta_2 E_t + \varepsilon_t$$

$$\text{Linear spline model}: CO2_t = \beta_0 + \beta_1 y_{t|y_0} + \beta_2 y^*_{t|y_0} + \beta_3 E_t + \varepsilon_t$$

$$\text{Quadratic spline model}: CO2_t = \beta_0 + \beta_1 y_{t|y_0} + \beta_2 y^2_{t|y_0} + \beta_3 y^*_{t|y_0} + \beta_4 E_t + \varepsilon_t$$

where

t is the time index;
$CO2_t$ is per capita CO_2 emissions;
y_t is per capita GDP in year t;
y_0 is the income threshold between the two sections of the regression;
E_t is energy efficiency defined as: GDP/energy consumption; and
ε_t is the stochastic error with mean value of zero and constant variance.

$$y_{t|y_0} = min(y_t, y_0) = \begin{cases} y_t \ if \ y_t \le y_0 \\ y_0 \ if \ y_t > y_0 \end{cases}$$

$$y^*_{t|y_0} = max(y_t - y_0, 0) = \begin{cases} 0 \ if \ y_t \le y_0 \\ y_t - y_0 \ if \ y_t > y_0 \end{cases}$$

Without accounting for energy efficiency, these models allow expressing several functional forms for the relation GDPpc–CO_2pc emissions: positive or negative linear function (or spline), environmental Kuznets curve (EKC) (inverse-U or inverse-V), and weak environmental Kuznets curve (Γ-curve or N-curve, that is, inverse-U or inverse-V shape, followed by a constant, positive or negative trench). These functional forms allow adjusting data in a very acceptable manner as well as creating long-term projections (20–30 years) for the dependent variable (CO_2pc).

The traditional EKC presents an inverted U-shaped empiric relation between income and pollution. In theory, higher income causes at first an increase in environmental impact, while this is reduced when income reaches a certain value. The peak of the inverted U is the inflection point of pollution. In the weak version of the EKC, once the inflection point is reached, pollution does not decrease but remains stable for a good review of the EKC, see [33].

To get an econometric model for a specific country, the following procedure was used.

1. First, we verified that emissions per capita and income per capita were co-integrated. For all countries, both time series were integrated of order 1, $I(1)$, with the exception of China, whose time series were integrated of order 2, $I(2)$. Then, the parameters were estimated using ordinary least squares (OLS). All econometric equations generated stationary residual at 5% level except for China and the Democratic Republic of Congo, whose residual were stationary at 10% level of significance. Therefore, the estimated parameters by OLS continued having good properties. In fact, the estimators were super consistent; they converged to the true value at a rate 1/T, instead of the habitual convergence ratio $1/\sqrt{T}$ [34].

2. For low income countries, we applied only the linear model; for lower-middle income countries, we selected between the linear and the linear spline model. In both cases, the assumption is made of a positive relation between CO_2 emissions and income. For upper middle and high income countries, we selected among the three models. The final section of the econometric function may have a positive, negative, or null slope, for those countries. The selection of the final model to be used was linked to the lowest value for the Akaike Information Criterion (AIC).

3. In the case of spline regression models, for each value of income, y_t, a regression was estimated, and then the income threshold y_0 was computed minimizing the Akaike information criterion, that is, $y_0 = \min\limits_{y_t} AIC$.

4. Additionally, errors autocorrelation was verified. In the presence of autocorrelation, the correction term AR (1) was applied.

5. Finally, we only included countries with a coefficient of determination R^2 larger than 0.6.

We ended up with 76 countries, which make up 76.7% of world's population and 76.9% of world's CO_2 emissions. A summary of the number of countries per income level and the resulting econometric regressions is presented in Table 6.

Table 6. Econometric models.

Income Group	Econometric Model			Number of Countries	Percentage of World's	
	Linear	Linear Spline	Quadratic Spline		Population (%)	CO$_2$ Emissions (%)
High income		8	23	31	12.8	28.6
Upper middle income	3	4	18	25	30.6	38.9
Lower middle income	3	12		15	29.9	9.3
Low income	5			5	3.4	0.1
Total	11	24	41	76	76.7	76.9

Low income countries have a real problem of data availability. Only 10 out of 31 countries included in this group have complete time series for energy consumption in the period 1971–2014. Data on variables such population, GP and CO_2 emissions are complete. The outcome was that half of these countries show deficient econometric adjustments. This is also due to their lack of a strong industrial sector, which implies the link between GDP per capita and CO_2 emissions per capita is not clear. There may also be problems with the reliability of data. However, the use of 5 out of 31 countries belonging to this group does not generate an important bias to our results. This is explained as follows: (1) the group of low income countries represents a small share in global CO_2 emissions (0.4%, see Table 3) and global income (0.5%, see Table 2); and (2) the econometric results are extended to the income group by means of expansion factors. In 2014, these five countries represented 25.4% of population, 38.2% of CO_2 emissions and 17.7% of income of their group, therefore the possibility of a bias is reduced.

As an example, the results of the parameters estimated for the USA, China, India and Ethiopia are shown in Table 7. Figure 2a–d shows the regression graphs. The complete estimates are provided in Appendix A.

(a) United States

(b) China

(c) India

(d) Ethiopia
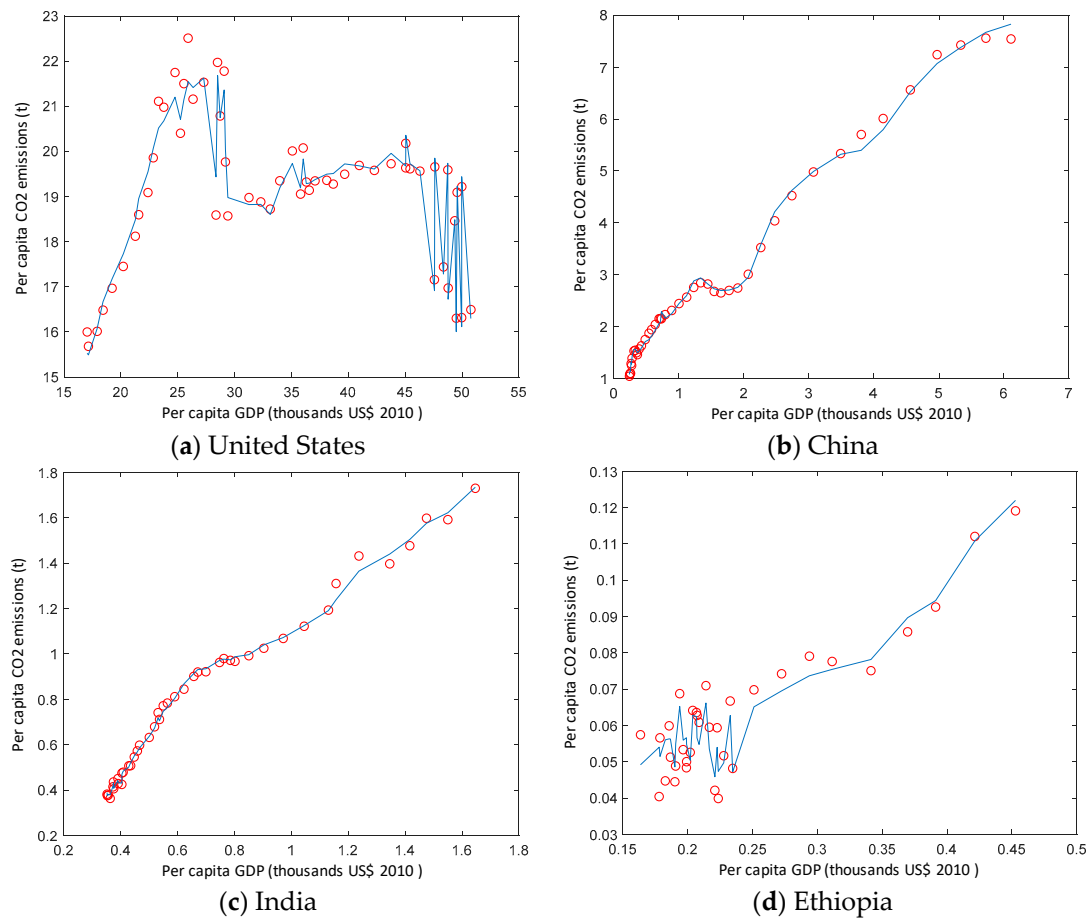
Figure 2. Per capita GDP-Per capita CO_2 emissions regressions.

