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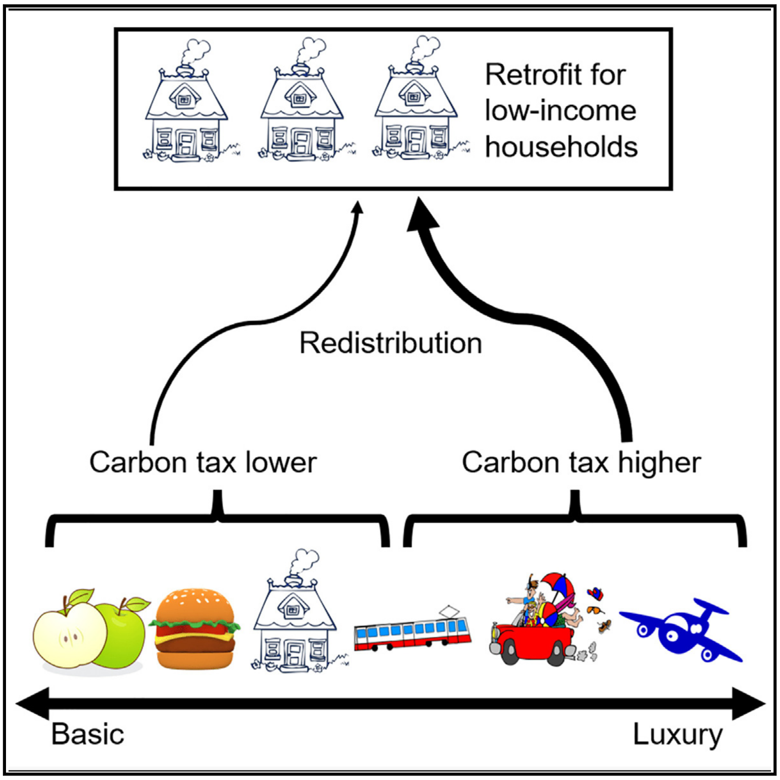
Luxury-focused carbon taxation improves fairness of climate policy

Graphical abstract



Highlights

- We compare luxury-focused and uniform carbon taxation of household consumption
- Luxury-focused taxes affect high-income households more
- Luxury-focused taxes are slightly better at reducing yearly household emissions
- Tax revenue can be recycled for retrofitting homes

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In brief

Luxury-focused carbon taxation is an underexplored approach to climate policy. We test it internationally and find that it is generally fairer with respect to emissions abatements and financial burden across the income spectrum of households.

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Luxury-focused carbon taxation improves fairness of climate policy

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SCIENCE FOR SOCIETY The Paris Agreement aims to limit global warming to below 2°C, ideally 1.5°C, which requires rapid emission reductions and addressing distributional conflicts. It can be challenging to determine which emissions can be curbed swiftly without harm and which would cause disruption if stopped immediately. For this purpose, some ethicists and economists suggest focusing climate policy on luxury goods. Luxury goods, such as flights and large cars, are mostly consumed by wealthy households as opposed to basic goods, such as day-to-day foods and home energy, which are crucial for lower- and middle-income households. Therefore, in this study we test a luxury-focused approach to carbon taxation, which is one of the most popular climate policies. Carbon taxation is a fee imposed on the carbon content of consumption and we examine the effects of higher fees on luxury goods versus basic goods.

SUMMARY

Equitable climate policies are required for a just and rapid energy transition. A widely discussed climate policy instrument is carbon taxes. Previous studies of the distributional implications of carbon taxation focused on uniform carbon taxes across sectors. Differentiated tax rates across goods and services received less attention. Here we model an alternative carbon tax design accounting for the distribution of household consumption and carbon footprints across 88 countries covering the global north and south. The policy distinguishes luxury and basic consumption and sets higher carbon prices for luxury. The policy reduces yearly global household emissions by 6% compared with no policy and inequalities are reduced compared with no policy and compared with a uniform carbon tax. By 2050, the policy saves around 100 gigatonnes carbon dioxide equivalents, which is 75% of what is needed for households to remain within a 2° consistent climate pathway.

INTRODUCTION

Proposed and implemented carbon taxes are uniform across sectors or limited to a few specific carbon-intensive ones such as fuel, industry, or residential heat.[1] In developed economies, this design has been proved to affect low-income households the most[2,3] and is not extensive enough to have a profound impact on emissions.[4] In contrast, what if there was carbon taxation of all household consumption, but with carbon prices that varied according to the purpose of consumption? Could this help achieve the Paris climate goals in a fair way? Some emissions are produced while contributing to decent living standards[5]; they cover essential needs such as housing, cooking, or accessing healthcare. Others are generated during the pursuit of luxury; for example, when flying long-distance on holiday or driving the convertible Porsche during summer. Affluence drives those emissions, not basic human needs.[6] The differentiated nature of consumption has been acknowledged for more than a century,[7] with respect to energy and carbon footprints for decades,[8] and recently has become a focal point in the analysis of carbon and energy inequality.[9–13] It has not been translated into climate policy, however, let alone into socially acceptable carbon pricing.

Economists traditionally have argued to keep the carbon price uniform across sectors.[14,15] One idea is that uniform carbon prices are optimal because they do not distort marginal abatement curves. A uniform price motivates exactly those abatements that cost less than the price of carbon.[16] Another argument is that, since a tonne of carbon emitted has the same impact on the climate irrespective of the source, the carbon price should be fixed,[17] and, moreover, there is concern about cross-border

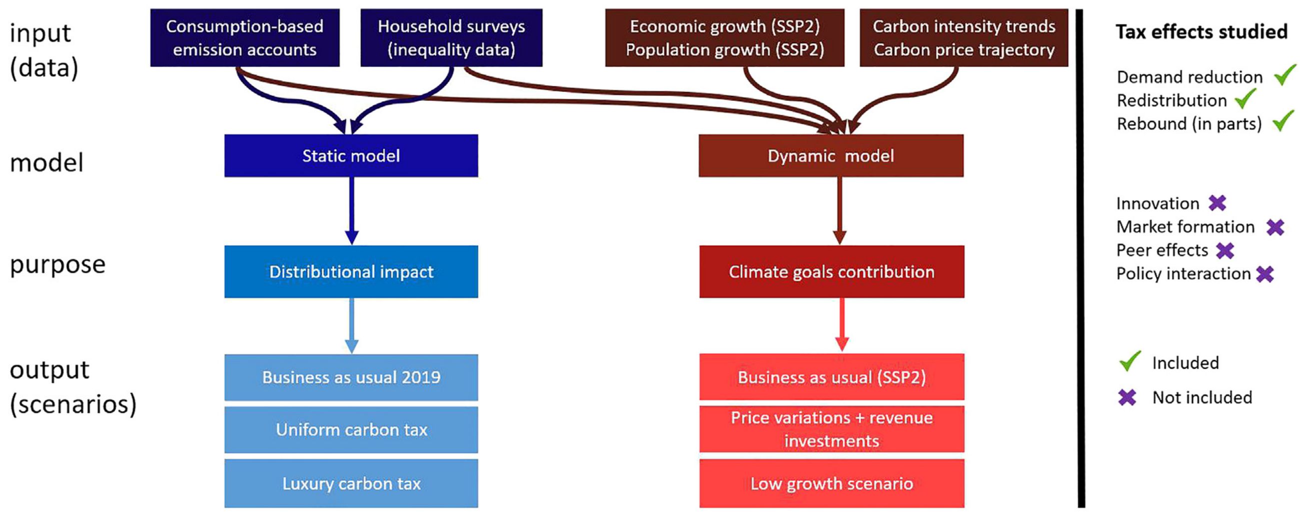

Figure 1. Study overview

This figure illustrates the overall structure of the study. We employ two modeling approaches for complementary purposes: static for distributional impact and dynamic for climate goals contribution. The figure is segmented into four levels vertically and two sections horizontally. The vertical levels refer to the model flow. The left section (blue shades) displays the static model. The right section (red shades) depicts the dynamic model. The right of the figure depicts the scope of effects studied.

carbon leakage if carbon prices across countries varied.[18] These perspectives are production oriented. While it is true that every tonne of carbon emitted is the same to the climate, this is far from accurate from the perspective of demand or social justice, since the same tonne of carbon delivers different benefits depending on who consumes for what purpose, and consequentially not every tonne of carbon is equally avoidable.[19] Recent studies explore differentiated carbon prices among countries. High-income countries could pay higher prices than low-income ones,[20,21] consistent with the fact that they are historically, and continue to be, the main cause of global warming.[22] A similar logic consequently applies to inequality within countries, because also here the contribution to climate change varies with socio-economic status.[23] Indeed, others demonstrate that prices applied to specific sectors, for instance electricity or fuel, vary in distributional impact depending on household spending and energy profiles across income classes within countries.[24,25] Despite this, in carbon taxation design, social equity is primarily addressed through revenue recycling[26,27] but rarely through differentiating consumption purposes of rich and poor. It therefore remains understudied how effective carbon taxation would be if it distinguished more explicitly between the lifestyles of high-income and low-income households, and also if there are any design-synergies between targeting luxury goods and recycling tax revenue for targeted programs, such as giving back to the poorest or retrofitting. Retrofitting homes and redistribution to low-income households by means of revenue has also mostly been studied for single countries[28] but not in international comparison using a larger sample of countries. It is expected that the impacts of such policies would vary from country to country, but it is unclear in what ways. This lack of understanding ensures luxury-focused carbon taxation remains unattractive as a policy option.

