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# Carbon Inequality in Switzerland: Exploring Household Carbon Footprints during the Kyoto Commitment Periods

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## Abstract

As current climate mitigation efforts fall short of international goals, concerns over the equity implications of climate policy are becoming more salient. This study analyzes the distribution and evolution of household carbon footprints in Switzerland from 2008 to 2019, focusing on carbon inequality across income quintiles. Using data from the Swiss Household Budget Survey and the multi-regional input-output database EXIOBASE v3.8, the findings align with international patterns: household emissions increase with income and are concentrated in the consumption categories of food, housing and energy, and transport. Despite Switzerland meeting its Kyoto Protocol targets under a production-based framework, the total carbon footprint of private households remained high throughout the commitment periods. After an initial upward trend, emissions began to decline across all income groups after 2013. However, a disproportionately larger reduction among lower-income households led to rising carbon inequality during the second commitment period. A simulated carbon tax on transport fuels, modeled after Switzerland's existing $CO_2$ levy, suggests that such a policy could generate revenue and deliver net benefits for low-income households, while having only limited effects on overall carbon inequality.

**Keywords:** Household Consumption, Carbon Footprint, Carbon Inequality, Household Budget Survey, Switzerland, Environmentally Extended Multi-Regional Input-Output Analysis

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## Abbreviations

| | |
|---|---|
| **BAFU** | Bundesamt für Umwelt (see FOEN) |
| **BBl** | Bundesblatt (Federal Gazette - official gazette of the federal government of Switzerland) |
| **BFE** | Bundesamt für Energie (see SFOE) |
| **BFS** | Bundesamt für Statistik (see FSO) |
| **CBA** | Consumption-based Accounting |
| **CES** | Consumption Expenditure Survey(s) |
| **CHF** | Swiss Franc (official currency of Switzerland) |
| **CO2** | Carbon Dioxide |
| **CO2e** | Carbon Dioxide Equivalents |
| **COICOP** | Classification of Individual Consumption according to Purpose |
| **EEC** | Environmental Engel Curve |
| **EU** | European Union |
| **EUR** | Euro (official currency of the eurozone) |
| **FOEN** | Federal Office for the Environment |
| **FSO** | Federal Statistical Office |
| **GHG** | Greenhouse Gas |
| **GWP100** | Global Warming Potential over 100 years |
| **HBS** | Household Budget Survey |
| **HSG** | University of St.Gallen |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IO** | Input-Output |
| **IOA** | Input-Output Analysis |
| **IOT** | Input-Output Table |
| **ISCED** | International Standard Classification of Education |
| **ISIC** | International Standard Industrial Classification of all Economic Activities |

**LULUCF** Land-use, Land-use Change, and Forestry

**MRIO** Multi-Regional Input-Output

**OECD** Organisation for Economic Co-operation and Development

**PBA** Production-based Accounting

**SFOE** Swiss Federal Office of Energy

**SNA** System of National Accounts

**SNB** Swiss National Bank

**STATPOP** Swiss Population and Household Statistics

**SUT** Supply-Use Table

**UN** United Nations

**UNESCO** United Nations Educational, Scientific, and Cultural Organization

**UNFCCC** United Nations Framework Convention on Climate Change

**UNSD** United Nations Statistics Division

**U.S.** United States of America

**USD** United States dollar (official currency of the U.S.)

# 1 Introduction

Climate change, a defining challenge of the 21st century, has already led to a 1.1°C rise in the average global temperature above pre-industrial levels (IPCC, 2023, p. 4). The increasing frequency and intensity of extreme weather events across the globe, as reported by the Intergovernmental Panel on Climate Change (IPCC), are causing significant damage (2023, pp. 5-6). Mitigating greenhouse gas (GHG) emissions, the primary cause of global warming (IPCC, 2023, p. 4), is not just a global but an urgent necessity to meet the international climate targets set by the United Nations Framework Convention on Climate Change (UNFCCC). Despite past efforts, such as the 1997 Kyoto Protocol and the 2015 Paris Agreement, current climate policies are struggling to stabilize the GHG concentrations in the atmosphere and limit the adverse effects of climate change (IPCC, 2023, pp. 10-11).

While climate change affects everyone, the responsibility for its causes, namely greenhouse gas emissions, is not shared equally. Among the recent academic interest in distributional concerns, the concept of *carbon inequality* has gained traction. It refers to the "disproportionate distribution of carbon emissions between various groups" (SEI, n.d.). Analyzing the global inequality of carbon emissions, Chancel and Piketty (2015, p. 9) found that although carbon inequality between countries has decreased over the past decades, inequality within countries has risen.

Recognizing and addressing these disparities is essential when designing climate policies that are not only effective in reaching climate goals but also politically feasible and sustainable. In the past, distributional concerns have been central to backlashes against environmental reforms, such as during the Gilets Jaunes protests in France (Douenne and Fabre, 2022, pp. 81-82). Swiss citizens have even vetoed progressive climate bills in direct-democratic processes due to their fear of weakening the middle class (gfs.bern, 2021, pp. 48-55), underscoring the need for equity-oriented climate policies. As mitigation efforts intensify, understanding how emissions are distributed across income groups becomes crucial to minimizing resistance to policy changes (Bernauer, 2024).

A central aspect of these distributional considerations is how emissions are measured and attributed to groups of people or countries. Two primary frameworks have evolved in this regard. Most international agreements, including the Kyoto Protocol and the Paris Agreement, rely on production-based accounting (PBA). The PBA framework attributes GHG emissions of goods and services to the territory where they are produced. For example, the emissions from manufacturing smartphones in China are assigned to China, even though the phones are sold and used worldwide. Therefore, PBA has significant limitations in a globalized economy, where some countries produce emission-intensive goods for the world market, as it does not account for emissions embedded in trade.

In most OECD countries, emissions embedded in imports account for over 20 percent - and in some cases, over 50 percent - of domestic production emissions (Ahmad and Wyckoff, 2003, p. 22). For example, 29 percent of U.S. $CO_2$ emissions occur abroad (Weber and Matthews, 2008, p. 383), while in Norway, trade-related emissions reach up to 67 percent of domestic emissions (Peters and Hertwich, 2006a, p. 384).

To address this issue, researchers have turned to consumption-based accounting (CBA), which attributes emissions to the consumers of goods and services, regardless of where production occurred (Druckman and Jackson, 2016, pp. 183-184). A key concept within the CBA framework is the *carbon footprint*. The carbon footprint aims to capture the total environmental impact associated with consumption[1]. It describes the "total amount of emissions of carbon dioxide ($CO_2$) that is directly and indirectly caused by an activity or accumulated over the life stages of a product" (IPCC, 2022, p. 2902, and first stated in Wiedmann and Minx, 2007, p. 5). Peters (2010) adds that the carbon footprint considers "all relevant emission sources, sinks, and storage in both consumption and production" (p. 245). In the smartphone example from before, the carbon footprint includes all relevant emissions from the extraction of rare earth minerals, the manufacturing process, the shipping emissions, and even the electricity used during its lifetime. All of these are added up and attributed to the buyer of the smartphone when using the CBA approach.

Previous studies have attempted to assess the carbon footprint on a global level. They confirmed household consumption as the most critical environmental pressure (Hertwich and Peters, 2009, p. 6414; Ivanova et al., 2016, p. 528). Motivated by the significance of consumption as a driver for GHG emissions, this thesis investigates the emissions of households by analyzing their carbon footprints. In shifting the focus from territorial production to household consumption, CBA may offer a more accurate reflection of a country's environmental impact and a clearer picture of carbon inequality.

[1]Based on the stated definitions, this study uses the term *carbon footprint* to encompass a variety of emission sources resulting from consumption, including carbon dioxide, methane, nitrous oxide, and sulfur hexafluoride. To account for the effects of different greenhouse gases, an equivalence scale is used, reflecting their global warming potential (GWP) relative to carbon dioxide ($CO_2$). Hence, the carbon footprint is generally expressed in carbon dioxide equivalents ($CO_2e$). Other environmental stressors, such as hydrofluorcarbons (HFCs), perfluorocarbons (PFCs), and nitrogen trifluoride (NF3), are not included when referring to the carbon footprint in this study, even though they are so-called 'Kyoto Substances' listed in Annex A to the Kyoto Protocol (see United Nations, 2012, p. 3). However, the methodological approach in this study did not support their use, as their emissions were not provided in the dataset. Nevertheless, their contribution to Switzerland's overall emissions inventory is only small (below 3 percent, see Frischknecht and Knöpfel, 2013, p. 72). Furthermore, negative emissions resulting from natural carbon sinks and storage in the LULUCF (land-use, land-use change, and forestry) sector, as well as those from direct air capture technologies, are not considered in the analysis. Therefore, this study does not span the entire range of the theoretical carbon footprint. Nevertheless, the carbon footprint used in this analysis covers the most critical greenhouse gases with the greatest global warming impact (Frischknecht and Knöpfel, 2013, p. 72).

International efforts to reduce global emissions began in 1992 with the draft of the UNFCCC. They increased with the Kyoto Protocol in 1997, which for the first time set binding targets for industrialized nations. During its initial commitment period (2008-2012), participating countries aimed to cut emissions by 5.2 percent below 1990 levels, followed by a target of 18 percent for a subsequent period lasting until 2020 (BAFU, 2023b; BBl *2018* 247). Despite these efforts, global temperatures continue to rise, prompting the adoption of the Paris Climate Agreement in 2015 to limit warming to below 2°C (BAFU, 2023a).

In light of the UNFCCC's reliance on production-based accounting, the mitigation burden to reduce greenhouse gases currently appears to be higher in developing countries. Emerging economies such as China and India are more carbon-intensive under PBA than deindustrialized Western economies. During the structural changes of the past few decades, many developed nations have reduced their territorial emissions by offshoring production, effectively shifting emissions abroad without necessarily decreasing consumption. An international PBA-based comparison is thus advantageous for economies that are import-heavy and service-oriented.

A country that exemplifies this imbalance is Switzerland: its territorial emissions were 45.14 million tons $CO_2$ equivalents in 2021 (BAFU, 2025), while its carbon footprint reached 111.7 million tons $CO_2$e (BFS, n.d.-b), yielding a CBA/PBA ratio of nearly 2.5 - one of the highest globally and leading among all developed nations (Franzen and Mader, 2018, pp. 36-37). As a wealthy nation with low-carbon electricity production (BFE, 2023), Switzerland is among the countries that benefit most from the PBA framework, since 57 percent of its consumption-based emissions occur outside its borders (Nathani et al., 2022, p. 102). Therefore, Switzerland serves as an interesting case study that can be analyzed through a CBA lens.

How have Switzerland's carbon emissions evolved, and how are they distributed across households? The Swiss Federal Statistical Office (FSO) offers detailed consumption and income data, enabling a nuanced analysis of the nation's carbon footprint and within-country carbon inequality. As a ratifying party to the Kyoto Protocol, the Swiss case further allows for a temporal analysis of carbon footprint and inequality trends across the two commitment periods.

However, changes in carbon inequality alone do not reveal whether emissions are rising or falling. Inequality may decrease if poorer households increase their emissions through improved living standards, or if wealthier households reduce their emissions by curbing consumption, each with different implications for future climate mitigation. Thus, carbon inequality must be assessed in conjunction with overall emission trends to inform effective climate policy.

This thesis thus investigates Swiss household carbon footprints across income quintiles between 2008 and 2019, covering the first and second Kyoto commitment periods[2]. The study sheds light on household emission levels, their trends, and the extent of carbon inequality in Switzerland.

Existing research consistently finds income to be a major driver of household carbon footprints, both across households and over time (see, for example, Weber and Matthews, 2008; Baiocchi, Minx, and Hubacek, 2010; Ivanova et al., 2017; Sager, 2019; Christis, Breemersch, Vercalsteren, and Dils, 2019). These studies emphasize the importance of CBA and use (multi-regional) input-output models to estimate emissions. Several key findings emerge across the literature (see also Tukker et al., 2014; Steen-Olsen, Wood, and Hertwich, 2016; Ivanova et al., 2016; Isaksen and Narbel, 2017): Firstly, household emissions rise with income, regardless of the geographical or temporal scope of the study. Secondly, neglecting international trade flows significantly underestimates carbon footprints. Thirdly, the consumption categories contributing most to emissions are transportation, housing, and food.

Regarding carbon inequality, Chancel (2022) finds that while the poorest 50 percent of the population worldwide emit only 12 percent of global emissions, the richest 10 percent emit 48 percent (p. 931). Zheng et al. (2023), analyzing 43 economies worldwide, observe that while overall emissions in developed countries are declining, carbon inequality is rising (p. 4). Notably, high-income groups show the least progress in reducing their footprints (p. 8). Starr et al. (2023) show that emissions of the top one percent in the U.S. even increased over the past years (p. 4). To address carbon inequality, Gao et al. (2024) propose that policies should include incentivizing low-carbon consumption patterns among high-emitting households and fostering innovation in low-carbon technologies that can lower overall carbon intensity (p. 1). However, Zheng and his co-authors warn that mitigation policies may inadvertently exacerbate carbon inequality (2023, pp. 8-9).

Against this backdrop, the present study analyzes Swiss household carbon footprints and the country's carbon inequality using a methodology not yet employed by the Swiss Federal Administration[3].

[2]The study refrains from including the year 2020 in the sample period because of the onset of the COVID-19 pandemic, which significantly altered household consumption behaviors.

[3]For an overview of the different methods and approaches used to calculate the official Swiss carbon footprints in the past, their strengths and limitations, as well as their corresponding estimates, see Nathani and Frischknecht (2019). Furthermore, the Swiss Federal Statistical Office is currently examining its methodological approach and will most likely switch to an EE-MRIO application similar to the one utilized in the study at hand by the end of 2025 (BFS, n.d.-b).

By applying environmentally extended multi-regional input-output (EE-MRIO) modeling with EXIOBASE data and microdata from the Swiss Household Budget Survey, this study replicates stylized facts regarding Switzerland's carbon footprint and provides novel estimates of its distribution. These results enable a consumption-based assessment of Switzerland's performance during the two Kyoto periods, identifying policy-relevant trends in emission levels and carbon inequality.

The results suggest that Swiss households emitted an average of 74.6 million tons of $CO_2$e annually during the Kyoto Protocol commitment periods, which is equivalent to approximately 9.3 tons per capita per year[4]. While Switzerland met its Kyoto targets under the production-based accounting framework (BAFU, n.d.), the total carbon footprint of private households changed only slightly from a CBA perspective, as this study shows. Therefore, Switzerland would probably have failed to meet the Kyoto targets if they had been specified through CBA.

However, per capita emissions declined by 10.9 percent between 2008 and 2019, a reduction driven by all households across the income distribution. Nevertheless, the lowest-income households contributed relatively more to the decline, even when normalized by household size. This uneven mitigation trend translates into a slight rise in carbon inequality during the second Kyoto commitment period.

