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Incidence of Carbon Pricing in Tanzania: Using Revenues to Empower Low-Income Households with Renewable Energy

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Abstract

While Tanzania's greenhouse gas emission levels still seem low by international comparison, the country is rapidly carbonizing, and most households still rely on kerosene, charcoal, and firewood for cooking and lighting. Carbon pricing can be an effective tool to discourage the creation of high carbon lock-ins, to generate substantial revenues, and to channel them toward sustainable development. Employing a microsimulation approach that integrates multiregional input-output and household-level data, we examine the distributional impacts of four different carbon pricing designs and five compensation schemes on Tanzanian households. We find that national carbon pricing would have progressive effects but with large horizontal differences. Revenue-financed cash or infrastructure transfers would effectively mitigate adverse impacts on low- and middle-income households. We suggest the use of carbon pricing revenues to provide low-income households with access to renewable energy appliances such as solar lights and solar cookers to empower them through long-term cost and time savings as well as health benefits. This would contribute not only to alleviating poverty but also to achieving Tanzania's electrification and clean cooking objectives.

Keywords: Climate policy, Carbon pricing, Tax incidence, Distributional effect, Inequality, Sustainable development, Renewable energy, Sub-Saharan Africa, Tanzania

JEL Classification Numbers: D57, H23 Q52, Q54, O55

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1 Introduction

Tanzania ranks 15th among the world's fastest growing economies, with a projected GDP growth rate of 6.1% in 2024 (International Monetary Fund, 2023), and has recently transitioned from a low-income to a lower-middle-income country (World Bank, 2023c). Meanwhile, it is one of several Sub-Saharan African countries whose carbon footprints are growing rapidly (Steckel et al., 2019). Despite Tanzania's greenhouse gas (GHG) emissions being still relatively low on a global scale, the country's CO_2 emissions from oil, coal, and gas have witnessed a steady rise since 2000 (Ritchie and Roser, 2023) and are expected to increase substantially unless further emission reduction efforts are undertaken (United Republic of Tanzania, 2021). For instance, there are plans to construct coal-fired power stations with a combined capacity of up to 2.9 GW by 2025 (Enerdata, 2015). At the same time, the country is already affected by climate change, with severe droughts and floods, rising sea levels, and declining water resources (National Bureau of Statistics Tanzania, 2019). To address this, the government has pledged to implement sustainable development initiatives that include both climate change mitigation and adaptation measures. As stated in its updated National Determined Contribution (NDC) in the context of the Paris Agreement, Tanzania has committed to reducing its total GHG emissions 30-35% by 2030 relative to the business-as-usual scenario (United Republic of Tanzania, 2021).

The updated NDC plan also mentions that Tanzania intends to use market-based mechanisms to achieve its mitigation goal. Until now, these mechanisms consist in offsetting or carbon-crediting projects and partnerships such as the UNFCCC Reduced Emissions from Deforestation and forest Degradation (REDD+) and Clean Development Mechanism (CDM), while a comprehensive carbon pricing instrument is yet to be implemented. There are two important reasons why a carbon price could help Tanzania achieve its goals in a more effective and sustainable way: First, a carbon price could discourage the creation of high carbon lock-ins due, for instance, to the construction of coal power plants, and instead incentivize sustainable low-emission development. Second, with Tanzania's low tax-revenue-to-GDP ratio of 11.8% in 2022/23, there is a need to increase domestic revenue mobilization to finance sustainable development (World Bank, 2023c,d). Many low- and middle-income countries are already implementing or considering the implementation of carbon pricing schemes with the intention to use the revenue for development (World Bank, 2023b). We argue that using carbon-pricing revenues for renewable energies has a high potential to boost sustainable development.

To guide the potential development of an effective carbon pricing mechanism, it is crucial to examine the effects on Tanzania's population, especially considering the socio-economic context and the lessons learned from similar policies in other developing countries. Over the past three decades, income and wealth inequality in Tanzania have grown, with the share of the bottom 50% declining and the share of the top 10% increasing, highlighting the population's socio-economic sensitivity (Alvaredo and Chancel, 2023). With around 45% of Tanzania's population living below the international poverty line based on purchasing power parity (PPP) in 2018 (World Bank, 2023a), it is essential to ensure that carbon pricing does not disproportionately burden vulnerable groups. In addition, the COVID-19 pandemic's impact on consumption, particularly in the lower quintiles (World Bank, 2023a), highlights the potential vulnerability of certain groups to economic shocks. Protests in the wake of carbon or fuel price reforms, like those in Nigeria in 2012 following fuel price increases, have often led to the abandonment of the respective pricing policies (IMF, 2013). This underscores the importance of understanding how such policies affect different segments of the population and shows that the public acceptance and, hence, political feasibility of a carbon price hinges on its distributional impacts.

An extensive literature on the distributional effects of carbon pricing[1] shows that while carbon pricing tends to have a regressive effect, it can be progressive in less developed countries or when only transport fuels such as petrol are targeted (Pizer and Sexton, 2019; Ohlendorf et al., 2021). Although there have been several ex-ante studies on the impact of carbon pricing in different countries, such as South Africa (Okonkwo, 2021), Nigeria (Dorband et al., 2022), Peru (Malerba et al., 2021), and Israel (Missbach et al., 2023), as well as cross-country analyses, for example, of developing countries in Asia (Steckel et al., 2021a), Latin America and the Caribbean (Missbach et al., 2024), and a global analysis on 87 countries (Dorband et al., 2019), to the best of our knowledge, there has been no analysis to date of the distributional effects of a carbon price in Tanzania. Therefore, in this paper, we analyze the distributional impacts of different carbon pricing and compensation schemes on Tanzanian households. To do so, we combine multi-regional input-output (MRIO) data and household-level data from a national household survey in a micro-simulation approach. First, we calculate the carbon footprints of households included in the survey and then estimate their additional cost burden in different carbon pricing scenarios, including a national and an international carbon price for the whole economy and carbon prices on fuels and electricity. Second, we analyze and compare the change in the household budget in different quintiles when using the revenues for the different compensation schemes.

Several studies have shown that the social acceptance of carbon pricing depends heavily on how the revenues generated are redistributed (Goulder, 1995; Rausch et al., 2011; Klenert et al., 2018). Soergel et al. (2021) point out that ambitious climate policy measures to meet the 1.5 degree target without progressive revenue recycling could lead to an additional 50 million people worldwide falling into poverty. Therefore, it is essential to combine carbon pricing with carefully designed compensation schemes to alleviate adverse effects. While lump-sum transfers are often the preferred recycling option as they are

[1] Wang et al. (2016), Ohlendorf et al. (2021) and Shang (2023) provide literature reviews.

typically easy to implement and yield progressive effects (Budolfson et al., 2021; Klenert and Mattauch, 2016; Wang et al., 2016), they do not exploit efficiency gains, unlike green tax reforms, where revenues are used to lower other distortionary taxes (Goulder, 1995; Böhringer et al., 2003). Furthermore, despite the significant potential of using carbon pricing revenues to reduce infrastructure access gaps in many countries (Jakob et al., 2016; Franks et al., 2018), only a few studies have focused on the distributional effects of infrastructure provisions (Calderón and Servén, 2014). Dorband et al. (2022) showed for the case of a carbon price in Nigeria that lower-income households would benefit more from revenue-financed infrastructure investments, as lower shares of these households have access to electricity, water, sanitation and telecommunication. However, in the few similar studies, the provision of renewable energy appliances like solar lights or solar cookers to individuals without access to the grid or to clean cooking options was not yet linked to carbon pricing.

Tanzania has a high potential to harness more clean and renewable energy sources such as solar, wind, and geothermal power (Aly et al., 2017; Petrovic and Margoshes, 2023). Currently, Tanzanian households still spend 96.5% of their energy expenditures on kerosene, charcoal, and firewood for cooking and lighting, and demand is relatively inelastic (Olabisi et al., 2019). Reliance on biomass fuels has been shown to have significant repercussions on health and lead to increased deforestation, which is expected to worsen with a growing population and rising demand (Olabisi et al., 2019; Zulu and Richardson, 2013). Therefore, in addition to the effects of monetary uniform lump-sum transfers and transfers targeted at lower-income households, we analyze the distributional effects of using carbon pricing revenues for non-monetary transfers of off-grid renewable energy appliances such as solar lights or solar cookers. In one compensation scheme, solar light systems are provided to all households without access to the electricity grid, and in the other, solar cookers are provided to lower-income households without clean cooking appliances. Using the revenues for providing renewable energy systems for cooking and lighting could significantly change consumption patterns, resulting in considerable cost and time savings, as well as health benefits. Insights derived from our analysis could pave the way for a more politically viable and socially inclusive transition to a future low-carbon economy in Tanzania.

One could argue that the non-monetary compensation schemes would be paternalistic and that it should be left up to households to decide how to spend the money. It is important to emphasize that the use of the revenues for solar lights or solar cookers is only an example, and that any such undertaking should be preceded by detailed analysis of what would improve the situation for the majority of households in Tanzania and which renewable systems would be suitable to change consumption patterns to sustainable alternatives.

The paper is structured as follows. Section 2 describes the data and methodology used for the analysis, which is based on a micro-simulation approach. Section 3 discusses the results, starting with a brief analysis of the status quo of infrastructure access and expenditure patterns based on the household survey data, followed by an examination of the incidence of different carbon pricing scenarios, first without then with impacts of different compensation schemes. The paper concludes in Section 4.

2 Methodology

We use a microsimulation approach to estimate the distributional impacts of different carbon pricing and compensation schemes on Tanzanian households. We combine MRIO data and household-level data from a national household survey to calculate, first, the carbon footprints of the households in the survey; second, the additional cost burden of a carbon price to the households in different scenarios without compensation; and third, the consumption incidence of a carbon price with different compensation schemes. This is similar to the method used, for instance, by Steckel et al. (2021a), Dorband et al. (2019), Dorband et al. (2022), Missbach et al. (2023) and Missbach et al. (2024).

2.1 Data sources

For the MRIO calculation of embedded CO_2 emission intensities of household consumption, we use the Global Trade Analysis Project (GTAP) 11 database for the year 2017 (Aguiar et al., 2022), consisting of 65 sectors and 160 regions. The environmental satellite data from GTAP includes CO_2 emissions from the combustion of fossil fuels from production processes in these sectors as well as direct CO_2 emissions from households. For the household data, we use the Tanzania National Panel Survey (NPS) 2020–2021 from the World Bank microdata library (National Bureau of Statistics (Ministry of Finance and Planning), 2020). We analyze comprehensive information on 3,352 households from 419 clusters in the NPS, which provided details on household characteristics such as size; socioeconomic variables such as income, education level, and employment status; and demographics such as age and sex. Furthermore, detailed information on consumption expenditures for both food and non-food items are provided.