Therefore, here we model a policy that takes the distinct consumption purposes of different income classes explicitly into account, and we consider 88 countries covering the global north and south. The tax distinguishes between luxury and basic consumption purposes. Luxury consumption is defined as consumption that is primarily undertaken by high-income households, and basic consumption is defined as consumption that constitutes the greatest share of expenditure for lower income households. A typical example of luxury consumption is flights, and a typical example of basic consumption is day-to-day food. Tax revenue is used for retrofitting homes and is redistributed back to low-income households. We find that luxury carbon taxes are fairer with respect to emission reductions; that is, high-income households must reduce their emissions more relative to their emissions per capita, as well as with respect to financial burden, than uniform ones, while reducing total emissions to similar extent. By 2050, in a medium-price scenario, the policy saves around 100 gigatonnes carbon dioxide equivalents, which is 75% of what is needed for households to stay within a 2° consistent climate pathway and almost a third of what is needed for 1.5° consistency. In sum, the luxury carbon tax can contribute substantially to the Paris Agreement.

RESULTS

Method summary

We model a data-driven proof of concept employing a dual strategy. First, we build a static-comparative model of carbon taxes on household consumption for 88 countries in 2019 (covering more than 90% of the global population and gross domestic product [GDP]). We explore the distributional implications with respect to emission reductions (and with respect to financial burden in Figure S1 for comparison) and apply the terms progressive and regressive accordingly. The focus on emissions emphasizes individual contributions to climate targets. For more comprehensive policy appraisal, we quantify impact on total emissions over time employing a dynamic model and therewith contribution to the Paris climate goals. Figure 1 displays the structure of our study.

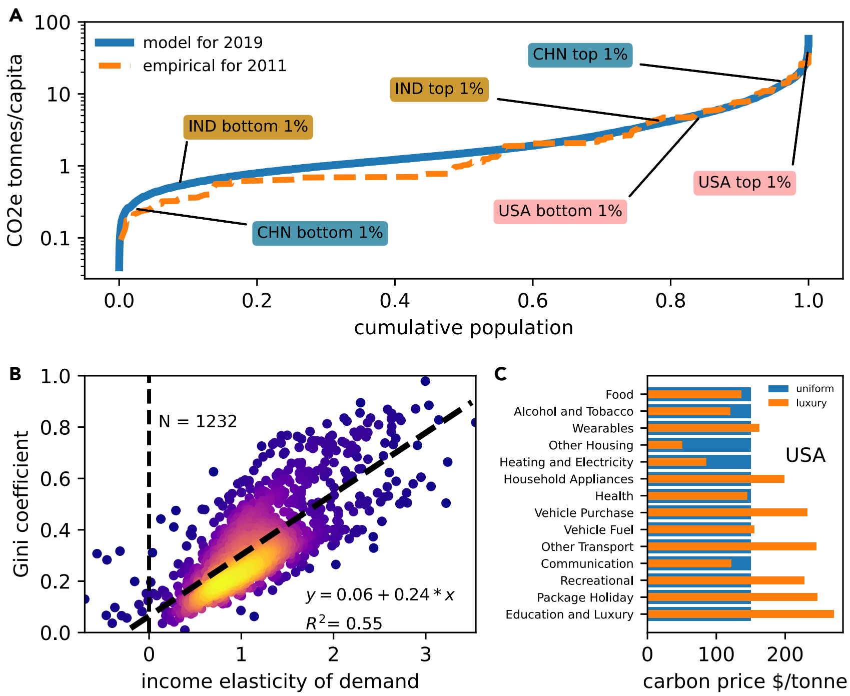

Figure 2. Data and model features

(A) Modeled international distribution of consumption-based emissions per capita in 2019 (blue line). It indicates the position of American, Indian, and Chinese top and bottom percentiles. It also plots the original data for 2011, which are not interpolated or updated to 2019.

(B) Correlation of income elasticity of demand (ϵ_d) and Gini coefficient across all 88 countries and all 14 consumption categories. It demonstrates that most consumption categories considered are normal goods (i.e., $\epsilon_d > 0$). The data exhibit heteroscedasticity, but we plot a linear least-squares regression simply to demonstrate the correlation trend.

(C) The 14 consumption categories we consider plus carbon prices for the USA under a uniform and luxury tax scenario.

Inequalities in emissions and consumption

Carbon inequality has previously been demonstrated to be large between and within countries, with the global top 10% of individuals being responsible for almost half of all emissions.[23] We test this finding based on our model of household emissions. We find the international Gini coefficient of household emissions is 0.56 and the global top 1% of individuals are responsible for ~10%, the top 10% for 45%, and the bottom 50% for less than 15% of emissions, which is similar to the distribution of household energy footprints.[9] The USA alone accounts for 25% of household emissions, China for 18%, and India for 9%. Top and bottom percentiles for the USA, China, and India are indicated in Figure 2A, confirming large international and national disparities. We show the modeled distribution for 2019 (blue line) plotted against the empirical distribution for 2011. The latter is directly based on household surveys and a multi-regional input-output (MRIO) model (orange dashed). Moreover, we estimate income elasticities of demand for 14 consumption categories across all countries and plot them against the corresponding national Gini coefficient for that consumption category in Figure 2B. There is a substantive correlation supporting our use of elasticities to infer about the distribution of consumption. Figure 2C illustrates an example of carbon prices in the luxury tax scenario compared with the uniform tax scenario for the USA across all 14 consumption categories. Given our tax design, the carbon price differences are explicitly linked to the relevant inequalities of consumption via the income elasticities. In this example, the average carbon price is set at $150 per tonne (blue bars) for both uniform and luxury cases, because the USA is a high-income country. This is also the price we set within the static modeling scenarios for high-income countries. For upper middle-income countries, we set the average carbon price to $50, for lower middle-income countries to $25, and for low-income countries to $10 per tonne within the static modeling exercises. Further discussion on the choice of these prices is included in the section "experimental procedures."

Static modeling: Distributional implications

Traditional carbon taxes are financially regressive because they apply the highest rates to energy necessities such as heating or fuel.[25] Here, we test how regressive or progressive a carbon tax is with respect to emissions per capita if applied to all of household consumption and how this depends on the tax design (in this section without considering revenue recycling): uniform vs. luxury. In both scenarios, the tax reduces global household emissions by 6%, and international Gini coefficients are reduced only marginally from 0.56 to 0.55. National Gini coefficients are reduced marginally but consistently across countries by up to 6% relative to the uniform tax scenario. Figure 3B plots national emission reductions against the tax revenue as a proportion of GDP. In high-income countries, tax revenue constitutes ~1%–4% of total GDP. For the remaining country types, this is substantially less at ~0.1%–~ 1%. National tax revenue as a share of GDP ranges roughly over two orders of magnitude and so do national emission reductions, from ~0.1% to ~10%. The relationship between the two variables is linear. There is a tendency to generate less revenue under the luxury tax but to reduce emissions more. Average national emission reductions are 4.4% in the uniform scenario and 4.8% in the luxury scenario. This is because the luxury design shifts taxes to price-responsive goods (i.e., elastic demand). Households are more likely to forgo this consumption when a tax is applied, resulting in more emission reductions but also less tax revenue. For instance, wealthy city dwellers might only use their cars for weekend leisure but not for commuting or shopping and thus are not reliant on the car for elementary needs satisfaction. This is an overlooked property of demand in climate mitigation strategies. Figure 3A highlights the USA and South Africa as both important representatives of the global north and the global south respectively. US household emissions reduce by ~8%, which is a ~6% reduction with respect to total emissions (including government and capital formation). This reduction is roughly the same in the luxury and