In light of these findings, this paper complements its empirical analysis of carbon footprints and carbon inequality with a static simulation of a transport fuel carbon tax, exploring its distributional effects and potential to reduce emissions. A closer look at consumption patterns revealed that transportation is a consumption category with a significant emission share, qualifying the sector as an obvious candidate for introducing a carbon tax. The simulation checks whether such a policy could help reconcile environmental effectiveness with social equity, particularly when combined with redistributive measures. Modeled after Switzerland's existing $CO_2$ levy, the simulated carbon tax suggests that introducing such a policy could raise revenue and lead to a net benefit for the lowest income group. Furthermore, it may have only a limited effect on carbon inequality in Switzerland.

The thesis is structured as follows: Section 2 details the data and methodology applied. It includes the description of the Swiss Household Budget Survey and the multi-regional input-output database used in this study. Section 3 presents the main results of the carbon footprint estimation across the income distribution and the carbon tax simulation. After displaying the results, Section 4 discusses the key findings and trends related to the Swiss carbon footprints. Finally, Section 5 concludes with implications for further research on carbon inequality and Swiss carbon footprints.

[4]The Swiss total population averaged around 8 million people between 2008 and 2019, steadily increasing from 7.5 million to 8.4 million inhabitants.

# 2 Methodology and Data

## 2.1 Methodological Framework

Multi-regional input-output (MRIO) analysis has become a widely accepted approach for evaluating consumption-based environmental impacts. As early as 2005, the UK Department for Environment, Food, and Rural Affairs identified MRIO as the most suitable method for carbon footprint accounting (Wiedmann et al., 2010, p. 20). Since then, the method has been refined with numerous applications in different countries and world regions (see, for example, Druckman and Jackson, 2016, p. 185).

MRIO models are particularly well-suited for assessing environmental impacts due to their ability to capture emissions embedded along global supply chains. As Steen-Olsen et al. (2016) argue, MRIO analysis enables a comprehensive understanding of the relationship between consumption and environmental pressures by linking final demand to emissions across all upstream production stages (pp. 589-590). The methodology employed in this study largely follows the framework proposed by Steen-Olsen et al. (2016), allowing for consistency with previous research and facilitating comparison.

The analytical foundation of household carbon footprints in this study rests on two data sources: consumption data gathered from consumption expenditure surveys (CES) and a global MRIO database. While the details of the respective datasets are introduced in the next section, the methodology to estimate carbon footprints distinguishes two main channels of household carbon emissions: direct and indirect (see e.g., Isaksen and Narbel, 2017, p. 155).

First, households can generate direct emissions resulting from on-site combustion of fossil fuels, such as using gasoline for private transport or natural gas for residential heating. Second, households have an indirect effect through their consumption choices, as emissions are embedded in the production and delivery of goods and services. These emissions occur upstream, across the supply chain, and are typically not visible to the consumer. They include emissions from activities such as raw material extraction, intermediary goods production, or final manufacturing.

Following Isaksen and Narbel (2017), the carbon footprint of a household is defined as the sum of its direct and indirect components (p. 155):

$$CF_{hh}^{total} = CF_{hh}^{direct} + CF_{hh}^{indirect} \tag{1}$$

Estimating direct emissions involves multiplying household expenditures in relevant consumption categories with corresponding direct emission intensities. This can be expressed as:

$$CF_{hh}^{direct} = e \; Y_{hh} \tag{2}$$

In the equation, $e$ is a vector of direct emission intensities (in $CO_2$/CHF), and $Y_{hh}$ is a vector of household consumption expenditures in the analogous categories.

The scope of direct emissions in this study includes expenditures on gas (natural gas), liquid fuels (heating oil), solid fuels (wood), and motor fuels (gasoline, diesel). Emissions from electricity consumption, while related to household activity, are treated as indirect emissions since they are generated outside the household. To illustrate, direct emissions from gasoline consumption would be estimated by multiplying how much a household spent on gasoline by the emission intensity of petrol, which was around 1.62 $kgCO_2$/CHF in 2020 (see an overview of direct emission intensities in the Appendix section D). Assuming a household spent CHF 1,000 on gasoline in 2020[5], their direct emissions would amount to 1.62$tCO_2$.

Indirect emissions, on the other hand, are captured through input-output analysis (IOA), which links sectors of the economy through interdependent supply chains. The MRIO model extends the IOA framework by focusing not only on one single economy, but also incorporating international trade and regional production technologies, enabling the tracing of emissions across national borders to their source (Weber and Matthews, 2008, p. 380). This is especially important when accounting for emissions embodied in imported goods, which may originate from countries with distinctive production practices, leading to differences in their carbon intensities (Peters and Hertwich, 2006b, p. 90; Isaksen and Narbel, 2017, pp. 155-156). For example, a car manufactured in Germany may have a different carbon footprint than a similar model produced in Mexico, depending on the energy mix and production technology used in the process.

[5]CHF 1,000 in 2020 corresponds to EUR 934 or USD 1,066. As a simple approximation, the reader can consider currency conversions between CHF, EUR, and USD on a 1:1 basis. The Appendix section D provides an overview of the official currency conversion rates during the study period.

The indirect household carbon footprint is calculated using the following input-output-based identity:

$$CF_{hh}^{indirect} = g\ (E\ L\ Y_{hh}) \tag{3}$$

Where $Y_{hh}$ is a final demand vector for household consumption in monetary units, $L$ denotes the multi-regional Leontief inverse matrix, capturing total output required per unit of final demand[6], $E$ represents an environmental impact multiplier containing emissions per unit of sectoral output[7], and $g$ characterizes a matrix to harmonize emissions of all greenhouse gas types into $CO_2$ equivalents[8].

Leontief (1970) proposed the original concept of integrating environmental concerns into economic input-output analysis. The MRIO framework applied in this study builds on his foundation and adopts standard environmental IOA principles as detailed in Miller and Blair (2009) as well as Peters and Hertwich (2004). For this thesis, the final demand vector is restricted to household consumption only, excluding expenditures by the government, non-profit institutions, and changes in inventories, as the focus is set on private households and their consumption footprint.

To compare household carbon footprints across the income distribution, household size and composition need to be taken into consideration. The Swiss data used in this study shows that high-income households tend to have more members than low-income households. To account for this structural difference, the household carbon footprint is deflated with the OECD square root scale where appropriate. This OECD equivalence scale divides the carbon footprint and the household income by the square root of the respective household size (for a comparison of equivalence scales, see OECD, 2013, pp. 173-175). The adjustment ensures that households are comparable in terms of their economic capacity in all subsequent analyses.

[6] $L$ can be calculated using the relation between total output of an economy, intermediate consumption, and final consumption: $X = AX + Y$, where $A$ is the economy's production function in matrix form (technical coefficients). From an MRIO perspective, $X$ can be thought of as the total economic requirements in all countries to meet the final demand in Switzerland. $A$ then denotes the inter-industry technical input coefficients representing the global economic structure. Solving for the total economic requirements yields the Leontief inverse $L = (I - A)^{-1}$.

[7] The environmental multiplier $E$ is a matrix of emission intensities calculated by dividing physical emissions for a given product-region combination by the respective output, where $E = F\ X^{-1}$.

[8] This study measures the carbon footprint using characterization factors from the midpoint ReCiPe 2008 method, indicating the global warming potential over a 100-year time horizon (GWP100) relative to $CO_2$ (see Steinmann et al., 2018).

## 2.2 Data

As previously stated, the analysis of Swiss household carbon footprints relies on two primary data sources: a consumption expenditure survey and an environmentally extended multi-regional input-output database. These two sources provide the necessary inputs to model household-level consumption and its associated environmental impacts.

### 2.2.1 CES Data: Swiss Household Budget Survey

The CES data source used in this study is the Swiss Household Budget Survey (HBS), administered by the Swiss Federal Statistical Office (FSO). The FSO collects detailed information on consumption expenditures and income from approximately 3,000 households per year. Each participating household records daily income, spending, and purchased quantities of goods over one month (BFS, n.d.-a). The annual publications report average monthly expenditures across more than 500 items. Every three years, results are further disaggregated by selected socio-economic characteristics, such as household type or income quintiles. This study uses publicly available HBS data from the periods 2006-2008, 2009-2011, 2012-2014, 2015-2017, and 2018-2019 (see datasets in the Appendix section D). The disaggregation by income quintile provided in these releases serves as the basis for the distributional analysis.

HBS expenditure data follows the United Nations Classification of Individual Consumption According to Purpose (COICOP). COICOP provides a framework of homogeneous categories of goods and services for household consumption expenditure and is an integral part of the United Nations System of National Accounts (SNA), used in several other statistical areas (UNSD, 2018, p. ii). While the Swiss survey strictly adheres to the first two levels of COICOP (groups), some deviations appear at the third level (classes) due to national categorization. Nevertheless, this study utilizes the third-level COICOP structure, which encompasses 117 commodity classes, with country-specific adjustments made as necessary. The mapping between Swiss-specific and international COICOP categories is based on the procedures and recommendations outlined by Froemelt et al. (2021), with some minor adaptations, whose details are provided in the Appendix section B.

Pre-processing of the raw HBS data was required before it could be integrated with the MRIO database. This included, among other steps, supplementing specific categories, especially housing, with additional external data. A complete account of the pre-processing steps is outlined in the Appendix section B.

### 2.2.2 MRIO Data: EXIOBASE

The environmentally extended MRIO database used in this study is EXIOBASE v3.8, developed as part of a European Union (EU) initiative to support sustainability assessments (Stadler et al., 2018, p. 503). EXIOBASE contains time-series MRIO tables for 44 countries (including all EU members and 17 major global economies), plus five aggregated regions representing the rest of the world (Europe, Asia, Africa, America, and the Middle East), covering roughly 90 percent of global GDP (Ivanova et al., 2016, p. 527). Though initially intended for EU-focused analysis, the database is well-suited for studies of the Swiss economy due to Switzerland's explicit inclusion in the database and its close trade ties with the EU.

EXIOBASE comprises monetary supply-use tables disaggregated into 200 product categories and is complemented by satellite accounts detailing environmental pressures[9]. These include data on various greenhouse gases, enabling the calculation of consumption-based carbon footprints in line with the methodology presented in the previous section.

### 2.2.3 Bridging CES and MRIO Data

To model the environmental impacts of household consumption, CES data from the Swiss HBS must be reconciled with the sectoral structure and valuation system of EXIOBASE. This step presents several methodological challenges, including differences in classification schemes, valuation methods, underreporting in survey data, and the allocation of imports.

The matching process employed in this thesis broadly follows the methodology described in Steen-Olsen et al. (2016, pp. 583-586), with minor adjustments tailored to the Swiss context. An overview of the bridging procedure and a summary of where this study diverges from previous approaches are provided in the Appendix section C.

Once the reconciliation is complete, the household carbon footprints – disaggregated by income quintile and year – can be estimated. This involves calculating and applying the Leontief inverse and environmental multipliers from EXIOBASE to the harmonized expenditure data. In doing so, the study estimates total and average household carbon footprints across the income distribution for 2008-2019, normalizing the results by household size where necessary.

[9] For more on the construction and structure of EXIOBASE, see Stadler et al. (2018) and the official database documentation at exiobase.eu.

## 2.3 Income-Emission Relationship

With the carbon footprints calculated, this thesis proceeds to examine their distribution across income quintiles. Environmental Engel Curves (EECs) are employed to characterize the relationship between household income and consumption emissions. While traditional Engel curves illustrate the link between income and expenditure, EECs extend this concept by mapping income against greenhouse gas emissions (Levinson and O'Brien, 2019, p. 121).

The analysis is based on income data provided in the Swiss Household Budget Survey, which reports average gross income for each income quintile. Coupled with the average carbon footprints derived for these quintiles, it is possible to estimate nonparametric EECs for 2008-2019. These curves depict the unconditional relationship between households' income and carbon footprints, allowing for visual inspection of their shape and evolution over time. The results section presents EEC estimates for 2008, 2013, and 2019 (see Figure 3), capturing the initial, middle, and final years of the study period, thereby offering insights into temporal changes during the Kyoto commitment periods.

To further investigate the nature of the income-emission relationship, this study tests three different functional forms: linear, quadratic, and cubic specifications of income. By comparing these functional forms, the study can assess the robustness of the carbon footprint estimates and evaluate whether the observed patterns are consistent with theoretical expectations and prior empirical findings. The results of the parametric estimation can be found in the Appendix section A.1.

## 2.4 Measuring Carbon Inequality

Following the analysis of the income-emission relationship, this study turns to the distributional aspect of emissions by examining carbon inequality. In line with previous studies (e.g., Wang and Yuan, 2022; Zheng et al., 2023; Gao et al., 2024), the disparity is quantified using the Gini coefficient, a well-established statistical measure of inequality ranging from 0 (perfect equality) to 1 (perfect inequality).

To apply the Gini coefficient in the context of carbon footprints, households are ranked by their income, and the cumulative share of households is plotted against the cumulative share of carbon emissions they emit. In a scenario of perfect equality, a given share of households should be responsible for an equivalent share of emissions. Though traditionally used to analyze income inequality, the Gini coefficient can be used to assess many disparities. Its application to emissions allows for a standardized and interpretable measure of how carbon footprints are distributed across the income spectrum (see, e.g, Zheng et al., 2023, p. 3; Hardadi, Buchholz, and Pauliuk, 2021, p. 105).

### 2.5 Simulating a Carbon Tax Scenario

To estimate the potential policy implications of carbon pricing on carbon inequality, this study simulates a static carbon tax scenario aimed at estimating the distributional and environmental effects of a $CO_2$ levy on transport fuel emissions. The scenario is informed by the 'Energieperspektiven 2050+' developed by the Swiss Federal Office of Energy (SFOE), which outlines pathways towards Switzerland's net-zero target by 2050 (see scenarios in BFE, 2022, pp. 46-49). Among the modeled trajectories, the Climate Mix 2 scenario places particular emphasis on market-based instruments, first introducing and then subsequently increasing the $CO_2$ levy on fossil fuels in the transportation sector.

Building on this framework, the present study simulates a $CO_2$ tax on transport fuels based on 2019 data, the most recent year in the sample. The simulation adopts a static partial equilibrium approach, assuming constant prices and no behavioral or substitution effects, following the work by Hardadi et al. (2021, pp. 105-106) as well as Filippini and Heimsch (2016, p. 98). The carbon tax only affects the fuel demand through the new price signal and does not impact other industry prices, production, or commodity flows. Further, the households' purchasing power is assumed to be unaffected by the tax. The simulation is thus isolated to the effect of consumers having to pay a higher price for transport fuels in the short and long run.

The simulation proceeds in two steps. First, it estimates the additional expenditure burden across income quintiles from the tax. This is done both without revenue recycling and with the application of a two-thirds recycling scheme, where households receive back a lump-sum transfer using the revenues generated by the tax, mirroring the redistribution mechanism currently in place for Switzerland's $CO_2$ levy on thermal fossil fuels (BAFU, 2024, p. 1). Second, the study estimates the emission-reducing effects of the tax for different tax rates using fuel price elasticities from Filippini and Heimsch (2016, p. 97) as well as Wadud et al. (2009, p. 2746). Based on 2019 gasoline prices and emissions, the price elasticities allow for an approximation of emission reductions under the simulated tax. Finally, the simulation investigates the distributional implications of the policy. By combining household fuel expenditures with estimated tax burdens and emission savings, the study assesses the potential impacts on carbon inequality.