2.2 Data cleaning and merging

To ensure the accuracy and representativeness of our analysis, we incorporate household weights from the survey data into all calculations. Data cleaning involves excluding households with zero expenditure, missing weights, item codes, household size information, or location details (urban or rural). Additionally, to address extreme expenditure outliers, we replace expenditures exceeding the 99.9th percentile with the median expenditure at the specific item level (Missbach et al., 2024, 2023). We only analyze purchased items and exclude self-produced items as carbon prices cannot be applied to them. The 115 items from the survey are categorized into the 65 GTAP sectors[2] and into broad expenditure sectors, namely food, energy, goods, and services. The appendices A3 and A4 provide a summary of the items included in our analysis and the corresponding GTAP sector. To ensure consistency, we adjust expenditures using the average consumer price index for the base year 2017, as provided by IMF (2020). After deflation, local currencies are converted to 2017 international dollars using exchange rates from World Bank (2024).

2.3 MRIO calculation

Using the GTAP 11 database, we calculate the embedded CO_2 emissions for household consumption and the related CO_2 emission intensities for each sector (in tCO_2 per US dollar of household expenditure) with a simple MRIO model, which can be found, for example, in Böhringer et al. (2017) and Böhringer et al. (2021). The total CO_2 emission intensity of a good is computed from (i) the CO_2 emissions directly emitted in its production process due to fossil fuel combustion, together with (ii) the CO_2 emissions from the production of intermediate inputs, and (iii) the CO_2 emissions from international transport services. We call cc_{it}^C the CO_2 emission intensity (or carbon content) of final consumption (C) of good i in Tanzania (t). Details of the MRIO calculation are provided in the Appendix.

2.4 Carbon footprint and incidence calculation

2.4.1 International carbon price

We analyze four carbon pricing schemes as summarized in Table 1 and start by calculating the effects of an international carbon price. After calculating the embedded carbon intensities of final consumption with GTAP data, we determine the carbon footprints of the individual Tanzanian households in the survey by multiplying the carbon intensities for household consumption in Tanzania (cc_{it}^C) by the expenditures of the households from the survey data. Every household h in the survey declares expenditures ex_{hi} for goods in different GTAP sectors i. We therefore calculate the carbon footprint of an individual household cf_h as follows:

$$\forall h \in H \qquad cf_h = \sum_i ex_{hi} \cdot cc_{it}^C \tag{1}$$

We derive the additional cost burden of each household if an international carbon price or a national carbon price with a carbon border adjustment mechanism were implemented by multiplying the carbon tax

[2] We have based this categorization on the International Standard Industrial Classification of All Economic Activities (ISIC), see United Nations. Statistical Division (2008).

of 40\$/tCO_2 by the carbon footprint of each household cf_h. The relative cost burden for each household can then be determined by dividing this number by the total consumption expenditure of each household.

Households are grouped into quintiles based on total per capita expenditure. By dividing the median incidence for each quintile by the median incidence of the poorest quintile, we obtain the relative effects, that is, the median incidence of every quintile in relation to the incidence of the first quintile as shown in Fig. 3.

2.4.2 National, electricity and fuel carbon prices

Similar to Steckel et al. (2021a), we calculate the incidence of a national carbon price in the absence of both a global carbon price and a Tanzanian carbon border adjustment. Only national CO_2 emissions in Tanzania are considered for the calculation of the direct and indirect household emissions and the carbon intensities. In the case of a national carbon price in the electricity sector, we consider only CO_2 emissions in the Tanzanian electricity sector for our calculations, and to calculate a carbon price for fuels, we consider only the CO_2 emissions of petrol or diesel and exclude emissions from public transport.

2.4.3 Compensation schemes

We analyze five compensation schemes where the total revenue is completely recycled back to households, as summarized in Table 2 in Section 3.3. To compute their distributional effects, we begin by determining the total revenue. The potential revenue from carbon pricing (PR) is the sum of each household's expenditure on the carbon price, that is, the product of the carbon price of 40\$/tCO_2 and the household's carbon footprint (cf_h). To determine the effect of a carbon price and a compensation scheme z on a household's budget change BC_h^z, we first define PR_h^z as the amount of the total potential revenue that would be spent on household h in compensation scheme z or that household h would receive if compensation z were implemented. We subtract this compensation scheme amount PR_h^z from the household's expenditure on the carbon price ($cf_h \cdot 40$) to obtain the absolute budget change and divide this by the total consumption expenditure of the household $\sum_i ex_h i$ to obtain the percentage change. See Section 3.3 for details and a thorough discussion of the different compensation schemes.

When interpreting our results, some limitations of the methodology should be considered. By combining MRIO and household-level data in a microsimulation approach, we focus on estimating the short-term

Table 1: Carbon pricing schemes

International carbon price	applied to all direct and indirect CO2 emissions, domestic as well as imported
National carbon price	applied to domestic direct and indirect CO2 emissions
Fuel carbon price	applied to domestic CO2 emissions from petrol and diesel use
Electricity carbon price	applied to domestic CO2 emissions from the electricity sector

distributional effects of different carbon price and compensation designs, assuming the household demand to be inelastic and the carbon price to be completely passed through to consumers. We therefore neglect general equilibrium effects, such as changes in demand or production through substitution to goods or inputs with lower emission intensity or changes in household income due to changes of wages. However, as the inclusion of general equilibrium effects tends to show a more progressive incidence (Rausch et al., 2011; Ohlendorf et al., 2021), our results can be interpreted as upper bounds. As Dorband et al. (2022) also argue, short-term effects of a carbon price are crucial to the public reaction to its introduction and hence to the chances of its continued existence. Furthermore, potential losses due to inefficiencies in tax enforcement and revenue recycling are not factored in; in this sense, the results are therefore also upper-bound.

3 Results and discussion

3.1 Baseline results

Our analysis will begin with a comprehensive overview of infrastructure access and consumption expenditure shares in Tanzania, based on our survey data, since these crucially influence the effects of the different carbon pricing and compensation schemes.

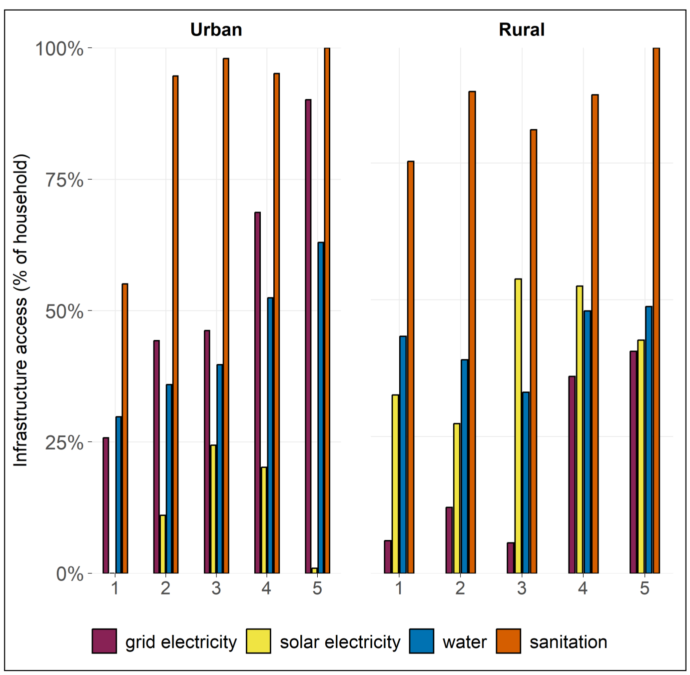
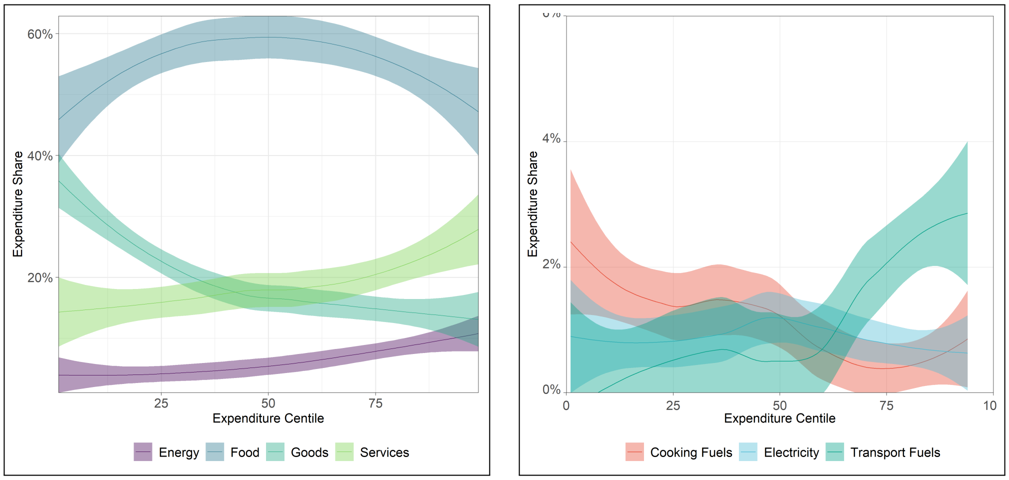


Figure 1: Infrastructure access for urban and rural

Notes: The figure shows the proportion of people in Tanzania's urban (U1–5; left) and rural (R1–5; right) household income quintiles that have access to basic infrastructure. It is based on estimates from 2020–2021, where the richest rural/urban quintiles are denoted by 5 and the poorest by 1.



(a) Broad Categories

(b) Energy Types

Figure 2: Engel Curves of Expenditure Shares

Notes: Fig. 2a provides a detailed analysis of the spending patterns of consumers across various expenditure levels within each consumption category. The graph is generated using non-parametric locally weighted regression estimates of Engel curves derived from micro-data. It provides a comprehensive view of how consumers spend their money across different categories, allowing for a better understanding of consumer behavior. On the other hand, Fig. 2b utilizes the same dataset to showcase Kernel density estimation of Engel curves for the energy expenditure items cooking fuels (kerosene and gas), electricity and transport fuels (diesel and petrol).

