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CASE STUDY

Regional carbon footprints of households: a German case study

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Abstract Households are either directly or indirectly responsible for the highest share of global anthropogenic greenhouse gas emissions. Hence, programs helping to improve human consumption habits have been identified as a comparatively cost-effective way to reduce household emissions significantly. Recently, various studies have determined strong regional differences in household carbon footprints, yet a case study for Germany has not been conducted. Local information and policies directed at household consumption in Germany thus devoid of any foundation. In this paper, we analyze the impact of different criteria such as location, income and size on household carbon footprints in Germany and demonstrate how the impact of GHG mitigation opportunities varies for different population segments. We use a multi-region input output hybrid LCA approach to developing a regionalized household carbon footprint calculator for Germany that considers 16 sub-national regions, 15 different household sizes, and eight different income and age categories. The model reveals substantial regional differences in magnitude and composition of household carbon footprints, essentially influenced by two criteria: income and size. The highest income household is found to emit 4.25 times as much CO_2e than the lowest. We identify indirect emissions from consumption as the largest share of household carbon footprints, although this is subject to fluctuation based on household type. Due primarily to local differences in vehicle availability, income and nutrition, an average household in Baden-Wuerttemberg is found to have 25 % higher carbon footprint than its

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Mecklenburg-West Pomeranian counterpart. Based on the results of this study, we discuss policy options for household carbon mitigation in Germany.

Keywords Carbon footprint · Household consumption · De-carbonization · Mitigation policies

1 Introduction

Carbon footprinting has attained increasing attention as a tool for decision making at national, regional and local scales; however, emissions must be reduced dramatically to accomplish the internationally agreed upon goal of keeping global warming to a maximum of 2 °C. The German Federal Environmental Agency (UBA) suggests a compatible level of 2.5 tons CO_2e emissions per year per capita (Umweltbundesamt 2012a). Assuming the global annual per capita average of 6.8 tons CO_2e, emissions have to be reduced by more than 60 % (Umweltbundesamt 2012a).

Many studies have quantified the greenhouse gas emissions of products and organizations and supply chains from a production-based view, e.g., Finkbeiner et al. 2006, Chester and Horvath 2011. Consumption-based analysis, however, is currently subject to increased attention (Finkbeiner 2009). Consumption-based emission accounting will not be able to replace production-based techniques, but may offer complementary information in order to introduce effective policies that would not have been adopted from a production view (Barrett et al. 2013).

Early studies aiming to identify the climate impact of households and communities have rarely identified examples of locally applicable green policies due to the limitations of focusing on national-level information. Indirect household-related energy requirements and emissions are currently absent from the scope of policy makers (Lenzen et al. 2004). Thus, Barret et al. identify a broad need for policy options adapted from consumption-based GHG accounting (Barrett et al. 2013). Programs helping to improve human consumption habits, e.g., improving diets or reducing material consumption, may represent a comparatively cost-effective way to reduce household emissions significantly (Barrett et al. 2013). Various studies have specified psychological and political as well as economic aspects of behavior change, e.g., via social marketing approaches (Bullard 1975; Andreasen 1994; Steg and Vlek 2009; McKenzie-Mohr 2011). For the USA, Dietz et al. (2009) have pictured a path to reduce national emissions by more than 7 % with the help of behavioral change programs for households and communities. Other studies come to similar results (Laitner et al. 2009).

Hertwich and Peters proved that magnitude and composition of carbon footprints (CF) of nations vary significantly with the state of a country's development (Hertwich and Peters 2009). Jones and Kammen (2011) identified considerable regional differences of household carbon footprints (HCF) within the USA and pictured a path to cost-effectively reduce emissions by applying marginal abatement cost curves for different population segments. Although regional differences in household and per capita CF have been identified by a number of other studies (Hertwich and Peters 2009; Jones and Kammen 2011; Minx et al. 2013), the empirical evidence on driving characteristics, e.g., socioeconomic and geographic aspects, of HCF is still limited. While agreement exists that household size reduces per capita CF due to increased sharing of resources, population density remains subject to discussion. Using a hybrid modeling approach for the UK, Minx et al. (2013) revealed that population density reduces emissions, while Jones and Kammen, as well as Finland Heionen and Junnila (2011), describe the connection as non-existent. Agreement also prevails that income is the main driver of HCF due to increased travelling and consumption. Aamaas et al. (2013) have shown that the climate impact of travel behavior from the highest income group in Germany is about 250 % higher than from the lowest income group.

Although accounting methods of CF have become increasingly sophisticated, a case study considering the entire household consumption in Germany has not yet been conducted. In this study, we use a multi-region input–output hybrid LCA approach to developing a regionalized HCF calculator for 578 different household types. We use data from an existing national-level GHG calculator and apply lifestyle data, e.g., expenditure and equipment, at the local level. The model includes direct and indirect emissions embodied in transportation, housing, food, goods and services. However, cost-effective emission reductions may be subject to the rebound effect (Greening et al. 2000; Sorrell and Dimitropoulos 2008; Berkhout et al. 2000; Birol and Keppler 2000; Hertwich 2005). An economy depends on consumption. Decision makers thus seek a robust approach to effectively reducing emissions while maintaining household consumption. The purpose of this study is to quantify the impact of different characteristics of HCF for the case of Germany. After introducing the methodology, we present results and discuss implications for future policy responses based on related literature.

2 Data and methodology

Considering various definitions found in the literature (Finkbeiner 2007, 2009; Wiedmann and Minx 2007) and based on the technical specification ISO/TS 14067:2013, a carbon footprint is understood as a tool to measure the global warming potential (GWP) of different greenhouse gases based on the consumption and equipment of various household types by using a macro-economic approach. Preferably, every sector of an economy shall be examined via multi-region input–output modeling from ‘cradle to consumer.’

2.1 Methodology

The HCF model allocates the global warming potential (GWP) of all relevant GHGs to either monetary or physical consumption categories via concordance tables. Two end users of products are assumed in the following: households and governments. Intermediate sectors are assumed to serve to the production process of goods and services finally consumed by end users. These sector emissions are allocated to the two end-user groups. Two studies serve as sources to quantify household consumption:

1. Income and expenditure control sample (EVS) 2008, published by the German Federal Statistical Bureau (2008a, b, c, d);
2. National food consumption study 2005 and 2006 (NVS), published by the Max Rubner Institute (2008a, b).