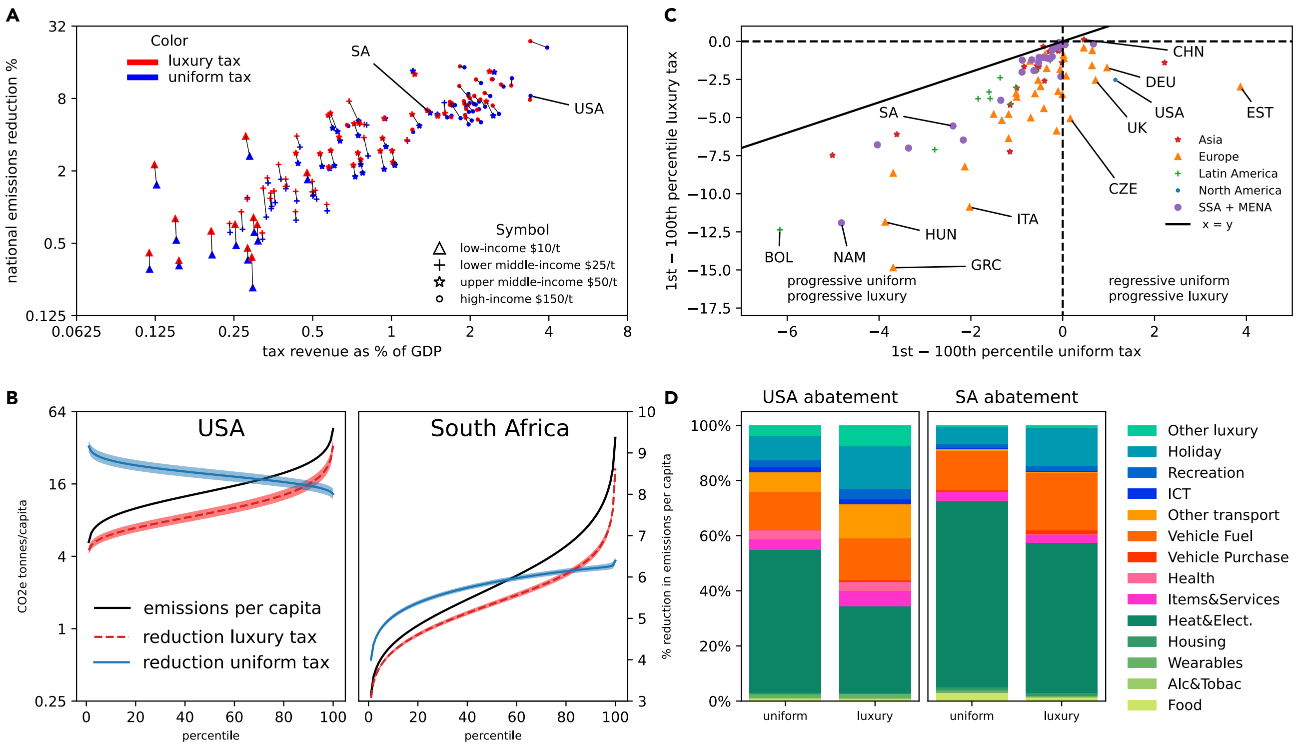

Figure 3. Distributional implications uniform tax and luxury tax

All results in this figure are averages over 100 simulation runs. The stochastic component is in the price elasticities of demand. (A) National emission reductions vs. revenue as percentage of GDP on log axes. Red markers denote the luxury tax scenario and blue ones the uniform tax scenario. (B) The emission distribution per capita for the USA and South Africa (left y axis and black line) on a log scale as well as the reduction in emission per capita under the uniform (right y axis and blue line) and the luxury tax (right y axis and red line) scenario on a linear scale. The range indicates the 99% confidence interval demonstrating that uncertainty in tax responsiveness is low. (C) Progressivity of the uniform tax and luxury tax into two quadrants: regressive uniform and progressive luxury (lower right), and progressive uniform and progressive luxury (lower left). The x axis measures the difference in percentage emission reductions between top and bottom percentile in the uniform scenario. The y axis does the same for the luxury scenario. The plot shows that, in most countries, both policies are progressive but the luxury scenario even more so. Nearly all points fall below the x = y line. (D) Emission reductions across sectors in the USA and South Africa (SA). ICT, information and communications technology.

uniform scenarios (~0.4 GtCO2e) and is almost twice as much as total annual household emissions in South Africa. South African household emissions reduce by ~6.5% in both scenarios, equivalent to ~3% of total consumption-based emissions.

Figure 3B plots the distributional implications for USA and in South Africa. The black line represents the national distribution of emissions per capita. The lowest US household percentile emits about 5 tonnes/capita/year, the highest around 50 tonnes/capita/year. The distribution in South Africa covers a wider range with 50% of the population emitting less than 4 tonnes/capita/year, the lowest percentile ~0.2 tonnes/capita/year and the highest ~40 tonnes/capita/year. The blue lines represent the reductions in emissions per capita in a uniform tax scenario. In the USA, the uniform tax is regressive, as expected because high-carbon-intensity consumption such as transport fuel is high even among low-income households. In South Africa, in contrast, even the uniform tax is progressive. The lowest 20% abate far less emissions than the upper 80%. This is because the lowest 20% spend a much larger fraction of their income on food than is common in high-income countries (40% on average compared with 15% on average in the USA). In both countries, the luxury tax is progressive.

Figure 3C generalizes the results from 3B across all countries. It shows a simplified measure of how progressive the tax policy is. We measure the difference in percentage points of emission reductions between the bottom and top percentile for each country (first percentile to 100th percentile). If the first percentile reduces emissions more than the 100th percentile, then the difference is positive, and the tax is regressive. If the first percentile reduces emissions less than the 100th percentile, the difference is negative, and the tax is progressive. We calculated these differences for both tax designs. The difference for the uniform one is plotted on the x axis and the difference for the luxury one on the y axis. If both policies are progressive, the difference between bottom and top percentile is negative for both (lower-left quadrant). South Africa is a typical representative of this quadrant. Most countries end up in this quadrant, which is evidence against the common narrative that carbon taxes are generally regressive. If applied to all consumer goods and when considering impact on emissions per capita they are more often progressive than regressive. However, there are also important cases where the uniform tax is indeed regressive and only the luxury one progressive, as, for instance, the USA, UK, Germany, and other industrialized economies (lower-right quadrant).

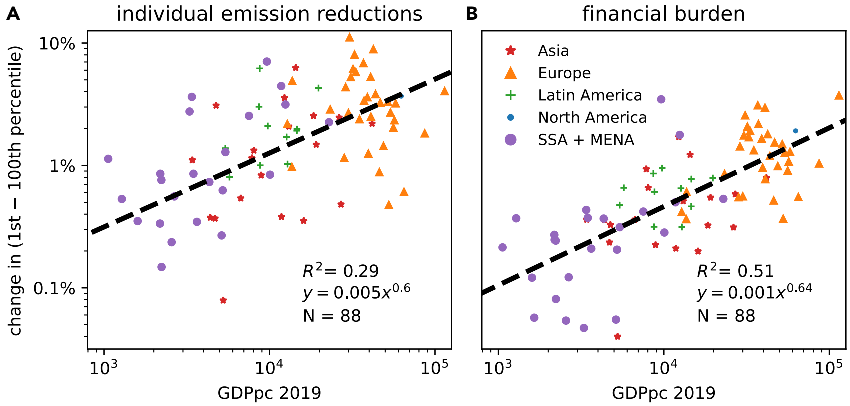

Figure 4. Progressivity gain from luxury carbon tax compared with uniform carbon tax
The fairness (or, more precisely, progressivity) gain is measured by considering the difference (between luxury and uniform design) in differences (between the top and bottom percentile) as illustrated in Figure 3C. (A) The additional progressivity gained through the luxury design with respect to individual emission reductions. It displays how much the gap in percentage emission reductions between the top 1% and bottom 1% amplifies in favor of the bottom 1% on a log scale. (B) The same vertical axis as (A) is used for clarity of scale and illustrates the same but in terms of financial burden (i.e., the share of disposable income that is spent on the tax). Clearly, the effect of a luxury tax scales with the average income (GDPpc) of countries. It is thus most beneficial to introduce luxury carbon taxes in high-income countries to achieve fair climate policy. One outlier, Madagascar, in (A) is not depicted. Its value on the vertical axis is below 0.01%, and so the difference that the luxury tax makes is negligible.

Cases where both are regressive or only the luxury one is regressive do not occur. Only China exhibits very slightly regressive but nearly flat behavior under both policies. The Chinese indifference to tax design originates from high spending on residential energy use across all income groups, but relatively low spending on private transport and other luxury consumer goods. Income elasticities in China are also all relatively close to 1, thus price differentials in the luxury scenario are not so pronounced (see Figure S2). Figure 3D illustrates emission reductions across sectors in the USA and South Africa. The uniform tax reduces residential emissions substantially in both countries, while the luxury tax design affects other consumption categories more strongly.

Overall, the luxury tax design improves the progressivity of carbon taxation across countries. The degree to which it does so depends on various factors. For one, it depends on how large the variance of elasticities is. If the variance of elasticities is large, it amplifies the price difference between the uniform and the luxury scenario and consequently the difference in impact. The composition of consumption across categories plays a role too. Concentration of consumption in a specific category constrains the difference between uniform and luxury tax. For instance, in several low-income countries in Sub-Saharan Africa, food is a dominating category, and here the difference between uniform and luxury tax is not very large. Another decisive factor is the average income of a country. The wealthier a country is, the lower are income elasticities of carbon-intensive transport,[27] and low-carbon-intensity luxuries (e.g., financial services) are consumed extensively by high-income households. Hence, uniform carbon taxes tend to be regressive, and switching to a luxury-focused design makes a great difference. For example, in North America and Europe, driving a car is common even among low-income households, yet spending a lot on financial services remains concentrated in high-income segments. In contrast, in Egypt, even driving a car is predominantly concentrated in high-income segments and hence a uniform carbon tax is progressive already. Therefore, all countries benefit from a luxury tax in terms of fairness, but the greatest fairness gains are made in high-income countries. This finding holds in terms of individual emissions as considered above but also in terms of financial burden expressed as the share of disposable income spent on the tax. Figure 4 illustrates the relationship between GDP per capita and the additional fairness (progressivity) gained by implementing a luxury carbon tax design compared with a uniform one.

Table 1 summarizes a few international statistics across major countries and aggregate regions.

Static modeling: Tax revenue with multiple objectives

Several planned carbon tax policies have been rejected by the public because they put a high burden on low-income households.[29,30] However, carbon taxes can even decrease poverty and inequality if revenue is redistributed appropriately. Lump-sum recycling of revenues, for instance, is progressive because the amount of money received by low-income households is much higher relative to their income than it is for high-income households.[27,31] Moreover, if revenue recycling programs focus specifically on poverty eradication, substantial reductions of poverty can take place. For example, it has been shown for Peru that, at a carbon price of $50/tonne, extreme poverty could be reduced by 17% if revenue is redistributed to the poorest.[32] An issue less often addressed is that this offsets some of the abated emissions if people re-spend the money, so there is a short-term trade-off between social protection and mitigating emissions. One option discussed in the literature is to redistribute the revenue but mandate green consumption through item-specific vouchers.[33] For example, regarding the future need for more thermal cooling in the global south, one such option would be to fund air conditioning devices for affected low-income households.