Table 7. Results of the estimated parameters.

(a)					
United States			**China**		
Model:	**Quadratic Spline**		**Model:**	**Quadratic Spline ***	
R^2	0.97		R^2	0.94	
β_0	1.00	(0.47)	β_0	1.30	(3.2)
$y_{t\mid y_0}$	2.14	(13.4)	$y_{t\mid y_0}$	5.60	(6.5)
$y_{t\mid y_0}^2$	−0.03	(−9.8)	$y_{t\mid y_0}^2$	−0.91	(−3.5)
$y_{t\mid y_0}^*$	0.53	(18.1)	$y_{t\mid y_0}^*$	1.57	(16.3)
E_t	−4.16	(−21.6)	E_t	−2.81	(−10.0)
y_0	31.27		$AR(1)$	0.79	(4.1)
d	1.80		y_0	2.26	
AIC	0.63		d	1.46	
ndat	55		AIC	−1.06	
			ndat	44	

Table 7. *Cont.*

(b)					
	India			Ethiopia	
Model:	**Linear Spline ***		**Model:**	**Linear**	
R^2	0.99		R^2	0.91	
β_0	0.27	(3.5)	β_0	0.067	(7.4)
$y_{t\vert y_0}$	2.48	(17.2)	y_t	4.248	(7.2)
$y^*_{t\vert y_0}$	1.36	(17.1)	E_t	−2.05	(−6.8)
E_t	−0.58	(−7.5)	d	2.211	
$AR(1)$	0.24	(2.4)	AIC	−7.434	
y_0	0.66		ndat	34	
d	1.83				
AIC	−4.77				
ndat	44				

t values between parenthesis. * Autocorrelation error model.

The estimate for toxic income was carried out through a simulation model that estimates the values of the variables for the period 2014–2040. GDP per capita and energy efficiency were projected using the values in the base year and applying growth rates. Those rates were established according to the simulation scenario. On the other hand, population projections were taken from United Nations Population Division.

The estimation of CO_2 emissions, greenhouse gases (GHG) and toxic income is described schematically in Figure 3.
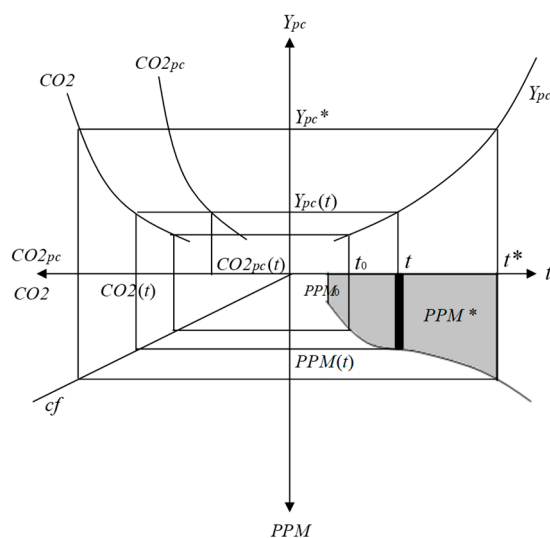
Figure 3. Toxic income estimation.

The positive side of the x-axis shows time; the negative one shows total and per capita CO_2 emissions. The positive side of the y-axis plots GDP per capita and the negative, total CO_2 emissions expressed in ppm.

As time goes from t_0 onwards, income per capita increases, determining the per capita income Y_{pc} locus. The econometric equation, represented graphically by the curve CO_{2pc}, establishes its value depending on the per capita income and energy efficiency (this latter variable is not shown

in Figure 3). Multiplying this value by population, total CO_2 is obtained (CO_2 locus). A percentage of the stream emissions are captured by the biosphere (soil, oceans and vegetation) and other, the residual, remains in the atmosphere (it is transformed into a stock). This lasting CO_2 flow is expressed in ppm units by applying the corresponding conversion factor (*cf* locus). $PPM(t)$ is the flow of CO_2 retained in the atmosphere and accumulated year by year to the initial stock (PPM_0)—the shaded area in the fourth quadrant of Figure 3. When the accumulated CO_2 emissions reach the critical threshold determined as PPM^*, that is when the shaded area is equal to PPM^*, the critical period t^* is reached. Then, the critical time t^* is defined by:

$$PPM_0 + \int_{t_o}^{t^*} PPM(t)dt \ = \ PPM^* \tag{1}$$

where PPM_0 is the atmospheric concentration of CO_2 in the base year for the simulation (year 2014). The toxic income is then defined as Y_{pc}^* where:

$$Y_{pc}^* \ = \ Y_{pc}(t^*) \tag{2}$$

Income per capita in each year t, $Y_{pc}(t)$, is a vector containing the GDP per capita values of the $m \ = \ 76$ countries included in the simulation model, thus the toxic income Y_{pc}^* is really a set with m elements ($Y_{pc}^* \ = \ \{Y_{pc}(t^*)_i, i \ = \ 1, 2, \ldots, m\}$).

A more refined definition of toxic income is to define it as the probability density of the income distribution over the critical period t^*. These 76 countries can be viewed as a sample of all countries in the world. To account for global emissions, we used the corresponding expansion factors for each income group, which were simply calculated by the quotient between total CO_2 emissions and CO_2 emission added up for the countries in the simulation model.

For simplicity, the model in Figure 3 only shows the flow for a single country. On the other hand, the graph presents the factors that affect the result for the toxic income: (1) the world's income distribution (levels of per capita GDP for the countries); (2) the diverse paths of economic growth; (3) the relation between real per capita income and per capita CO_2 emissions (which depend on economic structure, energy sources, technology and consumption levels); (4) population and population growth; and (5) CO_2 sinks ("bad" sinks: oceans and soil; and "good" ones: forests). Thus, the estimates for the toxic income Y_{pc}^* and for the critical time t^* change with the parameters and assumptions of the simulation.

Equations (1) and (2) can also be used to define the toxic input from the GHG concentration instead of CO_2 concentration. We assumed that there is a stable relation between global CO_2 emissions and global GHG emissions. For 2008–2012, the ratio of global CO_2 and GHG emissions was 0.6608. Following (IPCC, 2014), we assumed that 40% of CO_2 emissions remain in the atmosphere. For greenhouse gases (GHG), this percentage is 42% (this parameter was estimated from the equation: $GHG_t(ppm) \ = \ GHG_{t-1}(ppm) + \alpha * GHG(t)/7.8$, thus the values of GHG_t are equal for the extreme years of the period 1990–2013). On the other hand, the technical coefficient to transform the flow of CO_2 emissions in ppm is 7.8 (7.8 Gigatons of $CO_2 \approx 1$ ppm) [35].

As indicated in the Introduction, there is a great deal of uncertainty about the critical level of concentrations that can lead to an increase in global average temperature and the effects that could be caused by climate change. To simplify this analysis, we took as critical threshold a concentration of 530 ppm of GHG. Mitigation scenarios reaching concentration levels of about 530 ppm of GHG are more likely than not to limit temperature change to less than 2 °C [36].

Simulation scenarios

As is common in simulation studies, we considered two scenarios. *The* business as usual scenario considered that the future replicates the past, and the intervention scenario reflected the political will

to change current trends for a desired future. In this second scenario, an attempt was made to reflect the results of the commitments of the COP21 meeting held in Paris in December 2015. By 15 October 2015, 147 countries presented 119 Intended Nationally Determined Contributions (INDC).