# 3 Results

## 3.1 The Swiss Private Household Carbon Footprint

Based on the methodology outlined earlier, this first section presents the total and per capita carbon footprints of Swiss private households from 2008 to 2019. The results provide a baseline for the subsequent analysis of distributional patterns.

Figure 1: Total carbon footprint of Swiss private households

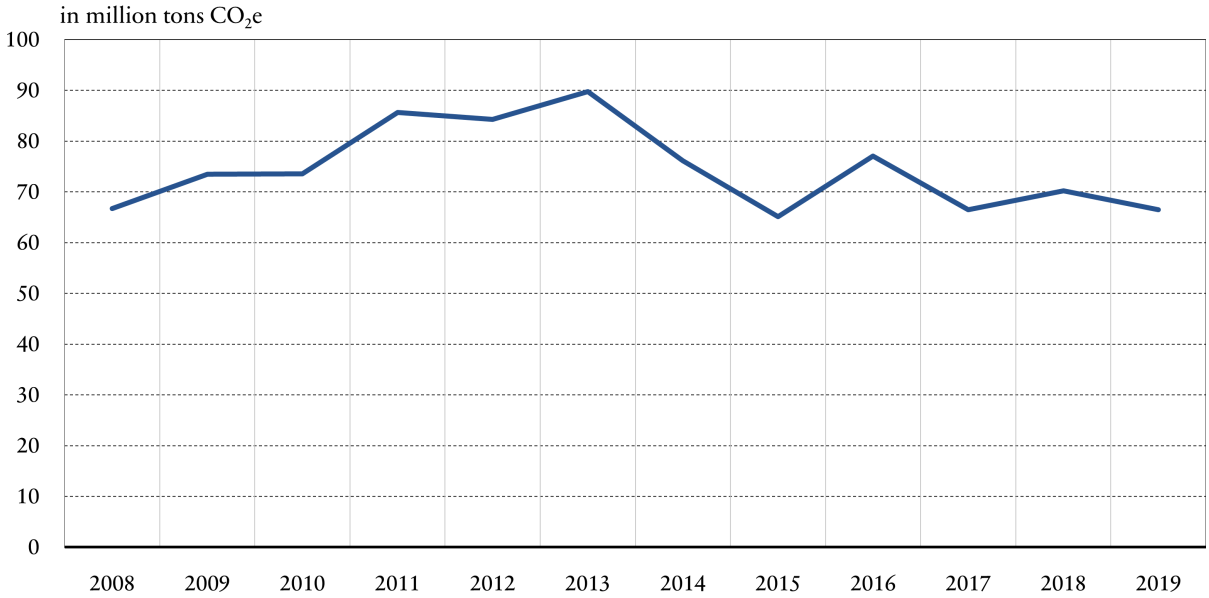


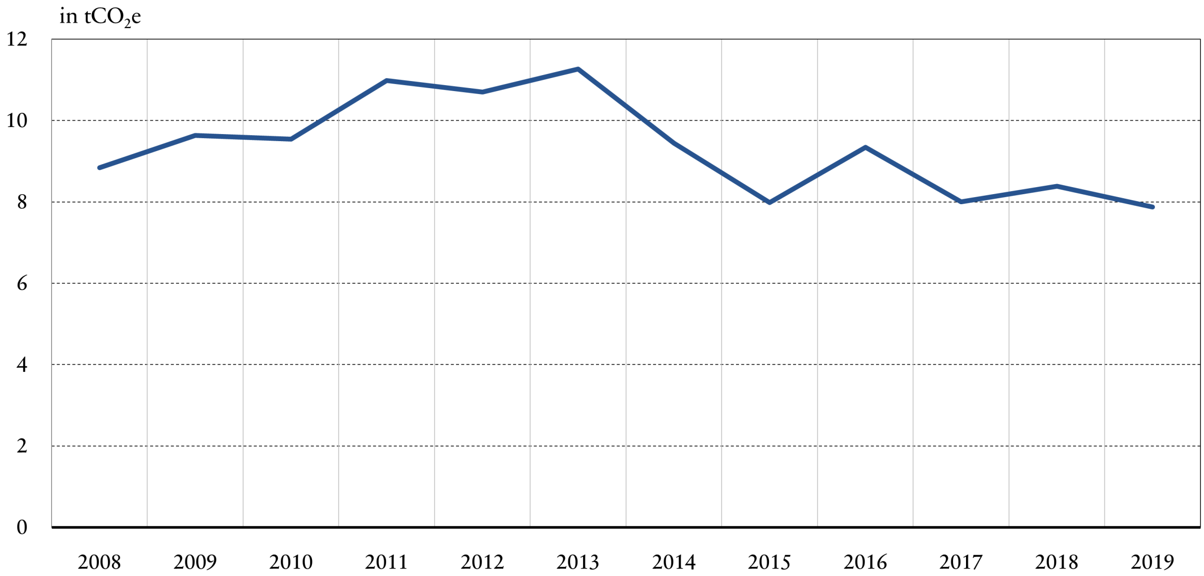

Figure 1 shows the development of total greenhouse gas emissions attributable to private household consumption. The total carbon footprint was 66,709 kilotons of $CO_2$ equivalents ($ktCO_2e$) in 2008. It increased to a peak in 2013 and subsequently declined, reaching 66,482 $ktCO_2e$ by 2019. This corresponds to an overall decrease of less than one percent. The average carbon footprint over the two Kyoto Protocol commitment periods was 74,594 $ktCO_2e$ per year, which constituted not even 0.2 percent of global greenhouse gas emissions[10].

[10] According to the Emissions Database for Global Atmospheric Research EDGAR, the average global greenhouse gas emissions between 2008 and 2019 were 47,998.56 million tons $CO_2e$ per year (European Commission, n.d.)

These estimates have to be put into perspective. The analysis focuses on private households and is based on consumption captured by the HBS. Therefore, these emission totals do not include specific emissions related to public goods and services provided by the government or non-profit institutions, such as healthcare, education, and social protection services. Only private expenses in these categories are part of this study's carbon footprint. Because of these omissions, the results pertain to consumption spending that private households have a direct influence on through their everyday choices. Hence, the estimates delineate a lower bound of the overall household-related carbon footprint.

Figure 2 illustrates the annual carbon footprint per capita attributable to private consumption. In 2008, the average was 8.84 tons of $CO_2$ equivalents ($tCO_2e$) per person. Emissions peaked at 11.27 $tCO_2e$ in 2013 before declining to 7.88 $tCO_2e$ per person in 2019. This corresponds to an overall reduction of 19.0 percent over the two Kyoto commitment periods. During this period, the Swiss population grew steadily, which explains the downward trend in per capita emissions, although the total household carbon footprint did not decline significantly.

Figure 2: Carbon footprint of household consumption per capita



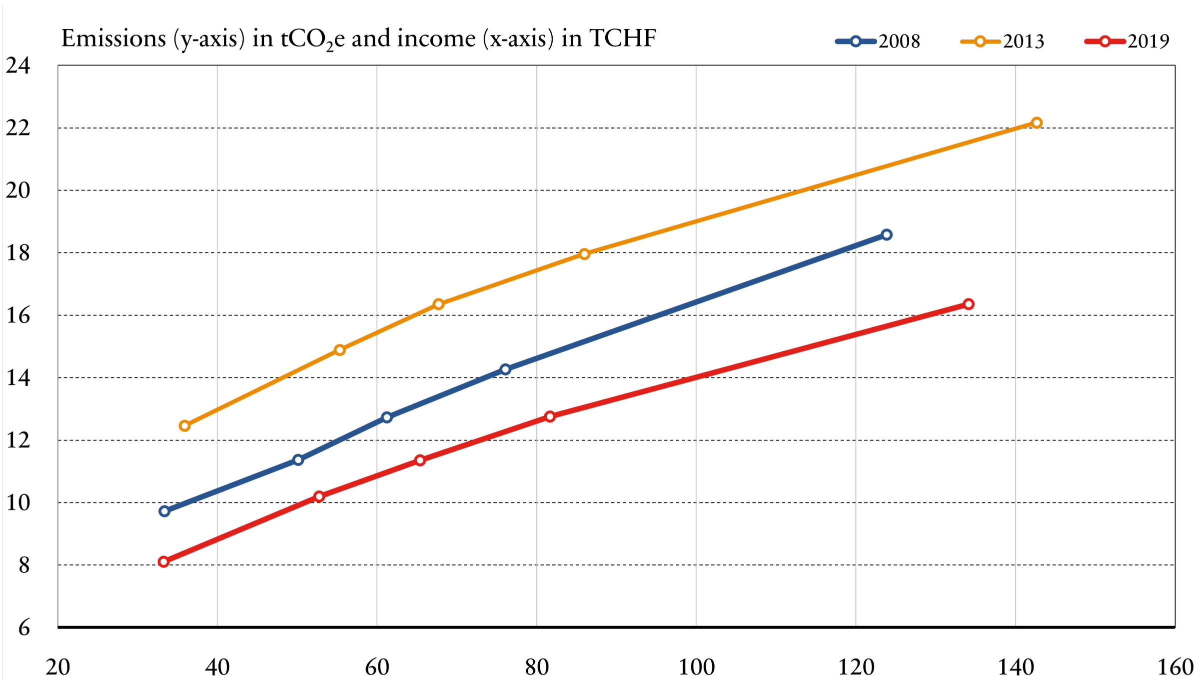

*Note:* To calculate the carbon footprints per capita, the private household carbon footprint was divided by the permanent population living in private households, which corresponds to about 98 percent of the permanent resident population of Switzerland on average (see population and household details in the Appendix section D).

Taking into consideration all emission sources (and not only households), the global average carbon footprint was at 6.9 $tCO_2$ per person in 2019 (IPCC, 2023, p. 5). Since the footprint of Swiss private households is already higher than the global average, which includes those of government and other actors, this indicates that Swiss consumption patterns have a significant environmental impact.

## 3.2 Carbon Footprints across the Income Distribution

To examine how household carbon footprints vary across the income distribution, Environmental Engel Curves for the first, middle, and last year of the sample period are plotted. These curves display the average greenhouse gas emissions for each income quintile without controlling for household characteristics other than household size through the OECD equivalence scale. As shown in Figure 3, three distinct patterns emerge:

Figure 3: Swiss Environmental Engel Curves for 2008 and 2019




*Note:* The figure displays the carbon footprint and income for the average Swiss household in each respective income quintile. The total emissions per quintile were divided by the corresponding number of private households (see details in the Appendix section D). Income data is gathered from the Swiss HBS. Both emissions and income are equivalized using the OECD square root scale for comparison. Household emissions are higher than per capita emissions, as households typically include more than one person.

First, EECs are upward-sloping, indicating that households with higher incomes also have higher carbon footprints. This result is consistent with a broad body of literature (see examples in Druckman and Jackson, 2016, pp. 186-188). In 2019, an average household in the highest income quintile emitted approximately 16.4 $tCO_2e$ adjusted for household size[11], which is more than double the emissions of the lowest quintile at 8.1 $tCO_2e$.

[11]The average household size in Switzerland increases along the income distribution. Between 2008 and 2019, a household in the lowest quintile consisted, on average, of 1.35 members, while a household in the highest income quintile had an average of 2.91 people. Thus, adjusting for household size delivers a more comparable result between quintiles.

Second, the EECs appear concave. This suggests that the elasticity of emissions with respect to income is less than one: as income increases, emissions also increase, but at a diminishing rate. Two primary mechanisms may explain this pattern (see Pottier, 2022, pp. 2-6): first, higher-income households tend to save a larger portion of their income, lowering their average propensity to consume. Second, lower-income households spend, in general, a greater share of their budgets on necessities such as heating or food, which are relatively emission-intensive per monetary unit. As income rises, the consumption share shifts towards other services and leisure activities, which are usually less carbon-intensive. This explains why the expenditure elasticity of emissions is typically below one, and the income elasticity, given increasing savings, must be even lower. The Swiss case may be somewhat exceptional as the expenditure elasticity could approach one due to the country's low-carbon electricity mix (BFE, 2023), similar to the Norwegian case described by Isaksen and Narbel (2017). Nevertheless, the income elasticity likely remains below one, as indicated by the shape of the EECs in Figure 3.

Third, the EECs have shifted upwards during the first Kyoto Protocol Commitment Period and downwards in the second, indicating an initial increase and a subsequent decline in emissions over time at every income level. This trend mirrors the broader carbon footprint trends shown in Figure 1. Several factors may explain these shifts (see Sager, 2019, p. 6). On the one hand, households may have allocated a varying share of their income to private consumption and saved more, thereby changing overall emissions. However, the Swiss savings rate in 2008 and 2013 was similar and in 2019 even lower than previously (see FSO, 2024). On the other hand, there might have been a shift in consumption patterns, such as a move away from meat toward more plant-based foods, even when total spending remained constant. Lastly, technological advancements may have contributed to changing carbon intensity in producing and delivering goods and services through improvements in domestic or foreign production methods or changes in import shares.

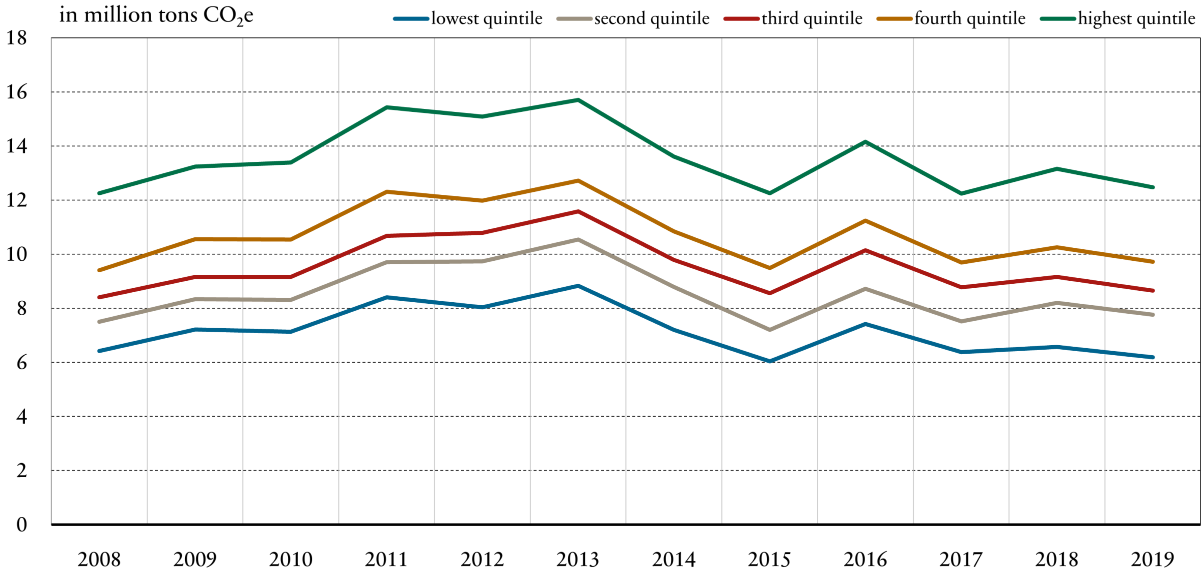
Among these, technological change is considered to be the primary driver (Sager, 2019, p. 6). Other factors, such as rising incomes or growing income inequality, contribute to movements along the EEC but do not explain the observed shifts of the entire curve.