Here, we take a more generic approach and ask whether we can find a revenue allocation between social and environmental purposes that reduces carbon emissions but protects low-income households. For answering this question, we conduct a simple numerical experiment: every country redistributes the tax revenue back to a specified number of households starting with the poorest. The revenue is spent such that their prior consumption levels are retained, and recipients are effectively exempted from the tax. In the first round, only the first percentile is paid back, then the first plus the second, then first plus second plus third, and so forth. The remaining revenue after redistribution is invested into retrofitting homes. We did this across all countries and aggregated the results in Figures 5A–5C. Figure 5B demonstrates how the investments affect emissions. It shows that redistribution increases emissions because it increases

Table 1. Tax design impact comparison

		World	USA	South Africa	China	India	Europe	SSA + MENA	Latin America	Rest of Asia
Total emissions reductions	luxury	6%	7.8%	6.3%	5.0%	1.6%	7.0%	3.3%	3.5%	7.5%
	uniform	6%	8.4%	6.1%	5.2%	1.3%	6.6%	3%	2.8%	7.5%
Revenue from national top 10%	luxury	25%	23%	51%	34%	24%	23%	38%	41%	24%
	uniform	23%	21%	44%	33%	20%	21%	33%	35%	22%
Revenue from luxury (ϵ_d >1)	luxury	52%	42%	53%	44%	43%	65%	50%	63%	63%
	uniform	37%	27%	36%	37%	24%	48%	34%	45%	50%

consumption. Retrofitting further lowers emission. We plot the magnitude of the effect. At a maximum, if all revenue is invested into retrofitting, it lowers total household emissions by another 1%. Here, it is important to keep in mind that this result concerns only 1 year of revenue recycling. Over several years, let us say 10 years, investments in retrofits can therefore reduce global household emissions by ~10%. Reductions achieved through retrofits are also permanent, and thus the effects of retrofitting are substantial. In case all revenue is redistributed back to households, it offsets nearly all emission reductions prior to revenue recycling, which is roughly ~6%. Figure 5B also shows the point where the two mechanisms, redistribution and retrofitting, cancel each other out. This zero-trade-off point is roughly located at the 35th percentile. From a global perspective about one-third of the population can benefit from redistribution without compromising climate mitigation at all. Figure 5C shows the reductions in emissions (y axis) as a function of how many percentiles receive revenue redistribution. Per-country decision making is more policy relevant. Therefore, in a next step, we calculate the zero-trade-off point for every country. Figure 5D correlates the national zero-trade-off points with the national Gini index of consumption expenditure. The correlation is modest but statistically significant and important. The higher the inequality of consumption in a country, the more households can receive redistribution, starting with the poorest, without offsetting reduced emissions. The most redistribution can, and thus arguably should, happen in unequal societies in Latin America and Africa, including South Africa. In these countries, then, richer percentiles carry the burden of reducing emissions. Figure 5E illustrates the lesson learned that revenue allocation should not just depend on the absolute level of income (GDP per capita) but also on the inequality of household consumption.

Dynamic modeling: Toward the Paris Agreement

Carbon taxes and their distributional implications are often exclusively studied in a static-comparative model probing the very short-term consequences, which is what we have done so far. However, carbon taxes are part of dynamic and complex economies, and their success ultimately depends on emission abatement over time. At a minimum, then, it should be tested how the luxury carbon tax performs when facing ongoing economic growth and population growth. Here we distil a simple dynamic model to evaluate impact on the Paris climate goals. The model builds on "vectors" of household consumption for 88 countries from 2020 to 2100. Figure 6 illustrates the structure of the model with (v) denoting exogenous parameters that vary with each scenario and (f) fixed in all scenarios.

There is a range of scenarios. All scenarios differentiate prices by country type and assume a linear carbon price trajectory as outlined in the section "average carbon prices and price trajectories." Table 2 provides a scenario overview.

First, we explore the influence of the average carbon price by employing three distinct price scenarios: low price, medium price, and high price. The goal is not to find the optimal carbon price but to test the model sensitivity. We compare each scenario with a business-as-usual (BAU) counterfactual and a 2° consistent emission pathway as well as 1.5° consistent pathway. Figure 7A (A) plots the carbon prices introduced in 2022 across country types and price scenarios, and (B) illustrates the linear carbon price trajectories for high-income countries across price scenarios.

The low-price scenario (blue line in Figure 7C) substantially reduces emissions compared with BAU (red line Figure 7C). By the end of the century, ~180 GtCO2e are cumulatively saved. This is significant but far less than what is needed for household emissions to stay within a Paris-consistent pathway. For comparison, 180 GtCO2e cumulative emission savings are required by 2039 for the 1.5° pathway compared with BAU. However, given that our model focuses on selected tax effects such as demand reduction and revenue recycling but not on innovation or social tipping points,[34] it is not expected to fulfil the Paris Agreement on its own. Nonetheless, the high price scenario alone achieves savings consistent with a 2° pathway by 2040 and cumulatively abates ~70 GtCO2e emissions up to this point. Revenue recycling further increases carbon savings. Investing into retrofits alongside high carbon prices achieves consistency with a 2° pathway beyond 2040. The 1.5° pathway, however, stays out of reach even with the most ambitious policy. Only in the very short term (the first 3 years) does the high-price scenario reduce demand enough to stay within the 1.5° pathway. Afterward, the effect of setting a high carbon price is overwritten by ongoing economic growth. Notably, under all scenarios, global household consumption keeps growing, albeit at lower rates than under BAU. Consumption growth pathways are depicted in Figure S3. The higher the carbon prices, the lower is consumption growth. Accordingly, the lowest emissions occur for low-growth pathways. In the low-growth scenarios (LG1 + LG2), we reduce economic growth rates across all countries and years by 50%. LG1 applies medium carbon prices and LG2 low ones. When global growth is already low, it is reasonable not to overprice emissions. The LG1 pathway is the only pathway that is 2° consistent beyond 2050. Note that we do not distribute growth rates in an equitable manner. In the real world, it is advisable that developing nations maintain high growth rates until they reach a decent level of income, while rich nations enter a steady

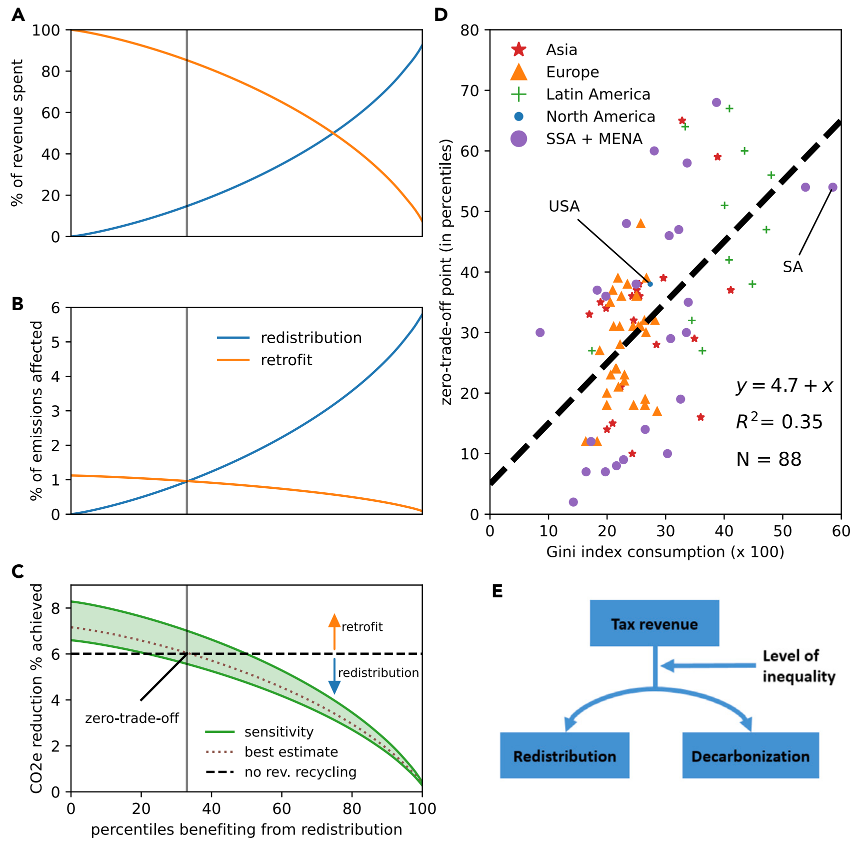

Figure 5. Revenue recycling trade-off

(A) The share of revenue that is spent on redistribution (blue) or retrofit (orange) as a function of how many percentiles benefit from redistribution. The x axis is plotted below (C) and is the same for (A) to (C).
(B) The effect on emissions. We plot the magnitude of the effect. Redistribution increases emissions. Retrofit reduces emissions. (C) How revenue allocation interferes with yearly emission reductions. The horizontal dashed line indicates how much emissions are reduced by the luxury carbon tax policy without investing any revenue. To the left, when $x = 0$, no household receives redistributed revenue, and all revenue is used for retrofits. The green range indicates a sensitivity analysis where the upper and lower bounds represent a doubling and halving of retrofitting costs respectively. To the right, when $x = 100$, every percentile receives redistributed revenue. (C) The global zero-trade-off point. This is the point where revenue is allocated to retrofitting and redistribution such that it does not interfere with the yearly emissions balance of the carbon tax. (D) The Gini index of consumption expenditure per country (x axis) plotted against the national zero-trade-off points (y axis). (E) The lesson learned that more revenue should be allocated to redistribution if consumption inequality is high.

state of throughput or even decrease output toward sustainable levels.[35] Later this century, when carbon intensities are low through technological progress but global GDP further grows, luxury carbon taxes have little impact. For the second half of the century, there must be other mechanisms in place for reducing emissions to zero. This could be a mix of post-growth policy and radical technological innovation, such as, for instance, absolute caps on conspicuous consumption plus entirely novel materials and energy carriers.