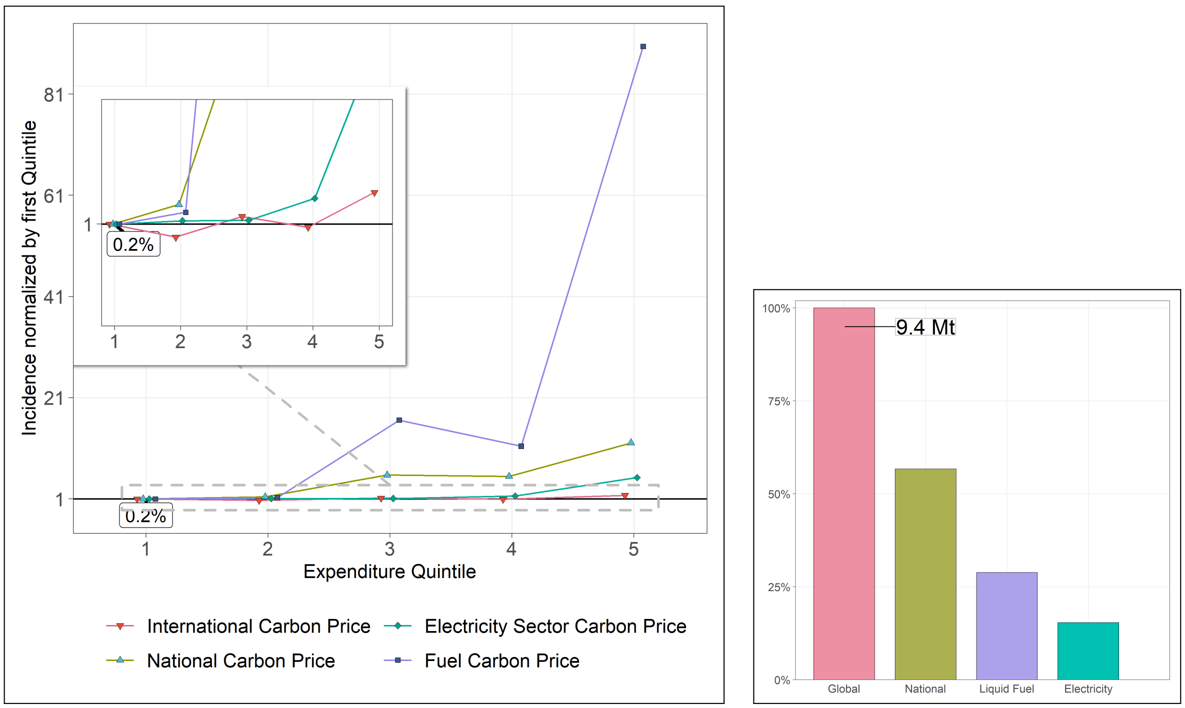
Our findings reveal that there are significant gaps in infrastructure access[3] between different income groups. In particular, Fig. 1 shows that individuals from lower-income groups tend to have lower access rates to infrastructure such as electricity (via grid or solar panels), sanitation, and water. Upon comparing the urban and rural areas, we observe that in the poorest quintile, access to sanitation and water is lower in urban areas than in rural areas. However, in the other quintiles, infrastructure access rates are generally higher in urban areas. Regarding electricity, grid access is more prevalent among households in cities, while solar panels are more commonly used in rural areas.

As Fig. 2a shows, the middle-class centiles, ranging from the 25th to the 75th centile, spend a substantially higher share of their total expenditures on food than the wealthier centiles, in line with previous studies (Steckel et al., 2021a; Dorband et al., 2019). However, it is noteworthy that the poorest income groups also have a lower food expenditure share due to a higher proportion of self-produced food[4] in the first 30 centiles. Moreover, our analysis reveals that low-income households spend a larger share of

[3]Access to infrastructure pertains to households with grid or solar electrification, in-house water supply, and a dedicated sanitation facility within the household compound. The percentage of households with each type of infrastructure is determined by dividing the total number of households possessing the specific infrastructure by the overall number of households in our sample, while accounting for survey weight.

[4]Note again that we exclude self-produced food from our analysis as carbon prices cannot be applied to this.

their total expenditures on goods, while richer households spend a comparatively larger share on energy (i.e., electricity, gas, kerosene, gasoline and diesel) and services (e.g., mortgage, maintenance of dwellings, vehicle services, insurances, wages for servants). This pattern becomes more pronounced starting from the 70th centile. Fig. 2b provides a more comprehensive view of households' energy expenditures. Poorer households allocate a larger share of their spending to gas and kerosene (cooking fuels) and a lower share to petrol and diesel (transport fuels), while wealthier households allocate a higher share to the latter. For electricity, the poorest 10% (centiles 1 to 10, corresponding to quintile 1) and the middle class 20% (centiles 41 to 60, quintile 3) have the highest expenditure shares.



(a) Relative median incidence **(b)** CO_2 Emissions

Figure 3: Relative median incidence of different carbon pricing scenarios

Notes: Fig. 3a compares the average carbon incidence of the first quintile to the normalized average incidence for five expenditure quintiles across different carbon pricing schemes. The carbon pricing schemes include an international carbon price (indicated by a red line with a downward-facing triangle), a national carbon price (green line with an upward-facing light blue triangle), an electricity sector carbon price (turquoise line with squares), and a fuel carbon price (violet line with squares). The value labeled as *0.2* represents the median incidence for the national carbon pricing scenario. Fig. 3b indicates the amount of CO_2 emissions covered for each carbon pricing scheme as the percentage of the amount covered by the global price, which is 9.4 Mt.

3.2 Incidence of carbon pricing

Fig. 3a depicts the additional costs that households in different income brackets would face if a specific carbon pricing scheme were implemented that would be completely passed through to consumers, assuming they maintained their current consumption patterns and without any revenue recycling to offset these costs. The analysis considers different carbon pricing schemes, including a global and national carbon price, as well as a carbon price specifically on electricity and one on the fuels diesel and petrol, which are mainly used in the transport sector but also for electricity generation[5].

A national carbon price on petrol and diesel would yield almost strictly progressive effects, as lower-income households typically spend less whereas wealthier households spend more on transport, which is consistent with other studies (see review by Ohlendorf et al. (2021)). Only the fourth quintile bears a lower burden than the third quintile. The electricity sector carbon price would be strictly progressive.

In the scenario where a national carbon price is implemented in all sectors, the median household in the poorest quintile would have to raise its spending by 0.2% to maintain the same consumption behavior as before the carbon price was in place. This carbon price would also have nearly strictly progressive effects, with the incidence curve having a similar shape to that of the fuel carbon price but a more balanced burden across quintiles because all sectors are included. Apart from petrol and diesel (GTAP sector "p_c"), also kerosene ("p_c") and gas ("gasgdt") have high carbon intensities (see Tab. A2), and lower income groups spend higher shares of their total household expenditures on these fuels, which are mostly used for cooking (see Fig. 2b). However, the richest quintile incurs substantially higher additional costs compared to the other quintiles, due to their higher expenditure on more carbon-intensive energy, mainly petrol and diesel (see Figs. 2a and 2b).

An international carbon price would not be progressive and shows a rather mixed incidence. Along with the fact that the fourth quintile has a lower burden than the third quintile, as is the case in the fuel and national carbon pricing schemes, the first is also more burdened than the second quintile, with a median incidence of 1.4%.

These findings should be understood in relation to the amount of CO_2 emissions covered by each of the carbon pricing schemes (see Fig. 3b): When we take into account all direct and indirect CO_2 emissions of all sectors in Tanzania and abroad that were created in the production and transport of goods that are then consumed by households in Tanzania, the total CO_2 emissions covered by a global carbon price (or a national carbon price with a carbon border adjustment mechanism) would amount to 9.4 Mt. If we only consider CO_2 emissions emitted for household consumption within Tanzania, the national carbon price covers 5.3 Mt, which is 57% of the emissions covered by a global price. Of these national CO_2 emissions, 51% are attributable to petrol and diesel and 27% to the electricity sector. Therefore, both the fuel and electricity carbon pricing schemes have the potential to substantially reduce national CO_2 emissions.

When considering the effectiveness and scope of a global versus a national carbon price, a global carbon

[5] It should be noted again that we exclude public transport from the fuel carbon price.

price would cover a greater amount of the emissions caused by Tanzanian households and prevent carbon emissions leakage to other countries. On the other hand, a national carbon price would be easier to implement. In the following, we focus on the effects of a national carbon price because it allows us to compare the results with studies on other countries that focus mainly on national carbon prices (e.g., Dorband et al. (2022)).

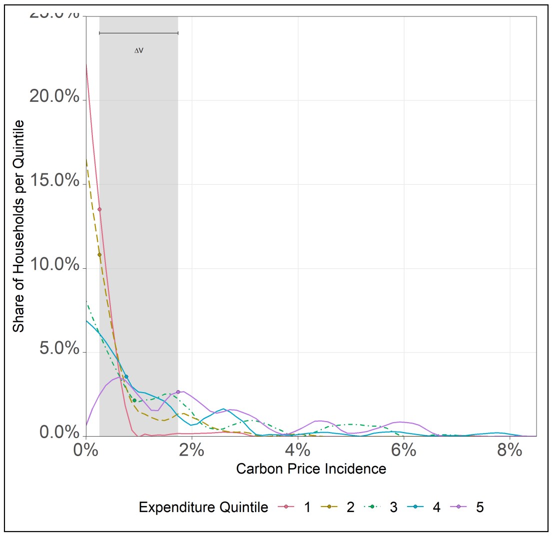
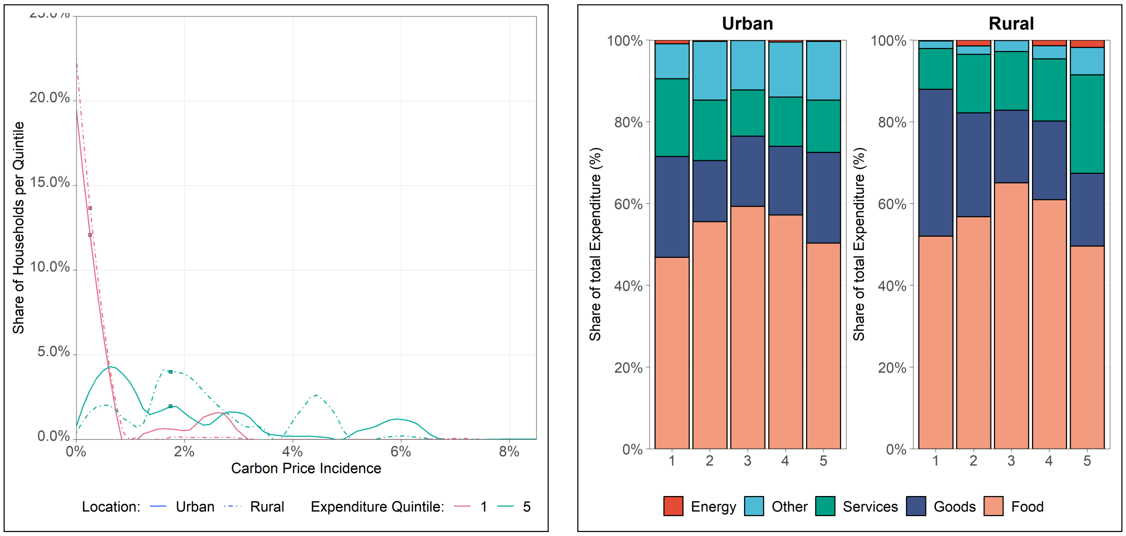


Figure 4: Incidence distribution of a national carbon price by quintile

Notes: The figure shows the impact of a national carbon price of $40\$/tCO_2$ on households of different expenditure quintiles on the x-axis, while the y-axis represents the percentage of households in each quintile. The curve depicts the smoothed density of the cost burden relative to household expenditure, and the dots show the median values in each quintile. The grey area (labeled as $\triangle v$) indicates the difference in medians between the quintiles of expenditures that are most and least influenced at the median. To create these curves, a $\triangle x$ of 0.1% was used over binned incidence levels. The total cumulative densities sum up to 100%.