To reinforce the visual findings, a simple regression analysis was conducted (see details in the Appendix section A.1). The results confirm the findings of rising but diminishing emissions with income and align with previous research (see e.g., Weber and Matthews, 2008; Ivanova et al., 2017; Sager, 2019). For Switzerland, the consistency between the descriptive EECs and the regression estimates confirms, at least for the second Commitment Period, three stylized facts initially identified by Levison and O'Brien (2019, p. 132) and Sager (2019, p. 5): EECs are increasing, they are concave, and they shift downward over time.

### 3.3 Income Quintile Footprints over Time

To investigate in greater detail which income groups are driving the observed decline in per capita carbon footprints and the downward shift of the EECs in Switzerland, the carbon footprints of each income quintile over the sample period are examined.

Figure 4: Equivalized carbon footprints across the income distribution and over time




*Note:* Each income quintile's total private household carbon footprint has been equivalized with the OECD square root scale.

Figure 4 displays the equivalized household carbon footprint for each income quintile from 2008 to 2019. The lowest income quintile emitted 6,416 kt$CO_2$e on average in 2008, decreasing to 6,185 kt$CO_2$e in 2019 – a reduction of approximately 3.6 percent. In contrast, the highest income quintile emitted 12,257 kt $CO_2$e in 2008 and 12,469 kt $CO_2$e in 2019, marking a slight increase of roughly 1.7 percent.

To move beyond point-to-point comparisons, a linear trend for the emissions of each income quintile is estimated. These trends suggest that all quintiles have declining emissions over time. The average annual reduction in emissions is highest for the lowest-income group, amounting to approximately 91 kt$CO_2$e per year. The top income quintile also exhibits a decreasing trend, albeit at a lower rate of 82 kt$CO_2$e per year.

When splitting the trends between the first and second Kyoto commitment period, the results reveal interesting distinctions. First, the commitment periods exhibit diverging shifts. While consumption-based emissions increased between 2008 and 2012 for all households, they subsequently decreased for all households across the income distribution. Thus, the second commitment period seems fundamentally different from the first. Second, the magnitude of increases and reductions is unequally distributed. During the first commitment period, the increases followed roughly the respective emission shares regardless of the household's socio-economic standing, averaging between 0.44 and 0.78 $tCO_2$ per year. However, the decline after 2013 was more balanced, ranging from 0.32 to 0.38 $tCO_2$ per year. This led to the emissions of the lowest income group shrinking by roughly 5.8 percent annually in the second period, while the highest income group reduced theirs by only 3.8 percent.

Figure 5: Evolution of carbon inequality


By analyzing the Gini coefficient of the carbon footprint distribution, the previously described evolution becomes apparent (see Figure 5. During the first commitment period, carbon inequality decreased slightly. The more equal decline of carbon footprints between income groups in the second commitment period, however, led the Gini coefficient to rise again after 2013, growing to around 0.13.

### 3.4 Carbon Footprints and Consumption Categories

To analyze how different types of goods and services contribute to household carbon footprints, household expenditures and their associated emissions are grouped into 12 categories according to the COICOP 1999 classification (see UNSD, 2000). These categories include:

(01) Food and non-alcoholic beverages

(02) Alcoholic beverages, tobacco and narcotics

(03) Clothing and footwear

(04) Housing and energy

(05) Household equipment and maintenance

(06) Health

(07) Transport

(08) Communications

(09) Recreation and culture

(10) Education

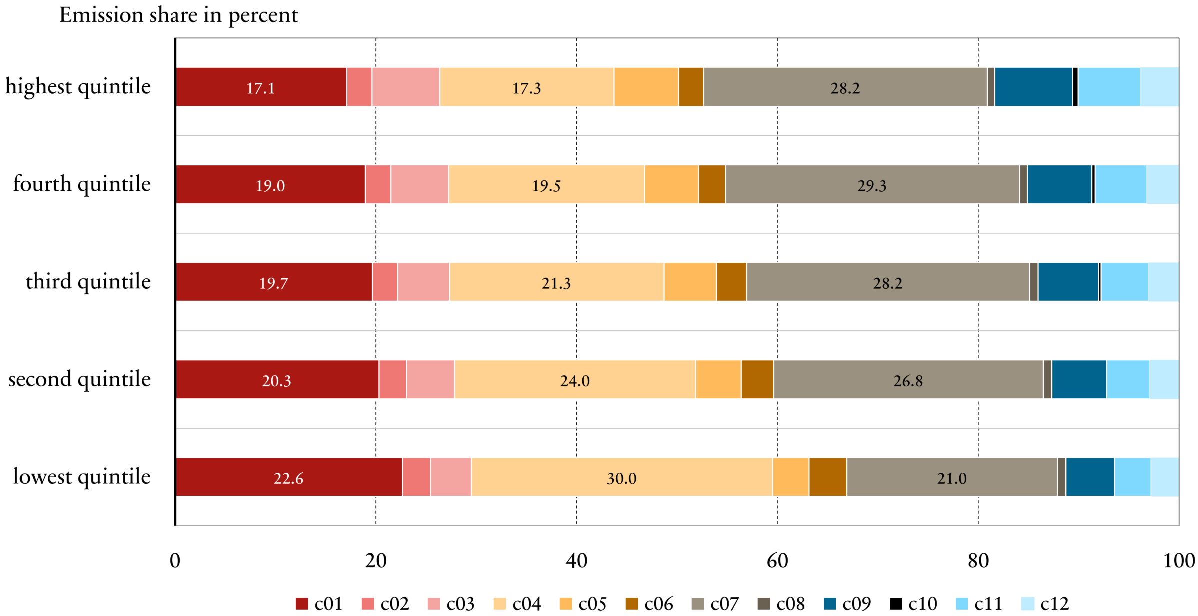
(11) Restaurants and hotels

(12) Miscellaneous goods and services

The remaining categories – (13) individual consumption expenditure of non-profit institutions serving households and (14) individual consumption expenditure of general government – are excluded, as they do not reflect direct private household consumption. Direct emissions from heating fuels (e.g., heating oil, gas, wood) are part of the housing and energy category, while emissions from vehicle fuels (diesel, gasoline) are attributed to transport.

Figure 6 presents the average distribution of the carbon footprint across the 12 COICOP consumption categories for Swiss private households during the Kyoto commitment periods. Irrespective of the income group, three categories dominate household emissions: food and non-alcoholic beverages, housing and energy, and transportation. These three categories account for approximately 60 percent of household emissions, a pattern that aligns with findings in previous studies (see e.g., Ivanova et al., 2016; Steen-Olsen et al., 2016; Christis et al., 2019).

Figure 6: Average emission shares by income quintile and consumption category



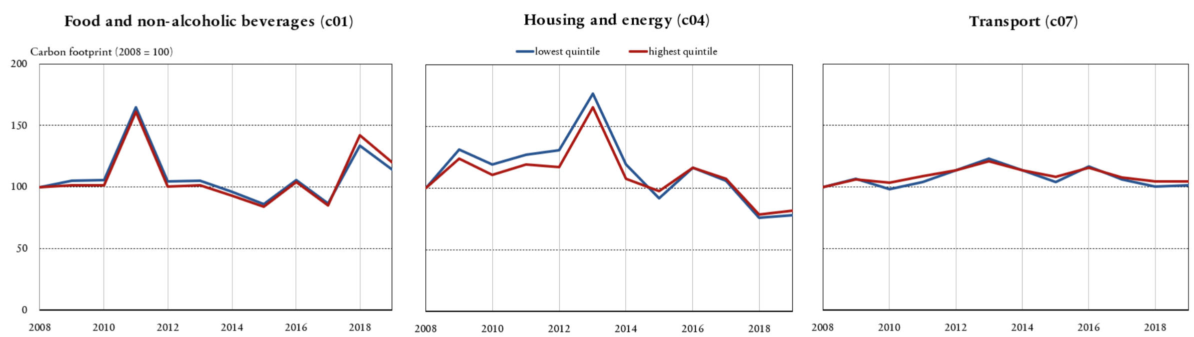

*Note:* The shares were calculated by separately averaging the emissions within each income quintile and each category over the entire sample period.

While the absolute carbon footprint of consumption categories generally increases with income, the share of emissions from necessities such as food and housing declines as income rises. An exception is the transport category, typically considered part of household necessities, which increases both in absolute and relative terms with income. In particular, the transport category accounts for 21 percent of household emissions for the lowest income group, while in the highest income group, it accounts for nearly 29 percent. Hardadi et al. (2021) observe the same phenomenon in the transport category for German households (p. 101). They explain the rising share with the difference in opportunity costs of travel time (p. 101): the incentives to use private transportation, which is faster and more convenient, increase for high-income groups. Therefore, transportation in Switzerland, unlike food or housing, cannot be considered a classic 'necessity' when analyzing carbon footprints.

Figure 7 displays the indexed equivalized carbon footprint for the lowest and highest income quintiles within the three COICOP categories with the highest emission share to explore how household emissions have evolved across different consumption categories. An overview of all 12 categories is provided in the Appendix section A.2.

Some key observations emerge: first, the categories exhibit high variation rather than consistent upward or downward trends. Second, the peaks in the first Kyoto commitment period are visible across the categories. Third, while emissions in the categories of food and transport were not lower in 2019 than in 2008, consumption-based emissions in housing and energy showed a remarkable decrease during the second commitment period.

Figure 7: Indexed developments of the carbon footprint for the highest and lowest income quintiles




*Note:* The equivalized total private household carbon footprints for every income quintile and category were indexed to 100 for the year 2008.

### 3.5 Static Simulation of a Carbon Tax Scenario

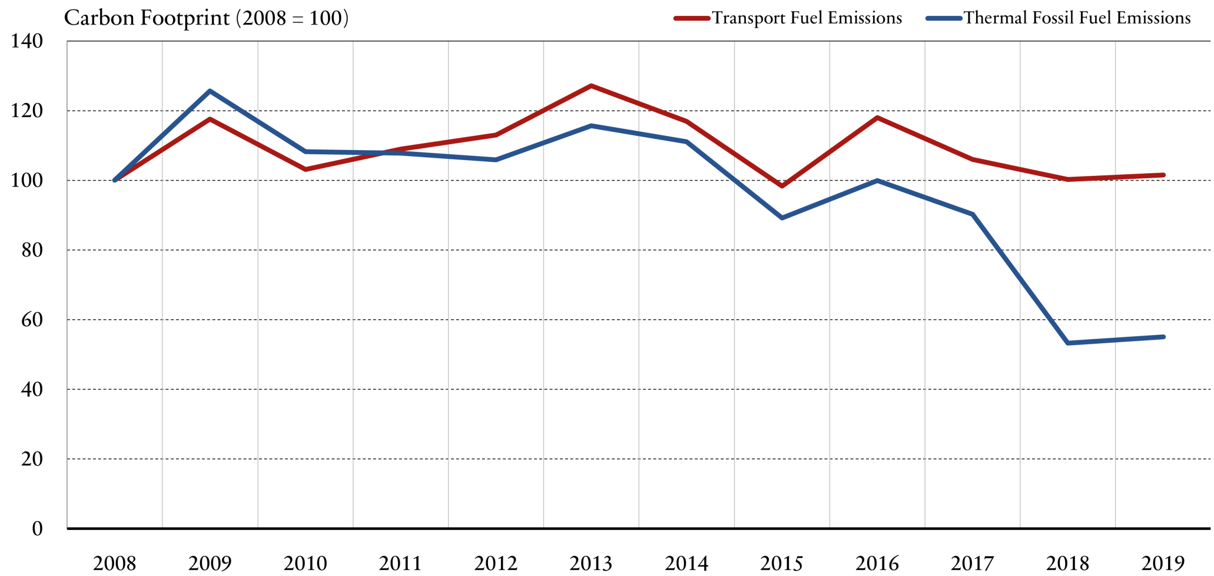
The comparison of trends between consumption categories reveals that housing and energy is one of the few categories where households from all income groups managed to decrease their carbon footprint during the Kyoto commitment periods. This decline could be partially attributable to the Swiss $CO_2$ levy, which was imposed on all fossil thermal fuels - including heating oil and natural gas[12]. In its first five years since its inception in 2008, the Swiss $CO_2$ levy reduced emissions cumulatively between 2.5 and 5.4 million tons of $CO_2$, effectively curbing emissions from fossil thermal fuels by up to 6 percent (Ecoplan, EPFL, and FHNW, 2015, p. 3).

From an economic point of view, market-based instruments such as pollution taxes or tradable pollution permits have a long tradition of accounting for externalities and balancing welfare goals efficiently (Pearce, 2002, pp. 73-75). Therefore, introducing a reasonable tax on $CO_2$-intensive goods to internalize the adverse effects of greenhouse gas emissions is a sound economic policy.

[12] Initially at CHF 12/t$CO_2$, it steadily increased to CHF 36/t$CO_2$ in 2010, CHF 60/t$CO_2$ in 2014, CHF 84/t$CO_2$ in 2016, CHF 96/t$CO_2$ in 2018 and is now at CHF 120/t$CO_2$ making it one of the highest taxes on carbon emissions worldwide (BAFU, 2024, p. 2)

Following this tradition, a static simulation of a different carbon tax was conducted, extending the relatively narrow scope of the current Swiss $CO_2$ levy to transport fuels. Transport, being among the consumption categories with the highest emission share and showing no noticeable decline among all income groups between 2008 and 2019, is an appropriate case study. This becomes especially apparent when comparing household emission trends between heating fuels and transport fuels, as displayed in Figure 8.

Figure 8: Developments of thermal fossil fuel emissions and transport fuel emissions

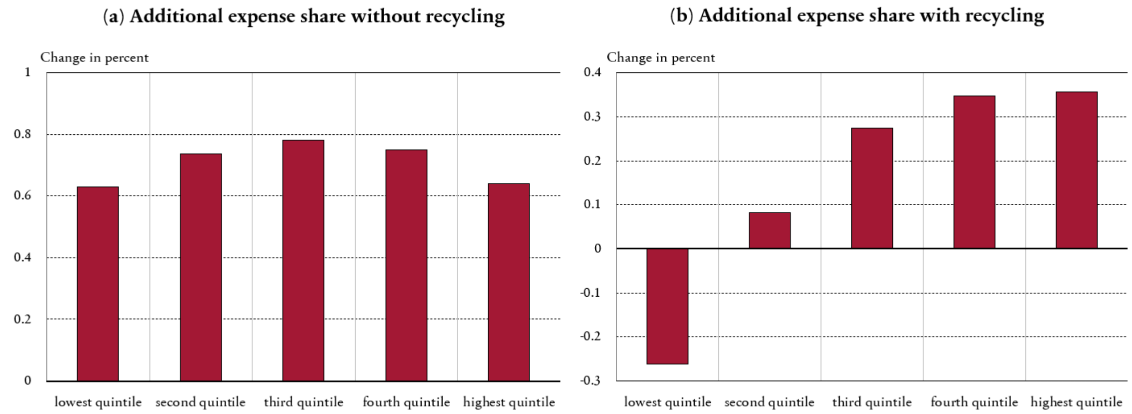



*Note:* Thermal fossil fuel emissions include emissions from the consumption categories c04.5.2 (Gas) and c04.5.3 (Liquid fuels). Transport fuel emissions consist of emissions from the category c07.2.2 (Fuels and lubricants for personal transport equipment). Total emissions were indexed to 100 for the year 2008.