Dynamic modeling: Rebound and low policy adoption

The modeling approach in this study is proof of principle, not a realistic assessment of future events, and there are various limitations to the current model. As economies become more energy efficient, studies suggest rebounds of up to 50%.[36,37] Here, we do not measure energy rebound but we do take financial savings into account. The principle is similar: savings in one place lead to expansion in another or even in the same sector. After taxation, households have a different spending profile than before taxation. Most of the time, the difference in their total expenses is minor (<1%). Demand reduces, but they must pay the tax and so households roughly end up with overall expenses similar to before tax. Sometimes the sum of expenses ends up less than before tax and thus they save money. A more substantial saving occurs after retrofitting a household. According to our model, this reduces spending on heat and electricity by 50%. This money is then free to be spent elsewhise. We estimate how financial rebound affects global emissions trajectories in a medium-price scenario by assuming an average consumption basket with average carbon intensity at every time step. We find the effect to be of modest magnitude. By 2030, cumulative differences in emissions are ~2 GtCO2e across all countries and by 2050 they are ~20 GtCO2e. The effect by 2050 is substantial but less than, for example, the difference between the low-price and the medium-price scenarios at cumulatively ~32 GtCO2e until 2050.

Further, there are numerous real-world barriers to implementation of the policy proposed here. The biggest barrier is that few or no countries adopt a carbon tax as stringent as proposed. Therefore, we take into account a corresponding sensitivity analysis with respect to the medium-price scenario. What if only the USA adopts the policy, or only Europe? What country has the largest impact on global emissions? We measure how cumulative emissions savings change as a function of the countries adopting the policy. The results are depicted in Figure 7E. The USA would be the most significant country to adopt a luxury carbon tax on household consumption, followed by Europe, India, Russia, and China. Over time, India would be more significant than China, even if they both introduce the same average carbon price. The carbon intensity of consumption decreases twice as fast in China compared with India, and Chinese population growth and economic growth slow down over time.

DISCUSSION

In 2022/2023, an energy crisis and inflation shape the global economy. Europe faces gas and fuel shortages. Asian post-pandemic recoveries suffered under limited coal supply. Renewable energy supply has grown fast but not fast enough.[38] While

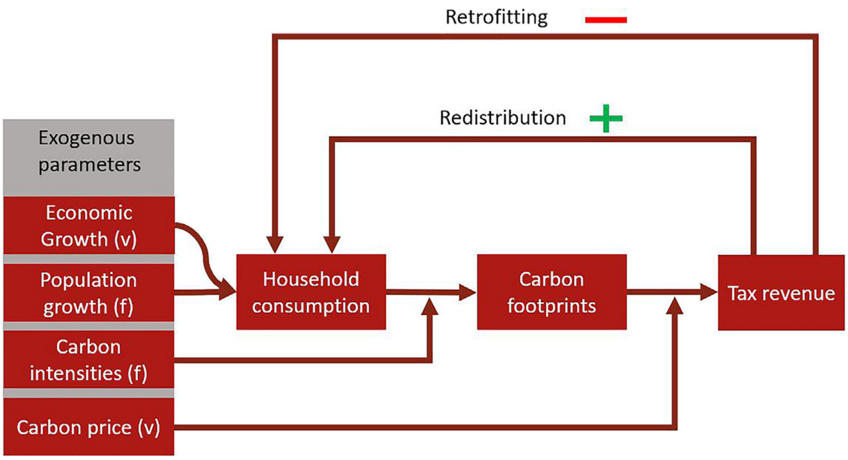

Figure 6. Dynamic model structure
This figure illustrates the core structure of the dynamic model. Exogenous drivers are economic growth, population growth, carbon intensity evolution, and carbon prices. Endogenous variables are household consumption, carbon footprints, and tax revenue. Retrofitting of dwellings is a negative feedback and redistribution is a positive feedback. Retrofit reduces demand (when no respending of the saved money is considered) and thus reduces tax revenue, and redistribution increases demand and thus increases tax revenue. However, the system exhibits no escalating or stabilizing behavior emerging from these feedbacks. The magnitude of the effects is too small.

the reasons for the crisis are manifold, ranging from a post-pandemic surge in demand to war, in the long-run costs always end up with households. At the least, climate policies should take high-income households more strongly into account than low-income ones. Here we have shown that luxury carbon taxation does that in many countries in the global north as well as the global south. Despite advantages over conventional designs, luxury carbon taxation of household consumption only contributes significantly to the Paris climate goals if introduced promptly, universally, and with high and rapidly rising carbon prices compared with any policy currently in place. Although, in 2021, the European Union Emission Trading Scheme's carbon price has reached all-time heights (~\$100/tonne), this policy still covers only 40% of European emissions and thus a fraction of what is needed globally. The scope of carbon pricing urgently needs to be extended. The USA could set an example. They are the largest emitter with respect to households and they carry huge historic climate debt. Demand-oriented climate policies in the USA could help achieve national and global climate goals.

The purpose of this study is not broad discouragement of materialistic lifestyles. Luxury carbon taxes are not sin taxes; they are ecologically motivated and are considerate of distributional implications. They originate from a realist's perspective on global problems. Climate change and biodiversity decline are threats to the long-term prospects of human civilization, and, so far, technological evolution has not caught up with the massive scale of economic output and its impacts.[39] Penalizing and reducing the output in parts must be an option. If future generations have fully solved some of the technological and social challenges we face today, for instance zero-emission flying available on an equitable per capita basis, they might then release these activities from restraints. It cannot remain the status quo to continue environmentally damaging luxury activities unabated while awaiting a technology fix.

There are several limitations to the present analysis that are important to discuss from a policymaker point of view. First, distributional impacts perhaps change significantly with time and perhaps so do government motives with new political or geopolitical circumstances. Likely, policies will require a much higher degree of adaptation over time than we have considered. This problem is also known as time inconsistency.[40] Second, currently in low- and middle-income countries many people might be "artificially" locked-out of consumption due to infrastructure constraints. For example, many people in the global south still cannot consume electricity simply because they do not have access to the grid, which in turn restricts the capability to use household appliances such as thermal cooling appliances. Hence a high elasticity, in that specific case, perhaps is not really representative of the entire population as it is strongly influenced not only by the raw purchasing power but also by infrastructural constraints. In that case, a luxury tax, due to high consumption elasticity, would restrict access to a necessary good. Policymakers need to be aware of such limiting circumstances and identify whether such an "artificial scarcity" exists before raising a luxury tax.

Table 2. Dynamic model scenario overview

Scenario key	BAU	LP	MP	HP	LP.RR	MP.RR	HP.RR	LG1	LG2
Scenario	BAU	Low price	Medium price	High price	Low price, retrofit, redistribution	Medium price, retrofit, redistribution	High price, retrofit, redistribution	Low growth, medium price	Low growth, low price
Luxury carbon tax	no	yes	yes	yes	yes	yes	yes	yes	yes
Retrofit	no	no	no	no	yes	yes	yes	yes	yes
Redistribution	no	no	no	no	yes	yes	yes	yes	yes

This table presents an overview of the dynamic scenarios with respect to whether they implement a luxury carbon tax or a standard uniform one as well as whether retrofitting and redistribution are included in the revenue recycling scheme. The scenarios listed are BAU, low carbon price (LP), medium carbon price (MP), high carbon price (HP), LP with retrofitting and redistribution (LP.RR), medium carbon price with retrofitting and redistribution (MP.RR), HP with retrofitting and redistribution (HP.RR), low growth and MP (LG1), and low growth and LP (LG2).