Emissions are based on the EUREAPA model (2004), a free access multi-region input–output (MRIO) model, based on the GTAP7 data base for the reference year 2004 (Narayanan and Walmsley 2008). While EUREAPA data have been transferred to consumption categories previously, other publically available MRIO models (e.g., EORA, WIOD) refer to emissions from sectoral production categories and thus hinder the transferability to EVS data (Lenzen et al. 2012, 2013; Dietzenbacher et al. 2013). MRIO models account imports to be produced with the respective technology of every exporting country. Hence, emissions embodied in trade are identified. Recent studies have shown that these emissions can account for a share of up to 50 % of entire country emissions (Ahmad and Wyckoff 2003; Barrett et al. 2013???). Compared to simple input–output (IO) models, assuming imported goods to be produced with the same technology as domestically produced goods and services, MRIO offers better accuracy and representativeness.

Mathematically, the HCF is expressed as the product of consumption C and respective emission factor EF summed over all consumption categories j:

$$\mathrm{HCF} = \sum C_j \times \mathrm{EF}_j \tag{1}$$

whereas the emission factor for every product j is calculated as the quotient of annual product-related emissions (PRE_j) and total German annual household consumption (TC_j).

$$\mathrm{EF}_j = \frac{\mathrm{PRE}_j}{\mathrm{TC}_j} \tag{2}$$

The harmonized consumer price index (HCPI) (Statistisches Bundesamt 2012) accommodates the impact of inflation between the reference years of both the EVS and EUREAPA, respectively, GTAP7, i.e.

$$\mathrm{Exp}_{i_{2004}} = \frac{\mathrm{Exp}_{i_{2008}}}{\mathrm{HCPI}_{i_{2008}}} \times \mathrm{HCPI}_{i_{2004}} \tag{3}$$

The model does not include a measurement of economic carbon efficiency gain, understood as the reduction in GWP per unit of output per sector between two different years. This indicator currently does not enable a reliable conclusion due to difficulties of excluding structural, monetary, weather and quantity effects. If future research provides reliable data, efficiency gains can be added to the model.

The current model divides household consumption into five sections:

- housing;
- transportation;
- food;
- goods and
- services.

Since local EVS data for each German state were not publically available, they had to be requested at the local statistical bureaus. These regional data are available solely for the standard household of each state. Thus, the authors assumed the national-level relation of expenditure categories of different household types by reference to the national standard household to remain the same on the local scale. Consumption data for different specific regional household types are hence based on the percentaged consumption data on the national-level related to the specific regional standard household.

EUREAPA does not allow a differentiation between direct and indirect emissions. Generally, people associate their respective contribution to climate change simply with the direct burning of fuels for vehicle transportation or residential heating (direct emissions). However, emissions that are embodied in the production of goods and services (indirect emissions) are an essential part of consumer impact (Minx et al. 2009). An examination of these effects becomes particularly important for transportation and housing. Life cycle emissions for different products are also not included in the EUREAPA model. Thus the determination of GWP had to be extended.

The *food section* is composed of nutrition as well as tobacco usage. Relevant consumption data are entirely based on the NVS, and emission data refer to the EUREAPA model. NVS differs between male and female consumption in each region. Thus, emission factors for each consumption category (e.g., dairy products, beverages, etc.) had to be calculated for an average person based on population data, provided by the Federal Statistical Bureau and the Oxford Equivalence Scale (OES) (2008).

Goods and services emission factors are entirely based on EUREAPA.

Transportation emissions are composed of vehicles usage such as automobiles or motor cycles, air travel, public transit and vehicle maintenance and related services. According to Pont (2007), emissions from motor vehicles have to consist of:

1. direct tailpipe emissions from fuel combustion in vehicles;
2. indirect well-to-pump (WTP) emissions as defined by Brinkmann et al. (2005) from the life cycle of fuels as well as;
3. indirect vehicle-related emissions from manufacturing, disposal, maintenance and repairs.

Due to the lack of appropriate EVS2008 expenditure data on gasoline, household equipment data [items/household] are applied. The German car fleet is assumed to be either gasoline or diesel driven, since other fuels account for less than 2 % in total (Kraftfahrtbundesamt 2011). Diesel and gasoline emissions per km are based on the free accessible database PROBAS, supported by the German Environmental Agency. Assuming an average distance of 14,100 km p.a. (Deutsches Institut für Wirtschaftsforschung 2011), a direct emission factor of 2.56 tons CO_2e/(a $\times$ vehicle) is calculated. Including WTP and manufacturing-related emissions, the overall emission factor accounts for 3.77 tons CO_2e/(a $\times$ vehicle) in Germany (Chester and Horvath 2011; Sullivan et al. 2010). Following a similar approach, the general motorcycle emission factor results in 1.22 tons CO_2e/(a $\times$ motorcycle). Emissions on public transit, air travel, fuels and lubricant as well as vehicle maintenance and reparations are entirely provided by EUREAPA (2004). However, air travel has to be analyzed more deeply. Generally, aviation GWP is composed of direct GHG emissions from the combustion of kerosene, indirect well-to-pump emissions from the kerosene life cycle and non-CO_2 atmospheric effects on global and local temperatures and weather patterns. Other emissions, e.g., from the life cycle of an aircraft are excluded from this model. Direct GHG emissions strongly depend on flight distance, aircraft type, number of stops, seat occupancy rate and seat class (Kollmuss and Crimmins 2009). In general, shorter flights tend to have higher emissions due to relatively higher emissions at takeoff and landing per passenger-mile. While direct aircraft emissions are based on EUREAPA, an additional 20 % are added for indirect WTP emissions of the kerosene life cycle. Yet other crucial factors are non-CO_2 warming and cooling effects of aviation. According to Kollmuss and Crimmins (2009), a common understanding of these effects does not exist. Generally, their impacts depend on various factors such as altitude, temperature, humidity and chemical composition of the air. Carbon footprint modelers usually take these effects into account through a multiplier such as the radiative forcing index (RFI) (Sausen et al. 2005). Although these simplifying assumptions increase the uncertainty of results, it remains the most applicable approach. The presented model applies a multiplier factor of 2 to cover indirect WTP emissions as well as non-CO_2 effects.

