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Abstract

In this paper we analyse the welfare effects of the social cost of carbon, defining per capita consumption net of the cost of CO2 emissions in OECD countries from 1960 to 2019. Our results show that internalising the social cost of carbon reduced welfare by approximately 2% on average in the last decade, but with significant differences between countries. We also show that, as most of the OECD countries have greater levels of CO2 emissions consumed than produced, the former reduces social welfare more than the latter, by an additional -0.6% on average. We find that the average elasticity of social welfare to CO2 emissions is equal to -0.014. Finally, our results show that the relationship between social welfare and the discount rate used in the social cost of carbon is non-linear, and that climate damages could affect welfare significantly.

Keywords: social welfare, social cost of carbon, CO2 emissions.

JEL Classification: L11; L43; F14.

1. Introduction

GDP per capita is the most widely used indicator in comparisons of economic performance between countries despite its well-known limitations. For one thing, it fails to capture the effect of variables not directly related to market income that have, nonetheless, a direct impact on personal well-being, like the unequal distribution of income. But GDP is also silent about the environmental damage associated to economic processes like production, trade and consumption of goods and services. In trying to overcome this shortcoming, there is a long tradition in the economic literature of welfare measures augmented with environmental sustainability indicators (see, for axample, Böhringer and Jochem, 2007). Nordhaus and Tobin (1973) defined sustainable consumption in their Measure of Economic Welfare as the amount that society can consume without shortchanging the future.

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Similarly, the report by Stiglitz, Sen, and Fitoussi (2009) recommended taking adequately into account environmental sustainability and degradation in the measurement of economic performance. However, in most cases, the normalization, weighting, or aggregation properties of these indices do not satisfy some basic theoretical requirements and are affected by subjective judgments or some degree of arbitrariness.

The Jones and Klenow (2016) welfare index is a natural measure to overcome these limitations, as it encompasses several key determinants of personal well-being whose relative weights can be rigorously derived from the basic principles of welfare analysis. In this article, we augment this welfare index by incorporating the notion of per capita consumption net of the cost of CO2 emissions (in tons) for a sample of OECD countries. It is true that environmental degradation also indirectly affects other components of the Jones and Klenow index, such as life expectancy or even inequality and leisure, but this impact is more difficult to grasp and quantify, so we focus on the CO2 emissions associated with the process of production and consumption. In particular we extend the work of Bannister and Mourmouras (2017) in four directions. First and foremost, instead of assuming an ad hoc estimate of the social cost of carbon (SCC), our calibration is based on Golosov et al. (2014), who propose a simple formula for the optimal carbon tax under quite plausible assumptions. Second, we analyze the effects on welfare of carbon emissions from 1960 to 2019, incorporating the effective carbon price of each country. Third, we check the robustness of our estimates by substituting the CO2 emissions produced with the CO2 emissions consumed. Fourth, we analyze the sensitivity of our measures to changes in the discount rate and the expected damage parameter that determines the SCC.

Our results show that internalizing the SCC to make the economic activity compatible with the optimal emissions path in OECD countries, from 2010 to 2019, would have reduced welfare by approximately 2% on average, but with significant differences between countries.[2] We also show that the estimated reduction in welfare is even more substantial (an additional -0.6% on average, from 2010 to 2019) when consumed emissions are considered instead of produced emissions. On average, we find that the elasticity of social welfare to CO2 emissions is equal to -0.014, being relevant in most of the countries. As expected, our results show that the relationship between social welfare and the discount

[2] According to Golsov et al. (2014), the optimal emissions path would entail a 2,5º Celsius increase in temperature above pre-industrial levels. We choose a 10-year average to avoid bias of year-specific emissions in countries with different cyclical positions. In addition, we do not adjust for the output-enhancing effect of reducing emissions to its optimal level, as it is expected to take much longer for that effect to become significant.

rate used in the social cost of carbon is clearly non-linear. Finally, we find that a SCC that gives a high probability of a catastrophic scenario significantly increases the welfare cost associated to the optimal tax.

The structure of this paper is as follows. In the second section, we succinctly review the different approaches to measuring social welfare available in the literature and discuss the approximation proposed by Jones and Klenow (2016). The third section examines the evolution over time and across countries of the correlation between consumption and CO2 emissions. In the fourth section, the primary findings regarding the welfare net of the social cost of carbon are presented. This includes an examination of sensitivity to CO2 emissions consumed and produced, sensitivity to changes in the social discount rate, and sensitivity to modifications in the damage parameter. Finally, Section 5 presents the concluding remarks.

2. Social welfare and consumption

GDP per capita is a very useful measure of economic performance, both across economies and time, since it summarizes the value of market activities. But it is an imperfect indicator of economic welfare since it does not include non-market activities, leisure, and the value of some goods and services associated, for example, with the digital economy (Aitken, 2019). Most importantly, being a mean concept, GDP per capita fails to capture the effect on personal well-being that the distribution of income has on aggregate welfare. Leaving aside preferences for more or less equity in the distribution, for risk-averse individuals, the risk of being at the lowest deciles of the income distribution may not compensate for an enhanced probability of being at the highest deciles. For this reason, most attempts to provide better measures of social welfare propose statistics that reflect how income is distributed among individuals or households in the economy. Berik (2020) distinguishes four different recent approaches to deal with the complexity of measuring welfare for comparison purposes: the composite index (as the UN Human Development Index), the subjective evaluation (as the UN World Happiness Report), the dashboard (as the OECD Better Life Initiative) and the monetary approach (for example, the Measure of Economic Welfare developed by Nordhaus and Tobin, 1972, or the more recent variant proposed by Jones and Klenow, 2016).

The monetary approach is less comprehensive than other alternatives, but it provides a theoretically grounded aggregation procedure of different determinants of welfare, in contrast to the composite index or the dashboard approaches, and it allows cross-country and intertemporal comparability, unlike the subjective evaluation approaches. In what follows we analyze the welfare cost of CO2 emissions building on the index proposed by Jones and Klenow (2016). As Jones and Klenow show, their social welfare indicator can be rigorously derived from the individual preferences normally used in the economic analysis of welfare. In particular, the expectation of individual welfare measured by utility over the life cycle is a function of consumption (C), leisure (ℓ, which in turn depends on the number of hours worked), and life expectancy (which in turn depends on the probability of survival, S, of living above a certain age, a):

$$U = E \sum_{a=1}^{100} \beta^a u(C_a, \ell_a) S(a) \tag{1}$$

Comparison of welfare between two countries (which also makes it possible to analyze their evolution over time) is made in terms of the equivalent annual consumption necessary for a person randomly chosen in any country to be indifferent between living in one country or another (e.g., the United States). This comparison logically depends on how consumption is distributed among the individuals of the countries for which the comparison is made. If the average levels of consumption, leisure, and life expectancy are the same, it is preferable to live in a country with less inequality, insofar as people are averse to the risk of living in the lower part of the distribution, with a lower level of consumption, leisure or life expectancy.