With a national carbon price, Fig. 4 shows that the majority of households, especially in the first two quintiles, would need to raise their yearly total expenditure by less than 2% to continue their consumption behavior from before the implementation of the carbon price. Meanwhile, the graph indicates that the variation in the horizontal effect within the quintiles is more prominent than the vertical effect between the quintiles (difference between the highest and lowest quintile incidence at median indicated by the grey area $\triangle v$). This suggests that certain households bear a significantly higher burden, aligning with findings from previous research in other countries (Steckel et al., 2021a; Dorband et al., 2019). However, the results show that only 5% of households from the poorest quintile would need to raise their spending by over 2% to maintain their previous consumption behavior, while in the richest quintile, 43% would have to raise their expenditures by more than 2%.

When comparing rural and urban areas, Fig. 5a indicates that in the poorest quintile, households in the rural areas are slightly less burdened than those in urban areas, where there are more households



(a) National Carbon Price Rural and Urban Areas **(b)** Expenditure Shares by Expenditure Type

Figure 5: Incidence Distribution of a National Carbon Price and Expenditure Shares in Rural and Urban Areas

Notes: Fig. 5a shows the impact of a national carbon price of $40\$/tCO_2$ on households of different expenditure quintiles on the x-axis, while the y-axis represents the percentage of households in each quintile. The smoothed density of the cost burden relative to household expenditure is represented by the curve, with median values in each quintile denoted by dots. The solid lines depict urban households and the dashed lines represent rural households, with the green lines indicating the 5th expenditure quintile and the red lines representing the first expenditure quintile. These curves were generated using a $\triangle x$ of 0.1% over binned incidence levels. The total cumulative densities add up to 100%. On the right-hand side, Fig. 5b showcases the expenditure shares by category for rural and urban income quintiles in Tanzania using microdata.

that would need to raise their yearly total expenditures by more than 1%. The median household has an incidence of 0.2% in the poorest quintile in rural areas and 0.3% in urban areas due to the fact that urban households spend twice as much on energy as rural households (see Fig. 5b). This is because urban households are more dependent on buying from energy suppliers whereas rural households have greater self-sufficiency and use more biomass such as firewood to meet their needs. This is not the case for rural households in the richest quintile, where the median household is slightly more burdened (1.8%) than the median household in urban areas (1.7%) due to higher energy expenditures, mainly on petrol and diesel. Fig. 5a highlights the heterogeneity of the burden on the richest households due to varying living standards and circumstances.

3.3 Incidence with compensation schemes

Table 2: Compensation schemes

	scheme	explanation	receiving households	value per household
monetary	***Lump sum transfer***	uniform lump-sum transfer, total revenue distributed equally per capita	all quintiles	116$/year
	Targeted transfer	lump-sum transfer, households without children receive 60% of the lump-sum amount, those with children the full amount[6]	quintiles 1-3	116$/year without children, 193$/year with children
non-monetary	***Solar light provision***	provision, installation and maintenance of solar lighting systems	all quintiles, without grid electrification	175$/year
	Solar cooker provision	provision of solar cookers, pots, training and maintenance	quintiles 1-3, without clean cooking	197$/year
combined	***Solar cooker & targeted transfer***	combination of solar cooker provision and targeted transfer, households which already use clean cooking appliances receive the targeted transfer	quintiles 1-3, without clean cooking	193$/year
			quintiles 1-3 with clean cooking	116$/year without children, 193$/year with children

While a nationwide carbon tax without revenue recycling would have a rather progressive effect overall (see Fig. 3a), there are large horizontal differences between households (see Fig. 4). As some households would bear a high burden and would be negatively affected, especially in the poorer quintiles, it is crucial to recycle revenue back to citizens to mitigate these adverse effects. This section presents an analysis of the effects of different revenue recycling schemes. If Tanzania were to impose a national carbon price of 40$ $/tCO_2$, it could generate total revenues of around 125 mio.$ per year[7]. The revenue could be utilized to reduce taxes or to provide transfers to households. Since taxes are already relatively low in Tanzania (see section 1), we focus on transfers to households by analyzing both monetary and non-monetary compensation scheme designs as summarized in Table 2. As depicted in Fig. 6, all compensation schemes considerably reduce the burden of the national carbon price, with households in the first three quintiles being better off than before the the carbon price was introduced and benefiting substantially.

[6] We distinguish between households with and without children as it helps to ensure a fair distribution of resources and is in line with Tanzania's Productive Social Safety Net (PSSN) program, which could be expanded using revenues from carbon pricing (Ajwad et al., 2018).

[7] For comparison, an international carbon pricing scheme would lead to total revenues of 163 mio.$ per year, a fuel carbon price to 63 mio.$ per year, and an electricity carbon price to 12 mio.$ per year.

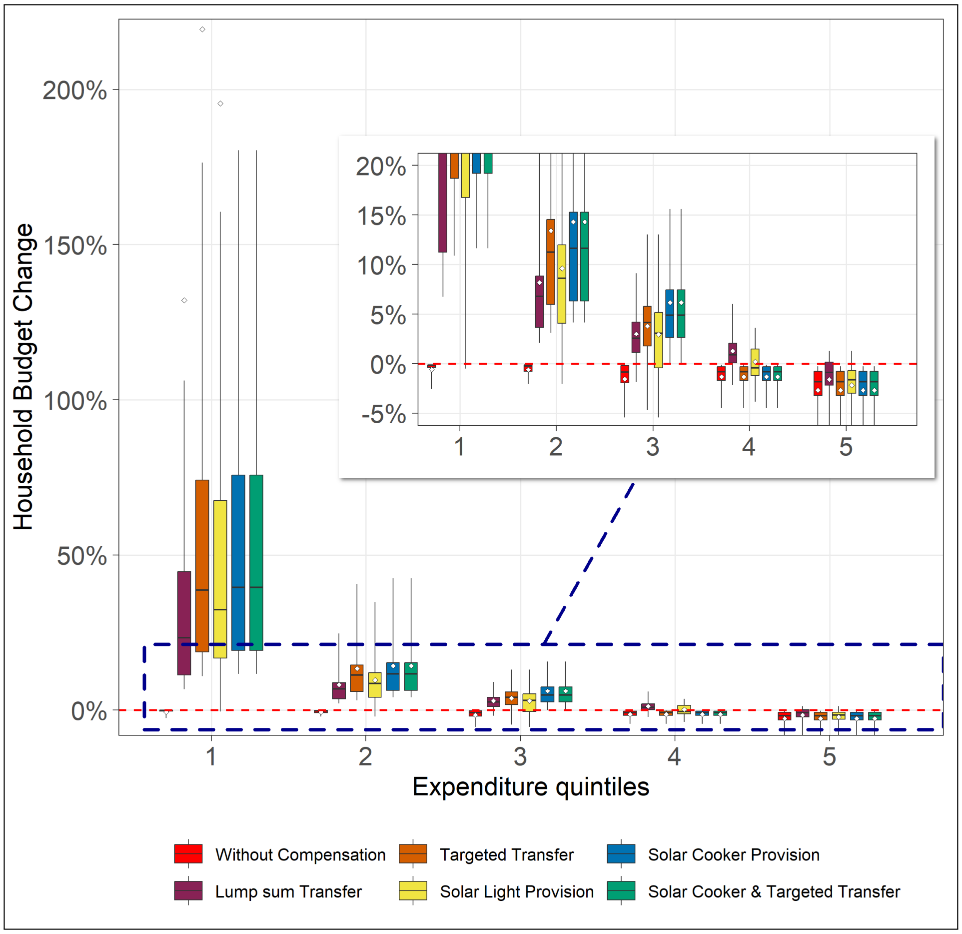


Figure 6: National Carbon Price: Change in Household Budget for Different Compensation Schemes

Notes: This graph displays the change in household expenditure budgets on the y-axis, while different expenditure quintiles are represented on the x-axis. Positive values on the graph indicate additional budget gains, expressed as a percentage of household expenditure. Conversely, negative values indicate additional expenditures that a household would need to incur if they wanted to purchase the same amount of goods they bought before the price increase. The graph uses rhombuses to represent the mean and whiskers to display the fifth and 95th percentiles. The smaller figure shows the area in the dashed box of the larger figure enlarged.

3.3.1 Monetary compensation schemes

The total revenue from a national carbon price could be used to introduce a lump-sum transfer of around 23$ per person or 116$ per household per year. As depicted in Fig. 6, households across all income groups would experience a decrease in their average expenditure or household budget without compensation. However, with the implementation of a lump-sum transfer, their burden would be reduced, and they might even be better off than they were before the carbon price was introduced. For households in the poorest quintile, there would be a 1% reduction in their average household budget without compensation, but with a lump-sum transfer, their household budget would more than double on average (an increase of 132%). Therefore, these households would be significantly better off than they were without carbon pricing. This is also true for households in other quintiles, except those in the richest quintile. The latter would face a 3% reduction in their average household budget without compensation, which would be reduced to 2% with a per capita lump-sum transfer.