Housing GWP is subdivided into household energy, appliances, furniture, textiles, maintenance and rent (including construction). Under the consideration of electricity imports (International Energy Agency 2012; Arbeitsgemeinschaft Energiebilanzen 2012) from each country, the German energy mix emission factor was calculated via life cycle data of the respective electricity generation technology, leading to a factor of 0.617 kg CO_2e/kWh (Arbeitsgemeinschaft Energiebilanzen 2012; Group and Europe 2008). Assuming an average electricity price for 2008 of 22.49 ct/kWh, the relevant emission factor for the model results in 2.742 kg CO_2e/Euro. Life cycle emission factors for oil and gas are based on GEMIS 4.6 and PROBAS. The emission factor for district heating of 0.244 kg CO_2e/kWh was found in a recent study published by the German Federal Environmental Agency (Umweltbundesamt 2008). A detailed differentiation between coal and wood burning within households was not possible. The direct emission factor for 'coal and coal burning' thus is calculated with 1.86 kg CO_2e/Euro. Indirect emissions for 'coal, wood and the like' account for 15 % of direct emissions. All energy prices are based on the 2009 data from the Federal Ministry for Economy and Technology (BMWi) (2010) and calculated back to the reference year 2008 applying the HCPI (Statistisches Bundesamt 2012). Such data might significantly affect the HCF and have to be further investigated.

2.2 Limitations

The model is subject to a variety of uncertainties. Uncertainty analyses in most current studies in the field of carbon footprinting, including the present study, do not fulfill high standards. Error calculation is limited to the sum of uncertainties from each applied data set. Future research in this field should focus on qualified quantification of errors. We identify four sources of errors and biases: the MRIO (EUREAPA/GTAP7) model, the EVS, the NVS and assumptions made.

First, general uncertainties of MRIO models have to be considered. Uncertainty analysis for MRIO has been carried out by many authors (Wiedmann et al. 2008; Lenzen et al. 2010). Hertwich and Peters sum up errors that may arise from MRIO while simultaneously pointing out the difficulty in estimating their magnitude, i.e., IO data and factor intensities, currency conversions, inflation, different sector classifications and aggregation (Hertwich and Peters 2010). Lenzen et al. (2010) estimate a relative standard deviation for consumption-based emissions from MRIO at the national level of 5 %. Based on a study conducted by Wiedmann et al. (2008), Minx et al. (2013) expect much larger errors for carbon footprints of individual products.

The second sources of uncertainty are consumption and equipment data from EVS. As a quota sample of 0.2 % of the entire German population, the German Federal Statistical Office points out its comparatively high accurateness (Statistisches Bundesamt 2013). Although a detailed error analysis has not been performed for the EVS 2008, the high number of sample households combined with the coverage of nearly all social groupings makes uncertainties insignificant on a national level. On a local level, the number of sample household data specifications partly declined, leaving room for increased relative standard errors up to 16.7 % (Statistisches Bundesamt 2008a, b, c, d). We thus assume an overall relative standard error of around 5 %.

Nutrition data from NVS represent another source of uncertainty. For the model, NVS data were chosen over EVS data due to higher accuracy on the regional level. The German Federal Regional Studies and Planning Research Institute questioned 19,372 participants from 500 randomly chosen rural districts in Germany, divided in nearly all social groupings. In order to minimize errors, five methods were applied over a period of

13 months to identify main food patterns. An explicit error analysis has not been performed within the NVS (Max Rubner Institut 2008a, b).

Beyond that, the model includes a variety of assumptions that are subject to errors themselves. Most importantly, we assumed prices of living to be constant over all regions. Particularly between metropolitan and rural areas, differences in prices of consumer goods might significantly influence consumption. A measure to track such differences within Germany currently does not exist. Second, since drawing clear boundaries in order to classify EVS and NVS consumption categories to sector emissions from EUREAPA via concordance tables was not possible, assumptions were necessary, e.g., an equal distribution of expenditures per consumption category of each household type percentally related to the standard household of each state. Third, the application of HCPI to account for inflation between reference years is subject to statistical errors. Fourth, we assumed an additional 20 % to account for short-lived climate forcers (SLCF) from aviation that impact the radiative balance of the atmosphere. This is consistent with other studies (Jones and Kammen 2011; Aamaas et al. 2013) but increases the uncertainty of the model.

3 Results

Based on the EVS statistical separation in size, income and age, HCFs are produced for 578 different household types (34 household types on the national level and in 16 regions) by the model. The average German household consists of 2.1 persons with an annual disposable income of approximately 35 k Euro (Statistisches Bundesamt 2008a, b, c, d) (Fig. 1).