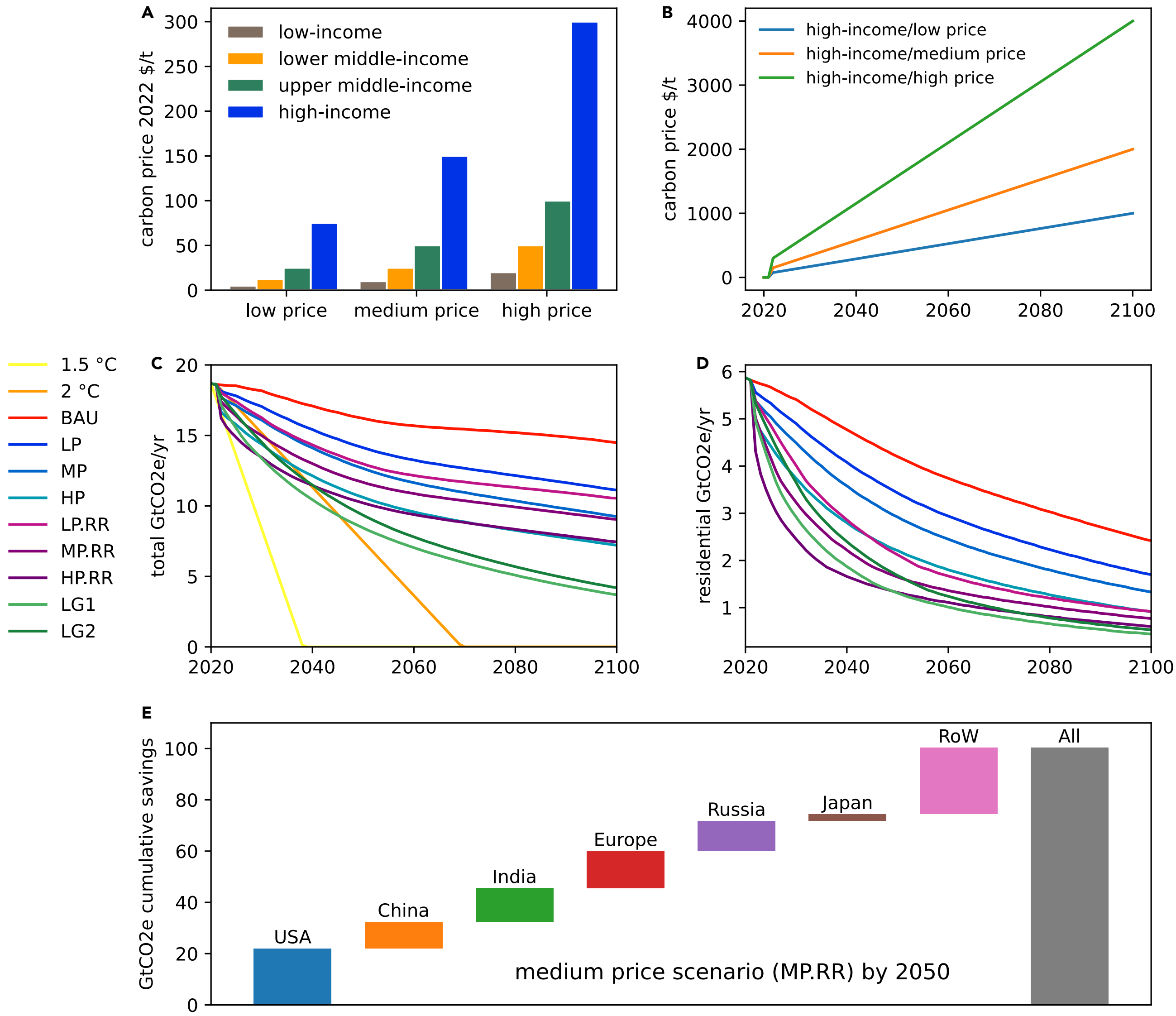

Figure 7. Emission pathways for household consumption in 88 countries

(A) The initial carbon price level across scenarios. The scenarios listed are BAU, low carbon price (LP), medium carbon price (MP), high carbon price (HP), LP with retrofitting and redistribution (LP.RR), medium carbon price with retrofitting and redistribution (MP.RR), high carbon price with retrofitting and redistribution (HP.RR), low growth and medium carbon price (LG1), and low growth and low carbon price (LG2). It also depicts the prices distinguished by country income level. (B) How carbon prices change over time for high-income countries. The trajectories are linear after initial prices are introduced in 2022. (C) Total household emissions over time. The BAU scenario is the red line. The linear slopes are the 1.5° (yellow) and 2° (orange) consistent pathways (different non-linear versions of these are possible). (D) Emission pathways for residential energy use (heating and electricity) across all scenarios. (E) Cumulative emission savings by 2050 in the medium-price plus retrofit and redistribution (MP.RR) scenario. RoW, rest of the world.

Third, there is the "information problem."[41] The information problem is about whether a government would even be capable of collecting all the necessary information to implement a tax that differentiates by consumption purpose. The question is whether it is feasible to know which items count as luxury and which as necessity. At a minimum, the income elasticity of demand for different consumption items needs to be estimated, and, in the best case regularly, so that information does not become outdated. This can be done; however, the question is with what detail. We do know the income elasticity for a vast range of goods and services, as used in this study, and many countries maintain regularly updated household consumption surveys from which this information can be drawn at a fine-granular level. Fourth, the interest-group problem asserts that differentiated consumption taxes are "unstable" because whoever is affected most by the tax,[41] which is in our case high-income earners consuming luxury goods, will form interest groups and undermine the policy via lobbying. In practice, however, newly introduced carbon pricing policies have proved more stable than was assumed before introduction. The European Emission Trading scheme, for instance, has proved stable despite enlargement of the European Union.

It was feared that new members, often still emerging economies in the east of Europe, would erode the scheme due to interest in cheap fossil energy.[42] These fears have not come about, and instead the scheme is more successful than ever, 17 years after its implementation. Fifth, luxury carbon taxes on consumption do not exist in a policy vacuum but need to accompany other existing policies or policy options with similar purposes. For example, recent research demonstrates that around 50% of emissions from the top 10% emitters globally speaking are due to capital investments rather than due to consumption; for the top 1% emitters, it might be more than 70%.[23] This implies that, to tackle carbon inequalities, and particularly to raise revenue, the taxation of luxury emissions associated with consumption is not the only option and perhaps not the optimal one. As Chancel argues, a tax threshold from modestly carbon-intensive investments upward would apply to the top 10% globally and spare most of the global population entirely.[23] This makes for a very progressive policy too, even without any revenue recycling scheme, similar to the luxury carbon tax on consumption and perhaps better so. It remains unclear so far, however, what the best possible choice is or if possibly a climate policy-mix considering taxes on consumption, income, and capital investments is optimal. Accordingly, policymakers need to consider the multiple economic dimensions of consumption, income, and investment when implementing tax strategies and, moreover, their likelihood for widespread adoption, the amount of revenue raised, the progressiveness, and the carbon emissions mitigated. Sixth, in practice, carbon leakage across borders remains a concern because luxury tax rates might differ across countries if scaled by the respective income elasticities. This concern is especially relevant to an economically integrated region such as the European Union where consumption is fluid across borders. However, the European Union could, for instance, introduce a union-wide luxury carbon tax instead of an individual one for each country to prevent carbon leakage. In any case, while luxury consumption remains prevalent alongside widespread deprivation around the world, tackling it should be a key consideration of climate policy.

EXPERIMENTAL PROCEDURES

Resource availability

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Materials availability

This study generated no new materials.

Data and code availability

The study has been implemented in Python Anaconda. All data and code are available at https://github.com/yloswald/luxury_carbon_tax.

Tax design and model summary

The core idea of the proposed tax is very simple: differentiate the carbon price according to consumption purpose. In other words, increase the taxes on luxury goods relative to necessities. However, distinguishing these seems like a highly contentious task. Who is to judge this categorization? There is, however, a standard economic approach offering one way of overcoming this difficulty, which is suitable for our theoretical model. Luxury goods are defined as having an income elasticity of demand >1, necessities those with an income elasticity <1.

Carbon tax rates can be derived via simple multiplication: carbon price multiplied by carbon intensity. Carbon intensity refers to the amount of emissions embodied in a good or service per unit of money spent. If p equals price and c equals carbon intensity, then the tax rate τ for a good is defined as:

$$\tau = c * p \qquad \text{(Equation 1)}$$

Indices distinguishing each good are omitted from Equation 1. The twist is multiplying by the respective income elasticity of demand ϵ_d, so that the level of elasticity sets the tax level. We do not tax only luxuries this way but instead linearly weight the tax by the elasticity, so luxuries are taxed at a higher rate and use a normalization factor A to preserve the average carbon price (see Equation 2).

$$\tau_{luxury} = c * A * p * \epsilon_d \qquad \text{(Equation 2)}$$

An elementary example is presented in Note S1. The logic behind this procedure is 2-fold: By integrating the elasticity, we integrate distributional information and create non-arbitrary price differentials, and, by keeping the average costs of carbon constant, we ensure that the information of how strong the price signal has to be in order to achieve a certain goal (e.g., net-zero emissions or internalizing social costs of carbon[43]) is preserved. The specific carbon prices we use in the current work are not goal driven in this way but are in line with those in the literature, as discussed in the section "experimental procedures." From here on we name this tax design "luxury tax."

Another critical component of the tax design is how the revenue is recycled. In the section, "static modeling: tax revenue with multiple objectives" and specified scenarios in the section "dynamic modeling," we invest revenue into retrofitting homes and redistribution. Residential energy makes up 45% of household energy consumption[9] and 31% of household emissions (in carbon dioxide equivalents, relative to energy, emissions are more skewed to other sectors, e.g., food). Most people's wellbeing relies on residential energy, yet low-income households often struggle to afford sufficient quantities. Instead of levying a heavy tax on emissions in this sector, as a uniform carbon tax would, we explore a public investment program to reduce energy demand and therewith emissions.