Given the limited funding for social assistance programs and the high number of people — particularly children — living below the poverty line, one solution is to use carbon pricing revenues to target transfers at those in greatest need, i.e. the lower-income households in the first three quintiles. According to a global study conducted by the World Bank (2018), social safety net transfers have been effective in reducing poverty in developing nations. The study found that approximately 36% of very poor individuals were able to lift themselves out of extreme poverty with the help of these transfers.

In Tanzania, it is feasible to implement cash transfers to low-income households in the first three quintiles, through the Productive Social Safety Net (PSSN) or similar programs. The PSSN program provides both unconditional and some conditional cash transfers to poor families, including support for children's education (Ajwad et al., 2018). As households with children receive an additional child benefit through the PSSN (Ajwad et al., 2018), we also distinguish between households with and without children. In this proposal, households in the first three quintiles without children would receive 116$, and those with children would receive 193$ if a national carbon price of $40\$/tCO_2$ is implemented. As can be expected and is shown in Fig. 6, households in the poorest quintile would benefit the most, with an average increase of 219%, which is significantly higher than the increase under a uniform lump-sum transfer. The household budget of the second quintile would increase by 13%, and that of the third quintile by 4%, on average.

3.3.2 Non-monetary compensation schemes

In countries with low- and middle-income populations where a large section of the population lacks basic infrastructure, implementing carbon pricing and using the revenue generated for infrastructure development can contribute to multiple sustainable development goals (SDGs), including "Climate action" (SDG 13), "No poverty" (SDG 1), "Affordable and clean energy" (SDG 7), and "Reduced inequalities" (SDG 10) (Thacker et al., 2019). Research has demonstrated that recycling revenue can significantly decrease infrastructure access disparities and benefit the impoverished (Jakob et al., 2016; Dorband et al., 2019). Tanzania's national electrification rate remains low (see Fig. 1), especially for poorer households. As illustrated in Figs. A1a and A1c in the Appendix, many households depend on alternatives such as lamp oil, candles, torches, or kerosene lamps for lighting, and charcoal or firewood for cooking. On average, 96.5% of household energy expenses are spent on kerosene, firewood, and charcoal (Olabisi et al., 2019). The reliance on fossil and biomass fuels poses challenges including households spending a considerable amount of money as well as time collecting firewood, which negatively impacts education and job market participation, and severe health risks such as respiratory infections due to indoor smoke (Smith, 2000; Kim et al., 2011; Hanif, 2018). Moreover, the use of these fuels causes GHG emissions, deforestation, soil erosion, and reduced agricultural productivity (Luoga et al., 2000; Butz, 2013; Zulu and Richardson, 2013). However, according to Olabisi et al. (2019), the demand for these fuels in Tanzania is relatively inelastic.

Furthermore, as an unintended consequence of introducing a carbon price, people may turn even more to self-collected firewood and charcoal as they are not subject to the price increase (Cameron et al., 2016). To tackle these issues, providing households with alternative renewable energy systems for cooking and lighting may be a viable solution. As Tanzania has substantial potential for solar energy (Alfayo and Uiso, 2001; Ondraczek, 2013; Kulworawanichpong and Mwambeleko, 2015), and biomass fuels are currently used mainly for cooking and lighting, there is considerable potential for households to use solar cookers and solar lights. Several studies on developing countries in general and Tanzania in particular have shown positive impacts of the use of solar cookers on the environment as well as on households, primarily as a result of long-term cost and time savings as these technologies have no operational costs, higher energy security, and health benefits (Beaumont et al., 1997; Wentzel and Pouris, 2007; Schwarzer and da Silva, 2008; Mosses et al., 2023). In comparison to candles and kerosene lamps, which provide very poor light and include health risks, solar modules do not only allow people to work or study safely after sunset through the use of linked LED lamps but also make it possible to charge small appliances such as phones (Kulworawanichpong and Mwambeleko, 2015). Further, although the intermittency of solar energy should be considered, both solar cookers and solar lights have the advantage that they are independent from the grid, which is prone to outages and breakdowns and in many cases is not feasible to expand due to the sparse population of rural areas (ibid.). Further, the use of revenues for renewable energy appliances aligns with Tanzanian government plans and objectives, such as the aim to increase the population's access to electricity to at least 75% by 2033 (Garcia et al., 2017) as well as plans to promote renewables and reduce charcoal consumption (United Republic of Tanzania, 2022). In 2022, Tanzanian President Hassan announced a target of 80% of the population using clean energy for cooking by 2032 and the establishment of a clean cooking task force (International Trade Administration, 2022). Revenues from a carbon price could be utilized to significantly accelerate this project.

We are therefore investigating the distributional effects of using carbon pricing revenues to provide off-grid solar systems to households without access to the electricity grid[8] and solar cookers to households

[8]We specifically chose to make the solar lighting system available to households without grid access, and thus potentially to households that already have solar lights, as we believe off-grid households are easier to identify on a large scale and

in the first, second, and third quintiles without clean cooking appliances, as these are more expensive. To estimate the distributional effects, we focus solely on the financial benefit to households receiving solar appliances. Therefore, like similar studies (Dorband et al., 2019; Missbach et al., 2023), we do not account for other non-monetary benefits such as economic, environmental, health, or educational improvements, which may also be substantial and should be considered when designing carbon pricing and compensation schemes.

In the case of the solar light compensation scheme, households without access to the electricity grid are targeted. Fig 1 and Fig. A1a in the Appendix show that lower income groups and people in rural areas are less likely to have lighting powered by grid electrification. If Tanzania imposed a national carbon price of 40$/$tCO_2$, the total revenues of around 125 mio.$ would allow 175$ to be spent per household without electricity grid access. This amount would, for example, be sufficient to cover the costs of the off-grid solar home system "Solar 4, a system with two 5 W solar panels with four lights, mobile phone charging and a radio" (Wagner et al., 2021, p.4) and to install it. As Fig. 6 indicates, households in the first and second quintile would benefit even more on average from this than from a uniform lump-sum transfer but not as much as they would from a targeted transfer. In quintile 3, the effects of these three compensation schemes are almost the same, and in the upper two quintiles, households would benefit slightly more from a lump-sum transfer, as most of these households already have grid access. Its noteworthy that especially the poorest quintile (in which many households lack grid access) would benefit significantly more when receiving a solar light system instead of the lump-sum transfer, with an average budget increase of 196% compared to 132%. The results highlight how solar light provision can help bridge the gap between rich and poor households.

The solar cooker compensation scheme is aimed at households in the first, second, and third quintiles without clean cooking appliances, that is, cooking stoves powered by gas, biogas, or electricity. Fig. A1c in the Appendix illustrates that most households depend on biomass for cooking, with firewood being more common in rural areas and charcoal in urban areas. Only the higher-income groups in cities use gas more widely for cooking. The revenue from carbon pricing could be used to support households without access to clean cooking appliances. However, due to the higher costs of solar cookers and equipment and the substantially lower rate of households using clean cooking fuel compared to households with grid access, we suggest focusing on low- and middle-income households in the first three quintiles without access to clean cooking appliances. With a national carbon price of 40$/$tCO_2$, each household could be provided with equipment and services worth 197$ per year. This amount could be used, for instance, to fund a solar box cooker or a parabolic panel cooker, which costs around 60$ (Aramesh et al., 2019; Arunachala

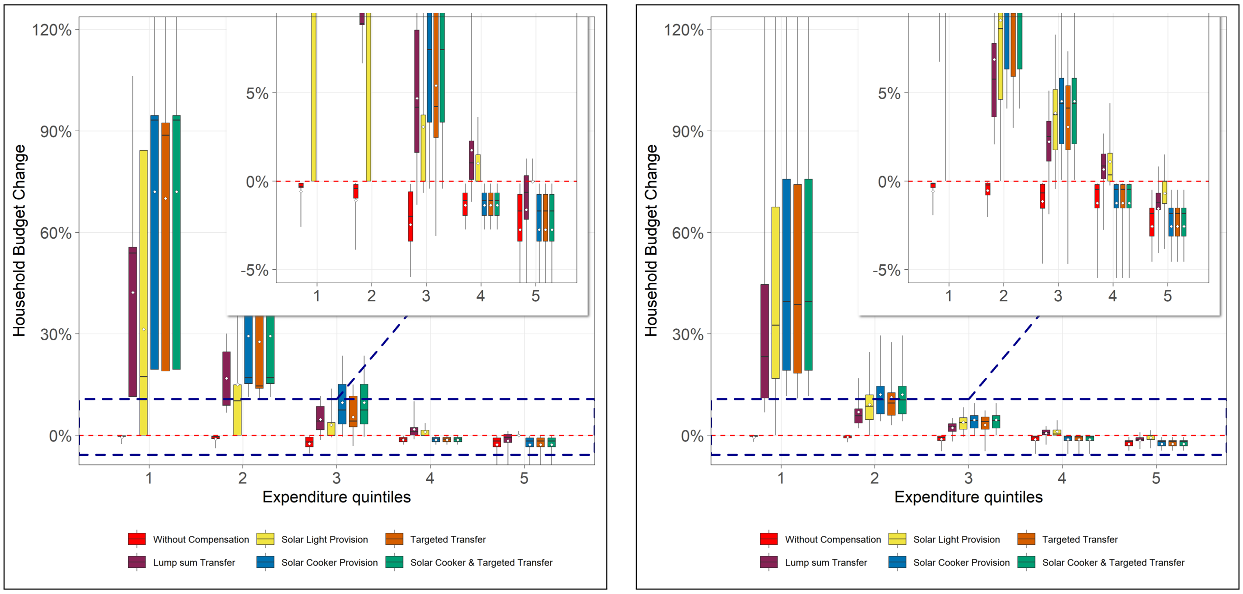
because low-income households' solar systems may be of poor quality or have other issues.

and Kundapur, 2020; Saxena et al., 2020), as well as a black pot and training and maintenance, which are essential for the successful and long-term use of a solar cooker (Wentzel and Pouris, 2007). Fig. 6 shows that while households in the fourth and fifth quintiles do not receive compensation, households in the first three quintiles benefit substantially from this measure, on average even more than with a uniform lump-sum transfer or the solar light provision. The household budget of the poorest quintile would increase by 224% on average.