In particular, the relative welfare measure ($lambda$) of each OECD country relative to the US is calculated from the following expression:

$$\begin{aligned} \log \lambda_i = {} & \frac{e_i - e_{us}}{e_{us}} \left(\overline{u} + \log c_i + \nu\left(\ell_i\right) - \frac{1}{2}\sigma_i^2 \right) \\ & + \log c_i - \log c_{us} \\ & + \nu\left(\ell_i\right) - \nu\left(\ell_{us}\right) \\ & - \frac{1}{2}\left(\sigma_i^2 - \sigma_{us}^2\right) \end{aligned} \tag{2}$$

where e, c, ν and σ are, respectively, life expectancy, per capita consumption, a function of leisure and the variance of income among individuals, for country i and the United States (us)[3]. When the needed information is available, the welfare measure for OECD

[3] Calibration of the intercept in flow utility, $\overline{u}$, is less familiar. This parameter is critical for valuing differences in mortality with all the rest equal. Jones and Klenow (2016) choose $\overline{u}$ so that a 40-year-old, facing the uncertainty of consumption and leisure in the 2006 US distribution, has a value of the remaining life equal to 6 million dollars at the 2007 prices.

countries has been calculated since 1960 or the first available year. Life expectancy at birth (e) is obtained from the Gapminder database (2020). Consumption per capita (c), GDP per capita (GDP), and the number of hours worked over the working-age population have been taken from PWT 10 (see Feenstra, Inklaar, and Timmer, 2015). For the inequality of disposable income after taxes and transfers, we use the Gini coefficient of Eurostat (2020) and OECD (2020). Data from SWIID 8.3 (Solt, 2020), Atkinson et al. (2017), and Prados de la Escosura (2008), in the case of Spain, are used to extrapolate backward.

Data availability allows us to construct an unbalanced or incomplete panel for 35 OECD countries, with observations since 1960 for Australia, Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Italy, Japan, Korea, Netherlands, Norway, New Zealand, Portugal, Sweden, and United States, since 1970 for Colombia, Mexico, and Iceland, since 1980 for Hungary, since 1990 for Estonia, Israel, Lithuania, Slovakia, Slovenia and Turkey, and since 2000 for Luxembourg, Poland, and Czech Republic.

The evidence in Figure 1 for OECD countries using averages from 2010 to 2019 shows that the measure of social welfare is closely related to private and public consumption per capita, which can explain 89 percent of the welfare differences between most countries. However, behind this high correlation there are interesting differences between these two indicators. For example, in the United States, consumption per capita is higher than in any other country in the sample. However, many countries have welfare levels as high as the US (for example, Australia, Austria, or Canada), or even higher (as Sweden, Iceland, Norway, or Switzerland), with lower levels of consumption.

Except for these particular cases and to a lesser extent Switzerland, if we compare the most advanced countries with the most backward OECD countries, the differences in welfare are greater (ranging from 14 to 120 percent) than those observed in terms of consumption per capita, precisely because in countries with lower consumption, inequality and the number of hours worked tend to be greater, and life expectancy lower. This explains that the best fit between consumption per capita and welfare is obtained using a quadratic function, as shown in Figure 1. In contrast to the more backward countries, in the case of the advanced economies, their differences in well-being concerning the United States are notably reduced in comparison with the distance measured in terms of consumption per capita. Longer life expectancy, a better distribution of per capita consumption, and fewer hours worked in most of these countries compared to the United States partially offset the advantage of the United States relative to European economies in consumption per capita. For example, the set of countries of the eight most advanced

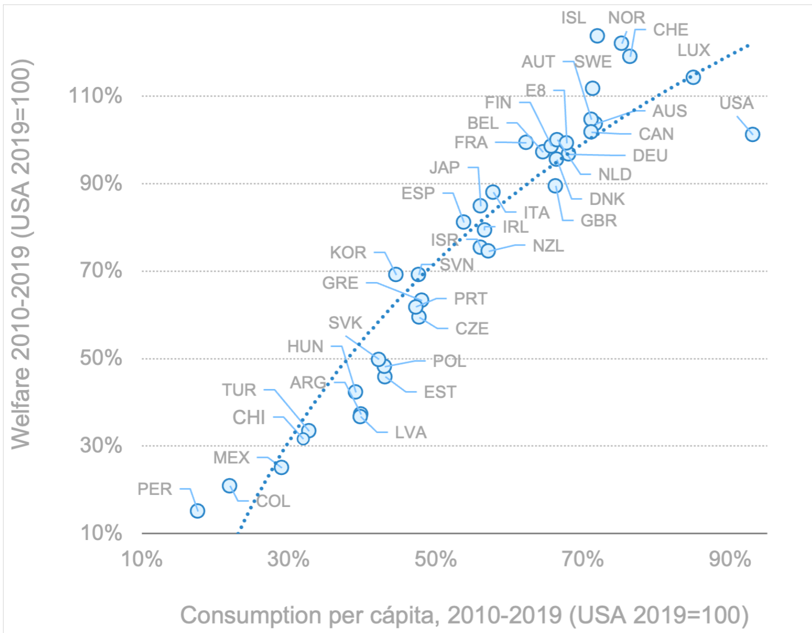

Figure 1: *private and public consumption per capita and social welfare, 2010-2019. Source: own elaboration based on Jones and Klenow (2016), PWT10, SWIID, OECD and Gapminder.*

European economies (E8) in 2018 went from having a gap of about 23 percentage points in consumption per capita to just over 8 in terms of welfare.

3. Consumption and CO2 emissions

The empirical correlation between economic activity and greenhouse gas emissions is well known. If until 1750 the concentration of CO2 in the atmosphere over the last 10,000 years barely ranged between 250 and 278 parts per million (ppm), most of the increase over the last 250 years is a consequence of the fact that industrial revolutions and economic development have been energy and fossil fuel intensive for decades (IPCC, 2021). Both time series and cross-sectional evidence across countries point to a strong positive correlation between CO2 emissions and GDP per capita income. For example, Chen et al. (2018) show that GDP per capita is, together with energy intensity, the main factor affecting CO2 emissions in OECD countries from 2001 to 2015, a result also consistent with the findings of Hamilton and Turton (2002) in the previous two decades.

Figure 2 shows the correlation between the averages from 2010 to 2019 for CO2 emissions per capita (the ratio of total CO2 emissions to population) and consumption per capita in our sample of countries. The correlation between consumption and CO2

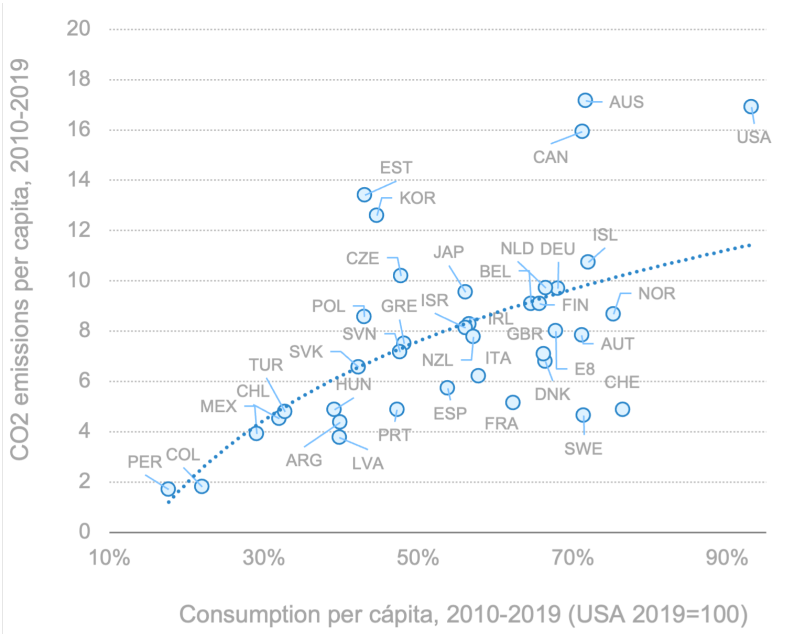

Figure 2: *Private and public consumption per capita and CO2 emissions per capita, 2010-2019. Source: own elaboration based on PWT10 and Global Carbon Budget.*