To calculate the critical time and the toxic income, data for 26 years were projected, from the base year 2014 to 2040. In both scenarios, estimated population corresponded to projections from the UN Population Division [31].

Additionally, since the USA, China and India combined represent 52% of global emissions and the USA alone accounts for 40.7% of emissions in its income group, China accounts for 61.4% of emissions of its group and India accounts for 52% of emissions of its group, each of these countries was analyzed as if it were a group itself.

Business as usual scenario

For the Business as Usual (BaU) scenario, in the case of per capita GDP and energy efficiency (EE) growth, we used the average growth rate for the period 1992–2014. In the period 2014–2016, we used actual per capita GDP data. As USA, China and India share the greatest percentage (52%) of global CO_2 emissions, we used their own growth rates; except for China's per capita GDP growth, which was assumed to be equal to India's growth as the economic growth of China has lowered in the last years. From 2031 onwards, we assumed these countries behave the same as their income group (see Table 8).

Table 8. Business as usual (BaU) scenario.

	GDP Growth (%)			EE Growth (%)	
	2014–2016	**2017–2030**	**2031–2040**	**2013–2030**	**2031–2040**
High income—USA		1.3		1.0	
Upper middle—China		1.8		1.6	
Lower middle—India		2.4		2.8	
Low income	Actual data	1.1		1.4	
USA		1.5	1.3	1.9	1.0
China		5.1	1.8	4.2	1.6
India		5.1	2.4	2.5	2.8

COP21 scenario.

When the estimates for per capita CO_2 emissions trajectory decreased, according to the C&C approach, we supposed the trajectory converged to the 2012 world's mean, 5 tons per capita.

In the so-called COP21 scenario, we assumed that CO_2 emissions follow a consistent path with the proposals presented by nations at the COP21. Following the synthesis report for these INDC [37], aggregate greenhouse gas emissions are expected to grow, when compared to 2010 levels, by 13% in year 2025 and 17% in 2030.

In this second scenario, we assumed that the abatement of CO_2 emissions was fulfilled by lessening the income growth rate and increasing energy efficiency. From 2018 to 2030, we established an ad-hoc growth rate for per capita GDP and adjust the energy efficiency growth rate to satisfy the restrictions on COP21 scenario. Specifically, we assumed that economic growth in rich countries (medium and medium-high income) is halved, India reduces its growth 1% and China grows at the same rate as India. Taking into consideration that, for lower-medium and low income level countries, the lack of growth is problematic, poor countries do not reduce their economic growth rate. From year 2031 onwards, we assumed that the changes in economic growth and energy efficiency return to their historical values (see Table 9a,b).

Table 9. (**a**) COP 21 scenario. GDP growth. (**b**) COP 21 scenario. Energy efficiency growth.

(a)			
	GDP Growth (g)		
	2014–2016	**2017–2030 (%)**	**2031–2040 (%)**
High income—USA		0.7	1.3
Upper middle—China		0.9	1.8
Lower middle—India	Actual Data	2.4	2.4
Low income		1.1	1.1
USA		0.8	1.3
China		4.1	1.8
India		4.1	2.4

(b)				
	EE Growth (%)			
	2014–2017	**2018–2025**	**2025–2030**	**2030–2040**
High income—USA	1.0	2.4	2.5	1.0
Upper middle—China	1.6	3.1	3.1	1.6
Lower middle—India	2.8	4.2	4.3	2.8
Low income	1.4	2.9	3.0	1.4
USA	1.9	3.4	3.5	1.9
China	4.2	5.7	5.8	4.2
India	2.5	3.9	4.0	2.5

3. Results and Discussion

The critical period t^* is reached when GHG concentration in the atmosphere reaches the threshold of 530 ppm (Figure 4). Under the assumptions of the BaU scenario, the critical time is $t^* = 2033$ that is, in 14 years from the current year 2019. For the scenario COP21, the critical period is extended only by three years, until $t^* = 2036$. The main explanation for this limited difference between the scenarios is that the level of GHG accumulated in the atmosphere until 2014 (PPM_0, Figure 3), as a consequence of CO_2 emissions by the current high-income countries since the industrial revolution, is quite high (GHG = 441 ppm, equivalent to 83% of the threshold of 530 ppm). Therefore, the room for change is rather limited, an example that responsibilities are common but (very) differentiated.

The main differences between these two scenarios are in energy and environmental indicators. The combined effort to reduce the rate of economic growth and increase the rate of growth of energy efficiency generates a significant reduction in global CO_2 and per capita emissions (Figures 5 and 6). In fact, in 2036, CO_2 emissions per capita under the COP21 scenario are 27.8% lower than the per capita emissions of the BaU scenario, while total CO_2 emissions are 27.3% lower.
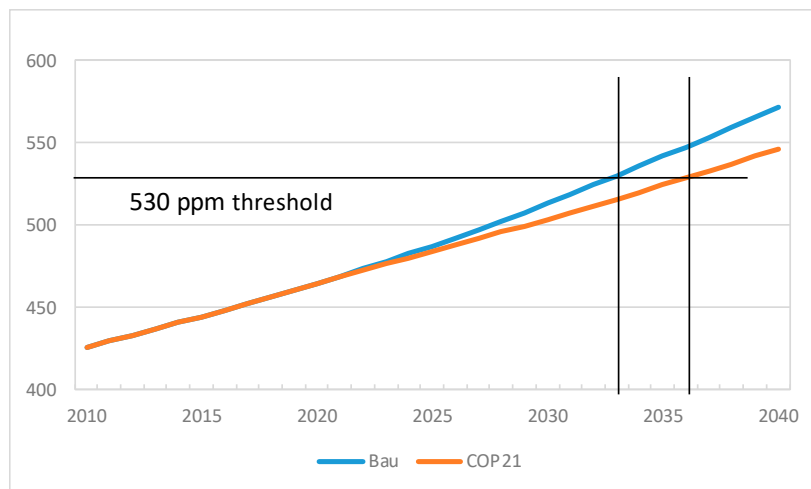
Figure 4. GHG concentration (ppm).

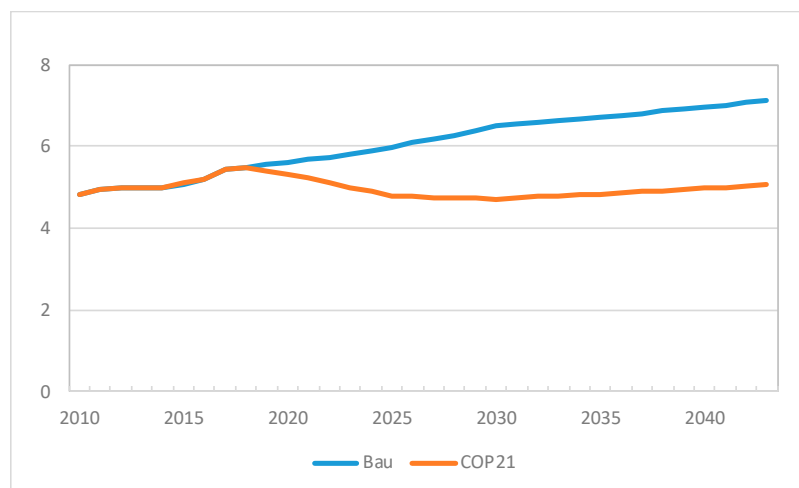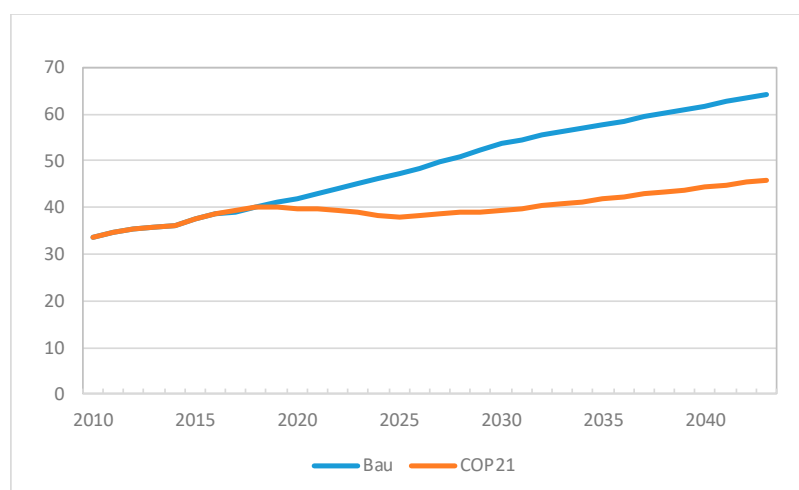**Figure 5.** CO_2 per capita emissions (tons per capita).