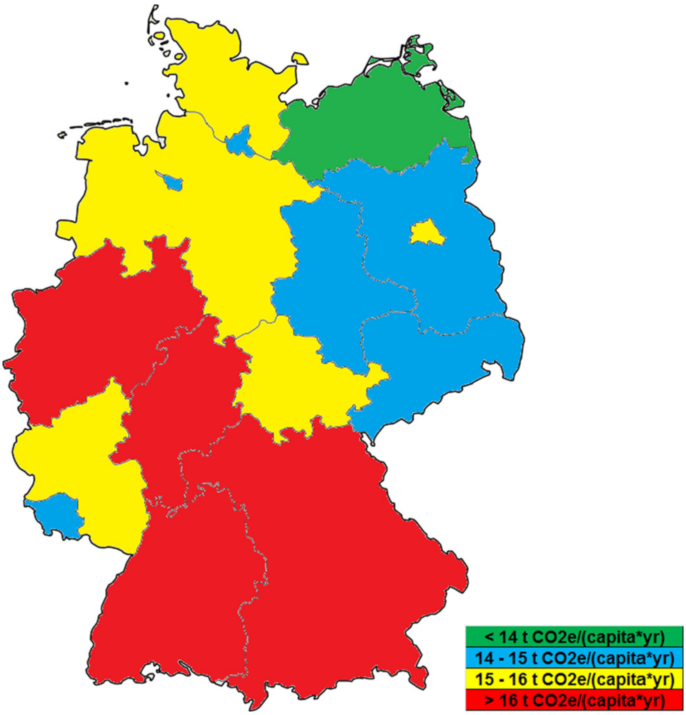

Fig. 1 Regional distribution of per capita carbon footprints in Germany

Figure 2 displays national-level results in detail. The model indicates an annual HCF of 30 tons CO_2e/year for this household type emitting 18 % directly and 82 % indirectly. A single person in Germany hence emits approximately 14.3 tons CO_2/a. This nearly equals the results of a study performed by Hertwich and Peters (2009) but is about 27 % higher than the results of the German CO_2 calculator (Umweltbundesamt 2012a). This comparatively large difference is essentially based on the usage of the MRIO model and life cycle data for transportation and household energy. In the order of contribution to total GWP, the housing section is responsible for the highest share of emissions (34 %) followed by transportation (24 %), food (18 %), goods (15 %) and services (9 %).

Transport emissions are almost entirely based on motor vehicle usage (66 %) and air travel (27 %) with a small share of public transit. This partly correlates to results from Aamaas et al. (2013) for Germany for which car usage was found to be responsible for 46 % of total climate impact, while air travel was 45 %. Differences in results of each transport mode are based on assumptions concerning both long- and short-lived greenhouse gases as well as the application of life cycle data.

Housing climate impact is dominated by energy- and waste-related emissions (65 %), while life cycle emissions for household appliances, furniture, textiles and construction account for 35 %. Main sources of emissions in the food category are dairy products, meat and other food (mostly candies, snacks and beverages) that together account for roughly 66 %.

Two main characteristics are identified to significantly influence a household's consumption and in turn its carbon footprint: household size and income. Household size is defined by the number of persons per household. Its impact on both HCF and per capita HCF is illustrated in Fig. 3a.

HCF increases with every additional person although with decreasing effect, whereas the per capita HCF decreases almost linearly. Decreasing per capita HCF with increasing household size is explained via economies of scale within a household. Every additional person offers a potential to share goods or services. Additionally, less waste is produced per capita. Another reason for decreasing CF is the increasing possibility of children per household which is not stated within the EVS. According to the OES, children tend to consume less (2008).

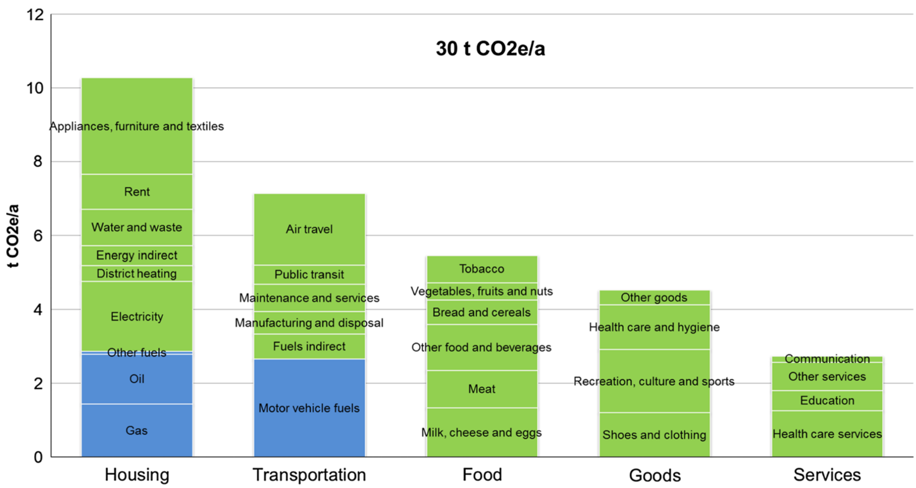

Fig. 2 Average German household carbon footprint (HCF)

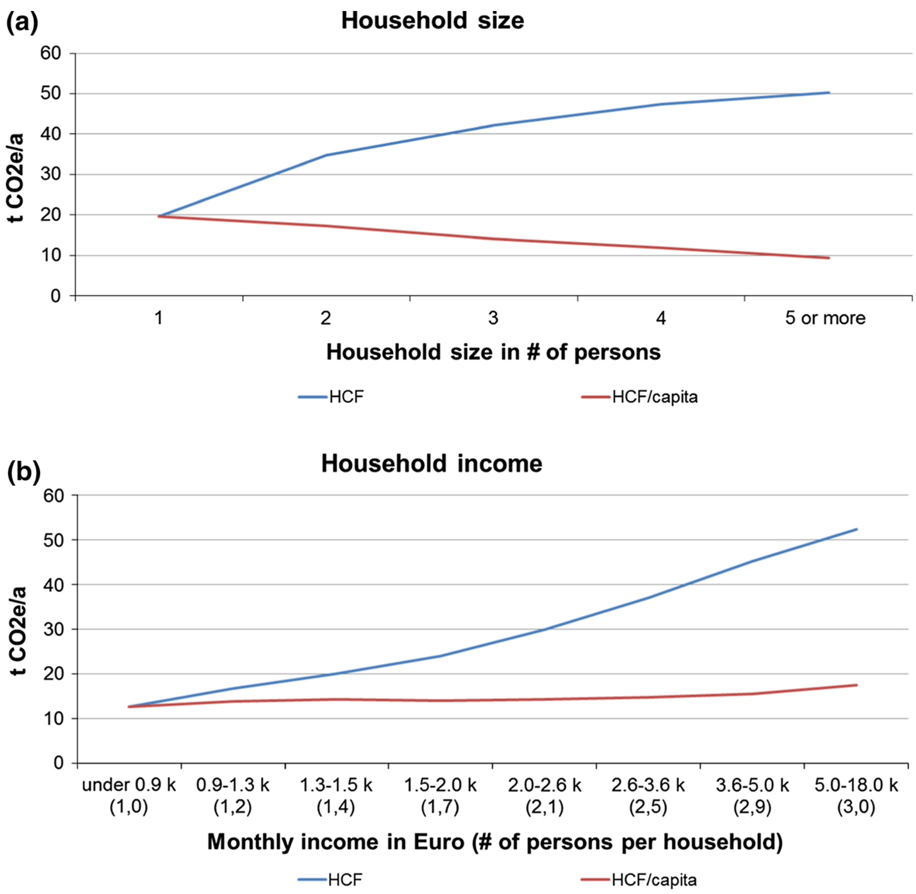

Fig. 3 Influence of main household parameter on HCF

Figure 3b depicts the HCF and per capita HCF of eight different income brackets. The relation between household income and size is based on the EVS 2008. The total HCF increases significantly with every income bracket, whereas per capita emissions are nearly flat except at very high incomes.