per capita is positive (0.63). In fact, if countries such as the US, Canada, Australia or Luxembourg are excluded from the sample, there might be some evidence of an inverted U-shaped curve, which shows that CO2 emissions increase faster than income in the early stages of development and more slowly when higher levels of GDP per capita are reached. As can be seen in the graph, rich countries such as Sweden or Switzerland emit the same levels of CO2 per capita as countries such as Mexico, Chile, or Argentina, with much lower consumption per capita. Also, there is a high dispersion between economies. For example, with similar levels of consumption per capita, Australia emits almost four times as much as Sweden.

However, the evidence in Figure 2 seems to be inconsistent with the hypothesis of an environmental Kuznets curve (Stern, 2004, or Dinda, 2004) when Canada, Australia or Canada are not excluded from the analysis. According to this hypothesis, in the same way that industrial revolutions can generate an inverted U-shaped relationship between inequality and per capita income, something similar can happen with environmental indicators, such as CO2 emissions, if as countries become richer, they use less polluting and more sustainable technologies. Nevertheless, this inconsistency cannot be concluded from just a cross-country comparison in a given period without taking into account the

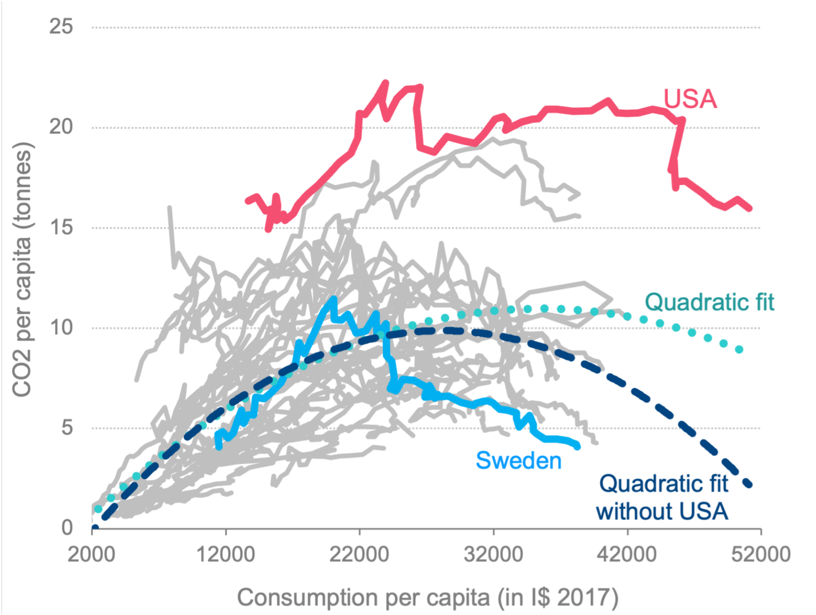

Figure 3: *Private and public consumption per capita and CO2 emissions per capita, 1950-2019. Source: own elaboration based on PWT10 and Global Carbon Budget.*

empirical evidence over time. Differences in natural resource endowments between countries can obscure the curve in cross-sectional analysis, as they significantly determine the energy mix of the country. The outliers Australia, Canada, and the United States, which have a high initial level of endowment due to their fossil resources and related policies, are a good example of that.

In fact, as shown by Churchill et al. (2018), whereas country-specific evidence is mixed, panel data estimates that account for cross-sectional dependence and parameter heterogeneity, for the OECD and from 1870 to 2014, support the environmental Kuznets curve (EKC) hypothesis. Although the empirical evidence on the evolution of some indicators of air quality and greenhouse gas emissions show some support for the environmental Kuznets curve, the results on the level of development at which environmental quality improves are again very heterogeneous (Stern, 2004; Sephton and Mann, 2016; Barrutiabengoa et al., 2021). These results depend on the environmental variables used, the sample of countries, and the period analyzed. This is precisely what Figure 3 shows for our sample of countries from 1950 to 2019. In this figure, each line represents the pairs of consumption and CO2 emissions per capita for each country, while the dotted green line is the quadratic trend estimated for the whole sample. However, as the red line points out, the US is a clear outlier that shows the highest levels of emissions for any level of consumption per capita. When we exclude the US, the quadratic line estimated for the rest of the sample shows a clear and statistically significant inverted U shape.

Figure 3 also shows significant differences in the consumption per capita levels beyond which this relationship begins to show a negative trend. The heterogeneity observed in Figure 3 has to do with the different sector specializations, the endowment of natural resources of each country, which determines its energy mix to a great extent, the differences in the timing of the industrialization process, which has allowed countries that have started later to access less polluting technologies, and the environmental regulations chosen by each country. As a result, maximum per capita emissions occur at different levels of consumption per capita. For example, in Sweden, the U-shaped inverted ratio peaked at a consumption level of around 44% of the United States in 2019.

In general, the peaks in CO2 emissions per capita occurred during the two oil crises: in 1973 in the US and 1979 in most European countries. Another remarkable result is that Sweden's emissions in 2019 were a quarter of those of the United States in 2001, at the same level of consumption per capita, and the same as Sweden had 70 years earlier when its per capita income level was only 22% of what it was in the United States in 2019. Sweden is one of the countries that first applied a tax on CO2 emissions, a tax that is nowadays among the highest in the advanced world. Still, its consumption per capita has increased at rates not much lower than in the US, showing that it is possible to combine economic growth and environmental sustainability without a notable cost in terms of social welfare. Quite to the contrary, as we show in the following section, the performance of social welfare (which has been larger in Sweden than in the US in the last decade) is even better as we take into account CO2 emissions per capita.

4. Social welfare and the social cost of carbon

The inclusion of environmental sustainability indicators in measures of well-being has a long tradition in the economic literature. Nordhaus and Tobin (1973) defined sustainable consumption in their Measure of Economic Welfare as the amount that society can consume without shortchanging the future, a principle that has been quite influential in subsequent literature (see, for example, Fleurbaey, 2009, or Jorgenson, 2018). Since then, many attempts have been made to properly take into account the social cost of environmental degradation. For example, Osberg and Sharpe (2002) developed an index of economic well-being for the US, UK, Canada, Australia, Norway and Sweden from 1980 to 1999 that values the natural resources and environmental costs, among 15 economic indicators.

Similarly, the well-known report by Stiglitz, Sen, and Fitoussi (2009) highly recommends taking into account environmental sustainability and degradation in the measurement of economic performance. Following these recommendations, some of the UN Sustainable Development Goals consider directly or indirectly environmental sustainability objectives. In the same vein, Eurostat has incorporated since 2017 natural and living environment variables among the nine dimensions of quality of life indicators.