However, as some poor households in the lower quintiles have access to clean cooking and hence would not receive compensation but be burdened by the carbon price, we also investigate a policy that combines solar cooker provision and targeted transfers to low-income households. This approach would ensure that those without access to clean cooking appliances can benefit from the solar cookers. At the same time, poorer households with access would be compensated for the additional costs related to the carbon price and would receive a targeted cash transfer. Moreover, as one issue with non-monetary compensation is also that there would probably be a time lag between the occurrence of the carbon price burden and the receipt of compensation via solar lights or cookers, it may be advisable to implement some form of combined transfer in which the immediate burden on low-income households is mitigated by targeted transfers early on to ensure public acceptance. Fig. 6 illustrates that this combined transfer has very similar effects to the solar cooker transfer without targeted cash transfer due to the small number of households that use clean cooking fuels such as gas in all quintiles (see Fig. A1c). The solar cooker provision and the combined transfer are the compensation schemes that are most beneficial for the first three quintiles.

Fig. 7 allows us to compare effects of the compensation schemes in urban and rural areas. On average, households in the poorest quintile would benefit significantly more in rural areas — around three times as much in all compensation schemes[9], for solar light provision even seven times as much due to the substantially lower grid access rate in rural areas (see Fig. 1). However, when comparing the effects on households in the second and third quintiles, those in urban areas would benefit more — in the second quintile, they would benefit roughly two times as much in all compensation schemes except solar light provision. This is because, from the second quintile onwards, households in cities show lower average expenditure than households in rural areas, explaining their more significant percentage increase in household budget. However, the effects on households in the richer quintiles would on average be similar in urban and rural areas.

[9]The average household budget changes for quintile 1 in rural areas are not visible in Fig. 7b as they are over 120% and therefore no longer in the displayed area. The average household budget change for the lump-sum transfer would be 142%, for solar light provision 214%, for solar cooker provision 242%, and for the targeted transfer 236%.



(a) Urban **(b)** Rural

Figure 7: Change in Household Budget for Different Compensation Schemes: Urban & Rural

Notes: This graph displays the change in household expenditure budgets on the y-axis, while different expenditure quintiles are represented on the x-axis. The left figure shows the change in household budget for households in rural and the right figure for households in urban areas. Positive values on the graph indicate additional budget gains, expressed as a percentage of household expenditure. Conversely, negative values indicate additional expenditures that a household would need to incur if they wanted to purchase the same amount of goods they bought before the price increase. The graph uses rhombuses to represent the mean and whiskers to display the fifth and 95th percentiles.

If a global scenario for pricing carbon were to be implemented, the burden on each income quintile would be higher as more CO_2 emissions are taken into account. However, the significantly higher total revenues, amounting to 163 mio.$, would also allow for more generous compensation per household. For example, a lump-sum transfer of 151$ per household or 228$ per off-grid household for a solar light system could be provided, which would enable the implementation of more advanced systems with additional solar panels and lights or could finance additional targeted or lump-sum transfers. As shown in Fig. A2 in the Appendix, all compensation plans with a global carbon price would have similar effects to those under a national carbon price, with only the scale of the effect changing due to the increased revenues.

Note that because we estimate short-term effects, we focus on how the total carbon pricing revenue collected in one year can be recycled. It should be noted that in the first few years thereafter, the total revenue would likely be lower if consumption behavior shifted and households substitute fossil fuels with renewable alternatives, especially with a non-monetary compensation through renewable systems. In subsequent years, however, the revenue could, for example, be used for a combination of maintenance and repairs of the solar lights or cookers and for lump-sum or targeted transfers. This would ensure that the solar appliances could be used effectively in the long term and that the carbon price would not disproportionately burden vulnerable income groups but lead to progressive effects.

Upon comparing our findings to those of Dorband et al. (2022), who conducted a similar analysis in Nigeria (see their Fig. 5), it becomes clear that solar light or electricity access provision would benefit urban households in Tanzania to a significantly greater extent than in Nigeria. This can be attributed to the lower grid access rate in Tanzanian urban areas, particularly among poorer households (refer to Fig. 1), in contrast to Nigerian urban areas, where the rate exceeds 75% for all quintiles (refer to Fig. 1 in Dorband et al. (2022)). These results emphasize the importance of tailoring policy recommendations to country-specific factors when analyzing the distributional impacts of carbon pricing and compensation schemes.

4 Conclusion

This study delves into the distributional effects of various carbon pricing and compensation scenarios on households in Tanzania. We argue that carbon pricing can be an effective tool to discourage the use of fossil fuels and the creation of high-carbon infrastructure lock-ins while allowing to use the revenues for renewable energies to boost sustainable development. Using a microsimulation approach that combines household-level data from a national survey with MRIO data, we found that while an international carbon price showed a mixed incidence without any compensation, national carbon pricing in all sectors or specifically on fuels or electricity would have relatively progressive effects. However, there would be large horizontal differences within the quintiles: some households would have a substantially higher burden that should be alleviated. Hence it is crucial to recycle the generated revenue back to households, also to promote social and political acceptance of carbon pricing.

We have examined and compared five viable compensation scheme options for Tanzania, both monetary and non-monetary, which would all considerably reduce the burden of a national carbon price. Starting with the monetary compensations, equal per capita lump-sum transfers would effectively offset adverse distributional impacts for the most economically disadvantaged segments of the population, consistent with the literature. Alternatively, a transfer targeted at lower-income households in the first three quintiles could be linked to Tanzania's Productive Social Safety Net program, allowing poorer households to escape poverty. Steckel et al. (2021b) discusses various problems of reaching the whole population for lump-sum transfers in low- and middle-income countries. Nonetheless, Tanzania has taken strides in this area by implementing unconditional cash transfer programs (Ajwad et al., 2018) and is currently developing a national digital social register to streamline the transfer process (United Nations Children's Fund, 2022).

We also analyze non-monetary compensation schemes in which the revenue is used to supply renewable energy alternatives, specifically solar lights and solar cookers. While solar light systems allow people to work or study safely after sunset and reduce dependency on lamp oil and candles, solar cookers have proven to be effective in reducing dependency on firewood and charcoal (Wentzel and Pouris, 2007; Olabisi et al., 2019; Mosses et al., 2023). Looking at the provision of solar lights to households without grid access and of solar cookers to households without clean cooking appliances, more affluent households benefit less on average than they do from a lump-sum transfer. In the case of solar light compensation, this is due to the higher share of households with access to the grid. However, the receiving households benefit substantially from this measure, on average even more than from a uniform lump-sum transfer. As solar cookers have no operational costs, households profit from long-term cost and time savings as well as health benefits. These non-monetary compensation schemes would not only mitigate the negative impacts of the carbon price but also contribute to Tanzania's electrification and clean cooking objectives and other SDGs.

As climate change continues to progress at an alarming rate, ambitious policies to mitigate climate change and promote sustainable development are of utmost importance. It is crucial to consider the distributional effects of these policies and to carefully design revenue redistribution schemes, especially in developing countries, to avoid exacerbating poverty and, ideally, to reduce it. Leveraging the revenue for renewable energy solutions can effectively achieve this and other SDGs. However, it is essential to emphasize that as climate policies still put additional pressure on developing countries, fair international burden sharing remains essential: Developed countries should implement substantially higher carbon prices (Soergel et al., 2021) and support developing countries with resources for both mitigation and adaptation, as stated in Article 9 of the Paris Agreement. While our focus is on Tanzania, we contribute valuable insights to the literature on distributional effects of carbon pricing that can be useful for analyzing similar policies in other developing countries. Further, we propose the use of revenues for off-grid renewable appliances, highlighting their potential to contribute toward multiple sustainable development goals.

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Appendix

A MRIO calculation

Using the GTAP 11 database, we calculate the embedded CO_2 emissions for household consumption and the related CO_2 emission intensities for each sector (in tCO_2 per US$ of household expenditure) with a simple MRIO model which can be found e.g., in Böhringer et al. (2017) or Böhringer et al. (2021). The total CO_2 emission intensity of a good is computed from (i) the CO_2 emissions directly emitted in its production process due to fossil fuel combustion, together with (ii) the CO_2 emissions from the production of intermediate inputs, and (iii) the CO_2 emissions from international transport services. To determine the total carbon content or the embedded CO_2 emissions, MRIO accounting identities are used which are provided by Equations (2)-(4). Thereby, we use the GTAPinGAMS notation by Lanz and Rutherford (2016) and extend it slightly by adding a set of the individual Tanzanian households and some variables for our calculations as listed in Table A1. Note that index r and the alias s indicate regions.

Table A1: Denotations

Sets	
R	Set of regions (r)
I	Set of production sectors / set of commodities (i)
G	Set of activities (g), covering production sectors (i), as well as final consumption ("C"), public spending ("G"), and investment ("I")
J	Set of international transport services (j)
H	Set of individual Tanzanian households in the household survey
Parameters	
vom_{gr}	Production output, including final consumption ("C"), government spending ("G"), investment ("I") in region r
vim_{ir}	Imports of commodity i in region r
$vxmd_{isr}$	Exports of commodity i from region s to region r
$vdfm_{igr}$	Domestic intermediate inputs of commodity i in activity g in region r
$vifm_{igr}$	Imported intermediate inputs of commodity i in activity g in region r
vst_{jr}	International transport service j produced in region r
$vtwr_{jisr}$	Input of transport service j to imports in sector i directed from region s to region r
CO_2e_{gr}	Direct CO_2 emissions in activity g in region r
Variables	
cc^Y_{gr}	Carbon content / CO_2 emission intensity in activity g in region r
cc^M_{ir}	CO_2 emission intensity of imported good i in region r
cc^T_j	CO_2 emission intensity of international transport service j
cc^C_{ir}	CO_2 emission intensity of final consumption of good i in region r
$tCO_2e^C_{ir}$	Total CO_2 emissions in final consumption of good i in region r
ex_{hi}	Expenditures of individual Tanzanian household h for good i
cf_h	Carbon footprint / embedded carbon emissions of household consumption of individual household h

Equation (2) specifies that the total CO_2 emissions embodied in output ($cc^Y_{gr} vom_{gr}$) of activity g in region r are the sum of direct CO_2 emissions (CO_2e_{gr}), embodied CO_2 emissions in domestic intermediate inputs ($\sum_i cc^Y_{gr} vdfm_{igr}$), and embodied CO_2 emissions in imported intermediate inputs ($\sum_i cc^M_{ir} vifm_{igr}$).