Strong regional distinctions are found between the German states. Figure 4 illustrates regional distinctions of total HCF, per capita HCF and HCF composition in Germany. Whereas the average household in Baden-Wuerttemberg is responsible for 35 tons CO_2e/year, its Mecklenburg-West Pomeranian counterpart is responsible for only 26 tons CO_2e/year. Strong HCF distinctions attenuate slightly for per capita emissions. Whereas an average person in North Rhine-Westfalia, Baden-Wuerttemberg or Hesse emits 16 tons CO_2e/year, the Mecklenburg-West Pomeranian average person is responsible for 13 tons CO_2e/year.

Similarly, the composition of the average HCF differs between regions. While the order of contribution to total household emissions remains steady over all regions (transportation followed by housing, food, goods and services), the shares of each section deviate from one another. Housing ranges from 31 to 40 %, transportation from 18 to 27 %, food from 16 to 23 %, goods from 12 to 17 % and services from 6 to 11 % of HCF.

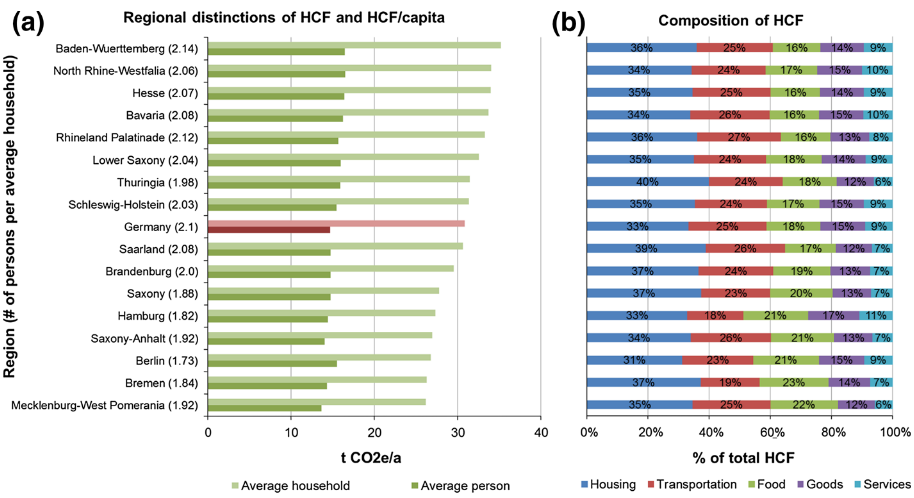

Fig. 4 Regional distinctions of HCF, per capita HCF and HCF composition

The results do not demonstrate correlation between HCF and population density in either magnitude or in composition. This is consistent with other studies, e.g., Heionen and Junnila (2011). Metropolitan areas such as Berlin, Hamburg and Bremen demonstrate substantial distinctions in HCF composition. Regional distinctions in population density, especially between rural regions such as Mecklenburg-West Pomerania and urban regions such as Berlin, may be a contributing factor.

Table 1 illustrates the per capita HCF of two significantly different household types. Household size, income and age are based on the EVS 2008 survey. The first household is located in Baden-Wuerttemberg, a rather rural region. With a size of 1.2 persons and disposable income of about 13 k Euro, it is a comparatively low-income household. Household type two is located in Hamburg and consists of 3.0 persons with an annual disposable income of around 84 k Euro. Thus it is considered as a rather high-income household in an urban area.

Significant distinctions become obvious between the two cases. Both household types have approximately similar per capita HCF, with 16 tons CO_2e/(year × household) for type one in Baden-Wuerttemberg and 18 tons CO_2e/(year × household) for type two in Hamburg. With a share of 26 %, direct emissions from fuel combustion are considerably higher in household one compared to household two with 13 %. Also, the composition of direct emission strongly differs. Household one is responsible for 2.3 times as much per capita emission from vehicle fuels as household two in Hamburg. Two main explanations can be quoted: (1) economies of scale within household two reduce per capita emissions

Table 1 Regional household comparison

	HCF/capita (tons CO2e/year)	Housing (%)	Transportation (%)	Food (%)	Goods (%)	Services (%)	Direct (%)	Indirect (%)
Household one	15.6	33.8	29.4	19.5	11.3	6.0	25.8	74.2
Household two	17.5	31.4	17.3	14.1	18.4	18.8	13.3	86.7

for vehicle usage, and (2) population density is roughly eight times higher in Hamburg than in Baden-Wuerttemberg (Statistische Aemter des Bundes und der Laender 2012). Its urban characteristics thus might lead to lower vehicle usage over all.

In the housing section, oil and gas are responsible for nearly all direct emissions. The contribution of emissions for oil burning is 1.5 times higher in Baden-Wuerttemberg, whereas emissions from gas burning remain nearly steady across the two households. Household energy in general, taking into account all energy carriers, waste and water, is responsible for 3.5 tons CO2e/(year × capita) in Baden-Wuerttemberg but only for 2.7 tons CO2e/(year × capita) in Hamburg. By comparison, 'household appliances, furniture and textiles' in household two are responsible for approximately double the emissions compared to household one. Vehicle-related emissions, taking into account all emissions from fuel, manufacturing, disposal as well as parts and maintenance, in Baden-Wuerttemberg (3.9 tons CO2e/year) also roughly double the emissions of Hamburg (1.9 tons CO2e/year), leading to considerably higher emissions for transportation overall. Per capita GWP from food of household one is 0.6 tons CO2e/year higher than of household two. This is mainly caused by significantly higher emissions from 'tobacco' and 'candies, snacks and other food.' For goods and services, in contrast, household two is responsible for higher emissions. Emissions from services of household two are 3.5 times higher than from household one, and emissions from goods are 1.8 times higher from household two compared to household one. In the services section, emissions are mainly from the extremely high share of 'health care.' In contrast, higher goods emissions are caused by higher expenses on 'jewelry and other goods' as well as higher expenses over all products.