Figure 6. CO_2 emissions (Gt).

On the other hand, Table 9a,b shows that, to meet the commitments of COP21, efforts to increase energy efficiency are of great magnitude. For example, according to our econometric estimates, were countries to reduce their economic growth to what is assumed for this scenario, energy efficiency

growth should increase 1.5% in all countries to fulfil the emissions reductions commitment. That is, high-income countries should increase their energy efficiency growth 2.5 times, medium-high and low income countries should double their energy efficiency, and medium-low income countries should increase it by 53%. On the other hand, the last two graphs show that the effort to slow down economic growth and increase energy efficiency must be permanent, i.e., it should go beyond 2030. Otherwise, CO_2 and GHG emissions will immediately resume their growing trends.

Even assuming that global CO_2 emissions stabilize at a certain value, for instance the value of 38.0 Gigatons from 2025, thermodynamics would imply that the flow would be absorbed by the good sinks (forests) or bad ones (oceans and soil, increasing the oceans acidity) or would be accumulated in the atmosphere (accentuating the greenhouse effect and climate change). The planet would not reach a stationary state in terms of emissions (when total emissions are absorbed by sinks), but rather would see CO_2 concentration in the atmosphere rising over time.

3.1. Results by Income Group

Figure 7a,b presents CO_2 emissions per capita and total CO_2 emissions for the four income groups under the Business as Usual scenario.

There is a big difference in CO_2 emissions in per capita terms among the four groups. The relation of higher income resulting in higher emissions is maintained, however the gap between higher income and upper middle income countries is closed from 2030 onwards, according to our simulation. On the other hand, the gaps among upper middle income countries, lower middle income and low income not only remain, but even grow over time. Low income countries, however, are characterized by very low levels of CO_2 emissions per capita. The final outcome is that the growth in per capita emissions at world level is 1.3% per year.

(**a**) CO_2 emissions per capita   (**b**) CO_2 emissions (Gt)
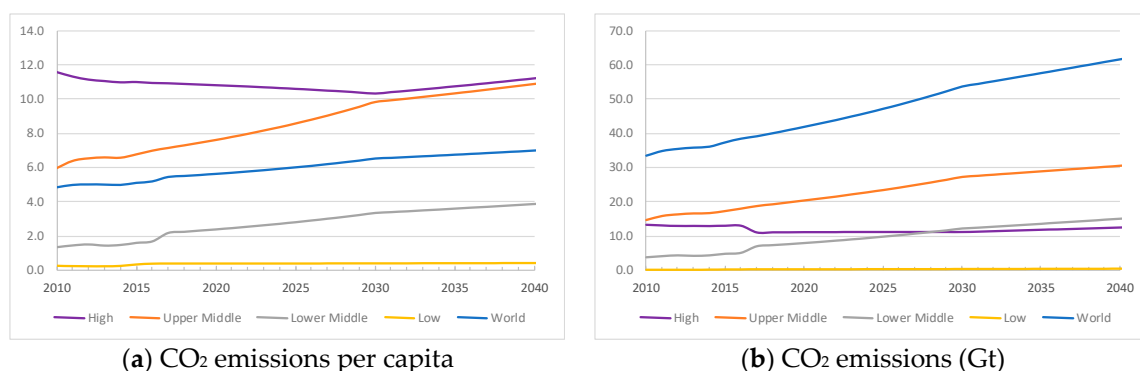
Figure 7. CO_2 emissions per income group. BaU scenario.

Global CO_2 emissions by income group show the effect of population upon emissions per capita, as the different groups have different levels of population. Upper middle income group, which includes China, shows the combined effect of emissions per capita, population and population growth, with the result that this group has 49% of total emissions. High income countries represent 24% of global emissions and lower middle income countries account for 21%. Despite the similar share in emissions, high income countries only have about 40% of the population of lower middle income countries. Low income countries account for only 0.7% of global emissions.

Figure 8a,b presents CO_2 emissions per capita and total CO_2 for the four income groups under the COP21 scenario.

Figure 8a shows the effects of the Intended Nationally Determined Contributions. The main efforts fall upon high income countries, which should almost halve their emissions, although they are still above the world's average emissions. Upper middle income countries, despite the reduction in the growth path for emissions, would become the group with higher emissions per capita. Lower middle income and low income countries, despite maintaining their trend in the growth

of emissions, would have lower than the average emissions per capita. The global average remains almost stable, keeping the average for the period 2010–2015, that is, 5.0 tons per capita.

(**a**) CO_2 emissions per capita (t) (**b**) CO_2 emissions (Gt)
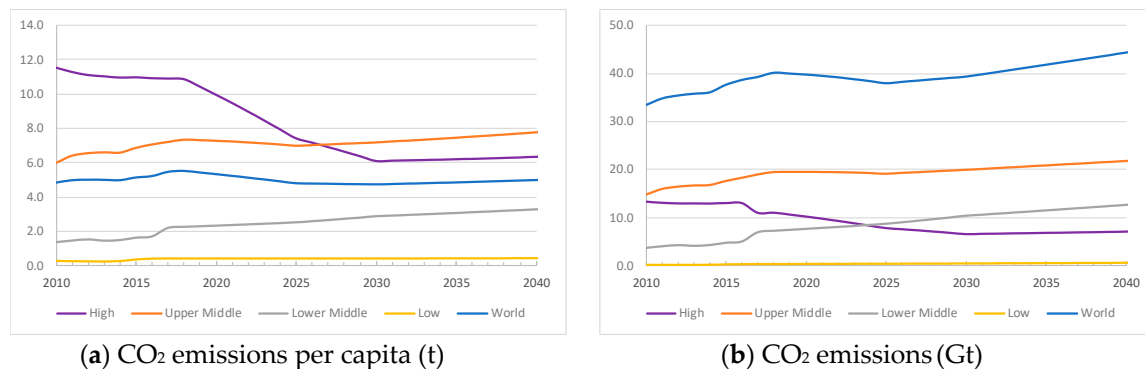
Figure 8. CO_2 emissions by income group. COP21 scenario.

Including population into the analysis shows the net effect on high income countries, which would see a reduction in total emissions. Upper middle income and lower middle income countries, however, would increase their emissions 1% and 4.3%, respectively. The impact of low income countries would be even more reduced than in the BaU scenario, accounting for only 0.4% of global emissions, on average.