Many of the indices analyzed by Böhringer and Jochem (2007) in their critical review of sustainability indices (such as the Living Planet Index, the Ecological Footprint, the Environmental Sustainability Index, the Environmental Performance Index, the Environmental Vulnerability Index, the Well-Being Index or the Green Net National Product) take into consideration environmental sustainability. However, according to these authors, the normalization, weighting, or aggregation properties of these indices do not satisfy fundamental requirements and are affected by subjective judgments or some degree of arbitrariness. To avoid these limitations, Bannister and Mourmouras (2017) extend the welfare measure proposed by Jones and Klenow (2016) to incorporate the effects of pollution on life expectancy and a tax to internalize the global costs of each ton of CO2 and to reduce consumption by the adjusted net saving (only if it is negative), which is defined as the net national saving plus education expenditure, minus energy, mineral and forest depletion.

In this article, we focus only on the effects of the social cost of carbon on consumption, ignoring its impact on life expectancy and inequality, as well as the impact of depletion of natural resources.[4] As Bannister and Mourmouras (2017), we assume that the representative consumer cares about the risks of global climate change and is willing to sacrifice current consumption to internalize carbon damages, which are charged to consumers in the emitting country. Given the evidence in Figure 3, it is clear that this assumption has the potential to change the comparison of welfare across countries, for example, between Sweden and the United States, as CO2 emissions per unit of consumption are lower in the former.

In particular, we define c^s as consumption net of the social cost of carbon, that is, $c^s_t = c_t - \tau^s_{it} g_t$, where c is private and public consumption, τ^s_{it} is the social cost of each ton of CO2 (net of effective national taxes on CO2), and g are emissions per capita. As many countries have already introduced taxes on CO2 emissions (τ^{CO2}_{it}), we define τ^s_{it} as

[4] There is a radical difference between environmental sustainability and carbon sustainability: the former is multidimensional (biodiversity loss, land use and degradation, air quality, water supply or emissions) and carbon sustainability, triggered by carbon emissions, has only one dimension.

$$\tau_{it}^{s} = \tau_{t}^{s} - \tau_{it}^{CO2} \tag{3}$$

where τ_t^s is the social cost of carbon, common for all countries. Therefore, if a country would be taxing CO2 emissions at the same tax rate than the social cost of carbon, τ_{it}^s would be equal to zero to avoid double taxation. Then, we modify equation (2) to define the aggregate measure of relative social welfare in terms of per capita consumption net of the social cost of carbon (c^s):

$$\begin{aligned}\log \lambda_i^s = & \frac{e_i - e_{us}}{e_{us}} \left(\overline{u} + \log c_i^s + \nu(\ell_i) - \frac{1}{2}\sigma_i^2 \right) \\ & + \log c_i^s - \log c_{us} \\ & + \nu(\ell_i) - \nu(\ell_{us}) \\ & - \frac{1}{2}\left(\sigma_i^2 - \sigma_{us}^2\right)\end{aligned} \tag{4}$$

Notice that we compare the consumption level net of the social cost of carbon (c_{it}^s) of each country with the consumption level (c_{USt}) of the United States. Thus, in the case of the United States, the comparison between λ_{USt}^s and λ_{USt} provides a quantification of the overestimation of welfare when CO2 emissions are not taken into account at the consumption level.

Contrary to Bannister and Mourmouras (2017), who focus only on the cross-country evidence for 2012 and use a unique estimate of the social cost of carbon ($\tau_{2012}^s = \$30$), here we analyze the effects on welfare of carbon emissions over time, taking also into account the effective tax rates in each country, and the sensitivity of these effects to changes in τ^s. For this purpose, we allow τ^s to vary over time.

Our calibration of τ^s is based on Golosov et al. (2014), who propose a simple formula for the optimal carbon tax under quite plausible assumptions, which is proportional to current GDP. This proportion depends only on three critical factors: the discount rate, the expected damage elasticity of output to an extra unit of carbon in the atmosphere, and the carbon depreciation in the atmosphere;

$$\tau_t^s = Y_t \bar{\gamma}_t \left(\frac{\varphi_L}{1-\beta} + \frac{(1-\varphi_L)\varphi_0}{1-(1-\varphi)\beta} \right) \tag{5}$$

where Y is global GDP, $\bar{\gamma}_t$ is the expected damage parameter (assumed constant from t onward and equal to 2.3793E-05), β is the discount factor (assumed at 0.985^{10} per decade), φ_L is the share of carbon emitted into the atmosphere that stays in it forever (equal to 0.2 in the baseline calibration), φ_0 is the share of emissions that do not exit the atmosphere into the biosphere and the ocean surface (assumed to be 0.393), and φ the geometric decay rate of those emissions that stay in the atmosphere for a limited period (assumed to be 0.0228).

In their benchmark calibration during the decade starting in 2000, for an annual discount rate of 1.5 percent as in Nordhaus (2008), Golosov et al. (2014) obtained that the average optimal carbon tax rate per ton represents 0.00807 percent of global output. In our baseline scenario, we assume their calibration of parameters in equation (5) and, therefore, the same share of the optimal social cost of carbon in global GDP from 1950 to 2019, in constant international dollars of 2017 as in PWT 10.[5] In Figure 4 we represent the global social cost of carbon in our baseline scenario obtained under the previous assumptions. According to this estimate, the optimal social cost of carbon has ranged from 7.9 in 1950 to 104.7 in 2019[6]. This level of τ^s in 2019 was well above the range of τ_i^{CO2} in our sample of countries, from its minimum value of 0 in Australia, Israel or Peru, to the maximum level in Sweden (43.2 international dollars of 2017).[7] This measure of the social cost of carbon can be understood as a mean since we are not considering cross-country differences in these critical parameters, nor household income heterogeneity within countries with the social cost of carbon affecting disproportionately some income groups (in particular low-income households). In the presence of these differences and under fairly general circumstances, Kornek, Klenert, Edenhofer, and Fleurbaey (2021) estimate that the social cost of carbon would be significantly higher. Furthermore, our analysis is focused on the

[5] Our estimate of the global GDP corresponds to the World Bank GDP from 2016 to 2019, in constant international dollars of 2017, and has been extrapolated backward using the rates of growth of the world GDP in Our World in Data based on the New Maddison Project Database and World Bank, which is expressed in international dollars of 2011 (see http://bit.ly/37NHQy4)

[6] The optimal carbon tax, as a percentage of GDP, is not time-dependent, but it may change over time due to changes in key factors. The tax formula from Golosov et al. (2014) is based on a steady-state approximation of the economy and climate system, so it may need to be revised over time for incorporating new information or changing conditions (e.g. unprecedented technological change). While the carbon cycle and the discount rate can be considered relatively stable over time, the calibration of the damage function is more susceptible to change due to the uncertainty surrounding climate sensitivity and the likelihood of adverse scenarios. To address this, Golosov et al. (2014) compared their damage function to alternative functions that vary concavely and convexly across a range of carbon concentration values from preindustrial levels to 3,000 GtC, concluding that their approximation, which is approximately linear over the range, is reasonable. Intertemporal variability can be also incorporated by relaxing economic assumptions or including non-linearities related to the carbon stock, but numerical simulations show that the optimal carbon tax formula provides robust carbon taxes under different assumptions about preferences and technology.