4 Outlook and policy discussion

The results of this study, i.e., differences in footprints at regional scales, suggest that some locations would be more impacted by a carbon tax. These differences are driven by demographics, which vary much more at subregional scales. Other important drivers are home size and location, which also vary within metropolitan regions. German HCF do not vary as much as USA due in part to more uniform electricity mix and less inequality; however, strong differences within regions, particularly urban cores and suburban areas, can be expected based on the results of this study. Nevertheless, higher spatial resolution footprinting in Germany will be necessary to fully understand the imitations of climate policy on different German sub populations and which policies may be more appropriate in different locations.

Based on the results of this study, we identify two main areas of operation for future mitigation policy making: generation of awareness and tailored policies. In order to ensure realization of eco efficiency provisions, engagement of populations at the local level is essential. Many authors have discussed effective strategies of community-based social marketing, including persuasive messaging, goal setting, commitments, norms, feedback, prompts, incentives, social diffusion and competitions, among other strategies (Bullard 1975; Andreasen 1994; Steg and Vlek 2009; Abrahamse et al. 2005). However, pure communication targeting human conscience might not suffice to achieve significant improvements, especially on the country level.

While present policies in Germany mainly focus on direct consumption, e.g., de-carbonizing electricity generation or energy efficiency, indirect emissions from household consumption have been mostly disregarded so far (Lenzen et al. 2004). Approaches that have been discussed targeting indirect consumption, e.g., via eco taxes on products, have not been explored sufficiently. An eco-tax for products for example is challenging due to the complexity of ensuring the required life cycle data for all products and the lack of a standardized approach. Regulating income or expenditures, while effective at reducing emissions, would not be possible, or even desirable, given the growth priorities of nearly all economies. Hence, novel approaches are needed to effectively reduce indirect household-related emissions.

Binding targets for households, in the following referred to as cap, deserves exploration as a policy to decrease HCF. Many authors have discussed the usability of carbon allowances or personal carbon trading for households, although mainly focusing on direct consumption (Fawcett 2004). Field testing showed some promising results, although the idea is certainly not without its challenges. The multitude of household types and the lack of knowledge concerning impact and interaction of various effects, e.g., income, size, and region, currently constitute a barrier to feasibility. However, results of this study offer useful information for future concepts. Another option in this regard might be the coupling of cap and tax. Cap and trade as well as cap and dividend systems have been discussed in literature sufficiently and implemented successfully on the industrial level (Ellerman and Buchner 2007; Skjærseth and Wettestad 2009; Kunkel and Kammen 2011). A to-be-developed approach may be a composition of both approaches, adapted to households. Based on a regionalized carbon footprint standard, caps could be introduced and adjusted each year. Similar to a cap and trade approach, a prize is set for each ton of CO_2e emitted that individuals have to convey within their taxes. Within this approach, MRIO emission inventory data are allocated to national as well as regional consumption data based on a standardized approach in order to calculate the per capita CF of different household types and regions. A cap is set on the per capita CF and a prize defined for each ton emitted above. Thereupon, households will have to pay an overall carbon tax each year.

Although this approach might not only lead to significant household de-carbonization but contribute to income equalization between high- and low-income households, major challenges remain. One crucial challenge will be to find an appropriate design. A person living in a rural household might be reliant on a vehicle and thus already pays a sufficient amount of fuel-eco-tax. In this context, a progressive or tiered tax system might be appropriate, i.e., the prize for over-consumption increases with every additional ton emitted. Another challenge would be the consideration of efficiency provisions. In this context, the household carbon tax might have to be adapted.

5 Conclusion

This study determined the carbon footprint of German households at different regional scales and demographic characteristics. Substantial regional differences were identified in both the magnitude and composition of carbon footprints. Two characteristics have been identified to significantly influence HCF: size and income. Since income and average household size vary between regions, further influenced by population density and state of economic development, we identified considerable regional differences in the size and composition of German household carbon footprints.

While households dispose of a variety of cash-positive mitigation actions that might easily be targeted by tailored incentives, current policies focus almost exclusively on the reduction of direct emissions, e.g., by de-carbonizing energy generation and encouraging energy efficiency. Household indirect consumption has been insufficiently targeted, even though these emissions account for the by far largest share of total household emissions. In this context, we suggest more comprehensive community-based social marketing programs, in combination with a cap and tax approach based on a regionalized carbon footprint calculator, might be able to strongly contribute to sustainable household consumption and income equalization. The implementation of the described cap and tax system for households requires further research and significant improvements of regional data quality, a standardized approach for calculation and improvements in the field of MRIO modeling. This study may help to define some basic requirements.

References

Aamaas, B., Borken-Kleefeld, J., & Peters, G. P. (2013). The climate impact of travel behavior: A German case study with illustrative mitigation options. Environmental Science & Policy, *33*, 273–82. http://linkinghub.elsevier.com/retrieve/pii/S1462901113001366.

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, *25*(3), 273–291. http://linkinghub.elsevier.com/retrieve/pii/S027249440500054X.

Ahmad, N., & Wyckoff, A. (2003). Carbon dioxide emissions embodied in international trade of goods. http://search.oecd.org/officialdocuments/displaydocumentpdf/?doclanguage=en&cote=dsti/doc(2003)15.

Andreasen, A. R. (1994). Social marketing—Its definition and domain. *Journal of Public Policy & Marketing, 13*(1), 108–114.

Argonne National Laboratory. (2012a). The greenhouse gases, regulated emissions, and energy use in transportation (GREET 2.8a). http://www.transportation.anl.gov/modeling_simulation/GREET/index.html.