3.2. Estimated Toxic Income

Mean toxic income. Under the assumptions of BaU scenario, at the critical time $t^* = 2033$, the mean value for toxic income would be $Y_{pc}^* = 14,208$ (in constant 2010 USD). For the COP21 scenario, the critical period is $t^* = 2036$ and the mean of the toxic income decreases slightly to a $Y_{pc}^* = 13,433$ (in constant 2010 USD). That is, a reduction of only 5.4% (complete results can be seen in Appendix B). Figure 9 shows that GDP per capita during the whole period of the simulation is lower in the COP21 scenario than in the BaU scenario. This result comes from the assumptions made regarding economic growth. The economic growth rate for high income countries is reduced because global GDP per capita is also reduced. This reduction, however, is small, at 5.4%, due to inequality in the distribution of income.
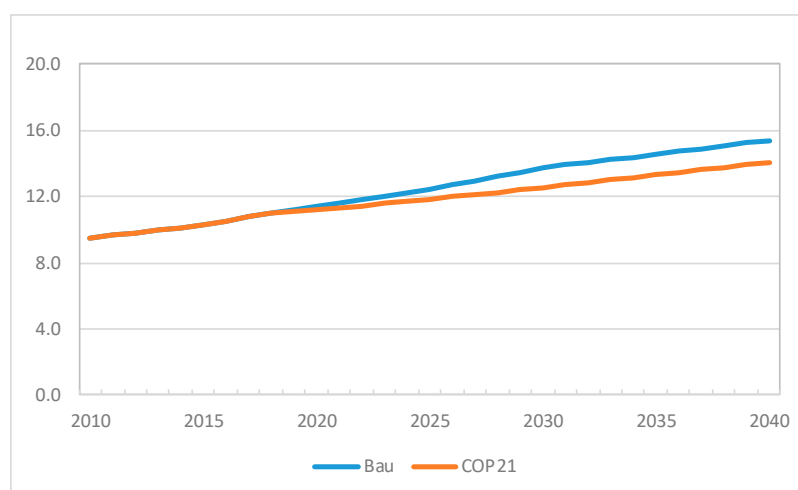
Figure 9. Toxic income (World per capita GDP) (thousand constant 2010 USD).

Toxic income distribution. The whole per capita toxic income (GDP) distribution is presented as a relative frequency graph, and as a probability density function in Figures 10 and 11.
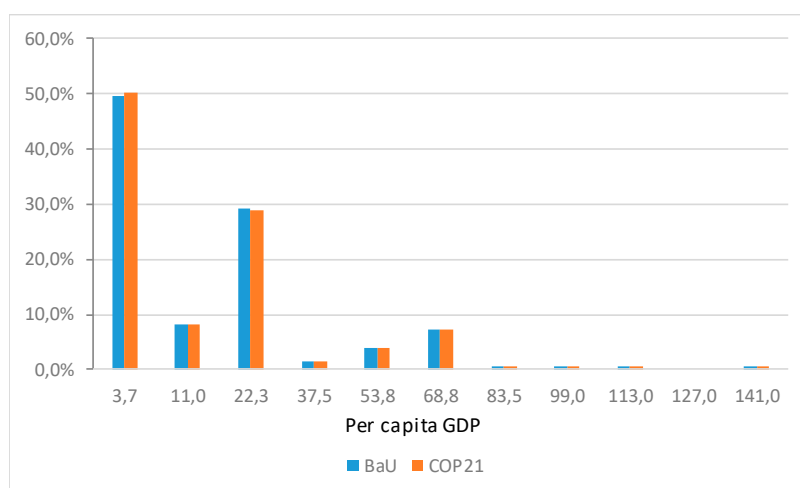
Figure 10. Toxic income (World per capita GDP) frequency.
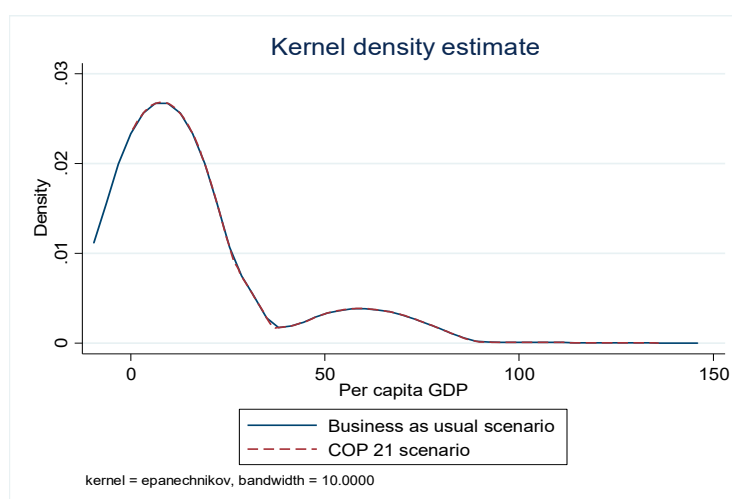
Figure 11. Toxic income (World per capita GDP) density function (the probability density function was estimated by using the "twoway kdensity" Stata command).

In relation to toxic income distribution, there are small differences between the BaU scenario and the COP21 scenario in the relative frequency and the probability density function.

It is worth mentioning that, in the period between 2014 and 2033 or 2036, income inequality is reduced. The explanation is the deceleration observed in both high income countries and upper middle income countries combined with the increase in the growth rate for lower middle income countries and low income countries. The Gini coefficient goes from 0.6225 in 2014 to 0.5613 in 2033 (BaU scenario) and 0.5602 in 2036 (COP21 scenario).

3.3. Historical Responsibilities Related to Toxic Income

We defined toxic income as the level of per capita income that would generate levels of GHG emissions incompatible with the maintenance of climate change under control. Under this framework, which would be the common but differentiated responsibilities that have driven income to become toxic?

The initial concentration level for GHG (PPM_0 in Figure 3) is one the factors that determines the critical level of concentration in this analysis. According to the literature [38], between 1750 and 2014 the world emitted 1.5 million Gt of CO_2. According to our simulation, in the BaU scenario (2015–2033), cumulated CO_2 emissions would total 885 thousand Gt, whereas, under the COP21 scenario (2015–2036), CO_2 emissions would be 871 thousand Gt. Under the assumption that GHG

emissions are proportional to CO_2 emissions, emissions in the critical period t^* would be distributed as indicated in Table 10.

Table 10. (**a**) Cumulated CO_2 emissions, historical period 1751–2014. (**b**) Cumulated CO_2 emissions. Simulation period 1751–2014.

(a)					
	Income Group (10^3 Gt)				
	High	**Upper Middle**	**Lower Middle**	**Low**	**World**
Cumulated emissions	872.0	423.2	112.8	7.4	1475.6
% share	59.1%	28.7%	7.6%	0.5%	

(b)								
	BaU Scenario				**COP21 Scenario**			
Income Group	**2015–2033**		**1751–2033**		**2015–2036**		**1751–2036**	
	10^3 Gt	**% Share**	**10^3 Gt**	**% Share**	**10^3 Gt**	**% Share**	**10^3 Gt**	**% Share**
High	214.9	24.3%	1086.9	46.0%	187.6	21.5%	1059.6	45.2%
Upper middle	436.2	49.3%	859.4	36.4%	431.1	49.5%	854.3	36.4%
Lower middle	179.0	20.2%	291.8	12.4%	196.9	22.6%	309.7	13.2%
Low	6.0	0.7%	13.4	0.6%	7.1	0.8%	14.5	0.6%
World	884.8		2360.4		870.6		2346.2	

Source: (a) [37]; (b) Simulation model.

Historical responsibilities for CO_2 emissions are absolutely differentiated. High income countries are responsible for 59.1% of cumulated CO_2 emissions, whereas the upper middle income group of countries is responsible for 28.3% of cumulated emissions. Both lower middle income group and low income group combined would represent only 8.1% of cumulated emissions. The inequality is even more noticeable if we consider that high income countries only represented 16.2% of world population in 2014.

The results for both simulation scenarios do not differ much. If we add historical data on emissions, the differences are even smaller. For instance, adding historical emissions in the case of the COP21 scenario, the share of cumulated GHG emissions by income group would be the following: 45.2% for high income countries; 36.4% for upper middle income countries; 13.2% for lower middle income countries; and 0.6% for low income countries.