[7] The τ_i^{CO2} values, which represent the effective price of CO2 emissions in different countries, were derived from the World Bank's Carbon Pricing Dashboard. The data include information on the price and coverage of carbon pricing policies in each country, which was used to calculate τ_i^{CO2}.

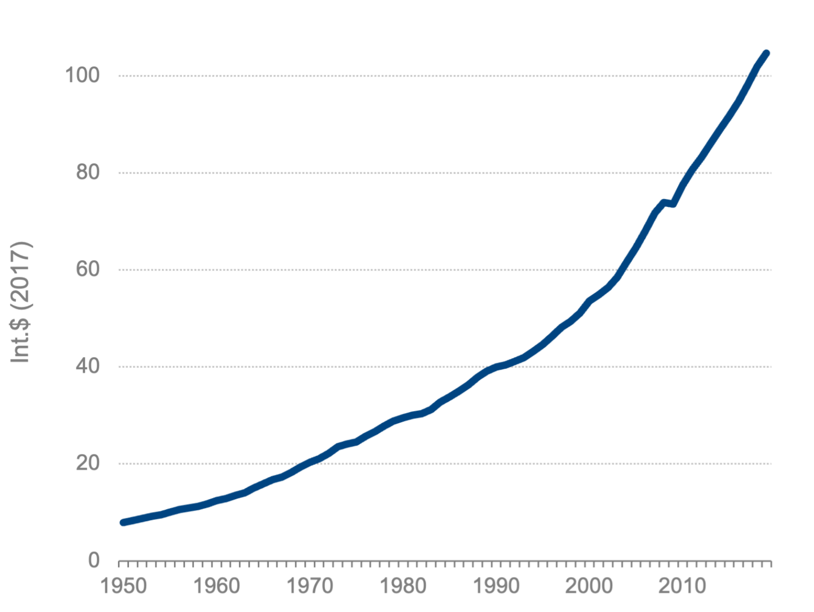

Figure 4: *Global optimal social cost of carbon in the baseline scenario, 1950-2019, Int.$ 2017 per ton. Source: own elaboration based on Golosov et al. (2014), World Bank and Our World in Data.*

global social cost of carbon, which may differ from national social costs of carbon, that as shown by Tol (2019), are more sensitive to specific rates of risk aversion.

4.1. Main results in the baseline scenario

Table 1 presents the main results in our baseline scenario, under the assumptions previously detailed, using the averages from 2010 to 2019. Column (1) shows the welfare levels obtained with equation (2), that is, without netting out the effects of CO2 emissions per capita. Seven countries in the OECD had a welfare level higher than the US in 2019, the last year in our sample, despite the fact that consumption per capita (column (2)) was higher in the latter. Eight additional advanced economies in the EU (EU8 from now on) had a welfare level (100.5%) only 0.8 percentage points below the US (101.3%), despite the difference of 26 points in the levels of consumption per capita.[8] This reduction in the gap between the United States and the EU8 is explained by differences in life expectancy (column (3)), the number of hours worked (column (4)) and inequality (column (5)).

[8] Luxembourg is not included in the EU8 despite its high level of welfare due to its small size compared to the rest of countries, and some other peculiarities of its economy. Being a small state, many workers with residence in the surrounding countries work in Luxembourg, making it difficult to compare some variables per capita, such as GDP or CO2 emissions.

Table 1: *Welfare, consumption per capita and CO2 emissions, 2010-2019.*

	Welfare λ (USA 2019=100)	Consumption per capita (USA 2019=100)	Life expectancy (years)	Working hours (per person & year)	Gini (%)	CO2 per cápita (tons per year)	C^S/C (%)	Welfare λ^s (USA 2019=100)	$\lambda - \lambda^s$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Australia	103.7%	71.7%	82.7	875	33.0	17.2	96%	99.3%	4.4%
Austria	104.6%	71.1%	81.5	809	27.5	7.8	98%	102.7%	2.0%
Belgium	97.2%	64.6%	80.9	655	26.1	9.1	98%	94.9%	2.3%
Canada	101.7%	71.1%	82.1	872	31.2	15.9	96%	97.6%	4.2%
Switzerland	119.0%	76.4%	83.5	916	29.6	4.9	99%	117.9%	1.1%
Chile	31.7%	32.0%	79.5	845	46.3	4.5	98%	30.9%	0.8%
Colombia	21.0%	22.0%	79.4	864	47.5	1.8	99%	20.7%	0.3%
Czech Republic	59.4%	47.7%	78.8	880	24.8	10.2	96%	57.3%	2.1%
Germany	96.7%	68.0%	80.9	729	29.5	9.7	98%	94.3%	2.4%
Denmark	95.5%	66.4%	80.6	708	27.3	6.8	98%	94.0%	1.5%
Spain	81.1%	53.8%	82.7	680	34.0	5.7	98%	79.6%	1.5%
Estonia	45.9%	43.1%	77.3	881	32.5	13.4	95%	43.6%	2.3%
Finland	98.7%	65.7%	81.4	754	25.6	9.1	98%	96.6%	2.1%
France	99.3%	62.3%	82.4	632	29.5	5.1	99%	98.0%	1.3%
United Kingdom	89.6%	66.2%	80.8	788	32.3	7.1	98%	88.1%	1.5%
Greece	63.3%	48.1%	80.8	792	33.6	7.5	97%	61.6%	1.7%
Hugary	42.3%	39.1%	75.9	759	27.9	4.9	98%	41.5%	0.8%
Ireland	79.3%	56.6%	81.5	750	29.9	8.3	98%	77.4%	1.9%
Iceland	123.9%	72.0%	83.5	809	24.0	10.7	98%	121.1%	2.8%
Israel	75.4%	56.1%	82.5	925	35.7	8.1	97%	73.4%	2.0%
Italy	88.1%	57.8%	82.7	715	32.6	6.2	98%	86.4%	1.7%
Japan	84.8%	56.1%	84.1	922	33.4	9.6	97%	82.2%	2.7%
Korea	69.1%	44.6%	82.2	1049	0.3	12.6	95%	65.7%	3.4%
Latvia	36.8%	39.7%	74.8	846	35.2	3.8	98%	36.2%	0.6%
Luxembourg	114.3%	85.0%	82.1	1084	29.3	18.0	97%	110.1%	4.1%
Mexico	25.0%	29.1%	75.5	890	42.9	3.9	98%	24.4%	0.6%
Netherlands	100.1%	66.5%	81.5	756	26.3	9.7	98%	97.6%	2.5%
Norway	122.1%	75.3%	82.2	728	24.0	8.7	99%	120.7%	1.4%
New Zealand	74.6%	57.1%	81.5	903	34.2	7.8	98%	72.8%	1.8%
Poland	48.2%	43.0%	77.5	841	30.0	8.6	97%	46.6%	1.6%
Portugal	61.9%	47.2%	81.2	853	33.7	4.9	98%	60.8%	1.1%
Slovaquia	49.9%	42.2%	76.8	742	24.2	6.6	97%	48.7%	1.2%
Slovenia	69.1%	47.6%	80.8	775	24.1	7.2	98%	67.6%	1.5%
Sweeden	111.7%	71.3%	82.4	797	26.7	4.6	100%	111.1%	0.6%
Turkey	33.4%	32.7%	77.4	618	42.5	4.8	97%	32.5%	0.9%
E8	100.5%	67.0%	81.5	730	27.3	7.8	98%	98.6%	1.9%
United States	101.3%	93.1%	79.0	822	39.4	16.9	97%	97.9%	3.4%