The static simulation of the hypothetical carbon tax on transport fuels (represented by COICOP category 07.2.2 in this study) examines both the distributional and environmental impacts of the policy (see calculations in the Appendix section D). As the interest lies in the actual changes in expenditure and emissions of each household, rather than comparing effects between households, the OECD equivalence scale was not used for these calculations.

The simulation reveals that implementing a carbon tax of CHF 120 per ton of $CO_2$, which corresponds to the current tax on thermal fossil fuels (BAFU, 2024), would increase household expenditures by 0.63 percent in the lowest income quintile and 0.64 percent in the highest income quintile. The additional tax burden is distributed in an inverted U-shape across the income distribution, with middle-income households experiencing the highest relative increase in expenditure (see Figure 9).

Figure 9: Scenario simulation of a CHF 120/t$CO_2$ carbon tax




*Note:* The figure shows the additional expense shares for all income quintiles in (a) a scenario without revenue recycling and in (b) a scenario with two-thirds lump-sum revenue recycling.

In terms of revenue, the policy is estimated to generate approximately CHF 1.6 billion annually, exceeding the revenue from the existing Swiss $CO_2$ levy, which amounted to almost CHF 1.3 billion in 2022 (BAFU, 2024, p. 2). Assuming a revenue recycling mechanism in which two-thirds of the revenue is returned to households through equal lump-sum transfers, each household would receive an average annual rebate of CHF 279.50[13]. Under this scenario, households in the lowest income quintile would become net beneficiaries, receiving more in transfers than they pay in taxes. Conversely, households in the highest income quintile would remain net contributors, with a post-recycling expenditure increase of 0.36 percent. The remaining one-third of the tax revenue, corresponding to more than CHF 500 million, would be available to the government to finance other climate-related expenditures or include it in the general budget.

[13]The calculation does not include the possibility of transferring part of the revenue back to the industry, as is provided for in the current $CO_2$ levy (BAFU, 2024, p. 1). Therefore, the actual rebate may be lower. However, Parliament could decide on the recycling mechanism and opt for considering only private households in this case, as they are paying the tax in the first place.

Table 1: Estimated impacts of a $CO_2$ tax on gasoline

| Carbon Tax ($CHF/tCO_2$) | Scenario | Gasoline price change (in %) | Effect on gasoline consumption (in %) | Projected savings (I) (in $tCO_2$ emissions) | Projected savings (II) (in % of transport emissions) |
|---|---|---|---|---|---|
| 60.- | SR | 8.7 | -2.33 | 136'401 | 0.72 |
| 60.- | LR | 8.7 | -7.09 | 415'310 | 2.18 |
| 96.- | SR | 13.9 | -3.73 | 218'241 | 1.15 |
| 96.- | LR | 13.9 | -11.34 | 664'496 | 3.49 |
| 120.- | SR | 17.4 | -4.66 | 272'802 | 1.43 |
| 120.- | LR | 17.4 | -14.18 | 830'620 | 4.37 |

*Note:* Calculations for the short run (SR) and long run (LR) are based on Swiss carbon tax elasticities on gasoline demand from the work of Filippini and Heimsch (2016). The detailed calculations are presented in the Appendix section D. Short run and long run in this simulation refer to the chosen parametrization by Filippini and Heimsch (2016) in their paper. In the short run, they modeled the capital stock to be constant, whereas in the long run, households could adjust the capital stock to an optimal level. These assumptions resulted in different demand elasticities for the short and long run.

In terms of environmental outcomes, Table 1 summarizes the effects of different carbon tax rates on emissions from gasoline combustion based on 2019 prices and emissions. A carbon tax of CHF 120.-/$tCO_2$ is projected to reduce emissions by approximately 1.43 percent in the short run and 4.37 percent in the long run. Applying distributional elasticity estimates from Wadud et al. (2009, p. 2746) that match closely with the average elasticity of the Swiss context from Filippini and Heimsch (2016, p. 97), Table 2 indicates that the most significant relative emission reductions are expected among households in the lowest income quintile (6.1 percent), followed by the highest quintile (5.0 percent). Middle-income households would reduce emissions by a smaller margin in relative terms. Overall, the policy is estimated to reduce emissions by more than 250,000 tons of $CO_2$ in the short term.

Table 2: Estimated tax impacts across the income distribution

| Income Quintile | Demand elasticity | Effect on gasoline consumption (in %) | Projected savings (I) (in $tCO_2$ emissions) | Projected savings (II) (in % of transport emissions) |
|---|---|---|---|---|
| 1 | -0.351 | -6.1 | 38’395 | 2.40 |
| 2 | -0.219 | -3.81 | 36’584 | 1.34 |
| 3 | -0.203 | -3.53 | 41’748 | 1.14 |
| 4 | -0.263 | -4.57 | 65’681 | 1.39 |
| 5 | -0.293 | -5.09 | 83’809 | 1.33 |
| **Total** | | | **266’218** | **1.40** |

*Note:* The short-run effects are estimated supposing a CHF 120.-/$tCO_2$ tax on gasoline. Calculations are based on demand elasticities from Wadud et al. (2009). The detailed calculations can be found in the Appendix section D.

Evaluating the policy from a carbon inequality perspective by recalculating the Gini coefficient while taking the projected savings from the carbon tax into account (see calculations in the Appendix section D) reveals that overall carbon inequality would increase only marginally (from 0.12966 to 0.12980)[14]. Compared to the shifts in the Gini coefficient between 2008 and 2019 (see Figure 5, this shift is almost negligible. Therefore, as proposed by this simulation, a carbon tax on transport fuels would likely not have a significant impact on carbon inequality. More affluent households would decrease their emissions similarly relative to poorer households, and the lowest-income households would be ’compensated’ for their emission reductions.

### 3.6 Limitations

Before discussing these results, it is necessary to acknowledge some limitations that may have affected the analysis. The following section highlights the limitations of the applied methodology and the data used in the estimation.

[14]For the Gini coefficient calculations, the OECD equivalence scale has been applied again. This was done to compare the tax scenario and the previously presented carbon inequality trend during the Kyoto commitment periods

On the one hand, MRIO analysis provides a robust and consistent framework for consumption-based emissions accounting. However, it also introduces several uncertainties. Aggregation bias is a key concern, as grouping high- and low-emission sectors together can misrepresent the carbon intensity of household consumption (Wiedmann, 2009a, p. 218). While EXIOBASE distinguishes 200 product categories, merging similar items can obscure product-level variation. This is particularly problematic when households consume qualitatively different goods within the same category.

For instance, higher-income households may purchase higher-quality goods with potentially lower embedded emissions (Christis et al., 2019, p. 1170). The MRIO approach, assuming product homogeneity within categories, does not account for such differences. Consequently, this 'quality effect' may lead to an overestimation of high-income households' carbon footprints, and thus of overall carbon inequality (Girod and De Haan, 2010, p. 32). Despite this limitation, if high-income households consistently choose higher-quality, lower-emission goods, the trend should nevertheless provide insight into differences across the income distribution. For a broader discussion of MRIO model uncertainties, including assumptions regarding sectoral disaggregation and price homogeneity, readers are referred to Weber (2008) and Wiedmann (2009b).

In addition to methodological constraints, several data-related limitations must be acknowledged. While the Swiss HBS is undoubtedly a valuable source of household consumption data, it also has some shortcomings: First, although based on approximately 3,000 Swiss households, the published data only provides average consumption per income quintile. More granular income categories, such as deciles or continuous income measures, could provide a more nuanced picture of the relationship between income and carbon footprints.

Second, due to the small sample size, the detailed HBS data, including the differentiation between income quintiles, is only publicly available as three-year averages rather than annual figures. Even with the triennial aggregation, some estimates in the original HBS dataset still carry coefficients of variation exceeding 10 percent, indicating potential unreliability in specific categories. This not only increases the uncertainty of the estimation but also limits the ability to capture short-term consumption dynamics or responses to particular policy changes and macroeconomic shocks.

Further, this study focuses almost exclusively on household income, due to the limited socio-demographic information available in the public HBS dataset. The only other factor included in the estimation was household size, as measured by the OECD square root equivalence scale. Other determinants such as dwelling characteristics or urban-rural distinction are known to influence household emissions (Druckman and Jackson, 2016, pp. 188-189) but could not be included here. This may lead to omitted variable bias in the results, especially with the EECs.

However, Sager (2019, p. 2) finds that the mentioned household characteristics have relatively minor effects on the shape of the income-emissions relationship and its evolution over time. Therefore, despite data limitations, it is still possible to identify general patterns of EECs based on income.

Finally, uncertainties in the EXIOBASE database itself must be considered. As an international MRIO database, EXIOBASE incorporates heterogeneous data sources across countries. Variations in trade accounting, emission factors, and technical coefficients introduce another layer of uncertainty (Hardadi et al., 2021, p. 108). While EXIOBASE developers have made efforts to harmonize conflicting methods, some inconsistencies may remain.

Rodrigues et al. (2018, p. 7584) estimate that uncertainties in global MRIO databases range from 10 to 200 percent for product-specific carbon accounts, and up to 16 percent for national consumption-based emission accounts. Without conducting a dedicated uncertainty analysis, which could be part of future research, it is reasonable to assume that the uncertainty range in this study is likely to be similar.

These limitations should be carefully considered when interpreting the results, especially in comparison to other studies. While the methodological and data constraints may overestimate or smooth some aspects of the carbon footprints, they should not undermine the broader patterns observed in the Swiss income-emissions relationship.

# 4 Discussion

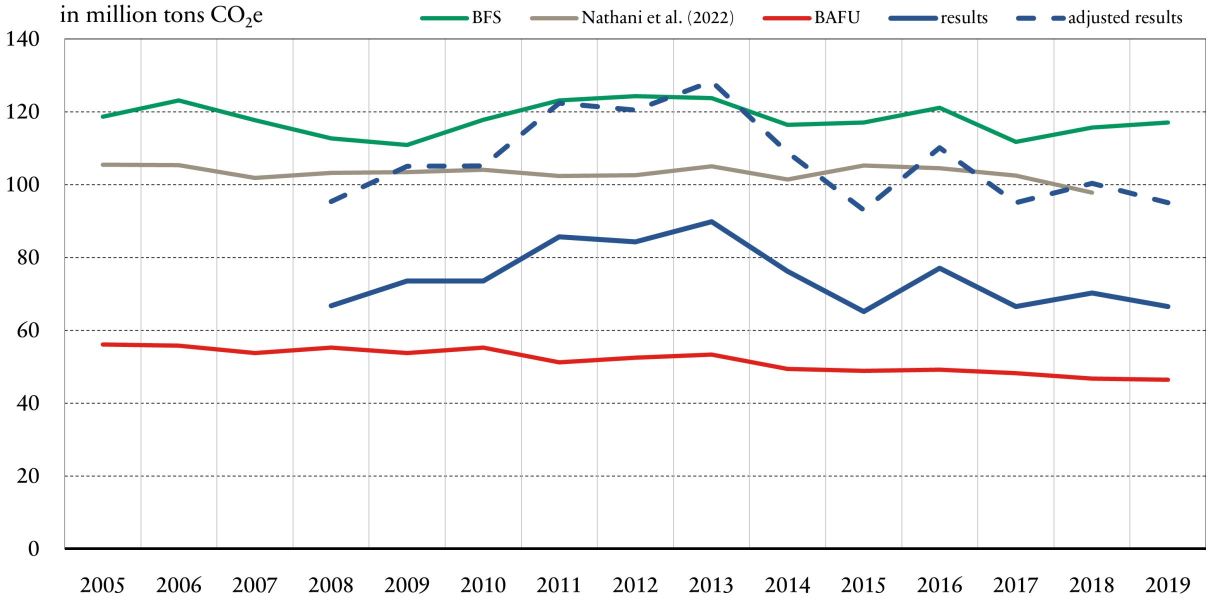
Switzerland ratified the Kyoto Protocol and committed to drastically reducing its greenhouse gas emissions. At the end of 2020, total emissions were expected to be 20 percent lower than in 1990, with an average reduction of 15.8 percent over the entire second Kyoto commitment period (2013-2020). Officially, Switzerland achieved these targets (BAFU, n.d.). In the FOEN report, the government highlights a significant reduction in emissions at the household level, reporting that Swiss households achieved a 7.9 percent reduction in emissions by the end of the first Kyoto commitment period and an impressive 32.6 percent reduction by the end of the second period compared to 2008 levels (BAFU, 2022, p. 17). However, these production-based figures starkly contrast with the results of this study, which show that the total carbon footprints of Swiss households did not significantly decline between 2008 and 2019 (see Figure 1).

The emission analysis, conducted using a consumption-based approach, reveals several interesting dynamics in Switzerland's decarbonization efforts, which will be discussed in the following sections. However, the estimations first need to be contextualized.

The carbon footprint estimates presented in this study align broadly with existing research on emissions in Switzerland, while reflecting the specific scope and methodological choices applied. The total emissions attributed to private household consumption lie between Switzerland's production-based (territorial) and full consumption-based footprint figures reported by the Federal Office for the Environment and the Federal Statistical Office, respectively (see Figure 10). This positioning is consistent with the study's focus on private household expenditures only, excluding emissions from public consumption and capital investment.

Previous research suggest that private household consumption accounts for approximately 70–75 percent of Switzerland's total greenhouse gas emissions, while public services contribute around 5 percent and capital formation 20–25 percent (Frischknecht, Nathani, Stolz, Wyss, and Itten, 2015-09-25, p. 67; Nathani and Frischknecht, 2019, p. 27). Adjusting this study's estimates upward by a factor of 1/0.7 to approximate total consumption-based emissions places them close to official figures, reinforcing the credibility of the applied EE-MRIO methodology.

Figure 10: Comparison with official results




*Note:* The figure displays data from official sources: the total carbon footprint provided by the Federal Statistical Office (BFS), the total carbon footprint estimated by Nathani et al. (2022) on behalf of the Federal Office for the Environment, and the official national GHG inventory of Switzerland calculated by the Federal Office for the Environment (BAFU). The national inventory follows the production-based approach, whereas the other results presented apply the consumption-based approach.

The per capita estimates also compare well with prior research. Studies using various methods - including bottom-up expenditure modeling, life cycle analysis, and top-down input-output approaches - report the average per capita footprints for Switzerland in the range of 8.5 to 13 $tCO_2e$ (see e.g., Girod and De Haan, 2010; Jungbluth, Stucki, and Leuenberger, 2011; Froemelt, Dürrenmatt, and Hellweg, 2018; Froemelt et al., 2021; Bruderer Enzler and Diekmann, 2019). The 2019 estimate from this study, at 7.88 $tCO_2e$ per person, is at the lower end of the spectrum, reflecting the limited scope of private consumption. When scaled to represent 70 percent of the national footprint, the implied per capita emissions reach 11.25 $tCO_2e$, which aligns with the higher end of prior findings. This is consistent with those of Nathani and Frischknecht (2019), who demonstrate that EE-MRIO-based methods tend to generate higher footprint estimates than bottom-up or hybrid approaches, due to the more comprehensive inclusion of import-related emissions (pp. 24-28).