Argonne National Laboratory. (2012b). The greenhouse gases, regulated emissions, and energy use in transportation model (GREET 1.8c). http://www.transportation.anl.gov/modeling_simulation/GREET/index.html.

Arbeitsgemeinschaft Energiebilanzen. (2012). Bruttostromerzeugung in Deutschland von 1990 bis 2011 nach Energieträgern. Berlin. http://www.ag-energiebilanzen.de/viewpage.php?idpage=1.

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., et al. (2013) Consumption-based GHG emission accounting: A UK case study. *Climate Policy*, *13*(4), 451–470. http://www.tandfonline.com/doi/abs/10.1080/14693062.2013.788858.

Berkhout, P. H. G., Muskens, J. C., & Velthuijsen, J. W. (2000). Defining the rebound effect. *Energy Policy, 28*, 425–432.

Birol, F., & Keppler, J. H. (2000). Prices, technology development and the rebound effect. *Energy Policy, 28*, 457–469.

Brinkman, N., Wang, M., Weber, T., & Darlington, T. (2005). Well-to-wheels analysis of advanced fuel/vehicle systems—A North American study of energy use, greenhouse gas emissions, and criteria pollutant emissions.

Bullard, C. W., & Herendeen R. A. (1975) Energy impact of consumption decisions. *Proceedings of IEEE*, *63*(3), 484–493. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1451705.

Bureau of Transportation Statistics. (2012). http://bts.gov.

Bundesministerium fuer Wirtschaft und Technologie. (2010). Energie in Deutschland—Trends und Hintergründe zur Energieversorgung. Berlin.

Chester, M., & Horvath, A. (2011). Vehicle manufacturing futures in transportation life-cycle assessment. *Research Reports, Institute of Transportation Studies*. Berkeley: UC Berkeley. http://www.escholarship.org/uc/item/1qp3f0vc.

Deutsches Institut für Wirtschaftsforschung. (2011). Kraftfahrzeugverkehr 2010—Weiteres Wachstum und hohe Bedeutung von Firmenwagen. Berlin. http://www.diw.de/documents/publikationen/73/diw_01.c.389477.de/11-48-3.pdf.

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C., & Vandenbergh, M. P. (2009) Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences USA*, *106*(44), 18452–18456. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2767367&tool=pmcentrez&rendertype=abstract.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M. P., & de Vries, G. J. (2013). The construction of world input–output tables in the WIOD project. *Economic Systems Research, 25*, 71–98.

DIN-EN-ISO. 14067: Carbon Footprint von Produkten—Entwurf. (2012).

Ellerman, A. D., & Buchner, B. K. (2007). The European Union emissions trading scheme: Origins, allocation, and early results. *Review of Environmental Economic Policy, 1*(1), 66–87.

EUREAPA. (2004). Regional comparison (2004—Baseline) from carbon footprint (all GHGs).

Fawcett, T. (2004). Carbon rationing and personal energy use. *Energy & Environment, 15*(6), 1067–1083.

Finkbeiner, M. (2009). Carbon footprinting—Opportunities and threats. *The International Journal of Life Cycle Assessment*, *14*(2), 91–94. http://www.ireea.cn/paddy/pd_admin/web_edit/uploadfile/20100409231728286.pdf.

Finkbeiner, M., Hoffmann, R., Ruhland, K., Liebhart, D., & Stark, B. (2006). Application of life cycle assessment for the environmental certificate of the Mercedes-Benz S-Class. *The International Journal of Life Cycle Assessment, 11*(4), 240–246.

Group, R., & Europe, C. (2008) Statistical yearbook.

Greening, L. A., Greene, D. L., & Difiglio, C. (2000). Energy efficiency and consumption—The rebound effect—A survey. *Energy Policy, 28*, 389–401.

Heinonen, J., & Junnila, S. (2011). Implications of urban structure on carbon consumption in metropolitan areas. *Environmental Research Letters*, *6*(1), 014018. http://stacks.iop.org/1748-9326/6/i=1/a=014018?key=crossref.d8d514fafda1b003bad19d08e1b3643e.

Hertwich, E. G., & Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology*, *43*(16), 6414–6420. http://www.ncbi.nlm.nih.gov/pubmed/19746745.

Hertwich, E. G. (2005). Consumption and the rebound effect—An industrial ecology perspective. *Journal of Industrial Ecology, 9*, 85–98.

Hertwich, E. G., & Peters, G. P. (2009) Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology*, *43*(16), 6414–6420. http://www.ncbi.nlm.nih.gov/pubmed/19746745.

Hertwich, E. G., & Peters, G. P. (2010). Multiregional input–output database OPEN: EU technical document OPEN: EU multiregional input–output database.

International Energy Agency. (2012). Statistics and balances. Paris: International Energy Agency. http://www.iea.org/stats/.

Jones, C., & Kammen, D. M. Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science & Technology*.

Jones, C. M., & Kammen, D. M. (2011) Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environmental Science & Technology*, *45*(9), 4088–4095. http://www.ncbi.nlm.nih.gov/pubmed/21449584.

Kunkel, C. M., & Kammen, D. M. (2011). Design and implementation of carbon cap and dividend policies. *Energy Policy*, *39*(1), 477–486. http://linkinghub.elsevier.com/retrieve/pii/S0301421510006622.

Kollmuss, A., & Crimmins, A. M. (2009). Carbon offsetting & Air Travel Part 2: Non-CO_2 emissions calculations (SEI Discussion Paper). Stockholm (pp. 1–43).

Kraftfahrtbundesamt. (2011). Bestand an Personenkraftwagen am 1. Januar 2012 nach Bundesländern und ausgewählten Kraftstoffarten. http://www.kba.de/cln_030/nn_269000/DE/Statistik/Fahrzeuge/Bestand/EmissionenKraftstoffe/2012__b__emi__eckdaten__absolut.html.

Laitner, J. A. S., Ehrhardt-martinez, K., & Mckinney, V. (2009) Examining the scale of the behaviour energy efficiency continuum. 217–223.

Lenzen, M., Dey, C., & Foran, B. (2004). Energy requirements of Sydney households. *Ecological Economics*, *49*(3), 375–399. http://linkinghub.elsevier.com/retrieve/pii/S0921800904001107.