Source: own elaboration based on PWT 10, AMECO, OCDE, SWIID and Gapminder
EU8 comprises Austria, Belgium, Germany, Denmark, Finland, France, Netherlands and Sweden

Column (6) presents the levels of CO2 emissions per capita. Australia, Canada, the Czech Republic, Estonia, Iceland, Korea, Luxembourg, and the United States are above the sample average. The EU8 has a level of emissions (7.8 tons per person per year) less than half that of the United States (16.9 tons). In column (7) we compute the ratio of $c_t^s = c_t - \tau_{it}^s g_t$ to c. In a country like Sweden the difference between both levels of consumption is close to zero, given its low level of emissions and its high effective tax rate on CO2 emissions. However, in the US the social cost of CO2 emissions is equivalent to 3 percentage points of consumption.

Column (8) shows the level of welfare taking into account the social cost of carbon

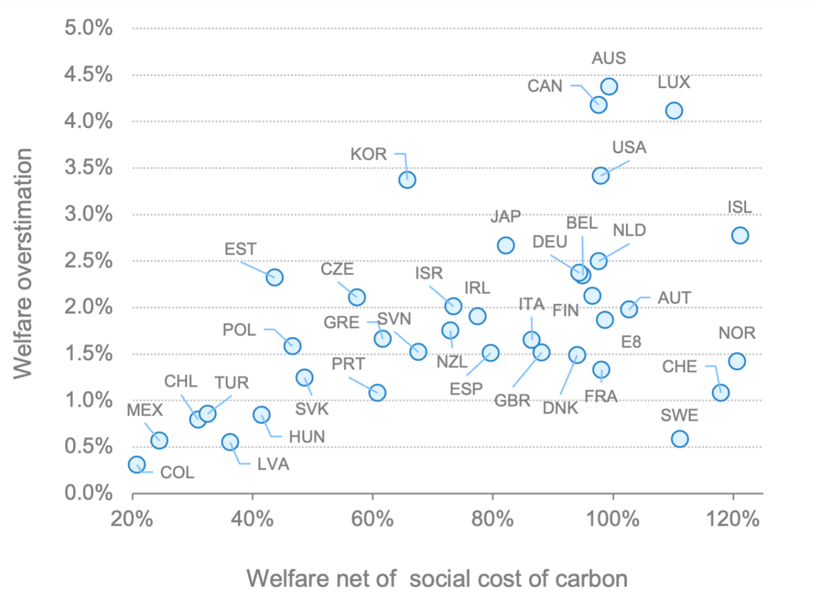

Figure 5: *Net welfare of the social cost of carbon* (λ^s) *and overestimation of welfare* ($\lambda - \lambda^s$)*, OECD countries, averages 2010-2019. Source: own elaboration based on Table 1.*

according to equation (3). The difference between this augmented welfare index and the one in column (1) is presented in column (9), which can be interpreted as an overestimation of welfare when the social cost of carbon is not taken into account or the welfare cost of implementing the optimal emissions tax: $\lambda - \lambda^s$. In countries like Sweden with large levels of welfare and low CO2 emissions, the overestimation of welfare is relatively small, 0.6 percent, whereas it ranges between 3 and 4 percent in countries with higher CO2 emissions like the US. On average, our results show that internalising the social cost of carbon would have reduced welfare in OECD countries from 2010 to 2019 by approximately 2%. There is a positive correlation between λ and λ^s since CO2 emissions are related to the level of economic development, and the variance of welfare overestimation also increases with the level of welfare. Therefore, for a similar level of welfare around 100%, the overestimation of welfare ranges from 1.3 in France to 4.4% in Australia. (Figure 5).

4.2. Sensitivity analysis

4.2.1. Consumed versus produced CO2 emissions

So far, we have used data on produced CO2 emissions in each country. However, consumption includes imported goods and services produced abroad, in countries with different levels of CO2 emissions. Therefore, an alternative measure of welfare can be obtained

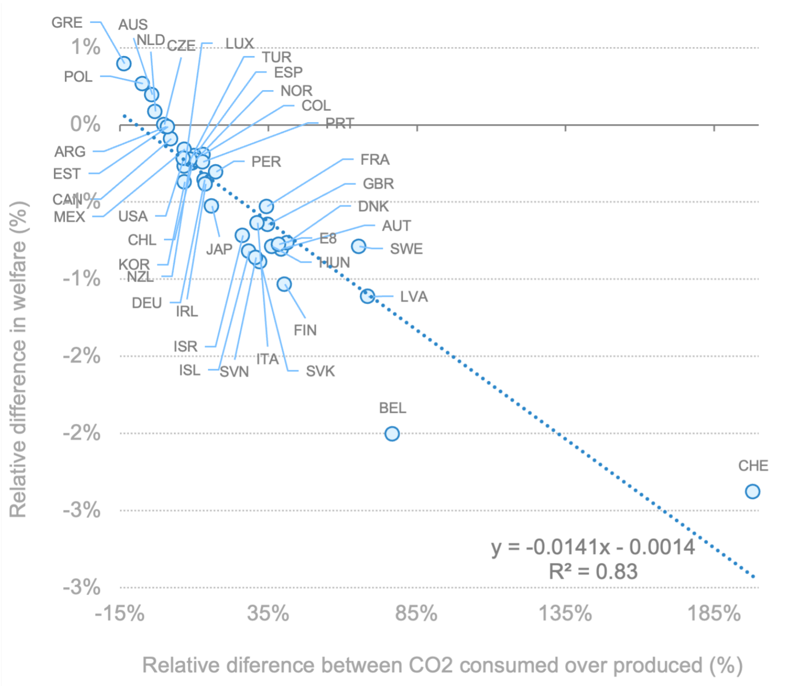

Figure 6: *Changes in relative welfare as a function of the relative difference between CO2 consumed and produced, OECD countries, averages 2010-2019.*

using data on consumed rather than produced CO2 emissions. Although this approach may improve our measure of welfare net of the social cost of carbon, the limitation is that this measure is only available for most countries in our sample since 1990. In the entire sample, for the years for which this measure is available, the correlation between CO2 consumed and produced, both in per capita terms, is equal to 0.91[9].

On the horizontal axis of Figure 6 we have represented the average from 2010 to 2019 of the relative difference between CO2 consumed (g^c) and produced (g), that is, $g^c/g - 1$. Most of the OECD countries have greater levels of CO2 emissions consumed than produced. On average, from 2010 to 2019 the only exceptions to this general pattern were Greece (where g was 13.6% greater than g^c), Poland (7.4%), Australia (4.1%) and the Netherlands (3.1%). At the other extreme, Switzerland (198.3%) is the country with the highest difference between CO2 emissions consumed and produced.

Figure 6 is also informative on the effects of the use of consumed instead of produced

[9] It should be noted that the correlation presented may vary depending on the sample of countries considered. Our sample does not include major emitters such as China or India.