Household consumption and emission accounts

The household accounts for consumption and consumption-based emissions comprise 88 countries (including Europe, USA, and BRICS nations) and include direct and indirect household emissions. The years represented are 2019 in the static model, so pre-pandemic conditions, and 2020–2100 in the dynamic model. Emissions due to capital formation and government expenditure are not included. For a comprehensive list of countries, please see Table S1. Consumption is measured in international dollars $PPP at constant 2017 prices. The emission accounts are carbon dioxide equivalents. Besides carbon dioxide, methane, nitrous oxide, and various F-gases are included, and appropriate global warming potentials have been applied[44] (please refer to Table S2 for specifics). The emission accounts have been calculated employing an MRIO model based on the Global Trade Analysis Project (GTAP 9) for the year 2011 based on a standard Leontief-matrix approach. The MRIO model is used to inform emission intensities and household accounts but is not further interacted with in the study. This means we do not test changes in the technology matrix and trade relationships of countries. Household consumption per income group is derived from the Global consumption database[45] and Eurostat household data[46] in line with Oswald et al.[9,11] For the USA and Japan, household surveys are from the US Bureau of Labor Statistics[47] and the Japanese Statistics Bureau,[48] respectively. Consumption has been aggregated to 14 categories according to type and purpose. Subsequently, we projected the data to 2019 combining national account data on household consumption from the World Bank,[49] national population data from the World Bank,[50] and historical trends of consumption-based carbon intensities from the Global Carbon Project[51] for the years 2010–2018. The household consumption data from the World Bank and the carbon accounts from the Global Carbon Project are national aggregates. Therefore, the growth rates applied from 2011 to 2019 are uniform averages. This is less realistic than using a specific growth rate for each consumption category, but it preserves the proportions of consumption and emissions estimated in line with the 2011 household surveys.

Interpolation of consumption

A good approximation to household expenditure distributions is a log-normal distribution.[52] We interpolate from four or five income groups for each country to percentiles. This is done for consistency across countries and detail with respect to high- and low-income groups. First, we calculate a Gini coefficient per consumption category. Every Gini coefficient corresponds to a log-normal model via the following equation where σ denotes the log standard deviation, G the Gini coefficient, and *erf* the error function.[53]

$$G = erf\left(\frac{\sigma}{2}\right) \quad \text{(Equation 3)}$$

Solving for σ and combined with the mean of the data we can solve the cumulative quantile function of a log-normal distribution for population percentiles. The quantile function is as follows.

$$exp\left(\sqrt{2}\,\sigma\, erf^{-1}(2p - 1) + \mu\right) = x \quad \text{(Equation 4)}$$

Here, *exp* denotes the exponential function, erf^{-1} the inverse error function, p the upper percentile bound, μ the mean of the log-normal values, and x the estimated income at the upper percentile bound. Deploying x, we estimate the consumption per category and per percentile and fix the distribution mean. Consumption category indices are omitted in Equation 3 and Equation 4 for simplicity. A critical assumption of this method is that consumption, in each category, increases monotonously with income. This is the case in 90% of the underlying data and, where it is not, the divergence from a monotonously increasing trend is minor. We study the main results of the analysis under alternative assumptions in Figure S4 and find that they are robust.

Additionally, we interpolated gaps in the original data. For instance, for a few countries, there are no reported data on the category package holiday. Data gaps occur in package holiday, recreational items, and in vehicle purchases. We interpolate using a constant income elasticity of demand of 1. This way we operate with the reasonable assumption of demand proportional to income. The interpolated expenditure always constitutes 1% of total expenditure per capita. This percentage corresponds roughly to the global average in the named categories. An alternative approach would be to fill gaps by shifting expenditure from other consumption categories, but this requires more assumptions about the detailed composition of expenditure. The proportion of all data points to be interpolated is ~3% but nearly negligible in terms of consumption volume and emissions. The interpolated data account for an additional 0.2% of consumption and another 0.5% of emissions. The additional emissions are based on the average global carbon intensity of the respective category.

Data cleaning

We removed a few outliers from income elasticities of demand and carbon intensities. The number of outliers is minor. In terms of income elasticities, we assumed inferior goods ($\epsilon_d < 0$) to be normal goods with low elasticity ($\epsilon_d =$ 0.1). This assumption is also of practical importance so that demand changes resulting from price changes do not exhibit opposing income and substitution effects.[54] This concerned 14 values in the category "Alcohol and Tobacco," which is ~1% of all data. In terms of carbon intensities, we removed the outlier "Heating and Electricity" in Belarus with a value of 92 kg/$. The value seems unrealistic and likely due to poor data quality on household spending in Belarus. None of these choices has a major impact on our results.

Income elasticity of demand

Why use the income elasticity of demand to adjust the carbon price? A high-income elasticity indicates that few rich people consume a good extensively, while most people very little. An elasticity well below one suggests that a good constitutes a largely fixed amount across households' consumption baskets and a smaller share out of total for wealthy households. Therefore, the elasticity integrates information about the distribution and purpose of consumption (see Figure 2B for the correlation between income elasticity and Gini coefficient across 88 countries and 14 consumption categories).

An income elasticity is empirically derived via Equation 5.

$$log(Y) = a + b\log(X) \quad \text{(Equation 5)}$$

Here, Y is consumption per good (i.e., one specific consumption category) and X is disposable income approximated by total expenditure. The coefficient b is the income elasticity of demand and otherwise denoted ϵ_d in this study. It represents how much the consumption in Y changes, given a change in X, and a is a coefficient estimating the income-independent part of consumption.[55] When b is large, then a is small, and vice versa. This is because, when consumption is sensitive to the level of income, the income-independent component is small. Both a and b are parameters describing the distribution of consumption across households, but knowing b suffices. Equation 5 can be transformed into a power law of the following form:

$$Y = a * X^b \quad \text{(Equation 6)}$$

This form illustrates that consumption follows a non-linear pattern and the elasticity defines the scaling behavior of consumption with disposable income. We find the income elasticity is, in 98% of cases, a number between 0 and 3.

Tax responsiveness

Modeling taxation across 88 countries requires pragmatism. We evaluate the households' responsiveness to the carbon tax by employing price elasticities of demand. The price elasticity ϵ_p is a standard parameter in economics and estimates the percentage change of quantity demanded in response to the percentage change in price. Again, for clarity, we omit product indices. The price elasticity of demand is given by the following identity where Q denotes quantity and P price:

$$\epsilon_p = \frac{dQ}{Q}\frac{P}{dP} \quad \text{(Equation 7)}$$

Income elasticities are an easy-to-estimate parameter. Price elasticities, on the other hand, are hard to estimate from empirical data, but we can rely on a theoretical model to infer them. Based on Sabatelli,[56] we map a price elasticity of demand onto each income elasticity of demand employing Equation 8.

$$\epsilon_p = -\frac{1}{\rho}\overline{\omega}{\epsilon_d}^2 + \left(\frac{1}{\rho} - \overline{\omega}\right)\epsilon_d \quad \text{(Equation 8)}$$

Here, ϵ_p is the price elasticity of demand for a specific consumption category, ρ is the elasticity of the marginal utility of income, $\overline{\omega}$ is the mean share of a category in the entire consumption portfolio, and ϵ_d is the income elasticity of demand. According to this model, price elasticities are proportional to income elasticities (to the squared additive inverse of income elasticities to be exact). If consumption is income sensitive, it is also price sensitive. The model is derived employing several neoclassical assumptions. For instance, it assumes additive preferences (utilities gained from different goods are independent of each other). Sabatelli shows that the map is consistent with empirical findings on price and income elasticities.

The parameter ρ is the only quantity that we have to derive from additional literature. It is nearly fixed around the world. Layard et al. estimate ρ across 50 countries and by means of five distinct datasets.[57] They find very similar values across geographies with a mean value of −1.26, a maximum value of −1.19, and a minimum value of −1.31. Since the variation is small, we employ the mean estimate across all countries. A full parameter space of Equation 8 is illustrated in Figure S5.

The data we employ for household consumption are entirely in monetary terms. The purchasing power parity is associated with a physical consumption basket and a carbon intensity, but there is no information about "quantity demanded" as such. We briefly illustrate a calculation. If we, for example, have a price elasticity of 1.5, and increase the price of a good by 10%, then the demand is expected to reduce 15%. In monetary terms, this means that $PPP 1,000 per year are reduced by 15% to $PPP 850 per year. However, now the household has to pay the additional tax rate of 10%. Therefore, the total expenditure of the good after taxation is $PPP 935 = $PPP 850 × 1.1. Only $PPP 850 continue to be associated with a carbon intensity though. Let us assume the carbon intensity is 1 kg/$. Then the emissions prior to taxation are exactly 1 tonne. After taxation, the carbon emissions are 850 kg. This approach is in line with other isoelastic models of carbon taxation.[58]

Average carbon prices and price trajectories

We set differentiated carbon prices for countries based on income class. According to several recent studies, the appropriate level for carbon prices is likely beyond $100/tonne and must increase throughout the century.[59–62] It has, however, been acknowledged that middle- and low-income countries cannot pay a very high carbon price early on.[20] It strains their development efforts and also goes against any logic of international justice. The cumulative emissions responsibility of high-income countries is much larger.[22] Carbon pricing policy is expanding around the globe but coverage so far is only ~20% of emissions and only ~4% are covered by carbon prices higher than $40/tonne.[1] Moreover, the 2020s are a crucial decade to limit global warming. Therefore, we set the average carbon price in our medium scenario to $150/tonne for high-income countries, $50/tonne for upper middle-income countries, $25 dollars for lower middle-income countries, and $10/tonne for low-income countries. These price levels are applied in the static model, in which we do not vary prices because the distributional implications are independent of the price level.