In light of the inherent uncertainty in the estimation, this contextualization provides a validation of the calculation. Furthermore, other previous findings could be replicated and reiterated for the Swiss case, substantiating the methodological approach taken.

The analysis of carbon footprints across the income distribution provides evidence of a persistent and robust correlation between income and emissions: higher-income households have larger carbon footprints; emissions rise less than proportionally with income; and carbon footprints have declined over time across all income groups, as exemplified by the downward shift in the EECs. This confirms the role of affluence as a key driver of emissions and suggests that the assumptions underlying the evaluation hold.

Contributing to the academic and political debate around climate change, the results of this study show that even though Switzerland fulfilled its international agreements by reducing domestic emissions, the corresponding carbon footprint stayed at a high level between 2008 and 2019. Since around 57 percent of all Swiss emissions originate abroad (Nathani et al., 2022, p. 102), it is not surprising that the two approaches diverge in their results and their developments over time.

On a macro-level, various effects can be distinguished when comparing the production-based and consumption-based approaches. On one side, population growth and economic development usually lead to increased environmental impacts, whereas technological efficiency gains generally decrease emissions. The differences between the Kyoto Protocol reports and this study suggest that Switzerland's domestic efficiency gains outweigh the population growth between 2008 and 2019, leading to a decrease in overall greenhouse gas emissions in the production-based approach (see Frischknecht et al., 2018, pp. 106-108). Analyzing the consumption-based approach, however, these domestic efficiency gains are offset by increased embedded trade emissions, resulting in only a marginally lower carbon footprint in the same period.

If the goal is to limit global warming to 1.5°C compared to pre-industrial levels and reduce the risk of climate change impacts, a mere shift of greenhouse gas emissions from domestic production to international supply chains does not serve its purpose. Despite a declining household carbon footprint per capita since 2013, current levels in Switzerland remain significantly above the thresholds necessary to stabilize GHG concentrations in the atmosphere. According to Kulionis et al. (2024), an annual Swiss emission level of approximately 1.3 $tCO_2e$ per capita would be necessary to remain within planetary boundaries and limit global warming (p. 27). Applying a 70 percent share of the burden falling on private household consumption implies a target of roughly 0.91 $tCO_2e$ per capita. Relative to the 2019 estimate of 7.88 $tCO_2e$, this would require substantial reductions of nearly 88 percent.

Even though these efforts currently seem out of reach, the results of the second Kyoto commitment period offer some reasons to be optimistic. The developments in Swiss household carbon footprints after 2013 point to a general reduction in emissions; a prominent emission peak is noticeable at the crossover of the commitment periods.

Several explanations could have led to the visible transition from an initially upward-trending household carbon footprint to a subsequent decline. First, the trend between 2008 and 2012 could include recovery effects following the global financial crisis and the Great Recession of 2007-2009. One indication of this is the previously decreasing trend in the FSO's official statistics, as shown in Figure 10: the total carbon footprint declined between 2006 and 2009 before increasing to previous levels. Therefore, the carbon footprint calculated based on household expenditure may follow general business cycles, rather than reflecting sustainable changes in consumption patterns. To substantiate this claim, however, additional analysis with a longer time series of carbon footprints would be necessary. On the contrary, there are arguments that the decreasing trend could persist beyond the studied period.

One possibility for the lower carbon footprint after 2013 could be the shift in public focus on climate change. Due to the accident at the Fukushima nuclear power plant in March of 2011, the Federal Council decided to phase out nuclear energy in Switzerland (BBl *2013* 7561). The $CO_2$ Act (SR 641.71) was revised in the same year, and measures to reach the climate goals were intensified. New strategic dialogues on the future of Swiss energy and the negotiation and ratification of the Paris Climate Accord followed shortly after (BBl *2018* 247). In a country where people are included in these decisions through direct-democratic processes[15], the confrontation with these topics and deliberation thereof could nudge people's attention and consumption patterns accordingly. The shift in focus is evident in the 'Worry Barometer', a yearly survey that reveals how the Swiss population feels about various issues. Whereas environmental protection and climate change were not at the forefront of Swiss people's minds during the first Kyoto commitment period, the concern increased substantially after 2016 (UBS, 2024, p. 13). Today, almost one-third of the Swiss population considers the environment a top issue (UBS, n.d.). This development could indicate that the decreasing trend is not just a business-cycle reflection but an ongoing transition in Swiss consumption patterns that started in 2013. These patterns can be reinforced when other major trading partners, such as Germany, advance environmental policy changes because of similar public sentiment.

[15] The Swiss electorate rejected the popular initiative "For a sustainable and resource-efficient economy" in 2016, they rejected the initiative "For an orderly withdrawal from the nuclear energy programme (Nuclear Withdrawal Initiative)" in the same year, they approved the revised Energy Act in 2017, and they rejected the revised $CO_2$ Act in 2021.

Another possibility for the continuing decrease could be attributed to the lagged effects of the policies introduced during the first Kyoto commitment period. The $CO_2$ tax, levied for the first time in 2008, has steadily increased ever since (BAFU, 2024, p. 2). Moreover, Switzerland institutionalized a federal and cantonal buildings program in 2010 that promotes energy-efficient renovations for homeowners to support the green transition (FOEN, 2020). Previous studies have shown that these policies have been effective (Ecoplan et al., 2015; Bundesrat, 2016). However, insulating homes or changing heating systems are infrequent consumption decisions, although they have a high impact on emissions. If policy changes take several years to materialize fully, it is possible to conceptualize the decrease in the second Kyoto commitment period as a lagged effect from policy choices made during the first period. The same logic suggests that the decline will continue after the second period, resulting from the policy choices made between 2013 and 2019.

The most striking result when comparing the first and second commitment period, however, is that the temporal developments are not only diverging between the periods but also across income groups, thereby increasing carbon inequality after 2013. Some authors attribute the rise in carbon inequality in other contexts to increases in income inequality (see Ivanova and Wood, 2020; Oswald, Owen, and Steinberger, 2020; Zheng et al., 2023). In Switzerland, however, income inequality has remained relatively stable over the past 20 years. Income shares of the top 10 percent, the top 1 percent, and quintile shares (S80/S20) fluctuated only slightly around their constant levels between 2008 and 2019 (Häner-Müller, Kalbermatter, Koch, and Schaltegger, 2024). Therefore, it is difficult to conclude that the increase in carbon inequality can be attributed to the rise in income inequality in Switzerland, mainly since the divergence is only observed in the second commitment period, but not in the first. Nevertheless, a more extended sample period and detailed research are needed to make a conclusive statement about the relationship between carbon inequality and income inequality in Switzerland.

If these reduction trends continue in a similar fashion, the gap between the rich and the poor in terms of their carbon footprint distribution will widen. From an economic perspective, this is not necessarily an issue. Focusing mitigation efforts on inexpensive, carbon-intensive products is more effective in maximizing the so-called 'bang for the buck'. Therefore, initial emission reductions might disproportionately target poorer households out of an efficiency argument. However, from a socio-political perspective, widening carbon inequality may become a problem when low-income households continue to contribute more to mitigation efforts, while high-income households resist adopting a low-emission lifestyle, especially since wealthy consumers have greater discretion to implement low-carbon technologies.

Overall, the target of climate policy in general should remain first to stabilize and, hopefully, reduce global greenhouse gas emissions in the long term. Otherwise, “adverse impacts and related losses and damages from climate change escalate with every increment of global warming” (IPCC, 2023, p. 14). This study highlights that Switzerland is currently profiting from the production-based approach of international agreements. The government has delivered progress over the past decades. However, taking responsibility for consumption-induced emissions would likely lead to changes in the current Swiss climate change agenda.

To minimize resistance to such policy changes needed to achieve the 1.5°C limit outlined in the Paris Climate Agreement, it is crucial to design equity-oriented climate policies. Carbon inequality as an indicator may help evaluate whether proposals disproportionately target certain income groups. The simple carbon tax simulation in this thesis has shown scenarios in which a carbon tax not only reduces emissions but also benefits the lowest income quintile when revenues from the tax are redistributed to households instead of being used to fund the general budget. With this ’tax and dividend’ scheme, the negative impact on households’ purchasing power can be counteracted, preventing social unrest such as the ’Yellow Vests’ protest in France (Douenne and Fabre, 2022, pp. 81-82). At the same time, the simulation revealed that carbon inequality would not increase; an outcome that could improve the perceived fairness of such a policy and potentially contribute to greater public support.

# 5 Conclusion

Gaining insights into different income groups' impact on the climate is essential to designing reasonable and sustainable climate policy. This study offers a first attempt at analyzing Swiss private households' carbon footprints with an EE-MRIO methodology, contributing to a deeper understanding of Switzerland's greenhouse gas emission trends and drivers.

By exploring carbon inequality and examining the dynamics between the first and second Kyoto commitment period, many findings from international studies could be substantiated for Switzerland. Reaffirming the importance of income as a key driver of household carbon emissions, a sectoral breakdown highlights three consumption categories with a significant emission share: food, housing, and transportation. Zooming in on transportation revealed a rising emission share along the income distribution and a diverging emission trend between the income groups. Building on these findings, a simulation of a carbon tax on transportation fuels suggests that a policy similar in design to the existing $CO_2$ levy could help address equity concerns, as it would not significantly increase carbon inequality - an aspect that may help mitigate, though not eliminate, political resistance.

To further support the results of this study, more in-depth research is necessary. On the one hand, the data quality as a basis for the analysis can be improved. By gaining access to and examining the confidential individual Household Budget Survey data from the FSO instead of the publicly available averages, it would be possible to include other socio-economic characteristics of Swiss households in the analysis and get a more nuanced picture of the carbon footprints. Furthermore, the study would not be restricted to income quintiles but could explore the entire income distribution. Nevertheless, some limitations would remain with the individual survey data as it apparently still contains numerous missing values, especially in the energy expenditure data, that must be dealt with (see Mutel et al., 2023). Another improvement could be made by consolidating expenditure data from the government and non-profit institutions, together with household consumption data, and including emissions from capital formation to obtain the extent of the total carbon footprint of Switzerland instead of focusing solely on private households.

There are plenty of future research opportunities that could potentially build on the results of this study. One strand would lead to exploring the reasons for the observed trends and movements of the Swiss household carbon footprints over time. Analyzing business cycle dynamics and their effects on carbon footprints, income inequality developments and their relation to carbon inequality trends, changing saving behaviors and associated economic uncertainty motives, shifts in the consumption baskets during the Kyoto commitment periods, or even technological changes and their impact on carbon footprint fluctuations could all contribute to a greater understanding of the consumption-based carbon-accounting framework and its usefulness in climate policy design.

Ultimately, this thesis - and future research - should inform and support policymakers in Switzerland and beyond in designing climate reforms that are grounded in evidence, economically sustainable, and responsive to equity concerns, contributing to more effective and inclusive climate action.

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# Appendix

## A. Additional Results

### A.1 Parametric Estimation of EECs

In chapter 3, the non-parametric visuals of the Swiss Environmental Engel Curves were presented. To substantiate these visual findings, Table A.1 shows the relationship between the carbon footprint and income with regression results. Three different functional forms are tested, similar to Isaksen and Narbel (2017, p. 157): a simple linear model with a linear income relationship, a quadratic income term, and a cubic income specification. The same data is used as depicted in Figure 3. Hence, the household size effect is already captured in the carbon footprint and not separately specified in the regression equation because of the already very limited number of observations.

The three functional forms are:

1. $y_i = \alpha + \beta x_i$
2. $y_i = \alpha + \beta x_i + \gamma x_i^2$
3. $y_i = \alpha + \beta x_i + \gamma x_i^2 + \delta x_i^3$

Whereas $y_i$ is the equivalized carbon footprint from private consumption for the average household of every income quintile in kg$CO_2$e, $x_i$ is the income for the same average household in thousand CHF.

Table A.1: EEC regression results

| Functional form | $\alpha$ | $\beta$ | $\gamma$ | $\delta$ | Adjusted $R^2$ | Observations |
|---|---|---|---|---|---|---|
| 1 | 6584.327*** | 97.920*** | | | 0.9963 | 5 (2008) |
| 1 | 5866.893*** | 80.156*** | | | 0.9849 | 5 (2019) |
| 2 | 5695.356** | 124.286** | -0.163 | | 0.9987 | 5 (2008) |
| 2 | 4187.097*** | 127.63*** | -0.275** | | 0.9999 | 5 (2019) |
| 3 | 7218.124 | 47.701 | 0.978 | -0.005 | 0.999 | 5 (2008) |
| 3 | 3819.597* | 145.49* | -0.528 | 0.001 | 1 | 5 (2019) |

*Note:* $(*)\ p < 0.05$ ; $(**)\ p < 0.01$ ; $(***)\ p < 0.001$ .

The regression reveals a $\beta$ coefficient between 80 and 98 when estimating a linear functional form. Increasing the household income by 1,000 CHF per year will generate an additional 80kg of $CO_2e$ emissions ceteris paribus. Adding a quadratic term to the regression equation, the $\beta$ coefficient rises, the $\gamma$ coefficient is negative, and $R^2$ increases compared to the linear form. It still shows emissions to increase with household income; however, less than proportionally. These results coincide with the visual descriptive EECs in Figure 3. Whereas the EEC of 2008 is depicted almost as a straight line, the EEC of 2019 shows its concavity. Unsurprisingly, the linear model (1) seems to fit the EEC of 2008 better, and the model (2) seems more appropriate for the EEC of 2019.

Further adding a cubic income term loses the significance of the results, and even the signs change in unexpected directions. Therefore, the cubic fit seems unrealistic. The short regression overview suggests that the quadratic form is the best fit, at least for the 2019 EEC, supporting previous research that used quadratic estimations (Weber and Matthews, 2008; Ivanova et al., 2017; Sager, 2019).