CO2 emissions on social welfare, given our baseline estimate of the social cost of carbon in Figure 4.[10] On average, in our sample of OECD countries from 2010 to 2019 the elasticity of social welfare to CO2 emissions is equal to -0.014. In general, this average elasticity is very relevant for most countries. Furthermore, as most of the OECD countries have greater levels of CO2 emissions consumed than produced, the former reduces social welfare more than the latter, by an additional -0.6% on average.

4.2.2. Sensitivity of welfare to the social discount rate

The social discount rate plays a crucial role in the determination of the social cost of carbon (Stern and Stiglitz, 2021, or Golosov et al., 2014). So far, we have used a (market) rate of 1.5% per year, as in Nordhaus (2008). However, Stern (2006) used a much lower rate of 0.1%, which is justified on the grounds that the social discount rate should be much lower than the market rate, to take into account the increasing risks of climate change and the welfare of future generations. Note that the phenomenon of climate change is highly uncertain and has the potential for catastrophic events (Pindyck, 2013). But there are other reasons to consider lower social discount rates. Firstly, the long-term trend of market interest rates, which serves as a proxy for the unobservable discount rate, has been decreasing. Second, a precautionary approach should also favor the use of lower discount rates. Therefore, given the combination of the potential severity and probability of occurrence of such events, it may be advisable to assign a higher present value to the welfare loss associated with climate change. To test the sensitivity of our results to changes in the social discount rate, we have calculated the different levels of welfare for the average OECD country in 2019 under the different values of the social costs of carbon that are obtained when the interest rate varies from 0.1% to 2.0% per year.

$$\begin{aligned}\log \lambda^{s}_{m,2019} = \frac{e_{m,2019} - e_{us,2019}}{e_{us,2019}} \left(\overline{u} + \log(c_{m,2019} - \tau^{s}_{2019}(\beta) g_{m,2019}) + \nu\left(\ell_{m,2019}\right) - \frac{1}{2}\sigma^{2}_{m,2019} \right) \\ + \log(c_{m,2019} - \tau^{s}_{2019}(\beta) g_{m,2019}) - \log c^{s}_{us,2019} \\ + \nu\left(\ell_{m,2019}\right) - \nu\left(\ell_{us,2019}\right) \\ - \frac{1}{2}\left(\sigma^{2}_{m,2019} - \sigma^{2}_{us,2019}\right)\end{aligned} \tag{6}$$

[10] In order to obtain a consistent welfare measure, when we subtract the social cost of carbon, either from the production or the consumption side, we take into account the effective taxes already paid in each country multiplied by the produced CO2 emissions. Then, the difference can be summarized to τ^{s}*((g)-(g^{c})). The lack of data availability prevents, for the moment, the calculation of consumption-side effective prices.

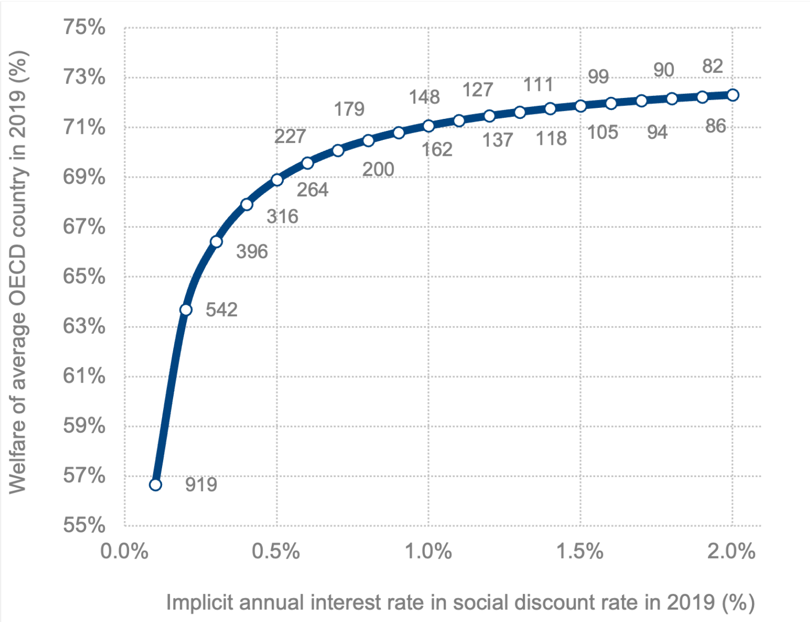

Figure 7: *Sensitivity of welfare for the average OECD country in 2019 to changes in the social discount rate. The numbers around the curve are estimates of the SCC per ton in 2017 international dollars.*

The subscript m refers to the average OECD country, $t = 2019$ and now τ is explicitly expressed as a function of the social discount rate (β)[11]. Using equation (4) we can simulate the effects of changes in the values of β on τ, and then equation (5) allows us to see how social welfare is affected.

The effect on welfare of variations in the discount factor is non-linear. For low values of the social discount rate, welfare declines rapidly. In fact, when the social discount rate approaches to 0.017% consumption net of the social cost of carbon and welfare converge to zero[12]. On the other extreme, there are small differences in welfare when the interest rate increases from 1.% to 2.0% per year.

We have also analyzed to what extent a decrease in the discount rate in the social

[11] For the average OECD country in 2019, life expectancy (e) in equation (5) was equal to 80.9 (78.9 in the US), consumption per capita (c) was 30,051.9 international dollars, per capita CO2 emissions (g) were 7.44 tons, the function of leisure ($v(\ell)$) was -0.148 (-0.150 in the US) and the variance of income per capita (σ^2) was 0.60 (0.73 in the US). With these values, the welfare level of the average OECD country, net of the social cost of carbon, was equal to 71.9% of the US welfare level when consumption is not corrected for CO2 emissions. In equation (4), World GDP in 2019 was set to 129.8 trillion of international dollars.

[12] When the interest rate approaches to 0.017%, τ goes to 4,040 per ton and $c^s_{m,2019} = 30{,}051.9 - 4{,}040 * 7.44$ goes to zero

cost of carbon affects some countries more than others. Thus, for the period 2010-2019, we have compared the welfare levels for each country in our baseline scenario in which the interest rate is equal to 1.5% ($\lambda_i^{s(1.5)}$) with respect to the situation in which it decreases to 0.2% ($\lambda_i^{s(0.2)}$), for the period 2010-2019. The correlation between both measures of welfare is very high (0.988) and the regression coefficient of ($\lambda_i^{s(0.2)}$) on ($\lambda_i^{s(1.5)}$) is equal to 0.87. As expected, the decline in welfare is greater in countries with a higher intensity of CO2 emissions per unit of consumption, such as Estonia, Korea, Canada, or Australia (see the Appendix).

4.2.3. Sensitivity to the damage parameter

Another source of uncertainty in the determinants of the SCC (τ) in equation (4) is the expected damage parameter ($\bar{\gamma}_t$). Golosov et al. (2014) calibrated this parameter assuming that a catastrophic scenario of 6-degree heating, in which climate damage produces a loss of 30% of GDP, has a probability $p = 6.8\%$. and that a moderate damages scenario of 2.5-degree heating, with a loss of 0.48% of GDP, occurs with a probability $1 - p$. This calibration also assumes that the global temperature increases with the concentration of CO2 in the atmosphere (S) according to the following equation:

$$T_t = 3 \log \left(\frac{S_t}{\overline{S}} \right) / \log 2 \tag{7}$$

where $\overline{S} = 581$ GtC is the atmospheric concentration of pre-industrial CO2 in gigatons of carbon. According to equation (7), the 2.5-degree heating could be reached with a CO2 concentration of 1,035 GtC, and the 6-degree heating with 2,324 GtC[13].