In the dynamic model, however, there are additionally a low price and high price scenario. These scenarios explore the model's sensitivity to the price level. Prices for 2022 are depicted in Figure 6A. The prices in the low-price scenario are the medium prices divided by 2 and, in the high price scenario, multiplied by 2. Moreover, prices increase year by year in linear steps, which is illustrated in Figure 6B for high-income countries. Often in climate-economy models, carbon price trajectories are assumed to be exponential because this corresponds to exponentially growing return on investments and economic growth (i.e., pay more later because you are wealthier later).[62] This, however, requires assumptions about the future of climate change impacts. For example, it implicitly assumes that economies continue to grow and flourish in a healthy way even with global warming beyond 2°. These assumption have been heavily criticized.[63] While we still assume conventional growth trajectories for this study and no climate feedback on growth, we do assume linear price trajectories so that large tax effects are not postponed to the second half of the twenty-first century. Target prices in 2100 are also based on ranges given in the literature.[61,62] They vary between $500/tonne and $4,000/tonne depending on the scenario and the country's income level. A detailed table of prices is given in Table S3.

Retrofit model and redistribution

Determining the costs and impact of retrofitting is complicated. Heterogeneity in housing types, interventions, and supply prices already makes this difficult within local contexts. Here, we aim for a pragmatic and simplistic approach in order to cover 88 nations and omit details around types of dwellings. We looked for a realistic estimate of costs per unit of net energy savings.[64] Considering costs per unit of energy is the key. Total costs are then proportional to total residential energy use, which varies significantly by income group. Because high-income groups use more energy, costs for retrofitting richer households are larger. This is a reasonable assumption because dwellings of richer households are expected to be larger. The estimate we rely on is based on a meta-analysis of single-family housing retrofits in the US. The analysis arrives at an average of ~0.77$ per megajoule (MJ) on-site energy savings in cold climate and at ~$ 0.42/MJ for warmer climate. We adopt the cold-climate costs for global north countries and the warmer climate average for global south countries, assuming both to be net energy savings (i.e., including life cycle energy and emissions of materials used). Future work might reconsider these assumptions based on more detailed data from several countries.

Walker and Less also suggest that a deep retrofit reduces residential energy demand by ~50%, which corroborates other findings on net emission savings of retrofits,[65] although the variation is high and some studies suggest values larger than 50%.[66] We adopt 50% net reduction of residential energy demand for all households. For calculating retrofit costs, we require residential final energy over time. We projected final energy intensities from 2011 to 2019 based on trends in primary energy intensity given by the World Bank for 1995–2015.[67] This is a simplification since primary and final energy intensity can diverge, but it is our best available estimate. For projecting final energy intensity beyond 2019, we assume a yearly decline in energy intensity of 1.1% uniformly across all sectors in line with the Shared Socio-Economic-Pathways (SSP2).

Another crucial component of the retrofit model is the number of dwellings that require retrofitting. We assume that the number of dwellings is equal to the number of households. We take household statistics from a UN survey.[68] The data are nearly complete across global south countries, and the only countries missing are Sweden, Denmark, and Sri Lanka. Sweden and Denmark are taken from Eurostat,[69] while Sri Lanka was estimated based on Statista.[70] A limitation is that the age of data varies. Some of the most recent estimates go as far back as the early 2000s. Most country estimates are from the late 2010s, though, and we assume them to be representative of 2019. From 2019 onwards, for the dynamic model, we calculate households per capita and together with population growth rates are able to project the total number of households.

Redistribution works in a simplified way too. We redistribute to low-income households according to the zero-trade-off policy determined in the section "tax revenue with multiple objectives." A country-specific set of percentiles, depending on the consumption inequality within the country, retains their previous consumption level. They are effectively exempted from the tax. Zero-trade-off points change over time but we assume them to be fixed.

Carbon budget allocation

We explore the contribution of household carbon taxes to the Paris climate goals. For this purpose, we employ the Intergovernmental Panel on Climate Change (IPCC)-AR6 carbon budgets to stay within 1.5°C and 2°C with 83% probability.[71] The budgets need to be adjusted for the sample size and scope. We cover 88 countries and only household carbon footprints (i.e., no government and capital-related footprints). We arrive at budgets of ~160 GtCO2 to stay within 1.5° and ~480 GtCO2 to stay within 2°. There are several carbon budget estimates depending on climate system variables and probabilities considered,[72] but the IPCC budget is a widely accepted reference point.

Dynamics: Economic growth, population, technology

The exogenous drivers are economic growth, population growth, carbon intensities, and carbon price trajectories. The endogenous variables are household consumption, carbon footprints, and tax revenue. We explore additionally a low-economic-growth scenario where growth rates are half as much as in the SSP2. Economic growth and population growth are based on the middle-of-the-road scenario of the SSP2.[73]. The SSP2 provides national GDP per capita (GDPpc) growth rates. We assume an elasticity of 0.83 between GDPpc and household consumption per capita.[11] Every GDPpc rate is multiplied by 0.83 to find consumption growth. For growth differentiated by consumption category, we employ income elasticities of demand fixed over time and normalize such that the total growth in consumption per capita matches the projections given by the SSP2 rates.

Consumption (excluding tax revenue) evolves according to Equation 9.

$$C_{t+1,i} = C_{t,i} * (1 + g_{t,i}) * (1 + \epsilon_{p_i} * \tau_{t,i}) + r_{t,i} \quad \text{(Equation 9)}$$

Here, $C_{t,i}$ is consumption per capita at time t for category I, $g_{t,i}$ the normalized growth rate, ϵ_{p_i} the price elasticity of demand per category i, $\tau_{t,i}$ the tax rate, and $r_{t,i}$ the effect of revenue recycling. The first bracket denotes the economic growth effect, which is >1, the second bracket the tax effect, which is <1 (because $\epsilon_{p_i} < 0$). While we differentiate growth across consumption categories, we assume uniform growth across income groups. As a consequence, within-country inequality does not change drastically. Largely fixed distributions imply that the income elasticity of demands can reasonably be assumed to be fixed because it is a measure of the distribution. These are not fully realistic assumptions but, according to the SSP2 narrative, divergence from historical income inequality is only minimal.

Trends in consumption-based carbon intensities, a proxy to technology and energy system change, are extrapolated averages from historical trends given by the Global Carbon Project.[51,74] The historical data are from 2011 to 2018, so only recent trends. There are some smaller countries where the historical trend is not a decline in emissions intensity but an increase. In those countries, we assumed a structural break with a yearly change rate of −1% until 2030 and −2% thereafter.

Limitations of the study

The model is subject to various limitations. The quality of the model is constrained by quality of data. Employing a multi-regional output model and household surveys for the year 2011 is somewhat outdated. To this day, however, there is no dataset across income classes and consumption categories in developing countries as comprehensive as the Global Consumption Database, and this dataset aligns with the GTAP 9 model for 2011.[9] Integrating recent and high-quality distributional data of household consumption into climate-economy models is a key challenge for future research. The implications of carbon taxation we explore are limited. We focus on price effects within broad consumption categories. In reality, interactions between goods are much more complex, and price changes in one good imply increased or declined demand in another (cross-price elasticities). Markets are interdependent networks and consumer choices intricate. It is also expected that households substitute pricier goods with cheaper ones or with features closer to their preferences (such as organic vegetables vs. conventional ones). The broad aggregation level of consumption categories is a substantial limitation. For instance, alone within the basic category food there is a diverse set of food items that may as well be considered luxury goods, such as expensive meat or expensive drinks. Hence, our model taxation program is intended only as a proof of concept for how a luxury tax may operate, and more detailed consideration of consumption would be required by policymakers before any real-world implementation. The dynamic model as well as the environmental earmarking considered (the investment into retrofits) are highly stylized and serve limited purposes. In the dynamic model, we focus on household consumption only and interactions with industry, government institutions, and other policies are not included. Endogenous innovation dynamics are not considered, which is potentially a significant shortcoming over long periods of time, although exogenously assumed trends are extrapolations of past patterns and thus should reflect a realistic rate of innovation. Moreover, since we assume constant income elasticities over time, and price elasticities depend on the income elasticities in our model, the tax responsiveness far into the future is perhaps not accurately captured. For instance, consumer preferences and infrastructure constraints that determine consumption patterns could drastically evolve and ultimately cause price elasticities to be very different from what they are today. We test a variant of our dynamics model in Figure S6 that captures consumer response to technology improvements. The investment into retrofit is built on very simplified assumptions about costs from one study only for proof-of-concept purposes and specifically assumes that the money can efficiently be translated into retrofits without considering constraints on productive capacity of the private sector executing the retrofits. Our goal is not to provide perfect guidelines for the retrofit of households but to demonstrate how revenue recycling of different forms (redistribution and environmental earmarking) interact in trade-offs that can be alleviated by optimizing the allocation of funds.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.05.027.

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AUTHOR CONTRIBUTIONS

Conceptualization, Y.O.; methodology, Y.O., J.M.H., J.K.S., A.O., and D.I.; software, Y.O.; formal analysis, Y.O.; validation, Y.O., J.M.H., J.K.S., A.O., and D.I.; resources, J.K.S.; data curation, Y.O.; writing – original draft, Y.O.; writing – review & editing, Y.O., J.M.H., J.K.S., A.O., and D.I.; visualization, Y.O.; supervision, J.M.H., J.K.S., A.O., and D.I.; project administration, J.K.S.; funding acquisition, J.K.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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