This very same inequality in the distribution of emissions among income groups can be seen when we compute the average per capita emissions per year (historical plus simulated) for both scenarios, as presented in Table 11.

Table 11. Average historical and simulated CO_2 emissions per capita per year.

	Income Group (t)				
	High	**Upper Middle**	**Lower Middle**	**Low**	**World**
BaU scenario1751–2033	10.6	5.2	1.7	0.2	4.8
COP21 scenario1751–2036	9.8	4.9	1.7	0.3	4.5

Source: [21], Simulation model.

Under the COP21 scenario, which is the one with less inequality, between years 1751 and 2036, a citizen of a high income country would have emitted twice the amount of CO_2 as a citizen of an upper middle income country; 5.8 times more emissions than a citizen of a lower middle income country; and 38.5 times more emissions than a citizen from a low income country.

Table 12 shows the inequality in income among the different groups.

Table 12. Income inequality among groups of countries.

	Income Group (constant 2010 USD)				
	High	**Upper Middle**	**Lower Middle**	**Low**	**World**
BaU scenario (2033)	54.980	14.186	4.031	731	14.208
COP21 scenario (2036)	52.607	13.372	4.045	754	13.433

Source: Simulation model.

As in the previous case, a citizen of a high income country, under the COP21 scenario, would have an average income in the critical period t^* (2036) 4.1 times higher than a citizen from a upper middle income country; 13.6 times higher than a citizen from a lower middle income country; and 73 times higher than a citizen from a low income country.

The dynamics of current economic growth generates pollution and social inequality. This is the essence of toxic income at the world level.

4. Conclusions and Policy Implications

If nothing changes in the mid-term, in about 14 years, the threshold for critical concentration in the atmosphere will be reached. This result makes us believe that INDC need to become mandatory commitments for the different countries. The impact of INDC on global CO_2 emissions is noticeable. INDC are not mandatory, but voluntary measures. If implemented, the environmental consequences would be very positive. There is a need for combining energy efficiency measures in productive processes with moderation in consumption and in population growth, as well as reducing economic growth. That decrease in growth is what Tim Jackson calls "prosperity without growth" for rich countries [39]: productive restructuring of developed economies towards economic sectors with lower environmental impact. Low-middle income and especially low income countries would still be able to grow, in per capita terms, to guarantee decent living standards for their citizens.

Global responsibilities of developed economies need not only be directed to avoid their own CO_2 emissions and mitigating environmental impacts, but also to help to reduce CO_2 emissions of the rest of the countries, especially in developing countries, and to improve living conditions in these countries. This can only be possible through scientific and technological cooperation and transfer of technology from the North to the South. This is the least that can be demanded in light of differentiated responsibilities, which are based on the historical contribution of rich countries to current concentration levels of greenhouse gases in the atmosphere.

The analysis shows that, if current trends of population growth, income, emissions per capita and energy efficiency will be maintained, at some point, by 2033, the critical threshold for mean toxic income per capita of $Y_{pc}^* = 14{,}208$ (in constant 2010 USD) would be reached. This means that any income level above that value could be considered as toxic income, as it would go hand in hand with CO_2 emissions and greenhouse gases concentration levels above 530 ppm, which inevitably would increase global mean temperature threshold above 2 °C.

The distribution of toxic income additionally shows the high level of inequality that characterizes the world (Gini = 0.5602). Combating climate change needs to go hand in hand with fighting income inequality at a world level, giving room for economic development of poorer and more vulnerable countries.

The essence of toxic income is pollution and inequality.

INDCs presented at the last COP21 in Paris in December 2015 [37], need to become mandatory commitments for the different countries. After 2030, the world will need to enter a path of decreasing global and per capita CO_2 emissions that will require a transition of our energy and transport sectors towards the massive use of renewable energies.

In this sense, international agreements on climate change, additional to INDC, should include the proposals under C&C and apply them, not just to CO_2 emissions as proposed in the past, but also

to income levels of countries. Countries with income levels above the critical threshold should contract, allowing countries with income levels below the threshold to converge towards that critical value that would avoid temperature rise above 2 °C. The verification of the existence of toxic income opens the discussion about the different strategies to confront climate change.

Technology plays a key role in combating climate change. High income countries have both the technology and the economic means to abate GHG emissions, as well as to introduce adaptation and mitigation measures. On the other hand, poor countries lack the technology or the economic resources to confront this pressing problem. World Bank data [21] shows that R&D per capita investment in low income and middle income countries was 16.4 times lower than in high income countries. This translates in low levels of knowledge production. Low income and middle income countries had 251 patent applications per million inhabitants, compared to 1118 applications for high income countries in 2016 [21]. Additionally, another explaining factor is the current asymmetry in the international regime for intellectual property rights, that penalizes poor countries that do not have the resources for protecting their inventions, and that do not have access to new technology due to the high costs of the royalties involved [40].

In any case, it is the opinion of the authors that future strategies oriented to reduce emissions need to consider the drop in renewable energy costs and therefore the likelihood that these technologies may represent an ever growing share of the energy mix.

As one can see, the consequences would not fall just on energy or climate policy, but also in pursuing certain levels of equality in the world distribution of income, which would be highly desirable. Future research will focus on the depiction of the convergence scenarios for the different groups of countries.

Appendix A Econometric Regressions

Low income countries

Table A1. Linear model.

Country	R^2	β_0	y_t	E_t	$AR(1)$	d	AIC	ndat
Ethiopia	0.913	0.067	4.248	−2.050		2.211	−7.434	34
		7.421	7.191	−6.817				
Benin	0.921	−1.000	2.445	−0.191	0.304	2.009	−3.181	44
		−8.684	14.721	−3.239	2.175			
Congo, Dem. Rep.	0.949	−0.014	0.283	−0.038	0.703	2.133	−5.983	44
		−1.053	5.117	−2.214	5.333			
Mozambique	0.751	−0.007	3.340	−1.224	0.423	1.723	−4.116	35
		−0.221	7.395	−7.391	1.647			
Nepal	0.909	−0.081	0.905	−0.162	0.740	1.634	−4.923	44
		−1.412	5.579	−1.971	6.781			

Lower middle income countries

Table A2. Linear model.

Country	R^2	β_0	y_t	E_t	$AR(1)$	d	AIC	ndat
El Salvador	0.760	0.095	0.554	−0.197		2.656	−1.005	44
		0.499	11.091	−4.041				
Guatemala	0.789	−0.357	0.552	−0.070	0.284	2.114	−1.921	44
		−0.830	5.905	−1.304	1.907			
Indonesia	0.931	0.191	0.699	−0.138	0.312	1.627	−0.898	44
		0.422	6.015	−0.709	4.062			

Table A3. Linear spline model.

Country	R^2	β_0	$y_{t|y_0}$	$y^*_{t|y_0}$	E_t	$AR(1)$		d	AIC	ndat
Bangladesh	0.997	0.103	0.887	0.707	−0.093		0.551	1.651	−7.073	43
		2.766	55.419	33.485	−8.541					
Bolivia	0.868	−1.444	2.042	0.928	−0.158		1.466	2.121	−1.042	44
		−2.297	4.537	8.135	−7.702					
Cote d'Ivoire	0.651	−0.823	1.069	0.040	−0.049		1.527	1.573	−2.106	44
		−3.856	4.893	0.569	−1.485					
Honduras	0.792	0.521	0.069	1.202	−0.037		1.498	2.354	−1.520	44
		0.815	0.107	10.440	−0.243					
Mongolia	0.796	4.920	1.647	4.705	−2.713		2.229	2.186	3.055	30
		3.418	1.792	8.090	−3.673					
Morocco	0.993	0.728	0.696	0.515	−0.173		2.508	1.892	−3.798	44
		6.363	51.437	12.178	−8.261					
Myanmar	0.801	0.078	0.928	0.572	−0.158		0.347	1.667	−4.331	44
		3.987	6.368	6.081	−5.037					
Pakistan	0.994	0.226	1.380	0.654	−0.340		1.014	2.017	−5.075	44
		2.865	35.227	2.700	−5.973					
Tunisia	0.988	0.988	0.919	0.540	−0.346		2.110	2.136	−2.840	44
		2.432	11.115	23.957	−5.186					
Egypt, Arab Rep.	0.975	0.954	0.760	1.021	−0.246	0.388	1.513	1.922	−1.803	44
		1.741	2.635	14.121	−2.669	3.442				
India	0.997	0.269	2.478	1.362	−0.584	0.242	0.657	1.833	−4.773	44
		3.500	17.217	17.105	−7.541	2.353				
Sri Lanka	0.964	0.140	0.455	0.345	−0.107	0.618	1.947	2.485	−3.567	44
		1.894	6.736	7.876	−2.925	3.938				

Upper middle income countries

Table A4. Linear model.