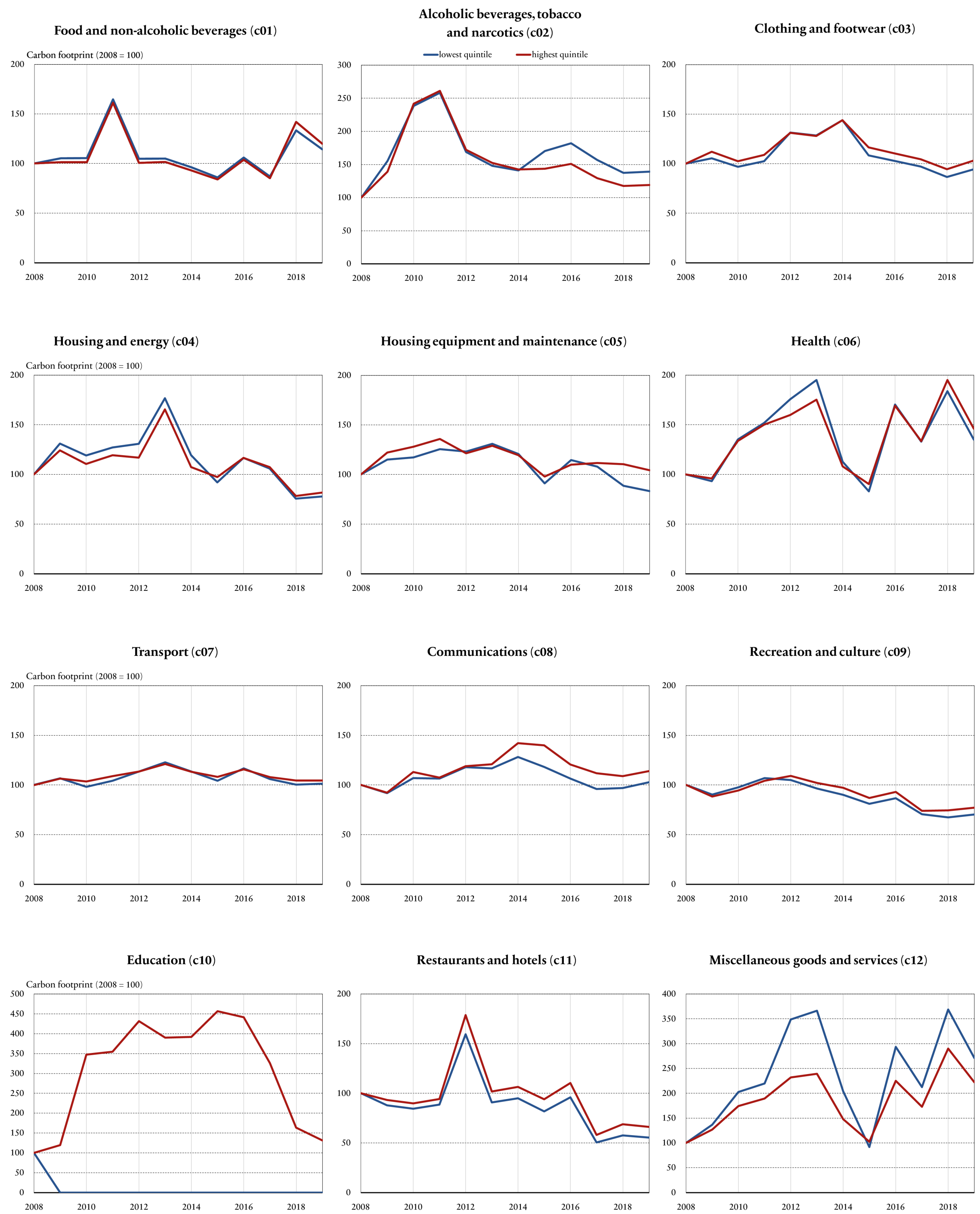
Of course, there are many limitations to the descriptive EEC and the regression analysis. First, essential predictors have been omitted due to data limitations. Even though income has the highest explanatory power for household carbon footprints (see, e.g., Ivanova et al., 2017, p. 8), other important variables could not be included, such as the educational background of the household members, dwelling size, or the age of the household head. Including these additional covariates would undoubtedly lead to more precise point estimates in the regression. Further controlling for time-invariant household-specific effects would most likely lead to flatter and more linear EECs (Wöhrmüller, 2023, p. 15). However, the general trends should still hold, as indicated by Sager's (2019) research.

The second and even more significant limitation concerns the number of observations. The descriptive EECs and the regressions rest only on an average observation for each quintile of the income distribution. Therefore, the results should be interpreted cautiously and not at face value. Nevertheless, the descriptive EECs, together with the regression estimations, seem to confirm the three stylized facts established by Levinson and O'Brien (2019) and Sager (2019) also for Switzerland: EECs are increasing ($\beta$ is positive), concave ($\gamma$ is negative), and shift down over time ($\alpha$ is smaller in 2019 than in 2008).

### A.2 Indexed Carbon Footprints

In chapter 3, the indexed equivalized carbon footprints for the COICOP categories food, housing and energy, and transport were presented. Figure A.1 completes the overview with all 12 COICOP categories.

Figure A.1: Indexed developments of the carbon footprint for all 12 COICOP categories




*Note:* The equivalized total private household carbon footprints for every income quintile and category were indexed to 100 for the year 2008. The blue line represents the carbon footprint of the lowest income quintile and the red line depicts the carbon footprint of the highest income quintile. For education (c10), the lowest income group either did not report private spending in the HBS or data was unavailable, resulting in an index of zero for 2009-2019.

## B. Processing of HBS Data

As mentioned in section 2 of the main body, the Swiss HBS data required some pre-processing steps before it was bridged to the MRIO database. The following paragraphs outline these steps and justify their necessity:

### B.1 HBS Categories

Generally, all four-digit HBS categories were considered if they have a corresponding COICOP 1999 class category. Only categories of the COICOP division 01-12 were used, as division 13 includes individual consumption expenditure of non-profit institutions serving households (NPISHs), and division 14 entails individual consumption expenditure of general government. For the COICOP categories of interest, this study selected the 117 categories provided by Richard Wood and available on the EXIOBASE webpage (see dataset references). Applying a classification strategy used for the original EXIOBASE dataset seemed reasonable. To bridge the HBS to the COICOP classification, this study closely followed the procedure applied by Froemelt et al. (2018) and Froemelt et al. (2021). Their research on carbon flows in Switzerland already linked the HBS codes to the COICOP codes (see Supporting Information in Froemelt et al., 2021).

The details of the HBS categories and their corresponding COICOP classification is provided in the Appendix section D. However, specific categories need to be explicitly highlighted:

- COICOP categories c02.3.0 Narcotics, c04.2.1 Imputed rentals of owner-occupiers, c04.2.2 Other imputed rentals, c07.1.3 Animal drawn vehicles, c09.2.2 Musical instruments and major durables for indoor recreation, c12.2.0 Prostitution, c12.6.1 FISIM:
  The Swiss Federal Statistical Office does not gather household expenditure data for these categories. Thus, the HBS has no information available that could be used for this study.
- The Swiss HBS makes several lower-level distinctions that are subsumed in one higher-level COICOP category. For example, the HBS distinguishes where external meals are consumed (5311 Restaurants, Cafés and Bars, 5312 Take-away, 5314 Private). However, COICOP subsumes these categories to c11.1.1 Restaurants, cafés, and the like. Thus, these HBS categories are combined. Another example involves the COICOP categories c03.1.2 Garments and c03.2.1 Shoes and other footwear. The Swiss HBS distinguishes between men's, women's, and children's clothing. However, the COICOP categorization does not separate them. Therefore, these categories were combined into the COIOP category Garments and Shoes, respectively. Whenever aggregation was possible and reasonable, it was adhered to.

- HBS category 5810 furniture:
  Most categories were classified as pertaining to COICOP c05.1.1 Furniture and furnishings, except 5810.05, which belongs to COICOP c05.1.2 Carpets and other floor coverings.
- COICOP categories concerning repairs:
  Some COICOP categories deal with the repair of goods (c05.1.3 Repair of furniture, furnishings and floor coverings, c05.3.3 Repair of household appliances, c09.1.5 Repair of audio-visual, photographic and information processing equipment, c09.2.3 Maintenance and repair of other major durables for recreation and culture). The HBS expenditure data, however, includes the costs of repairs in the specific category of the good itself and usually does not state the repair costs separately. Therefore, these COICOP categories are not used in the present study. However, Froemelt et al. (2021, SI2) use these categories by splitting the acquisition and repair costs. As they do not specify any details on the splitting process, I do not attempt to follow their recommendation. The same holds true for other categories where they split expenditures (such as 6110.01 medicine, or 5711 rent). Whenever their split is not described in detail, I avoid assuming arbitrary category shares.
- HBS categories 583 household and kitchen appliances:
  5831.01 and 5831.02 were combined to c05.3.1 Major household appliances whether electric or not.
- HBS categories 612 medical services:
  6120.03 and 6120.05 were combined to c06.2.3 Paramedical services.
- HBS category 670 education:
  Whereas COICOP distinguishes five expense categories relating to education, the Swiss HBS only records four categories. The breakdown into the 5 COICOP education categories is based on the International Standard Classification of Education (ISCED) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) (see UNSD, 2018, pp. 156-159). To mitigate these differences, the Swiss ISCED categories 0-2 were combined into c10.1.0 pre-primary and primary education (officially ISCED 0 and 1), and the Swiss ISCED category three was classified as c10.2.0 secondary education (officially ISCED 2 and 3). The same approach was taken in Zheng et al. (2023). In line with Zheng et al. (2023), this study does not consider the COICOP category c10.3.0 post-secondary non-tertiary education for the HBS education category. This is contrary to Froemelt et al. (2021, SI2), who split parts of the continuing education courses (6700.4) and attributed the expenses to post-secondary non-tertiary edu-

cation. However, I refrain from following the same approach as the splitting process is again unspecified.

- HBS category 6811 appliances, articles, and products for personal care:
  Most categories were classified as pertaining to COICOP c12.1.3 Other appliances, articles, and products for personal care, except 6811.01, which belongs to COICOP c12.1.2 Electric appliances for personal care.

- HBS categories 6820 personal effects:
  6820.02 and 6820.03 were combined to c12.3.2 Other personal effects.

- HBS category 4410 charities:
  There is no COICOP category for charitable donations and other contributions since it does not constitute a household expenditure per se but rather a transfer to non-profit organizations whose expenses are not considered as part of this study.

- HBS category 30 mandatory transfers, 35 monetary transfers to other households, and 43 fees:
  In general, transfers are not part of the COICOP categorization because they do not directly express the consumption expenses of the household in question. For example, social security payments are registered as consumption expenditures (food, housing, etc.) for retired people and thus shall not be counted twice in the aggregate. Alternatively, income tax payments will lead to government consumption, which is not within the scope of this study. Furthermore, COICOP specifies several insurance categories, such as health and life insurance. Froemelt et al. (2021, SI2) included insurance categories in their study. Nevertheless, as stated by the UN (2000, p. 111), only service charges for insurance shall apply to the COICOP categorization. Yet, in household budget surveys, it is impractical to ask households about their expenditure on insurance service charges as would be required by COICOP (UNSD, 2000, p. 18). Therefore, the CES usually states the insurance premium expenses and neglects the insurance claim offsets and other inputs needed to calculate the actual service charges. This also holds true for the Swiss HBS. Hence, in contrast to Froemelt et al. (2021), this study focuses on actual consumption expenditures as defined by the Swiss HBS ('50: Konsumausgaben') and does not include any other categories such as transfers or insurance.

- HBS category 442 gifts and invitations:
  Gifts and invitations are handled similarly to donations. They are recorded as transfers in the System of National Accounts (SNA) and are, therefore, out of the scope of COICOP categories (UNSD, 2018, p. 15).

Further assumptions had to be made to classify specific HBS categories accordingly. These exceptional cases are described in the following:

### B.2 Utility Costs ('Nebenkosten')

Switzerland is a country of renters. More than half of Swiss households do not own their house or apartment (see BFS, n.d.-c). Many tenants cannot access a detailed breakdown of their utility costs, but pay a lump sum (called 'Nebenkosten pauschal' in German). They only know their aggregated utility costs, and details of specific expenses are hidden. The Swiss HBS recognizes a separate category for these lump sum payments, namely 'Nebenkosten pauschal' (5712.01). However, to make use of the information that comprises expenditures for water supply, sewage collection, heating costs, and maintenance costs, the expenses in the utility lump sum category were split according to their respective shares in the total utility costs (5712 utility costs for primary residence) of those households that can report explicitly. This approach is modeled after the steps taken by Froemelt et al. (2018, SI pp. 5-6). They also highlight that the refuse collection costs are not part of the utility lump sum in Switzerland. Therefore, these costs were not a factor in this study's distribution of the utility lump sum.

For the distribution of utility costs for secondary residences, see the approach taken below.

### B.3 Energy Costs

The Swiss HBS reveals three categories of energy costs: electricity (5713.01), gas and other fuels (5713.02), and centralized heating (5713.03). Even though the costs are known, the energy carrier used by the household's heating system is not specified in the HBS. Following the approach in Froemelt et al. (2018, SI p. 13), an average Swiss energy mix is assumed to convert the expenses in the categories gas and other fuels to their corresponding COICOP categories: c04.5.2 Gas, c04.5.3 Liquid fuels, and c04.5.4 Solid fuels. These conversions take into account the particular year of the HBS. The shares in the final energy consumption of households were calculated by consulting the statistics on the final energy consumption ('Gesamtenergiestatistik') of households in Switzerland (see dataset references). The overall energy statistics encompass all forms of energy households use in a particular year, including information on coal, district heating, and renewable energy sources. However, for this study, only the major household energy carriers, heating oil, gas, and wood, were considered (as in Froemelt et al., 2018, p. 13). Since electricity has a separate category in the HBS, the information regarding electricity use from the energy statistics was disregarded. Furthermore, the other energy sources in the statistics on final energy consumption only constituted a minor share of total energy consumption (e.g., coal with 0.1 percent on average) and were thus omitted from the calculation. In the first step, the shares of the primary energy carriers were calculated for each year based on the energy statistics. Then, the expenses of the category 'Gas und andere Brennstoffe' were distributed according to these shares to the COICOP categories: gas, liquid fuels, and solid fuels. The energy statistic does not provide information on the distribution of energy consumption shares across income groups. Low-income households may use more of one energy carrier than high-income households. However, since no data is available on the income distribution of household energy shares, especially over time, the same share was assumed across all income groups.

### B.4 Secondary Residence

Another peculiarity of the Swiss HBS is the categories for secondary residences. It is common for Swiss people to own or rent a secondary residence, for example, for skiing in the winter months, so assessing these expenses in the HBS is reasonable. Unfortunately, the HBS does not provide details of these expenditures but aggregates them into the categories of rent (5721), utilities (5722), and energy (5723). Following Froemelt et al. (2018, p. 53), the costs of these categories for secondary residences are proportionally distributed to their corresponding primary home category.

### B.5 Transport Fuels

Even though COICOP only has one category for fuels for personal transportation (c07.2.2), the Swiss HBS categories for gasoline (6215.01), diesel (6215.02), and lubricants and other products for vehicles (6215.03) are used to extract their relative shares of the total COICOP category for further analysis. Since gasoline and diesel are important drivers of direct emissions, it is essential to use more precise and separated data to calculate the direct carbon footprint of Swiss households instead of their aggregate.