In previous exercises, we employed the baseline damage parameter, which was derived from the probabilities outlined by Golosov et al. (2014). However, it is evident that as the concentration of CO2 in the atmosphere increases, the likelihood of experiencing more severe scenarios also increases. Thus, in 2021 CO2 levels in the atmosphere reached a high of 883 GtC, compared to 1960 levels that were around 671.8 GtC, increasing the probability of exceed of S assumed in the moderate damages scenario. Additionally, Tol (2022) conducted a comparative review of the impact of warming on economic welfare, which illustrates the substantial sensitivity of the social cost of carbon, and thus, welfare, to the damage parameter.

[13] A standard value for the climate sensitivity parameter is 3.0 degrees Celsius. That means that doubling the stock of atmospheric carbon leads to a 3-degree Celsius increase in the global mean temperature. As noted by Golosov et al. (2014), there is substantial discussion and, perhaps more importantly, uncertainty about this parameter, among other things due to an imperfect understanding of feedback effects.

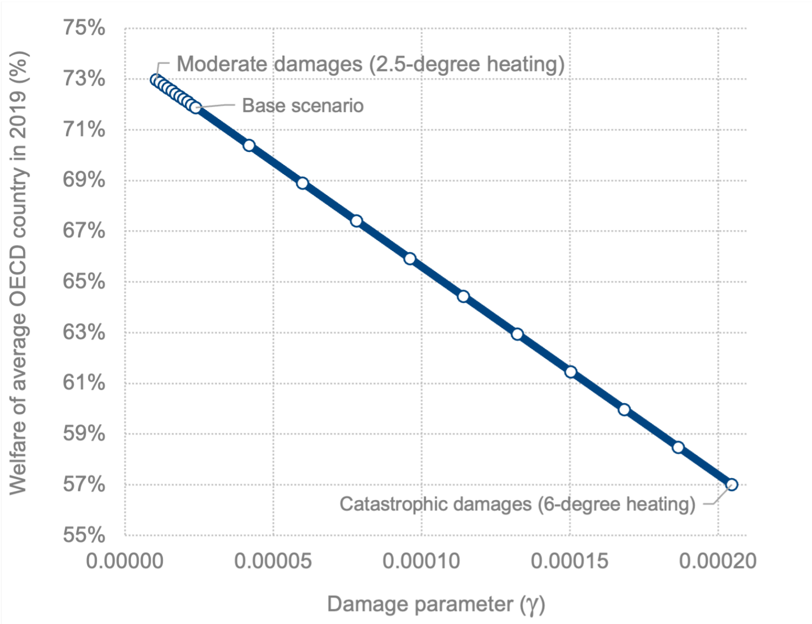

Figure 8: *Sensitivity of welfare for the average OECD country in 2019 to changes in the damage parameter.*

In Figure 8 we represent the sensitivity of welfare for the average OECD country in 2019 to changes in the damage parameter ($\bar{\gamma}$). In the upper left corner, we have the scenario of low damage ($\bar{\gamma} = 1.06E - 05$). With respect to the base scenario (in which moderate damages occur with 93.2% probability), the SCC falls to I$46.7 per ton and welfare increases by slightly more than 1 percentage point. On the contrary, in the catastrophic damages scenario ($\bar{\gamma} = 2.05E - 04$), the SCC would increase to I$900.7 per ton and welfare would fall 15 percentage points, reaching similar levels to those simulated when the discount rate falls to 0.1%, as shown in Figure 7.

5. Conclusions

In this paper we have extended the welfare measure proposed by Jones and Klenow (2016) to incorporate the effects of the social cost of carbon, defining per capita consumption net of the cost of CO2 emissions in OECD countries from 1960 to 2019. Instead of assuming an ad hoc estimate, our calibration of the social cost of carbon is based on Golosov et al. (2014), who propose a simple formula for the optimal carbon tax under quite plausible assumptions, which is proportional to current GDP and depends on three factors: the discount rate, the expected damage elasticity of output to an extra unit of carbon in the atmosphere, and the carbon depreciation in the atmosphere.

Our results show that internalising the social cost of carbon would have reduced welfare in OECD countries from 2010 to 2019 by approximately 2% on average, but with significant differences between countries. We also show that, as most of the OECD countries have greater levels of CO2 emissions consumed than produced, optimally taxing consumed emissions would have entailed an additional 0.6% welfare decrease, on average from 2010 to 2019. Furthermore, we find that the average elasticity of social welfare to CO2 emissions is equal to -0.014. As expected, our results show that, the relationship between social welfare and the discount rate used in the social cost of carbon is clearly non-linear. Finally, we find that optimally taxing CO2 emissions under high risks of a catastrophic environmental scenario would lead to a much larger fall in aggregate welfare.

Appendix

Figure 9 shows the welfare of each country when the interest rate is equal to 0.2% ($\lambda_i^{s(0.2)}$), against its value when the interest rate is 1.5%, as in the base scenario ($\lambda_i^{s(1.5)}$), for the period 2010-2019. The diagonal represents the values of $\lambda_i^{s(0.2)} = \lambda_i^{s(1.5)}$.

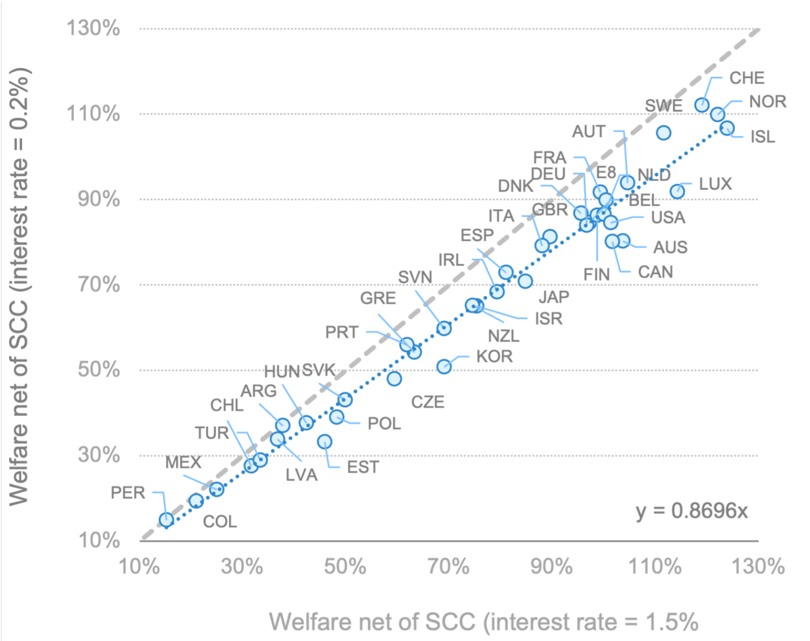

Figure 9: *Sensitivity of the welfare of OECD countries to changes in the social discount rate from 1.5% to 0.2%, 2010-2019*

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