Lenzen, M., Wood, R., & Wiedmann, T. (2010). Uncertainty analysis for multi-region input–output models—A case study of the UK'S carbon footprint. *Economic Systems Research, 22*(1), 43–63.

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science and Technology, 46*(15), 8374–8381.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-regional input–output database at high country and sector resolution. *Economic Systems Research, 25*, 20–49.

Max Rubner Institut. (2008a). Nationale Verkehrstudie II—Ergebnisbericht (Teil 1). Karlsruhe.

Max Rubner Institut. (2008b). Nationale Verkehrstudie II—Ergebnisbericht (Teil 2). Karlsruhe.

McKenzie-Mohr, D. (2011). *Fostering sustainable behavior: An introduction to community-based social marketing*. Cabriola Island: New Society Publishers.

Minx, J. C., Wiedmann, T., Wood, R., Peters, G. P., Lenzen, M., Owen, A., et al. (2009). Input–output analysis and carbon footprinting: An overview of applications. *Economic Systems Research, 21*(3), 187–216.

Minx, J., Baiocchi, G., Wiedmann, T., Barrett, J., Creutzig, F., Feng, K., et al. (2013). Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters*, *8*(3), 035039. http://stacks.iop.org/1748-9326/8/i=3/a=035039?key=crossref.32c84bcdbabd115e117d24e9c54b71a1.

Narayanan, B. G., & Walmsley, T. L. (2008). *Global trade, assistance, and production—The GTAP 7 data base*. USA: Center for Global Trade Analysis, Purdue University.

Pont, J. (2007). Full fuel cycle assessment—well-to-wheels energy inputs, emissions and water impacts. *State plan to increase the use of non-petroleum transportation fuels, assembly bill 1007—Alternative transportation fuels plan proceeding. TIAX LLC Consultant Report*. Cupertino.

Sausen, R., Isaksen, I., Grewe, V., Hauglustaine. D., Lee, D. S., Myhre, G., et al. (2005). Aviation radiative forcing in 2000: An update on IPCC (1999). Meteorologische Zeitschrift, *14*(4), 555–561. http://openurl.ingenta.com/content/xref?genre=article&issn=0941-2948&volume=14&issue=4&spage=555.

Seyfang, G., Lorenzoni, I., & Nye, M. (2007). Personal Carbon Trading: Notional concept or workable proposition? Exploring theoretical, ideological and practical underpinnings. Norwich, UK

Skjærseth, J. B., & Wettestad, J. (2009). The origin, evolution and consequences of the EU emissions trading system. *Global Environmental Politics, 9*(2), 101–122.

Sorrell, S., & Dimitropoulos, J. (2008). The rebound effect—Microeconomic definitions, limitations and extensions. *Ecological Economics, 65*, 636–649.

Statistisches Bundesamt. (2008a). Wirtschaftsrechnungen—Einkommens- und Verbraucherstichprobe 2008—Aufwendungen privater Haushalte für den Privaten Konsum (Fachserie 15 Heft 5). Wiesbaden.

Statistisches Bundesamt. (2008b). Wirtschaftsrechnungen—Einkommens- und Verbraucherstichprobe 2008—Aufwendungen privater Haushalte für Nahrungsmittel, Getränke und Tabakwaren (Fachserie 15 Heft 3). Wiesbaden.

Statistisches Bundesamt. (2008c). Wirtschaftsrechnungen—Einkommens- und Verbraucherstichprobe 2008—Ausstattung privater Haushalte mit ausgewählten Gebrauchsgütern (Fachserie 15 Heft 1). Wiesbaden.

Statistisches Bundesamt. (2008d). Wirtschaftsrechnungen—Einkommens- und Verbraucherstichprobe 2008—Einnahmen und Ausgaben privater Haushalte (Fachserie 15 Heft 4). Wiesbaden.

Statistisches Bundesamt. (2012). Preise—Harmonisierte Verbraucherpreisindizes, Deutschland. Wiesbaden: Statistisches Bundesamt

Statistisches Bundesamt. (2013). Einkommens- und Verbrauchsstichprobe (EVS). https://www.destatis.de/DE/Meta/AbisZ/Einkommens_Verbrauchsstichprobe.html.

Statistische Aemter des Bundes und der Laender. (2012). Gebiet und Bevölkerung—Fläche und Bevölkerung. http://www.statistik-portal.de/Statistik-Portal/de_jb01_jahrtab1.asp.

Sullivan, J. L., & Burnham, A., & Wang, M. (2010). Energy-consumption and carbon-emission analysis of vehicle and component manufacturing. Argonne.

Steg, L., & Vlek, C. (2009) Encouraging pro-environmental behaviour: An integrative review and research agenda. *Journal of Environmental Psychology*, *29*(3), 309–317. http://linkinghub.elsevier.com/retrieve/pii/S0272494408000959.

The Carbon Trust. (2007). *Carbon footprint measurement methodology—Version 1.1*. London. http://www.carbontrust.co.uk.

Umweltbundesamt. (2012a). Der CO2-Rechner., Deutschland. http://uba.klimaktiv-co2-rechner.de/de_DE/page/.

Umweltbundesamt. (2012b). Prozessorientierte Basisdaten für Umweltmanagement-Instrumente—PROBAS Datenbank. Umweltbundesamt. http://www.probas.umweltbundesamt.de/.

Umweltbundesamt. (2008). Bestimmung spezifischer Treibhausgas-Emissionsfaktoren für Fernwärme (Forschungsbericht 360 16 008; UBA-FB 001145). Dessau-Roßlau. http://www.umweltdaten.de/publikationen/fpdf-l/3476.pdf.

What are equivalence scales? (2008). Paris. http://www.oecd.org/social/familiesandchildren/35411111.pdf.

Wiedmann, T., Minx, J. (2007). *A definition of "Carbon Footprint"*. ISA Research and Consulting, editor (pp. 1–11). Durham: Nova Science Publishers.

Wiedmann, T., Lenzen, M., & Wood, R. (2008). Uncertainty analysis of the UK-MRIO model—results from a Monte-Carlo analysis of the UK multi-region input–output model (Embedded Emissions Indicator). London.