Equation (3) states that total CO_2 emissions embodied in imports of good i in region r ($cc^M_{ir} vim_{ir}$) equal the sum over all other regions' (s) embodied CO_2 emissions in their exports to region r ($\sum_s cc^Y_{is} vxmd_{isr}$), plus the CO_2 emissions embodied in international transport services ($\sum_s \sum_j cc^T_j vtwr_{jisr}$). Equation (4) indicates that the CO_2 emissions embodied in international transport service j ($cc^T_j vtw_j$) equal the sum of embodied CO_2 emissions required for providing international transport service j in all countries r.

$$\forall g \in G \qquad \forall r \in R \qquad cc^Y_{gr} vom_{gr} = CO_2 e_{gr} + \sum_i cc^M_{ir} vifm_{igr} + \sum_i cc^Y_{gr} vdfm_{igr} \tag{2}$$

$$\forall i \in I \qquad \forall r \in R \qquad cc^M_{ir} vim_{ir} = \sum_s \Big(cc^Y_{is} vxmd_{isr} + \sum_j cc^T_j vtwr_{jisr} \Big) \tag{3}$$

$$\forall j \in J \qquad cc^T_j vtw_j = \sum_r cc^Y_{jr} vst_{jr} \tag{4}$$

This system of $[card(G) + card(I)] \times card(R) + card(J)$ unknowns and linear equations can be solved recursively with a diagonalization algorithm to receive the CO_2 emission intensity in activity g in region r, namely cc^Y_{gr}. The total CO_2 emissions for household consumption $tCO_2 e^C_{ir}$ are then derived as the sum of direct and indirect CO_2 emissions:

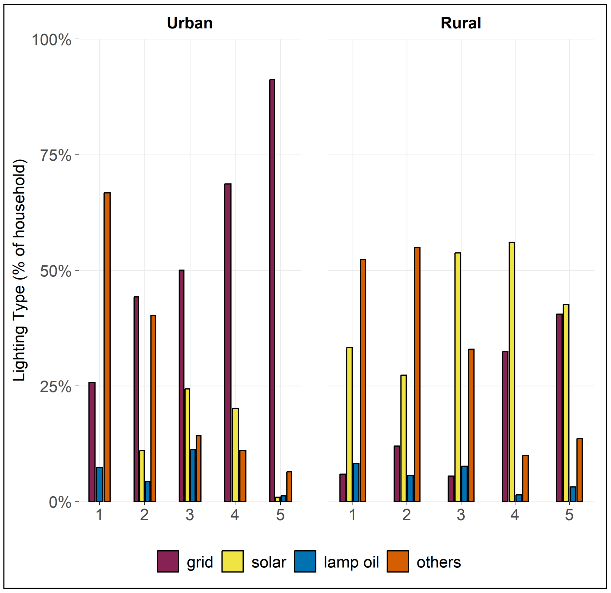
$$\forall i \in I \qquad \forall r \in R \qquad tCO_2 e^C_{ir} = CO_2 e_{ir} + cc^Y_{ir} vdfm_{icr} + cc^M_{ir} vifm_{icr} \tag{5}$$

Then we can easily calculate the CO_2 emission intensity for household consumption cc^C_{ir} in tCO_2 per US$ of household expenditure by dividing the total CO_2 emissions of household consumption by the total expenditures of households in sector i in region r:

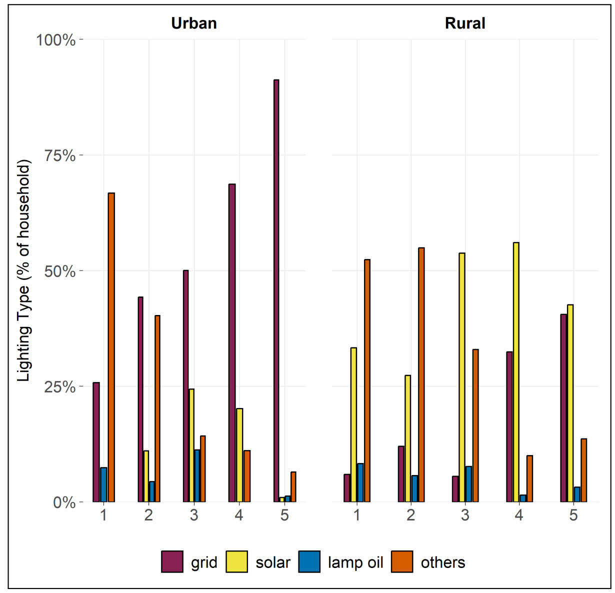
$$\forall i \in I \qquad \forall r \in R \qquad cc^C_{ir} = \frac{tCO_2 e^C_{ir}}{vdfm_{icr} + vifm_{icr}} \tag{6}$$

See table A2 for the determined carbon intensities of households in Tanzania.

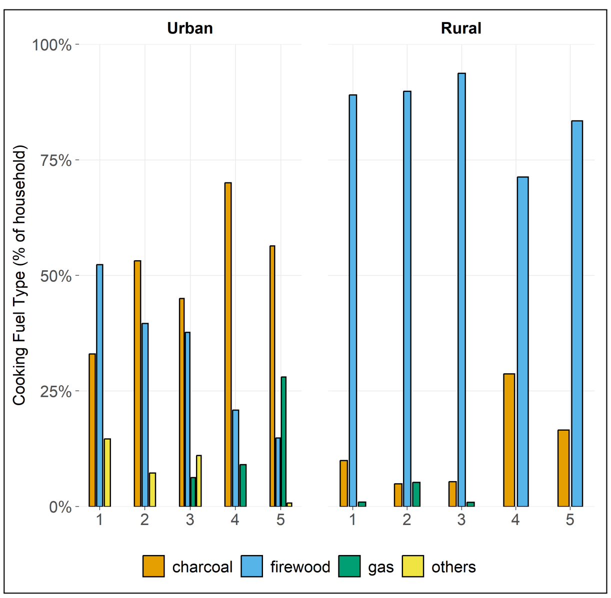
B Figures



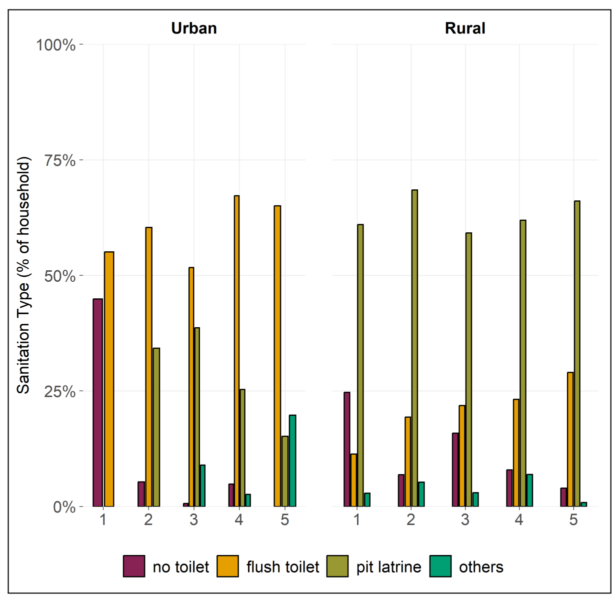
(a) Lighting Type



(b) Water Type



(c) Cooking Fuel Type



(d) Sanitation Type

Figure A1: Shares of Population with Access to Different Infrastructure Types

Notes: This figure displays the proportion of households in Tanzania's urban (U1–5; left) and rural (R1–5; right) income quintiles who have access to certain lighting, water, cooking fuel and sanitation types, based on estimates from 2020–2021.

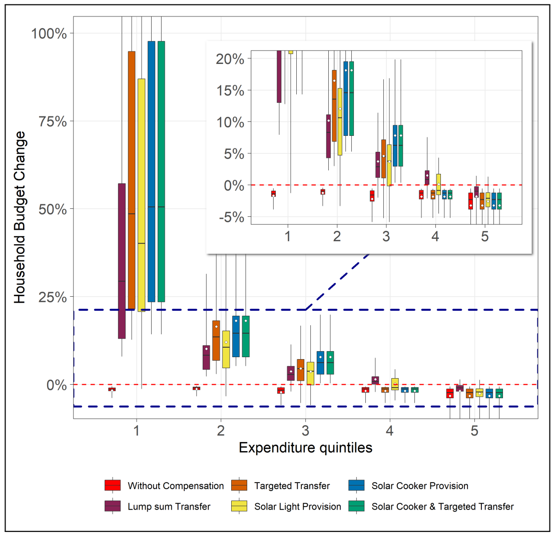


Figure A2: Global Carbon Price: Change in Household Budget for Different Compensation Schemes

Notes: This graph displays the change in household expenditure budgets on the y-axis, while different expenditure quintiles are represented on the x-axis. Positive values on the graph indicate additional budget gains, expressed as a percentage of household expenditure. Conversely, negative values indicate additional expenditures that a household would need to incur if they wanted to purchase the same amount of goods they bought before the price increase. The graph uses rhombuses to represent the mean and whiskers to display the fifth and 95th percentiles. The smaller figure shows the area in the dashed box of the larger figure enlarged.