Country	R^2	β_0	y_t	E_t	d	AIC	ndat
Argentina	0.872	2.470	0.333	−0.253	2.449	−0.952	44
		6.893	14.607	−2.880			
Ecuador	0.753	0.857	0.645	−0.247	1.743	0.314	44
		1.460	8.749	−3.610			
Mexico	0.934	4.185	0.368	−0.589	1.742	−1.040	44
		12.263	19.784	−11.287			

Table A5. Linear spline model.

Country	R^2	β_0	$y_{t\mid y_0}$	$y^*_{t\mid y_0}$	E_t	$AR(1)$	y_0	d	AIC	ndat
Costa Rica	0.936	0.446	0.274	0.046	−0.078		6.606	2.348	−1.954	44
		1.303	11.236	1.913	−2.841					
Panama	0.848	0.896	0.545	0.292	−0.304		6.523	2.308	−0.538	44
		5.389	10.185	7.270	−8.757					
South Africa	0.896	4.491	1.996	0.828	−3.181		6.217	2.045	0.492	44
		3.174	7.541	7.983	−17.026					
Turkey	0.997	1.845	0.459	0.324	−0.327	0.513	8.332	1.967	−2.544	55
		6.061	29.324	17.580	−9.248	3.240				

Table A6. Quadratic spline model.

Country	R^2	β_0	$y_{t\mid y_0}$	$y^2_{t\mid y_0}$	$y^*_{t\mid y_0}$	E_t	$AR(1)$	y_0	d	AIC	ndat
Albania	0.895	0.181	2.784	−0.446	1.149	−0.749		3.001	2.064	0.203	35
		0.182	3.186	−2.203	7.376	−13.06					
Algeria	0.644	−5.021	4.907	−0.696	1.249	−0.134		4.091	2.065	0.816	44
		−1.466	2.516	−2.446	2.567	−3.752					
Botswana	0.910	4.127	−1.503	0.389	0.544	−0.567		4.011	1.835	−0.412	34
		3.183	−1.608	2.729	5.605	−3.890					
Brazil	0.938	0.734	0.806	−0.037	0.266	−0.395		9.762	1.854	−1.865	44
		1.317	3.918	−2.836	8.088	−5.648					
Bulgaria	0.931	−121.8	77.278	−10.73	2.716	−6.991		3.782	2.351	1.502	35
		−2.318	2.610	−2.582	13.685	−16.77					
Dominican Republic	0.951	3.399	−2.130	0.630	0.204	−0.189		3.194	1.776	−1.351	44
		3.804	−2.737	4.329	2.632	−3.330					
Gabon	0.714	35.089	−7.053	0.413	0.292	−0.352		12.131	1.985	3.506	44
		1.937	−1.985	2.461	1.688	−2.482					
Iran, Islamic Rep.	0.880	9.644	−2.986	0.471	0.450	−0.498		5.964	2.525	1.938	44
		1.950	−1.471	2.306	2.050	−9.868					
Jamaica	0.878	844.7	−470.6	66.019	0.297	−0.947		3.674	1.652	0.086	44
		2.320	−2.311	2.320	3.487	−13.354					
Jordan	0.969	4.225	−0.198	0.181	0.261	−0.709		3.349	2.540	−1.434	40
		5.463	−0.367	1.816	1.416	−21.15					
Malaysia	0.988	2.654	−0.934	0.241	0.747	−0.047		5.500	2.380	0.228	44
		2.367	−2.584	5.429	19.695	−0.264					
Mauritius	0.998	0.596	0.739	−0.013	0.362	−0.310		6.747	2.025	−3.025	39
		3.934	13.067	−2.185	11.702	−8.939					
Paraguay	0.891	0.720	−0.173	0.142	0.332	−0.172		2.912	1.652	−2.486	44
		2.808	−0.538	2.121	3.203	−2.851					
Peru	0.922	2.506	−0.935	0.203	0.322	−0.080		4.070	2.677	−2.013	44
		2.717	−1.723	2.496	7.972	−5.417					
Thailand	0.996	0.746	0.481	0.105	0.585	−0.279		3.969	1.828	−1.911	44
		5.344	2.760	3.029	14.106	−3.696					
China	0.944	1.296	5.599	−0.906	1.569	−2.807	0.788	2.259	1.456	−1.058	44
		3.205	6.536	−3.451	16.266	−10.03	4.094				
Colombia	0.773	−0.662	1.550	−0.152	0.440	−0.245	0.299	4.862	1.986	−2.377	44
		−0.685	3.304	−2.686	10.182	−9.132	1.805				
Cuba	0.810	−10.857	9.691	−1.537	0.963	−0.621	0.263	3.473	1.909	−0.306	44
		−1.282	1.756	−1.730	7.750	−8.657	1.720				

High income countries

Table A7. Linear spline model.

Country	R^2	β_0	$y_{t|y_0}$	$y^*_{t|y_0}$	E_t	$AR(1)$	y_0	d	AIC	ndat
Israel	0.958	1.714	0.450	0.009	−0.424		25.509	1.835	0.798	44
		2.027	25.738	0.234	−5.058					
Oman	0.666	9.153	−0.150	2.163	−0.066		15.473	2.275	4.825	44
		2.265	−0.537	6.245	−2.058					
Trinidad and Tobago	0.975	17.319	0.013	2.085	−2.459		7.198	2.515	3.622	44
		2.274	0.012	24.748	−6.239					
United Kingdom	0.962	14.051	0.076	0.310	−0.846		34.442	1.748	0.245	55
		82.263	4.944	7.320	−13.792					
Uruguay	0.928	2.838	0.329	0.053	−0.403		9.439	2.068	−1.548	44
		23.158	15.428	3.085	−19.476					
Hong Kong SAR, China	0.970	1.992	0.411	0.173	−0.278	0.513	13.191	1.914	0.149	44
		1.521	4.085	11.037	−9.293	3.570				
Netherlands	0.929	16.579	0.156	0.254	−1.476	0.207	32.148	1.979	1.114	55
		17.995	8.061	10.476	−16.966	2.032				
Switzerland	0.923	11.825	−0.002	0.068	−0.320	0.267	67.385	1.973	−0.790	35
		13.043	−0.207	2.037	−6.161	1.446				

Table A8. Quadratic spline model.