### B.6 Total Household Expenses

After the pre-processing steps outlined above, the HBS expenditure data is distributed to the corresponding COICOP category according to the correspondence overview (see Appendix section D for detailed categorization) and multiplied by 12 to have yearly expenses instead of monthly expenses. At this point, the dataset consists of average triennial expenditure for the average household in each income quintile and COICOP category (a 117x5 matrix for each three-year period). These expenses must be scaled up to calculate the carbon footprint of all Swiss households and not only the average household of each income quintile. One possible approach would be to keep the proportionality within each COICOP division (structure level 1) and between the income groups of the average households and scale up the household expenses to match the final consumption expenses of private households according to the Swiss System of National Accounts (SNA) for each year. This scaling method was applied by Zheng et al. (2023). However, there are important differences between the HBS consumption expenditure data and the consumption expenditure recorded in the SNA. Whereas the survey tends to underestimate some consumption categories such as alcohol, tobacco, or drugs (see also section C.3 in the Appendix), or does not take into account specific households like people living in elderly care homes or prisons, the SNA adds certain expenses to private household consumption for conceptual reasons, which are not evaluated in the HBS. These differences are especially prominent in housing (by estimating the imputed rents of homeowners), financial services (such as including all types of insurances), the health sector (estimating the households' consumption of goods and services provided by hospitals or doctors' offices even though insurance companies or the government pays them), and the education sector (mainly provided by the local, regional and federal government). Therefore, by simply scaling up the average household's expenses to the totals provided by the SNA, these conceptual differences bias the results to a great extent, mainly in the above-mentioned consumption categories. For example, the expense share in the consumption category on health in 2018-2019 is 16 percent, as stated in the SNA, whereas it only amounts to 4 percent in the HBS (see SNA and HBS datasets in the data references). By scaling up, the corresponding carbon footprint in the health category reaches a level comparable with the carbon footprint in the food and beverages category, which is a highly implausible result stemming from the bias in the scaling method. In a private inquiry to the Federal Statistical Office, they concurred that the estimation of the final consumption of private households in the SNA cannot be simply extrapolated from the survey data but must be adjusted appropriately to ensure macroeconomic coherence. However, since they did not share the adjustment methods, this study used a different approach. Instead of scaling up the average household expenses to match the official SNA data perfectly, the average household expenses were multiplied by the number of private households registered by the Swiss Population and Household Statistics (STATPOP) of the Federal Statistical Office. Official statistics are provided from 2012 onwards (see data references). The missing values were linearly extrapolated back to 2008 (see population and household values in the Appendix section D).

With the approach of multiplying the average household expense by the number of actual households, the total household expense data used in this study stays close to the original values estimated by the Swiss Household Budget Survey. This has several implications for the interpretation of the household carbon footprints: first, only carbon footprints from people living in private households are estimated. The estimation neglects carbon footprints from people living in assisted care facilities, people imprisoned, undocumented people not appearing in the official statistics, or people living in what the FSO defines as 'implausible households'. These households do not meet one of the five quality criteria of the FSO to be classified as a household. These criteria include, for example, a household with more than 12 people or a household where only minors live (see footnote in original dataset). Overall, this distinction leads to excluding about 2 percent of the permanent residents in Switzerland from the study, likely underestimating the total carbon footprint of Switzerland. Nevertheless, with this approach, the study stays consistent with the HBS data, as the expenses of these people do not form part of the HBS in the first place. Second, only direct spending that is traceable to a specific household is considered in this study. By not using SNA consumption data, governmental expenses benefiting households are not attributed to them directly, leading to an underestimation of household expenses vis-à-vis the SNA and, therefore, an underestimation of the total carbon footprint, especially the impacts in categories such as health or education. In this case, Froemelt et al. (2018) concur by highlighting that "only environmental impacts directly associated with a certain household's behavior were considered" (p. 8470). The estimated carbon footprint in this study can thus be thought of as the impact households have direct control over with their spending decisions.

Finally, in preparation for bridging the CES data with the MRIO database, the expenditures had to be converted to Euros instead of Swiss Francs because the information in the MRIO dataset is based on Euros. Therefore, the CES data was converted to Euros using the yearly average CHF/EUR exchange rate provided by the Swiss National Bank and used by the Federal Tax Administration (see data references).

### B.7 Final CES dataset

The final dataset consists of yearly total Swiss household expenses for each income quintile according to the COICOP categorization. When COICOP categories with zero aggregate expenses are removed (see categorization details in the Appendix section D), the dataset consists of a 105x5 matrix for each year between 2008 and 2019.

## C. Linking CES Data and EXIOBASE

As mentioned in section 2 of the main body, CES data has to be linked to the EXIOBASE database. In general, coupling HBS-consumption categories with EXIOBASE followed the approach outlined in Steen-Olsen et al. (2016). However, some deviations applied, which are addressed in the following:

### C.1 Time Series

Steen-Olsen et al. (2016) worked with a previous version of EXIOBASE v2, whose IOTs were based on 2007 prices. Therefore, they had to convert the CES purchase data to 2007 prices. However, the newest EXIOBASE version does not have a base year but states IOTs in current prices. Therefore, it was not necessary to apply price conversions in this study.

### C.2 Classification Schemes

Whereas Swiss HBS data was compiled in the COICOP classification, EXIOBASE works with 200 product categories based on the International Standard Industrial Classification of All Economic Activities (ISIC) from the United Nations Statistics Division. This study used a concordance matrix generously provided by Lea Fricke and the SIAW-HSG team at the University of St.Gallen to match CES consumption vectors to the IO system. The provided concordance matrix was augmented by the concordance matrix of EXIOBASE (see dataset references) for a small number of missing COICOP categories. The final concordance matrix is attached in the Appendix section D.

Because the relation between COICOP and EXIOBASE is generally many-to-many, the RAS-based method was used "to cope with the problem that one CES category corresponds to two or more EXIOBASE product categories" (Zheng et al., 2023, p. 3). The RAS balancing is described in more detail by Oswald et al. (2020) and Miller & Blair (2009). With the help of the concordance matrix, the two classification schemes could be harmonized.

### C.3 Underreporting

Underreporting is a well-known issue when matching CES data to other datasets. In general, underreporting might be attributable to factors such as recall bias, non-responses, or imputation errors and is typically biased toward certain goods and services (Hardadi et al., 2021, p. 97). Some goods and services (e.g., narcotics or prostitution) were not even reported in the Swiss HBS. Usually, this results in a discrepancy between the CES dataset and the household demand in the System of National Accounts (Hardadi et al., 2021, p. 97). This difference can partially be explained by underreporting but also by the conceptual differences between the two datasets (see the explanations in section B.6 of the Appendix). To compare the two datasets, average coverage rates of each consumption category are presented in Table A.2. Coverage rates are calculated as the percentage ratio between the HBS aggregated data and the SNA data adjusted to the reference population of the HBS (Eurostat, 2018).

Table A.2: Coverage rates of household consumption

| Consumption Category | Average Coverage Rate | Standard Deviation |
|---|---|---|
| Food and non-alcoholic beverages (01) | 91.7% | 2.6 |
| Alcoholic beverages, tobacco, and narcotics (02) | 34.5% | 0.8 |
| Clothing and footwear (03) | 98.4% | 8.5 |
| Housing and energy (04) | 77.5% | 3.1 |
| Household equipment and maintenance (05) | 84.5% | 9.7 |
| Health (06) | 21.9% | 3.7 |
| Transport (07) | 93.3% | 3.6 |
| Communications (08) | 96.0% | 3.1 |
| Recreation and culture (09) | 93.0% | 3.3 |
| Education (10) | 59.5% | 3.7 |
| Restaurants and hotels (11) | 77.3% | 2.9 |
| Miscellaneous goods and services (12) | 168.7% | 9.4 |

*Note:* Coverage rates of household consumption (averages of 2008-2019) between the micro (HBS) and macro (SNA) approach. The coverage rate in the consumption category 12 still includes expenses on insurance payments.

Various consumption categories show coverage rates between 90 percent and 100 percent. These are of no particular concern. As a point of comparison, the data gap for total household consumption in European Statistics is 27 percent on average (Eurostat, 2018). However, other categories have coverage rates well below 90 percent. Eurostat attributes data gaps in restaurant and hotel consumption to conceptual differences between the SNA and the HBS (2018). Microdata collected in the HBS does not cover non-resident consumption in Switzerland. Assuming large numbers of cross-border commuters and tourists, non-resident consumption is included in the SNA; however, it is largely missing from the HBS, contributing to a lower coverage ratio. On the other hand, education, health, and housing categories are necessarily lower as the HBS does not include household consumption expenditure provided by the government or non-profit institutions (see discussion in section B.6 of the Appendix). Furthermore, the data gap in the category alcoholic beverages, tobacco, and narcotics is likely due to a behavioral bias. Survey respondents will underestimate their expenses on so-called demerit goods, negating or ignoring the damaging effects of the consumption of these products (Steen-Olsen et al., 2016, p. 585). To mitigate, at least to a certain degree, the measurement errors in COICOP category 2, this study doubles all household expenses in this category, including consumption expenses of wine, beer, and tobacco. With this approach, the coverage rate of alcoholic beverages and tobacco gets closer to the coverage rate of restaurant consumption, which is more plausible. Lastly, by including various insurance premiums in the HBS, the miscellaneous goods and services consumption category overshoots the SNA by more than two-thirds. This led to the decision against previous approaches (e.g., Froemelt et al., 2018) and disregarding insurance premiums from the analysis (see also discussion in section B.1 of the Appendix).

Underreporting vis-à-vis the SNA is an issue in this study. However, instead of trying to match the SNA with scaling approaches like Zheng et al. (2023), leading to large distortions between the categories, or using proportional gap allocation methods as suggested by Eurostat (2018), I mostly stick with the expenses estimated by the Swiss Household Budget Survey. The implications are that the household carbon footprints are likely underestimated and only encompass the environmental impacts of private household behaviors. Therefore, the results of this study can be interpreted as lower-bound carbon footprints. Nevertheless, the underestimation is conceptually similar for all years under investigation, which should lead to informative insights regarding household carbon footprint developments over time.

Furthermore, there is a difference between the SNA data and the final demand assumed in EXIOBASE. The EXIOBASE 3 consumption data is around 4 percent higher than attributed in the Swiss SNA. This difference occurs in all years under observation; therefore, I assume that the gap between the SNA and EXIOBASE SUT relates to the fact that EXIOBASE might attribute additional spending positions to households not included in the SNA. To mitigate this difference, the Swiss HBS household demand was set as the benchmark for the CES-EXIOBASE concordance matrix. Using the RAS method, the aggregated CES data aligned with the EXIOBASE classification and remained equal to the original demand instead of converting to the higher household demand in EXIOBASE. Therefore, the demand assumed in EXIOBASE was disregarded for the benefit of keeping the official HBS data reported by the Federal Statistical Office of Switzerland.

### C.4 Purchasers' Prices and Basic Prices

HBS data relates to purchases made by consumers. Therefore, the expenses are recorded in purchasers' prices. However, standard IOTs record trade and transport margins as well as taxes on products separately and only state product expenses in their basic prices. Before conducting an IOA analysis, CES consumption data must be converted from purchasers' prices to basic prices. Fortunately, EXIOBASE includes consumption values in purchasers' prices and provides their breakdown in the basic price, taxes, and margin components (Steen-Olsen et al., 2016, p. 586). Thus, the Swiss HBS data can easily be converted from purchasers' prices to basic prices using the information provided by EXIOBASE. Furthermore, the retail and wholesale trade margin payments were redistributed to the corresponding consumption categories.

### C.5 Imports

In the Swiss HBS, only the total amount of each good or service is recorded. It is unclear from the HBS data what part of these goods were imported or produced locally. However, when produced in different countries, the same products can have vastly different embodied emissions. Therefore, it is essential to estimate the share of household imports and include them in the analysis (Steen-Olsen et al., 2016, p. 586). Using the information provided by EXIOBASE, namely the household purchases of all 200 products from all 49 regions, the direct import shares can be estimated explicitly, and the CES data can be split into 9800 region-products based on their regional shares. This ensures the correct association of amounts to the origins of all consumed products.

### C.6 Direct Household Emissions

Most of a household's carbon footprint is embodied in the goods and services it purchases and consumes. However, there is also a non-negligible part consisting of direct emissions by households that are not modeled in IO systems (Steen-Olsen et al., 2016, p. 585). These emissions have to be calculated and added separately. Secondary sources and the amounts allocated to the respective sectors and households must be considered for direct emissions analysis.

This study uses emission coefficients compiled from different sources to calculate the direct emissions. As mentioned in the main body, direct emissions categories include gas (natural gas), liquid fuels (heating oil), solid fuels (wood), and gasoline (petrol, diesel). Therefore, emission coefficients for these categories had to be computed. Following the logic of Felder and Schleiniger (2002, p. 522) in their general equilibrium model on Swiss $CO_2$ policy, this study determines the emissions embodied in one Euro for every fuel category. These coefficients change year by year as the respective unit prices vary, even though the emission factors ($tCO_2/TJ$) stay relatively constant.

Table A.3 provides the ranges of the emission coefficients for the direct emission categories in the years under investigation (2008-2019). The respective direct emissions were calculated as described in the methodology section of the main text.

Table A.3: Direct emission coefficients

| Fuel type | $CO_2$ emission factor ($tCO_2/TJ$) | Emission coefficient ($kgCO_2/EUR$) |
|---|---|---|
| Gasoline | 73.8 | 1.543 – 2.3171 |
| Diesel | 73.3 | 1.6338 – 2.4279 |
| Heating Oil | 73.7 | 3.0773 – 5.4036 |
| Natural Gas | 56.2 – 56.6 | 2.2058 – 3.6732 |
| Wood | 99.9 | 3.9802 – 6.2324 |

*Note:* For a detailed overview of the calculations and the various sources, see the time series (1990–2022) of the derivation of fuels' $CO_2$ contents in the Appendix section D.

## D. Supporting Information

The supporting information provides additional material to complement the main text and the appendix of this thesis. The documents contain the code used for the carbon footprint estimation and detailed calculations of the carbon tax simulation, among other things.

The supporting information can be accessed through this link 'Supporting Information' with the passcode 'Thesis2025-PMG'.

The data will also be provided when writing directly to philippe.guettinger@hsgalumni.ch.

The supporting information contains the following documents:

- Python Code for the HBS Preparation
- Python Code for the EXIOBASE Preparation
- Python Code containing Own Functions
- Python Code for the Carbon Footprint Estimations
- Categorization of HBS Expenses to COICOP Structure
- Concordance Matrix HBS-COICOP
- Concordance Matrix COICOP-ISIC
- Carbon Footprint Estimation Results
- Tax Scenario Calculations I (Effects on Emissions)
- Tax Scenario Calculations II (Effects on Expenses)
- Gini Calculations
- Direct Emission Coefficients
- Swiss Private Household Information
- Official Currency Exchange Rates
- HBS Datasets used in the Estimation

## List of Aids

This list of aids serves to show the digital tools that were used in connection with the thesis. Content (e.g. text, images, data) that was created by an AI tool and used for this work is correctly cited at the relevant point in the text in accordance with current citation standards.

| Tool / Aid | Intended Use |
|---|---|
| DeepL Translator (Free Version) | Translation |
| ChatGPT (Free Version) | Explanation and support for coding with R and Python; support with the layout of the thesis in Overleaf; reformulating sentences |
| NotebookLM (Free version) | Providing summaries of research paper |
| Overleaf (Premium) | LaTeX text editor for the thesis |
| Spyder (Anaconda) | Python Integrated Development Environment |
| R Studio | Support with preparing the data foundations for the figures and tables |
| Grammarly (Premium) | Typing assistant to review spelling, grammar, punctuation, clarity, engagement, and delivery mistakes in English |