C Tables

Table A2: Sectoral carbon intensities

GTAP Sector	Description	Carbon Intensities	
		International	National
pdr	Rice: seed, paddy (not husked)	0.05	0.02
gro	Other Grains: maize (corn), sorghum, barley, rye, oats, millets, other cereals	0.05	0.02
v_f	Veg & Fruit: vegetables, fruit and nuts, edible roots and tubers, pulses	0.02	0.01
c_b	Cane & Beet: sugar crops	0.10	0.08
ocr	Other Crops: stimulant; spice and aromatic crops; forage products; plants and parts of plants used primarily in perfumery, pharmacy, or for insecticidal, fungicidal or similar purposes; beet seeds (excluding sugar beet seeds) and seeds of forage plants; natural rubber in primary forms or in plates, sheets or strip, living plants; cut flowers and flower buds; flower seeds, unmanufactured tobacco; other raw vegetable materials nec	0.13	0.01
oap	Other Animal Products: swine; poultry; other live animals; eggs of hens or other birds in shell, fresh; reproductive materials of animals; natural honey; snails, fresh, chilled, frozen, dried, salted or in brine, except sea snails; edible products of animal origin n.e.c.; hides, skins and furskins, raw; insect waxes and spermaceti, whether or not refined or coloured	0.04	0.03
fsh	Fishing: hunting, trapping and game propagation including related service activities, fishing, fish farms; service activities incidental to fishing	0.45	0.38
cmt	Cattle Meat: fresh or chilled; meat of buffalo, fresh or chilled; meat of sheep, fresh or chilled; meat of goat, fresh or chilled; meat of camels and camelids, fresh or chilled; meat of horses and other equines, fresh or chilled; other meat of mammals, fresh or chilled; meat of mammals, frozen; edible offal of mammals, fresh, chilled or frozen	0.05	0.04
omt	Other Meat: meat of pigs, fresh or chilled; meat of rabbits and hares, fresh or chilled; meat of poultry, fresh or chilled; meat of poultry, frozen; edible offal of poultry, fresh, chilled or frozen; other meat and edible offal, fresh, chilled or frozen; preserves and preparations of meat, meat offal or blood; flours, meals and pellets of meat or meat offal, inedible; greaves	0.03	0.01
vol	Vegetable Oils: margarine and similar preparations; cotton linters; oil-cake and other residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; vegetable waxes, except triglycerides; degras; residues resulting from the treatment of fatty substances or animal or vegetable waxes; animal fats	0.20	0.00
mil	Milk: dairy products	0.06	0.02
pcr	Processed Rice: semi- or wholly milled, or husked	0.14	0.07
sgr	Sugar and molasses	0.26	0.01
ofd	Other Food: prepared and preserved fish, crustaceans, molluscs and other aquatic invertebrates; prepared and preserved vegetables, pulses and potatoes; prepared and preserved fruits and nuts; wheat and meslin flour; other cereal flours; groats, meal and pellets of wheat and other cereals; other cereal grain products (including corn flakes); other vegetable flours and meals; mixes and doughs for the preparation of bakers' wares; starches and starch products; sugars and sugar syrups n.e.c.; preparations used in animal feeding; lucerne (alfalfa) meal and pellets; bakery products; cocoa, chocolate and sugar confectionery; macaroni, noodles, couscous and similar farinaceous products; food products n.e.c.	0.09	0.03
b_t	Beverages and Tobacco products	0.12	0.04
tex	Manufacture of textiles	0.57	0.04
wap	Manufacture of wearing apparel	0.36	0.03
lum	Lumber: manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	0.20	0.05
ppp	Paper & Paper Products: includes printing and reproduction of recorded media	0.74	0.16
p_c	Petroleum & Coke: manufacture of coke and refined petroleum products	7.40	6.87
chm	Manufacture of chemicals and chemical products	1.01	0.05
ele	Manufacture of computer, electronic and optical products	0.43	0.20
eeq	Manufacture of electrical equipment	0.54	0.06
omf	Other Manufacturing: includes furniture	0.55	0.20
ely	Electricity; steam and air conditioning supply	2.66	2.52
wtr	Water supply; sewerage, waste management and remediation activities	0.20	0.18
cns	Construction: building houses factories offices and roads	0.23	0.09
trd	Wholesale and retail trade; repair of motor vehicles and motorcycles	0.08	0.05
afs	Accommodation, Food and service activities	0.17	0.02
otp	Land transport and transport via pipelines	1.37	1.26
cmn	Information and communication	0.11	0.04
ins	Insurance (formerly isr): includes pension funding, except compulsory social security	0.10	0.06
obs	Other Business Services nec	0.09	0.03
ros	Recreation & Other Services: recreational, cultural and sporting activities, other service activities; private households with employed persons (servants)	0.13	0.08
osg	Other Services (Government): public administration and defense; compulsory social security, activities of membership organizations n.e.c., extra-territorial organizations and bodies	0.13	0.09
dwe	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)	0.11	0.05
gasgdt	Gas: extraction of natural gas, service activities incidental to oil and gas extraction excluding surveying (part); Gas manufacture, distribution	9.14	9.11

Notes: The table shows sectoral carbon intensities of household consumption in tCO_2/1,000$ as derived from GTAP 11 for the sectors to which we have household consumption items assigned (see tab. A3). *International carbon intensity* includes CO_2 emissions from sectors outside of Tanzania and from transport. *National carbon intensity* includes only national CO_2 emissions. Note that we combined the GTAP sectors "gas" and "gdt".

Table A3: Included Household Items: Part 1

GTAP Sector	Original Code	Item Code	Definition
pdr	101	f101	Rice (Paddy)
gro	103	f103	Maize (Green, Cob)
gro	104	f104	Maize (Grain)
gro	105	f105	Maize (Flour)
gro	106	f106	Millet and Sorghum (Grain)
gro	107	f107	Millet and Sorghum (Flour)
gro	112	f112	Other Cereal Products
gro	1082	f1082	Wheat, Barley Grain and Other Cereals
v_f	201	f201	Cassava Fresh
v_f	202	f202	Cassava Dry/flour
v_f	203	f203	Sweet Potatoes
v_f	204	f204	Yams/cocoyams
v_f	205	f205	Irish Potatoes
v_f	206	f206	Cooking Bananas, Plantains
v_f	401	f401	Peas, Beans, Lentils and Other Pulses
v_f	501	f501	Groundnuts in Shell/shelled
v_f	502	f502	Coconuts (Mature/immature)
v_f	503	f503	Cashew, Almonds and Other Nuts
v_f	504	f504	Seeds and Products From Nuts/seeds (Excl. Cooking Oil)
v_f	601	f601	Onions, Tomatoes, Carrots and Green Pepper, Other Viungo
v_f	602	f602	Spinach, Cabbage and Other Green Vegetables
v_f	603	f603	Canned, Dried and Wild Vegetables
v_f	701	f701	Ripe Bananas
v_f	702	f702	Citrus Fruits (Oranges, Lemon, Tangerines, Etc.)
v_f	703	f703	Mangoes, Avocadoes and Other Fruits
c_b	704	f704	Sugarcane
ofd	1003	f1003	Salt
ocr	1004	f1004	Other Spices
oap	805	f805	Wild Birds and Insects
oap	806	f806	Other Domestic/wild Meat Products
oap	807	f807	Eggs
fsh	808	f808	Fresh Fish and Seafood (Including Dagaa)
cmt	801	f801	Goat Meat
cmt	802	f802	Beef Including Minced Sausage
omt	803	f803	Pork Including Sausages and Bacon
omt	804	f804	Chicken and Other Poultry
vol	1001	f1001	Cooking Oil
vol	1002	f1002	Butter, Margarine, Ghee and Other Fat Products
mil	901	f901	Fresh Milk
mil	902	f902	Milk Products (Like Cream, Cheese, Yoghurt Etc)
mil	903	f903	Canned Milk/milk Powder
pcr	102	f102	Rice (Husked)
sgr	301	f301	Sugar
ofd	207	f207	Other Starches
ofd	111	f111	Macaroni, Spaghetti
ofd	302	f302	Sweets
ofd	303	f303	Honey, Syrups, Jams, Marmalade, Jellies, Canned Fruits
ofd	809	f809	Dried/salted/canned Fish and Seafood (Incl. Dagaa)
ofd	810	f810	Package Fish
ofd	1081	f1081	Wheat Flour
ofd	110	f110	Buns, Cakes and Biscuits
other	208	n208	Milling Fees, Grain
ofd	109	f109	Bread
b_t	1103	f1103	Other Raw Materials for Drinks
b_t	1102	f1102	Coffee and Cocoa
b_t	1101	f1101	Tea Dry
b_t	1104	f1104	Bottled/canned Soft Drinks (Soda, Juice, Water)
b_t	1105	f1105	Prepared Tea, Coffee
b_t	1106	f1106	Bottled Beer

Notes: The table shows the expenditure items from the national household survey included in our analyses and the GTAP sectors to which they are assigned.

Table A4: Included Household Items: Part 2

GTAP Sector	Original Code	Item Code	Definition
b_t	1107	f1107	Local Brews
b_t	1108	f1108	Wine and Spirits
b_t	101	n101	Cigarettes or Tobacco
tex	302	n302	Linen - Towels, Sheets, Blankets
wap	319	n319	Garments for Men
wap	320	n320	Garments for Women
wap	321	n321	Garments for Children & Babies
wap	322	n322	Footwear for Men
wap	323	n323	Footwear for Women
wap	324	n324	Footwear for Children and Babies
wap	304	n304	Mosquito Net
lum	207	n207	Charcoal
lum	325	n325	Wood Poles, Bamboo
chm	102	n102	Matches
ppp	212	n212	Toilet Paper
p_c	205	n205	Petrol or Diesel
p_c	201	n201	Kerosene
chm	215	n215	Household Cleaning Products (Dish Soap, Toilet Cleansers, Etc.)
chm	209	n209	Bar Soap (Body Soap or Clothes Soap)
chm	210	n210	Clothes Soap (Powder)
chm	211	n211	Toothpaste, Toothbrush
chm	213	n213	Glycerine, Vaseline, Skin Creams
chm	214	n214	Other Personal Products (Shampoo, Razorblades, Cosmetics, Hair Products, Etc.)
ele	307	n307	Film, Film Processing, Camera
eeq	216	n216	Light Bulbs
omf	301	n301	Carpet, Rugs, Drapes, Curtains
omf	303	n303	Mat - Sleeping or for Drying Maize Flour
omf	305	n305	Mattress
ely	202	n202	Electricity, Including Electricity Vouchers
gasgdt	203	n203	Gas (For Lighting/cooking)
wtr	204	n204	Water
cns	308	n308	Building Items - Cement, Bricks, Timber, Iron Sheets, Tools, Etc.
cns	326	n326	Grass for Thatching Roof or Other Use
trd	219	n219	Motor Vehicle Service, Repair, or Parts
otp	103	n103	Public Transport
cmn	206	n206	Cell Phone Voucher
cmn	217	n217	Phone, Internet, Postage Stamps or Other Postal Fees
ins	310	n310	Insurance - Health (Masm, Etc.), Auto, Home, Life
obs	220	n220	Bicycle Service, Repair, or Parts
obs	223	n223	Repairs to Household and Personal Items (Radios, Watches, Etc.)
obs	316	n316	Repairs to Consumer Durables
obs	318	n318	Repairs & Maintenance to Dwelling
obs	312	n312	Fines or Legal Fees
ros	221	n221	Wages Paid to Servants
ros	218	n218	Donation - to Church, Charity, Beggar, Etc.
ros	306	n306	Sports & Hobby Equipment, Musical Instruments, Toys
ros	313	n313	Bride Price/Marriage Costs
ros	314	n314	Funeral Costs
osg	1001	n1001	Household Contributions to Informal Social Security Institutions
osg	1002	n1002	Contributions to Community Development Activities
osg	1003	n1003	Contributions to Social and Political Activities
osg	309	n309	Council Rates
osg	317	n317	Taxes for Income, Property, Etc.
dwe	222	n222	Mortgage - Regular Payment to Purchase House
other	311	n311	Losses to Theft (Value of Items or Cash Lost)
other	315	n315	Other Costs Not Stated Elsewhere

Notes: The table shows the expenditure items from the national household survey included in our analyses and the GTAP sectors to which they are assigned.

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