Country	R^2	β_0	$y_{t|y_0}$	$y^2_{t|y_0}$	$y^*_{t|y_0}$	E_t	$AR(1)$	y_0	d	AIC	ndat
Austria	0.958	10.542	0.350	−0.002	0.081	−1.214		44.029	1.921	0.036	55
		15.634	14.285	−4.544	2.191	−15.016					
Canada	0.963	11.256	1.290	−0.016	0.508	−4.495		35.648	1.738	0.926	55
		3.627	8.292	−5.467	12.441	−12.682					
Chile	0.958	1.943	1.705	−0.134	0.385	−0.831		6.309	1.655	−0.205	44
		0.847	1.762	−1.472	16.860	−7.380					
Cyprus	0.994	3.452	0.626	−0.011	0.241	−0.665		22.560	2.403	−1.545	40
		11.679	15.223	−8.821	29.469	−28.514					
Denmark	0.970	15.441	0.122	0.002	0.156	−1.112		50.262	2.098	0.618	55
		12.761	2.060	2.232	6.115	−25.735					
France	0.920	−1.365	1.376	−0.029	0.094	−0.794		31.853	0.663	1.034	55
		−0.814	13.615	−13.286	2.704	−5.810					
Greece	0.983	20.967	−0.891	0.021	0.243	−0.629		15.738	2.562	0.726	55
		11.643	−3.632	2.040	17.648	−15.459					
Japan	0.984	8.238	0.328	−0.002	0.946	−0.850		44.394	2.137	0.259	55
		13.181	14.006	−4.428	9.250	−16.436					
Korea, Rep.	0.996	8.486	0.440	0.067	0.450	−2.072		5.405	1.938	0.026	44
		9.252	1.261	1.496	51.835	−12.215					
Luxembourg	0.938	−43.958	5.207	−0.074	0.321	−3.170		43.986	2.112	4.168	55
		−2.227	4.665	−4.721	7.387	−9.767					
Malta	0.983	2.711	0.615	−0.008	0.230	−0.486		13.333	1.983	−0.165	44
		7.976	6.207	−1.435	9.519	−15.029					
New Zealand	0.886	10.302	−0.206	0.010	−0.074	−0.672		30.363	1.734	0.859	38
		1.431	−0.390	1.020	−1.127	−5.208					
Portugal	0.967	5.622	0.768	−0.038	0.155	−0.555		12.667	1.794	0.664	55
		5.856	3.508	−2.952	7.536	−8.153					
Singapore	0.664	6.093	1.129	−0.026	0.329	−0.668		38.117	1.905	4.048	44
		2.407	6.636	−6.857	2.237	−2.060					
United States	0.966	1.001	2.143	−0.032	0.531	−4.161		31.269	1.800	0.628	55
		0.469	13.448	−9.796	18.080	−21.608					

Table A8. *Cont.*

Country	R^2	β_0	$y_{t|y_0}$	$y^2_{t|y_0}$	$y^*_{t|y_0}$	E_t	$AR(1)$	y_0	d	AIC	ndat
Australia	0.980	15.323	0.017	0.011	0.303	−1.770	0.374	31.939	2.190	1.138	55
		2.377	0.038	1.339	6.550	−5.857	2.779				
Belgium	0.920	6.111	1.283	−0.025	0.145	−1.710	0.533	29.914	1.925	1.187	55
		1.747	4.442	−4.066	4.451	−12.347	6.090				
Finland	0.962	12.515	1.035	−0.015	0.372	−3.604	0.572	29.783	2.146	1.467	55
		4.434	4.110	−2.651	10.338	−14.972	3.370				
Ireland	0.987	6.944	0.444	−0.003	0.304	−0.853	0.215	48.672	1.963	−0.686	45
		21.229	17.876	−7.108	9.762	−30.418	1.438				
Italy	0.948	28.179	−1.720	0.056	0.203	−1.064	0.735	22.421	2.606	0.898	55
		7.205	−3.829	4.341	6.749	−19.555	6.321				
Norway	0.835	8.743	0.341	−0.002	0.183	−1.061	0.754	70.458	1.935	2.745	55
		1.604	1.486	−0.862	1.970	−6.057	8.580				
Spain	0.966	15.863	−0.265	0.008	0.415	−0.848	0.439	29.008	2.219	0.729	55
		11.514	−2.816	3.550	3.130	−15.830	3.166				
Sweden	0.955	−15.067	2.484	−0.047	0.200	−1.266	0.443	35.239	2.020	1.228	55
		−4.588	11.399	−11.995	5.843	−9.595	3.312				

* *t*-values on the second row.

Appendix B

Table A9. Simulation results.

	Business as Usual Scenario						COP 21 Scenario					
Year	Popul Mill	PIBpc US$	CO2pc t	CO2 Gt	GHG Gt	CO2 ppm	GHG ppm	PIBpc US$	CO2pc t	CO2 Gt	GHG Gt	CO2 ppm	GHG ppm
2014	7269	10.1	5.0	36.1	54.7	397.5	440.9	10.1	5.0	36.1	54.7	397.5	440.9
2015	7355	10.3	5.1	37.4	56.6	399.9	444.6	10.3	5.1	37.7	57.0	399.9	444.7
2016	7442	10.5	5.2	38.5	58.3	402.3	448.5	10.5	5.2	38.7	58.6	402.3	448.6
2017	7550	10.8	5.4	39.2	59.3	404.8	452.5	10.8	5.5	39.3	59.5	404.8	452.5
2018	7633	11.0	5.5	40.1	60.6	407.3	456.5	11.0	5.5	40.2	60.8	407.3	456.6
2019	7715	11.2	5.5	41.0	62.0	409.9	460.7	11.1	5.4	40.0	60.6	409.9	460.7
2020	7795	11.4	5.6	41.9	63.5	412.5	464.9	11.2	5.3	39.8	60.3	412.4	464.7
2021	7875	11.6	5.7	42.9	65.0	415.2	469.2	11.3	5.2	39.6	59.9	414.9	468.7
2022	7954	11.8	5.7	43.9	66.5	418.0	473.7	11.4	5.1	39.2	59.4	417.3	472.6
2023	8032	12.0	5.8	45.0	68.1	420.8	478.2	11.6	5.0	38.9	58.8	419.8	476.6
2024	8110	12.2	5.9	46.1	69.8	423.7	482.9	11.7	4.9	38.5	58.2	422.2	480.4
2025	8186	12.5	6.0	47.3	71.5	426.7	487.7	11.8	4.8	38.0	57.5	424.6	484.3
2026	8261	12.7	6.1	48.5	73.3	429.8	492.6	12.0	4.8	38.3	57.9	427.0	488.1
2027	8335	12.9	6.2	49.7	75.2	432.9	497.6	12.1	4.8	38.6	58.4	429.5	492.0
2028	8408	13.2	6.3	51.0	77.2	436.1	502.7	12.2	4.7	38.8	58.8	431.9	496.0
2029	8480	13.5	6.4	52.4	79.3	439.4	508.0	12.4	4.7	39.1	59.2	434.4	499.9
2030	8551	13.7	6.5	53.8	81.4	442.8	513.5	12.5	4.7	39.4	59.6	436.8	503.9
2031	8621	13.9	6.5	54.6	82.6	446.3	519.0	12.7	4.7	39.9	60.3	439.4	507.9
2032	8691	14.0	6.6	55.4	83.8	449.7	524.6	12.8	4.8	40.4	61.1	441.9	512.0
2033	8759	14.2	6.6	56.2	85.0	453.3	530.2	13.0	4.8	40.8	61.8	444.5	516.1
2034	8826	14.4	6.7	57.0	86.2	456.9	536.0	13.1	4.8	41.3	62.6	447.1	520.3
2035	8893	14.5	6.7	57.8	87.4	460.5	541.8	13.3	4.8	41.8	63.3	449.7	524.5
2036	8958	14.7	6.8	58.6	88.6	464.2	547.7	13.43	4.9	42.3	64.1	452.4	528.8
2037	9023	14.9	6.8	59.4	89.9	468.0	553.7	13.6	4.9	42.8	64.8	455.1	533.1
2038	9086	15.0	6.9	60.2	91.1	471.8	559.8	13.7	4.9	43.3	65.6	457.8	537.5
2039	9149	15.2	6.9	61.0	92.3	475.6	566.0	13.9	4.9	43.9	66.4	460.6	541.9
2040	9210	15.4	7.0	61.8	93.6	479.5	572.2	14.1	5.0	44.4	67.1	463.4	546.4

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